WORKSHOP REPORT

ARCTIC WINTER HEATWAVES: AN EVER-INCREASING PHENOMENON CHALLENGING THE ARCTIC ENVIRONMENT AND LOCAL COMMUNITIES

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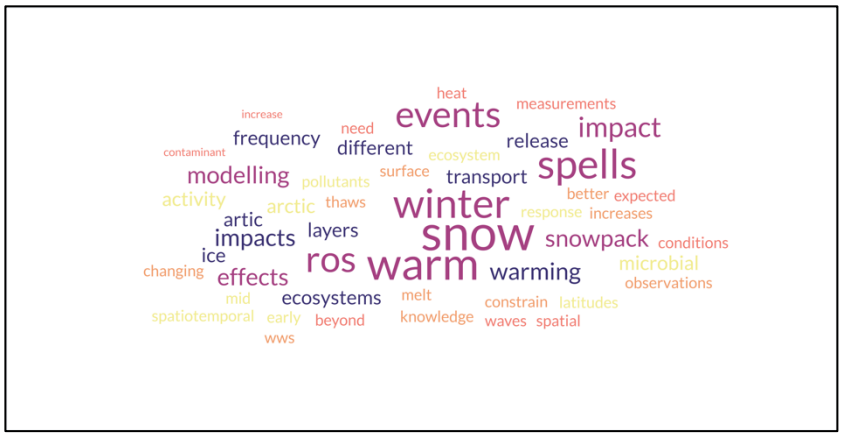
1. RESEARCH PRIORITY TOPIC OVERVIEW

Rising temperatures are increasing the frequency of extreme events, such as summer and winter heatwaves. Such heatwaves, characterized by persistent warm and humid air masses known as "warm spells", bring periods lasting for several days of unusually high temperatures and often result in "rain-on-snow" events (ROS). This phenomenon represents an emerging challenge to the Arctic ecosystem and its inhabitants, affecting environmental, ecological, and socioeconomic aspects. Despite their sporadic nature, winter heatwaves impact both coastal and inland areas of the Arctic region. They influence both the cryosphere and snow-free terrestrial ecosystems by altering the snow-albedo feedback, accelerating the hydrological cycle, triggering the snow and ice microbial communities' activity, increasing heat transfer to the permafrost, causing early remobilization of contaminants deposited during winter, and modifying the atmospheric dynamics and composition. Studying the effects of these heat waves throughout the snow accumulation and melting periods is crucial for understanding their impact on the winter Arctic environment.



World cloud exercise from a brainstorming session among the invited participants at the workshop when they were asked to include a maximum of three words related to Arctic heat waves

These extreme events stem from meteorological conditions that transfer warmer and wetter air masses northwards. Over the last decade, these events have become more common due in part to reduced sea ice coverage and thickness. Oceans with thinner or no sea ice coverage warm faster, promoting water evaporation and altering atmospheric circulation, which leads to more recurrent and intense heatwaves. In terrestrial ecosystems ROS events have a pronounced effect on snowpacks. When rain falls on snow, it creates hard refrozen crusts or percolates through the snowpack, forming pools at the snowpack base. These processes alter the snow-albedo feedback and accelerate the hydrological cycle associated with snow melting. Therefore, winter heatwaves and ROS events disrupt the snow season by impacting snow accumulation, moistening, and ripening processes, and triggering water runoff through the snowpack. Ultimately, this water presence leads to state transformations and heat transfer processes at the base of the snow pack, resulting in soil warming and permafrost thawing

