RESERVOIR EVAPORATION IN THE WESTERN UNITED STATES

Current Science, Challenges, and Future Needs

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Reservoir evaporation represents a substantial loss of available water. Improved understanding, estimation, and forecasting of evaporation rates will help to manage this water loss more efficiently, particularly when water is scarce.

Water scarcity has become—and will remain—the greatest threat to food security, human health, and natural ecosystems during the twenty-first century (Seckler et al. 1999). More than one billion people living in arid regions are expected to face water scarcity by 2025, forcing reductions in per capita water use across multiple sectors, including food production (Seckler et al. 1999; Oki and Kanae 2006). Worldwide, but especially in arid regions, the effects of climate change and rising temperatures threaten to reduce available surface water through enhanced evaporation, especially in surface storage reservoirs. Recently, reservoirs across the southwestern United States have been experiencing extremely low water levels, with water demands increasing and supplies decreasing (Figs. 1, 2; Fulp 2005; Barnett and Pierce 2008). The effective capacity of water stored by the mountain snowpack has been reduced by recent intense droughts, as well as from earlier snowmelt and runoff as a result of rising temperatures, rain-on-snow events, and enhanced dust on snow (Christensen et al. 2004; Seager et al. 2007; Barnett and Pierce 2008;

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Overpeck and Udall 2010; Rasmussen et al. 2014).

Currently, freshwater demands in arid and semiarid regions of the western United States exceed the available supply in a given year (Fig. 2), increasing the dependence on reservoirs and water-harvesting techniques (see sidebar "The cost of water in the southwestern United States" for more information; WWAP 2015). Water consumption in the western United States has been reduced in recent years through programs such as "conservation at the spigot" (e.g., Southern Nevada Water Authority 2014; Addink 2005; *Las Vegas Sun*, 27 April 2015), but additional conservation is still needed in order to meet current and future water demands. One mitigation strategy for water scarcity

Fig. 1. Low water levels at Lake Mead (Nevada), shown as white bathtub rings and highlighting the importance of quantifying reservoir evaporation (credit: Kyle Simourd, CC 21). Between the high water mark in 1942 (33,000,000,000 m^3) and the present photo (2015), the lake has lost about 66% (21,000,000,000 m^3) of its water, based on stage and storage data at Hoover Dam (http://goo.gl/fktcft). According to the U.S. Bureau of Reclamation, Lake Mead's water level reached an all-time low in May 2016 (Jacobo 2016).

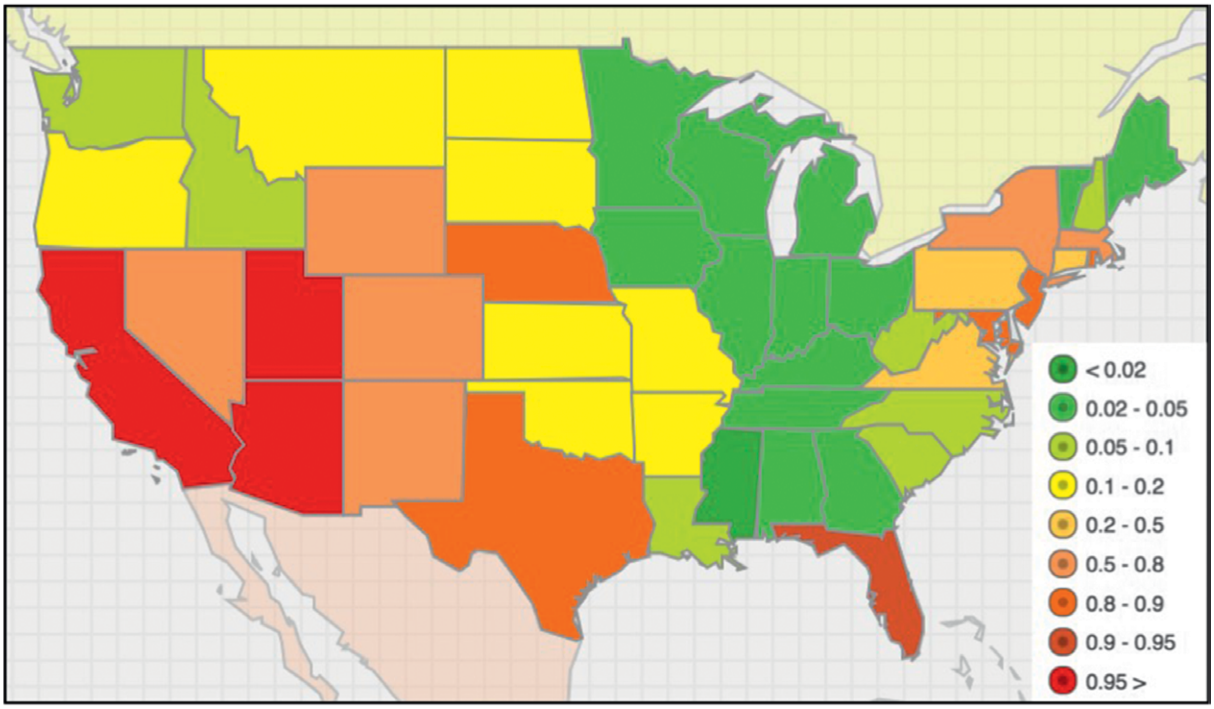

Fig. 2. Water stress level as defined by Pfister et al. (2009) for the United States. Levels for each state indicate the ratio of water withdrawal to hydrologic availability, along with a variation factor to account for the variability in precipitation.

is to manage and store water more efficiently at the source. Reservoirs act as critical buffers to ensure agricultural and municipal water deliveries throughout the entire United States (Fig. 3), to provide recreation and flood control, and to generate hydroelectric power, yet they often contribute to increased evaporative water losses as a result of the presence of extensive open water (Goldsmith and Hildyard 1984, chapter 5). Evaporation is a key component of the water budget for reservoirs in different climate regimes, as shown in Fig. 4 for the arid and semiarid climate of Lake Tahoe and Lake Mead and the humid climate of Lake Superior. Therefore, reducing reservoir evaporation offers a potential option for "water conservation at the source" through the concepts of *smart location* (i.e., applying scientific understanding to specific sites with respect to their climatic and geographical setting) and *geoengineering* (i.e., using engineering principles to reduce reservoir evaporation regardless of location) (see sidebar "Conservation at the source" for more information).

The importance of reservoir evaporation has been understated in some water resource analyses because of practical and logistical challenges and large uncertainties in its estimation (U.S. Bureau of Reclamation 2012), such that state-of-the-art methods are not often used in operational water resource management (Lowe et al. 2009). Instead, the pan evaporation method, which is considered to be one of the least accurate approaches (Grayson et al. 1996; Alvarez et al. 2006; Trask 2007; Tanny et al. 2008; Chu et al. 2012), is commonly used to quantify reservoir evaporation rates. Given the increasing need for efficient water storage and the current lack of information on reservoir evaporative losses, this article discusses the growing need to quantify and forecast reservoir evaporation using state-of-the-art methods for measuring, modeling, and managing evaporative losses in the United States while also highlighting the value of cooperation between researchers and water managers.

To begin the conversation on reservoir evaporation, management, and operations, the University of Colorado Boulder and the Desert Research Institute (DRI) in Reno, Nevada, hosted a workshop (http://clouds.colorado.edu/home.html) in October 2015 to bring together recognized experts in the fields of atmospheric science, hydrology, land use, and water resource management (Livneh et al. 2016). This paper builds on the findings of the 2015 workshop. The main conclusion from the workshop was the recognition of the increased importance of reservoir evaporation loss and the need to bring new ideas and state-of-the-art practices for the estimation of reservoir evaporation into operational use in the United States for modern water resource managers.

THE COST OF WATER IN THE SOUTHWESTERN UNITED STATES

Depending on the location, evaporative losses from reservoirs can be large, sometimes even exceeding the consumptive water usage (Wurbs and Ayala 2014; Figs. 2, 3). The annual water balance for Lake Superior (the largest of the North American Great Lakes) and Lake Tahoe (the largest alpine lake in North America), for example, indicates that evaporation rates can be as high as 40%–60% of the total reservoir output (Fig. 4) and also greatly exceed precipitation rates in arid regions. Recent estimates using the eddy correlation method from Lake Mead [the largest reservoir in the Colorado River basin (CRB) and situated in a desert] show recent annual evaporation exceeding 2 m (Moreo and Swancar 2013). Along with estimates from Lake Powell (~1.2 m yr^{-1}; Clayton 2004; R. Clayton 2008, unpublished report), the second largest reservoir in the CRB, upstream of Lake Mead, and also located in a desert (Fig. 5), the two reservoirs' evaporation totals roughly 1,400,000,000 m^3 (1,400,000,000,000 L) of water annually.[SB1] This represents about 15% of the annual upper basin allocation of water resources among the Colorado River basin states and is approximately 5–6 times the annual water usage of a medium-sized city in the United States, such as Denver, Colorado (227,000,000,000–303,000,000,000 L yr^{-1}; Denver Water, www.denverwater.org/your-water/water-supply-and-planning/water-use). This is also equivalent to the water consumption of 3 million households in the arid state of Colorado[SB2] (Waskom et al. 2011). Assuming a residential water price of $1 per 3,785 L (1,000 gal) of water (2016 water rates in Colorado; Denver Water), that volume of evaporated water is worth up to $370 million annually. Similar examples of the costs of large evaporative loss exist for other lakes and reservoirs in arid and semiarid regions around the world (e.g., Sadek et al. 1997; Stanhill 1994; Shiklomanov 2000; Vallet-Coulomb 2001; Gökbulak and Özhan 2006; Al-Khlaifat 2008).

