



# EXTRAORDINARY EARLY START OF GROWING SEASON 2024 AT ALPINE TREELINE ECOTONE IN SLOVAK HIGH TATRAS (WESTERN CARPATHIANS)

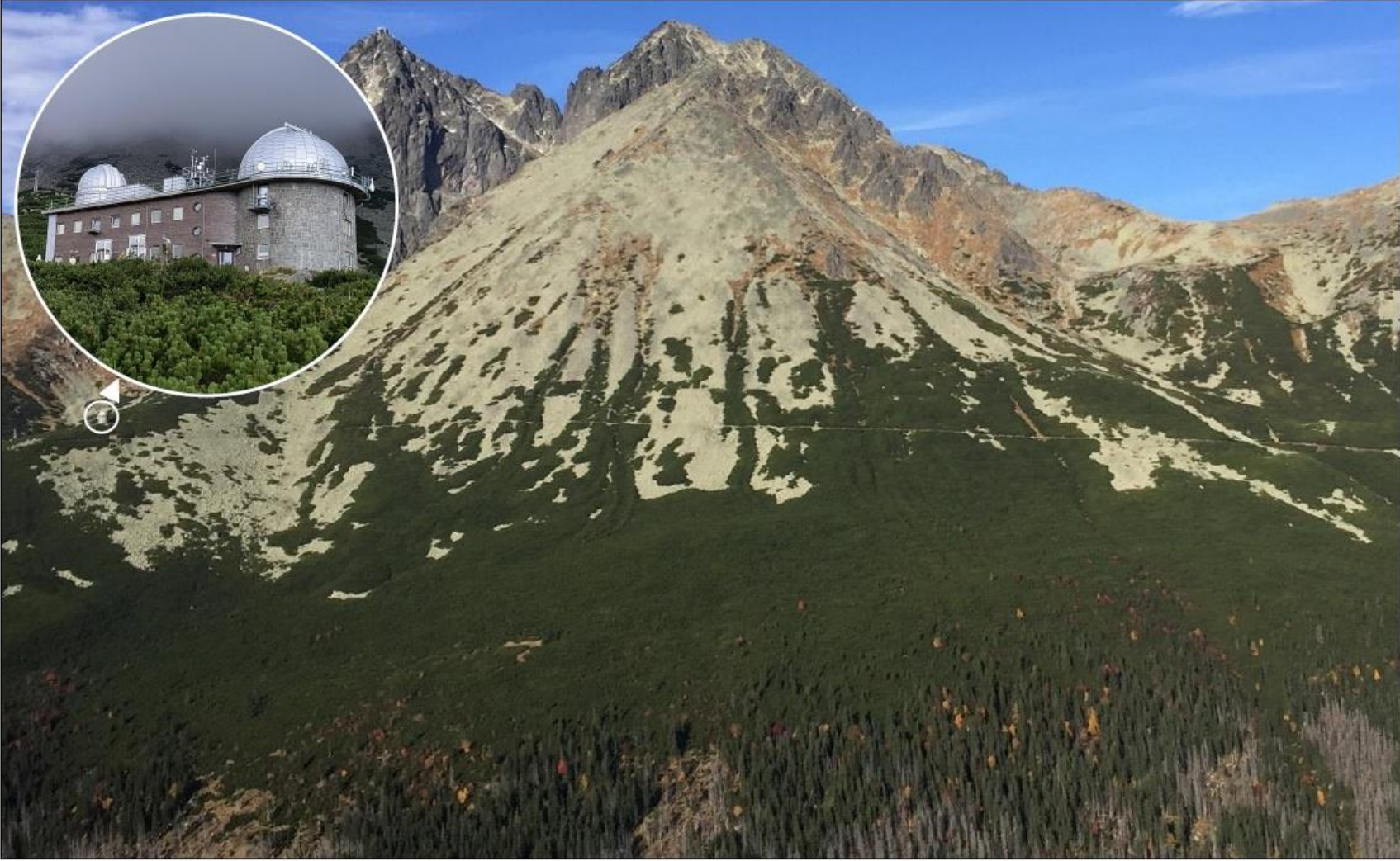
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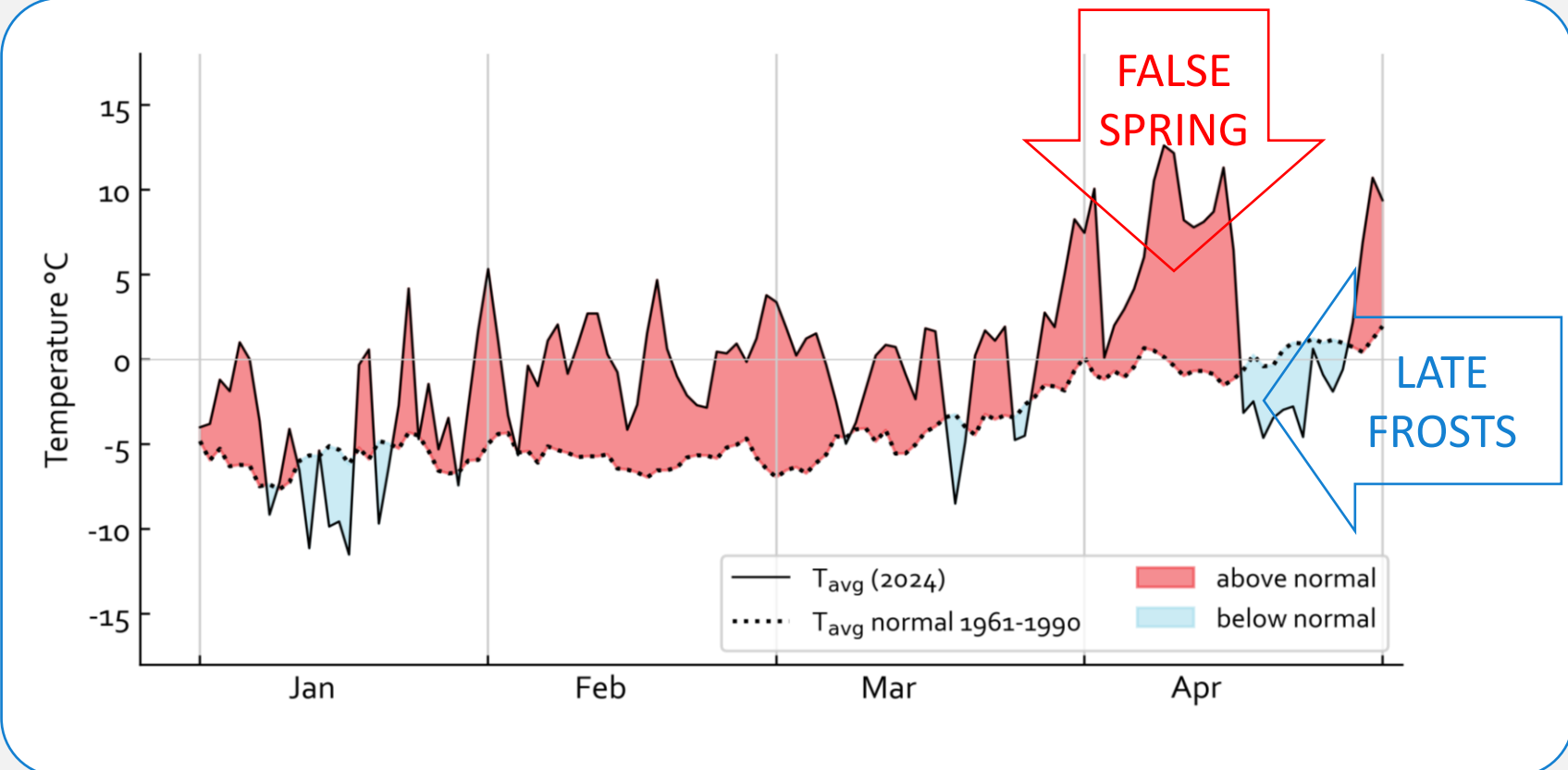
## 1 INTRODUCTION

