HOW DO MONTHLY TEMPERATURE VARIATIONS AND LEVELS OF WINTER TOURISM INFLUENCE THE FREQUENCY AND TYPE OF AVALANCHES IN DAVOS, SWITZERLAND?

ESA Climate Detectives program

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1. Title

Research question: How do monthly temperature variations and levels of winter tourism influence the frequency and type of avalanches in Davos, Switzerland?

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2. Abstract

This research investigates the relationship between seasonal temperature variation, human activity, and the frequency and type of avalanches in Davos, Switzerland. By analyzing long-term avalanche records alongside meteorological data and tourism statistics, the study explores how climate change and increasing winter tourism may influence avalanche dynamics. Results indicate a weak correlation between diurnal ground temperature differences and avalanche frequency, but a notable trend of rising wet avalanche occurrences as overall temperatures increase. Additionally, while a slight positive correlation was found between tourist activity and avalanche frequency, natural environmental factors remain the dominant contributors. Survey responses also revealed a lack of public awareness regarding avalanche preparedness and safety. These findings underscore the importance of adapting avalanche risk management strategies in the face of climate change, while also promoting education and awareness to reduce human vulnerability in high-risk alpine environments.

3. Introduction

Avalanches are rapid downward movements of snow, ice, and debris that vary in size, speed, and impact. They can range from small slides to massive destructive events that bury infrastructure and endanger lives. (1)

There are many types of avalanches; however, they can be categorized into two main types: dry and wet avalanches. Dry snow avalanches usually occur in colder conditions and move at high speeds, up to 300 km/h, generating powerful air blasts. In contrast, wet snow avalanches contain more water and move slower but are heavier and more destructive. (2)

Avalanches seriously threaten human life and infrastructure, particularly in alpine regions like Davos, Switzerland, where tourism and winter sports are central to the local economy. Every year, avalanches cause fatalities, with many victims being skiers, snowboarders, and mountaineers caught in backcountry terrain. In addition to the human toll, avalanches can damage infrastructure, including ski resorts, roads, and mountain villages, resulting in economic losses and disruptions to local communities. They also have significant environmental consequences, altering landscapes, damaging forests, and disturbing ecosystems. (3)

Multiple factors can impact the types and frequency of avalanche events. Weather conditions like temperature, snowfall, wind, and precipitation significantly influence snowpack stability and formation, determining the likelihood of avalanche events as weak layers in the snowpack will increase avalanche risks. (4) Other factors like vegetation can prevent the formation of wet slab avalanches and stabilize slopes, while human activity can trigger avalanches if precautions are not taken. (6) However, this study will focus specifically on the influence of temperature and human activity, namely winter tourism.

Global warming is a worldwide phenomenon, resulting in an increase of approximately 1.6˚C above the preindustrial level as of 2024 and marking the warmest year since records began in 1850. It has also been projected that global temperature could rise well beyond 2˚C without aggressive climate action by 2050. (5) The rising temperature could have different implications for avalanches. Many studies have suggested that due to snow crystals melting at close or above freezing points, wet snow avalanches will replace dry avalanches, leading to a possibly more destructive avalanche. However, the frequency of avalanches can vary depending on geographical formation. Teich et al. (6) have shown a negative correlation between increasing temperature and avalanche frequency in the Swiss Alps, which is hypothesized to be caused by increased forest density due to a more habitable temperature. However, Eckert has found that avalanche frequency remained the same in the French Alps. (7)

In terms of tourism, no direct studies explicitly link tourist activity to avalanche frequency, but research on avalanche accidents suggests a possible correlation. Backcountry skiing in Switzerland tripled from 1999 to 2013, (8)increasing exposure to avalanche risks as 94% of avalanche incidents are self-triggered or caused by nearby recreationists. (9)These statistics suggest a potential link between tourism and avalanche frequency.

This study investigates the correlation between seasonal temperature variations, tourist activity, and avalanche frequency in Davos, Switzerland. Given the ongoing rise in global temperatures and the growing popularity of winter tourism, understanding how these factors interact is essential for improving avalanche forecasting and risk management strategies while raising awareness of global warming’s effect on real-life activities.

4. Methods

Survey analysis

Avalanche safety posters were placed at key mountain locations, including Mountain Eggli, Schönried, and Saanenmöser. Each poster featured a QR code linking to an interactive quiz, including multiple-choice and open-ended questions designed to test and reinforce knowledge of avalanche safety principles. An email containing a link to the survey was also sent to the whole school, with responders aged 11-18 and teachers. The questions and responses to the study were then graded and collected for further analysis.