[SB1] This relates to 1,100,000 acre-feet or 370,000,000,000 gal (1 acre-foot = 1,233.5 m^3 = 325,851.4 gal = 1,233,481.8 L).

[SB2] Assuming about 570,000 L of water per year for residential home and lawn usage.

CURRENT AND FUTURE CHALLENGES.

Physical drivers and complexities of reservoir evaporation. At first glance, the physical "drivers" of reservoir evaporation might seem relatively straightforward given that the flux of water vapor from a reservoir is largely governed by the magnitude of the vapor pressure gradient between the water surface and the overlying air. This gradient is determined by the surface temperature of the water, the absolute humidity in the atmosphere (e.g., vapor pressure), and the amount of turbulent mixing of air, resulting in high evaporation rates when the water is warm and the air is cold, dry, windy, and unstable. This description, however, belies some of the hidden physical drivers, time-scale-dependent feedbacks, and complex heterogeneities that govern reservoir evaporation rates (Lenters et al. 2014): namely, 1) evaporation is an energy-consuming process that decreases water temperature, thus reducing the surface vapor pressure and the rate of evaporation (i.e., a negative feedback); 2) the rate at which this feedback occurs, as well as responses to other energy budget drivers, depends on both the intensity and time scale of the meteorological forcing and the thermal inertia of the water body (e.g., mean depth, ice cover); and 3) forcing fields such as air temperature, water temperature, humidity, and wind-induced turbulent mixing are heterogeneous, particularly on small reservoirs with complex geography (e.g., topography, vegetation) and large, deep water bodies with strong lake–land boundary layer modifications and horizontal gradients (e.g., surface temperature, ice cover).

Given the abovementioned considerations, the meteorological and limnological factors that influence reservoir evaporation go well beyond wind and humidity. This includes not only integrative energy budget terms such as net radiation, which provides much of the available energy for latent and sensible heat fluxes, but also individual factors such as incoming shortwave radiation (dependent on latitude, cloud cover, and elevation), surface albedo (dependent on snow/ice cover and light attenuation), reservoir heat storage (dependent on mean depth, volume, clarity, and ice thickness), incoming longwave radiation (dependent on atmospheric profiles of temperature, humidity, and cloud cover), sediment heat flux, and advective sources of energy (i.e., precipitation, groundwater, surface inflows, and outflows). Variations in reservoir water level can also affect evaporation rates through changes in water surface temperature (Rimmer et al. 2011) or, more directly, by changing the surface area of the reservoir itself and therefore the volumetric loss of water. Finally, consideration must also be given to the effect of managed water releases and reservoir–atmosphere feedbacks, such as changes in atmospheric stability or variations in the local wind field caused by thermal gradients

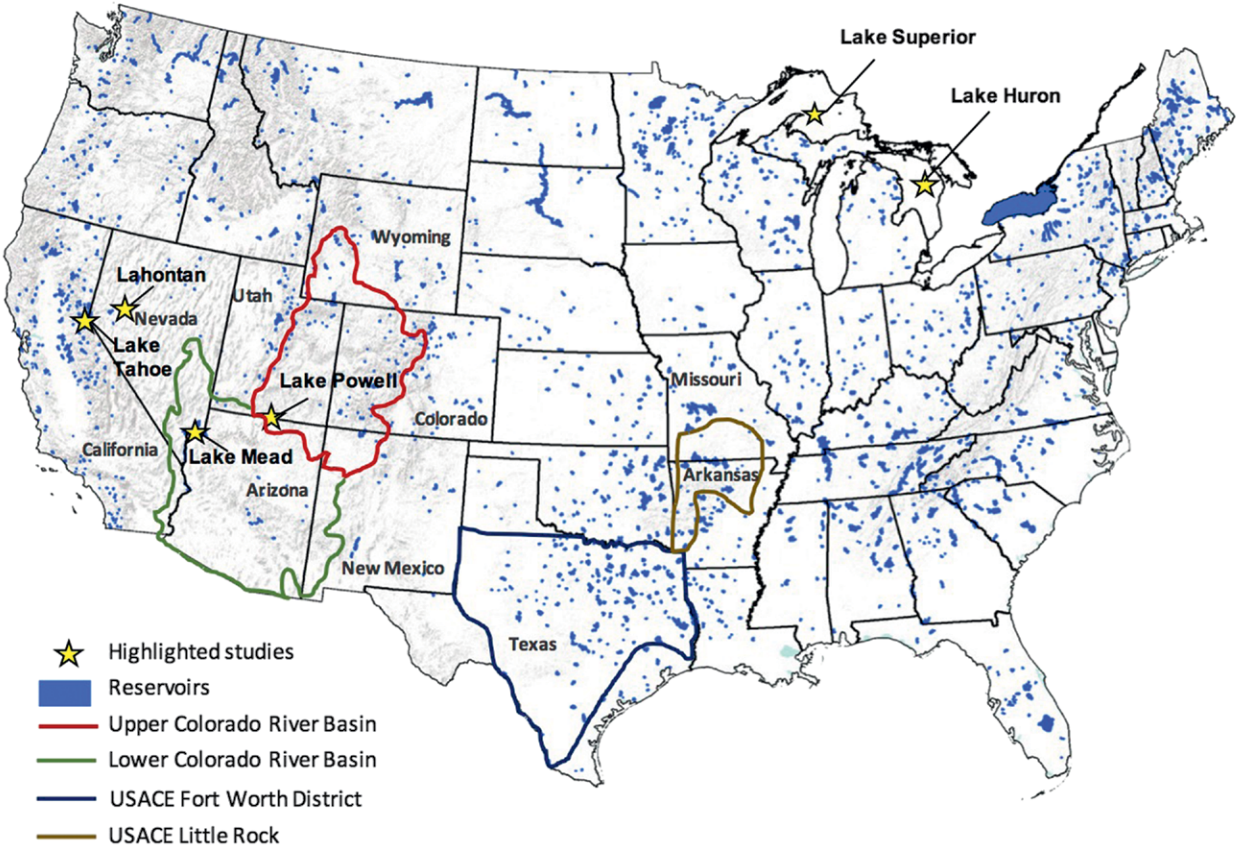

Fig. 3. Map showing the distribution of reservoirs throughout the United States (blue areas) as defined by the U.S. Committee on Large Dams (USCOLD) database. Reservoir evaporation studies discussed in this paper are highlighted by the yellow stars. Source: USCOLD Register of Dams, http://sedac.ciesin.columbia.edu/data/set/grand-v1-reservoirs-rev01.

CONSERVATION AT THE SOURCE

Conservation at the Source (CAS) focuses on two methods using scientific principles to determine the best location and management of current and future reservoirs: smart location and geoengineering. Using the method of smart location, reservoirs can be characterized based on their evaporation rates using scientific criteria that are primarily linked to the atmospheric and reservoir properties. Some of the physical properties include elevation, wind speed and direction, air temperature and humidity, depth and area, channelization based on length-to-width aspect and reservoir shoreline slope of the reservoir, and upwind vegetation and land use. In addition to using these criteria for consideration of new reservoirs, they can be used to characterize existing reservoirs that might be candidates for increasing reservoir volume.

Evaporation can also be artificially reduced using engineering methods such as i) applying organic monolayers (e.g., Langmuir and Schaefer 1943; Archer and La Mer 1955; Costin and Barnes 1975; Rosano and La Mer 1956; Bean and Florey 1968; Folkers et al. 1994; Barnes 1986; McJannet et al. 2008), ii) bringing cooler water to the surface, and iii) applying shade cloths (Craig et al. 2005; Martinez-Alvarez 2009, 2010) or floating covers (Myers and Frasier 1970; Cooley and Myers 1973; Craig et al. 2007). Some research has claimed that shade cloths can reduce evaporation rates by 50%–90%, while monolayers can reduce rates by between 5% and 30%. Such studies are usually performed over small artificial surfaces, not actual reservoirs, and the performance of these engineering methods strongly depends on atmospheric conditions. For instance, increased wind speed, temperatures, and radiation significantly decrease the performance of monolayers, often making them ineffective (Gallego-Elvira et al. 2013). An alternative to covering reservoirs is to redirect surface water or reclaimed water into groundwater aquifers, also referred to as managed aquifer recharge [for a review, see Dillon et al. (2010) and Prathapar et al. (2015)].

(e.g., lake–land breezes), evaporation-induced modifications to the atmospheric boundary layer (e.g., increased humidity, lake-effect cloud cover, and precipitation), and feedbacks to heat and moisture fluxes from internal reservoir processes (e.g., vertical and horizontal mixing, ice formation).