The workshop was organized on 11-13 June 2024 in Montegrotto (Padua), Italy to develop a multidisciplinary strategy to enhance and promote the study of winter warm spells and present these findings to the ICARP IV process. Although war-spell and heat waves occur in also during summer, the increasing frequency and the impact of the winter events are more severe since they are able to directly impact and change the cryosphere environment by changing the liquid water content and the refreezing amounts with consequence in snow stratigraphy and temperature, albedo, runoff, microbial activity, contaminants release ect.. The objective was to create a roadmap for investigating the impact of winter warm spells on the Arctic environment and to highlight their potential socioeconomic effects on local communities and activities in the Arctic region. The event, organized by the Institute of Polar Science (ISP-CNR, Dr. Andrea Spolaor) in collaboration with the Institute of Atmospheric Pollution Research (IIA-CNR, Dr. Roberto Salzano). It brought together experts and researchers from various European and non-European institutes specializing in the polar environment. Topics covered by the invited participants included the impact of Arctic winter warm spells on snow chemistry and aerosol composition, including anthropogenic contaminants (Spolaor, Cairns, Wang, Barbaro, Ardini); snow physics (Van Pelt, Luks, Salzano, Valt, Scoto); snow albedo (Pirazzini, Salzano, Cappelletti); composition and microbial activity in the snow (Larose, Keuschnig); remote sensing of the snow cover (Salzano); and the role of snowmelt in surface and subsurface hydrology (Diogo Costa, Moser, Guyennon). The scientific meeting aimed at deepening discussions about the consequences and activities necessary for understanding the impact of winter warm spells on the Arctic environment and related socioeconomic aspects.

2. RESEARCH PRIORITIES, NEEDS AND LINKS WITH ICARP IV TOPIC AREAS

Research Priority 1: *Will Winter Arctic Warm Spell Events in the Arctic Become More Widespread, Frequent and Intense in a Changing Climate?*

The priorities for this emerging question implies the following needs:

a. **Develop a shared definition of Arctic Winter Warm Spells (AWaS)**: Establish a standardized definition that is relevant across the entire Arctic region that is applicable to the whole ecosystem. Standardize several existing definitions (focused mainly on human health, marine environments and ecosystems located at mid-latitudes), with a set of indicators aimed at assessing the impact of extreme events on the cryosphere. This definition will facilitate consistency, clarity, and communication across various disciplines and regions.

b. **Access to long-term, intercomparable, and harmonized datasets and observations**: Increase both in-situ and remote data to study the frequency, duration, and intensity of AWaS from a pan-

Arctic perspective. These datasets should include Essential Climate Variables (ECV) to ensure comprehensive monitoring and analysis. Consistent and high-quality data are crucial for understanding long-term trends and variations.

c. **Improve model performance**: Enhance climate and numerical weather prediction model to better simulate AWaS at the finest possible scale, ensuring they can accurately represent spatial variability. This improvement is essential for making reliable climate projections and understanding future scenarios. High-resolution models will help predict localized impacts and aid in developing targeted adaptation strategies.

Link to ICARP IV Topic Area 2: Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses

Observing and Predicting Climate Dynamics: The need for standardized definitions, harmonized datasets, and improved climate models directly supports efforts to observe and predict future climate dynamics, including the occurrence and intensity of winter warm spells. Extreme events are now defined for specific domains such as Health, Marine and Ecosystems. A cryosphere-oriented definition is highly recommended to emphasize how cryospheric components are impacted by extreme events, as the cryosphere interacts with numerous other spheres and, in turn, influences various other environmental systems.

Research Priority 2: *Process-Based Understanding of Winter Warm Spells on the Arctic Environment at Event and Seasonal Timescales.*

The knowledge required for assessing the impacts of extreme events on the cryosphere needs:

a. **Source and composition of air masses**: Investigate the origins and characteristics of air masses that lead to winter warm spells. Understanding the pathways and properties of these air masses will reduce uncertainties in predicting future events and their impacts.

b. **Precipitation phase change**: Study how winter warm spells affect the phase change of precipitation (from snow to rain or mixed precipitation). This has significant implications for the hydrological cycle, snowpack dynamics, and overall Arctic climate system.

c. **Improve snowpack representation in Earth system models**: Enhance the representation of multi-layered snowpacks in Earth system models, using new and existing observational data. Accurate snowpack modelling is crucial for predicting melt, refreezing and runoff water contributions and changes in albedo.

