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Brief communication: Growth and decay of an Ice Stupa in alpine conditions: a simple model driven by energy-flux observations over a glacier surface

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Abstract. We present a simple tool to calculate the evolution of an ice stupa (artificial ice reservoir). The model is formulated for a cone geometry and driven by energy balance measurements over a glacier surface for a 5-year period. An 'exposure factor' is introduced to deal with the fact that an ice stupa has a very rough surface and is more exposed to wind than a flat glacier surface. The exposure factor enhances the turbulent fluxes.
For characteristic alpine conditions at 2100 m, a stupa may reach a height of typically 6 to 10 m in early spring and obtain a volume of 100 to 250 m^3. We also discuss a case where the stupa grows on an inner structure.
We show sensitivites of stupa height to temperature changes and exposure factor. Effects of snow cover, switching off water during daytime, different starting dates, etc. can easily be evaluated.

1 Introduction

Ice stupas (Fig. 1), also referred to as Artificial Ice Reservoirs (AIR), are used more and more as a means to store water in the form of ice (Nüsser, 2018). In Ladakh, India, engineer Sonam Wamchuk has initiated and developed the use of ice stupas to provide water for irrigation purposes in spring and early summer. The stupas grow in winter by sprinkling water on the growing ice structure, and melt in spring and summer to deliver water; a typical turnover volume is up to 1 million liters. Ice stupas also form interesting touristic attractions with a distinct and special artistic flavour. They come in the same class as ice sculptures, which are popular in all regions of the world that have a cold winter.

The possibility to grow ice stupas of appreciable size depends on the meteorological conditions and the availability of water. When a surface has a negative energy balance and water is sprinkled on it, ice will form (a well-known technique to make skating rinks). The more effective the latent heat of fusion can be removed by contact with cold air and effective emittance of longwave radiation, the faster the ice layer may grow. In spring and summer incoming solar radiation will dominate and the ice stupa will lose mass. In this note we present a model of ice stupa growth and decay, based on a simple consideration of the total energy budget, and driven by energy flux observations over a glacier surface (half hourly observations over a 5-year period). We believe that the energy balance of a glacier surface and of an ice stupa have much in common, and therefore consider this data set as ideal for a first study. The focus is on alpine conditions at a typical height of 2100 m a.s.l. The purpose of this study is to obtain first-order estimates of how fast a stupa may grow and melt, and what processes are most important. The approach taken here is complementary to a much more elaborate study by Balasubramanian et al. (2021), in which the morphology and the energy fluxes at the stupa surface are treated in much more detail and parameterizations are included to calculate radiative fluxes from standard meteorological observations.

We emphasize that in this note the focus is on the energetics of the stupa system, not on the technical aspects that have to be dealt with in constructing an ice stupa.

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Figure 1. Left: ice stupa in Ladakh, India (c. Sonam Wamchuk). Middle: early growing stage of ice stupa with inner structure in Val Roseg, Switzerland (c. Conradin Clavuot). Right: simple geometrical representation. The stupa can have an inner structure (brown).

2 Geometry

Ice stupas have different and often complex shapes. The *cone* is probably the most appropriate simple geometric shape to represent an ice stupa (Fig. 1), but alternatively a *dome* (half sphere) could also be considered.

The geometric characteristics of a cone with radius *r* and height *h* are:

Area of base: πr^2 , (1a)

Lateral area: $\pi r\sqrt{r^2+h^2}$, (1b)

Volume: $\pi r^2 h/3$. (1c)

It is useful to introduce a shape parameter $s = h/r$. The volume can then also be written as:

$$V = \pi h^3/3s^2 \ . \quad (2)$$

So for a given volume the height of the stupa can be calculated from:

$$h = \left\{\frac{3}{\pi} V s^2\right\}^{1/3} . \quad (3)$$

We assume that during growth and decay of the stupa its geometry always remains a cone with fixed shape parameter.

3 Energy exchange

Ice stupas exchange energy with the surroundings by absorbing and reflecting solar radiation, absorbing and emitting longwave (terrestrial) radiation, and by turbulent fluxes of sensible and latent heat. Because of the complex shape of a stupa, as compared to a horizontal ice/snow surface, it is hard to describe these processes in detail. However, some simplifying assumptions may help to arrive at reasonable approximations.