As a result of the two-way coupling of evaporation and water temperature in the reservoir energy balance, as well as the aforementioned complexities from other reservoir–atmosphere feedbacks, the effects of meteorological forcing on reservoir evaporation are often reservoir specific, forcing specific, and time-scale dependent. For example, an instantaneous increase in wind speed (or decrease in absolute humidity) would almost certainly lead to immediately higher evaporation rates on any given water body;

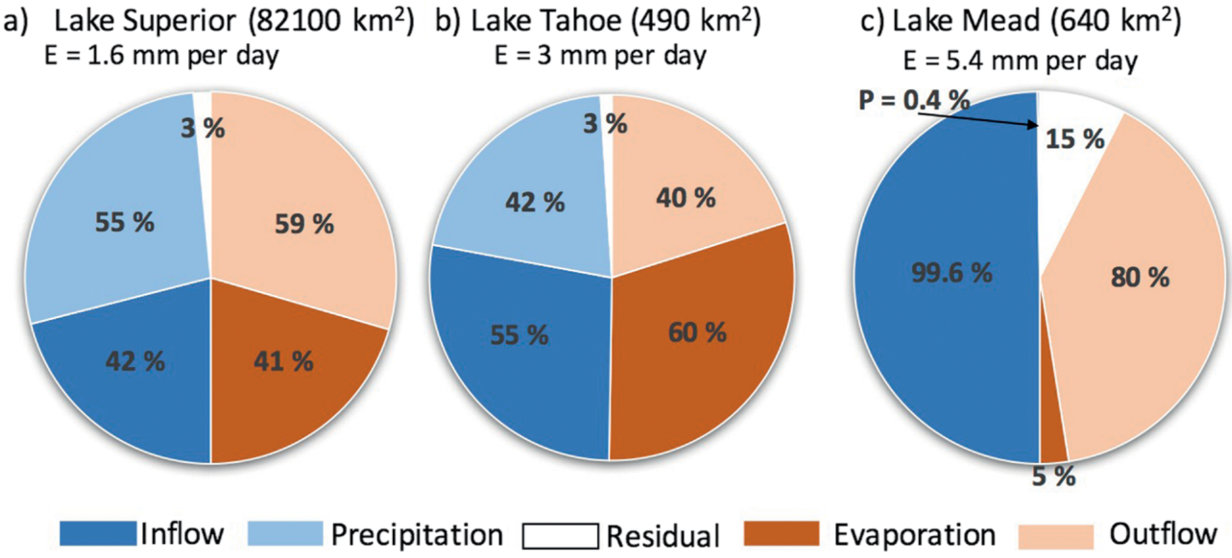

Fig. 4. Annual-mean water budgets for (a) Lake Superior (data from Lenters 2004), (b) Lake Tahoe (data from Myrup et al. 1979), and (c) Lake Mead (data from Moreo and Swancar 2013). Water supply terms include precipitation P and river inflow I, while loss terms include river outflow O and evaporation E. A residual term R is also calculated from the annual water balance ($R = P + I - O - E$), representing the total error in component terms, as well as long-term changes in storage. Annual supply, loss, and residual amounts are expressed as a percentage of the total supply ($P + I$) or total loss ($O + E$), depending on whether R is negative or positive, respectively. Annual mean reservoir E rates and surface area are indicated. Reservoir locations are shown in Fig. 3.

RESERVOIR EVAPORATION AND WATER RIGHTS: AN EXAMPLE FOR COLORADO

The way water is managed and how losses through evaporation are being addressed is centered around federal law, state law, individual water rights, and international treaties; these vary depending on the country and region. In the state of Colorado, for instance, evaporation is a key component of state water administration and state water management activities. Colorado water rights are established and administered pursuant to water court decrees and are subject to prior appropriation. Water right decrees are annual water allocations, which are based on the amount of water that the water rights applicant can put to beneficial use and the timing of use [e.g., some rights could be for *x* acre-feet (1 acre-foot = 1,233.48 m^3) for the entire year, and some can be for x ft^3 s^{-1} (1 ft^3 s^{-1} $\approx$ 0.028 m^3 s^{-1}) for a specific period of time]. The administration is based on the basin's water budget, including source terms (e.g., precipitation, inflow) and losses (e.g., evaporation), and other decreed rights within the basin. This means that senior (older) decreed rights, the oldest of which dates back to 1852 (Colorado Foundation for Water Education 2004), receive priority over the junior (newer) decreed rights.

It should also be noted that decreed water rights may not reflect changes in the water cycle (e.g., earlier runoff, enhanced evaporation). If there is not enough water to fill every right on the system, then the senior rights can put a call on the river, and any junior rights must ensure that they will not injure senior rights in the same basin. For example, a new reservoir must account for reservoir evaporation by releasing a volume of water equal to the evaporation when there is a call so that the junior water right associated with the reservoir does not impact senior downstream water rights. In this example, the reservoir owner would be required to release water in a manner that replaces the evaporative effects of the reservoir, because that much evaporation was not present on the river when the senior rights were decreed. Reservoir owners are not required to replace evaporation if there is a free river condition, meaning there is enough water for everyone and there are no calls on the river. It should be noted that releases to replace evaporation are made in addition to any releases required under the reservoir's decree. Evaporation estimates in these decrees are usually developed by the applicants, with assistance from the Colorado state and division engineers (and other water rights' holders), and they are mainly based on pan evaporation data or estimates from the NOAA national evaporation map. The final decreed evaporation rate, however, is the result of a negotiation between the applicant and other water rights holders in the system, with the negotiated amounts usually being based on assumptions, rather than direct evaporation measurements.

such a condition often occurs at the windward edge of a reservoir as dry air flowing from land to water experiences a decrease in friction. On the other hand, an increase in net radiation would require significantly more time for an evaporative response, because of delayed changes in water temperature (Lenters et al. 2005). Such a response could happen quickly (approximately hours to days) for a very shallow reservoir, but much more slowly (approximately months) for a deep reservoir, particularly if the water body is in a well-mixed, unstratified state. Complicating matters even further, any increase in evaporation (i.e., latent heat flux) eventually cools the reservoir (or at least limits the warming), which tends to decrease evaporation. In summary, all of these considerations point to significant complexities in defining the physical drivers of reservoir evaporation and their spatial and temporal variations. Figure 5 depicts these trade-offs for a variety of drivers, illustrating that—relative to shallow reservoirs—an evaporative response in deeper reservoirs generally requires longer time scales to respond to similar external forcing.

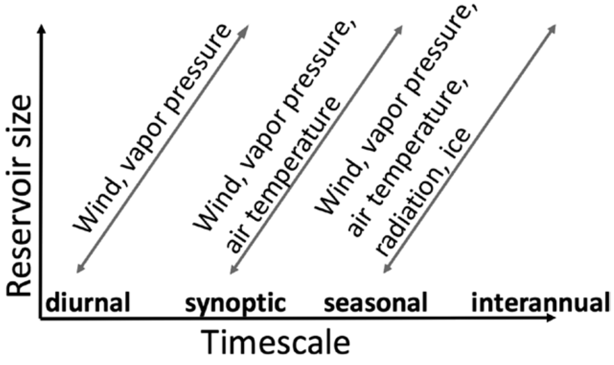

Fig. 5. Illustration of the trade-off that occurs between reservoir size and temporal response when defining the physical drivers of reservoir evaporation. Here, "size" refers primarily to mean water depth, but it can also indicate reservoir surface area (which plays a role in boundary layer modification). Vapor pressure effects are noted separately from air temperature, since the latter typically becomes more important at longer time scales (i.e., through sensible heat flux, longwave radiation, and water temperature).

Reservoir evaporation in a changing climate. Given the complex and interacting climatic and limnological factors that influence reservoir evaporation rates, understanding and predicting the impacts of climate change poses a challenging problem. The effects of a changing climate on hydrologic processes (including evaporation) occur at various time and space scales, with trends being highly nonlinear and sometimes

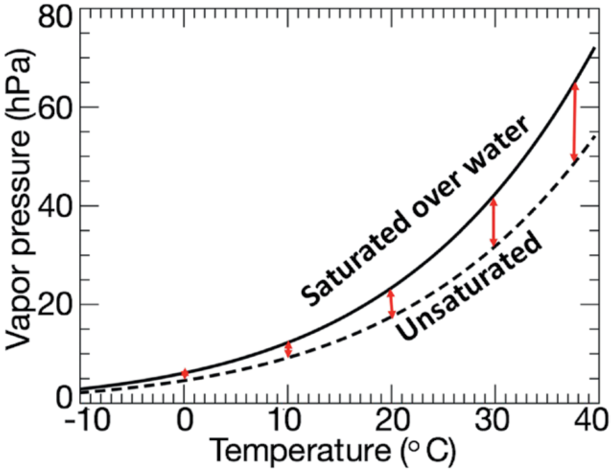

Fig. 6. Illustration of the impact of increasing water and air temperature on the vapor pressure gradient between a reservoir surface and the overlying atmosphere (red arrows), based on the Clausius–Clapeyron relationship. Vapor pressure gradient is evaluated at equal temperatures of water and air (solid black line) and in the presence of an unsaturated atmosphere with a relative humidity of 75% (dashed black line).

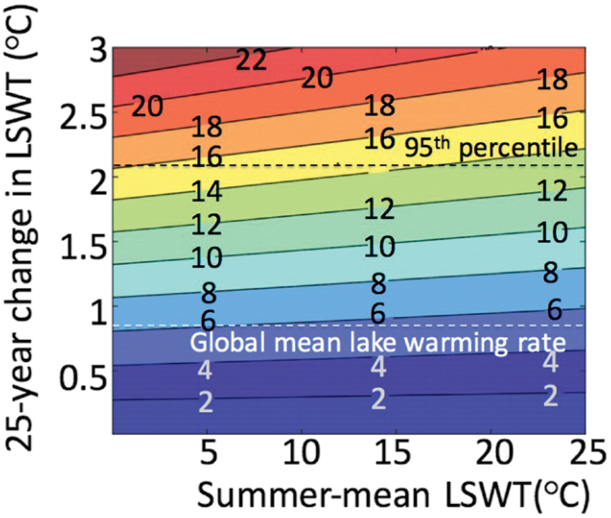

Fig. 7. Simulated percentage change (color coded) in lake–air vapor pressure gradient as a function of summer-mean LSWT (*x* axis) and LSWT warming rate (y axis) over the 25-yr period from 1985 to 2009. Model assumes equal air and water temperatures and a constant relative humidity of 75%, which is representative of most land areas (Dai 2006). Note that since the results are shown as a percentage change in vapor pressure gradient, the model output is largely insensitive to the specific value of relative humidity that is chosen. Plausible ranges of LSWT and 25-yr trends, including the global-mean lake warming rate (dashed white line) and the 95th percentile (dashed black line), are based on data from O'Reilly et al. (2015).

counterintuitive (e.g., North et al. 2013; Van Cleave et al. 2014). For instance, decreasing trends in pan evaporation have been observed despite increasing trends in terrestrial evapotranspiration (Brutsaert 2006) and an overall enhancement of the global hydrologic cycle (Brutsaert and Parlange 1998).

