Mountain Partnership

Mountains as Early Indicators of Climate Change

Proceedings of the International Conference, 17-18 April 2008, Padova, Italy

Crowfoot Glacier, Rocky Mountains

UNEP

EvK2CNR

EURAC research

Proceedings of the International Conference on

Mountains as Early Indicators of Climate Change

It is not the mountain we conquer but ourselves.

Edmund Hillary

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Foreword

Every mountain range around the world has its own characteristics and feature. They all host a unique environment, which is embedded in a complex natural system. Mountain ranges are also confronted with various threats of which climate change is now perhaps the most sobering.

Mountain ecosystems are emerging as highly sensitive such that even small impacts can have profound implications on their ecology and economically-important nature-based services. Researchers from a wide range of disciplines are striving to understand these relationships mindful that climate change is set to make the sustainable management of ecosystems ever more complex.

UNEP, though its office in Vienna, is the global Environmental Reference Centre (ERC) of the Mountain Partnership and actively works to factor environmental sustainability into the initiative's strategic planning and activities.

The ERC's role is to assist access by the Mountain Partnership to UNEP's expertise in the six thematic priorities of its Medium Term Strategy including climate change.

UN General Assembly Resolution 62/196 requested "the scientific community, national governments and inter-governmental organisation to collaborate with mountain communities to jointly study and address the negative effects of global climate change on mountain environments."

In response to this call for action, UNEP promoted and organized the conference on "Mountains as Early Indicators for Climate Change" in order to exchange state-of-the art research on climate change and mountains and to evolve understanding on the ecosystem services they provide to the globe not least water.

The outcomes of the conference are presented in this publication. They underline the acute vulnerability of mountains in a climate constrained world and the urgent need for coordinated and concrete adaptation strategies if they are to continue to contribute to achieving, for example, the UN’s Millennium Development Goals

Points that more than 190 nations must take on board when they meet at the crucial UN climate convention meeting in Copenhagen, Denmark later this year to Seal the Deal on a compressive, equitable and scientifically-credible new agreement.

Achim Steiner
UN Under-Secretary General
Executive Director

United Nations Environment Programme (UNEP)

Respected authorities and friends, allow me to greet you on behalf of the Ev-K2-CNR Committee, an organization which is marking its 20th anniversary this year. As I have always said and as many of you know, this organization was created by Prof. Ardito Desio, a great geologist, geographer and explorer who led Ev-K2-CNR towards its original Earth Sciences vocation. In the subsequent 20 years, the Committee has evolved and expanded its fields of investigation to include human physiology, medicine, anthropology, ethnography and renewable technologies: an organization which is becoming increasingly multi-disciplinary and progressively more aware of the importance of certain pressing issues such as climate change.

Today, I received a national flag to carry to the summit of Mt. Everest. While I will not be the person planting that flag, Ev-K2-CNR will soon be taking advantage of its decades of mountaineering/scientific experience which have led to development of a team of skilled technicians and climbers. Silvio Mondinelli, Marco Confortola and Michele Enzio are already in Nepal, preparing for their ascent of Everest, where they will carry this flag and this weather sensor to the summit. I will join them to do what I am experienced in: oversight of logistics and organization of both the technical and scientific elements. It was my passion for mountains that led me to meet Prof. Desio over 20 years ago. My skills as a climber, coupled with his scientific expertise took us to the Karakorum to continue the investigations that Prof. Desio had begun during the successful Italian expedition in 1954 on Mt. K2, a mountain I consider more fascinating albeit lower than Everest ever since I summited it myself.

Moving back into the present and to the important topics of this conference, today we are certain of the role of mountains as privileged indicators of global climate change. I still remember the difficulty we had some years ago, in early 2000, of confirming the need to see mountains recognized as non-marginal with the declaration of an International Year of Mountains. Our friends at UNEP and FAO will surely also remember our efforts in this sense. Mountains are commonly considered nice places to live or visit, but they have traditionally lacked a significance which today we are finally ready to bestow upon them.

It was back in 2000 that some basic figures were released on the world's mountains: 48% of the Earth's surface is at or above an elevation of 500 m, 27% is above 1000 m, and 11% is above 2000 m. 10% of the world's population lives in mountainous areas. Surely these figures confirm that mountains are not marginal. Therefore, as Mr. Leone has mentioned and today's speakers will confirm, through this conference, we aim to understand the extraordinary wealth of the world's mountains, watersheds, deposits and water reserves and we will take a close look at, for example, the Tibetan Plateau's problems regarding atmospheric circulation.

The Ev-K2-CNR Committee is proud of its team of researchers, including those present here today: Sandro Fuzzi, Paolo Bonasoni and Gianni Tartari, who have been skillfully working with us on these topics for 15 years. In confirmation of this, just yesterday a High Elevation special interest group was created within the framework of the CEOP program.

This also demonstrates that mountains cannot be considered as marginal but as also important from a political and cultural point of view, even if at times it would seem otherwise. The importance of a region is often linked to the amount of electoral votes it can bring in and the error is often made to disregard mountainous areas because of their limited political clout. Today we must promote the knowledge that these areas are amongst the most important in the world for helping us better understand the dynamics of our planet and the effects of climate change, just as the UN has pointed out.

What else is there to say? Ev-K2-CNR is a small organization affiliated with the Italian National Research Council, a relationship which was institutionalized about a year ago with the creation of an external CNR research unit within the Committee itself. We can count about 80 scientists and administrators whose work is dedicated full time to high altitude within this context. We are proud to be seen practically as an agency, and certainly as in international organization with staff working around the world. We are good at doing what we love, or at least what I love: working for the mountains. I am confident that we are working for them in the right way. Thank you.

Agostino Da Polenza
President Ev-K2-CNR Committee

Ecosystems of cold environments are assumed to be very sensitive to higher temperatures and evapotranspiration rates, which will occur as a consequence of global warming. Indeed, high altitude and high latitude communities are severely limited by low temperatures (lack of energy), so any variation to this parameter should result in relevant ecosystem responses.

Among the different types of ecosystems on mountain ranges, forests are surely one of the most important as they provide essential services to human communities (e.g. runoff control, wood production, carbon storage, maintenance of biological biodiversity, etc.). Any change in structure or functionality of forest ecosystems will impact on all of these services.

Assessing possible forest ecosystem changes is a demanding task for several and often inter-correlated reasons such as: uncertainty over future scenarios of air temperature changes, particularly in mountain regions; spatial-temporal heterogeneity of the changes; species-specific responses and sensitivity to different temperature values considered as annual, seasonal, daily means and extremes; a number of processes that are temperature-mediated, such as frost resistance, mineral nutrient supply, photosynthetic rate, rate of cell division, rate of mitochondrial respiration; variation in snow cover patterns and soil temperature; disturbance introduced by direct (e.g. livestock grazing) or indirect (e.g. nitrogen depositions) human activity.

Some of the most relevant effects of climate change in cold ecosystems appear to be related to the advancing of the treeline position towards higher altitudes and latitudes, melting of the permafrost with modification to the water regime, and an increase in the number and severity of fires in the boreal forests.

However a precise quantitative assessment of the changes to ecosystem services is far from being delineated.

The aim of this Conference is to present the most up-to-date results concerning the indications of global warming that are being monitored by the scientific community in mountain areas.

The invited speakers have dealt with different ecosystems and mountain ranges, but a common signal has emerged: climatic conditions and ecosystems are changing. This will force us to revise our future expectations of a stable and constant use of natural resources. The University of Padova has proudly collaborated with the other organizers of the conference and looks forward to continuing its engagement in research on mountain sustainable developement.

Tommaso Anfodillo
Marco Carrer
Davide Pettenella
Dip. TeSAF – University of Padova

The environmental change, which may be induced by those phenomena also known as “climate change” in different regions of the world, has become a primary item on the global agenda. Much attention has been recently devoted to this modification in the climate, many studies started and several environmental cooperation initiatives launched. Still, a growing attention is developing on how climate change is likely to impact on a few particular zones of special environmental importance, among which mountains certainly play a central role.

The expected impact of climate change on the mountain environment is a primary concern for the Italian Ministry for the Environment, Land and Sea. It is widely known how important the mountains are for a country like Italy, where more than 50% of the total surface is covered by mountain ranges and specific measures for mountain areas are envisaged in the national constitutional law, though it was written few years after World War II. The Italian effort to support and enhance scientific research on “climate change”, its expected impacts, and the possible strategies to tackle it is widely known, as well as Italy’s strong commitment in several international cooperation initiatives in favour of mountain areas.

Another important issue on which the Italian Ministry for the Environment has been working is the need of a stronger coordinated action among different stakeholders living in mountain regions. In these areas, in fact, international cooperation among scientific institutions has been fostered and long-term links have been deepened and new ones started between the scientific and the policy makers’ communities. Appropriate policies for mountain areas can only be achieved if based on robust scientific knowledge – even more so in the field of “climate change” which is subject to many variables.

Mountain ranges host sensitive natural environments, which need to be analyzed with particular attention and, as demonstrated by the contributions brought forth by the distinguished participants in this conference, can rightly be seen as early indicators of environmental change. What happens in the mountains is likely to happen also in other regions; therefore, it can be extremely wise to start studying these areas with the aim to identify critical points and issues, which go far beyond the sole mountain environment.

Our attention has always been very focused on the mountains: Italy participates in the Alpine Convention; it supports the development and capacity building process of the Carpathian Convention and other international initiatives of cooperation for mountain areas; it promotes projects focusing on the science that studies the phenomena linked to“climate change” and its peculiar impact on the mountain environment – that is in a field where substantial improvements in the comprehension of the phenomena are needed.

Mountains represent a unique environmental, economic and cultural scenery. The Conference "Mountains as early indicator of climate change" held in Padua, which we had the honour to promote, has highlighted the role that the mountains can play as a natural laboratory in better understanding the impact of "climate change", even in regions that are not mountainous. In this line, the Italian Ministry for the Environment has already participated in cooperation initiatives and projects focused on mountain areas, some relevant results of which have been presented during the Conference itself.

In this spirit, I welcome the present volume collecting the valuable contributions of the speakers who took part in the Padua Conference.

I wish that this and other similar initiatives can follow in the near future and their outcomes be disseminated, stressing once again the role that mountains can play in this and other fields.

Paolo Angelini
EURAC Research

Preface

The vulnerability of ecosystems other than mountain is well known to the public as it its well publicized. What is not so evident is that mountains are very sensitive to small temperature changes. Changes of alpine glaciers, in high altitude lakes, along the upper tree line or of the mountain vegetation in general can provide early indications for climate change.

The UN General Assembly states in its 2008 resolution on sustainable development of mountainous regions that "*mountains provide early indications of global climate change*."

To discuss such early indicator role on a scientific level, the international conference on "Mountains as Early Indicators for Climate Change" was held at the University of Padua, Italy, on 17 and 18 April 2008.

Scientist with different backgrounds and coming from different parts of the world presented their research and open questions regarding the mountains' role in a changing climate. The conference was jointly organized by UNEP Vienna, Envornmental Reference Centre of the Mountain Partnership, the Ev-K2-CNR Committee, the University of Padua and in collaboration with the European Academy in Bolzano, Italy.

The conference received the high patronage of the President of the Italian Republic and of the Ministries for Foreign Affairs, Environment, Land and Sea and of Regional Affairs as well as the support from the Region Veneto and the Province and Municipality of Padua.

The overall objective of the conference was to discuss the role of mountains as early indicators of climate change and the impact of global warming on mountain ecosystems. Specifically, the actual state and the open gaps of scientific research were presented on several early indicators and in different mountain regions around the world. The conference followed the UN General Assembly's call, which in its resolution encourages "*the scientific community, national governments and inter-governmental organisation to collaborate with mountain communities to jointly study and address the negative effects of global climate change on mountain environments*."

Climate change effects are not limited to mountain regions in facts mountain ecosystem services (such as climate regulation or water purification) extend beyond their geographical boundaries and affect the continental mainland. As a result, changes in the mountains' ecosystem services have direct consequences on the densely populated areas in the lowlands.

At the moment, only few data from high mountain stations are available. Mountain regions provide unique opportunities to detect and analyze global change processes and phenomena.

In fact, high mountain stations are locations where atmospheric background conditions and global change processes can profitably be studied by means of continuing monitoring activities. Maintaining high mountain stations however is costly and their valuable return is often not evident to the funding bodies. Therefore, the network of high mountain stations around the globe is loose. Moreover, data provided by the stations is often discontinued and not long-term. The conference emphasized the importance of extending the network of high altitude stations at least in the main mountain regions around the world in order to acquire a considerable, comparable and long-term data set.

Finally, the conference experts recommended an integrated approach considering the importance of addressing all the aspects of climate change effects in mountain regions. Therefore, the experts stressed the necessity of a consultative process ensuring a harmonized regional strategies for adaptation to climate change effects.

UNEP Vienna
Environmental Reference Centre Mountain Partnership

▲ *Glaciers on retreat. Aletsch Glacier, Switzerland*

Mountain Climate Change: Overview of Snow Cover and Glaciers

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University of Colorado, Boulder, USA

Abstract

Fluctuations of the Earth's snow and ice cover provide one of the most visually obvious and dramatic examples of climate change. Direct and indirect measurements of air temperature over past centuries indicate periods of both cooling and warming, although in the most recent decades the Earth, in almost all locations, has experienced a dramatic warming trend. There is also evidence that climate warming in some mountain areas has exceeded that measured at lower elevations. Some ice core records indicate that the last 50 years have been the warmest within the last 1000 years. It is not surprising that snow and ice cover have been responding to this trend of increased warming. Although glaciers exist at both high latitude and high altitude, it is the latter, the mountain glaciers, which are most important with respect to water resources. Glaciers in virtually all regions of the world have been shrinking in area since the end of the Little Ice Age, or since about 1850. However, in apparent response to the more recent significant increases in air temperatures, the retreat of glaciers has greatly accelerated. This paper provides examples of glacier retreat trends as well as decreasing trends in seasonal snow cover. The accelerating loss of mountain snow and ice cover impacts society in many ways including winter recreation, tourism, water resources for agriculture and human consumption, hydropower, and management of hazards. Accurate predictions of the response of mountain snow and ice reserves to future climate change patterns will be essential to successful resource planning in many regions of the world.

Keywords: Snow Cover; Glaciers; Climate Change

If we look at the historical temperature records, certainly in previous millennia, we interpreted what we observed in terms of solar variability and volcanic eruptions and consider those to be accounting for most of the changes. In more recent era, there were still indirect measurements, but based on such things as tree rings and ice cores. In most recent decades, we have the possibility to directly measure temperature changes and the response of snow covers and glaciers, which provide certainly one of the most visually obvious evidences of climate warming.

Since the 1970s, a rapid increase in temperature can be observed. This increase is thought to be resulting from an enhanced greenhouse effect driven by increased carbon dioxide in the atmosphere. The increase has been strongest in the northern latitudes, whereas it is weaker in the low and southern latitudes. In general, temperature changes in the mountains have been comparable to those observed at lower elevations. However, there are some striking exceptions, where mountain temperatures have risen at rates approaching twice that of lower elevations.

The long-term temperature record of Sonnblick, Austria shows one example. This record shows an increase of about 1.5°C, which is twice the increase of the average surface air temperature in the northern hemisphere. Two possible causes are the snow albedo feedback and higher night time cloudiness. The more snow is melted, the more bare ground is exposed, resulting in a lower albedo (reflectivity) and greater absorption of solar radiation leading to higher temperatures. This in turn leads to more available heat energy and finally to additional snow melting. An increase in night time cloudiness would reduce the outgoing of long-wave radiation leading to a higher daily mean temperature at higher elevations. Whether either of these mechanisms is to be the reason for greater temperature increases at high elevations is still under discussion.