The questions and answers to the survey were as follows:

1. At what slope angle do avalanches typically occur?

- More than 60 degrees (Extreme off-piste terrain)
- 30–45 degrees (red/black slope)
- Less than 20 degrees (green slope)

Correct answer: 30–45 degrees (red/black slope)

2. Is it generally possible to escape from an avalanche if you get completely buried on your own?

- Yes
- No

Correct answer: No

3. What kind of sounds might you hear during an avalanche? *(Select 2 choices)*

- "whumph" sound
- Powdery sound
- Buzzing sound
- Birds chirping

Correct answers: "whumph" sound and Powdery sound

4. What is the best way to avoid getting injured in an avalanche?

- Check avalanche forecasts before heading out
- Run downhill to outrun the avalanche
- Dig straight down into the snow to escape

Correct answer: Check avalanche forecasts before heading out

5. Do you know what equipment you need to take when skiing in areas where avalanches might occur?

- Yes
- No

6. (if choose yes on question 5) Name one equipment *(Open-ended response)*

- Correct answers: Avalanche beacon, Avalanche probe, Avalanche shovel, Avalanche airbag backpack, RECCO reflector, Helmet, Snow saw, Avalung, GPS device, Radio, First aid kit, Extra layers, Emergency whistle, Avalanche escape rope, Arva

Tourism and avalanche frequency analysis

Avalanche data were obtained from EnviDat covering the years 1999 to 2019. For the purposes of this study, records were filtered to include only avalanches occurring within the commune of Davos during the period 2013 to 2019 to align with the temporal range of the available tourism data. Additionally, only avalanches classified as human-triggered were retained, and total annual avalanche counts were calculated.

Tourism data, specifically arrivals and overnight stays, were sourced from the Swiss Federal Statistical Office for the same 2013–2019 period to ensure temporal consistency. The data were aggregated annually, summing all monthly values, and filtered to include only entries associated with Davos. No further filtering or preprocessing was applied to the tourism dataset.

Temperature and avalanche frequency analysis

Land surface temperature data were obtained using NASA's Application for Extracting and Exploring Analysis Ready Samples (AppEEARS; https://appeears.earthdatacloud.nasa.gov) to incorporate thermal conditions into the analysis. The selected product was Terra MODIS Land Surface Temperature & Emissivity (LST&E), specifically MOD11A1.061, which provides daily observations at a 1 km spatial resolution from February 24, 2000, to the present. The spatial extent for data extraction was defined using a GeoJSON bounding box corresponding to the Davos region. This region was derived from the metadata of the avalanche dataset hosted on EnviDat. A `package_show` query to the EnviDat CKAN API returned a `Polygon` in the `spatial` field, defining the region with the following bounding coordinates: west = 9.7614°, east = 9.9564°, south = 46.7399°, and north = 46.8733°. These boundaries were used to extract temperature data that precisely matched the avalanche observation area. Two MODIS LST layers were selected: daytime land surface temperature (LST_DAY_1km) and nighttime land surface temperature (LST_NIGHT_1km). The data were exported in NetCDF-4 format and projected using the geographic coordinate system (WGS 84). These thermal variables were then used to examine daily temperature conditions concerning avalanche occurrences throughout the study period.

Processing and analyzing data

Jupyter Notebook is used with Python, Numpy, Pandas, and Xarray to process and analyze temperature and avalanche data. The necessary libraries are imported, and the temperature dataset is loaded. The time values are reformatted into a standard date format. The temperature data for a given date is then extracted and displayed. A new table contains average day and night temperatures, valid data counts, and the temperature difference between day and night.

Avalanche data is loaded from a CSV file and merged with the temperature data based on the release date. The merged data is stored for further analysis. The data is grouped by month to calculate avalanche trigger counts and snow conditions. Unnecessary snow and trigger types are filtered out, and the occurrence of different snow types is analyzed over time.