Of all the potential influences of climate change on evaporation, arguably the most robust and anticipated impact is through direct changes in air and water temperatures. Recent global studies of lake surface water temperature (LSWT) trends (Schneider and Hook 2010; O'Reilly et al. 2015) suggest that lakes and reservoirs worldwide are warming rapidly (~0.34°C decade^{-1}), and at rates similar to the regional ambient air temperature (but much higher than the global-mean rate of air temperature warming). Some individual lakes, on the other hand, are warming even faster than the local summer air temperature (Austin and Colman 2007; Schneider and Hook 2009). Many of these are deep lakes that are responding to the lingering effects of rapidly warming winter air temperatures, rather than summer air temperature (Lenters 2004). Nevertheless, it is important to note that increasing LSWT leads to higher vapor pressure gradients (Fig. 6), even in the presence of increasing air temperature and atmospheric humidity. This is due to the saturation vapor pressure of a lake surface being typically higher than the vapor pressure of the overlying air, and this gradient increases with temperature (Fig. 6).

A more explicit quantification of the potential effects of increasing water temperature on reservoir evaporation is illustrated by the simple model results shown in Fig. 7. Although changes in vapor pressure gradient do not fully encompass the range of other potential climate change impacts (e.g., changes in wind speed), Fig. 7 clearly implies a pronounced effect of increasing LSWT on evaporation, even in the presence of increasing air temperatures. More specifically, the model results suggest that—in the absence of other changes—recent 25-yr trends in global LSWT may have already led, on average, to a ~6% increase in summer evaporation rates. For some of the most rapidly warming lakes, the increase in vapor pressure gradient could be as high as 15%–20% (Fig. 7), following the Clausius–Clapeyron relationship (Fig. 6).

Trends in evaporation from reservoirs are dependent not only on changes in air and water temperature but on other variables as well, such as humidity, wind speed, and net radiation. Although global trends in humidity are small, some regional trends have been found to be large (Dai 2006), and significant trends in global wind speed have also been observed (McVicar et al. 2012).

TABLE 1. List of common methods for estimating evaporation, including the basic formulas, required measurements, and advantages and disadvantages of each method.

Pan method	$E = \Delta z_w^* k_p$ Summary: Rate E is measured as the change in daily water levels Δz_w in a shallow pan that is typically replenished manually on a daily basis. A "pan coefficient" k_p, typically ~0.70, is multiplied by the change in water depth to account for the overestimation of E. Pros: Simple, inexpensive, and long-term global datasets are available. Cons: Uncertainties in magnitude and timing; uncertainties as a result of measurement errors (splashing, solar heating of the pan, wind effects); freezing conditions limit use (in colder climates not operational between September and May when maximum in evaporation occurs in colder climate); little heat storage in a pan; often poorly sited and maintained (offshore sites do not represent conditions within the reservoir; Winter et al. 2003; Masoner et al. 2008); must determine k. References: Lowe et al. (2009); Martinez-Granados et al et al. (2011); Harwell (2012)
Dalton/mass transfer/ bulk aerodynamic	$E = f(u)(q_0 - q_r)$, where $f(u) = m(u) + b$ Summary: Rate E is calculated from the difference in water vapor pressure or specific humidity at the water surface q_0 and the atmosphere at a given reference level q_r. A "wind function" $f(u)$ is used to account for the advective drying effects of wind. Pros: Relatively simple and physically sound, requiring measurements of q at two heights (water surface temperature is typically used to estimate the water surface saturation vapor pressure) and u if the coefficients of the wind function, the slope m, and y intercept b are already known. Cons: Assumes a fully adjusted boundary layer and neutral atmospheric stability over the entire water surface; $f(u)$ varies with fetch and stability; generalization of $f(u)$ across water surface; spatial variability of q and u. References: Dalton (1802); Penman (1948); Singh and Xu (1997)
Eddy covariance	$\lambda E = \lambda\left(\overline{w'q'}\right)$ Summary: Evaporation is calculated from high-frequency (typically 10 Hz) measurements of the deviation of specific humidity q' and vertical wind speed w' relative to a time-averaged mean (overbar: typically 30 min). Pros: Theoretically simple with measurements at one height above the water surface. Cons: Instruments are relatively expensive; voluminous, high-frequency data; adequate fetch is required. Several well-known corrections should be applied to the raw data. References: Bean and Florey (1968); Brutsaert (2005); Blanken et al. (2000)

In particular, the term *global stilling* is often used to describe the phenomenon of declining global wind speeds, which—in the absence of other trends—would lead to a decrease in evaporation (McVicar et al. 2012). On the other hand, inconsistent trends in wind speed from diverse datasets have occasionally been noted (Pryor et al. 2009), as have increasing wind speeds over large lakes with strong warming trends (Desai et al. 2009). Thus, both the sign and magnitude of trends in regional wind speed may be highly uncertain, at least in comparison to the global pattern of heterogeneous, but consistently warming, LSWT (O'Reilly et al. 2015). Global trends in cloud cover and therefore solar and longwave radiation also tend to be spatially heterogeneous, though periods of global "dimming" and "brightening" have been well documented (Wild 2009). Changes in net radiation, however, should largely be accounted for by trends in LSWT, suggesting that simulated changes in vapor pressure gradient may provide a good first-order approximation for anticipating climate-induced long-term trends in reservoir evaporation.

CURRENT SCIENCE AND MANAGEMENT PRACTICES.

Evaporation methods and observations. Reducing errors and uncertainties in reservoir evaporation estimates requires the use of modern meteorological approaches. A selection of the most commonly used approaches is listed in Table 1. The standard method used today for measuring turbulent fluxes, including evaporation, is the eddy covariance technique (Table 1), which is also considered the most accurate method if environmental conditions, physical setting, and experimental design are appropriate. The eddy covariance technique has been used successfully over several lakes and reservoirs, such as the North American Great Lakes (Fig. 8; Blanken et al. 2000, 2011), Lake Mead (Fig. 9; Moreo and Swancar 2013; Moreo 2015), and Ross Barnett Reservoir in Mississippi (Liu et al. 2011). However, with this technique it is necessary that measurements be made either over the reservoir (far from the shore) or immediately at the shoreline to have a homogeneous and representative fetch (Wang et al. 2006,

Table 1. Continued.

Water balance	$E = (P + Q_{\text{in}} + G_{\text{in}}) - (Q_{\text{out}} + G_{\text{out}} + D) + \Delta z_w$ Summary**:** Evaporation is calculated as the residual of the water balance input terms (precipitation P, surface inflow Q_{in}, groundwater inflow G_{in}) and output terms (surface runoff Q_{out}, groundwater outflow G_{out}, diversions and withdrawals D) and changes in water level Δz_w. Pros: Accounts for evaporation over the entire reservoir; thus, complex shapes and locations that do not meet meteorological-based fetch requirements can be measured. Cons: All of the water balance terms must be accurately measured (seldom possible); therefore, large errors can accumulate in the E estimation. Reference: Brutsaert (2005)
BREB	$\lambda E = \dfrac{R_n - J_T}{1 + \beta}$ Summary**:** Vertical gradients in air temperature and humidity are used to determine the Bowen ratio β, which is then combined with the surface energy balance equation; R_n is net radiation. Pros: Has been applied with success over small reservoirs where the heat storage term J_T can be accurately measured. Cons: Difficult to accurately measure the heat storage term (requires water temperature profiles and bathymetric measurements) over large and/or complex reservoirs. Other important energy budget terms that need to be considered (not shown here) are the net advected energy to the water body from surface and groundwater inflows and outflows, and direct precipitation. See Winter et al. (2003) and Eqs. (42.5) and (42.29) in Hobbins and Huntington (2016) for a full description of BREB for open water. References: Lenters et al. (2005); Winter et al. (2003); Hobbins and Huntington (2016)
CRLE	$E_T + E_{\text{TP}} = 2E_{\text{TW}}$ Summary**:** Land-based temperature and humidity measurements are adjusted to simulate overwater conditions, which are then used to calculate E using conservation of energy and mass equations; E_T is areal evapotranspiration, E_{TP} is potential evapotranspiration, and E_{TW} is the wet-environment evaporation (a surface with no limitations on water availability). Pros**:** Land-based meteorological data are much more available than overwater measurements. Cons**:** Heat storage measurements or estimates are required. Other important energy budget terms that need to be considered (not shown here) are the net advected energy to the water body from surface and groundwater inflows and outflows, and direct precipitation. See Hobbins and Huntington (2016) for a full description of CRLE for open water. References: Morton et al. (1985); Morton (1986); Hobbins and Huntington (2016)

and references therein). Another accurate alternative to the eddy covariance approach is the Bowen ratio energy balance (BREB) method, which has been used successfully over many small lakes and reservoirs (Table 1; Lenters et al. 2005; Rosenberry et al. 2007). However, this method is usually applied to longer time scales (weekly, monthly, annual) to reduce uncertainty and error in measurements or estimates of the heat storage and net advection energy terms, as well as other energy balance terms (Winter et al. 2003; Hobbins and Huntington 2016). Figure 10 shows the deployment of an instrument platform designed for evaluation of both the BREB and bulk aerodynamic (mass transfer) methods (Table 1) on Lahontan Reservoir, Nevada. For larger reservoirs such as Lake Tahoe or Lake Mead, however, determination of the heat storage term can be problematic because of spatial and temporal variations in reservoir thermal structure (Kondo 1994; Rosenberry et al. 1993) and the large thermal inertia of deep reservoirs. The latter causes surface water temperature to lag well behind the seasonal decline in air temperature and vapor pressure, altering both the rate and timing of evaporation, depending on regional climate and reservoir depth. For example, peak evaporation for deep reservoirs (Lake Tahoe, Lake Mead) typically occurs between late summer and early winter (Figs. 9, 11) rather than during the midsummer months, as is often incorrectly suggested by shallow pan evaporation measurements.