We use five years of energy balance measurements with an automatic weather station (AWS) on the Vadret da Morteratsch (e.g. Oerlemans et al., 2009), which was located at an elevation of about 2280 m a.s.l. The surface energy flux is written as

$$energy\ flux = S_{in} - S_{out} + L_{in} - L_{out} + H + G \ . \quad (4)$$

S stands for solar radiation, *L* for longwave radiation, *H* is the total turbulent heat flux and *G* the ground heat flux (conduction from or into the surface layer - generally small compared to the other components). So the energy flux is positive when directed towards the surface. A positive energy flux will be used for melting of ice or snow; when the energy flux is negative freezing of water can take place (when available).

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How to apply these measurements over (almost) flat terrain to an ice stupa ? The *direct* part of the solar radiation (fraction q) will hit the stupa on one side, and nothing will be received by the shaded side. As a crude approximation it is reasonable to take the amount of direct radiation that would impinge on the base if there were no stupa. For the *diffuse* part illumination is on all sides and the relevant area therefore is the lateral area as given in eq. (1b). So the total amount of absorbed solar radiation per unit of time can be estimated as:

$$F_{sol} = q(S_{in} - S_{out})\,\pi r^2 + (1-q)(S_{in} - S_{out})\,\pi r\sqrt{r^2 + h^2} \tag{5a}$$

Alternatively, one may wish to prescribe the albedo α separately, i.e.

$$F_{sol} = qS_{in}(1-\alpha)\,\pi r^2 + (1-q)S_{in}(1-\alpha)\,\pi r\sqrt{r^2 + h^2} \tag{5b}$$

For the longwave radiation and turbulent exchange the exposed surface is also the lateral area. The longwave radiation balance then becomes:

$$F_{lw} = (L_{in} - L_{out})\,\pi r\sqrt{r^2 + h^2} \tag{6}$$

The turbulent heat fluxes depend on the roughness and exposure of the surface. Since we do not calculate the surface (skin) temperature, we simply assume that it is close to the melting point. The sensible and latent heat input are written using the well-known bulk transfer equations:

$$F_H = \mu CU(T - T_s)\,\pi r\sqrt{r^2 + h^2} \tag{7a}$$

$$F_L = 0.623 L_v\, c_p^{-1}\, \mu CU p^{-1}(e_s - e)\,\pi r\sqrt{r^2 + h^2} \tag{7b}$$

Here C is the bulk turbulent exchange coefficient over a flat surface, T is the air temperature, T_s is the surface temperature (set to the melting point), L_v is the latent heat of sublimation (2 830 000 J kg^{-1}), c_p is the specific heat capacity of air (1004 J kg^{-1} K^{-1}), e is the vapour pressure, e_s is the saturation vapour pressure, p is atmospheric pressure, and U is the wind speed. The parameter μ is an 'exposure / roughness parameter' that deals with the fact that an ice stupa has a rough appearance and forms an obstacle to the wind regime. So μ is expected to be larger than one, and could perhaps have a value to 2 or more. When water availability is unlimited, the mass gain or loss is given by

$$\mathrm{d}M/\mathrm{d}t = (F_{sol} + F_{lw} + F_L + F_H)/L_m + F_L/L_v \tag{8}$$

M is the mass of the stupa and L_m is the latent heat of melting/fusion (334 000 J kg^{-1}). For typical alpine conditions the last term in Eq. (8) is normally quite small. Since the volume of the stupa is simply related to the mass ($V = M/\rho_{ice}$), the height of the stupa can directly be calculated with Eq. (3).

