Impact of glacial ice melt on alpine tourism in Austria

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Overview:

Glaciers play a crucial role in the environment, they influence not only our holiday destinations and sporting events but also the way that our climate metabolises incoming radiation. The extent and mass balance of glaciers impact the temperature of our atmosphere and the levels of our oceans. As this article will demonstrate, the data gathered from glaciers can be incredibly useful for monitoring the progression of global warming as well as give us an idea of the trends we can expect to continue unless drastic measures are taken to conserve these biomes.

- Data shows that by 2070, some of the largest glaciers in Austria, namely Hintereisferner, will no longer exist.
- The last recorded year of net mass accumulation in any of the glaciers investigated was 1983.

Background:

- Tourism contributes a significant amount to the Austrian economy, it accounts for approximately 5-7% [1] of the national GDP pre-covid. Of that proportion, roughly half is attributed to winter tourism, of which approximately 80% is due to Alpine activities such as snow sports. This makes ski tourism responsible for roughly 2-3% of the Austrian GDP.
- Employment levels in the country are also dependent on the Alpine resort industry which makes up approximately 3.3% of all jobs [2], providing between 120,000 and 160,000 positions pre-covid.
- Each winter, Austria welcomes around 20-25 million tourist arrivals [3] which is representative of almost half of Austria's total annual tourist visitors, the vast majority of these arrivals are for the purpose of alpine activities, predominantly snow sports.

Geographic Proximity:

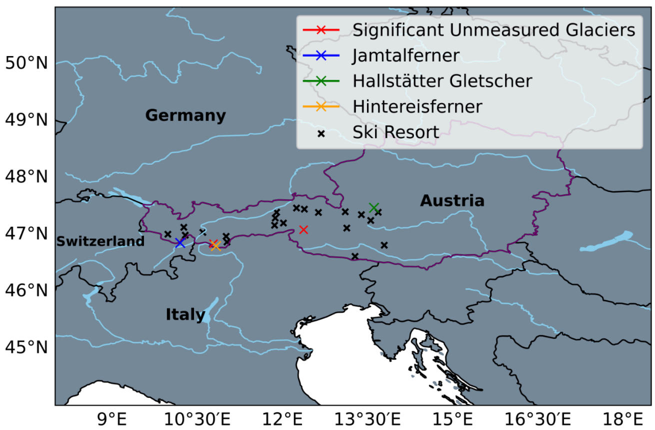

Figure 1, PlateCarree map projection detailing the location of the 5 key glaciers in Austria [4][5] and their position relative to the 20 largest ski resorts in the country [6].

Generally, major ski resorts tend to be located close to the glaciers, particularly in the far west of the country however some of the more eastern resorts are found further from the glaciers. Many resorts lie directly on top of glaciers with some ski runs over the top of them, these resorts are affected most directly by changes in glacier area and mass balance. Other resorts lying near to glaciers in the surrounding mountain range will also experience similar trends in snowfall quantities and season lengths as many of the underlying processes that govern glacial ablation apply to the alpine environment as a whole.

Overview of Time Series Trends:

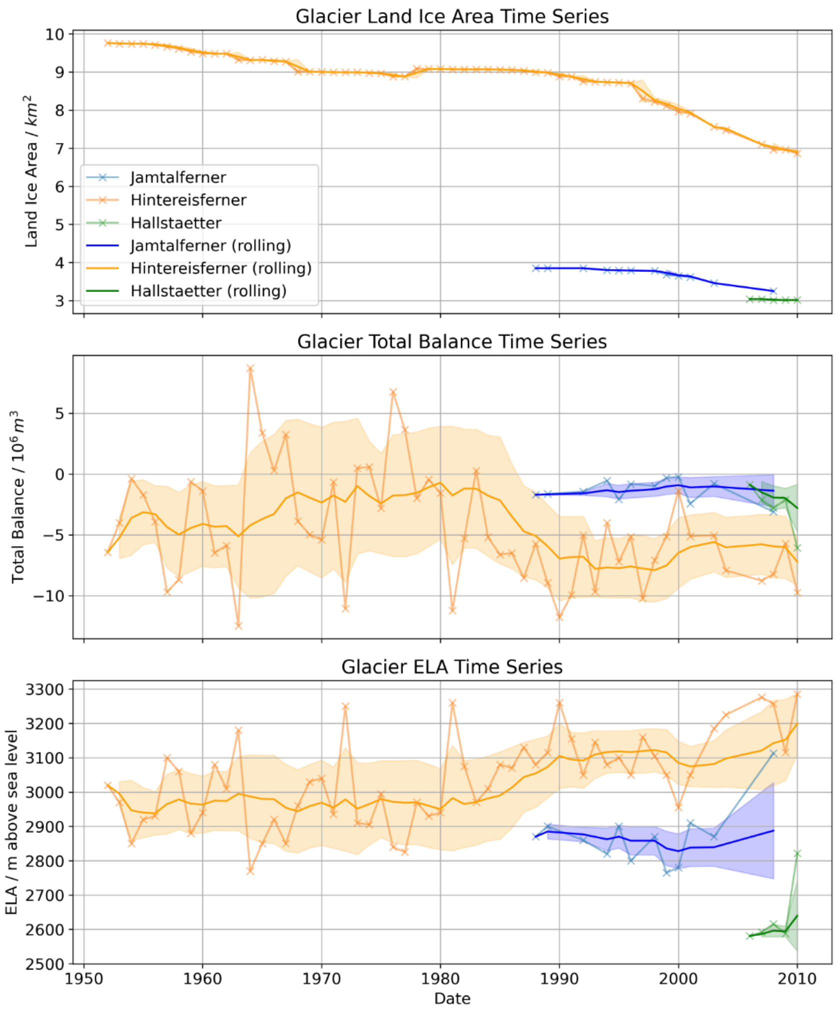

Figure 2, raw data, rolling means and ±1 standard deviation envelopes for the overall time series data of total glacier area (top), total volume balance (middle) and equilibrium line altitude, ELA (bottom).

The time series data shows a clear and certain negative trend in total land ice area. Since recording began for Hintereisferner, land coverage of the glacier has fallen by 30% and the rate of glacial retreat has only been rising over time. By extrapolation of the graph from 1997, an estimate for complete destruction of the glacier (referred to as glacier loss day, GLD) would be by 2070, if not sooner.

Glacier Total Balance is a measure of the volume of ice accumulated or ablated from the glacier in one year. As shown by the ± 1 standard deviation envelope in the second plot, it is significantly more variable than the Land Ice Area. Despite this, the rolling mean since data began recording for any of the glaciers hasn't been above 0 once, and 1983 was the last year of net accumulation ever recorded.

Glacial ablation occurs through a number of mechanisms, the largest contributors in Austria being: surface melting, basal lubrication and in certain cases, calving into proglacial lakes. Both Hintereisferner and Jamtalferner have developed small proglacial lakes in recent years due to the volume of meltwater collecting in the mountains. In this sense, the ablation processes feed into one-another causing acceleration of volume loss. Surface melting is primarily caused by incident radiation, the power of which is increasing due to a thinning ozone coverage caused by CFC production and increased greenhouse gas emissions. Basal lubrication, caused by basal melting, results in increased ice flow rates which shift the glacier to lower altitudes where warmer conditions result in further melting.

Sea level rise due to glacial ablation can also be calculated using the total balance metric. Globally, glacial ablation accounts for approximately 25-30% of sea level rise [7] which corresponds to 1.5mm per year [8].

Equilibrium line altitude refers to the point on the glacier at which the net accumulation of mass is equivalent to the net ablation of mass in one year. ELA analysis also displays discouraging trends in recent years with a variable but definitive upwards trajectory. This is an indication of conditions for accumulation becoming ever more scarce at lower altitudes, which is also likely to be the case for mountains and major ski resorts nearby. Comparing the ELA of each glacier to it's maximum altitude reached, (Hintereisferner: 3750m, Jamtalferner: 3116m, Hallstaetter: 2905m), it is clear that net accumulation is unlikely to be taking place at any altitude within a decade.