The presented research contributes to understanding the impact of extreme weather events associated with global warming on the growth and distribution limits of high-elevation species, including the negative effects of frost during the extraordinarily early onset of spring phenological phases.

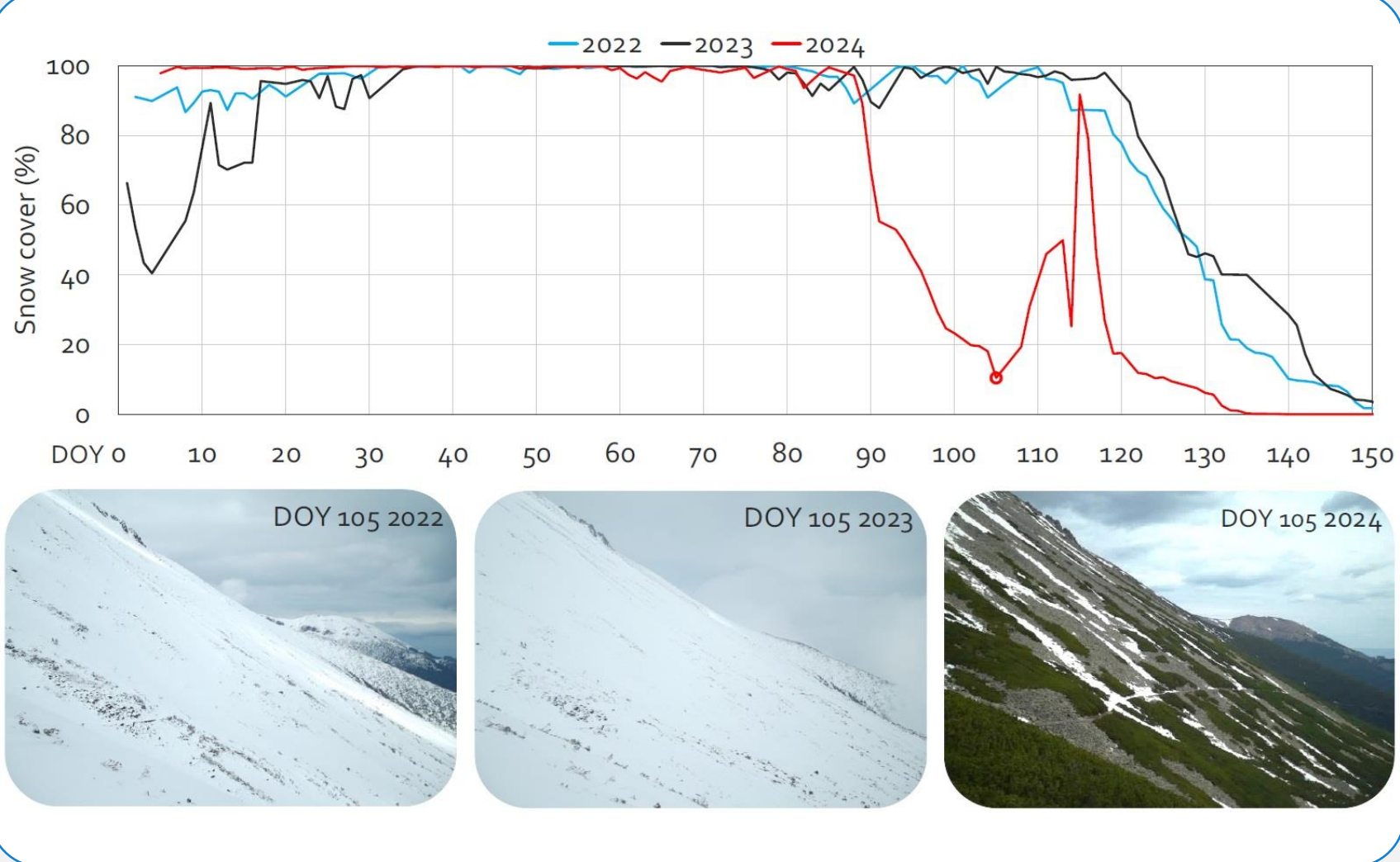


## 2 CLIMATE

January–April 2024 was exceptionally warm, with air temperatures exceeding 1961–1990 normals by 3.7 °C (min), 3.8 °C (avg), and 4.4 °C (max). A false spring followed by late frosts occurred in April.



Despite relatively high precipitation levels, we observed a significantly early and rapid reduction in snow cover in late winter in 2024 compared to previous years.



## 4 TRENDS

Frost damage to high-elevation vegetation can disrupt plant growth, especially when phenological advances outpace the retreat of late-spring frosts.

| Parameter                             | Shift over 1979–2024        |
|---------------------------------------|-----------------------------|
| GDD for BBCH01 in <i>V. myrtillus</i> | <b>–4.8 days per decade</b> |
| GDD for BBCH07 in <i>P. cembra</i>    | <b>–4.7 days per decade</b> |
| Late hard frost below –2.2 °C         | –3.7 days per decade        |
| Snowmelt day                          | <b>–3.6 days per decade</b> |

\*GDD – Growing Degree Days with temperature base 5 °C. Significant trends are set in bold.

## 3 PHENOLOGY

Following the weather conditions, bud development in Swiss pine (*Pinus cembra*) and bilberry (*Vaccinium myrtillus*) was recorded more than a month earlier than in previous years. This early onset of phenophases was subsequently interrupted by an 11-day cold spell starting on April 16, with an average daily temperature of –2.0 °C, an average minimum temperature of –5.3 °C and the occurrence of 3 days, when maximum temperatures did not exceed 0 °C. This episode led to the freezing of buds during the sensitive development stages. While the damaged buds at bilberry were visible directly after the hard freezes, the damage at Swiss pines became apparent over time during flowering. Flowers were undeveloped and did not produce pollen.

*Vaccinium myrtillus*

UNDAMAGED

DAMAGED

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*Pinus cembra*

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## 5 CONCLUSION

This work highlights a growing mismatch between climate-driven cues and actual frost risk for mountain vegetation at the alpine treeline ecotone. We found that the advancement in GDD is outpacing the retreat of the last hard frost, particularly in early-developing species. Although snow cover still provides protection to low-stature shrubs, its diminishing duration may increasingly limit this protective effect in the future. The resulting mismatch could profoundly affect reproductive success, species competition, and trophic interactions.

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