Most of the glacier ice, outside Antarctica, exists in the northern hemisphere. In addition, the northern hemisphere seasonal snow cover represents about 98% of the global snow extent and at its seasonal maximum it may exceed 50% of the northern hemisphere land surface (Armstrong and Brodzik, 2001). Seasonal snow cover plays an important role as a climate change variable due to its influence on energy and moisture budgets. This land surface characteristic is responsible for the largest annual and inter-annual variations in albedo leading to the important temperature – albedo feedback mechanism. Therefore, realistic simulation of snow cover in models and forecast schemes is essential for the correct representation of the surface energy balance (including soil heat flux), winter water storage, and year-round runoff.

Figure 1 shows the inter-annual variability of the Snow Covered Area (SCA) in the northern hemisphere as measured by satellites. At its maximum, the SCA is close to 50 million km^2 and drops than to a minimum of only a few million km^2 during summer. Evaluation of the data in *Figure 1* shows that the snow covered area has been shrinking over the last few decades. Measurements based on visible satellite techniques indicate that the SCA in the northern hemisphere is shrinking by 1.5% per decade. Measurements from passive microwave based remote sensing show a shrinking of 0.7% per decade. There is, however, variability in the shrinking of SCA within dif-

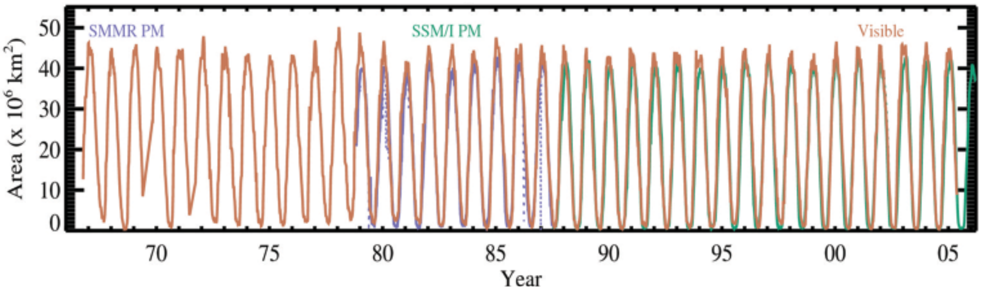
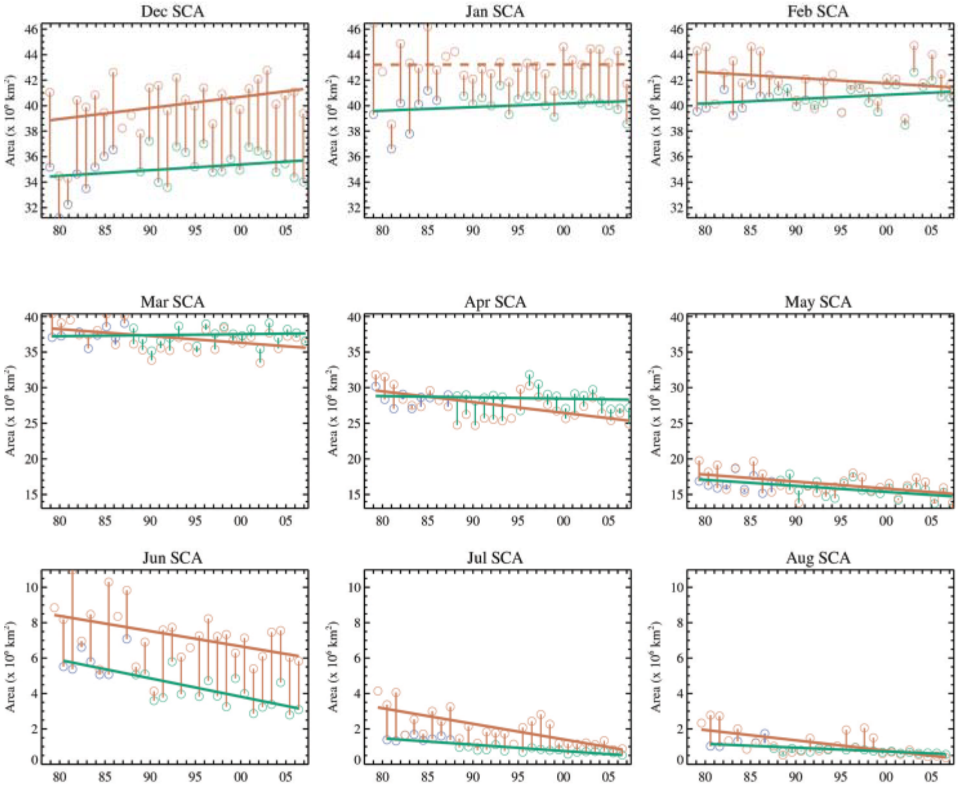


Figure 1: Northern Hemisphere Snow Covered Area (SCA) Time Series based on two remote sensing techniques: Visible (1966-2006) vs. Passive Microwave (SMMR; 1978-2006) (Source: National Snow and Ice Data Center - Boulder).

ferent regions of the northern hemisphere. If we look at North America, the SCA decreased by 2.1% per decade (visible data) and 1.2% per decade (microwave data). In Eurasia, on the other hand, SCA reduced in size between 1.8% per decade (visible data) and 0.3% (microwave data). If we look at the Tibetan Plateau, both data sets indicate a decrease on the order of 2% per decade.

To obtain more detail, a closer look is taken at the data as a function of season. *Figure 2* presents the remote sensing data for the winter, spring and summer seasons. In December, the trend lines of the two data sets are rather widely separated simply because the two sensors early in the season do not see the same amount of snow (the microwave underestimates snow extent in the early winter season when snow is shallow). It is important though that their trends are quite similar. The data shows an increase in SCA in December by both sensors. This increasing trend is supported by ground measurements in many locations, especially in Siberia. Uncertainties occur during January and February, because the passive microwave data set indicates a slight increase of SCA, while visible SCA trend changes to negative by February. The real story on the snow cover pattern comes, however, in spring. From March until May, the visible data set shows significant decreasing trends in all months. The passive microwave data shifts from slightly positive in March to negative in May. Decreases for visible date during the spring months amount to approximately 5% per decade. This is the period during which significant melting is occurring. This pattern is logical as a slight increase in temperature in mid-winter does not lead to the melting of snow while an increased temperature in spring, when air temperatures are near or at 0°C, will lead to increased melting and diminished snow extent. For the summer months June until August, while there is only a minimal SCA, both data sets show significant decreasing trends.

Another way to look at the two data sets is by analyzing the duration of the snow cover. For the United States, for example, one of the most troublesome region exists in the mountainous area of the Western United States, where 50%, and in some cases much more, of the stream flow is provided by melting



Dec SCA

Jan SCA

Feb SCA

Mar SCA

Apr SCA

May SCA

Jun SCA

Jul SCA

Aug SCA

Figure 2: Development of SCA from 1976-2006 in Winter (Dec-Jan), Spring (Mar-May) and Summer (Jun-Aug); red = visible remote sensing, green = passive microwave satellite technique (Source: National Snow and Ice Data Center - Boulder).

snow. Decreases in snow cover duration of up to 3 days per decade have been calculated for this area. The conclusions derived from satellite remote sensing are corroborated by data measured on the ground. At many stations throughout the mountainous regions of the western United States, measurements of snow depth and extent support the conclusion that SCA trends are decreasing. The only increasing trend that shows up is in the southern Sierra Mountains in California where this rising trend is apparently driven by the El Niño phenomenon.

Typically, snow cover decreases are most evident in spring and summer but it is worth noting that at some locations, e.g. in Eurasia, increasing snow depths during mid-winter have been observed, along with earlier onset of snowfall during the autumn season in Siberia. In spring, on the other hand, the opposite patterns exist, as in the Western US with a decreased duration in snow cover occur. Duration of winter season snow cover in Switzerland at a full range of elevations shows a sharp decrease, step change, within the past 20 years when compared to the previous 40 years. It appears to be a unique pattern even over the past 130 years. The number of snow days for 1987 to 2007 was reduced to only 20 to 60% of the period 1948-1987. The same step change was found for air temperature. Similar temperature and snow patterns were found for surrounding countries. Higher than normal temperatures are attributed to a persistent blocking high pressure system over the region during the winter months (December-March) (Marty, 2008).

The impacts on winter recreation due to increased temperature and reduced snow cover duration can be severe. The reduced number of days of operation for ski resorts, especially those at the lower elevations in Europe, is already being felt as a negative impact within many tourist economies. Also, the avalanche hazard (highway, ski resort, back-country, etc.) may decrease or increase depending on local snow climate. In general, it can be stated that in regions with a maritime climate, hazard may increase. More rain on snow is expected, which is a near-certain avalanche trigger. Due to the fact that warmer air temperature results in a more stable snow structure, the hazard could possibly decrease in regions with a continental climate.

With regard to glaciers, which is the next topic, another hazard that arises with warming temperatures is glacier retreat resulting in the danger of Glacier Lake Outburst Floods (GLOF). It can happen that when the glacier tongue is retreating, the size of the lake, which may be dammed behind the terminal moraine can increase significantly. As long as the moraine continues to constrain and hold the water, the situation is stable. But when more rapid glacier melt occurs, producing large volumes of water, the moraines may break open and cause catastrophic flooding, known as GLOFs. At the moment there is considerable research going on to determine, which glacier lakes are dangerous and which are not (e.g. Mool *et al.,* 2001).

The retreat of glaciers provides perhaps the single most compelling, visually obvious, evidence of a warming climate. There are many examples of strong retreats of glaciers. Tidewater glaciers, like the Muir Glacier, Alaska, as well as mountain glaciers, like the Rhone Glacier in Switzerland, are frequently seen in photo pairs comparing current with previous terminus locations. The fraction of the glacier area lost in the Western United States is around 40% since the 1900 (Fountain, 2008).

More interesting than only the reduction of the glacier area, is the actual loss of glacier mass. To calculate the mass loss, the change in thickness of glaciers is needed. This has been estimated, based on limited measurements at a few “small” mountain glaciers, as a reduction in the average thickness by about 12 m from 1961 to 2005 (Dyurgerov and Meier, 2005). From the limited measurements available, we can also obtain some indication of the geographic distribution of this ice loss. *Figure 3* shows some of the most significant loses to be in the North Western United States, Alaska, in the Andes and Europe, and to some degree, in the Himalaya. It is most important that we obtain regional signals rather than simply data from individual glaciers, which may or may not be representative of the surrounding region. Nevertheless, wherever you go, the signal seems to be the same these days, generally negative.

Not too long ago, the discussion on the change of glaciers revolved around the fact that there were certain areas where glaciers were observed to be retreating and others where they were advancing. It was, however, a matter of timing of the response of the glaciers. Some glaciers reacted later to the warming compared to others. *Figure 4* shows that the growth of the Tien Shan mountain glaciers, for example, steadily decreased from 1974 on. While the Tien Shan glaciers showed continuous average annual volume loss into the 1990s, the Scandinavian glaciers were still growing during that time. Eventually, however, all glaciers in the sample began to lose volume, with decreases for Scandinavia beginning in about the year 2000.

To summarize, previous to the late 1980s or early 1990s, glacier volume changes were variable and in some cases even increasing. During recent decades, however, there has been less variability combined with consistent negative trends virtually everywhere in the world.

Another way of looking at the importance of mass loss from these small glaciers is their contribution to see level. The cumulative contribution to sea level from small glaciers and ice caps has been increasing since the early 1990s. Although the small glaciers and ice caps only contribute 4% to earth's total glacier ice cover, they currently contribute about 60% to sea level (*Figure 5*). The Greenland and Antarctic ice sheets, with their large area and volume, currently contribute only about 40% to sea level. Nevertheless, it should be noted that the large ice sheets may contribute significantly to sea level rise in the future.

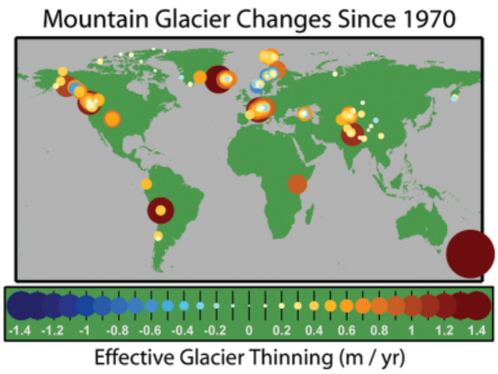


Figure 3: Mountain Glacier Changes since 1970. The effective glacier thinning is indicated in m/yr (Source: World Glacier Monitoring Service – Zurich).

Finally, how does global warming effect regions currently supplied with water from glacier melt? At the moment, streams carry more water from melting glaciers compared to the average runoff during previous decades, but what about the future? There is a need to correctly assess and quantify current situations before future conditions can be predicted. The problem is, however, that hardly any comprehensive study exists on future runoff of mountain glaciers. This deficiency makes it very difficult to produce a system-wide assessment, such as that needed for the Himalaya. At the moment, future runoff can be estimated by combing melt models with climate models, which is simply putting "models into models" which is often not all that satisfying.

There is clearly a need for a better understanding of the contribution of melting of glaciers to the total basin hydrology. Indeed, there is a need for a long-term monitoring of glaciers, which needs the help of international organizations such as UNEP.

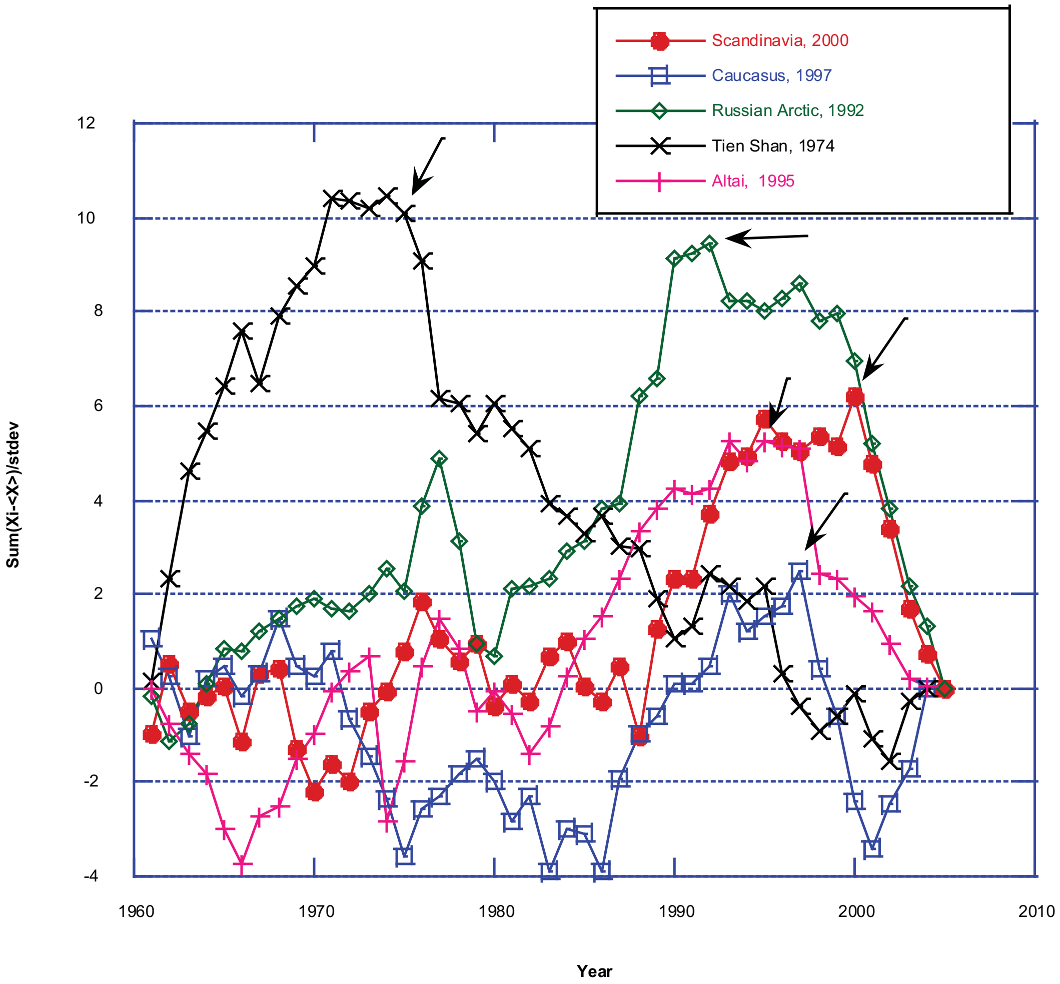


Figure 4: *Volume change calculated as the weighted values by the area of individual glaciers and by glacier systems (archipelagos, mountain rages). The timing of glacier regime changes from more stable to the acceleration of wastage is indicated (arrows in figure and years in the legend). The results are presented as the cumulative standardized departures (Source: Dyurgerov and Meier, 2005).*

