

Mass and energy balance calculations for an artificial ice reservoir (Icestupa)

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2 ABSTRACT

Artificial Ice Reservoirs (AIRs) can successfully store water during winter and release the water during spring and summer. This makes them a reliable fresh water resource for irrigation in dry environments. Several AIRs have been built but studies of their water storage capacity and efficiency are scarce. This study models a cone-shaped AIR popularly called Icestupa. Processes involved in the development and temporal evolution of an Icestupa are calculated by a physically-based model using equations governing the heat transfer, vapour diffusion and transport of water that undergoes phase changes. These processes were quantified using meteorological data in conjunction with fountain spray information (mass input of an Icestupa) to estimate the quantity of frozen, melted, evaporated and runoff water at a location called 'Eispalast' in Fribourg, Switzerland. At this measurement site, an Icestupa was built for model validation purposes. The model was further tested by performing a sensitivity and uncertainty study showing that the most sensitive parameters are the ice emissivity and the temperature threshold used to determine precipitation phase. Model calculations estimate that the Eispalast Icestupa stored about 5% of the total water sprayed as ice. In addition, we found that reducing nozzle diameter of the fountain from 5 mm to 3 mm increases the water storage up to 78% without compromising on the storage duration.

Keywords: ictestupa, mass balance, water storage, climate change adaptation, geoengineering

1 INTRODUCTION

Seasonal snow cover, glaciers and permafrost are expected to change their water storage capacity due to climate change with major consequences for downriver water supply (Immerzeel et al., 2019). The challenges brought about by these changes are especially important for dry mountain environments such as in Central Asia or the Andes, which directly rely on the seasonal meltwater for their farming and drinking needs (Hoelzle et al., 2019; Apel et al., 2018; Buytaert et al., 2017; Chen et al., 2016; Unger-Shayesteh



Figure 1. Icestupa in Ladakh, India on March 2017 was 24 m tall and contained around 3700 m^3 of water. Picture Credits: Lobzang Dadul

25 et al., 2013). Some villages in Ladakh, India have already been forced to relocate due to glacial retreat and
26 the corresponding loss of their main fresh water resources (Grossman, 2015).

27 Artificial ice reservoirs (AIRs) have been considered to be a feasible way to adapt to these changes (Hock
28 et al., 2019; Nüsser et al., 2019b). An AIR is a human-made ice structure typically constructed during the
29 cold winter months and designed to slowly release freshwater during the warm and dry spring and summer
30 months. The main purpose of AIRs is irrigation. Therefore, AIRs are designed to store water in the form of
31 ice as long into the summer as possible. The energy required to construct an AIR is usually derived from
32 the gravitational head of the source water body. Some are constructed horizontally by freezing water using
33 a series of checkdams and others are built vertically by spraying water through fountain systems (Nüsser
34 et al., 2019a). The latter are colloquially referred to as Icestupas and are the subject of this study.

35 A typical Icestupa just requires a pipeline attached to a vertically mounted metal pipe with a fountain
36 nozzle for construction. Their water source is usually a high altitude lake or glacial stream. Due to the
37 altitude difference between the pipeline input and fountain output, water ejects from the fountain nozzle as
38 droplets that eventually lose their latent heat to the atmosphere and accumulate as ice around the metal pipe.
39 The fountain nozzle is raised through addition of further pipes as and when significant ice accumulates.
40 Typically, a dome of branches is constructed around the metal pipe so that such pipe extensions can be
41 done from within this dome. During the winter, the fountain is manually activated from sunset to sunrise.
42 Threads, tree branches and fishing nets are used to guide and accelerate the ice formation.

43 Since their invention in 2013 (Wangchuk, 2014), Icestupas have gained widespread publicity in the region
44 of Ladakh, Northern India since they require very little infrastructure, skills and energy to be constructed
45 in comparison to other water storage technologies. Compared to other AIR geometries, Icestupas (Fig.
46 1) can be built at lower altitudes and last much longer into the summer than other types of ice structures
47 (Wangchuk, 2014). However, to date, no reliable estimates exist about the amount of sprayed water that
48 is necessary to create them and the meltwater they provide (Nüsser et al., 2019a). Rough estimates of
49 Icestupa meltwater in Ladakh suggest that the water loss during the construction process is considerable
50 (see Appendix 8.1). A complete set of measurements of the water storage and energy balance are required
51 to understand the cause of the water losses better and increase the construction efficiency.

In this paper, we aim to develop a physically-based model of a vertical AIR (or Icestupa) that can quantify their storage efficiency using existing weather and water usage information. Mass and energy balance equations were used to estimate the quantity of water frozen, melted, evaporated and runoff. Sensitivity and uncertainty analysis were performed to identify the most critical parameters and the variance caused by them. For validation, we created an Icestupa at an accessible site (called Eispalast) near Schwarzsee close to the city of Fribourg, Switzerland, allowing easy maintenance and control of the measurements. Due to the low altitude of the site with relatively high winter temperatures, only a small Icestupa could be established during winter 2018/19 to provide us with model validation data. Our model and validation experiments provide first steps towards evaluating the effectiveness of a vertical AIR for irrigation and allow us to outline some preliminary guidelines for consideration when a construction of an Icestupa for water storage is envisaged.

2 STUDY SITE

The Eispalast (EP) site in the Schwarzsee region lies at 967 m a.s.l.. In the winter (Oct-Apr), mean daily maximum and minimum air temperatures vary between -4 and 14 °C. Clear skies are rare, averaging around 7 days, and precipitation amounts average 155 mm per month during winter (Meteoblue, 2020). The site was situated adjacent to a stream resulting in high humidity values across the study period. Within the EP site, an enclosure with a 1.8 m radius was constructed for the experiment. An automatic weather station (AWS) was adjacent to the wooden boundary as shown in Fig. 2. The fountain used for spraying water had a nozzle diameter of 5 mm and a height of 1.35 m, and was placed in the centre of the wooden enclosure. The water was transferred from a spring water source at 1267 m a.s.l. by pipeline and flowed via a flowmeter and an air escape valve to the nozzle, where it was sprinkled with a spray radius of around 1.7 m. The air escape valve was installed to avoid errors in the flow measurements due to air bubbles. In addition, a webcam guaranteed a continuous survey of the site during the construction of the Icestupa.

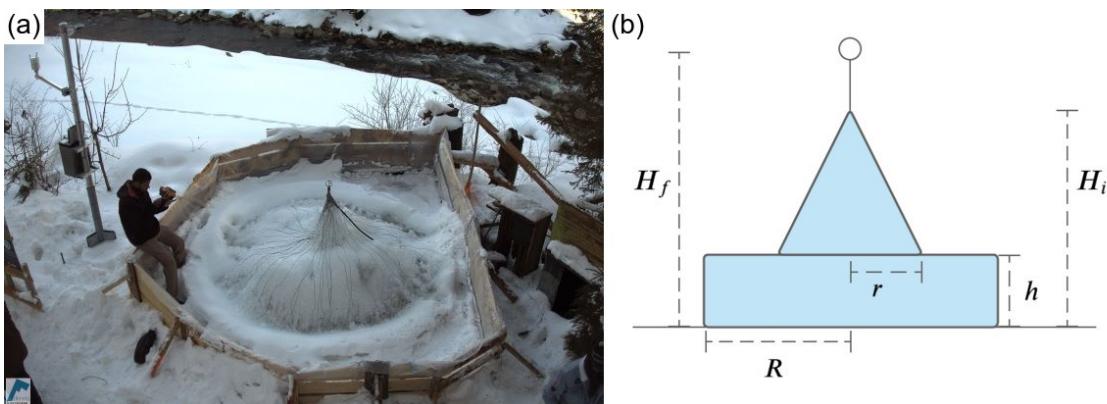


Figure 2. (a) The ice structure during the first validation measurement as seen on the webcam image of 14th Feb. (b) The corresponding cross section of the EP ice structure with the field estimates of r , R , h , H_i , H_f used to determine the Icestupa volume is shown on the right.

2.1 Construction

From 30th January to 18th March 2019 the Icestupa was constructed through the fountain spray, which was manually switched on if measured air temperature was below -5 °C after sunset and was switched off as soon as the ice was exposed to daylight or temperatures were above 0 °C. The water spray of the fountain was initially adjusted so that most of the water droplets land within the wooden boundary zone. The ice formation was guided by adding a metal framework at the ice structure base after the first night of

80 operation. Several cotton threads were tied between the ice structure base and fountain pole for accelerating
 81 and further guiding the ice formation process.

2.2 Measurements and Data

83 Measurements comprising air temperature, relative humidity, water flow rate, wind speed and direction
 84 were made every 5 minutes throughout the construction period. The water flow rate or discharge was
 85 measured via an ultrasonic sensor attached to the fountain supply pipeline. Precipitation data was derived
 86 from the Plaffeien AWS (IDAWEB, 2019) located 8.8 km away from the measurement site at an altitude of
 87 1042 m a.s.l.

88 In addition, we used ERA5 reanalysis dataset (Copernicus Climate Change Service (C3S), 2017) for
 89 filling data gaps and adding data that were not measured directly at the EP site. We recognised during
 90 our data analysis that, except precipitation, all the other meteorological variables of the EP site correlated
 91 much better with the ERA5 dataset than the nearby Plaffeien AWS dataset. The 2 m temperature parameter
 92 correlated with air temperature ($r^2 = 0.9$), surface pressure parameter correlated with air pressure ($r^2 = 1$)
 93 and 10m wind speed parameter (derived from horizontal and vertical components) correlated with wind
 94 speed ($r^2 = 0.6$). The ERA5 reanalysis dataset has a good correlation with lower elevation sites in
 95 Switzerland (Scherrer, 2020). The hourly ERA5 data and the 10 minute Plaffeien AWS data were linearly
 96 interpolated to the 5 minute data frequency of the EP AWS.

97 Due to a power failure, all data from the EP AWS was lost from 27th February 15:20 2019 to 2nd March
 98 15:00 2019 (equivalent to around 7% of the measurement period). During heavy snowfall events, the
 99 ultrasonic wind sensor was blocked and recorded zero values. ERA5 was used to fill such errors and data
 100 gaps. Near-surface humidity is not provided directly in ERA5 dataset, but from near-surface (2 m from the
 101 surface) temperature (T_{ERA5}) and dew point temperature (Tw_{ERA5}) the relative humidity (RH) at 2 m
 102 was calculated as:

$$RH = 100 \cdot \frac{e_{sat}(Tw_{ERA5})}{e_{sat}(T_{ERA5})} \quad (1)$$

103 where the saturation vapour pressure function e_{sat} is expressed with the Teten's formula (Tetens, 1930):

$$e_{sat}(T) = a_1 \cdot e^{(a_3 \cdot \frac{T}{(T+273.16-a_4)})} \quad (2)$$

104 with T in °C and the parameters set for saturation over water ($a_1 = 611.21$ Pa, $a_3 = 17.502$ and $a_4 = 32.19$
 105 K) according to Buck (1981). Zero wind speed values were recorded whenever snow accumulated on the
 106 ultrasonic wind sensor. All such null values were replaced using the ERA5 dataset.