d. **Impact on the cryosphere**: Examine the effects of winter warm spells on the physical and optical properties, chemistry, and biology of the cryosphere. This includes studying changes in sea and lake ice, snowpack, permafrost, and glacier dynamics. Understanding these impacts is vital for assessing the broader implications for the Arctic environment.

e. **Impact on hydrology**: Analyze how winter warm spells influence hydrological processes, such as flooding and ice jams. Changes in river and stream flows can have downstream effects on ecosystems and human communities.

f. **Nutrient and contaminants (re-)mobilization and microbial signatures**: Investigate how winter warm spells affect the biogeochemical cycles, including the mobilization of nutrients and pollutants, the translocation of microbes as well as their altered activity and function. These

processes are important for preserving impurity records that are useful climate and environmental proxies and understanding ecological impacts.

g. **Increased occurrence of avalanches**: Assess how winter warm spells contribute to the frequency and intensity of avalanches and landslide. This is crucial for hazard prediction and mitigation, especially for communities and infrastructure in avalanche-prone areas.

Link to ICARP IV Topic Area 2: Topic Area 2: Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses

Process-based Understanding**:** Studying air mass sources, precipitation phase changes, snowpack dynamics, and impacts on the cryosphere contribute to understanding how these processes influence Arctic climate dynamics and ecosystem responses.

***Link to ICARP IV Topic Area* 7: Technology, Infrastructure, Logistics, and Services**

Infrastructure and Services**:** Addressing the technological and logistical challenges of monitoring and predicting winter warm spells and their impacts supports advancements in technology, infrastructure, logistics, and services necessary for effective Arctic research and adaptation efforts.

Research Priority 3: *Knowledge Co-Creation of Current and Future Downstream Consequences on Ecosystems and Society together with Arctic Communities.*

The involvement of indigeneous communities is the right strategy for the definition of:

a. **Current and future effects on terrestrial ecosystems**: Study the impacts of winter warm spells on terrestrial ecosystems, such as the formation of ice layers that affect reindeer (and potential other Arctic herbivores) herding, burrowing animals, and downstream habitats, as well as vegetation changes. These effects can have profound implications for biodiversity and the livelihoods of Indigenous communities.

b. **Current and future effects on marine ecosystems**: Examine the consequences of winter warm spells on marine ecosystems, including sea ice, coastal and fjord regional ecology, coastal erosion, and freshwater-marine coupling. Understanding these impacts is essential for managing marine resources and protecting coastal habitats.

c. **Related hazards for local populations**: Identify the hazards posed by winter warm spells to human populations, such as challenges to winter mobility, tourism, water and food safety, security, and energy production. Addressing these hazards requires comprehensive risk assessments and the development of mitigation strategies.

d. **Developing adaptation strategies**: Create and implement adaptation strategies to help Arctic communities and ecosystems become more resilient in the face of changing climate conditions. These strategies should be co-developed with Indigenous communities to ensure they are culturally appropriate and effective.

e. **Knowledge Co-production with Indigenous communities**: This will involve incorporating their traditional knowledge and perspectives to enhance the relevance, applicability, and accessibility of research outcomes. Collaborative approaches will foster resilience and sustainability in the Arctic region.

Link to ICARP IV **Topic Area 3: Understanding the Vulnerability and Resilience of Arctic Environments and Societies and Supporting Sustainable Development**

Understanding Vulnerability and Resilience**:** Assessing the impacts on terrestrial and marine ecosystems, hazards to human populations, and developing adaptation strategies aligns with understanding the vulnerability and resilience of Arctic environments and societies. Knowledge co-production with Indigenous communities ensures the relevance and effectiveness of adaptation strategies.

Link to ICARP IV **Topic Area 5: Co-Production and Indigenous-led methodologies**

Co-Production and Indigenous Knowledge**:** The recognition of the necessity to co-develop with Indigenous communities for research and adaptation strategies directly supports Topic Area 5, which focuses on co-producing knowledge and including Indigenous-led methodologies.