Analysis of Elevation Zone Trends:

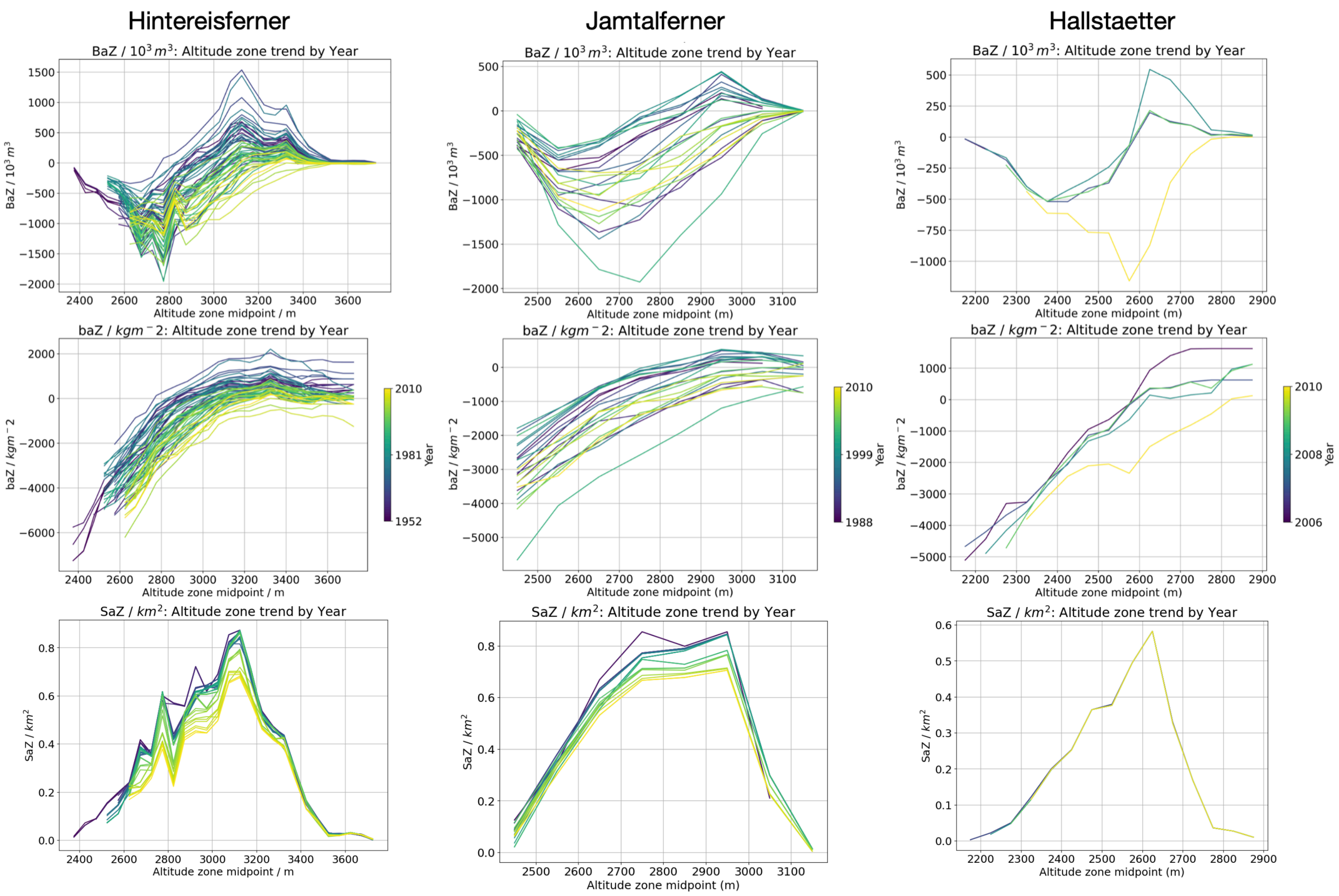

Figure 3, BaZ - total balance (top), baZ - specific mass balance (middle) and SaZ - land ice area (bottom) variation with altitude zone for: Hintereisferner (left), Jamtalferner (middle) and Hallstaetter (right).

Total balance is in this case broken down into altitude regions. Specific mass balance is the change in ice mass over one year per unit area of the glacier at a specific altitude zone. Specific mass balance is useful as a comparative metric as it normalises the data relative to the glaciers size allowing glaciers of varying land area to be compared.

As shown in figure 3, total balance is significantly more negative at lower altitudes; taking Hintereisferner as an example, modern measurements show that beneath 3200m, total balance is rarely positive. This metric aligns well with the ELA data in figure 2 where the ELA can be determined as the point in the total balance graph where the switch from positive to negative occurs. It is evident from the colour gradient between the years that it used to be the case that for high altitudes, annual total balance would be positive and the volume accumulated would feed into the lower parts of the glacier over time as the ice flowed under its own weight. In recent years however, very few altitudes if any experience a net positive total balance, a concept that is shown well by the graph of total balance on Hallstaetter where the trend drastically flips above 2500m.