107 The ERA5 grid point chosen (Latitude 46° 38' 24" N, Longitude 7° 14' 24" E) for the EP site was around
 108 9 km away from the actual site. All the ERA5 variables were therefore fitted with the EP dataset via linear
 109 regressions. With the modified ERA5 dataset, we were also able to further extend the EP dataset and allow
 110 the model to run beyond 18th March 2019. Precipitation was filled as null values beyond 18th March 2019.

111 **2.2.1 Field Measurements for validation**
 112 The volume was determined by decomposing the ice structure into a cylinder (length $2R$ and height h)
 113 and a cone (radius r and height $(H_i - h)$) through the following equation:

$$V = \pi \cdot R^2 \cdot h + 1/3 \cdot \pi \cdot r^2 \cdot (H_i - h) \quad (3)$$

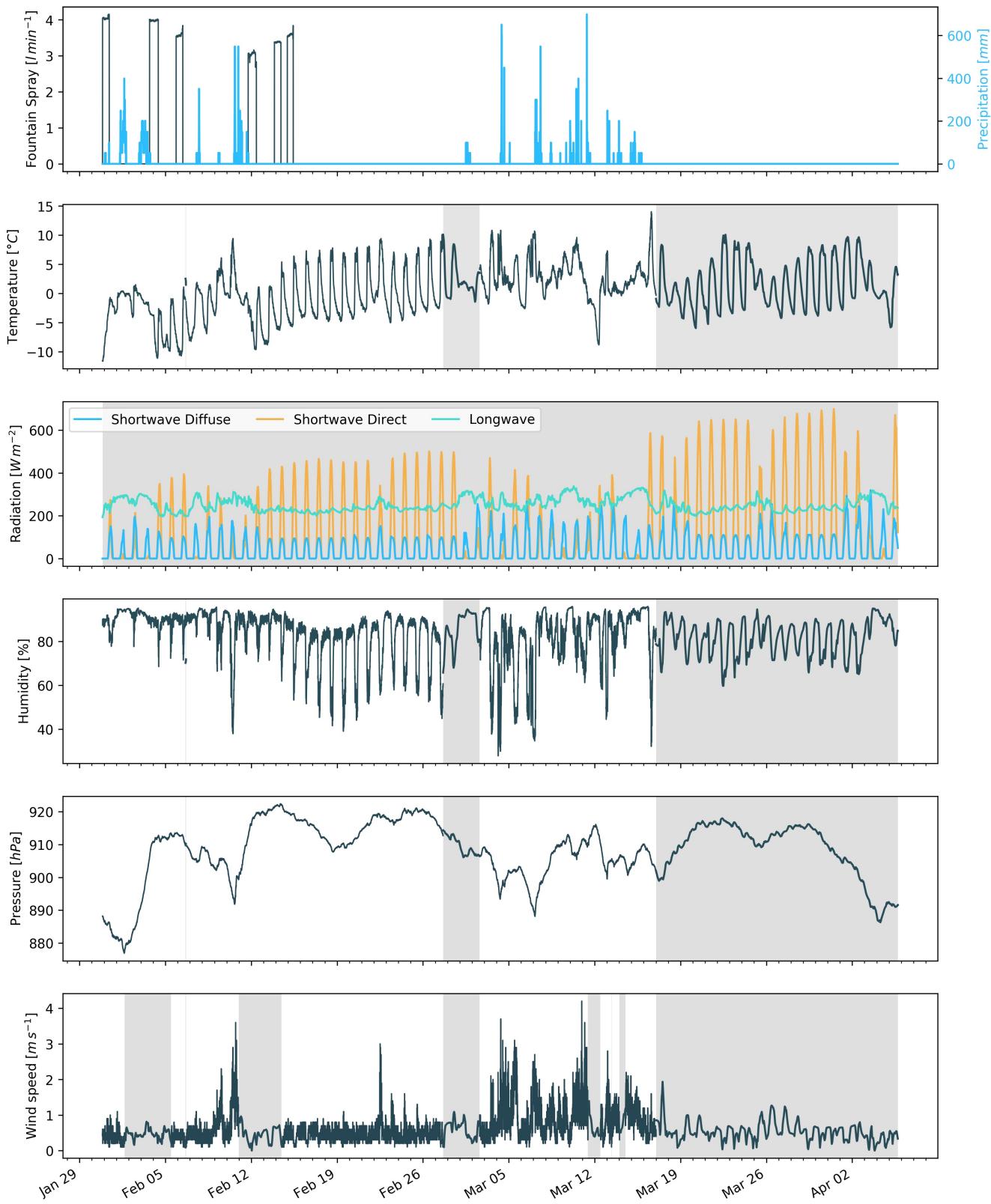


Figure 3. Measurements at the AWS of EP were used as main model input data in 5 minute frequency. Plaffeien AWS provided the precipitation data. Incoming shortwave and longwave radiation were obtained from ERA5 reanalysis dataset. Several data gaps and errors were also filled from the ERA5 dataset (shaded regions).

114 Manual measurements were performed at the end of the freezing period on 14th February 16:00 2019
 115 (only one more fountain run was possible after this date) to estimate r, R, h, H_i, H_f (see Fig. 2 for the
 116 different geometry components):

$$0.55 \leq r \leq 1m ; 1.1 \leq R \leq 1.2m ; 0.1 \leq h \leq 0.2m ; 0.6 \leq H_i \leq 0.8m ; 1.3 \leq H_f \leq 1.4m$$

117 The ranges of the variables show the variance of the Icestupa's dimensions across different compass
 118 orientations. Correspondingly, the volume range estimated for the first validation point was 0.857 ± 0.186
 119 m^3 on 14th February 16:00 2019.

120 The second validation point corresponds to the end of the melting process on 10th March 18:00 2019.
 121 Based on the webcam imagery and manual measurement, a thin layer of ice with an observed thickness
 122 between 0.01 to 0.06 m could be quantified. This results in the volume range for the second validation to
 123 be $0.13 \pm 0.09 m^3$ on 11th March 2019

124 In reality, the EP ice structure was more cylindrical until a height of 0.2 m and conical afterwards until a
 125 height of 0.6 m with a radius of 1.18 m. However, we assume a conical shape of this ice structure in order
 126 to apply the modelling strategy described below.

3 MODEL SETUP

127 The model consists of three parts which calculate, a) the geometric evolution of the Icestupa, b) the energy
 128 balance and c) the mass balance as shown schematically in Fig. 4. A bulk energy and mass balance model
 129 is used to calculate the amounts of ice, meltwater, water vapour and runoff water of the Icestupa every 5
 130 minutes.

3.1 Icestupa geometric evolution

131 Radius r_{ice}^i and height h_{ice}^i define the dimensions of the Icestupa assuming its geometry to be a cone as
 132 shown in Fig. 5. The surface area A^i exposed to the atmosphere and volume V^i are:

$$A = \pi \cdot r_{ice} \cdot \sqrt{r_{ice}^2 + h_{ice}^2} \quad (4)$$

$$V = \pi/3 \cdot r_{ice}^2 \cdot h_{ice} \quad (5)$$

134 Note that we do not specify the time step superscript i of the shape variables A, V, r_{ice} and h_{ice} for
 135 brevity. The equations used henceforth display model time step superscript i only if it is different from the
 136 current time step.

137 With the mass of the Icestupa M_{ice} , its current volume can also be expressed as:

$$V = M_{ice}/\rho_{ice} \quad (6)$$

138 where ρ_{ice} is the density of ice ($917 kg m^{-3}$). The model of the Icestupa is initialised with a thickness
 139 of Δx (defined in 3.2) and a circular area of radius r_F . The constant r_F represents the mean spray radius
 140 of the fountain. This fountain spray radius is determined by modelling the projectile motion of the water

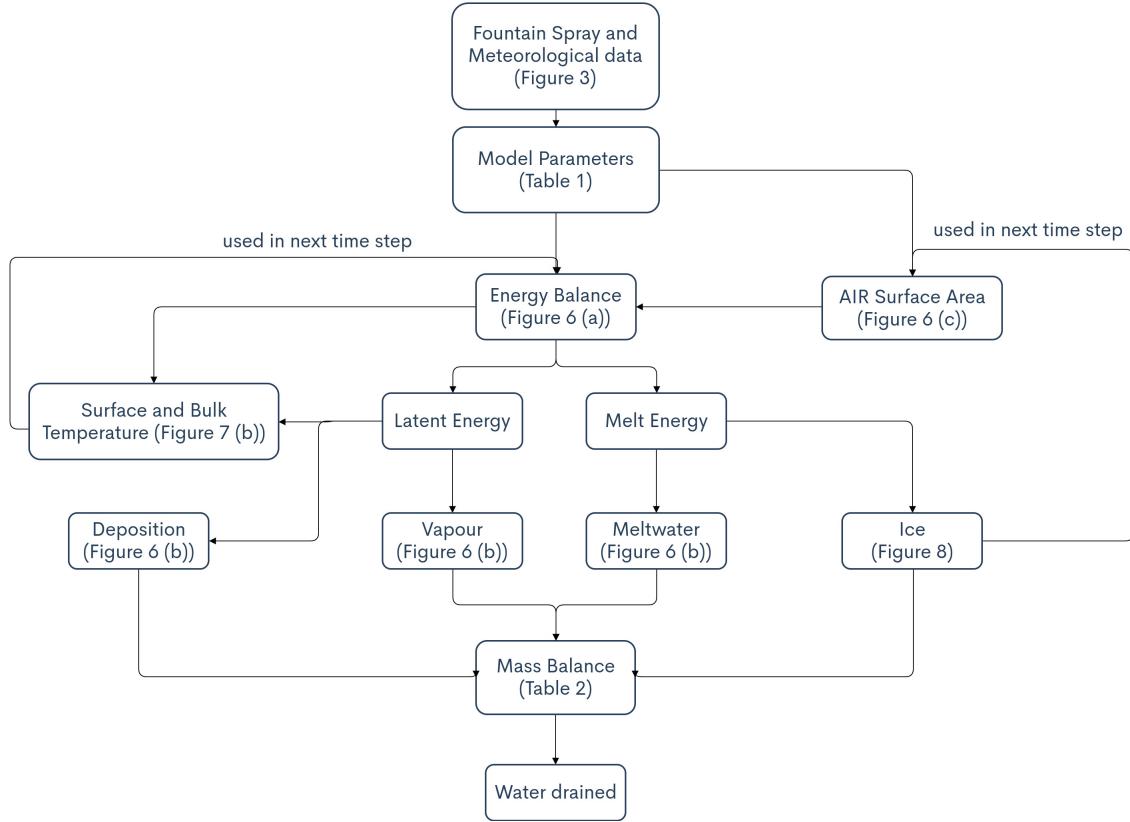


Figure 4. Model schematic showing the algorithm used in the model at every time step. Further details about the variables can be found in the associated tables and figures.