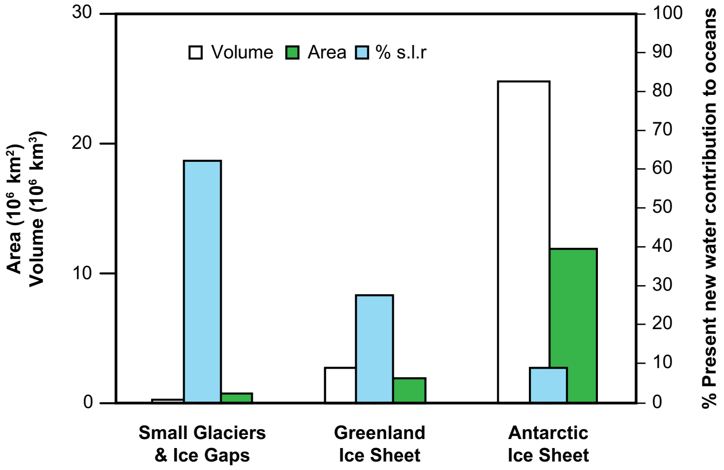


Figure 5: Comparison of volume (white), area (green) and percent contribution to sea level rise (blue) by small glaciers and ice caps, and the Greenland and Antarctic Ice Sheets (Source: Meier et al., 2007).

Conclusion

- Typical variability of mountain snow and glacier cover during the decades leading up to about 1990 has given way to a strong and consistent pattern of decreasing snow and ice.

- The reduction of glacier area and volume, once associated with lower elevations and dryer climates, has given way to decreases in nearly all mountain regions of the world. Hazards result from short effects (GLOF) while water shortages result from the long-term effects.

- Decrease of seasonal snow cover is primarily during spring and summer and often occurs in locations heavily dependent on water resources coming from snow melt runoff. Depending on location, from 20 to 80% of annual stream flow is from snow melt and it has been estimated that up to 1 billion people depend on snow melt for their water supply.

- The total impact on all regions of the world where these changes are occurring has yet to be comprehensively investigated.

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▲ *Altai Mountains, Russia*

GAW Mountain Observatories
in Detection of Atmospheric Changes

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Abstract

The Global Atmosphere Watch (GAW), the long-term global atmospheric chemistry programme of the World Meteorological Organization (WMO), focuses on greenhouse gases, ozone, UV, aerosols, selected reactive gases, and precipitation chemistry and their role in climate, weather, air quality and long range transport/deposition of air pollution. GAW is a partnership involving contributors from around 80 countries, and coordinating activities and data from 24 Global GAW stations, several hundred regional stations and about 20 contributing stations. Information on stations is available from the GAW Station Information System (GAWSIS). High altitude surface-based observatories on mountains, ice sheets or plateaus are a critical part of the GAW global atmospheric chemistry observation system. These include South Pole, Mauna Loa (Hawaii), Izana (Tenerife), Mt. Cimone (Italy), Jungfraujoch (Switzerland), Zugspitze-Hohenpeissenberg (Germany), Sonnblick (Austria), Mt. Waliguan (China), Assekrem (Algeria) and Mt. Kenya (Kenya). These stations are located in background areas where global climate change can be detected on one hand and, on the other they are located in separate air sheds and thus offer different perspectives on regional air chemistry and transport. Long-term observations are necessary to determine trends in atmospheric constituents. In addition, due to the need to detect small changes, the measurements require excellent accuracy, which is obtained through the WMO calibration and standardization facilities. The global networks are still incomplete and should be augmented with continuous measurements on the continents, the Arctic, the tropics, and the oceans. GAW products include the WMO Greenhouse Gas and Antarctic Ozone Bulletins.

Keywords: Mountain Observatories; Ozone; Halocarbon; Boundary Layer; GAW

Introduction

The Global Atmosphere Watch (GAW) programme was established in 1989 by the World Meteorological Organization (WMO) to address the issue of atmospheric change. GAW focuses on global long-term measurements of greenhouse gases (GHGs; CO_2, CH_4, N_2O, CFCs, etc.), ozone, UV, aerosols (chemical and physical properties, AOD), selected reactive gases (CO, VOC, NO_X, SO_2), and precipitation chemistry. It systematically monitors atmospheric chemical and physical parameters globally. In addition, GAW carries out analysis and assessments and develops predictive capacity.

▲ *Jungfraujoch Research Station, Switzerland, part of the GAW network.*

High mountain observatories are very suitable for the measurement of greenhouse gas trends. These stations are normally in the free troposphere (see below section Locating origin of air mass). GAW stations such as Mauna Loa (US), Mt. Waliguan (China), and Izana (Spain) are measuring the global background of for instance carbon dioxide (CO_2), which is constantly rising. It is very important to make long-term measurements, as otherwise one would not note changes that are significant in the decadal picture but small from year to year.

In this paper, a closer look is taken at ozone, at the tracing of air masses, and the detection of pollution hot-spots on GAW mountain observatories.

Trends in Tropospheric Ozone

Intensive analysis of surface ozone data combined with different primary trace gases and meteorological parameters at Hohenpeissenberg Meteorological Observatory led to the assumption that not local or regional, but rather supra-regional, hemispherical or even global increase of tropospheric ozone determine the increasing trend of the average values at the Hohenpeissenberg Observatory. This thesis is supported by the fact that also other stations in the northern hemisphere, to a large extent uninfluenced by regional effects, show increasing mixing ratios (*Figure 1*). There is no trend at Pallas (Finland), only a weak trend at Barrow (Alaska) and a somewhat stronger trend at Mauna Loa (Hawaii), but not as pronounced as at the Hohenpeissenberg. The neighboring station "Schauinsland" in the Black Forest (Germany) approximately on 1200 m a.s.l. along with the station Ryori (Japan), all in mid-latitudes, show a similar positive trend in ozone mixing ratios as the Hohenpeissenberg site. Also the high-alpine stations Jungfraujoch (Switzerland), Sonnblick (Austria) and Zugspitze (Germany) have similar upward gradients, though at higher concentrations caused by the higher elevation. The Zugspitze trend is somewhat more pronounced caused by the longer time series.

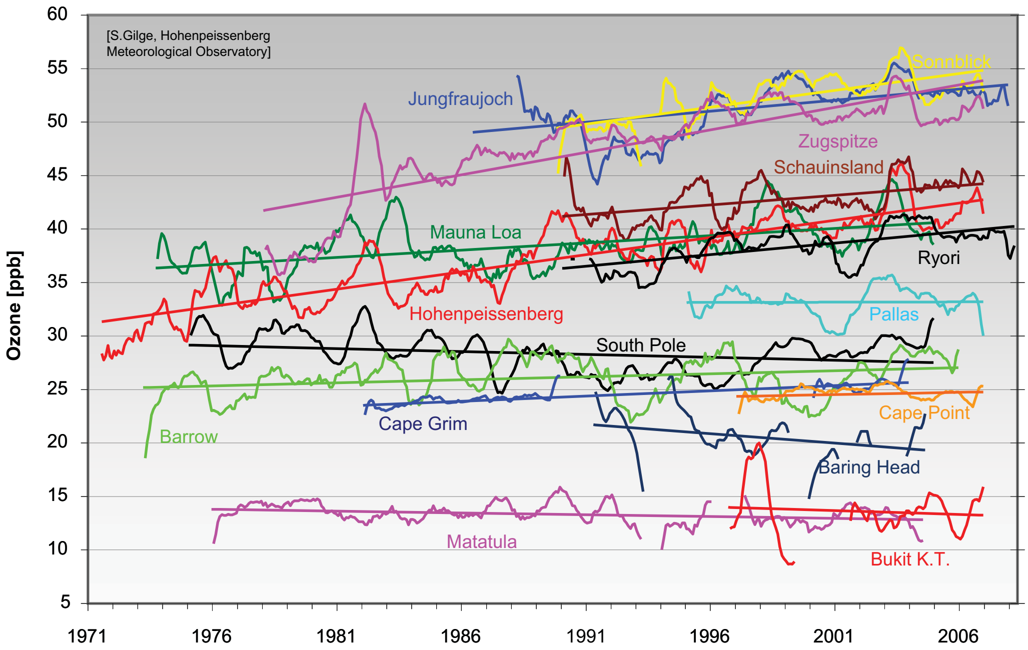

Figure 1: Time series (12 month running mean and linear trend) of near surface ozone at different GAW sites (Source: Gilge, 2007; World Data Centre for Greenhouse and Related Gases (WDCGG) of GAW programme, http://gaw.kishou.go.jp/wdcgg.html).

As expected, the temporal development at the South Pole station is independent of the trend in the northern hemisphere: with still an overall negative trend, the measured values have been slightly rising since the 1990s. The stations Bukit Koto Tabang (Indonesia) and Matatula, situated on 14° S in the Pacific, show a weak decrease besides a very small concentration level. Also Baring Head (New Zealand), situated in the moderate latitudes of the southern hemisphere, shows a downward trend in mixing ratios. The sites Cape Point (South Africa) and Cape Grim (Australia) show a slightly increasing trend. Unfortunately the southern hemisphere data are limited and the existing time series are sometimes interrupted.

In summary, the stations at the moderate latitudes in the northern hemisphere (where most of the anthropogenic emissions take place) show a positive trend, which cannot be observed in the southern hemisphere and in high latitudes of northern hemisphere.

Locating Origin of Air Mass

At high altitude stations free tropospheric conditions prevail normally. However, this is not always true and it is important to note during which time of the year and at which time of the day measurements are taken. To properly assess this challenge, a study based on aerosol climatology has been car-

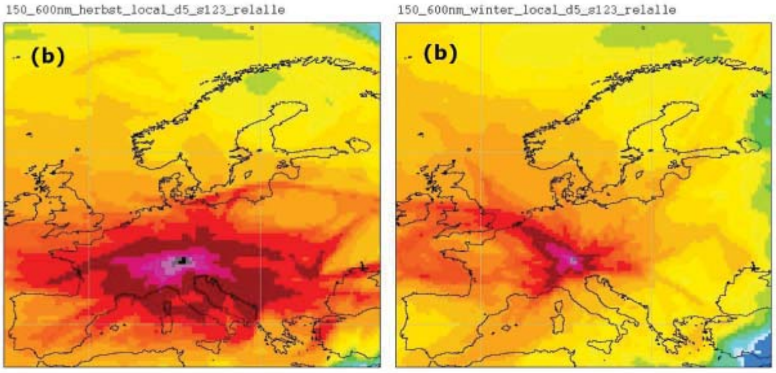

Figure 2: Source receptor relationships, boundary layer, left during autumn, right during winter at Zugspitze, Germany.

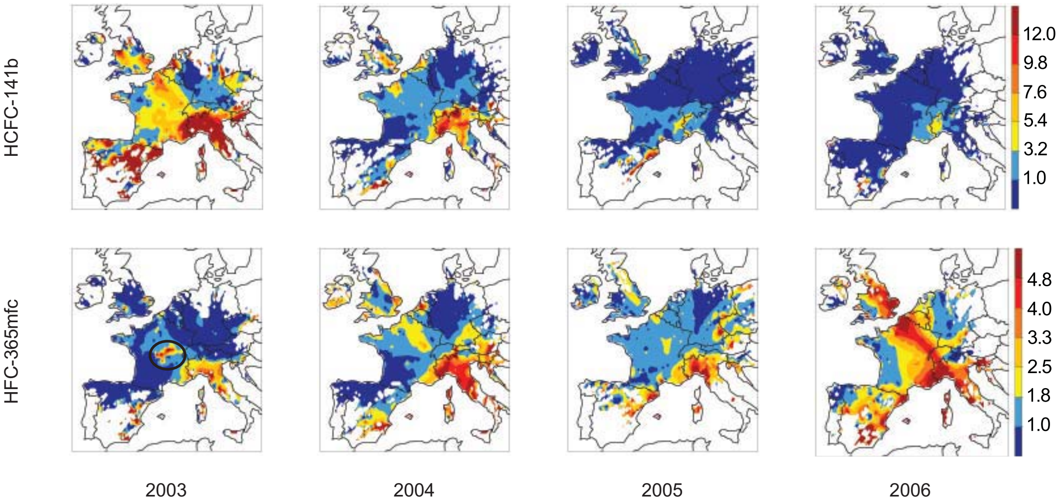

Figure 3: Distribution of HCFC-141b (top) and HFC-365mfc (bottom) between 2003 and 2006 as detected at Jungfraujoch. For HCFC-141b, the pollution strength is decreasing in most regions after this compound has been banned in 2003. HFC-365mfc, on the other hand, has been increasingly used as substitute for HCFC-141b after 2003. The result is an increased pollution strength of this halocarbon in many regions in Europe. The circle in the bottom left figure indicates the factory in France, which was the only producer of HFC-365mfc in 2003. Units are relative to the smallest emissions, having a given value of 1 (in blue).

ried out at Zugspitze, Germany, where GAW has two stations at 2650 m a.s.l. and 2950 m a.s.l. This study shows that Zugspitze station usually lays above the atmospheric boundary layer from October to February. Conditions of the lower free troposphere can be measured especially well during this time at night from 22h in the evening to 6h in the morning. During summer season, on the other hand, convection occurs usually starting at noon bringing up air masses with more particles from below the boundary layer. The measured particle number concentration is closely connected with the daily duration of radiation input (maximum at about 21st June) and not with temperature. The lowest particle number concentrations are then again observed during nighttime with a typical particle number concentration of 1500 P./cm^3 showing the influence of the continental boundary layer. For other times of the year the influence of the maritime boundary layer results in a typical particle number concentration of 1000 P./cm^3. A typical value for air from free troposphere is 500 P./cm^3.

Measurements on particle number concentrations for particles between 10 nm and 800 nm were carried out from December 2004 to February 2008. The evaluation of this data accompanied by continuous transport modeling (Flexpart simulation, Prof. A. Stohl, Nilu) shows that the accumulation mode, which is based on aged air masses and usually transported a longer distance, receives quantitative contributions from the following source regions: Central Europe, including alpine region over 33%; Western, Southern, and Eastern Europe, each slightly below 20%; northern Europe, Atlantic, each below 5% (*Figure 2*). This result is valid during spring, summer and autumn when measurements are taken at noon time. It is not applicable for winter time as Zugspitze is then laying above the boundary layer.

The largest fraction of particles arrives from the European boundary layer or from the North Atlantic. Especially low number concentrations occurred with recent air or fast moving Atlantic air. High values, on the other hand, were measured in stationary air over the European continent. Maximum values were transported from Eastern European air. Despite of those high concentrations, the statistical influence on the mean number concentrations at Zugspitze was quite limited. Long range transport from distant continents only happen sporadically and show a low contribution to the annual mean values.