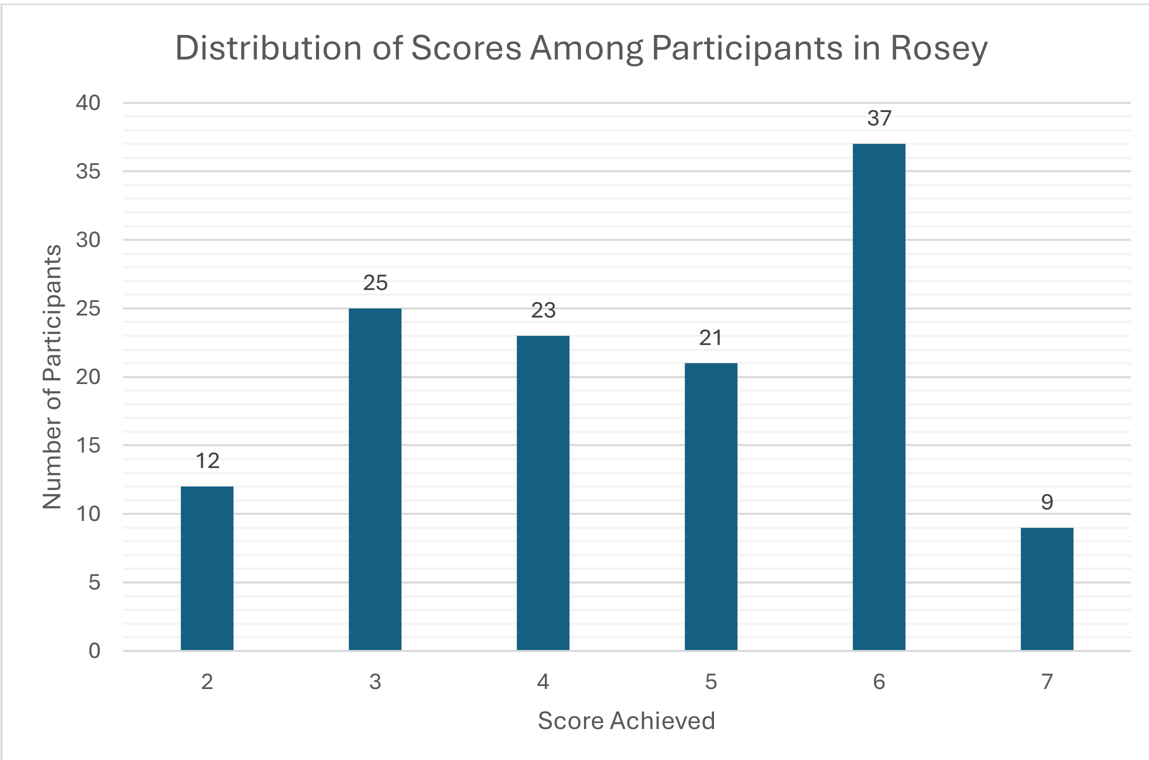
The average temperature is calculated for each record, and the data is categorized into temperature bins. The distribution of snow types and avalanche triggers across these temperature bins is analyzed, and the results are saved in a new CSV file. This method helps to identify patterns in how temperature variations relate to snow conditions and avalanche events.

How it works (open with Google Colabs):https://drive.google.com/file/d/15jj-DTAbgR8hZF2bBtcKoIGbor_NzBnH/view?usp=sharing

5. Results and Discussion

Survey analysis

Figure 1:



The survey results (fig. 1) show that few people in the Gstaad/Rougemont/Saanen population who either live or visit a high-risk area know about the dangers of avalanches and avalanche prevention.

The question that most people got wrong was: Do you know what equipment you need to take when skiing in areas where avalanches might occur? This is likely because the answer is a list of specific items, while many other questions could be guessed/answered logically. Out of the 127 people interviewed, 27 left the question blank, and 100 inputted incorrect answers.

Other than that, 68 people were asked the question, ‘ At what slope angle do avalanches occur?’ While it is logical to answer the question of steeper slopes, most people are not aware of the angle of the slope they are skiing on.

Another question many people got wrong was: ‘What kind of sounds might you hear during an avalanche?’ A lot of people didn’t know that you might hear a cracking sound or a loud roar.

Many people also got the question wrong about whether escaping from an avalanche is possible if you get entirely buried. Some people may believe they could dig themselves out, but surviving without help is very hard.

Tourism and avalanche frequency analysis

Figure 2:

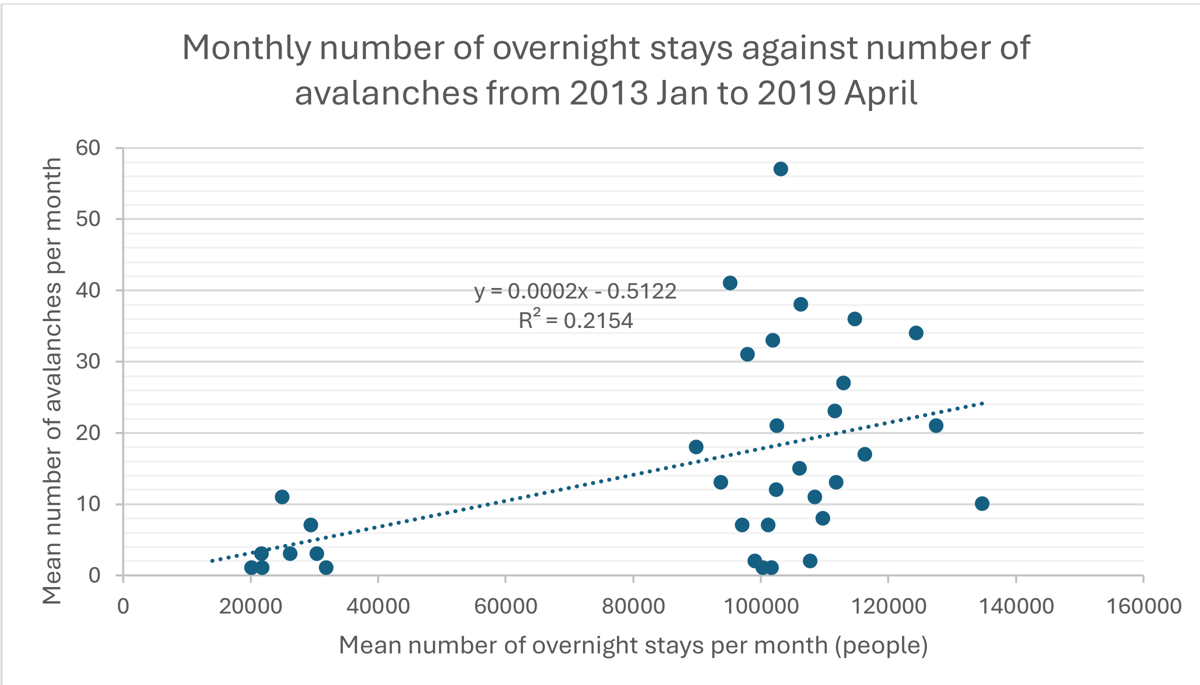
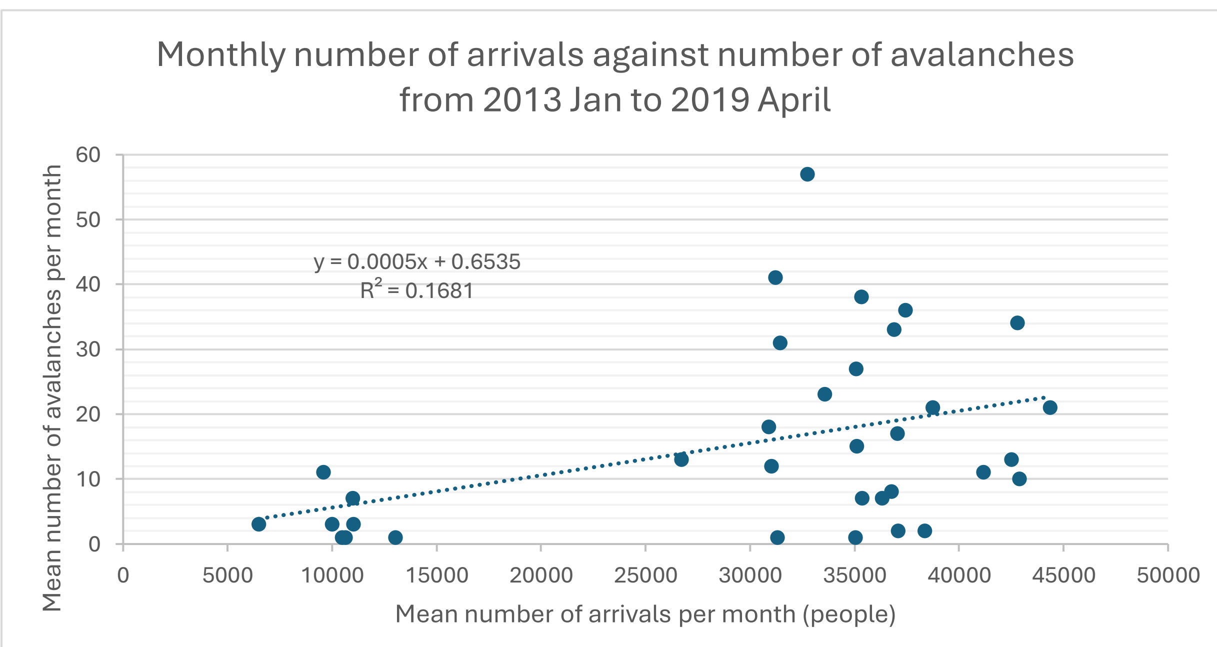


Figure 3:



Figures 2 and 3 illustrate the relationships between the mean number of overnight stays and arrivals per month with the mean number of avalanches per month from January 2013 to April 2019. Linear regression analyses yield equations of $y = 0.0002x - 0.5122$ (R^2 =0.2154) for overnight stays and $y = 0.0005x + 0.6535$ (R^2 = 0.1681) for arrivals, both indicating weak positive correlations. While the trend lines suggest a slight increase in avalanche occurrences with higher numbers of overnight stays and arrivals, the data exhibit high variability. The low R^2 values (21.54% and 16.81%, respectively) indicate that only a small proportion of the variation in avalanche occurrences is explained by these factors, suggesting the influence of additional variables.