141 droplets. Using mass conservation, the droplet speed v_F can be determined from the spray rate d_F and the
 142 diameter dia_F of the nozzle as follows:

$$v_F = \frac{d_F}{\pi \cdot dia_F^2 / 4} \quad (7)$$

143 Afterwards, we assume that the water droplets move with an air friction free projectile motion from
 144 the fountain nozzle with a height h_F to the ice/ground surface. The resulting spray radius r_F was then
 145 determined from the projectile motion equation as follows:

$$r_F = \frac{v_F \cdot \cos\theta_F (v_F \cdot \sin\theta_F + \sqrt{(v_F \cdot \sin\theta_F)^2 + 2 \cdot g \cdot h_F})}{g} \quad (8)$$

146 where $g = 9.8 \text{ ms}^{-2}$ is the acceleration due to gravity and $\theta_F = 45^\circ$ is the angle of launch.

147 During subsequent time steps, the dimensions of the Icestupa evolve assuming a uniform ice formation
 148 and decay across its surface area with an invariant slope $s_{cone} = \frac{h_{ice}}{r_{ice}}$ as shown in Fig. 5. During these time
 149 steps, the volume is parameterised using Eqn. 5 as:

$$V = \pi / 3 \cdot r_{ice}^3 \cdot s_{cone} \quad (9)$$

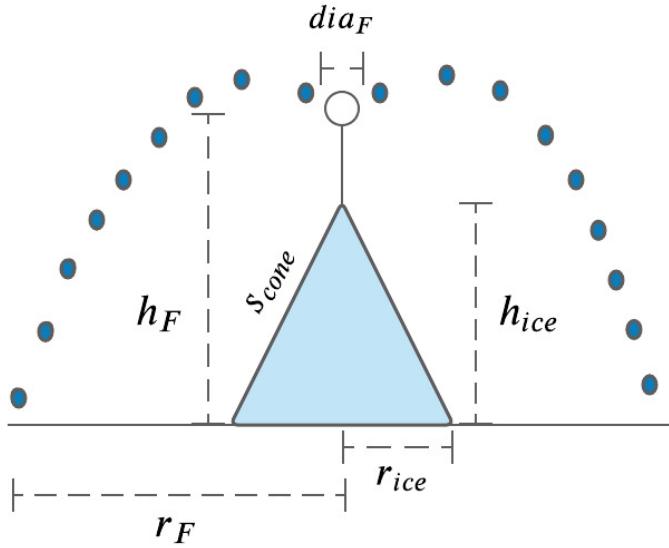


Figure 5. Shape variables and fountain constants of the EP Icestupa. r_{ice} is the radius, h_{ice} is the height and s_{cone} is the slope of the ice cone. r_F is the spray radius, h_F is the height and dia_F is the nozzle diameter of the fountain.

150 However, the Icestupa cannot outgrow the maximum range of the water droplets ($(r_{ice})_{max} = r_F$).
 151 Combining equations 5, 6 and 9, the geometric evolution of the Icestupa at each time step i can be
 152 determined by considering the following rules:

$$(r_{ice}, h_{ice}) = \begin{cases} (r_F, \Delta x) & \text{if } i = 0 \\ (r_{ice}^{i-1}, \frac{3 \cdot M_{ice}}{\pi \cdot \rho_{ice} \cdot (r_{ice}^{i-1})^2}) & \text{if } r_{ice}^{i-1} \geq r_F \text{ and } \Delta M_{ice} > 0 \text{ where } \Delta M_{ice} = M_{ice}^{i-1} - M_{ice}^{i-2} \\ (\frac{3 \cdot M_{ice}}{\pi \cdot \rho_{ice} \cdot s_{cone}})^{1/3} \cdot (1, s_{cone}) & \text{otherwise} \end{cases} \quad (10)$$

153 3.2 Energy Balance

154 The energy balance equation (Hock, 2005) for the Icestupa is formulated as follows:

$$q_{net} = q_{SW} + q_{LW} + q_L + q_S + q_F + q_G \quad (11)$$

155 where q_{net} is the net energy flux in $[W m^{-2}]$; q_{SW} is the net shortwave radiation; q_{LW} is the net longwave
 156 radiation; q_L and q_S are the turbulent latent and sensible heat fluxes. q_F represents the heat exchange of the
 157 fountain water droplets with the AIR ice surface during fountain on time steps. q_G represents ground heat
 158 flux between Icestupa surface and Icestupa interior. Energy transferred in the direction of the ice surface is
 159 always denoted as positive and away as negative.

160 Equation 11 is usually referred to as the energy budget for “the surface”, but practically it must apply to a
 161 surface layer of ice with a finite thickness Δx . The energy flux acts upon the Icestupa surface layer which
 162 has an upper and a lower boundary defined by the atmosphere and the ice body of the Icestupa, respectively.
 163 The parameter selection for Δx is based on the following two arguments: (a) the ice thickness Δx should

164 be small enough to represent the daily surface temperature variations and (b) Δx should be large enough
 165 for these temperature variations to not reach the bottom of the surface layer. Therefore, we introduced a 5
 166 mm thick ice surface layer, over which the energy balance is calculated. A sensitivity analysis was later
 167 performed to understand the influence of this factor. Here, we define the surface temperature T_{ice} to be
 168 the modelled average temperature of the Icestupa surface layer and the energy flux q_{net} is assumed to act
 169 uniformly across the Icestupa area A .

170 3.2.1 Net Shortwave Radiation q_{SW}

171 The net shortwave radiation q_{SW} is computed as follows:

$$q_{SW} = (1 - \alpha) \cdot (SW_{direct} \cdot f_{cone} + SW_{diffuse}) \quad (12)$$

172 where SW_{direct} and $SW_{diffuse}$ are the ERA5 direct and diffuse short wave radiation, α is the modelled
 173 albedo and f_{cone} is the area fraction of the ice structure exposed to the direct shortwave radiation.

174 We model the albedo using a scheme described in Oerlemans and Knap (1998). The scheme records the
 175 decay of albedo with time after fresh snow is deposited on the surface. δt records the number of time steps
 176 after the last snowfall event. After snowfall, albedo changes over a time step, δt , as

$$\alpha = \alpha_{ice} + (\alpha_{snow} - \alpha_{ice}) \cdot e^{(-\delta t)/\tau} \quad (13)$$

177 where α_{ice} is the bare ice albedo value (0.35), α_{snow} is the snow ice albedo value (0.85) and τ is a decay
 178 rate, which determines how fast the albedo of the ageing snow reaches this value. The decay rate τ is
 179 assumed to have a base value of 10 days similar to values obtained by Schmidt et al. (2017) for wet surfaces
 180 and its maximal value is set based on observations by Oerlemans and Knap (1998) as shown in Table 1.
 181 Furthermore, the albedo α varies depending on the water source that formed the current Icestupa surface.
 182 Correspondingly, the albedo is reset to the value of bare ice albedo if the fountain is spraying water onto
 183 the current ice surface and to the value of fresh snow albedo if a snowfall event occurred. Snowfall events
 184 are assumed if the air temperature is below $T_{ppt} = 1^{\circ}C$ (Fujita and Ageta, 2000).

185 The area fraction f_{cone} of the ice structure exposed to the direct shortwave radiation depends on the
 186 shape considered. The direct solar radiation incident on the AIR surface is first decomposed into horizontal
 187 and vertical components using the solar elevation angle θ_{sun} . For a conical shape, half of the total curved
 188 surface is exposed to the vertical component of the direct shortwave radiation and the projected triangle
 189 of the curved surface is exposed to the horizontal component of the direct shortwave radiation. The solar
 190 elevation angle θ_{sun} used is modelled using the parametrisation proposed by Woolf (1968). Accordingly,
 191 f_{cone} is determined as follows:

$$f_{cone} = \frac{(0.5 \cdot r_{ice} \cdot h_{ice}) \cdot \cos\theta_{sun} + (\pi \cdot r_{ice}^2 / 2) \cdot \sin\theta_{sun}}{\pi \cdot r_{ice} \cdot (r_{ice}^2 + h_{ice}^2)^{1/2}} \quad (14)$$

192 The ERA5 diffuse shortwave radiation is assumed to impact the conical Icestupa surface uniformly.

193 3.2.2 Net Longwave Radiation q_{LW}

194 The net longwave radiation q_{LW} , for which there were no direct measurements available at EP, is
 195 determined as follows:

$$q_{LW} = LW_{in} - \sigma \cdot \epsilon_{ice} \cdot (T_{ice} + 273.15)^4 \quad (15)$$

where T_a represents the measured air temperature, T_{ice} is the modelled surface temperature, both temperatures are given in $^{\circ}\text{C}$, $\sigma = 5.67 \cdot 10^8 \text{ J m}^{-2} \text{ s}^{-1} \text{ K}^{-4}$ is the Stefan-Boltzmann constant, LW_{in} denotes the incoming longwave radiation derived from the ERA5 dataset and ϵ_{ice} is the corresponding emissivity value for the Icestupa surface (see Table 1).

3.2.3 Turbulent sensible q_S and latent q_L heat fluxes

The turbulent sensible q_S and latent heat q_L fluxes are computed with the following expressions proposed by Garratt (1992):

$$q_S = c_a \cdot \rho_a \cdot p_a / p_{0,a} \cdot \frac{\kappa^2 \cdot v_a \cdot (T_a - T_{ice})}{(\ln \frac{h_{AWS}}{z_{ice}})^2} \quad (16)$$

$$q_L = 0.623 \cdot L_s \cdot \rho_a / p_{0,a} \cdot \frac{\kappa^2 \cdot v_a (p_{v,a} - p_{v,ice})}{(\ln \frac{h_{AWS}}{z_{ice}})^2} \quad (17)$$

where h_{AWS} is the measurement height above the ground surface of the AWS (in m), v_a is the wind speed in m s^{-1} and M_F denotes fountain water spray mass in kg . c_a is the specific heat of air at constant pressure ($1010 \text{ J kg}^{-1} \text{ K}^{-1}$), ρ_a is the air density at standard sea level (1.29 kg m^{-3}), $p_{0,a}$ is the air pressure at standard sea level (1013 hPa), κ is the von Karman constant (0.4), L_s is the heat of sublimation (2848 kJ kg^{-1}) and z_{ice} (1.7 mm) denotes the roughness length of ice (momentum and scalar) described in (Garratt, 1992). The vapor pressures over air ($p_{v,a}$) and ice ($p_{v,ice}$) was obtained using the following formulation given in WMO (2018):

$$\begin{aligned} p_{v,a} &= 6.107 \cdot 10^{(7.5 \cdot T_a / (T_a + 237.3))} \\ p_{v,ice} &= (1.0016 + 3.15 \cdot 10^{-6} \cdot p_a - 0.074 \cdot p_a^{-1}) \cdot (6.112 \cdot e^{(22.46 \cdot T_{ice} / (T_{ice} + 272.62))}) \end{aligned} \quad (18)$$

where p_a is the measured air pressure in hPa .