Locating Sources of Pollution

Measurements of a compound can be combined with trajectories to locate potential sources. Trajectory analysis looks at the route of the air mass to determine its origin. At Jungfraujoch, Switzerland, 3580 m a.s.l., a closer look has been taken at two halocarbons, HCFC-141b, which was banned in 2003, and its substitute HFC-365mfc (pentafluorobutane, Stemmler *et al.,* 2007). *Figure 3* (top row) shows that the pollution strength of HCFC-141b is decreasing in many regions in Europe after its ban. The pollution strength of HFC-365mfc, on the other hand, increased in many regions after its increased use as substitute (bottom row). The study could detect a factory in France, which was the only HFC-365mfc manufacturing site globally in 2003.

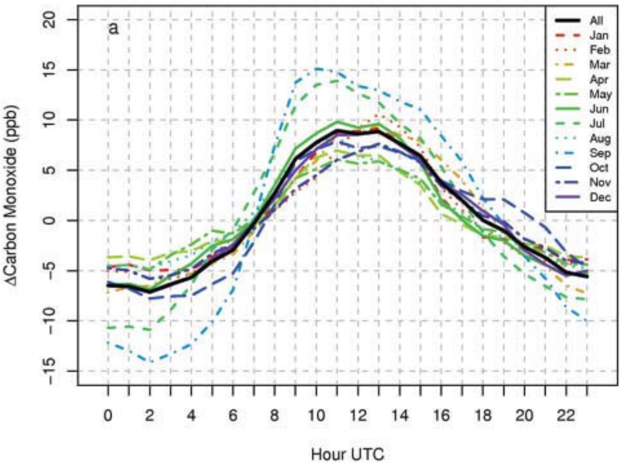

Figure 4: CO (ppb) diurnal cycle by season at Mt. Kenya GAW station for the period 2002-06 to 2006-06 (Source: Henne et al., 2008b).

Mount Kenya

As part of GAW the Kenyan Meteorological Department maintains a station at Mt. Kenya, (37.297° E, 0.062° S, 3678 m a.s.l.). Mt. Kenya exhibits a strong diurnal cycle all over the year. This is typical for mountains influenced by the atmospheric boundary layer during day-time. Slope winds dominate the site, carrying boundary layer air towards the top during day-time. Measurements on carbon monoxide (CO), which is not a greenhouse gas but strongly influences atmospheric chemistry, clearly show this diurnal cycle for all months (*Figure 4*). The wind flow is generally up the slope during day-time, carrying up CO, emitted within the atmospheric boundary layer, towards the top. During night time, the general wind direction is down-slope, carrying lower CO mixing ratios that are representative for the lower free troposphere (Henne *et al.,* 2008a). Henne *et al.* (2008b) illustrate that most of the air masses arriving at Mt. Kenya originate from the Indian Ocean, Southern and Eastern Africa and the Arabian Peninsula. Hardly any air is reaching Mt. Kenya from western or northern Africa. The site is only seldom directly influenced by pollution from biomass burning (the most important air pollution source in Africa) and therefore offers important baseline measurements in this data sparse region of the world.

Conclusion

Mountain observatories give a good picture of the chemical composition of the free troposphere and therefore provide relevant knowledge for climate change studies. Every station, however, has its individual characteristics, which is evident from pollutant source studies, diurnal and seasonal variations, and from observing the life cycles of chemicals.

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Photo: Ev-K2-CNR

▲ *Part of the GAW network: "O. Vittori" Research Station on Mt. Cimone, Italy*

Atmospheric Composition Change and Climate in High Mountain Areas

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Abstract

Changes in atmospheric composition directly affect many aspects of life, determining climate, air quality and atmospheric inputs to ecosystems. In turn, these changes affect the fundamentals of life necessary for human existence: health, food production, and water availability. It is now well recognized that human activities have perturbed the chemical composition of the atmosphere on local, regional, and global scales. Mountain regions provide unique opportunities to detect and analyze global change processes and phenomena. In fact, high mountain stations are locations where atmospheric background conditions and global change processes can profitably be studied by means of continuous monitoring activities. The Mt. Cimone Observatory in the Italian Northern Apennines and the Pyramid Observatory in the Khumbu Valley of the Nepalese Himalayas are two examples of such high mountain stations where long-term monitoring of atmospheric composition are underway, providing important data to document changes induced by human activity and to understand the associated effects on climate and ecosystems.

Keywords: Apennines; Himalaya; Atmospheric Brown Clouds; Black Carbon; Halocarbon; Ozone; Saharan Dust Transport

Introduction

Over the past century, humanity has been altering the chemical composition of the atmosphere in an unprecedented way. Worldwide emissions from growing industrial and transportation activities and more intensive agricultural practices have caused widespread increases in atmospheric concentrations of photochemical oxidants, acidic gases, aerosols, and some toxic chemical species. Many of these air pollutants are known to have detrimental impacts on human health and/or natural and managed ecosystem viability. Furthermore, higher fossil fuel consumption coupled with agriculturally driven increases in biomass burning and fertilizer usage have led to increased emissions of key greenhouse gases, such as carbon dioxide, methane, and nitrous oxide. The net effects of the buildup of radiatively active trace gases and the changing burden of atmospheric particles appear to be responsible for much of the climate trend observed during the 20th century, particularly the warming over the last few decades (IPCC, 2007). Predicted impacts of climate change include disruptions of agricultural productivity, fresh water supplies, ecosystem stability, and disease patterns. Significant increases in sea level and changes in the frequency of severe weather events are also forecast. The resulting effects of all these stresses on biogeochemical cycles could exacerbate changing atmospheric composition and result in further effects on climate. If current trends go unchecked, much more significant warming is predicted, potentially driving a wide range of perturbations in other components of the climate system (Steffen *et al.,* 2004).

Prediction of future changes in atmospheric composition requires information on past and present atmospheric composition, and the World Meteorological Organization (WMO) has underlined in a recent report the need for a global observing system “to monitor global change, sustained and long-term measurements of the distribution, sources and sinks of greenhouse gases (H_2O, CO_2, CH_4, O_3, N_2O) and related precursors (CO, NO_X, NMHC), aerosols and meteorological variables (e.g. wind, temperature, clouds) with appropriate spatial and temporal resolution and global representativeness” (IGACO, 2004).

However, unlike meteorological parameters that have been routinely collected by meteorological services for 250 years and for which global satellite observations have existed for over 30 years, there is no coordinated system to measure atmospheric composition, which still represents a challenge. Validation of numerical models, in fact, requires accurate information concerning the variability of atmospheric composition for targeted species through comparison with observations.

Satellite measurements can provide some global information. They are, however, not always suitable and measurements from ground stations are required. In addition, no long-term measurements exist for several compounds or variables. Another difficulty that often arises with monitoring projects is funding (e.g. even the famous Mauna Loa curve has a gap in 1964 due to discontinuation of funding). Nisbet (2007) observed that “monitoring is science’s Cinderella, unloved and poorly paid” and also “monitoring does not win glittering prizes, publication is difficult, infrequent and unread”.

Mountains are marginal environments highly sensitive to global change. At the same time, mountains provide unique opportunities to detect and analyze global change processes and phenomena, and at high mountain stations atmospheric background conditions and global change processes can profitably be studied by means of continuous monitoring activities.

In this paper, a closer look is taken at data provided by two high mountain stations: the Mt. Cimone "O. Vittori" Research Station (lodged in a building of the Italian Air Force Meteorological Service), located in the Italian Apennines (44° 12' N, 10° 42' E; 2156 m a.s.l.) and the Everest-Pyramid Atmospheric Research Observatory, located in the Himalayas (27.9° N, 86.7° E; 5079 m a.s.l.). Both stations are contributing to the Global Atmospheric Watch Program (GAW) of WMO.

Mt. Cimone "O. Vittori" Research Station

Mt. Cimone is the highest peak of the northern Apennines, characterized by a completely free horizon for 360°, which lies at the border of two climatic regions, continental Europe to the North and the Mediterranean to the South. Due to its altitude and geographical position, the site is considered to be representative of European continental background conditions (Fischer *et al.,* 2003; Bonasoni *et al.,* 2000). For this reason, Mt. Cimone is an ideal site where atmospheric background conditions and environmental change processes can be studied thanks to continuous monitoring activities that constitute an important means to understand global change processes.

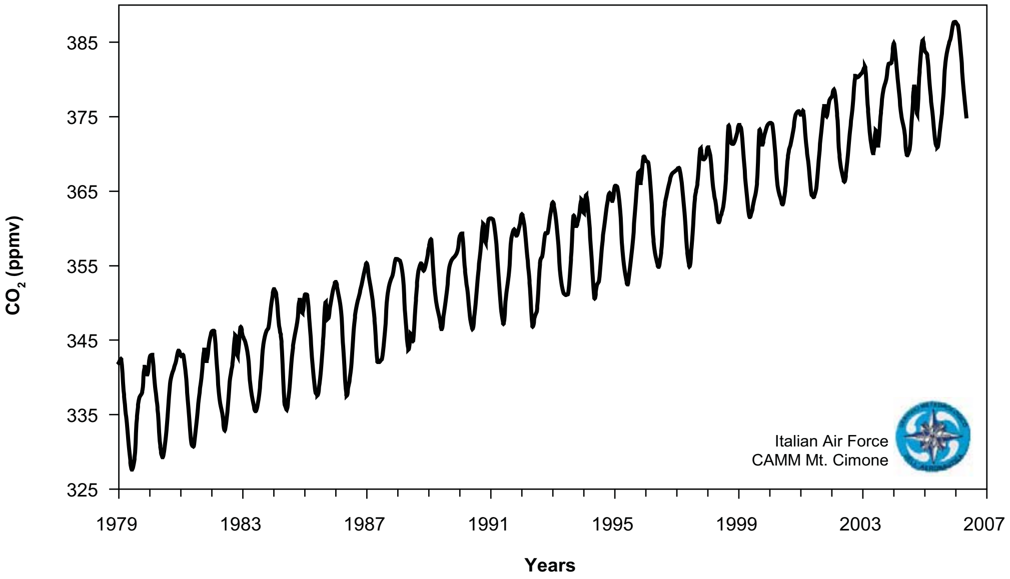

Figure 1: Carbon dioxide concentration trend, measured since 1979 by the Italian Air Force Meteorological Service at the Observatory of Mt. Cimone (Italy).

This station has recorded variations of CO_2 concentration in Europe for the longest period of time, dating back to 1979 (*Figure 1*) with measurements carried out by Italian Air Force Meteorological Service (Cundari *et al.,* 1995; Colombo *et al.,* 2000).

At Mt. Cimone, continuous observations of other atmospheric components are carried out through collaboration with several national and international institutions.

These measurements include surface ozone, carbon monoxide, methane, and several halocarbons. Number concentration and size distribution of atmospheric aerosols, PM10, black carbon, aerosol scattering and absorption properties as well as aerosol chemical composition are also measured at the station.

The IPCC (2007) ranks tropospheric ozone as the third greenhouse gas after carbon dioxide and methane. Ozone increase can also indirectly affect global warming by suppressing plant growth, reducing the land carbon sink for CO_2 and therefore increasing the rate at which CO_2 increases in the atmosphere (The Royal Society, 2008). At Mt. Cimone, surface ozone is monitored since 1996 and the monthly concentration trend exhibits a seasonal cycle characterized by a minimum in winter, a principal maximum in summer and a secondary one in spring (*Figure 2*), typical of the clean northern hemispheric atmosphere (Logan, 1985). At the station, a contribution to high O_3 values is provided by stratospheric-tropospheric exchange events (on average 36 days/year) that can transport downwards O_3-rich air masses from the stratosphere

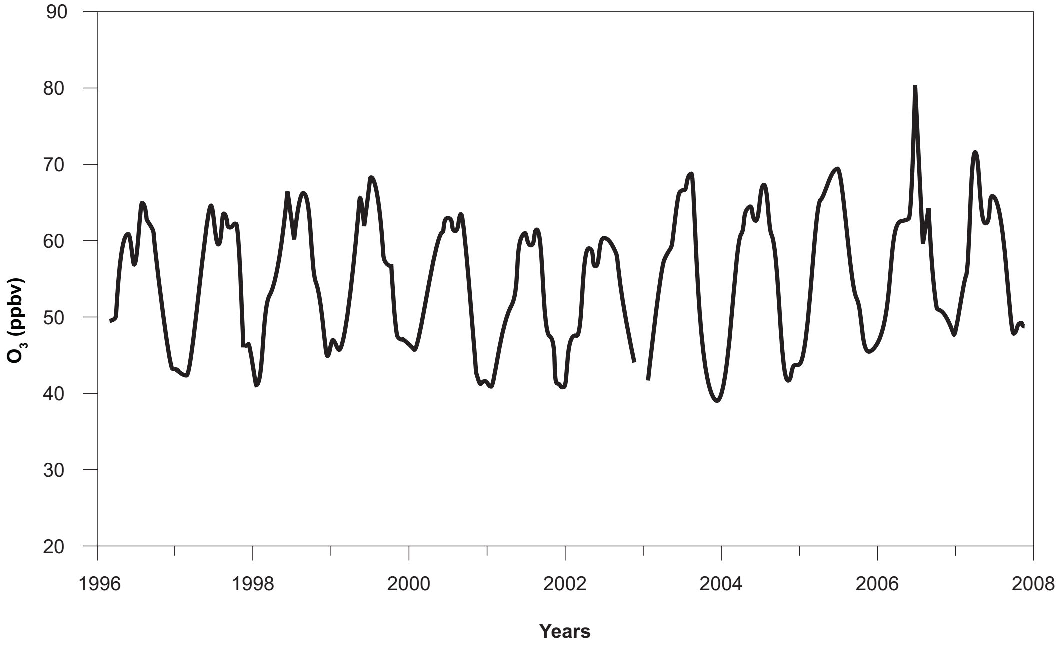

Figure 2: Monthly ozone concentration trend at Mt. Cimone.

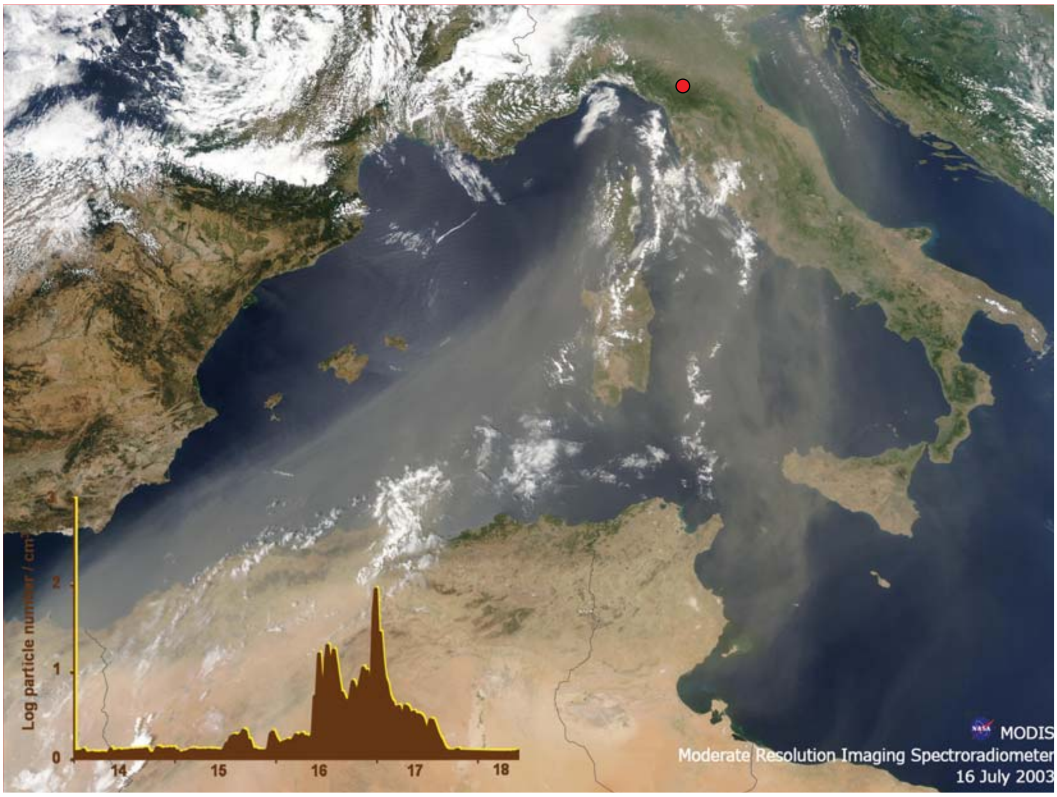

Figure 3: Saharan dust transport towards Europe occurred on July 16, 2003 (MODIS-NASA) and the trend of mineral dust concentration measured at the Mt. Cimone station (identified by a red dot), showing a simultaneous increase on July 16 and 17.