Temperature analysis

Figure 4:

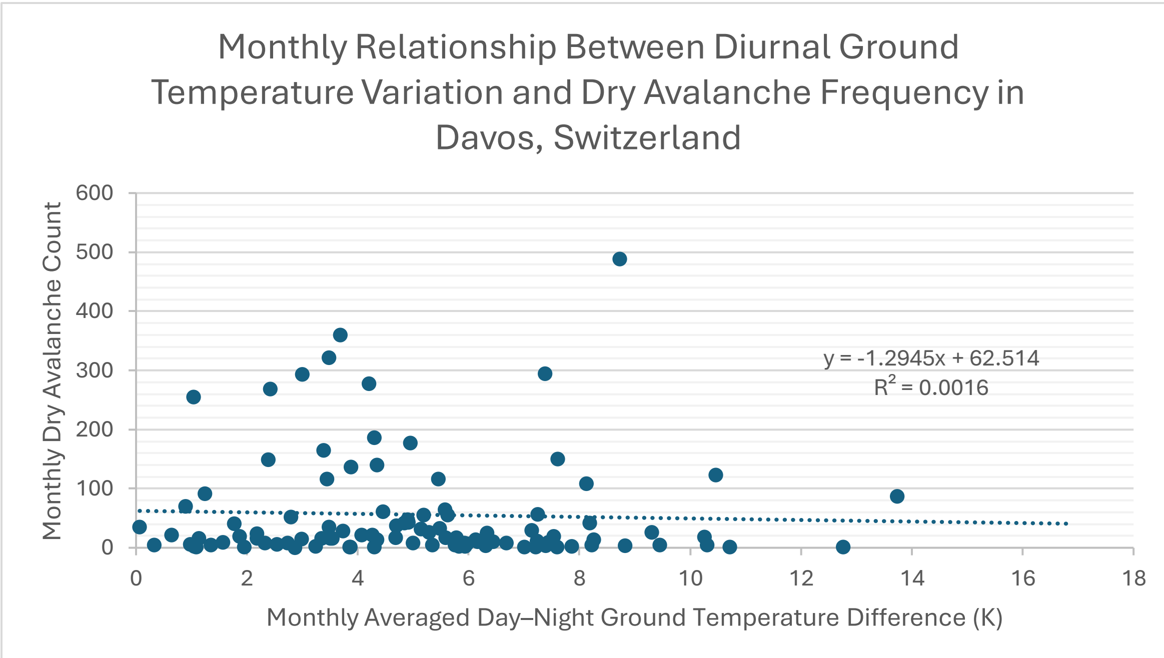


Figure 5:

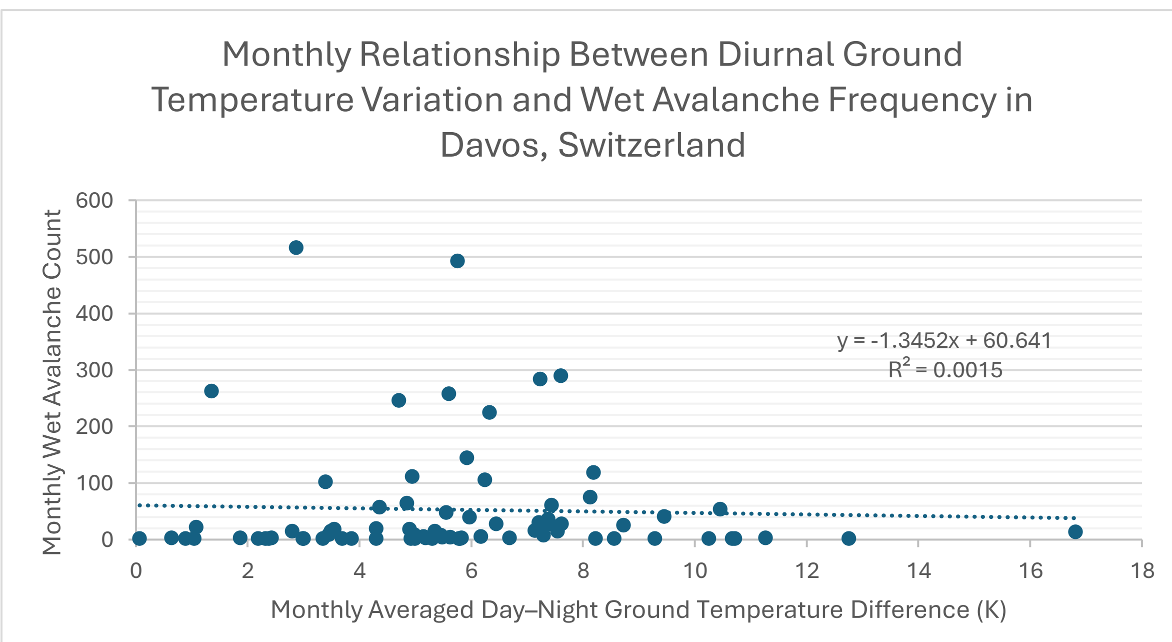
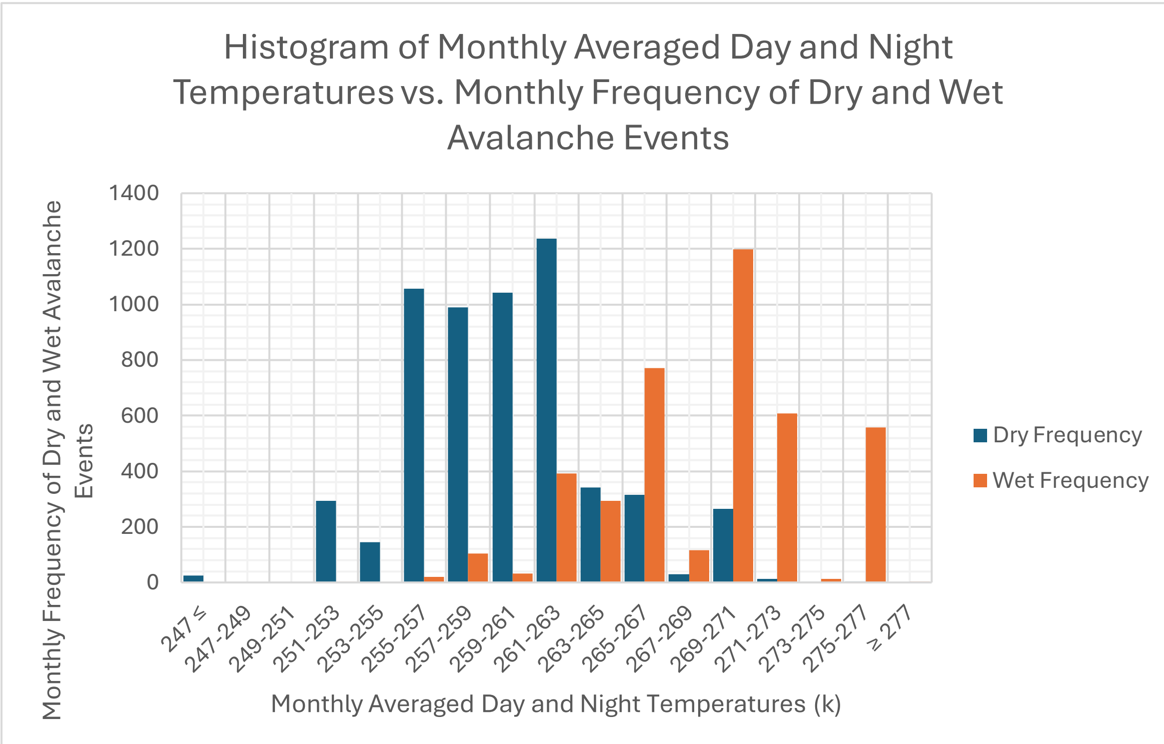


Figure 6:



Figures 4 and 5 illustrate the relationship between diurnal ground temperature variation and the frequency of dry and wet avalanches in Davos, Switzerland. Both graphs show a weak negative correlation, as indicated by the trendlines with slopes of -1.2945 and -1.3452 for dry and wet avalanches, respectively. However, the R^2 values (0.0016 and 0.0015) suggest an extremely weak association, implying that variations in day-to-night temperature differences have minimal influence on avalanche frequency.

Figure 6 compares monthly dry and wet avalanche occurrences across different average temperature ranges. Dry avalanches are most frequent between 255-265 K, while wet avalanches dominate above 267 K, becoming the predominant type as temperatures increase. This trend suggests a shift in avalanche type with rising temperatures, with wet avalanches becoming more frequent in warmer conditions while dry avalanches decrease.