Probably the most cost-effective approach for operational monitoring because of low instrument maintenance needs (and cost) is the bulk aerodynamic or mass transfer approach (Brutsaert 1982), which follows the Dalton equation (Table 1). Since this approach can be measured at high temporal resolution (e.g., minutes), the method can be applied at the subhourly or daily time steps for near-real-time operational monitoring (Fig. 11). However, the technique is not ideal for reservoirs that have limited fetch or are located in highly advective environments. Furthermore, data need to be collected over open

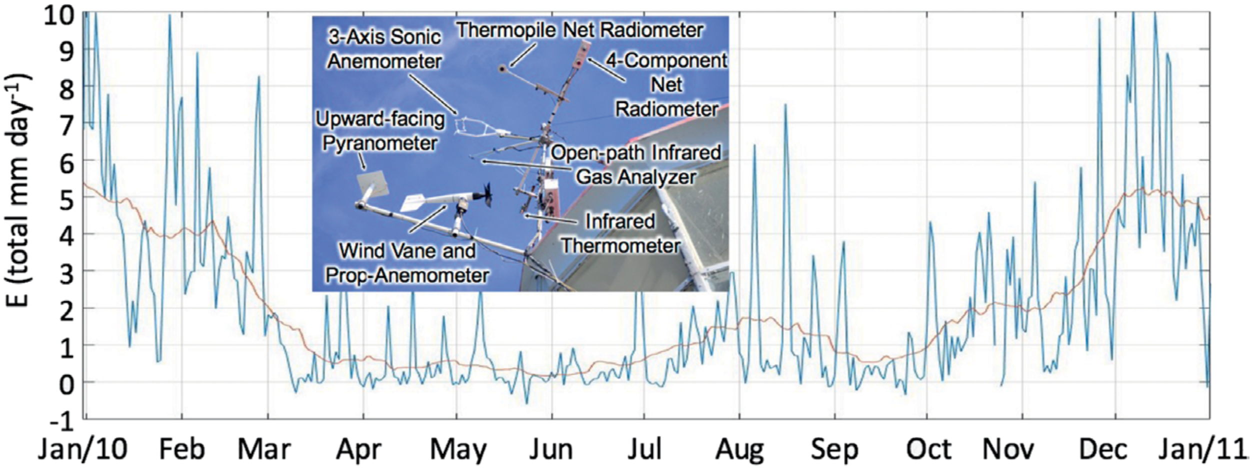

Fig. 8. Daily mean evaporation rates (blue line) in 2010 from Lake Huron, one of the North American Great Lakes, using an eddy covariance approach. Shown is the 30-day running-mean evaporation rate (red line). Eddy covariance instruments (inset) are located offshore, atop the lighthouse at Spectacle Reef. Reservoir locations are shown in Fig. 3.

water, and estimation of mass transfer coefficients typically requires calibration via more accurate estimation methods (e.g., eddy covariance).

Satellite and airborne observations can also be used to measure some of the necessary parameters for determining evaporation, such as LSWT. Infrared-derived LSWT coverage at high horizontal resolution (e.g., see Fig. 12 for examples from Lake Superior and Lake Tahoe) allows for the possibility of estimating the spatial variability of evaporation using satellite remote sensing. As part of this effort, the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) and the University of California, Davis, established four continuous monitoring stations in 1999 on Lake Tahoe that provide the means for calibration and validation of satellite and airborne observations, as well as satellite-based reservoir evaporation estimation (NASA JPL 2016). As shown in Fig. 13, the comparison of in situ surface temperature data with satellite retrievals is used for

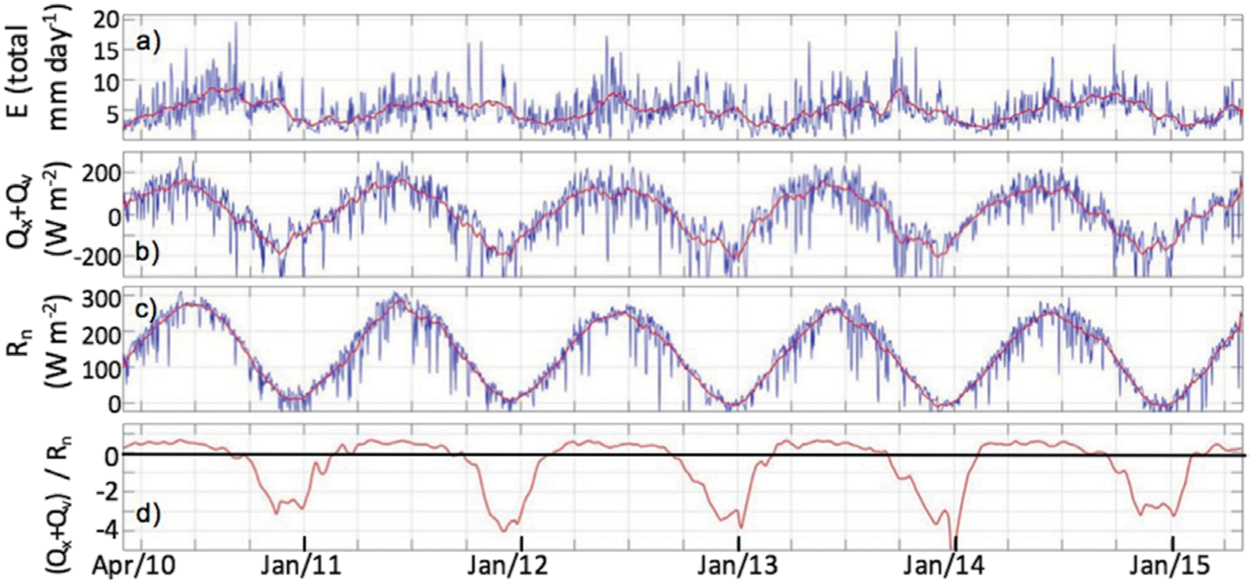

Fig. 9. Eddy covariance evaporation data for Lake Mead from Moreo and Swancar (2013) and Moreo (2015). Daily mean (blue lines) and 30-day moving averages (red lines) are shown for (a) *E*, (b) heat storage ($Q_x + Q_v$), (c) net radiation R_n, and (d) ratio of heat storage to net radiation [$(Q_x + Q_v)/R_n$]. Positive ratios during spring and early fall in (d) indicate a net influx of energy, while negative ratios in late fall and winter indicate a net loss. Reservoir locations are shown in Fig. 3.

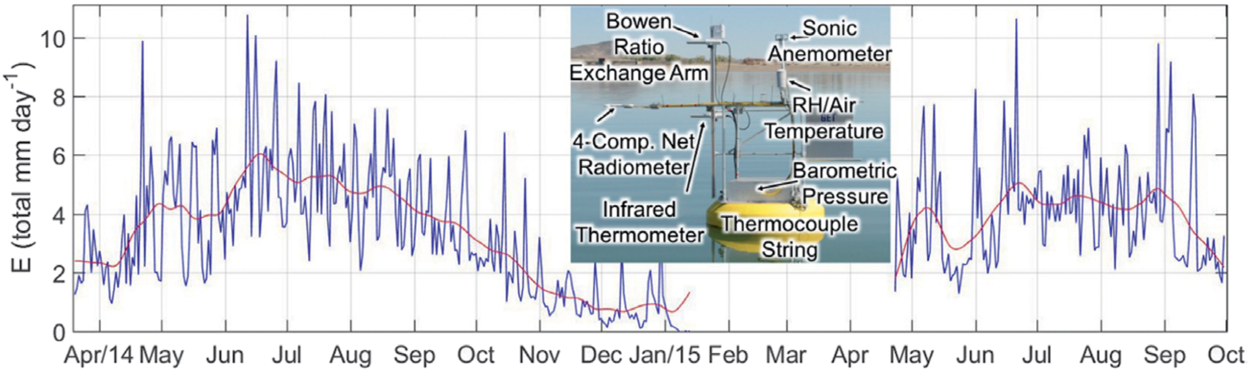

Fig. 10. Estimates of daily mean evaporation rates (blue line) from a BREB and mass transfer buoy station (inset) at Lahontan Reservoir during Apr 2014–Jan 2015 and May–Oct 2015. Shown is the 30-day running-mean evaporation rate (red line). Measurements include net radiation, air temperature and vapor pressure (both at two heights), wind speed, surface water temperature, and water temperature at depth (Source: OWEN). Reservoir locations are shown in Fig. 3.

routine validation of absolute radiometric calibration of reflectance, temperature, and emissivity.