3.2.4 Fountain water heat flux q_F

The total energy flux is further influenced through the heat flux caused by the water that was additionally added to the surface of the Icestupa during the time the fountain was running. We take this interaction between the fountain water and the ice surface into account by assuming that the ice surface temperature remains constant at 0°C during time steps when the fountain is active. This process can be divided into two simultaneous steps: (a) the water temperature T_{water} is cooled to 0°C and (b) the ice surface temperature is warmed to 0°C . Process (a) transfers the necessary energy for process (b) throughout the fountain runtime. We further assume that this process is instantaneous, i.e. the ice temperature is immediately set to 0°C within just one time step Δt when the fountain is switched on. Thus, the heat flux caused by the fountain water is calculated as follows:

$$q_F = \begin{cases} 0 & \text{if } \Delta M_F = 0 \\ \frac{\Delta M_F \cdot c_{water} \cdot T_{water}}{\Delta t \cdot A} + \frac{\rho_{ice} \cdot \Delta x \cdot c_{ice} \cdot T_{ice}}{\Delta t} & \text{if } \Delta M_F > 0 \end{cases} \quad (19)$$

221 with c_{ice} as the specific heat of ice.

222 3.2.5 Bulk Icestupa heat flux q_G

223 The bulk Icestupa heat flux q_G corresponds to the ground heat flux in normal soils and is caused by the
224 temperature gradient between the surface layer (T_{ice}) and the ice body (T_{bulk}). It is expressed by using the
225 heat conduction equation as follows:

$$q_G = k_{ice} \cdot (T_{bulk} - T_{ice}) / l_{ice} \quad (20)$$

226 where k_{ice} is the thermal conductivity of ice ($2.123 \text{ W m}^{-1} \text{ K}^{-1}$), T_{bulk} is the mean temperature of the
227 ice body within the Icestupa and l_{ice} is the average distance of any point in the surface to any other point in
228 the ice body. T_{bulk} is initialised as 0°C and later determined from Eqn. 20 as follows:

$$T_{bulk}^{i+1} = T_{bulk} - (q_G \cdot A \cdot \Delta t) / (M_{ice} \cdot c_{ice}) \quad (21)$$

229 Since we assume a conical shape with $r_{ice} > h_{ice}$, l_{ice} cannot be greater than $2r_{ice}$ and also cannot
230 be less than Δx . Therefore, the average distance from any point on the surface to any point inside is
231 $\Delta x \leq l_{ice} \leq r_{ice}$. We calculate q_G here assuming $l_{ice} = r_{ice}/2$.

232 3.2.6 Surface temperature changes and melt energy q_{melt}

233 The available net energy q_{net} partly increases surface temperature, but also contributes to ice melt at the
234 surface of the Icestupa. q_T denotes the energy used on changing the surface temperature T_{ice} and q_{melt}
235 denotes the energy used to produce meltwater. So Eqn. 11 can be rewritten as:

$$q_{net} = q_{melt} + q_T \quad (22)$$

236 We define the freezing energy as $q_{freeze} = (q_{net} - q_L)$. This is because the latent heat always contributes
237 to temperature fluctuations. Now, the temperature fluctuates based on three scenarios, namely (1) the
238 freezing energy flux is negative but cannot freeze all the fountain water output; (2) the freezing energy flux
239 is negative and can freeze all the fountain water output; (3) the freezing energy is positive or the fountain is
240 inactive ($\Delta M_F = 0$). Therefore, we express the rate of change of temperature as follows:

$$\frac{\Delta T}{\Delta t} = \begin{cases} -T_{ice}^{i-1} / \Delta t & \text{if } q_{freeze} < 0 \text{ and } \Delta M_F \geq -q_{freeze} \cdot A \cdot \Delta t / L_f \\ (\Delta M_F \cdot L_f) / (\rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot A \cdot \Delta t) & \text{if } q_{freeze} < 0 \text{ and } \Delta M_F < -q_{freeze} \cdot A \cdot \Delta t / L_f \\ q_{net} / (\rho_{ice} \cdot c_{ice} \cdot \Delta x) & \text{if } \Delta M_F = 0 \text{ or } q_{freeze} > 0 \end{cases} \quad (23)$$

241 Whenever the model predicts $T_{ice}^{i+1} > 0^\circ\text{C}$, then the surface temperature is set to 0°C in the corresponding
242 time step and additional energy contributes to q_{melt} . Combining these requirements, we get:

$$(q_T, q_{melt}) = \begin{cases} (\rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{\Delta T}{\Delta t}, q_{net} - q_L - \rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{\Delta T}{\Delta t}) & \text{if } T_{ice}^{i+1} \leq 0^\circ\text{C} \text{ and } \Delta M_F > 0 \\ (\rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{\Delta T}{\Delta t}, q_{net} - \rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{\Delta T}{\Delta t}) & \text{if } T_{ice}^{i+1} \leq 0^\circ\text{C} \text{ and } \Delta M_F = 0 \\ (-\rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{T_{ice}^i}{\Delta t}, q_{net} - q_L + \rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{T_{ice}^i}{\Delta t}) & \text{if } T_{ice}^{i+1} > 0^\circ\text{C} \text{ and } \Delta M_F > 0 \\ (-\rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{T_{ice}^i}{\Delta t}, q_{net} + \rho_{ice} \cdot c_{ice} \cdot \Delta x \cdot \frac{T_{ice}^i}{\Delta t}) & \text{if } T_{ice}^{i+1} > 0^\circ\text{C} \text{ and } \Delta M_F = 0 \end{cases} \quad (24)$$

Table 1. Free parameters in the model categorised as constant, uncertain and site parameters. Base value (B) and uncertainty (U) were taken from the literature. For assumptions (assum.), the uncertainty was chosen to be relatively large (5 %). For measurements (meas.), the uncertainty due to parallax errors is chosen to be (1 %).

Constant Parameters	Symbol	Value	References
Van Karman constant	κ	0.4	B: Cuffey and Paterson
Stefan Boltzmann constant	σ	$5.67 \cdot 10^{-8} W m^{-2} K^{-4}$	B: Cuffey and Paterson
Air pressure at sea level	$p_{0,a}$	1013 hPa	B: Mölg and Hardy
Density of water	ρ_w	$1000 kg m^{-3}$	B: Cuffey and Paterson
Density of ice	ρ_{ice}	$917 kg m^{-3}$	B: Cuffey and Paterson
Density of air	ρ_a	$1.29 kg m^{-3}$	B: Mölg and Hardy
Specific heat of water	c_w	$4186 J kg^{-1} ^\circ C^{-1}$	B: Cuffey and Paterson
Specific heat of ice	c_{ice}	$2097 J kg^{-1} ^\circ C^{-1}$	B: Cuffey and Paterson
Specific heat of air	c_a	$1010 J kg^{-1} ^\circ C^{-1}$	B: Mölg and Hardy
Thermal conductivity of ice	k_{ice}	$2.123 W m^{-1} K^{-1}$	B: Bonales et al.
Latent Heat of Sublimation	L_s	$2848 kJ kg^{-1}$	B: Cuffey and Paterson
Latent Heat of Evaporation	L_e	$2514 kJ kg^{-1}$	B: Cuffey and Paterson
Latent Heat of Fusion	L_f	$334 kJ kg^{-1}$	B: Cuffey and Paterson
Gravitational acceleration	g	$9.81 m s^{-2}$	B: Cuffey and Paterson
Uncertain Parameters		Range	
Precipitation	T_{ppt}	$1 ^\circ C$	$\pm 1 ^\circ C$
Temperature threshold			B + U: Fujita and Ageta, Zhou et al.
Ice Emissivity	ϵ_{ice}	0.95	[0.949,0.993] B: Cuffey and Paterson; U: Hori et al.
Ice Albedo	α_{ice}	0.35	$\pm 5 \%$ B: Cuffey and Paterson; U: assum.
Snow Albedo	α_{snow}	0.85	$\pm 5 \%$ B: Cuffey and Paterson; U: assum.
Albedo Decay Rate	τ	10 days	[1, 22] days B: Schmidt et al.; U: Oerlemans and Knap assum.
Ice layer thickness	Δx	5 mm	[1, 10] mm
Site Parameters			
Fountain diameter	nozzle	dia_F	5 mm $\pm 1 \%$ B: meas. ; U: assum.
Fountain height		h_F	$\pm 1 \%$ B: meas. ; U: assum.
Fountain temperature	water	T_{water}	$[0, 9] ^\circ C$ B: meas. ; U: meas.
AWS height		h_{AWS}	$\pm 1 \%$ B: meas. ; U: assum.

243 **3.3 Mass Balance**

244 The mass balance equation is used to derive the water that drains away (M_{runoff}) as follows:

$$\frac{\Delta M_{runoff}}{\Delta t} = \frac{\Delta M_F + \Delta M_{ppt} + \Delta M_{dpt} - \Delta M_{ice} - \Delta M_{melt} - \Delta M_{vapour}}{\Delta t} \quad (25)$$

245 where $\Delta M = M^i - M^{i-1}$. Here $\frac{\Delta M_F}{\Delta t} = d_F$ where d_F is the spray of the fountain measured in $[kg s^{-1}]$;
 246 M_{ppt} is the cumulative precipitation and M_{dpt} is the cumulative accumulation through water vapour
 247 condensation or deposition; M_{ice} is the cumulative mass of ice; M_{melt} is the cumulative mass of melt water
 248 and M_{vapour} represents the cumulative water vapor loss by evaporation or sublimation.

249 Precipitation input is calculated as:

$$\frac{\Delta M_{ppt}}{\Delta t} = \begin{cases} \pi \cdot r_{ice}^2 \cdot \rho_w \cdot ppt & \text{if } T_a < T_{ppt} \\ 0 & \text{if } T_a \geq T_{ppt} \end{cases} \quad (26)$$

250 where ρ_w is the density of water ($1000 kg m^{-3}$), ppt is the measured precipitation rate in $[m s^{-1}]$ and
 251 T_{ppt} is the temperature threshold below which precipitation falls as snow. Here, snowfall events were
 252 identified using T_{ppt} as $1^\circ C$. Snow mass input is calculated by assuming a uniform deposition over the
 253 entire circular footprint of the Icestupa.

254 The latent heat flux is used to estimate either the evaporation and condensation processes or sublimation
 255 and deposition processes. To differentiate between these two possibilities, we classify the time steps into
 256 humid or non-humid depending on whether the corresponding relative humidity value is above or below
 257 60% (Stigter et al., 2018). On humid time steps, we assume condensation or evaporation to occur whereas
 258 on non-humid time steps deposition or sublimation can occur. Correspondingly, latent heat of evaporation
 259 (L_e) is used for humid time steps and latent heat of sublimation (L_s) is used for non-humid time steps.
 260 Water accumulation and vapour loss from the Icestupa surface is calculated as follows:

$$\left(\frac{\Delta M_{vapour}}{\Delta t}, \frac{\Delta M_{dpt}}{\Delta t} \right) = \begin{cases} (-q_L \cdot A/L, 0) & \text{if } q_L < 0 \\ (0, q_L \cdot A/L) & \text{if } q_L \geq 0 \end{cases} \quad (27)$$

261 where $L = \begin{cases} L_s & \text{if } RH < 60 \\ L_e & \text{if } RH \geq 60 \end{cases}$

262 Using the melt energy q_{melt} , we estimate the frozen and melted ice mass (ΔM_{ice} , ΔM_{melt}). Removing
 263 the contribution of precipitation and combining Eqn. 27 we are left with the contribution from the melt
 264 energy as follows:

Table 2. Summary of mass balance components for the EP experiment after the fountain spray was stopped (on 15th February 2019) and at the end of the model run (on 5th April). All parameters except M_F were modelled.