4 Application to the Oberengadin region, Switzerland

Over the past few years, several ice stupa's have been constructed in the Oberengadin, southeast Switzerland. In the winter of 2017/18 a stupa was constructed in the Val Roseg at 2000 m a.s.l. (Fig.1, maximum height about 12 m). In the winter of 2018/19 several smaller ice stupas (height about 5 m) were built at a site in the Val Morteratsch at about 1900 m a.s.l. Since February 2021 a test site for ice stupa construction is in operation at the Diavolezza Talstation at an altitude of 2080 m a.s.l. To obtain first-order estimates of growth and decay rates for typical climatic conditions in the Oberengadin, we used the energy balance measurements from the automatic weather station on the Vadret da Morteratsch as a proxy for this high alpine region. During the period 1 July 2007 - 30 September 2012, the AWS on the Vadret da Morteratsch was located at an altitude of about 2280 a.s.l. and has produced a unique data set without any gaps. The annual melt at the AWS location was between 5 and 7 m

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of ice. With a focus on the Diavolezza site, which is at an altitude of 2080 m a.s.l., a temperature correction of +1.3 K was applied to the input data (based on a standard atmospheric temperature lapse rate of $0.0065\ \mathrm{K\,m^{-1}}$). We note that all the locations mentioned above are within a distance of 10 km from each other (interactive map to find locations: https://map.wanderland.ch).

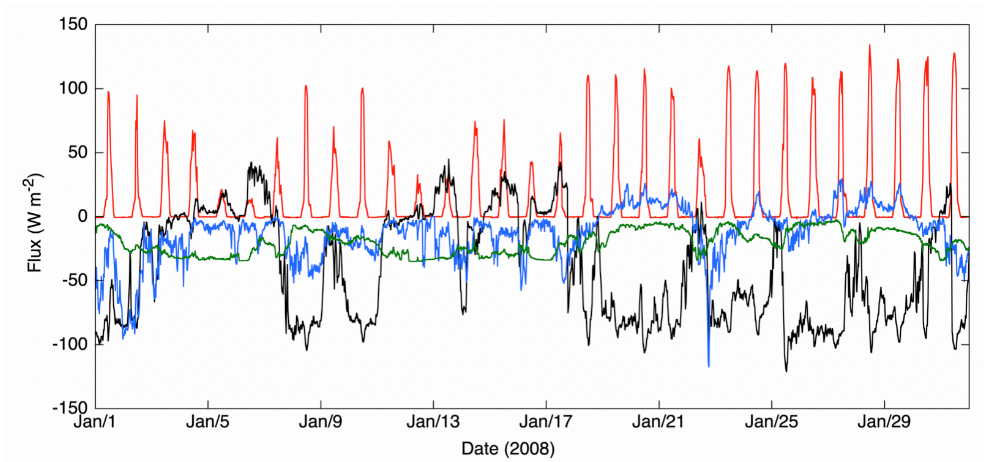

Figure 2. Energy balance components as measured by the AWS on the Vadret da Morteratsch for January 2008. Net solar radiation in red, net longwave radiation flux in black, turbulent sensible heat flux in blue, turbulent latent heat flux in green.

Fig. 2 shows an example of data from the AWS. The data have been stored as 30-minute averages. The turbulent heat fluxes have been calculated from the wind speed, air temperature and humidity, where the turbulent exchange coefficient was used as a tuning parameter (to obtain the correct amount of observed ice melt over a 5-year period). The example shown is just for one relatively sunny winter month (January 2008). Note the large degree of compensation between net solar radiation and net longwave radiation - the well-known effect of a clear sky on the radiation balance. Therefore the turbulent heat fluxes are more important than it appears at first sight.

Fig. 3 shows the result in terms of stupa height and volume. Values of the model parameters are: ratio of direct to diffuse solar radiation $q = 0.5$, ratio of height-to-radius of stupa $s = 2$, albedo $\alpha = 0.6$, exposure parameter $\mu = 2$. It has been assumed that water availability is unlimited and that water can be spread uniformly over the entire stupa area. For the standard run (red curve) the maximum height is close to 7 m, reached in early April. The decay of the stupa is hardly faster than the growth. A faster decay would occur if the albedo were not constant but would decrease during the melt phase.

The black curve in Fig. 3 results when the air temperature is increased uniformly by 1 K. The stupa height decreases by about 10 %, and its volume by about 25 %. The blue curve represents a case in which the dimensionless exposure parameter μ is set to 3, so the turbulent heat flux plays a larger role. The growth of the stupa is much faster, and the decay as well. In the end the disappearance of the stupa is at about the same date as for the standard run. In terms of volume the differences between the years and the various cases are much larger, because $V \propto h^3$. The dependence on the exposure / roughness parameter μ appears to be quite significant.

