Detection and attribution related to anthropogenic climate change in the cryosphere from a global perspective

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The cryosphere on earth is close to melting conditions. As a consequence, climate-related changes in snow and ice can be spectacular and well recognisable even for a broad public. Together with information from deep ice cores, widespread knowledge about the reduction of arctic sea ice or about the worldwide shrinking of mountain glaciers indeed constitutes a fundamentally important component of the now-existing awareness with respect to anthropogenic climate change.

Early detection strategies are among the primary goals of snow and ice monitoring in global climate-related observing systems (GCOS 2009). Criteria considered in such detection strategies are (a) rates of change and acceleration trends, (b) present conditions in relation to pre-industrial variability ranges and (c) spatial patterns of change as compared to modelled climatic scenarios. The following briefly mentions the most prominent cryosphere indications with their signal characteristics (detection of change, attribution with respect to causes and impacts) as related to climate change (cf. IGOS 2007, the overview in UNEP 2007 and a summary of most recent research on key aspects of cryosphere change by UNEP 2009).

**Continental ice sheets:**
Greenland and Antarctica are important drivers in the climate system. Slow changes in their mass balance and flow are complex and relate to centennial to millennial time scales, making attribution to causes difficult. Modern altimetry and gravimetry technologies are now strongly improving detection possibilities at shorter (decadal) time scales. This is especially important in view of possible ice-sheet instabilities from recent flow acceleration of outlet glaciers with beds far below sea level and corresponding surface draw down of large catchment areas. Attribution to impacts primarily relates to long-term sea level rise and atmosphere/ocean circulation.

Probably the clearest and most significant cryospheric information on past climate change is from ice core analysis in Antarctica and Greenland. Especially high resolution GHG and isotopic ice core records reaching 105 to 106 years back in time are fundamental for detection/documentation of past climate changes and for attribution of corresponding causes. They clearly show the extraordinary level of modern GHG concentrations and contain quantitative evidence from the past about possible anthropogenic effects.

Borehole temperature profiles in cold firm/ice provide independent checks on records of isotopic temperature proxies and reflect changes in atmospheric (annual) temperatures. If more systematically monitored (change of temperature at depth with time) and analyzed (numerical modelling of heat diffusion and flow effects), they would be important for detecting and attributing atmospheric warming as compared to conditions over very long time periods in the past.

**Sea ice:**
Via its albedo effects and its influence on the formation of deep ocean water, sea ice relates to the climate system with important interactions and feedbacks. The continued decrease in Arctic sea ice extent, age and volume and especially the sudden shrinking to a new record low in 2007 is probably the most dramatic recent change in the Earth’s cryosphere, taking place at a rate which by far exceeded the range of previous model simulations. Sea ice around Antarctica shows little change – a fact, which is still not fully understood. Continued sea ice monitoring is a key element of detection strategies for global climate change.

Attribution to causes is complex as the development is influenced by higher air and ocean temperatures and by particular ocean circulation patterns (acceleration of the transpolar drift in the case of the arctic ocean). The development of the arctic sea ice is of great importance.
Annex 3: Extended Abstracts - Haeberli

concern, because attribution with respect to impacts involves aspects of highest global importance such as global albedo and ocean circulation as well as navigation through the NW- and NE passages.

**Glaciers and ice caps:**
The shrinking of mountain glaciers and (smaller) ice caps is among the clearest and most easily understood evidence in nature for rapid climate change at a global scale and, hence, constitutes a key element of detection strategies for global climate change. Especially mountain glaciers are considered to be “unique demonstration objects” concerning ongoing climate change. Mass balance monitoring shows a striking acceleration of loss rates since the mid 1980s. Glacier extent (length, area) may have reached “warm” limits of pre-industrial (Holocene) variability ranges and is far out of equilibrium conditions at many mid- and low-latitude sites.

Attribution to atmospheric (summer) temperature rise as a primary cause is relatively safe as air temperature not only relates to all energy balance factors but also to rain/snowfall and hence accumulation. Complications are due to variable englacial temperature conditions (cold, polythermal, temperate firn/ice) and strong feedbacks (positive: albedo, elevation/ mass balance; negative: adjustment of geometry, debris cover). Attribution to impacts involves landscape changes, runoff seasonality, hazards (lake outburst floods, slope instability) and erosion/sedimentation cascades (debris flows, river load, lake filling etc.). Modern satellite-based glacier inventories with digital terrain information (SRTM, global ASTER DEM since 2009) now enable documenting and modelling large glacier ensembles in entire mountain ranges.

**Lake and river ice:**
The duration of ice on lakes and rivers is an indicator of winter and lowland conditions, complementing summer/altitude evidence from mountain glaciers. Shortening of the season with lake and river ice in wide northern regions can be generally attributed to “winter warming” effects. Highly complex influences from short-term weather patterns (wind, precipitation/snowfall) and limnological conditions (water circulation, groundwater influx, lake turnover, etc.) make attribution to exact causes and modelling difficult. Trafficability and ecosystem evolution are primary aspects of attribution to impacts.

**Ice shelves:**
The rapid disintegration and collapse of ice shelves in the Antarctic Peninsula and the almost complete disappearance of the Canadian ice shelves on Ellesmere Island are well-documented changes. The anticipated progression of ice-shelf collapse towards colder parts of Antarctica forms a key element of cryospheric detection strategies.

Complex air/ocean/ice interactions make attribution to exact causes difficult but “warming” as a general cause appears to be evident. Attribution to impacts concerns high-latitude marine ecosystems, the stability of outlet glaciers and ice streams in Antarctica and with this indirectly long-term sea level.

**Permafrost:**
Perennially frozen ground at high latitudes is an important feedback element in the climate system (CH\textsubscript{4}, surface drainage, vegetation). Important information on rising ground temperatures as compared to historical conditions can be derived from changing subsurface temperatures and from heat flow anomalies in deep boreholes. Observed changes in active layer thickness must be complemented by measurements of subsidence from thaw settlement in ice-rich materials and so far do not show clear trends. In both cases, attribution to climatic causes is complicated by multiple interactions of frozen ground with vegetation, snow and surface water. Attribution to impacts involves large terrestrial ecosystems and living conditions (water resources, infrastructure, hazards) at high latitudes and high altitudes.

**Ice patches/miniature ice caps:**
Important climatic information exists from cold/old ice patches/miniature ice caps not usually described in cryosphere overviews (Farnell et al., 2004; Haeberli et al., 2004). Dating of organic matter from disappearing ice patches shows that ice (and summer air temperature?) conditions without precedence during the past 5 to 8 millennia have now been reached in sub-arctic and alpine regions. Detection and attribution need improvement.

**Snow cover:**
With its large area, small volume and
correspondingly extreme spatio-temporal variability, snow is a “nervous interface” between the atmo-, litho-, cryo-, hydro- and biosphere. In fact, snow cover is an important feedback in the climate system rather than an ideal indicator of change. Observed trends (decreasing spring snow extent in the northern hemisphere) point to some effects from warming but remain vague. Attribution to impacts concern many parts of the climate systems – especially cryosphere components and the water cycle.

References