Lake models coupled with weather and climate modeling systems. The goals of using coupled atmospheric–hydrologic models in reservoir evaporation research and predictions are as follows: 1) improving the physical representation of evaporation and the factors driving evaporation in hydrologic forecasting systems, 2) estimating evaporation for reservoirs without evaporation measurements, 3) assisting in determining optimal instrument network design, 4) predicting evaporation under a changing climate, and 5) evaluating how evaporation estimates from numerical models can be used for improved water management operations. To address these goals, the atmospheric–hydrologic models are operated at different spatial and temporal scales, ranging from mesoscale studies of synoptic events (or seasonal climate variability) to large-eddy simulations with resolution from tens to hundreds of meters for more detailed studies.

An increasing variety of lake and reservoir numerical models have been developed and integrated for use within coupled weather and climate modeling systems (MacKay et al. 2009; Mallard et al. 2015). These lake or ocean models include mixed-layer models (Bonan 1995; Lofgren 1997, 2004), one-dimensional thermal diffusion models with parameterized eddy diffusivity (e.g., Hostetler and Bartlein 1990; Bennington et al. 2014), one-dimensional multilayer models based on similarity theory (e.g., Flake, www.flake.igb-berlin.de; Mironov et al. 2010), and three-dimensional ocean models (e.g., Princeton Ocean

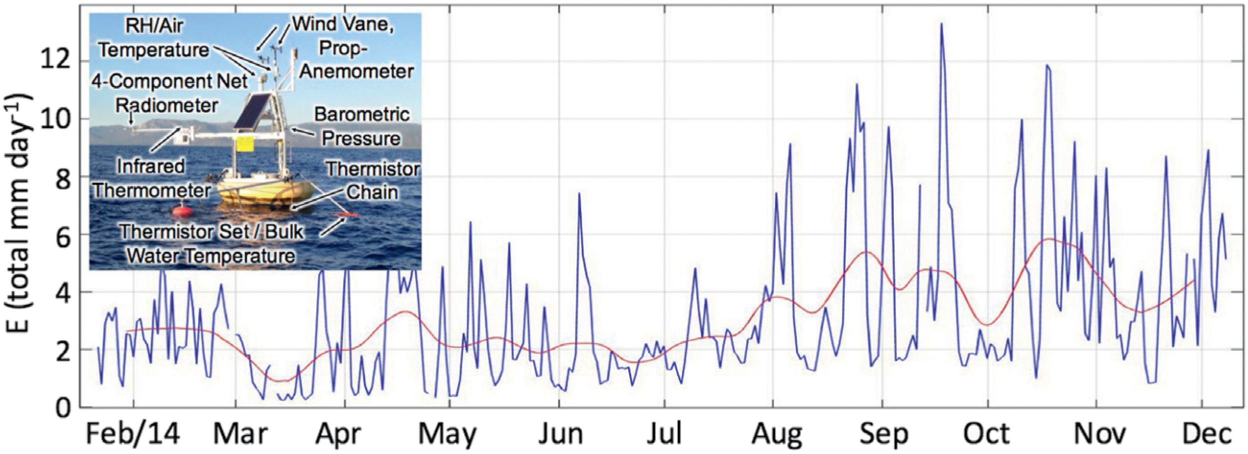

Fig. 11. Estimates of daily mean evaporation rates (blue line) from a buoy (inset) at Lake Tahoe in 2004 using a mass transfer approach with measurements of surface water temperature, air temperature, vapor pressure, and wind speed collected at the NASA JPL buoy. Shown is the 30-day running-mean evaporation rate (red line). (Source: J. L. Huntington et al. 2015, unpublished manuscript). Reservoir locations are shown in Fig. 3.

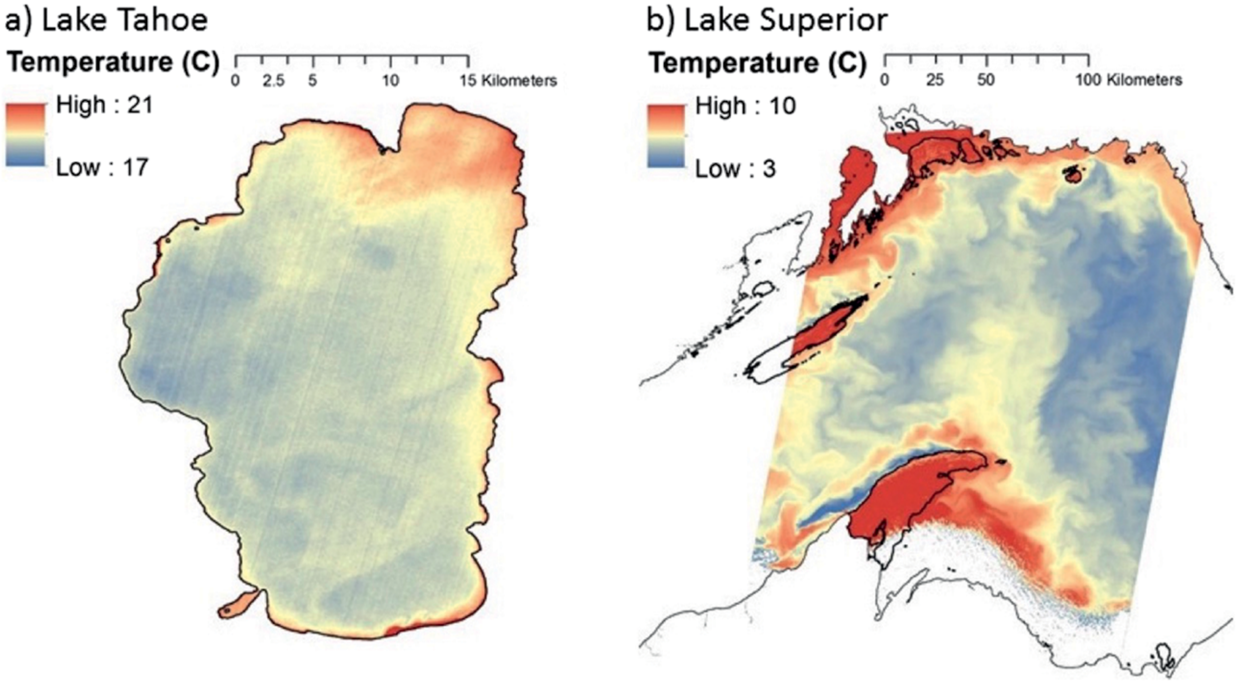

Fig. 12. Surface water temperature measured by the *Landsat-8* TIRS for (a) Lake Tahoe on 22 Sep 2015 and (b) a portion of Lake Superior on 30 Sep 2014 (Source: ClimateEngine.org, http://clim-engine.appspot.com). Large variations in lake surface temperature suggest similarly large spatial variations in evaporation rate. Reservoir locations are shown in Fig. 3.

Model; Sun et al. 2014). Except in rare instances (e.g., Xue et al. 2017), lake and reservoir representations in fully coupled surface–atmosphere modeling systems tend to be fairly simplified compared to state-of-the-art stand-alone lake or ocean models. For example, the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) is a widely used atmospheric model with a default scheme for modeling energy and water exchanges between water bodies and the atmosphere that is based on a fairly simplistic bulk aerodynamic formulation for calculating evaporation over an open water surface (see Table 1). The lake parameterization within the Community Earth System Model's (CESM) Community Land Model (CLM) has been coupled to the WRF atmospheric modeling system. It consists of a 10-layer 1D lake column model (Subin et al. 2012) and uses an iterative thermal diffusion approach to solve for the surface layer and vertical profile of lake temperature. The CLM lake model uses a constant depth of 50 m or can apply available bathymetric data for larger lakes. However, no lake circulation dynamics are included.

Management practices in the United States. In the United States, reservoirs are owned, operated, and managed by a number of different private, local, state, and federal organizations. The largest agencies include the U.S. Army Corps of Engineers (USACE), managing over 600 reservoirs across the United States (www.usace.army.mil/Locations.aspx), and the U.S. Department of Interior's Bureau of Reclamation (referred to here as Reclamation), which manages 476 dams and 348 reservoirs, with the capacity to store 302,000,000,000 m^3 of water (www.usbr.gov/projects/maps.php). These organizations are often required to estimate reservoir evaporation at monthly, seasonal, and annual time scales for water budgeting, water distribution, and legal accounting, and at decadal and multidecadal time scales for long-term planning at each reservoir. In addition, the management of water is often dictated by rules prescribed by federal law, state law, international treaties, and water rights, often disregarding changes in climate or advances in technology and forecasting (e.g., AgAlert, 20 April 2016; Weiser 2016; see sidebar "Reservoir evaporation and water rights: An example for Colorado" for more information).