(Stohl *et al.,* 2000).These events are linked to the North Atlantic Oscillation (NAO) phenomenon, in particular during the winter season (IPCC, 2007).

High O_3 values can also be related to air mass transports from polluted areas (Bonasoni *et al.,* 2000), especially during the warm season when persistent high pressure and high temperature facilitate an efficient photochemical production of O_3 in urban and industrialized areas (Staehelin *et al.,* 1994; Jacobson, 2002). In fact, during the heat wave episodes (defined as a sequence of days with exceptionally high temperatures) recorded in Europe in August 2003 and July 2006, extremely high O_3 concentrations were recorded at Mt. Cimone, in connection with air masses coming from continental Europe and the Po basin boundary layer (Cristofanelli *et al.,* 2007).

Mt. Cimone is also particularly suitable to study the transport of tropospheric air masses advected from North Africa, which carry Saharan dust transported towards Europe (*Figure 3*).

About 22 events/year of high dust transport to Mt. Cimone are normally recorded, with the highest frequency during spring and summer. These events are usually characterized by high concentrations of mineral aerosols and a reduction of ozone concentration (about 10%) with respect to background values (Balkanski *et al.,* 2003; Bonasoni *et al.,* 2004; Umann *et al.,* 2005).

Figure 4: MODIS-NASA Satellite image showing forest fire plumes and Saharan dust over the Mediterranean basin on August 29, 2007. Black carbon and dust clouds were detected at Mt. Cimone on August 30 and 31.

Not only dust is transported from North Africa to Europe, but also products of forest fires. In summer 2007, widespread forest fires occurred at the northern coast of Africa with a peak on August 29, 2007 (*Figure 4*). Products of the forest fires, like carbon monoxide and black carbon, were measured at Mt. Cimone. The observations clearly showed the fire plume peak of August 29, which reached the station on August 30/31, 2007. Together with the fire-derived particles, also Saharan dust was transported northwards. Such a transport of dust and biomass burning particles had an effect on solar radiation: in the period from August 26 to September 1, 2007 in fact, a decrease in irradiance of around 10% was observed at the ISAC-CNR radiometric station in Bologna.

As reported above, a number of well mixed greenhouse gases (WMGHGs) is also continuously monitored at Mt. Cimone, including methane, nitrous oxide and halocarbons. Halocarbons contribute to climate forcing being powerful greenhouse gases able to absorb long-wave radiation re-emitted by the Earth’s surface in the 8-13 μm atmospheric window. Moreover, halocarbons containing chlorine and bromine atoms can also influence the climate system via stratospheric ozone depletion. The importance of long-term measurements of such gases at a high mountain station is that here both background values and concentration peaks due to the transport of air masses from nearby polluted regions can be detected.

In this way it is not only possible to observe long-term trends and assess rates of increase (or decrease) of the WMGHGs, but also to localize their regions of origin and quantify emissions on a regional (European) scale (Greally *et al,* 2007; Maione *et al.,* 2008), as can be seen in *Figure 5*. Moreover, observations at Mt. Cimone are linked, through the use of the same calibration scale, to the two international networks SOGE (System for Observations of halogenated Greenhouse Gases in Europe) and AGAGE (Advanced Global Atmospheric Gases Experiment). The exploitation of data from the whole network, allows to determine emissions on a global scale. Results are useful to ascertain compliance to international protocols regulating production/emission of halogenated greenhouse gases (Stohl *et al.,* 2008).

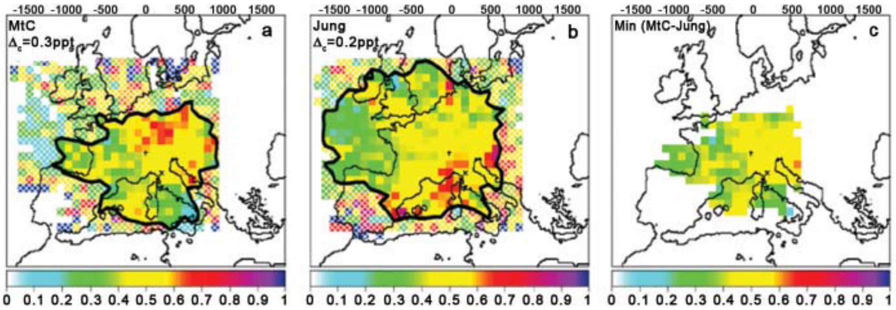

Figure 5: Maps of conditional probability for potential sources of the refrigerant HFC-125. a) map obtained using observations at Mt. Cimone; b) map obtained using observations at the Jungfraujoch (Switzerland) mountain station; c) map obtained considering for each cell the minimum value between the two stations (Source: Maione et al., 2008).

The Atmospheric Brown Clouds (ABCs) Project and the Everest-Pyramid GAW station

A brown haze is very often observed over South-East Asia during the dry season. This phenomenon has been given the name of Atmospheric Brown Clouds (ABCs). ABCs are regional scale plumes consisting of tiny particles composed of black carbon, organics, sulfates, nitrates, dust, and other pollutants. They can stretch over several thousand square kilometers and can be 2 to 3 kilometers thick. The compounds in ABCs mainly originate from burning of fuels in industries and from burning of biofuels for cooking (Ramanathan *et al.,* 2008).

ABCs have several effects on the climate. On the one hand, carbonaceous particles absorb sunlight, heat the atmosphere and cool the surface. In this way, they affect climate. On the other hand, black carbon particles deposit on snow/ice surfaces lowering their albedo and accelerating melting of the glaciers. This is a very important issue especially in Himalaya, where glaciers represent the main freshwater resource for hundreds of millions of people. In addition, ABC particles nucleate cloud droplets altering cloud microstructure and inhibiting precipitation. It has also been suggested, and there are some scientific evidences that ABCs can weaken the monsoon circulation leading to a decreased monsoon rainfall. Finally, ABCs also have an impact on agriculture and human health.

To find out more about ABCs, the project “Atmospheric Brown Clouds” promoted by UNEP has been set up (Ramanathan *et al.,* 2008). This project has established a network of observatories all over South East Asia. Among these measuring points, the Everest-Pyramid GAW station, named in the ABC framework Nepal Climate Observatory-Pyramid (NCO-P) has been set up at 5079 m a.s.l. in the Khumbu Valley of Nepal within the Ev-K2-CNR project (Bonasoni *et al.,* 2008). The sampling program is active since March 2006.

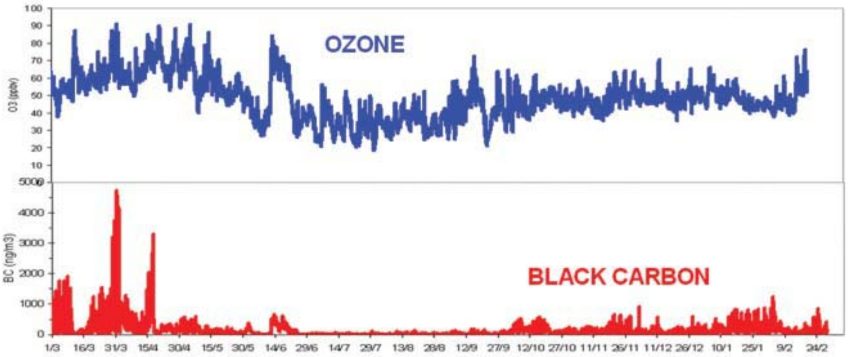

Figure 6: Surface ozone and black carbon concentration trends from March 2006 to February 2007 at the Everest-Pyramid GAW station in Himalaya.

The continuous measurements at the station include: black carbon concentration, aerosol size distribution from 10 nm to 10 mm, aerosol scattering coefficient, aerosol optical depth, surface ozone concentration. In addition, sampling systems are available for collecting aerosol for chemical analysis and grab air samples for halocarbon analyses.

As an example, the temporal trend of black carbon and surface ozone concentrations are reported in *Figure 6*. During the monsoon season (from June to October), the concentration of black carbon is very low as expected at such an altitude and also the ozone values are characteristic of background free tropospheric condition. However, in the dry season and in particularly during polluted air mass transport episodes, the concentration of these compounds get to levels that are usually found in urban areas, as showed in *Figure 6*.

Halocarbons are also measured at the NCO-P in the Himalayas, through flask samples collected on a weekly basis. The resulting time series are used to assess background values. When compared with background values observed at the European high mountain station at Mt. Cimone, the following features can be observed:

- the fully halogenated species, phased out under the Montreal Protocol, exhibit baseline concentrations similar to Europe but with frequent concentration peaks due to "fresh" emissions;
- the hydrofluorocarbons, recently introduced as replacement for the ozone depleting substances, are nevertheless powerful greenhouse gases included in the Kyoto basket. They have been introduced in the 1990s but their use in developing Countries is not as widespread as in the western world. Moreover, they are characterized by a higher reactivity allowing a more efficient removal from the atmosphere. Background values are lower than those measured at the European site (*Figure 7*).
- the methyl halides, which are emitted also by biomass burning, show frequently high concentrations at the NCO-P station.

Conclusion

There are several networks of research stations around the world to monitor atmospheric composition changes and their effects on regional pollution and climate change. Only a few of these stations are located at high elevation. This is mainly because of the great challenges regarding management of such sites. On the other hand, mountains are important environments, essential for Earth's survival yet fragile, highly sensitive to global change and subject to rapid modifications. At the same time, mountains provide unique opportunities to detect and analyze global change processes and phenomena, and at high mountain stations atmospheric background conditions and global change processes can profitably be studied by means of continuous monitoring activities. Valuable examples, described in this paper, are the Mt. Cimone "O. Vittori" Research Station in the Italian Apennines and the Everest-Pyramid Atmospheric Research Observatory in the Himalayas, which are part of the SHARE project (Stations at High Altitude for Research on the Environment) established by the Ev-K2-CNR Committee. Both stations are also contributing to the Global Atmospheric Watch Program (GAW) of WMO.

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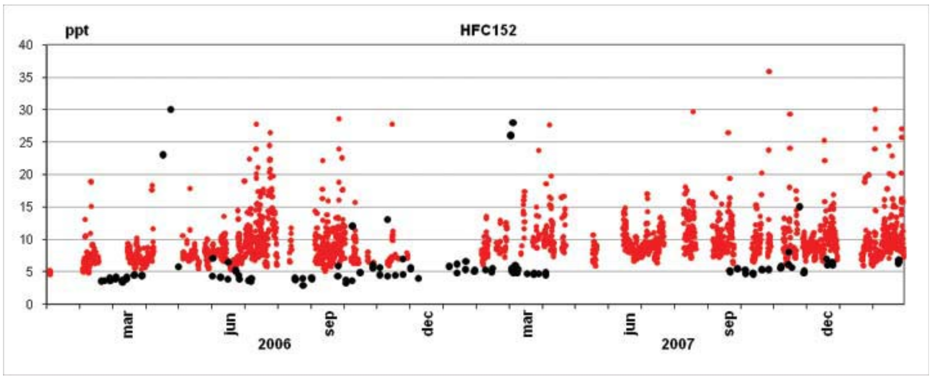

Figure 7: Time series for the blowing agent HFC-125 recorded at Mt. Cimone (red) and NCO-P Himalaya station (black).

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▲ *Forest Road in the Ardennes, Belgium.*

Ecosystems and Global Services: An Outlook on Forest and Mountain Region

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Abstract

The biosphere plays an important role in the Global Carbon Balance. Today, the biosphere, especially the areas in the northern hemisphere, act as a carbon sink. Most uptake occurs in northern temperate areas and decreases towards the pole. As temperature increases globally due to climate change, the biosphere will most likely turn from a carbon sink to a carbon source within the next century. Global warming will also affect the species distribution within different ecosystems. Models made on forest biomes in the Italian Alps show that 77-82% of the biomes will be affected by climate change. Some biomes will move upwards, others will disappear and a few will expand. As a result, the biodiversity will decrease. Forests in mountain areas, especially the European ones, are influenced by human activities, which influence the forests' carbon budget. Younger forests (<10 years) act as a carbon source, whereas older forest act as a carbon sink. Even very old forests (> 110 years) still accumulate carbon. Therefore, conservation of old forests must be reconsidered as they accumulate carbon and provide essential ecosystem services. Not only forests are affected by global changes, but also mountain grasslands. Data from Malga Arpaco, Italy, indicated an increased productivity and an increased carbon accumulation for the year 2003. While the productivity in low elevation ecosystem decreased strongly in this very hot year, ecosystems at higher elevation seem to have profited from higher temperatures. In conclusion, climate change will influence mountain ecosystems in different and possibly unexpected ways, like increased productivity or decreased biodiversity.

Keywords: Climate Change; Forest; Mountain Ecosystem; Global Carbon Budget

Introduction

It has been proposed that we have entered a new geological area. This new area is the so called Anthropocene, which is based on the fact that mankind has dominated the globe in the recent past and will do so in the future. Whether the term Anthropocene will be generally accepted or not is still under discussion. It is, however, not negligible that humans are dominating the Earth and that we are strongly interfering with our environment. We play, for example, an important role in the current climate change, or we change ecosystems with our activities.

A good functioning of the world's ecosystems is very important as ecosystems provide vital services for our human life. One of the services of ecosystems is the provisioning of goods produced or provided by ecosystems, like food or wood. In addition, ecosystems have regulation effects. For example, they regulate floods or influence the spreading of diseases, like malaria. Furthermore, ecosystems have a cultural value. Forests are used for recreation or they are important for different religions, for instance in Asia a number of tree species are considered sacred and are protected by local people. There are other ecosystem services that are of increasing importance, despite the fact that in the past these services were unknown. In this respect terrestrial ecosystems play a fundamental role in shaping the concentration of carbon dioxide in the atmosphere, through the uptake and release of carbon dioxide through to photosynthesis and respiration. In turn carbon dioxide concentration is responsible of the greenhouse gas effect, which affects the climate system. Thus any change or modification we apply to terrestrial ecosystems have a profound effect on climate and our environment.

Nevertheless, it can be stated that all services provided by ecosystems are under stress today. They are under stress due to human pressure or due to global changes, like climate change.

Most areas in the globe are covered by vegetation. Nevertheless, there are only a few areas in the world, where humans have not interfered with the vegetation and its ecosystem yet. Untouched ecosystems can be found in the boreal regions, in Canada and Siberia, in the Amazon basin or in desert areas. On the other hand, humans strongly interfered with their environment in temperate areas. Such interferences influence the global carbon cycle.