	Mass Component	Fountain spray ends	Model ends
Input	M_F	18060 kg	18060 kg
	M_{ppt}	438 kg	461 kg
	M_{dpt}	7 kg	33 kg
Output	M_{melt}	154 kg	1005 kg
	M_{ice}	808 kg	0 kg
	M_{vapour} M_{runoff}	11 kg 17532 kg	16 kg 17532 kg

$$\left(\frac{\Delta M_{ice} - \Delta M_{ppt} - \Delta M_{dpt} + \Delta M_{vapour}}{\Delta t}, \frac{\Delta M_{melt}}{\Delta t} \right) \text{ if } RH < 60 \\ \left(\frac{\Delta M_{ice} - \Delta M_{ppt} - \Delta M_{dpt}}{\Delta t}, \frac{\Delta M_{melt} + \Delta M_{vapour}}{\Delta t} \right) \text{ if } RH \geq 60 \right\} = \begin{cases} \frac{q_{melt} \cdot A}{L_f} \cdot (-1, 1) & \text{if } q_{melt} \geq 0 \\ \frac{q_{melt} \cdot A}{L_f} \cdot (-1, 0) & \text{if } q_{melt} < 0 \text{ and } \frac{\Delta M_F}{\Delta t} \geq -\frac{q_{melt} \cdot A}{L_f} \\ (\frac{\Delta M_F}{\Delta t}, 0) & \text{if } q_{melt} < 0 \text{ and } 0 \leq \frac{\Delta M_F}{\Delta t} < -\frac{q_{melt} \cdot A}{L_f} \end{cases} \quad (28)$$

265 Now, with all the other terms known in Eqn. 25, the water drainage/runoff can be determined.

266 Considering AIRs as water reservoirs, we can quantify their potential through the amount of water they
267 store (storage quantity) and the length of time they store it (storage duration). Another means of comparing
268 different Icestupas is through their water storage efficiency defined accordingly as:

$$\text{Storage Efficiency} = \frac{M_{melt}}{(M_F + M_{ppt} + M_{dpt})} \cdot 100 \quad (29)$$

4 MODEL RESULTS

269 The model was forced with meteorological data from 30th January to 5th April 2019 (Fig. 3) and various
270 parameters (see Table 1) to calculate the mass and energy balance of the Icestupa.

4.1 Energy and mass balance calculation

272 Daily averages of some components of the energy balance are shown in Fig. 6 (b). On average during
273 the experiment duration, the total energy balance was almost zero. Net shortwave radiation (32 W m^{-2}),
274 sensible (9 W m^{-2}) and latent heat flux (2 W m^{-2}) with a mostly positive flux towards the surface of the
275 icestupa were compensated by the net longwave radiation (-32 W m^{-2}) and the melt energy (-12 W m^{-2}).
276 The contributions of other fluxes were negligible in comparison.

277 Net shortwave radiation is the main input to, and the most varying energy flux on the ice surface. Its
278 variability is controlled by the surface albedo α and the area fraction f_{cone} which therefore represent key

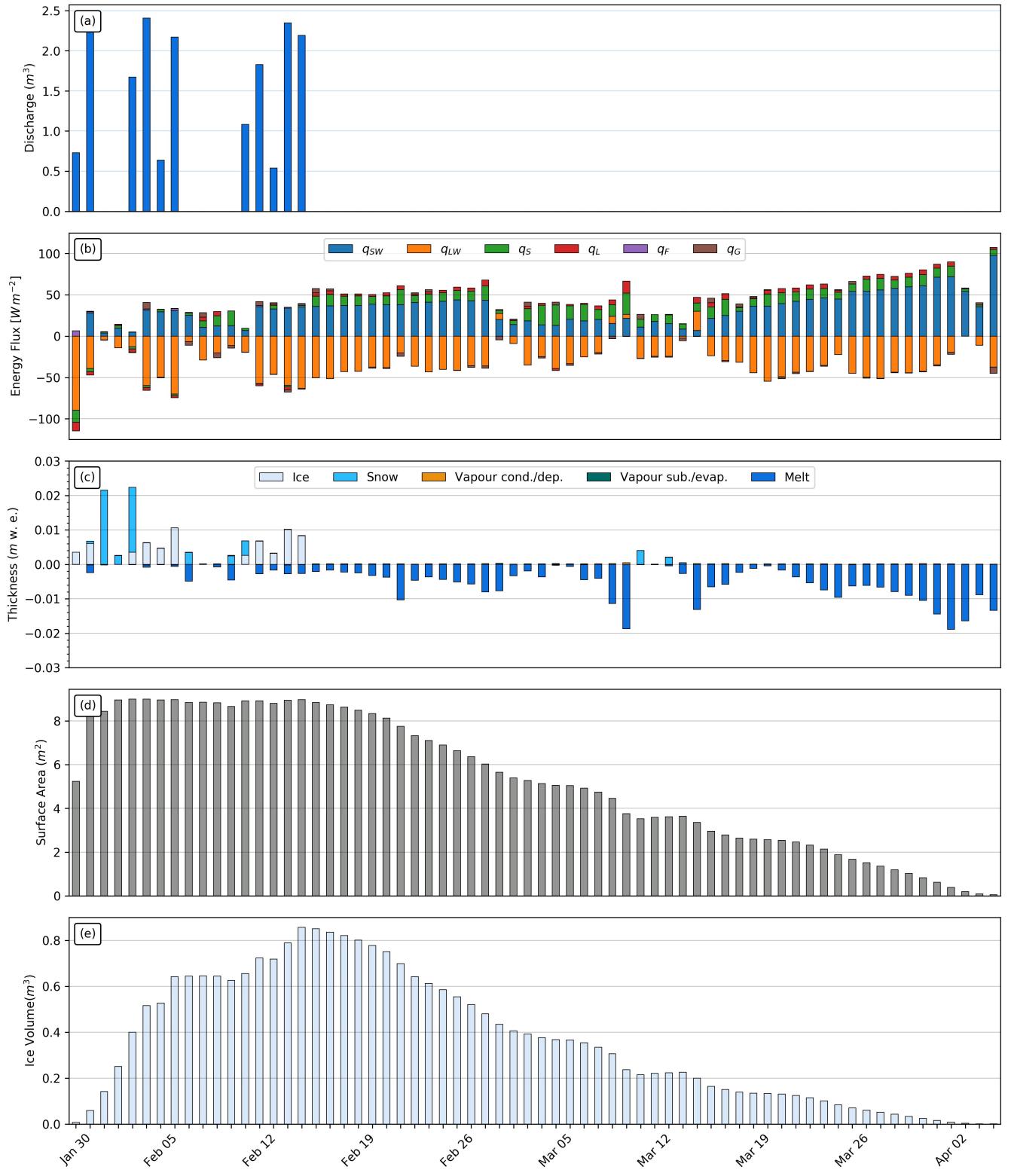


Figure 6. (a) Fountain discharge (b) energy flux components, (c) mass flux components (d) surface area and (e) volume of the Icestupa in daily time steps. q_{SW} is the net shortwave radiation; q_{LW} is the net longwave radiation; q_L and q_S are the turbulent latent and sensible heat fluxes. q_F represents the interactions of the ice-water boundary during fountain on time steps. q_G quantifies the heat conduction process between the Icestupa surface layer and the ice body.

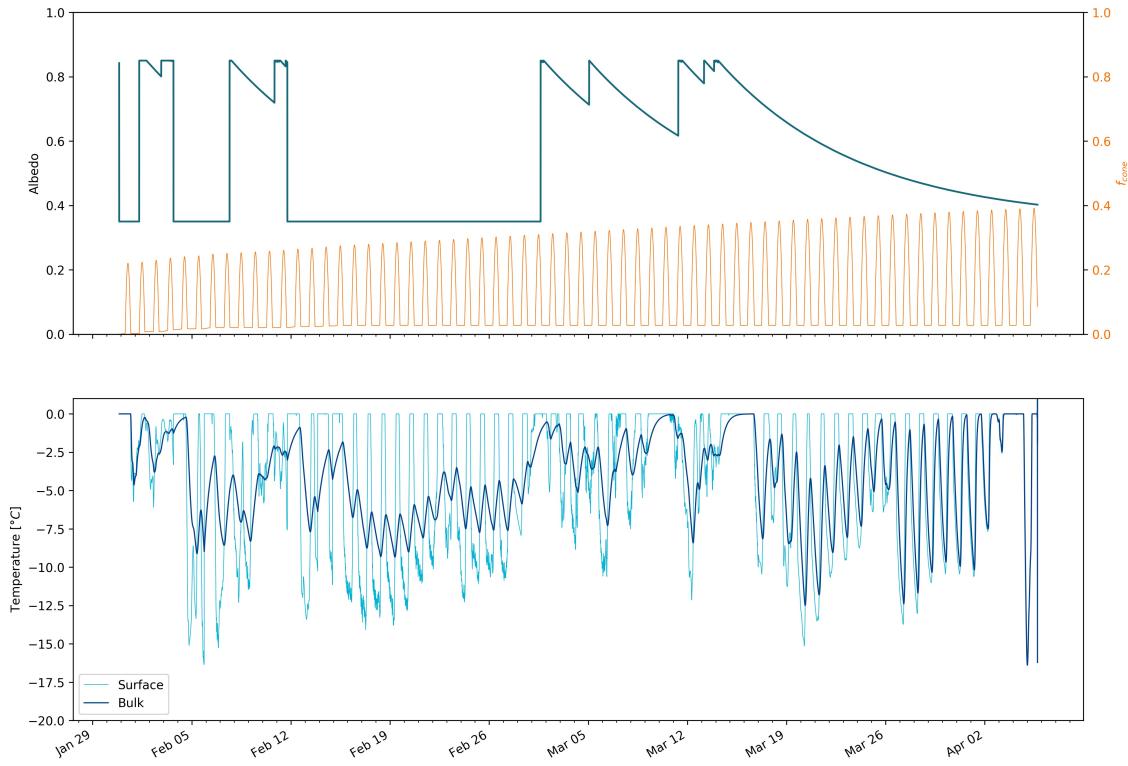


Figure 7. Some derived parameters of the model, namely, albedo and f_{cone} (a), Surface and bulk temperature (b). In (a), the green curve shows how snow and fountain-on events reset albedo between ice albedo and snow albedo. The decay of the snow albedo to ice albedo can also be observed. The orange curve shows how the solar radiation area fraction varied diurnally with variations in the solar elevation angle. In (b), the surface temperature (light blue curve) was forced to be $0\text{ }^{\circ}\text{C}$ during fountain activity. The corresponding bulk temperature is shown with the dark blue curve.