We also did some sensitivity tests with respect to the formulation of solar radiation. Instead of using a constant albedo we used Eq. (5a). It appears that the stupa becomes slightly higher and the growth curve more asymmetric (not shown). The decay is faster now, because a lower albedo during the melt phase is implicitly included. This is probably realistic, because the

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measurements were taken over a glacier surface that gets rather dark in the melt season, due to accumulation of dust. Observations reveal that during the melt phase, ice stupas also become darker.

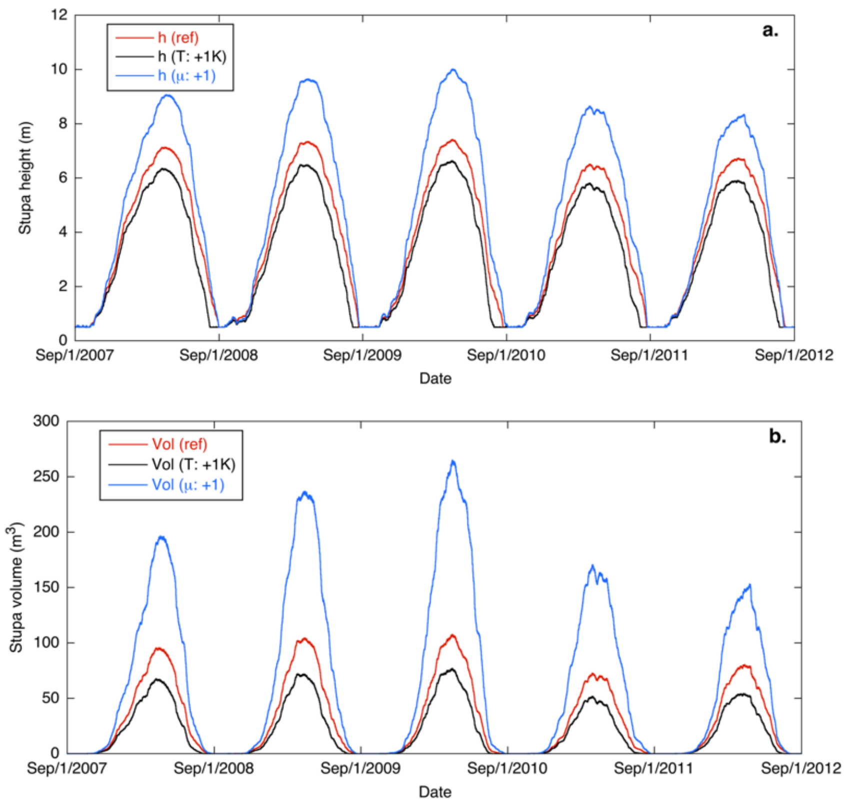

Figure 3. Calculated evolution of ice stupa for the case of unlimited water supply for five winters in terms of height (a) and volume (b). The standard run is in red. The blue curve refers to a case with increased exposure parameter, the black curve for a case with a 1 K higher temperature (through the year).

5 Stupa with an inner structure

A stupa can have an inner structure on which it grows. The advantage of an inner structure is that in the early phase ice can grow on a much larger area. When the inner structure has more or less the same form, the present model can easily simulate the growth and decay by setting as initial condition (and minimal value) the height of the structure h_0 (and corresponding volume V_0). The total volume then is

$$V = V_0 + M/\rho_{ice} \; , \tag{9}$$

from which the stupa height is easily calculated.

An example is shown in Fig. 4. The height of the inner structure has been set to 5 m. A few calculations have also been done to see what happens if the water supply has to be stopped for higher wind speeds. The black curve in Fig. 4 is for a wind speed limit during the growing phase of 4 m/s, i.e. for speeds above this value the water supply is simply switched off. Although this happens only about 20% of the time, it has a large impact on the maximum stupa height (maximum total height 7.5 m instead

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of 9.5 m), because two processes work in the same direction: (i) the duration of the freezing process is shortened, and (ii) the rate of refreezing is smaller for a smaller wind speed (weaker cooling of the surface).