7. Uncertainty and data reliability

Tourism data

This study draws on tourism data from the Swiss Federal Statistical Office (FSO), specifically the dataset "Hotel sector: arrivals and overnight stays of open establishments for 186 communes by year, month, commune, and visitors' country of residence." The FSO operates under the *Charter of Swiss Official Statistics* (10), which mandates adherence to rigorous principles of professional independence, methodological transparency, and quality assurance. Although the dataset does not include explicit measures of statistical uncertainty (e.g., standard errors or confidence intervals), the FSO's published quality guidelines emphasize regular validation of data, alignment with national and international standards, and transparent dissemination of methods. The institution's formal commitment to quality and its legal obligation to ensure statistical confidentiality and impartiality provide a strong basis for considering the data reliable for research purposes.

Avalanche data

This study also draws on the "Snow avalanche data Davos, Switzerland, 1999–2019" dataset, published on EnviDat and compiled by the WSL Institute for Snow and Avalanche Research SLF. The dataset includes 13,918 avalanche records over 21 winter seasons, each linked to the corresponding daily forecast avalanche danger level. While the dataset does not report explicit measures of statistical uncertainty (e.g., standard errors or confidence intervals), its scientific reliability is supported by several factors. First, the data was collected using consistent observational methods and standardized danger levels as defined in the European avalanche warning system. Second, the dataset has been used in peer-reviewed research by Schweizer et al. (2020) (11), which analyzed patterns in avalanche frequency and size concerning danger levels. Third, publication via EnviDat—a repository operated by the Swiss Federal Institute for Forest, Snow, and Landscape Research—ensures the dataset meets open-access standards and is accompanied by structured metadata and documentation. Together, these elements support the dataset's methodological rigor and suitability for scientific analysis, even without formally quantified uncertainty measures.

Land surface temperature data (LST)

When interpreting the results involving MODIS land surface temperature (LST) data, it is crucial to consider the known uncertainties associated with the MOD11A1 product. According to a recent validation study by Zhao et al. (2024) (12), the MOD11A1 LST estimates exhibit a mean bias of approximately +0.88 K and a root mean square error (RMSE) of 2.37 K for daytime temperatures and a mean bias of −1.07 K with an RMSE of 0.99 K for nighttime temperatures. These findings indicate that the product tends to slightly overestimate daytime LST and underestimate nighttime LST, with generally higher uncertainty during the day. While these uncertainties are relatively small, they may be more pronounced in areas with complex terrain, such as the alpine region around Davos. As such, the interpretation of correlations between LST and avalanche activity in this study should take into account the potential measurement error inherent in the remote sensing data. Nevertheless, the consistent spatial coverage and long-term continuity of the MODIS product provide a valuable dataset for understanding thermal patterns relevant to snowpack stability and avalanche occurrence.

To make the uncertainty more applicable to this study, the uncertainty of the monthly diurnal ground temperature difference in the data set used for our temperature analysis was calculated in the following steps based on the researched uncertainty of the sensor:

Known sensor uncertainties: (12)

- MODIS LST_DAY_1km: ±2.37 K
- MODIS LST_NIGHT_1km: ±0.99 K

Input data:

- Average number of valid daytime pixels per day: 161.32
- Average number of valid nighttime pixels per day: 207.13

Daily uncertainty of spatial averages

$$\sigma_{\text{day}} = \frac{2.37}{\sqrt{161.32}} \approx 0.1865\ K$$

$$\sigma_{\text{night}} = \frac{0.99}{\sqrt{207.13}} \approx 0.0688K$$

Uncertainty of daily diurnal temperature difference

$$\sigma_{\text{diff-daily}} = \sqrt{(\sigma_{\text{day}}{}^2 + \sigma_{\text{night}}{}^2)}$$

$$\sigma_{\text{diff-daily}} = \sqrt{(0.1865^2 + 0.0688^2)} \approx \sqrt{0.0395} \approx 0.1988\ \text{K}$$

Step 3: Propagate uncertainty to monthly average (30 days)

$$\sigma_{\text{monthly}} = \frac{\sigma_{\text{diff-daily}}}{\sqrt{30}}$$

$$\sigma_{\text{monthly}} = 0.1988 / \sqrt{30} \approx 0.0363\ \text{K}$$

Propagated uncertainty of the monthly diurnal ground temperature difference: ±0.0363 K

In Figure 6, temperature data was binned by average MODIS LST. The uncertainty of the monthly LST data is calculated by the following steps based on the same sensor uncertainty:

Average LST uncertainty propagation:

$$\sigma_{\text{day}} = \frac{2.37}{\sqrt{161.32}} \approx 0.1865\ K$$

$$\sigma_{\text{night}} = \frac{0.99}{\sqrt{207.13}} \approx 0.0688K$$

Average ground temperature per day = (Day + Night)/2

Uncertainty of daily average:

$$\sigma_{\text{avg}} = (1/2) \times \sqrt{(\sigma_{\text{day}}{}^2 + \sigma_{\text{night}}{}^2)} \approx 0.0994\ \text{K}$$

Monthly uncertainty:

$$\sigma_{\text{monthly\_avg}} = 0.0994 / \sqrt{30} \approx 0.0181\ \text{K}$$

In conclusion, each bin is based on monthly averaged MODIS land surface temperature (LST) data, with a propagated uncertainty of ±0.0181 K.