variables in the energy balance (Fig. 7 (b)). Although global radiation flux reached a daily maximum value of $339\text{ }Wm^{-2}$, q_{SW} only went up to $98\text{ }Wm^{-2}$. This is caused by the fact that only about 30 % of the direct solar radiation influenced the Icestupa surface as shown by the area fraction f_{cone} in Fig. 7 (a). Snowfall is the atmospheric variable connected most closely and proportionally to albedo. Higher and/or more frequent snowfall thus decreases the energy available for melt due to the corresponding increase in α .

q_{LW} was predominantly negative indicating that this energy balance component drove the freezing of the ice structure. Daily values of q_{LW} ranged from -90 to $23\text{ }Wm^{-2}$. Turbulent sensible heat flux q_S contributed mostly to the melt of the ice structure. Daily values of q_S ranged from -15 to $26\text{ }Wm^{-2}$. Deposition/condensation was favored over evaporation/sublimation so the mean of the turbulent latent heat flux q_L across model runtime was positive. Daily values of q_L ranged from -10 to $14\text{ }Wm^{-2}$. Therefore, the Icestupa gained mass cumulatively from the atmosphere due to the deposition/condensation process. Fountain water heat flux q_F had a mean of zero as it was only nonzero during 1002 time steps or around 100 hours. Daily values of q_F ranged from -1 to $7\text{ }Wm^{-2}$. The contribution of heat flux by conduction q_G was also minimal as it only varied between -7 to $8\text{ }Wm^{-2}$ with a mean of $0\text{ }Wm^{-2}$. The energy contributing to surface temperature changes (q_T) was insignificant in comparison to the energy spent on freezing and melting (q_{melt}). The resulting bulk temperature and the surface temperature are shown in Fig. 7 (b). For the total considered period, q_{LW} accounted for 32.5% of overall energy turnover. The energy turnover is

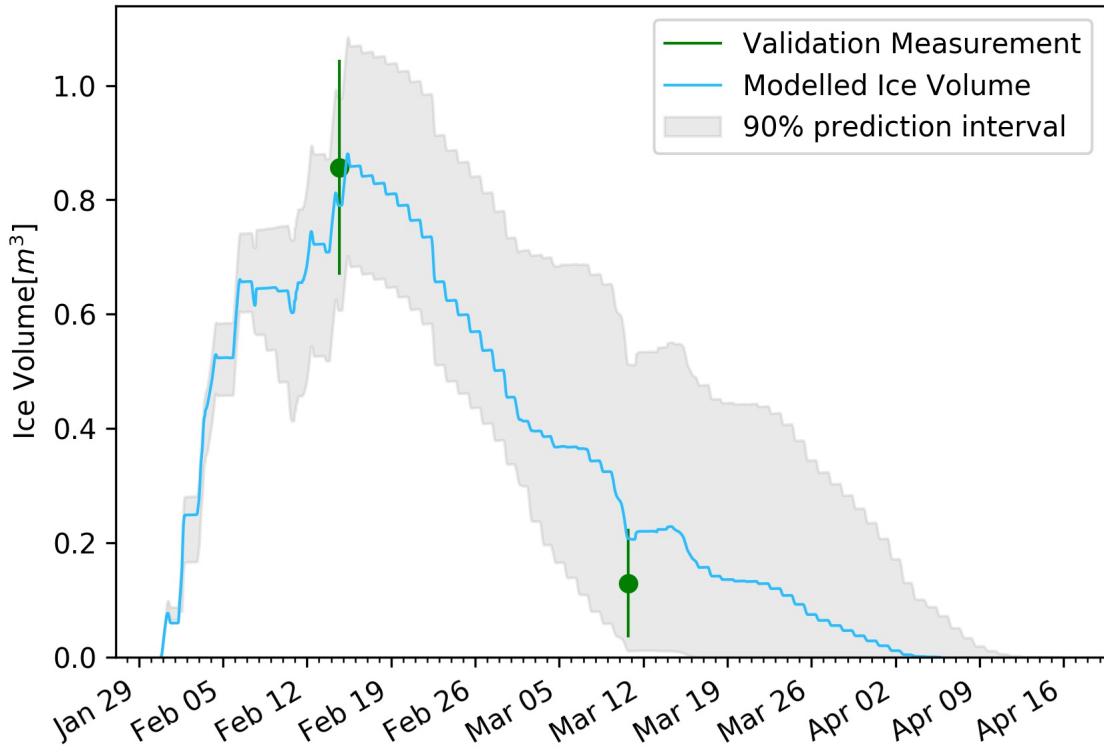


Figure 8. Modelled ice volume during the lifetime of the EP Icestupa (blue curve). Green line segments indicate the first and second validation measurements. The prediction interval is based on the ice volume uncertainty caused by the most sensitive parameters, namely, temperature threshold below which precipitation falls as snow and the ice emissivity.

296 calculated as the sum of energy fluxes in absolute values. q_{SW} accounted for 31.5%, followed by q_{melt}
 297 (20%), q_S (9.8%), q_L (3.2%), q_G (2%), q_F (0.2%) and q_T (0.4%).

298 Fig. 6 (c) represents the mass fluxes associated with these energy exchanges expressed in m w.e. It
 299 shows the ice and meltwater formed due to q_{melt} , snow accumulated due to precipitation, water vapour
 300 deposition/condensation and sublimation/evaporation due to q_L . Growth rate ($\frac{\Delta M_{ice}}{\Delta t}$) shows a strong
 301 correlation with net energy flux ($r^2 = 0.31$) but poor correlation with Icestupa surface area ($r^2 = 0.03$).
 302 This is because the variance in growth rate is mostly due to the variance in q_{net} as illustrated in Fig. 6.
 303 Since r_{ice} was initialised with the spray radius r_F , the surface area maintains a maximum initially until the
 304 energy flux becomes positive. This trend favours the positive over the negative thickness changes resulting
 305 in a steep increase and gradual melting of ice volume as can be seen in Fig. 8.

306 The total water used for the Icestupa development includes contributions from the fountain (97.3%),
 307 snowfall (2.5 %) and deposition/condensation (0.2 %) as shown in Table 2. The maximum ice mass during
 308 the whole measurement period was 806 kg, which occurred after the last fountain run on Feb 16th 2019
 309 in the morning. Therefore, in the case of EP we used a water input of 18,560 kg, with a resultant storage
 310 efficiency of only 5.4 %.

5 MODEL SENSITIVITY AND UNCERTAINTY ANALYSIS

311 The icestupa model can be regarded as a function $f(x_1, x_2 \dots, x_n) = (y_1, y_2 \dots, y_m)$, where
 312 $(x_1, x_2 \dots, x_n)$ are the model parameters and $(y_1, y_2 \dots, y_m)$ are the model outputs. The influence of each

parameter on the output variables of interest were quantified and the most important physical parameters for the subsequent uncertainty analysis were determined. The sensitivity of a parameter x_j is determined by keeping all other parameters $x_i, i \neq j$ fixed at their baseline value and varying x_j within values that are physically plausible.

A sensitivity study on the parameters (listed in Table 1) was performed with the maximum ice volume as the target variable. All the parameters were assumed to be independent of each other with a uniform distribution. This assumption ignores the auto-correlation present among the parameters associated with the albedo parameterisation. The range of uncertain parameters were set based on available literature values or varied $\pm 5\%$ from the base value if no such reference was available. The uncertainty of all the site parameters were caused due to parallax errors during manual measurement. This was quantified with a range of $\pm 1\%$ from the base value. However, it must be kept in mind that, even though intended to be as objective as possible, the selection of a parameter range has a subjective part that influences the results and conclusions obtained in this analysis. The variation of the model outputs y_k is evaluated to quantify the local sensitivities $s_{j,k}$ that are defined here as the 95% range of the simulated outputs.

To perform the uncertainty analysis, we included only parameters that influence the maximum ice volume by at least $0.1 m^3$. All other parameters were fixed at their baseline value. Fig. 9 shows all the variance produced by these uncertain parameters in maximum ice volume calculation. It shows that ϵ_{ice} and T_{ppt} are the only parameters with a maximal sensitivity of more than $0.1 m^3$ for the maximum ice volume estimate. Consequently, all other parameters were excluded from the subsequent uncertainty analysis.

The temperature threshold below which precipitation falls as snow (T_{ppt}) was found to be the most sensitive parameter. It is used in the model to reset the albedo to snow albedo and determine snow precipitation events. The lower T_{ppt} parameter the higher the albedo (as the Icestupa surface has a lower albedo when ice-covered than when snow-covered). The variation of T_{ppt} by $\pm 1^\circ C$ caused maximum ice volume variation of $0.83 \pm 0.2 m^3$.

Ice emissivity was also found to be a sensitive parameter. The higher the ice emissivity the larger the maximum ice volume as the emitted longwave radiation increases with ice emissivity. Variation of ϵ_{ice} by 5% caused a maximum ice volume range from $0.98 \pm 0.1 m^3$.

In total, the sensitivity analysis required 120 simulations, and the uncertainty analysis a total of 32 simulations.

6 DISCUSSION

6.1 Model validation quality

We first evaluate the model against the validation measurements at the EP site. The uncalibrated model is able to capture both the freezing and the melting process sufficiently well as the modelled ice volume lies within the uncertainty of both validation measurements. Furthermore, the validation measurements fit well within the estimated model uncertainty. However, since this validation is based on only two points, it does limit the confidence in the model results. Even though the model estimates validate well with the ice volume, the same is not the case for the surface area. The surface area estimated from the first validation measurement is just around $4 m^2$, roughly half the model estimated surface area. However, the validation surface area estimate again underestimates the surface area as the actual surface area in contact with the atmosphere could have been amplified by the inherent roughness of the ice surface. Another major cause of this discrepancy was the conical shape assumption, as in reality, the Icestupa shape ranged between a cone and a cylinder (Fig. 2). The sensitivity of the model results to these errors was further amplified due to the

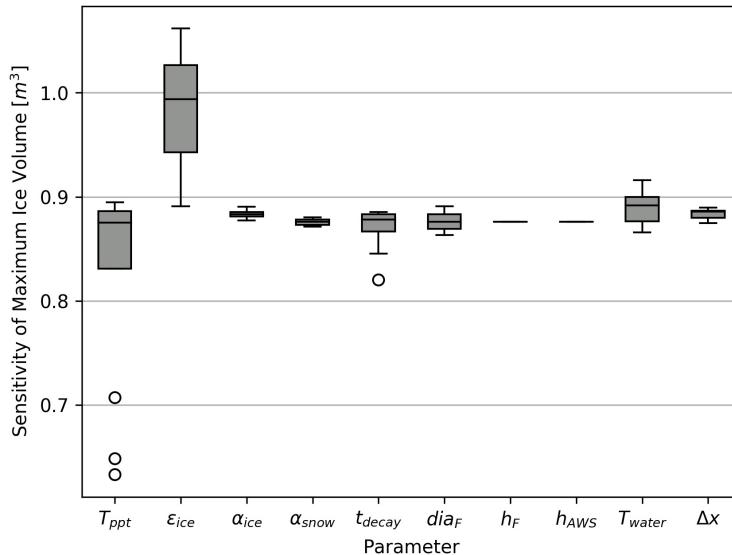


Figure 9. Sensitivities of maximum ice volume to all the uncertain and site parameters used in the model (Table 1). Outliers in the bar plot are shown as 'o'.