In another run we simulate the situation that the stupa growth cannot start before 1 January, for instance due to technical problems (blue curve in Fig. 4). Apparently an early start is to be advised ! Actually it can be seen in the standard run that normally the growth rate is largest in December when the amount of incoming solar radiation is very small.

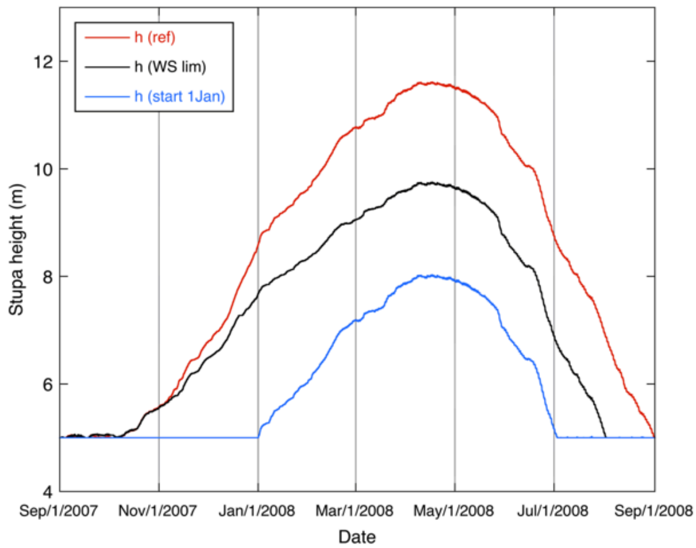

Figure 4. Stupa height for the case with inner structure (cone) with a height of 5 m. The standard run is in red (with constant albedo). The black curve refers to a case in which the water supply is switched off when the wind speed exceeds 4 m/s. The blue curves refer to a case in which the water supply starts on 1 January.

6 Discussion

The data set used to simulate stupa growth and decay for typical conditions in the Oberengadin is probably quite appropriate. The setting of the location of the AWS (on the lower tongue of the Vadret da Morteratsch when it still existed) and the Diavolezza Talstation are rather similar: the altitude is about the same, and the valley is relatively wide. However, differences in the wind statistics are likely, but difficult to assess. The Morteratsch AWS reveals a steady katabatic (glacier) wind most of the time, whereas the Diavolezza Talstation is more exposed to the larger scale wind regime. It seems likely that the average wind speed at the Diavolezza Talstation is somewhat higher than at the AWS site, where the 5-year average wind speed is 2.8 m/s. In contrast, the sites in the Val Roseg and Val Morteratsch are more sheltered and wind speeds are probably lower.

The examples presented here are best-case scenarios with respect to stupa growth. In practice it is not always possible to have unlimited water availability, and it may be difficult to sprinkle the water more or less evenly over the stupa, especially at higher wind speeds. Inner structures help to make the initial growth rate larger.

We note that the typical ice stupa volume calculated here for alpine conditions at ~2100 m a.s.l. (~100 to 250 m^3) is an order of magnitude smaller than the volumes obtained in the big stupas in Ladakh. Winter conditions in Ladakh are considerably colder and therefore growth rates can be much larger.

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In this exploratory study a solid comparison between observed and simulated stupa sizes was not attempted. However, we note that the maximum height of the stupa in the Val Roseg was 12 m, which is in good agreement with the stupa height shown in Fig. 4.

The model presented here is simple, basically because we consider the ice stupa to be a single unit with a surface temperature close to the melting point. As soon as this constraint is relaxed and the surface temperature of the stupa is taken as a dependent variable, the whole procedure becomes more complicated (Balasubramanian et al., 2021), and some processes can be studied more explicitly. Nevertheless, we believe that the simple approach presented in this note, which requires not more than one page of coding, is a useful tool to obtain first-order estimates of growth and decay rates under various conditions. Effects of snow cover, switching off water during daytime, different starting dates, differences between warm and cold winters, etc. can be evaluated. We finally note that the model can easily be reformulated for another geometry, e.g. a dome.

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