8. Conclusion

Survey Data Analysis

The data from the survey suggests that those living and visiting high-risk areas are not fully aware of protection from an avalanche and how to adequately protect themselves during an avalanche. However, there are some things we can do to improve this.

Regarding those not knowing which equipment to bring or use in case of an avalanche, we can work on solving the issue through proper avalanche training to tourists and those living in high-risk areas. However, it is essential to note that much of the required equipment can be expensive, which may be off-putting to tourists especially. However, through advancements in engineering and safety management, as well as possible government subsidies, the equipment may become cheaper and more accessible to people in high-risk areas.

Slope angle was another issue - to work on this, it can be suggested to make equipment for off-piste skiers to measure slope angle, or two add additional information (such as average or steepest slope angle) to slope information markings.

Identifying an avalanche with sound also proved to be tricky to many - this could be because most people have never seen or heard an avalanche before. Adding short videos or audio clips at ski resorts or during safety briefings could help people recognize the warning signs more quickly.

Finally, in the worst-case scenario, how to survive if you are eventually buried by snow during an avalanche was also an issue. Most people don't know that after about 15 minutes, the chances of survival are reduced significantly (13). This shows why it's important to always ski with others, carry safety gear, and know how to use it.

Tourism and avalanche frequency

The weak positive correlations between the number of overnight stays and arrivals with avalanche occurrences (R^2 =0.2154 and R^2 = 0.1681, respectively) indicate that while human presence may have some influence on avalanche frequency, it is not the primary determining factor. The high variability in the data suggests that natural environmental conditions play a much more significant role in avalanche occurrences. Factors such as snowfall accumulation, temperature fluctuations, and slope stability are critical in avalanche formation. (4) Heavy snowfall increases the load on existing snow layers, while rapid temperature changes can weaken bonds between layers, leading to slab avalanches. Additionally, variations in wind patterns can redistribute snow, creating unstable deposits on slopes prone to failure.

Although the slight positive trend in the data could be attributed to human activity—such as skiers or hikers triggering avalanches, the weak correlation suggests that most avalanches occur independently of tourism levels. Many avalanches are naturally triggered by changes in snowpack structure due to weather conditions rather than direct human influence. (14) In addition, increased human presence in avalanche-prone areas may contribute to a higher number of reported incidents, as more observers and recreationists are present to witness and document them. (15)

Despite the weak correlation, the results reinforce the need for public awareness and safety measures, particularly during peak tourist seasons when both natural and human-triggered avalanches may be more frequent.

These findings highlight the importance of incorporating meteorological and geological factors into avalanche risk assessments. Since this study could not control these variables, no clear conclusion or trend can be drawn. Future research should control snowfall data, temperature patterns, and terrain characteristics to develop more accurate predictive models.

Temperature and avalanche frequency

The results indicate that diurnal ground temperature variation has a negligible impact on avalanche frequency, as demonstrated by the weak correlations in both dry and wet avalanche datasets (R^2 = 0.0016 and R^2 = 0.0015, respectively). This suggests that short-term temperature fluctuations between day and night do not significantly influence the formation or triggering of avalanches.

However, Figure 6 reveals a clear shift in avalanche type based on overall temperature, with dry avalanches occurring predominantly at lower temperatures (255-265 K) and wet avalanches increasing in frequency as temperatures exceed 267 K. This aligns with existing research suggesting that warmer conditions favor wet avalanches due to increased snowmelt and reduced snow cohesion. (6,7)

These findings highlight the potential impact of climate change on avalanche dynamics. As global temperatures continue to rise, the frequency of wet avalanches may increase, posing heightened risks due to their more significant destructive potential. (2) Additionally, while diurnal temperature variation appears to have little effect, long-term warming trends may lead to shifts in snowpack stability and avalanche behavior. Future studies should investigate other meteorological factors, such as precipitation patterns and wind conditions, to better understand the complex drivers of avalanche activity. Expanding the geographical scope beyond Davos to include other alpine regions will be essential for enhancing forecasting models and improving risk assessment and mitigation strategies across diverse mountain environments.

9. Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used GPT-3.5 to assist in the writing process. After using this tool/service, the author(s) reviewed and edited the content as needed and took full responsibility for the publication's content.

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