Although evaporation is an important component of reservoir water budgets, it is not directly or consistently measured by water management agencies because maintaining numerous instrumented sites is logistically challenging and expensive (Lowe et al. 2009). Consequently, evaporation estimates for reservoirs across the 43 USACE districts and five

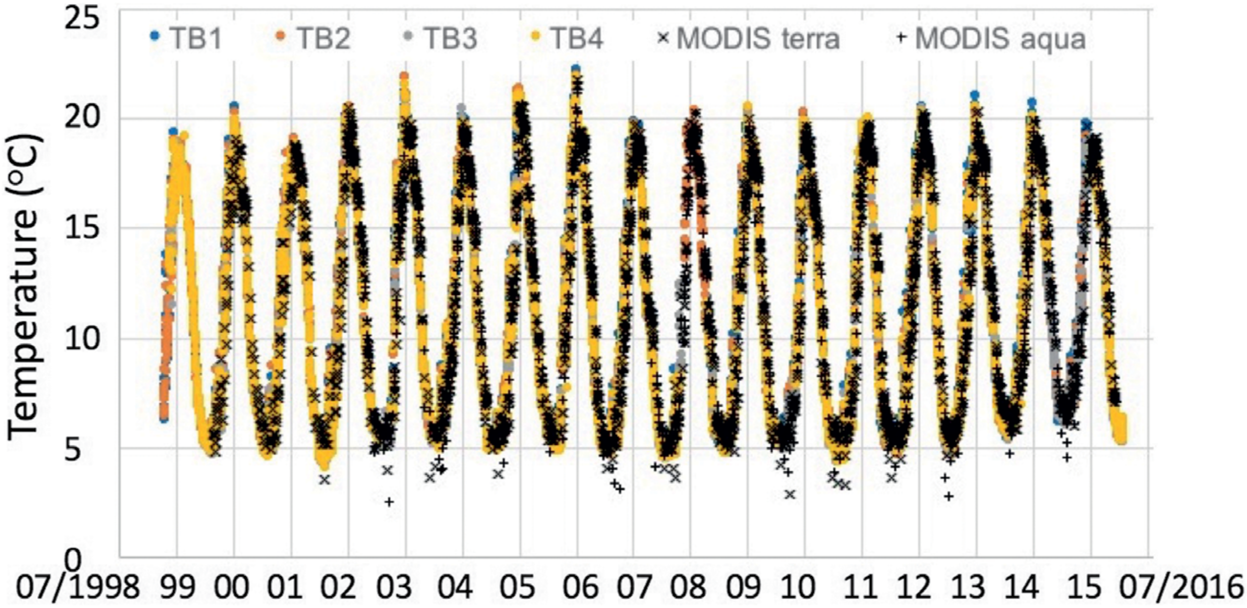

Fig. 13. Radiometric skin temperature observations during 1999–2016 at Lake Tahoe from the four in situ NASA JPL buoys (TB1–TB4) and from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board the *Terra* and *Aqua* satellites.

Reclamation regions often rely entirely upon in situ pan evaporation data or analyses of historical pan evaporation, also referred to as the NOAA national evaporation map[1] (Farnsworth et al. 1982; Farnsworth and Thompson 1982; Harwell 2012). For instance, the USACE Fort Worth District in Texas (Fig. 3) collects pan evaporation data from 19 reservoirs, while 6 reservoirs without instrumentation use evaporation estimates from nearby reservoirs (Table 1; Harwell 2012). Other districts, such as the USACE Little Rock District in Arkansas and Missouri (which manages 15 reservoirs; Fig. 3), have no in situ pan observations and therefore use estimates from the NOAA national evaporation map. In Arkansas, for instance, the six pan evaporation stations are distributed essentially randomly, rather than being installed at reservoirs.

As with USACE, methods to estimate evaporation can vary within Reclamation area offices and river basins. For instance, within the upper Colorado River basin (UCRB; Fig. 3), some reservoirs solely use estimates from NOAA's national evaporation map, while others—like the main stem reservoir Lake Powell—estimate reservoir evaporation based on historical (typically performed in the late 1960s and early 1970s) or reservoir-specific pan evaporation studies using limited mass-transfer-method-based measurements (Jacoby et al. 1977; U.S. Bureau of Reclamation 2015). In the UCRB, there are currently 11 measured and 849 unmeasured reservoirs. The 11 measured reservoirs account for 80% of the UCRB's estimated annual reservoir evaporation.

The pan evaporation method is widely used in operational water management despite its limitations and assumptions (Table 1; Fig. 14; Winter et al. 2003; Masoner et al. 2008; Lowe et al. 2009; Martínez-Granados et al. 2011). To overcome some of the pan technique limitations, some agencies have recently started exploring alternative methods (Harwell 2012). For instance, meteorological observations have been combined with different forms of the Penman equation (or combination of energy–aerodynamic algorithms) to estimate daily evaporation at some USACE test sites (Harwell 2012). Empirical and semiempirical estimates of evaporation based on the Hamon method (Hamon 1961) and a modified Penman approach have also been used by USACE (Table 1; Harwell 2012). Reclamation recently partnered with the U.S. Geological Survey (USGS) to estimate monthly and annual evaporation at Lake Mead and Lake Mohave using the eddy covariance and Bowen ratio energy balance methods (Table 1; Moreo and Swancar 2013; Moreo 2015), with results to be directly used for water management operations. They also partnered with DRI to estimate monthly and annual evaporation at 12 western U.S. reservoirs for baseline and future climate studies using the numerical

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[1] This map contains annual-mean evaporation determined from pan evaporation measurements collected between 1956 and 1970 from roughly 800 locations (but only 210 with yearlong measurements) across the United States.

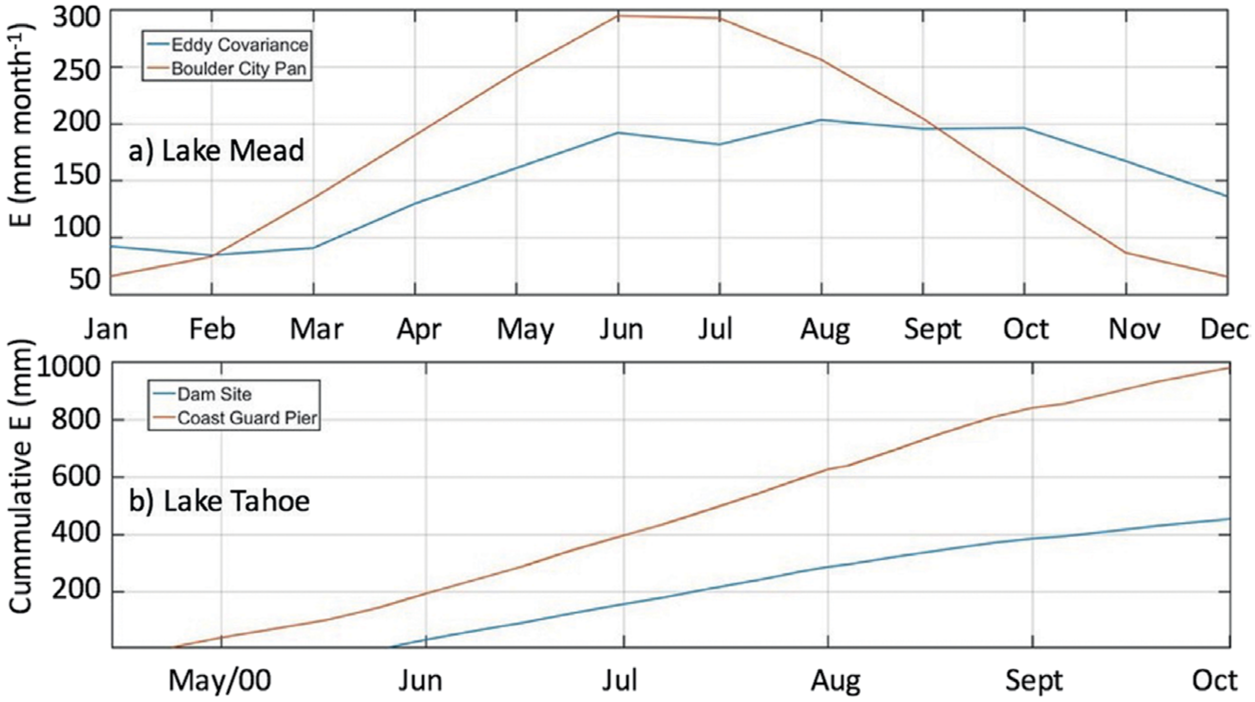

Fig. 14. (a) Estimates of monthly mean evaporation rate at Lake Mead from eddy covariance measurements (2010–12; blue line; Moreo and Swancar 2013; Moreo 2015) and an evaporation pan located ~10 km west of and 363 m above Lake Mead at Boulder City (1931–2014, red line; source: http://wrcc.dri.edu/htmlfiles/westevap.final.html). Pan estimates have been scaled by 0.7. Shallow pan techniques cannot capture the heat storage effect of larger reservoirs, creating differences in both evaporation timing and magnitude. Tanny et al. (2008) showed that pan measurements can be up to 65% higher than those obtained from the eddy covariance technique. (b) Cumulative evaporation measurements from two pan locations at Lake Tahoe [figure modified from Trask (2007)]. The instruments are separated by less than 1 km and show the high sensitivity and variability of pan estimates relative to their location.

energy–aerodynamic combination of the Complementary Relationship Lake Evaporation (CRLE) approach (Table 1; Huntington et al. 2015).

Reclamation and USACE have started to implement modern evaporation forecasting techniques and improved water cycle predictions from the NOAA National Water Model (NWM/WRF-Hydro; Gochis et al. 2013) into their water management operations. In addition, NOAA's Great Lakes Environmental Research Laboratory (GLERL; www.glerl.noaa.gov/res/glcfs-fvcom/heatflux.html) currently uses its experimental Great Lakes hydrodynamic models to simulate evaporation and related heat fluxes. These simulated evaporation rates will ultimately be transferred into their operational water management models, providing real-time evaporation estimates (A. Gronewold, NOAA GLERL, 2016, personal communication). McEvoy et al. (2016) showed that even fully coupled forecast models like the Climate Forecast System, version 2, have moderate skills to forecast evaporative demand up to 5 months, which can be used for long-term water management.

Despite the few recent trials, many questions and concerns about how evaporation estimates and forecasts should be implemented into water resource management still remain. Currently most river basin modeling software—such as RiverWare (Zagona et al. 2001), which is used by Reclamation; Reservoir System Simulation [ResSim: Hydrologic Engineering Center (HEC)-ResSim], which is used by USACE; and the Water Evaluation and Planning (WEAP) model (Yates et al. 2005)—required improved characterization of potential changes in evaporation rates or have limitations on how to implement high-resolution reservoir estimations and forecasts. For an overview of various water management systems, the reader is referred to Wurbs (2011).