The Biosphere as Part of the Global Carbon Cycle

Gruber *et al.* (2004) estimated the global atmospheric accumulation rate of carbon in the 1990s to 3.2 GtC per year. The sources of this accumulation, therefore, mainly are fossil fuel burning and the cement industry, releasing together around 6.3 GtC per year. In addition 2.2 GtC per year are emitted to the atmosphere due to land use change, like deforestation. The sinks are the ocean and the land taking up 2.4 GtC per year and 2.9 GtC per year respectively. The ocean is quite stable and therefore, it is difficult to enact proper measures that would lead to an increased carbon uptake by the ocean. The uptake on the land side, however, can be influenced much easier to eventually increase the sequestration of carbon. Nevertheless, carbon sequestration on land is a different task as it takes a lot of time. Reforestation is a slow process, which takes between 103 and 104 days to revert a bare soil into a new forest. The destruction of a forest, on the other hand, can occur within a day or within one century. As a result, deforestation occurs much faster than reforestation.

Today, land carbon uptake occurs mainly in the temperate regions in the northern hemisphere. The sequestration has a strong seasonal variation. In summer, more carbon is stored in the vegetation than released, lead-

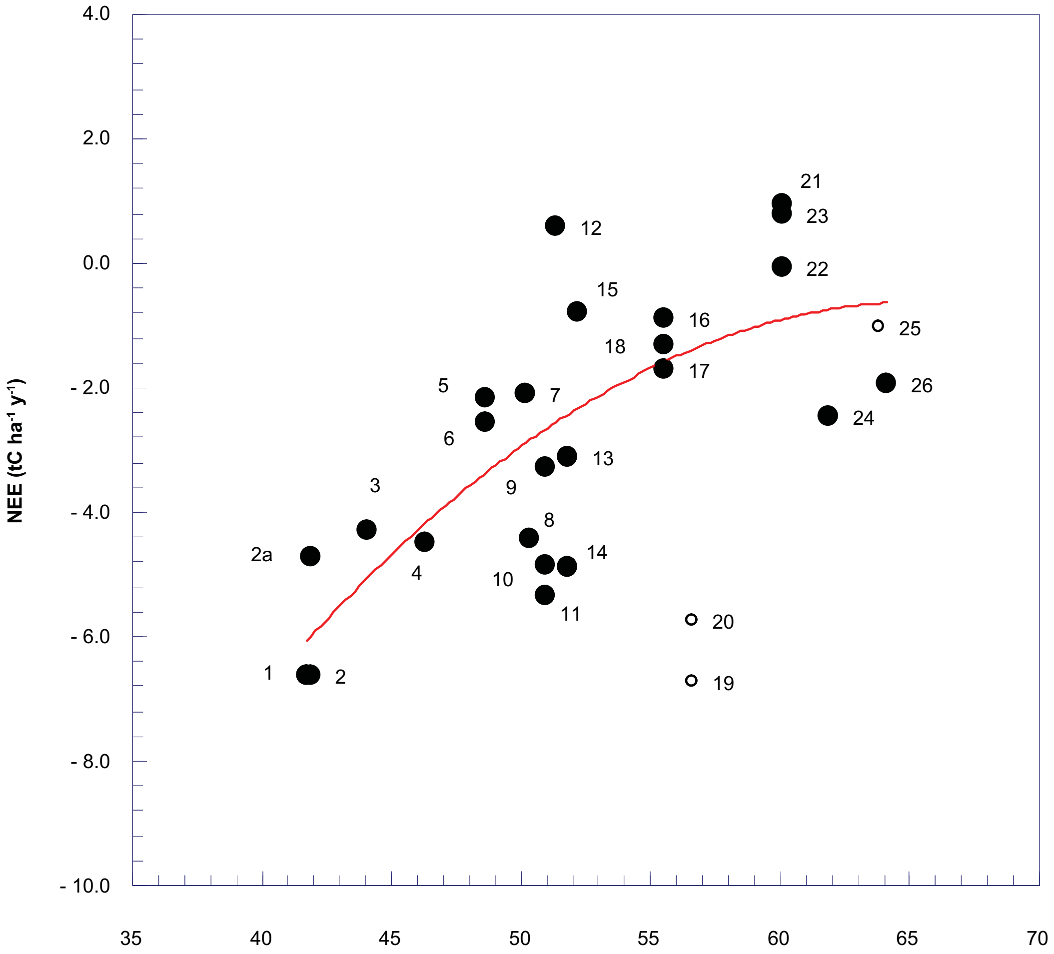


Figure 1: Net ecosystem exchange (NEE; in tC ha^{-1} yr^{-1}) of 15 European forests versus the Latitude. Closed symbols, forests of natural origin and planted stands with traditional forest management; open symbols, intensively managed plantations. Negative values indicate a carbon uptake from the atmosphere, whereas positive values signify a carbon source to the atmosphere (Source: Valentini et al., 2000).

ing to a carbon uptake. During winter, the opposite is the case as more carbon is released by respiration than taken up by photosynthesis. Nevertheless, the biosphere in the northern hemisphere stores, on an annual average, more carbon than it releases. *Figure 1* shows that there is a strong latitudinal variation in carbon uptake in Europe. Most carbon uptake occurs in the temperate regions and the further we go north the smaller the carbon sequestration gets. Carbon uptake by land is definitely not the silver bullet for the climate change problem. Coupled carbon climate models show that the land may switch from a carbon sink to a carbon source within the next century. Increased temperatures lead, for instance, to an increased oxidation of soil carbon or to more forest fires. This again leads to a release of carbon species, mainly CO_2, to the atmosphere. As more carbon in the atmosphere leads to a temperature increase, the cycle closes to a positive feedback loop. Thus, the land may become an important contributor to global warming in the future.

At high elevation, most carbon is accumulated in the soil. This carbon is at the moment quite stable. Due to climate change, however, this stable carbon can get mobilized and released to the atmosphere. There are a few “carbon bombs” around the globe that can be stimulated by the climate warming. These “bombs” are large carbon pools and mainly located in wetlands, permafrost or tropical forests. If this carbon is released, the atmospheric CO_2 can increase with up to 200 ppm over the coming century (Gruber *et al.,* 2004). This risk, however, is not included in most climate simulations. As a result, there is an uncertainty, how the biosphere will respond to climate change and we can therefore not just rely on the vegetation as a sink for carbon dioxide.

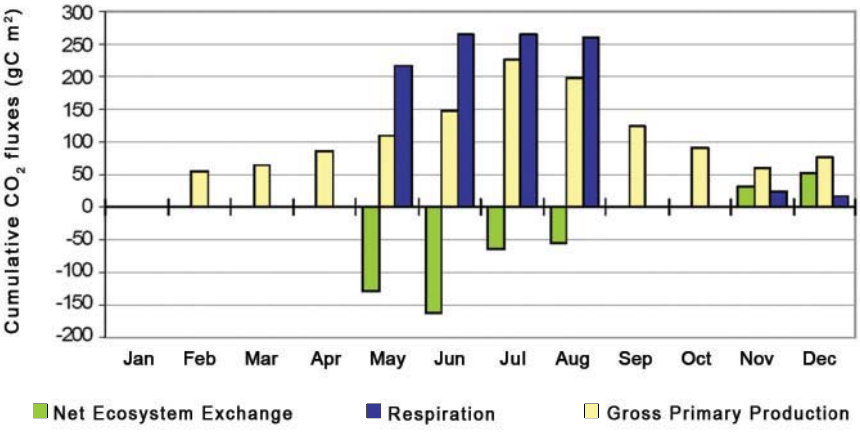


Figure 2: CO_2 fluxes from a station at Malga Arpaco, Italian Alps, at 1699 m a.s.l. from the year 2006. The Net Ecosystems Exchange (NEE) is the difference between the Respiration and the Gross Primary Production (GPP). Negative NEE indicates carbon storage, positive NEE relates to carbon loss from the soil pool.

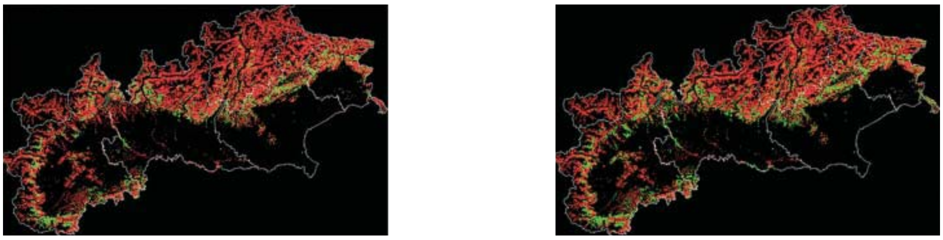
Mountain Ecosystems and Carbon Balance

At high elevations, the vegetation period lasts only for a few months. During the rest of the year, the soil is most of the time covered by snow. Consequently, carbon can only be accumulated during these few summer months, which means that the Net Ecosystems Exchange (NEE) gets negative (*Figure 2*). In case of the mountain grassland ecosystem at Malga Arpaco, Italian Alps, the accumulation lasts four to five months, depending on the year. During the winter months, carbon is lost to the atmosphere as respiration is still occurring due to activities in the snow covered soil. The CO_2 flux in the winter caused by respiration can, again depending on the year, represent a considerable proportion of the annual carbon balance. There is, however, a strong inter-annual variability of the NEE. The year 2003 was a very hot year with a heat wave going over Europe during summer. A lot of ecosystems had problems with these hot and long going weather conditions. Therefore, most temperate, low elevation ecosystems experienced a dramatic decrease in production. On the other hand, high elevation ecosystems in the Alps experienced an increase in production. In 2003, the NEE at Malga Arpaco, was about two times as large (~400 gC m^{-2} yr^{-1}) as in 2004 (~250 gC m^{-2} yr^{-1}). Such variations derive directly from different weather conditions. Hence, the climate modulates the extent to which ecosystems are able to capture atmospheric carbon. In this case, temperature increase leads to an increased carbon sequestration compared to low elevation ecosystems, where carbon sequestration decreased.

The summer 2003 was not only hot but also very dry. For that reason, the water content in the soil was also quite low. As a result, N_2O emissions, which are strongly coupled to the soil water content, were much lower in 2003 than in 2004. (Methane uptake depends also on soil water content and during dry years the uptake reduces, however I think it is fine to leave as an example N_2O). The variability of the carbon flux and of the N_2O emissions shows the sensitivity of the Malga Arpaco ecosystem to climate variability. In addition, the two examples show that higher temperatures are favorable in terms of carbon storage and greenhouse gas emissions.

Forests and Climate Change

Forests are also dominant ecosystems. It is important to stress that forests are not only influenced by the climate, but also by strong human activities. Such human activities also influence the carbon balance of forests. Young forests (<10 years) are mainly a carbon source due to activities in the soil. As the forest grows and matures, the carbon accumulation increases and the forest becomes a carbon sink. Hence, human activity on forests plays a role, whether the forest is a carbon sink or source (Magnani *et al.,* 2007). Based on the “Odum Paradigm” the theory has been established that forests cannot act as a carbon source or sink forever. Their carbon balance will become neutral at a certain point, because carbon losses by respiration get as high as the carbon capture by primary production. Such a theory, however, is not supported by actual data. Even at older age (>110 years old) forests still accumulate carbon. Thus, the service “carbon accumulation” is maintained for more than five centuries (Luyssaert *et al.,* 2008). This implies that conservation of old forests is often better than planting of new



Scenario a

Scenario b

Figure 3: Alpine area in northern Italy. In scenario a), which is based on statistical analysis only, 82% of the area (red) will be affected by species changes, while 18% will be unaffected (yellow). In this scenario, the species are not allowed to refuge from one area to another. In scenario b), which is based on statistical analysis and neighborhood criteria, the affected area accounts for 77,8% (red). This scenario allows the species to migrate to another habitat close to its original habitat. Hence, scenario b) is more realistic than scenario a).

forests. Preserving the storage of carbon is often more efficient than the accumulation, which is very slow.

Climate effects affect forests through different mechanisms. Firstly, winds have strong effects on forests. In Europe, wind is the largest contributor to forest damages caused by natural disturbances. Wind is far more important than fire or biotic disturbances. Nevertheless, the damages to forests caused by insects, plants or other pathogens can increase in the future as climate changes. When temperature shifts occur, pathogens can expand to other areas and damage the located forest of the invaded area. *Phythopthora cinnammomi*, for instance, is a pathogen that grows in areas with a moderate temperature range. A shift in temperature range at high elevations could push this pathogen into areas, where it is not present today. This will create new diebacks of forests and a change within the affected ecosystems. This phenomenon has already been observed in mountain areas (Vettraino *et al.,* 2007).

Biodiversity and Climate Change

Today, 1.7 Million species are known worldwide. This is only a small part of the estimated 15 Million species that may exist on the globe. This means that around 90% of the species are not known. Nevertheless, we strongly depend on these unknown species since they are part of ecosystems that provide us with essential services. For instance, new medicines are discovered based on products from different plant species. So, these plants are a source of chemicals for our well being. Today, a lot of species are in danger and may become extinct in the future. The extinction rate is very likely to increase in the future. In geological times the extinction rate of species was between 0.1 and 1 species per thousand years. In recent times, around 100 species per thousand years disappear. This rate will increase dramatically in the future. Estimates show that between 1000 and 10’000 species per thousand years will be eradicated in the future (Hassan *et al.,* 2005).

As a result, climate change has direct effect on the biodiversity within ecosystems. Nearly the whole alpine area in Italy will be affected by biodiversity changes. Statistical analysis show that the changes in species distribution will occur on 77-82% of this alpine region (*Figure 3*). Some of the forest biomes will disappear or heavily shrink as they cannot find a new suitable environment. Some biomes will shift to other altitudes and finally, some forest biomes will expand strongly and dominate the alpine region in the future.

Conclusion

Climate change will impact mountain ecosystems in different and possible unexpected ways (increased productivity, decrease biodiversity). The human beings strongly influence mountain areas, especially in Europe. Finally, conservation of old forests, particularly those of mountain regions, must be reconsidered since such forests provide essential ecosystem services.

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▲ *View on the Illimani Mountain and Kasiri Lake close to La Paz, Bolivia.*

Glacier Evidences of Climate Change in the Tropical Andes

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Abstract

The recent retreat of glaciers in the Central Andes (0°-16° S) can be considered as a good proxy of recent changes occurred over the last 30 years in the Tropical atmosphere at the 500 hPa level. Since the GCM are not yet accurate enough to simulate climatic change at the scale of the Andean cordillera, glaciers can be used as good indicators provided that the physical processes, which behave from the surrounded atmosphere to the surface can be accounted for. However, local conditions can mask the global evolution of glaciers and for that it is essential to dispose of a network of representative glaciers well distributed along the chain between the tropic and the equator to allow a signal to emerge.

We have at our disposal since 1991-1995, thanks to IRD and Andean partners, a permanent observatory on glaciers extending from Ecuador to Peru and Bolivia, giving a detailed image of conditions, which provoked the general glacier recession. We estimate that the retreat rates observed since 1976-1980 were unequalled since the end of the Little Ice Age (ca. 1880 AD), suggesting the effect of the recent global warming at high elevations. However, the recession was not continuously strong, but interrupted by several periods of stagnant or even advancing glaciers, suggesting the impact of the climate variability at the regional scale. Mass balance observations show that the glacier behaviors in the inner (5° N-5° S) and the outer (5°-16° S) tropics were quite coherent throughout the region, despite different sensitivities to climatic forcing such as temperature, precipitation, cloudiness, humidity etc. The coherent behaviors at the regional scale were mainly driven by the ENSO variability, which induced substantial modulations in the precipitation regime and the temperature of the atmosphere at high elevation. The processes, which control ablation at the glacier surface, seemed to vary from the inner to the outer tropic, but in any case albedo is the best factor, which traduces, through the precipitation (amount, frequency and phase), the atmospheric changes. In the outer tropic, as well as close to the equator, the seasonality of ablation was more important than expected at low latitude, particularly due to humidity, cloudiness and winds, factors, which control long-wave radiation and sublimation. Lastly, ablation at year scale was controlled by the few months, which combine a strong extraterrestrial radiation and humid conditions, i.e. DJF (summer solstice) in Bolivia-Peru and MAM/SO (equinox) in Ecuador. In the future, a warmer atmosphere could strengthen ablation during these months and extend melting conditions to other months.