354 relatively small volume of the EP Icestupa. In summary, better and frequent validation measurements on a
 355 **6.2 Important assumptions** have increased confidence on the model results.
 356
 357 In the sensitivity and uncertainty analysis presented above, we did not account for several general
 358 assumptions and parametrisation choices that may cause model errors. Some assumptions and their
 359 potential to cause errors are discussed below.

- 360 • Turbulent Sensible and Latent Heat Fluxes: The method used to calculate the turbulent heat fluxes
 361 by Garratt (1992) assumes that the turbulent heat fluxes are acting over a uniform planar surface to
 362 determine the roughness length. Since our application is on a conical surface, the distance to the ice
 363 surface is not uniform and well defined. Hence, z_{ice} has no real physical significance here.
- 364 • Droplet flight time loss: Water losses during the flight time of fountain droplets were neglected making
 365 all the fountain spray available for freezing. For the EP experiment, inclusion of this parameter does
 366 not influence results since it is already accounted for in the runoff water discharge rate which was at
 367 least 3 l min^{-1} .
- 368 • Nucleation of droplets: Corresponding to droplet flight time, ice/snow formation is also possible before
 369 surface contact if nucleation occurs during flight time. For the EP experiment, this process will further
 370 increase the freeze rate and hence the storage efficiency. This process is neglected for model simplicity.
- 371 • Shape Effects: The suppression of heat exchange between the snow/ice surface and the air adjacent
 372 to the surface effectively slows down snow/ice ablation in spring and promotes the stagnation of the
 373 cold air within topographical depressions (Fujita et al., 2010). The quantitative contribution of the
 374 atmospheric decoupling over melting snow/ice for the total mass and energy balance is ignored in the
 375 model.

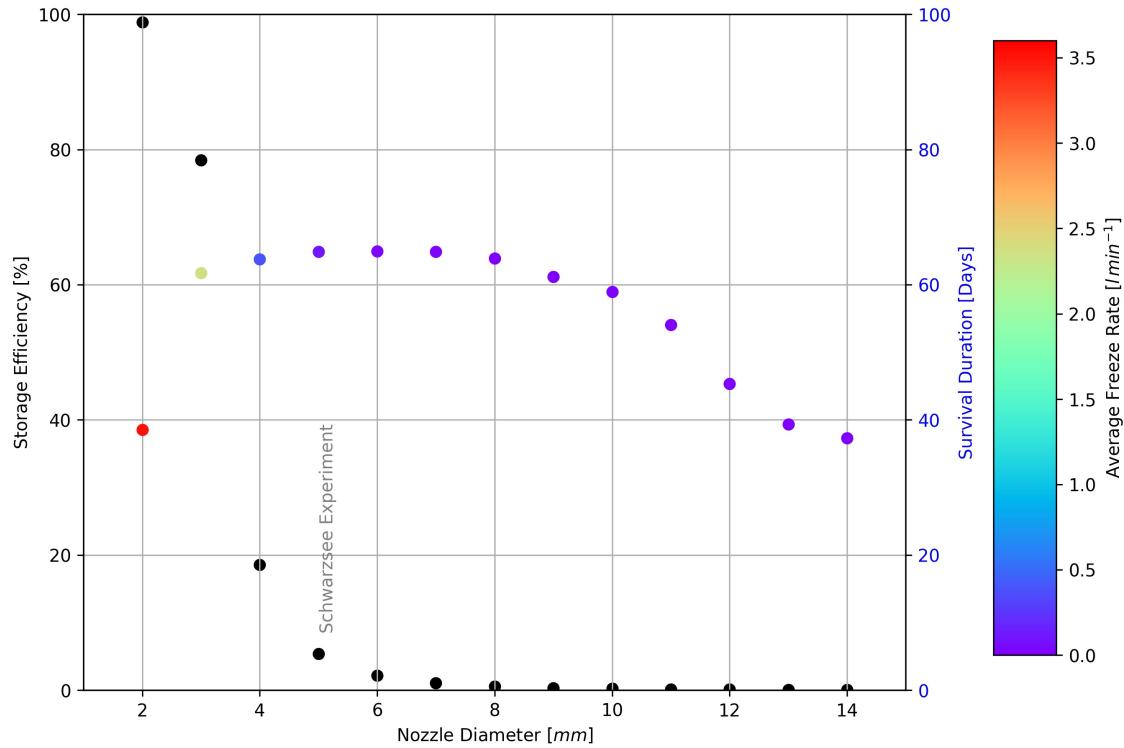


Figure 10. Variation in storage efficiency (black dots) and storage duration (coloured dots) with changes in fountain nozzle's nozzle diameter. The dot colours represent average freeze rate based on the color bar.

376 6.3 Schwarzsee vs Leh Icestupa

377 It could be argued that the relatively small EP Icestupa cannot be compared with the much larger Icestupas
 378 in Ladakh which store millions of litres of water for several months (see Appendix 8.1). However, this is
 379 the only Icestupa dataset currently available for such a model validation.

380 Table 2 clearly shows that for our EP experiment most of the input water (94.5 %) simply drained away
 381 (M_{runoff}) . This high water loss through drainage is due to the fact that the average spray rate of the fountain
 382 ($(\frac{\Delta M_F}{\Delta t})_{mean} = 3.6 \text{ l min}^{-1}$) far exceeded the max Icestupa growth rate ($(\frac{\Delta M_{ice}}{\Delta t})_{max} = 0.9 \text{ l min}^{-1}$ (w.e.)
 383).

384 In the city of Leh, Ladakh at an altitude of 3500 m a.s.l. the air temperature shows values down to
 385 -27.9°C in winter (Chevuturi et al., 2018) whereas EP had a minimum temperature of just -11.6°C
 386 during the study period. Moreover, subzero temperatures were only reached for 7 nights of fountain
 387 operation at the EP site compared to the 43 nights of fountain operation possible in Ladakh (see Appendix
 388 8.1). Thus, the Icestupa growth rate is expected to be much higher in Ladakh. However, water spray rates
 389 in Ladakh are also much higher (around 210 l min^{-1}). This suggests that the water losses in Ladakh could
 390 be caused by excessive fountain spray.

391 6.4 Icestupa construction decisions

392 There are several decisions one has to take when constructing Icestupas. These can be broadly divided
 393 into two types of decisions, namely location and fountain decisions. Both the meteorological conditions
 394 of the location and the surface area produced by the fountain significantly influence the observed growth
 395 rate. Since our validation is restricted to just one location, we restrict our discussion to the optimization
 396 possibilities of Icestupa constructions through fountain decisions.

397 Assuming a constant spray for the fountain, we can divide the fountain decisions into fountain state
 398 (on/off) and type (height and nozzle diameter). From an energy balance point of view, the fountain should
 399 be switched on for all time intervals when $q_{net} < 0$. However, in our experiment, the fountain state
 400 decision was set on the basis of prior Icestupa construction experience where a critical temperature of
 401 $-5^{\circ}C$ was recommended. Ambient temperature can serve as an indicator of q_{net} as it was correlated
 402 ($r^2 = 0.53$). However, q_{net} was found to be negative already at a critical temperature of $-1^{\circ}C$. Therefore,
 403 using air temperature to determine when the fountain should be switched on is justified but a higher critical
 404 temperature could have been used in the case of the EP Icestupa.

405 The fountain type used can be characterised by the physical structure of the fountain, namely its height and
 406 nozzle diameter. Maintaining the same spray rate and height, one can optimize the Icestupa development
 407 by identifying the minimum nozzle diameter that yields the maximum storage efficiency. Since we never
 408 changed the fountain height for the EP Icestupa, we only focus on optimization of fountain diameter below.

409 Fig. 10 shows reducing the nozzle diameter to 3 mm increases storage efficiency up to 78 % without
 410 compromising much on storage duration. The corresponding storage quantity of the 3 mm nozzle diameter
 411 was more than 20 times higher than the 5 mm fountain used in our experiment. This is because the spray
 412 radius r_F of the 3 mm fountain was much higher at 8.5 m compared to the 1.7 m spray radius of the 5
 mm fountain. Here, we define growth rate as freeze rate when fountain is active and melt rate otherwise.
 414 Therefore, this higher spray radius both increases the freeze rate and increases the melt rate since they are
 415 both directly proportional to the surface area. However, since the freeze rate cannot increase beyond a spray
 416 rate of 3.6 l min^{-1} (except during precipitation or deposition/condensation events), an optimum spray
 417 radius or nozzle diameter exists, beyond which storage duration suffers due to a disproportionate increase
 418 in melt rate compared to the freeze rate. So even though 3 mm nozzle diameter had a much higher storage
 419 quantity than the 5 mm nozzle, its storage duration was around 3 days less than the 5 mm nozzle. One
 420 physical cause of this effect is the different shapes of both the ice structures. A flat sheet of ice (effectively
 421 a cone with a high spray radius) with higher mass might have a storage duration shorter than a conical ice
 422 structure. As the spray radius decreases with increasing nozzle diameter, the ice structure's average slope
 423 increases and so the 5 mm nozzle's ice structure is "more" conical than the 3 mm ice structure. Fig. 10
 424 shows that a nozzle diameter of 3 mm has an average freeze rate ($2.4\text{ l min}^{-1}\text{w.e.}$) which is large enough
 425 to increase the storage efficiency and small enough to not reduce the storage duration of the Icestupa
 426 significantly.

427 6.5 Artificial snow production vs Artificial ice reservoirs

428 Both artificial snow and ice are produced by expelling small liquid water droplets from the snow gun or
 429 fountain nozzles at high speed (Olefs et al., 2010). The crucial factor that determines ice or snow production
 430 is whether these water droplets remain unfrozen or freeze before reaching the ice/snow surface. According
 431 to (Hartl et al., 2018), the production potential of artificial snowmaking is proportional to the wet-bulb
 432 temperature and the threshold mean daily wet bulb temperature for potential snow making days was $-2^{\circ}C$
 433 which corresponds well with the threshold mean daily air temperature for potential ice making days of EP
 434 site ($-1^{\circ}C$).

7 CONCLUSIONS

435 We outlined a methodology for estimating ice, liquid water, water vapour and runoff quantities produced
 436 during the construction of an Icestupa using measurements of fountain spray rate, air temperature, radiation,
 437 humidity, pressure, wind and cloudiness at the EP study site. The comparison with validation measurements

438 at two different dates during the experiment led to satisfying results, although a more rigorous model
439 validation was not possible due to few icestupa volume measurements.