Between 2005 and 2010, an unexpected trend emerged in specific mass balance on Jamtalferner, the curve against altitude zone began to increase slightly year on year showing signs of reduced ablation rate. The concept of ice flowing under it's own weight and acting as a viscous fluid may explain this and mathematical analysis suggests that the glaciers rate of ablation may slow over time. This is because as less snow is deposited at higher altitudes and more of the surface is melted, the weight of ice above any given point decreases resulting in a lower hydrostatic pressure driving the flow and hence lower velocity as shown in the following derivation:

$$p = p_0 + \rho g(h - z)$$

$$\frac{\partial p}{\partial x} = \rho g \frac{\partial h}{\partial x}$$

$$\frac{\partial p}{\partial x} = \rho g \frac{\partial h}{\partial x} = \eta \frac{\partial^2 u}{\partial z^2}$$

$$u = -\frac{\rho g}{2\eta} \frac{\partial h}{\partial x} z(2h - z)$$

The use of this model to determine the velocity of ice flow (and hence to calculate mass flux due to viscous flow) captures a key process but is not comprehensive and contains a number of flaws. One major flaw with the formulae is that viscosity is assumed to be constant, this is not the case and in reality viscosity of ice is shear thinning, a concept explored in Glenn's flow law.

Specific mass balance provides a particularly informative metric for comparison when quoted by elevation band. The data in the middle row of subplots of the figure show the mass balance normalised against the glaciers area within that altitude region. It is clear to see that despite being at the same altitude, ablation per unit area can vary, Hintereisferner is seen to lose around 5000-6000 kg per unit area at an altitude of 2600m whereas Jamtalferner and Hallstaetter only lose around 2000-3000 kg per unit area at the same altitude. This is a clear indicator that the ablation rate is not entirely dependent on the altitude of the glacier, it may also be dependent on how steep the underlying bedrock is as explained below.

When specific balance is compared to the total balance, it is clear that the area of the glaciers within different altitude zones varies, as confirmed by the bottom row of subplots. The highest proportion of the glacier sits around the centre of its total altitude range, which based on the formulae above, indicates a shallower inclination of the mountain around that region causing a build up of ice. Depending on the topological profile of the mountain that the glacier lies on, the majority of the area may be concentrated at a narrow altitude range upon which a shallower bedrock gradient is found (Eg: Hallstaetter) or spread over a larger altitude range (Eg: Jamtalferner).

Recommendations:

In order to safeguard against the changes taking place in the Austrian Alps, two strategies must be considered, the idealistic solution of slowing and even reversing the trends in Glacier mass balance / area and the more realistic solution of reducing the countries socio-economic dependancy on ski tourism.

In the ideal case, we would need to consider the leading causes of glacial ablation and policies to reduce their impact not only in Austria but also internationally. The key contributing factors to glacier ablation consist of: incident radiation on the surface, ambient air temperature and basal melting. Significant changes in radiation levels and ambient air temperature (due to pollution and global warming) are out of Austria's control as it is a small country by land area and population without a large manufacturing industry. To make a significant impact on global warming, shifts in consumer culture, industrial production methods and the green energy transition are required.

In the realistic case, alternative motivations for winter tourism that don't rely on the snow conditions need to be considered and advertised. In order to make this a viable solution, the new form of the winter tourism industry in the mountains should be one easily adaptable from the current infrastructure in order to reduce costs. For example, with a reduction in skiable area comes an increase in area accessible by foot, hence winter hiking could begin to replace skiing activities. This solution utilises the existing infrastructure in ski resorts such as ski lifts and would only require incentivisation for winter sports shops to provide suitable hiking equipment such as footwear. An issue with this approach is that until similar issues in the ski industry occur on a global scale, placing a strain on the number of people who are able to go on a ski holiday annually, tourists are likely to relocate rather than change the activities of their holiday.

To make a permanent impact in the near future on glacier ablation and hence preserve the ski tourism industry and its contribution to the Austrian economy, international bodies such as the United Nations would have to intervene. Major policy changes in global emissions targets as well as realistic solutions both for the general population as well as regulations on businesses would have to be proposed for example in the next Conference of the Parties .

References:

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