Keywords: Andes; El Niño; Glacier Melting; Climate Change; Surface Energy Balance

Introduction

This paper gives a short compilation of the results of more than 15 years of glacier study in the Andes, lead by the Great Ice group of IRD, the Institute of Research and Development in France. This paper is divided in four parts. Firstly, an illustration is given of glacier retreat with variations of lengths, and areas, as well as some mass balance measurements. Secondly, the processes governing the melting at the glacier surface are discussed. In the third part, the glacier response at the regional scale is presented. Finally, an example of the expected impacts of glacier shrinkage, like the impact on water resources, is given.

Glacier Retreat in the Tropics

Figure 1 shows two pictures of the Chacaltaya glacier in 1994 and 2005. Chacaltaya glacier is a small size glacier in Bolivia. It is famous, because it was the highest ski resort in the world at 5300 m a.s.l. This small glacier, however, has been shrinking strongly in the last two decades and has entirely disappeared in 2008. At the beginning of the 1990s, the glaciated area had a size of more than 0.1 km^2, but in 2007 the area was smaller than 0.01 km^2. The story of Chacaltaya is rather common in the Andes, where about half the glaciated areas are small size glaciers (less than 0.5 km^2). Most of these small glaciers are presently disappearing. Larger glaciers of the Andes are also experiencing a fast retreat, as for instance the glacier at Cotopaxi volcano in Ecuador. Between 1976 and 2006, the glacier cover has been reduced by almost 40%.

Andean tropical glaciers have been retreating continuously, since the maximum extension of the little ice age in 1660. *Figure 2* shows the development of 15 glaciers in northern Bolivia distributed over 4 different massifs. Rabatel *et al.,* (2008) identified different moraine positions and dated those moraines by lichenometry. The areas of all the glaciers have been clearly decreasing. In addition, the decrease rate tends to accelerate during the last decades of the 20th century. The shrinkage was not a steady process though. Every moraine indicates a period of glacier growth, although the growth may have been only small. In the 20th century, there are

Figure 1: Illustrative pictures of the small Chacaltaya glacier, Bolivia, left in 1994 and right in 2005. In 2008, the glacier has disappeared (Source: Francou et al., 2007).

hardly any moraines left to find. Hence, almost no glacier growth occurred during the last hundred years. Francou *et al.* (2007) took a closer look at the length and area variations within the last century of 10 glaciers in Ecuador, Peru, and Bolivia. Their data show an additional acceleration of the glacier shrinkage since the end of the 1970s. This acceleration is rather synchronous between the three countries.

Why do glaciers actually shrink? The general shrinkage of tropical Andean glaciers is due to negative mass balances. The mass balance (MB) of a glacier is its volume change during a given period, usually one year, divided by its surface area. The MB is expressed in m water equivalent (m we) and is a straightforward consequence of the climate variation, although length and area changes are related not only to the climate but also to the proper dynamics of each glacier. To assess the MB in the field, accumulation measurements are performed in various points in the upper part of the glacier (using a drilling device, and performing density measurements). In addition, stake readings are made in the ablation area to have an idea of the ablation in various places of the glacier.

During the last 15 years, small glaciers (≤0.5 km^2) experienced a very negative mass balance with values around -1 m we/year, whereas the mass balance of larger glaciers (≥1.5 km²) is half of it (around -0.5 m we/year). Although the glaciers are generally shrinking, there is still a large inter-annual variability of the glacier retreat. The Antizana glacier in Ecuador, for instance, has been retreating between 1994 and 1998. It advanced slightly between 1999 and 2000 and finally retreated again since then.

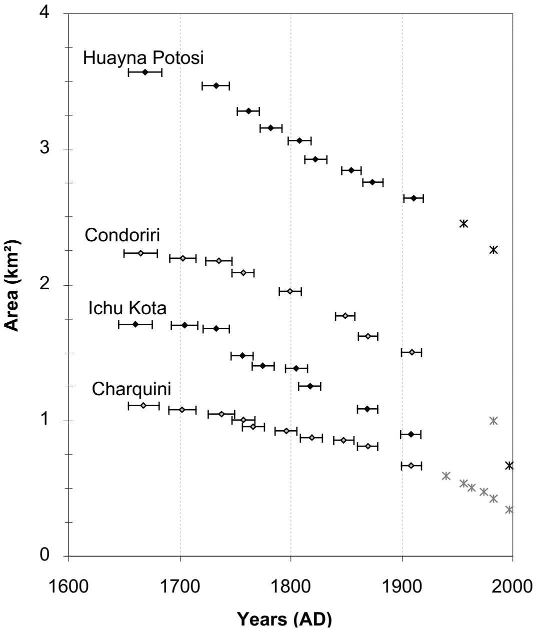

Figure 2: Reconstruction of the areas of 15 glaciers, which are part of the four massifs Charquini, Ichu Kota, Condoriri and Huayana Potosi. The reconstructions are based on moraines dated by lichenometry (1600-2000) in northern Bolivia. All glaciers have been retreating since the end of the little ice age in ~1660. The speed of melting, however, increased towards the end of the 20th century. Before 1950, dots stand for glacier areas reconstructed from moraine positions although after 1950, dots stand for areas measured by photogrammetry, or direct field measurements (Source: Rabatel et al., 2008).

Looking at annual specific mass balances, there is a strong inter-annual variability with mostly negative years and some positive ones (*Figure 3*). Comparing glaciers in Ecuador, e.g. Antizana, and those located in Bolivia, e.g. Zongo, there is a good synchronism in the inter-annual variability. This synchronism leads to the suggestion that the glaciers in those regions are sensitive to the same climatic forcing.

Processes Governing the Melting at the Glacier Surface

In order to study the processes responsible for the glacier melting, an assessment must be carried out including all the energy fluxes directed toward or away from the surface. Such an assessment provides information for the surface energy balance (SEB) of the glacier. The following fluxes are included in the SEB: the incident short-wave radiation S_{in}, coming from the sun. Part of it is reflected by the surface, which is the reflected short-wave radiation S_{out}. If the surface is white, the surface can efficiently reflect the incident short-wave radiation. This means that the albedo is high. Inversely, if the surface is covered by dirty bare ice, the albedo is low and the glacier efficiently absorbs the incident short-wave radiation. Albedo is defined as the ratio of the reflected short-wave radiation S_{out} divided by incident short-wave radiation S_{in}.

Furthermore, the incoming long-wave radiation L_{in}, emitted by the atmosphere and the clouds, contributes to the SEB. Some of this incoming long-wave radiation is again emitted by the surface as outgoing long-wave radiation L_{out}. Most of the time, the lower part of the glacier is in melting conditions at 0°C. Therefore, the outgoing long-wave radiation L_{out} is almost constant throughout the year.

Finally, turbulent fluxes are also part of the SEB. These fluxes directly depend on the wind speed and the vertical gradients of air temperature (for sensible heat, H) or specific humidity (for latent heat, LE). Energy can also be brought by precipitation (P), but it is negligible compared to the other fluxes. Finally, also a conductive heat flux G exists inside the glacier, which, however, is also negligible for temperate glaciers, like tropical glaciers. All these fluxes lead to the following SEB:

$$S_{in} - S_{out} + L_{in} - L_{out} + H + LE + G + P = \text{Melt}$$

When the sum of all the energy fluxes gives a positive amount of energy then the temperature of the surface layers increases to 0°C and melting starts. Thus, the above equation of the SEB allows us to quantify the melting, directly from all the energy fluxes.

The SEB, therefore, gives insight into the processes governing the melt. Usually, the key-variables of the SEB are, the incoming long-wave radiation L_{in} , the turbulent fluxes H and LE, and the net short-wave radiation $S_{in} - S_{out} = S$. S is directly related to albedo. The albedo itself is again controlled by the atmospheric key-variable precipitation. Besides the albedo, precipitation also controls the mass alimentation of the glacier. Other key-variables of the atmosphere are cloudiness and relative humidity, which influence S_{in}, L_{in} and LE. In addition, wind velocity controls LE and H. At last, air temperature plays an important role in controlling H and L_{in}. In conclusion, the main meteorological forcing comes from wind speed, air temperature

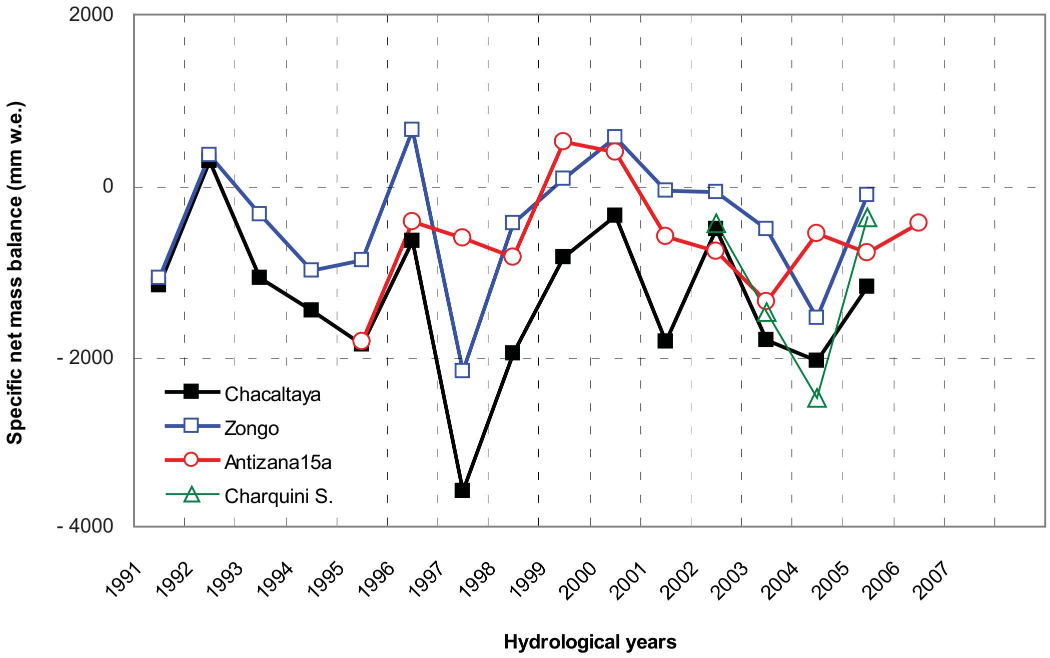

Figure 3: Specific net mass balance (in mm w.e.) of different glaciers between 1991 and 2007. Presented are data from the Chacaltaya, Zongo and Charquini glaciers, Bolivia, and the Antizana glacier in Ecuador (Source: Francou et al., 2003 and 2004).

and solid or liquid precipitation, which directly influence the albedo of the surface, the cloudiness and relative humidity (Wagnon *et al.,* 1999, 2001, 2003; Favier *et al.,* 2004a; Sicart *et al.,* 2005).

To set up the SEB, meteorological stations located outside the glacier (on moraines) gather information on meteorological trends. In addition, stations on the glacier itself provide data to derive the heat fluxes.

During the dry season, from May to August, ablation of the Chacaltaya glacier in the outer tropics of Bolivia is reduced and varies very little from year to year. There is, on the other hand, a very large variability of the ablation during the wet season from October to March. In some years, almost positive mass balances were measured during this period. Other years show a strong ablation. Consequently, the inter-annual variability of the mass balance comes mainly from the months of the wet season. The months of the wet season are also the months, during which the incident solar radiation is the highest (summer austral solstice). In the inner tropics, there is less seasonality of the mass balance but again, the inter-annual variability of the mass balance comes from the months, during which the incident solar radiation is the highest. That is to say close to

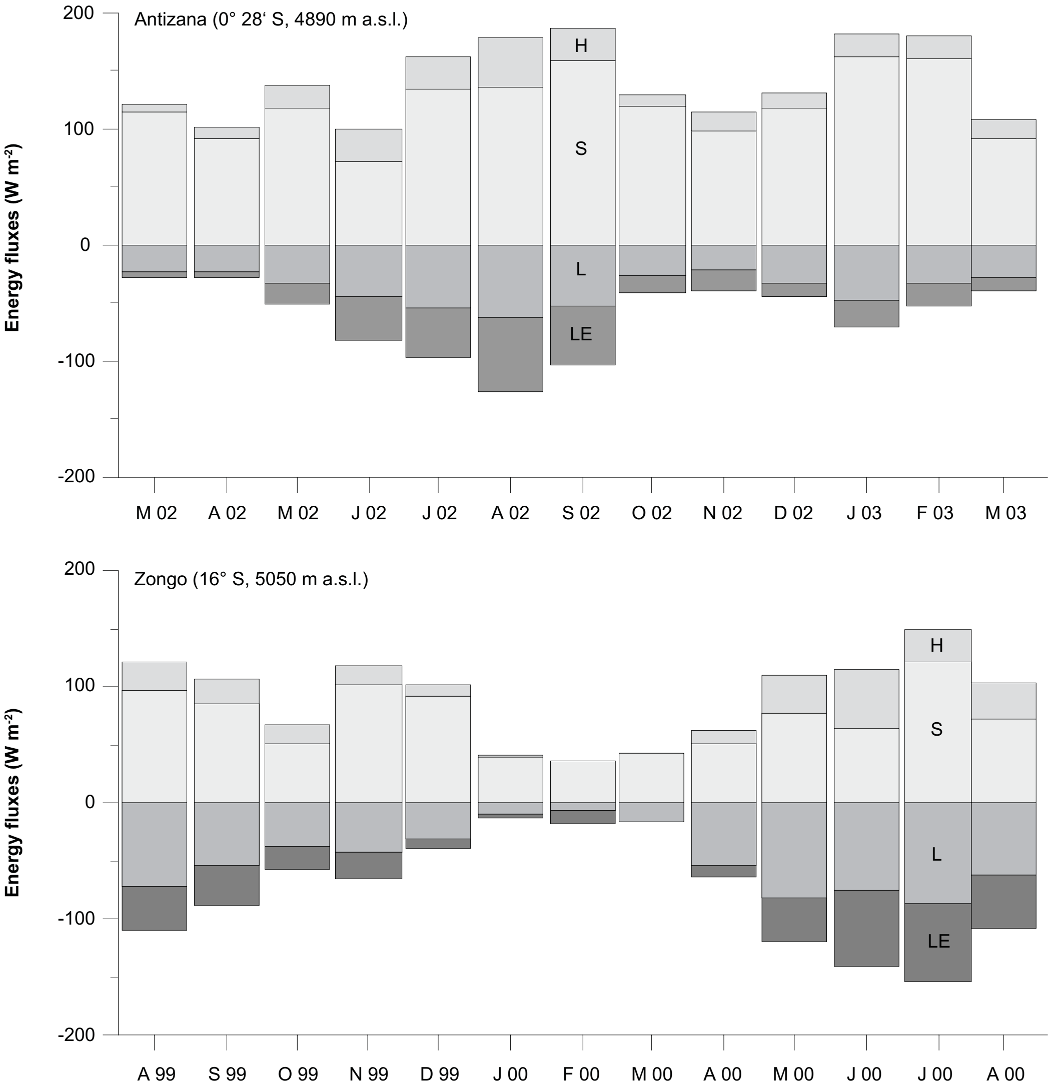

Figure 4: Annual cycle of the SEB of Antizana Glacier (from March 2002 to March 2003) and of Zongo Glacier (from August 1999 to August 2000). S = net short-wave radiation; L = net long-wave radiation; H = Turbulent sensible heat flux; LE = turbulent latent heat flux (Source: Favier et al., 2004a and 2004b; Sicart et al., 2005).

the equinoxes around March and September. Consequently, the melting is the highest during the precipitation season (Wagnon *et al.,* 1999; Favier *et al.,* 2004b; Sicart *et al.,* 2005; Francou *et al.,* 2003, 2004).

