**Melting Mountains: A Focus on the European Alps and Beyond**

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The notion of "Melting Mountains" is very appropriate as a metaphor for mountain regions since it may concern water in both its solid and liquid state and links these to current trends in climate and man-induced global change. In this statement, "melting" can also be considered as a metaphor for "loss" in the sense of melting, sublimation or evaporation of snow, ice, glaciers and permafrost. The melting, sublimation and evaporation of natural snow and ice is apparent and includes the decay of glaciers, snow, firn or permafrost. Current climate change scenarios indicate the rapid acceleration of glacier retreat, which will initially augment river discharge but will considerably reduce discharge once a minimum threshold in glacier volume is attained.

Parallel to this, the scenarios predict that snowfall will decrease over space and time so that snowmelt discharge will also decrease, but seasonality will change. To compensate for the decreases in winter precipitation, especially snowfall, professionals have resorted to produce their own artificial snow to sustain winter ski tourism in many regions over the globe. As such, the loss of artificial snow and ice through evaporation and melting is less evident. Since the production of artificial snow and ice is derived from existing or man-made surface and subsurface water resources in the highest and most vulnerable regions, the water lost by evaporation from a combination of sources (estimated at 30 percent) cannot be transformed into discharge and cause an increasing deficit for groundwater as well as surface resources. The loss of water through artificial snow production exasperates the problem of available water resources and climate change in the precipitation-poor periods. This affects areas in the European Alps as well as Mediterranean mountain regions, even in Turkey, and in the Rockies.

This contribution will therefore focus on glacier, permafrost, natural and artificial snow.

***Glaciers***

Climate change scenarios according to the Intergovernmental Panel on Climate Change (IPCC) indicate that on the one hand precipitation should increase by 25 percent, but that on the other hand temperatures are to increase by between 2 - 4°C depending on the scenario. Temperature increases are expected to be even more severe in the mountains and in winter. This does not mean that we are on the safe side for precipitation, because an increase in precipitation will not compensate for a temperature increase. Under the mildest temperature increase scenarios, the snow season will be menaced, since warmer temperatures will cause more rainfall at the cost of snowfall and a faster decay of any existing snow cover. Under the highest temperature increase scenarios it is expected that the winter season can be shortened by two months in the mountains. This all has important repercussions for glaciers and snow volume. Less snow-rich and warmer winters will mean that glaciers will simultaneously experience a deficit in their accumulation areas and faster melting in their ablation zone as well as increased evaporation and sublimation.

The fact that glaciers are retreating at the fastest rate recorded over the last 100 years is unprecedented and has been investigated by numerous glaciologists. This retreat is now a global phenomenon, although some few regions still exist with glacier advance, for example the Calderone glacier in the Apennines and the Franz Joseph glacier in New Zealand. However, glacier retreat, whether recorded in the Alps, Greenland or Antarctica, is faster than predicted by the majority of climate change models as demonstrated at the European Geosciences Union (EGU) Cryospheric Sciences sessions in Vienna this year.


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predictions indicate that snow duration and extend will be reduced in mountain areas. In the long term this deficit will considerably reduce reservoir volumes and cause a risk for hydroelectric production.

***Permafrost***

Permafrost decay due to sub-surface ice melt associated with global warming is of concern for many mountain areas since it can increase the frequency and magnitude of natural hazards such as rockfalls, landslides and subsurface differential movements. Ice in rock fissures normally has a stabilizing effect – when it melts, weathered material is released more easily and together with the in and exfiltration of water, large rockfalls and landslides can be triggered. At present the permafrost limit is at 2500 m in the European Alps, with climate change this limit is expected to increase and so is the region of impact of natural hazards. Another phenomenon that requires investigation is the destabilizing impact of rapidly retreating glaciers. Where glaciers at one time physically stabilized the valley walls, their lacking support after retreat together with the exposure to large fluctuations in temperature and air can significantly accelerate rock mechanical processes (such as stress release, lack of cohesion, new hydrodynamic pressures and weathering). This causes major risks for infrastructure and areas frequented by tourists.

Other concerns are the direct effects of permafrost melting threatening the stability of infrastructure such as railways. A recent study of the Qinghai - Tibet railway with an average altitude of 4000 m shows that rapid permafrost decay is already menacing the railways foundations in many places. Such examples are not unique and will affect other regions in Europe that are under higher human pressure like the Narvik railway in Norway and the Glacier Express in Grisonia/Switzerland.

***Snow***

Climate change scenarios prognoses important effects on snowfall (as mentioned in the glacier section) so that less snowfall is expected at higher altitudes. This will have important impacts on river discharge as well as snow-related economy such as winter tourism. Since the actual trend in the European Alps shows a decrease in the total winter precipitation including snowfall, the ski industry is depending more and more on the production of artificial snow over approximately 25 percent of its pistes. This has major effects on the cryosphere. In contrast to natural snow ablation that originates from snowfall, artificial snow ablation concerns artificial snow that originates from water reserves that have not been replenished by snowfall. Natural snow ablates by a combination of processes that depend on a combination of meteorological and snow physical factors, while artificial snow instead is directly lost to a large extent via evaporation during the production of snow. The remaining snow is lost from stagnating snowmelt water on highly impervious surfaces or from high altitude reservoirs constructed to store water for snow production. The deficit in available discharge is slowly becoming a reality. In some regions in the French Alps, conflicts between drinking water uptakes and uptakes for artificial snow production exists. Also, the winter discharge of alpine torrents has been reduced by between 40 – 70 percent due to this water abstraction and will not re-enter the water cycle in its full amount due to high probable losses en route.

In summary, much more monitoring and measurements are required to better understand the current situation, and together with reconstructions from the past, projections for the future can be ameliorated. On the short term, prognoses can be based on monitoring, for example on a monthly or seasonal basis but for longer term strategic decisions, reconstructions of the past are necessary. Depending on the data available(e.g. based on air photos, moraine stages, paintings and chronics), the reconstruction of glacier variability will be easier than the reconstruction of snow cover and snow depth which is temporarily and spatially much more variable and difficult to capture in the pre-remote sensing era. Human influences based on population projections or developments in tourism, hydro-electricity, industry and agriculture in mountain areas need to be considered.

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