FUTURE NEEDS. *Uniform, coherent, and long-term measurements*. There is a clear need for consistent, long-term, high-resolution measurements of "core" variables (listed in Table 1) to enable accurate calculations of reservoir evaporation. This requires uniformity in installation, calibration, and maintenance and a central, open-source, and easy-access database across basins. At large reservoirs, multiple core measurement sites are required to capture the spatial variability of evaporation and precipitation. In addition to core measurements, there is a need for "super sites" or test beds with high density, multiyear measurements in and around reservoirs with different characteristics for focused studies of reservoir evaporation, including comparison, validation, and calibration of reservoir evaporation estimation from ground-based, airborne, and satellite remote sensing instruments. Reservoirs that are currently well instrumented and part of ongoing evaporation research could be considered as super sites, such as Lake Tahoe and Lake Mead. These super sites will also complement future NASA missions, such as the Surface Water and Ocean Topography (SWOT) instrument scheduled for launch in 2020 (Fu et al. 2012) and the continuity of high-spatial-resolution (100 m) thermal infrared sensor (TIRS) measurements via Landsat-9 (scheduled launch in 2020).

Coordinated observing networks. We see a strong need for coordinating and expanding existing regional, national, and global networks. Currently, the Great Lakes Evaporation Network (GLEN; Lenters et al. 2013) and the Open Water Evaporation Network (OWEN, https://owen.dri.edu) provide integrated observing systems for measuring evaporation over the North American Great Lakes and reservoirs in California, Nevada, and Idaho; the Global Lake Ecological Observatory Network (GLEON) collects evaporation-relevant measurements for many small lakes around the world. To address current and future water shortages in the western United States, we propose the creation of a Western Reservoir Evaporation Network (WREN) to host initiatives such as OWEN and new super and core sites. WREN could serve as a resource for providing research on best practices and evaporation estimation for water managers; partnerships among managers, scientists, water-law professionals, and other stakeholders who learn how to create and maintain a resource system; and education and outreach opportunities for the general public.

Coordinated regional, national, and even global networks have the advantage of assuring data uniformity from current and proposed reservoirs; uniformly archiving raw and processed data to be used for future analyses; performing identical quality assurance and control procedures across all sites; and providing data access to water managers in a timely manner. Currently, even though Reclamation shares some reservoir information through a number of publicly accessible data sources, reservoir evaporation is not included. We see a strong need for making reservoir evaporation estimates and meteorological observations at reservoirs publically available for research and monitoring (e.g., Project Open Data, https://project-open-data.cio.gov/).

Improved representation of reservoirs in high-resolution coupled atmospheric–hydrologic models. While observations can provide fundamental insights into reservoir and atmospheric conditions, only with the use of coupled atmospheric–hydrologic models are we able to diagnose the complex physical processes that affect the temporal and spatial variability of evaporation within complex reservoir systems. More coordinated and collaborative community model development efforts are needed, similar to approaches taken by the climate and weather modeling community, which allow for unified development and holistic evaluations of modified or improved model physics schemes. We identify four priority areas where further development of evaporation formulations is needed in order to improve the representation of reservoirs in high-resolution coupled atmospheric–hydrologic models: i) improving the physiographic description of reservoirs to understand how spatial distribution of reservoir inundation depths and total mass and energy exchanges affect reservoir evaporation; ii) applying new methods, such as advanced multiscale modeling systems or subgrid parameterization, to improve the spatial resolution of reservoir topography and bathymetry and the structure of the atmospheric boundary layer upstream of, surrounding, and overlying the reservoir; iii) improving the representation of reservoir circulation dynamics to correctly forecast LSWT and water and energy fluxes [Bennington et al. 2014; many stand-alone lake dynamics models already possess such formulations (e.g., Bennington et al. 2010), but few (if any) have been coupled to atmospheric models]; and iv) improving the time-varying description of lake turbidity and water quality, as it impacts absorption and attenuation of sunlight, thus affecting reservoir stratification and the radiative budget of the water body.

Managing water systems using better measurements and forecasts. Research should be conducted to determine how observations and forecasts of reservoir evaporation and its driving factors, as well as improved short-term and seasonal forecasts of evaporation and the water cycle, can be best included into water management models, as well as what the quantifiable benefits are of including this information. Recently, water managers have realized the need for improved estimates and forecasts of reservoir evaporation to help with a number of decisions, ranging from short-term planning of episodic and synoptic events to seasonal- to climate-scale forecasts and projections. With accurate reservoir evaporation estimates and probabilistic short-term reservoir evaporation forecasts, differences in evaporation rates at upstream and downstream reservoirs within a system would enable reservoir operators to consider strategically repositioning storage within the reservoir system while abiding existing laws and regulations. On longer time scales, better estimates of reservoir evaporation are needed to improve projected annual water delivery estimates by refining available information on both the availability of water supply and the potential demands on the system. There is also value in improved evaporation estimates for other areas of reservoir management, such as understanding or predicting water quality conditions (e.g., temperature, vertical mixing, turbidity).

CONCLUSIONS AND RECOMMENDATIONS. Reservoir evaporation has been an inconsistently and inaccurately estimated component of the water cycle within the water resource infrastructure of the arid and semiarid western United States. This is partly due to both practical and logistical challenges, as well as water abundance in the past that did not require efficient water management and storage. However, reservoir evaporation in arid and semiarid regions is substantial, and it represents an important consideration for the future of water management in a water-scarce environment. Motivated by the inevitable clash of population growth and its attendant demands for water use, as well as uncertain precipitation projections and earlier, reduced snowmelt runoff in a rapidly changing climate, the University of Colorado and DRI organized a workshop on reservoir evaporation (http://clouds.colorado.edu/home.html) in 2015. The following list of concerns and recommendations that emerged from the workshop and that have been discussed herein can serve as the basis for a long-term research plan focused on, but not limited to, challenges and needs in the western United States:

- Modern methods of reservoir evaporation estimation are urgently needed to improve estimates and forecasts of reservoir evaporation for water management systems.
- Partnerships among researchers, water managers, water-law professionals, state and basin officials, the environmental community, and other stakeholders should be built to develop a common language and prioritize needs and approaches.
- Expansion of existing experimental sites to super sites and core sites for instrument and model validation, method testing, and analyses of the role of physical drivers (and reservoir characteristics) in determining reservoir evaporation.
- Establishment of integrated research-to-operations networks (e.g., WREN) for developing best practices that water managers can implement in estimating reservoir evaporation.
- Comprehensive, coordinated, and collaborative community models of coupled reservoir–atmosphere interactions should be developed that integrate expertise within the limnological, hydrological, remote sensing, and atmospheric science communities.
- Research on how physical drivers and changing climate affect reservoir evaporation should be expanded using observations and numerical modeling. This includes estimating short- and long-term reservoir evaporation rates for existing, expanded, and new reservoirs following the idea of smart location.
- Implementation of existing, improved evaporation estimates and forecasts into water management systems is needed, including provision of a task list for operation-focused research.

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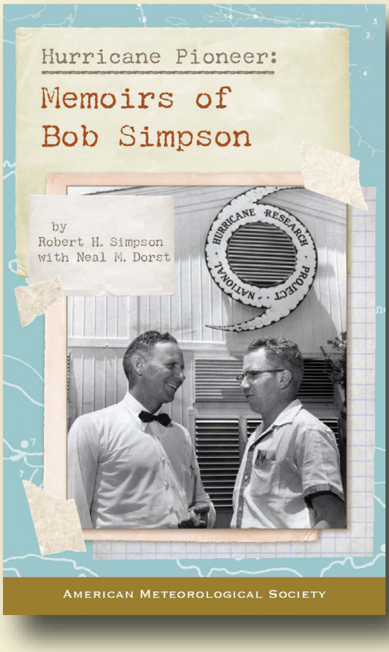

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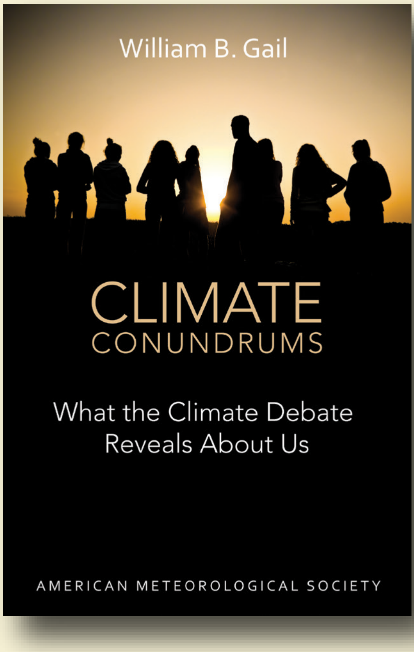

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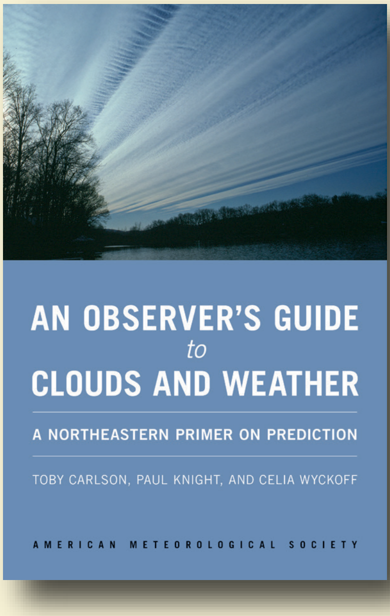

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