440 According to the model, the EP Icestupa achieved a storage quantity of 1005 litres of water with a storage
441 duration of 65 days. However, the corresponding storage efficiency of 5.4 % was very low for a water
442 input of 18,560 litres. These estimates were most sensitive to the temperature threshold that determined
443 precipitation phase and ice emissivity parameters which created an uncertainty of $0.2m^3$ in the maximum
444 ice volume calculated. This is to be expected as net longwave radiation and net shortwave radiation together
445 accounted for around 64 % of the overall energy turnover.

446 Although the location, storage quantity and duration of our experimental EP Icestupa are not representative
447 of the much larger Icestupas of Ladakh, the model results do support the hypothesis that there could be
448 considerable water loss during the formation of Icestupas particularly due to excessive fountain spray.
449 Using model calculations, it was shown that a decreased fountain nozzle diameter of 3 mm can increase the
450 storage efficiency drastically. This is because a change in the fountain nozzle diameter causes an effective
451 change of the ice surface area over which the net energy flux can act. This result has relevance on the future
452 design of Icestupa fountains. However, care has to be taken as our model is currently only validated by one
453 experiment at the EP site. Further experiments at different locations with different fountains are required to
454 better understand the influence of construction decisions on the results.

8 APPENDIX

455 8.1 Ladakh Icestupa 2014/15

456 A 20 m tall Icestupa (Wangchuk, 2015c) was built in Phyang village, Ladakh at an altitude of 3500
457 m a.s.l. Assuming a conical shape with a diameter of 20 m, the corresponding volume of this Icestupa
458 becomes $2093 m^3$ or $1,920 m^3$ w.e. The fountain sprayed water at a rate of $210 l min^{-1}$ (Wangchuk,
459 2015e) from 21st January (Wangchuk, 2015a) to at least until 5th March 2015 (Wangchuk, 2015b) (around
460 43 nights). Assuming fountain spray was active for 8 hours each night, we estimate water consumption to
461 be around $4,334 m^3$. Thus, during the construction/freezing period of the Icestupa, roughly 56 % of the
462 water provided was wasted. The actual water loss is bound to be much higher due to further vapour losses
463 during the melting period. This Icestupa completely melted away on 6th July 2015 (Wangchuk, 2015d).
464 Therefore, the storage duration was 166 days or roughly 5 months.

CONFLICT OF INTEREST STATEMENT

465 The authors declare that the research was conducted in the absence of any commercial or financial
466 relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

467 SB wrote the initial version of the manuscript. MH, ML, SW, JO, and FK commented on the initial
468 manuscript and helped improve it. SB developed the methodology with inputs from MH. SB performed the
469 analysis with support from MH and ML. SB and MH participated in the fieldwork.

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DATA AVAILABILITY STATEMENT

477 The data and code used to produce results and figures will be published at a later stage and can, until then,
478 be obtained from the authors upon request.

REFERENCES

- 479 Apel, H., Abdykerimova, Z., Agalhanova, M., Baimaganbetov, A., Gavrilko, N., Gerlitz, L., et al. (2018).
480 Statistical forecast of seasonal discharge in central asia using observational records: development of a
481 generic linear modelling tool for operational water resource management. *Hydrology and Earth System
482 Sciences* 22, 2225–2254. doi:10.5194/hess-22-2225-2018
- 483 Bonales, L. J., Rodriguez, A. C., and Sanz, P. D. (2017). Thermal conductivity of ice prepared under
484 different conditions. *International Journal of Food Properties* 20, 610–619. doi:10.1080/10942912.
485 2017.1306551
- 486 Buck, A. L. (1981). New equations for computing vapor pressure and enhancement factor. *Journal of
487 Applied Meteorology and Climatology* 20, 1527 – 1532
- 488 Buytaert, W., Moulds, S., Acosta, L., Bievre, B. D., Olmos, C., Villacis, M., et al. (2017). Glacial melt
489 content of water use in the tropical andes. *Environmental Research Letters* 12, 114014. doi:10.1088/
490 1748-9326/aa926c
- 491 Chen, Y., Li, W., Deng, H., Fang, G., and Li, Z. (2016). Changes in central asia's water tower: Past, present
492 and future. *Nature* doi:10.1088/1748-9326/aa926c
- 493 Chevuturi, A., Dimri, A. P., and Thayyen, R. J. (2018). Climate change over leh (ladakh), india. *Theoretical
494 and Applied Climatology* 131, 531–545. doi:10.1007/s00704-016-1989-1
- 495 [Dataset] Copernicus Climate Change Service (C3S) (2017). Era5: Fifth generation of ecmwf atmospheric
496 reanalyses of the global climate
- 497 Cuffey, K. M. and Paterson, W. S. B. (2010). *The Physics Of Glaciers* (Elsevier)
- 498 Fujita, K. and Ageta, Y. (2000). Effect of summer accumulation on glacier mass balance on the
499 tibetan plateau revealed by mass-balance model. *Journal of Glaciology* 46, 244–252. doi:10.3189/
500 172756500781832945
- 501 Fujita, K., Hiyama, K., Iida, H., and Ageta, Y. (2010). Self-regulated fluctuations in the ablation of a snow
502 patch over four decades. *Water Resources Research* 46, W11541. doi:10.1029/2009WR008383
- 503 Garratt, J. R. (1992). *The Atmospheric Boundary Layer* (Cambridge University Press)
- 504 Grossman, D. (2015). As himalayan glaciers melt, two towns face the fallout
- 505 Hartl, L., Fischer, A., and Olefs, M. (2018). Analysis of past changes in wet bulb temperature in relation to
506 snow making conditions based on long term observations austria and germany. *Global and Planetary
507 Change* 167, 123 – 136
- 508 Hock, R. (2005). Glacier melt: a review of processes and their modelling. *Progress in Physical Geography:
509 Earth and Environment* 29, 362–391
- 510 Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., et al. (2019). 2019: High mountain
511 areas. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C.

- 512 Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegria, M. Nicolai,
513 A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]
- 514 Hoelzle, M., Barandun, M., Bolch, T., Fiddes, J., Gafurov, A., Muccione, V., et al. (2019). *The status and
515 role of the alpine cryosphere in Central Asia*. doi:10.4324/9780429436475-8
- 516 Hori, M., Aoki, T., Tanikawa, T., Motoyoshi, H., Hachikubo, A., Sugiura, K., et al. (2006). In-situ
517 measured spectral directional emissivity of snow and ice in the 8–14 micrometer atmospheric window.
518 *Remote Sensing of Environment* 100, 486 – 502
- 519 [Dataset] IDAWEB (2019). Meteoswiss, federal office of meteorology and climatology
- 520 Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2019). Importance
521 and vulnerability of the world's water towers. *Nature* 577, 364 – 369. doi:10.1038/s41586-019-1822-y
- 522 Meteoblue (2020). Climate schwarzsee
- 523 Mölg, T. and Hardy, D. R. (2004). Ablation and associated energy balance of a horizontal glacier surface
524 on kilimanjaro. *J. Geophys. Res.-Atmos.* 109, 1–13. doi:10.1029/2003JD004338
- 525 Nüsser, M., Dame, J., Kraus, B., Baghel, R., and Schmidt, S. (2019a). Socio-hydrology of artificial glaciers
526 in ladakh, india: assessing adaptive strategies in a changing cryosphere. *Regional Environmental Change*
527 doi:10.1007/s10113-018-1372-0
- 528 Nüsser, M., Dame, J., Parveen, S., Kraus, B., Baghel, R., and Schmidt, S. (2019b). Cryosphere-Fed
529 Irrigation Networks in the Northwestern Himalaya: Precarious Livelihoods and Adaptation Strategies
530 Under the Impact of Climate Change. *Mountain Research and Development* 39. doi:10.1659/
531 MRD-JOURNAL-D-18-00072.1
- 532 Oerlemans, J. and Knap, W. H. (1998). A 1 year record of global radiation and albedo in the
533 ablation zone of morteratschgletscher, switzerland. *Journal of Glaciology* 44, 231–238. doi:10.
534 3189/S0022143000002574
- 535 Olefs, M., Fischer, A., and Lang, J. (2010). Boundary conditions for artificial snow production in the
536 austrian alps. *Journal of Applied Meteorology and Climatology* 49, 1096 – 1113
- 537 Scherrer, S. C. (2020). Temperature monitoring in mountain regions using reanalyses: lessons from the
538 alps. *Environmental Research Letters* 15, 044005
- 539 Schmidt, L. S., Aðalgeirs ðóttir, G., Guðmundsson, S., Langen, P. L., Pálsson, F., Mottram, R., et al. (2017).
540 The importance of accurate glacier albedo for estimates of surface mass balance on vatnajökull: evaluating
541 the surface energy budget in a regional climate model with automatic weather station observations. *The
542 Cryosphere* 11, 1665–1684. doi:10.5194/tc-11-1665-2017
- 543 Stigter, E. E., Litt, M., Steiner, J. F., Bonekamp, P. N. J., Shea, J. M., Bierkens, M. F. P., et al. (2018).
544 The importance of snow sublimation on a himalayan glacier. *Frontiers in Earth Science* 6, 108.
545 doi:10.3389/feart.2018.00108
- 546 Tetens, O. (1930). Über einige meteorologische begriffe. z. *Geophys.* 6, 297–309
- 547 Unger-Shayesteh, K., Vorogushyn, S., Farinotti, D., Gafurov, A., Duethmann, D., Mandychev, A., et al.
548 (2013). What do we know about past changes in the water cycle of central asian headwaters? a review.
549 *Global and Planetary Change* 110, 4 – 25. doi:10.1016/j.gloplacha.2013.02.004. Water in Central Asia
550 – Perspectives under global change
- 551 Wangchuk, S. (2014). Ice stupa artificial glaciers of ladakh
- 552 Wangchuk, S. (2015a). The good news at ice stupa 24th january 2015
- 553 Wangchuk, S. (2015b). Ice stupa artificial glacier inaugurated 5th of march 2015
- 554 Wangchuk, S. (2015c). Ice stupa surpasses guiness world record
- 555 Wangchuk, S. (2015d). Ice stupa way of celebrating a special day
- 556 Wangchuk, S. (2015e). World water day at ice stupa

- 557 WMO (2018). *Guide to Instruments and Methods of Observation* (World Meteorological Organization ;
558 2018 (2018 Edition))
- 559 Woolf, H. M. (1968). *On the Computation of Solar Elevation Angles and the determination of sunrise and*
560 *sunset times* (National Aeronautics and Space Administration)
- 561 Zhou, S., Kang, S., Gao, T., and Zhang, G. (2010). Response of zhadang glacier runoff in nam co basin,
562 tibet, to changes in air temperature and precipitation form. *Chinese Science Bulletin* 55, 2103–2110.
563 doi:10.1007/s11434-010-3290-5