Figure 4 shows the annual cycle of the SEB of Antizana Glacier and of Zongo Glacier. For both glaciers, the main energy source at the glacier surface is the net short-wave radiation *S*, which is very dependent on albedo. In the case of Zongo, during the dry season, from May to August, most of the energy available at the surface is consumed. Energy consumption derives, on the one hand, by the net long-wave radiation L_{in} - L_{out} = L. L is then very negative due to low incoming long-wave radiation caused by reduced cloudiness. On the other hand, energy is consumed by latent heat flux caused by dryness of the air. Therefore, melting is reduced during the dry season, sublimation is high, and in total ablation remains low and poorly variable from year to year.

During the wet season, the pattern is totally different. The heat sink from net long-wave radiation is low, due to a higher incoming long-wave radiation. The turbulent fluxes are insignificant and therefore all the energy available as net short-wave radiation is used for melting. Depending on the year, however, this amount of energy is very variable and depends on the solid precipitation. Indeed, if there is a generous precipitation season, the snow cover on the glacier is thick enough to efficiently reflect the incident short-wave radiation, limiting the melting. On the other hand, with a deficit of precipitation, dirty bare ice is exposed at the glacier surface favoring the absorption of incident short-wave radiation. Consequently, melting is stronger in such a case.

In conclusion, the most important variables controlling the inter-annual variability of the mass balance of tropical glaciers are the amount and frequency of solid precipitation and the air temperature. Precipitation has a direct control on albedo and the air temperature controls the rain-snow limit and therefore plays indirectly on albedo. The seasonality of the mass balance is mainly controlled by the moisture-related variables like cloudiness or relative humidity. Cloudiness is responsible for the seasonality of incoming long-wave radiation. On the contrary, the relative humidity (or specific humidity) controls the latent heat flux.

Glacier Response at Regional Scale

The comparison of the cumulative mass balance over the last 15 years for two glaciers in Bolivia, and the Antizana glacier in Ecuador shows that there is a rather good synchronism between inner tropic glaciers and those located in the outer tropics. All glaciers show the same periods of high ablation, or low ablation (*Figure 5*). Consequently, all the tropical glaciers of the Andes seem to respond to the same climatic forcing, but the question remains, which one?

Figure 5 also contains the multivariate ENSO Index (MEI), indicating once positive El Niño events, and inversely La Niña events while negative. There is a good correlation between periods of high ablation and El Niño events, as for instance during the very strong El Niño event of 1997-98. Inversely, low ablation occurred during La Niña events, like in 1999-2000. During the El Niño situation between 1991 and 1995, there was still a reduced ablation, which can be explained by the fact that Mount Pinatubo erupted in 1991. This eruption emitted large quantities of volcanic ashes into the atmosphere. The consequence was a reduction of incident shortwave radiation in the tropical belt at global scale (Francou *et al.,* 2003, 2004).

Francou *et al.,* (2003) showed that the monthly mass balance of Chacaltaya glacier (in Bolivia) and the Sea surface temperature (SST) of the Pacific Ocean strongly correlate. Some areas in the Pacific have a positive correlation with the mass balance, others have a negative one. The best anticorrelation is obtained between Chacaltaya mass balance and SST for the Region Niño 1-2, with a two month difference between both series. This indicates that there is a link between surface temperature in the Ocean and the behavior of glaciers. A similar corre-

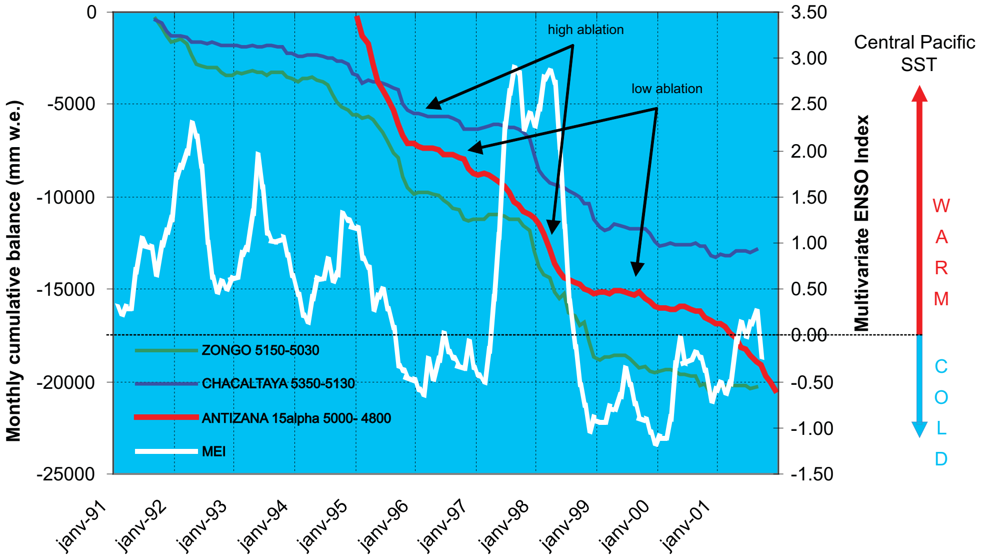

Figure 5: Monthly cumulative balance of the Zongo and Chacaltaya glacier in the outer tropics, Bolivia, as well as of Antizana glacier in the inner tropics, Ecuador (left scale). The curves show similar patterns for all glaciers with periods of high ablation and low ablation. These different ablation phases correspond with the El Niño/La Niña phenomenon expressed through the Multivariate ENSO Index (MEI; right scale). Positive MEI values indicate El Niño phases. They correlate with high ablation and increased sea surface temperatures (SST) in the Central Pacific. During La Niña stages, low ablation occurs and the Central Pacific is colder. Between 1991 and 1994, the ablation is reduced although a steady El Niño phase took place. A possible reason is the eruption of Mount Pinatubo, whose ashes may have reduced the incident short-wave radiation leading to a cooling of ~2 W m^2 (Source: Francou et al., 2003, 2004).

lation can be observed for glaciers in Ecuador. For these glaciers, correlation is best with El Niño 3-4 region with a difference of 3 month. These correlations (or anticorrelations) between SST in various areas of the Pacific Ocean, and Andean glacier mass balances show that these glaciers are influenced by the climate not only at local scale (10-100 km) but also at regional scale (100-1000 km).

There are different mechanisms, how El Niño/La Niña affect the glaciers in Bolivia and Ecuador. During El Niño events, precipitation decreases in the region. In Bolivia the decrease can amount -10 to -30%. The reverse situation prevails during La Niña events. Such a precipitation change directly influences the albedo. Increased snowfall during La Niña stages augments the albedo towards one. During El Niño events, less snow is falling and the glaciers get a darker surface. Such a darker surface can decrease the albedo down to 0.1, leading to a more efficient absorption of incident short-wave radiation during El Niño events, and consequently, to a more pronounced ablation.

El Niño events are also characterized by warmer situations, and the condition is also reversed during La Niña. Due to the indirect influence of air temperature on the elevation of the snow-rain limit, the albedo is reduced during El Niño, as the limit is located at higher elevations. Therefore, less fresh snow covers the glacier surface, which again leads to increased ablation. Actually, the deficit of precipitation is the main factor affecting the albedo in the outer tropics while the rising snow-rain limit is the main one in the inner tropics. The consequences, however, are the same: strong ablation during El Niño events, and reduced ablation during La Niña phases. During El Niño (La Niña), there is also a reduced (increased) cloudiness, which has an impact on the amount of incident short-wave radiation. This effect is partly counterbalanced since changes in cloudiness also affect the long-wave radiation (Wagnon *et al.,* 2001; Francou *et al.,* 2003, 2004).

Impacts on Water Resources: The Zongo Glacier

Most of the glaciers in the Andes are small glaciers. Most of these glaciers will disappear in the coming decades, which has direct impacts on the water resources.

As illustration of expected impacts on water resources, the Zongo glacier serves as example. This glacier is located 30 km from the capital of Bolivia, La Paz. Water coming from its melted ice is collected for domestic water supply and to fill dams for hydropower production. In the region, most of the water is available during the wet season, but there is still a consequent amount of water available during the dry season, thanks to glacier melt. Without the glacier, the situation would be very different. More or less the same amount of water would be available during the wet season, but almost no water would be available during the dry season. The expected consequences are very heavy, because a large part of the population in the La Paz area relies on the glacier during the dry season. If the glacier shrinks or even disappears, water supply for drinking water, irrigation or hydropower, will become a very challenging task to tackle.

Conclusion

In conclusion, the glacier retreat in the Central Andes is mainly a consequence of climate change, which occurred in the middle of the 1970s:

- Glaciers are not in equilibrium with the present conditions (1991-2007). Therefore, a rapid shrinkage is under process and might be more and more important in the future.

- Small glaciers have their Equilibrium Line Altitude above their upper limits and they will disappear in the next decades. This is important, because almost half the glaciated areas in the Andes are small glaciers.

- Albedo is the key factor of the SEB and, consequently, meteorological variables affecting albedo (solid precipitation (amount and frequency) and/or air temperature controlling the rain/snow limit) have the main effect on glacier mass balance (MB). These variables especially influence the inter-annual variability of the MB.

- Moisture related variables (relative humidity, cloudiness) are responsible for the seasonality of the melting and therefore also influence the MB.

- Andean glaciers are very good climatic indicators at regional scale and they are heavily influenced by ENSO events.

Acknowledgment and Outlook

So what can we expect in the future? This paper has shown that tropical glaciers are very sensitive to global warming predicted by several models. The studies cited herein are based mainly on measurements in the field. I want to emphasize the fact that a monitoring network of glaciers in the Andes is very important. Thanks to IRD, local partners, and other international institutions, like the Glaciology group at the Innsbruck University, we have now a good network on the glaciers in the Andes. This network, however, must be maintained and developed in the future, in order to study the glaciers, and the climate in high altitudes. Special thanks must be addressed to all organizations that have contributed to bring financial support to the monitoring programme.

In the framework of our IRD group, we are also developing a similar programme in the Himalayas. For the moment, two glaciers are monitored for mass balance, one in India in the arid-monsoon transition zone, and the other one in Nepal, directly influenced by the Asian monsoon. This monitoring will be completed in 2008 by meteorological and hydrological monitoring, as it is done in the Andes. Again, here, the aim of this project is to study the glaciers as climatic indicators. In addition, we want to try to forecast the impacts of retreating glaciers on the population, which relies on glaciers for water resources. Glaciers are not just located far up in the mountains. They cannot be ignored since they provide large amounts of the global population with water. Therefore, the shrinkage or even the disappearance of glaciers will directly affect several million people. To minimize the negative effects of the shrinkage, research on glacier must be continued.

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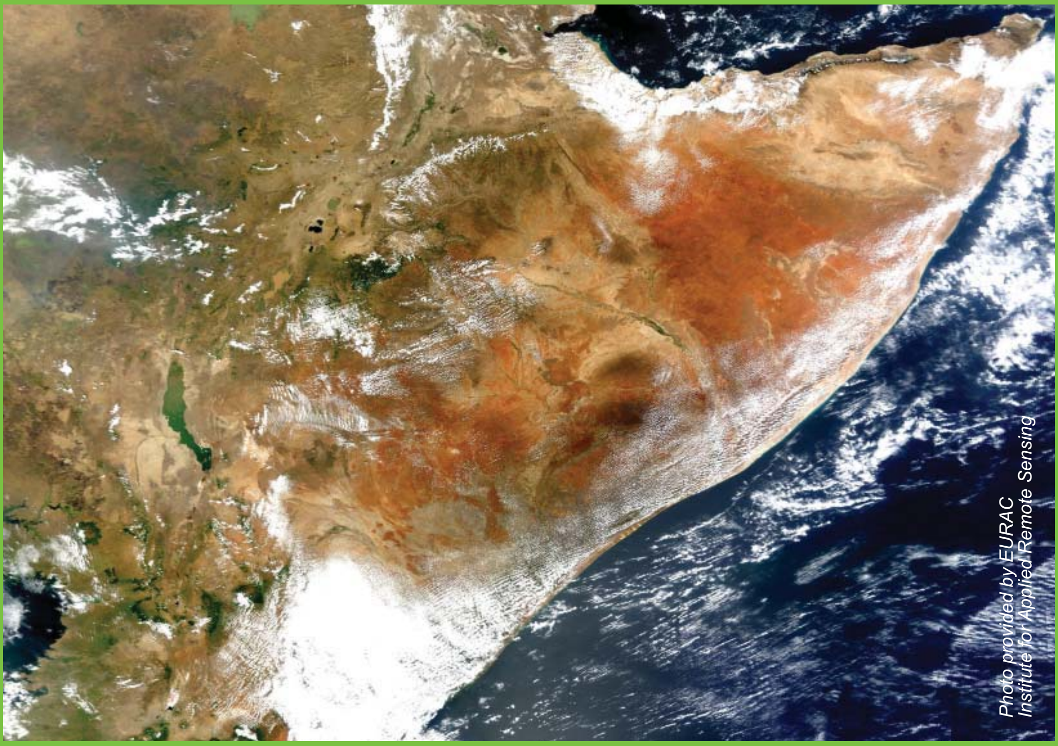

▲ *The Ethiopian Highlands from Space.*

Climate and Cryospheric Changes within the Trans-African Alpine Zone: Scientific Advances and Future Prospects

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Abstract

The eastern arc of African high mountain environments spans from northern Eritrea (Jabal Hamoyet: 2780 m a.s.l.) at ca. 18° N to the southern Cape (Matroosberg: 2249 m a.s.l.) at ca. 33° S. This synopsis briefly examines the scientific contributions made towards our current understanding of the climatic and cryospheric dynamics across the eastern arc mountains of Africa. Whilst some mountains of international interest such as Kilimanjaro, Mt. Kenya and the Rwenzori have had some well established science programmes focusing on glacier recession, ice core data, and contemporary climate monitoring, many other high altitude ranges exceeding 3000 m a.s.l. have few or no climate/cryogenic records. A full understanding of climate change within the African alpine belt requires an assessment of Quaternary (particularly Holocene) climate changes through paleoclimate records, historical changes (last 2 to 3 centuries) through archival documentary and instrumental records, and contemporary changes through ongoing long-term climate and cryospheric monitoring. To this end, a Global Change Research Network for African Mountains was established in 2007 and a subsequent initiative to establish observatories at high elevations in Ethiopia was discussed at a workshop in Addis Ababa, Ethiopia in January 2008.

Keywords: Review; African High Mountains; Eastern Arc; Cryosphere; Climate

Introduction

In Africa, limited work has focused on mountain climatology, whilst the quality of previous data outputs should also be brought to question. However, in the recent years there have been some significant contributions made to broadening our understanding of Afro-alpine climate dynamics, particularly from Kilimanjaro (Tanzania) and the Rwenzori mountains (Uganda/DR Kongo) (e.g. Mölg *et al.,* 2003a,b). Many of the numerous other African mountain environments, despite their absence of glacial ice, are equally important water towers to surrounding drier regions. African mountains are thus important landscape components requiring an understanding of site-specific climate change, particularly given that many subsistence livelihoods are dependent on the resources from such mountains. The aim of this paper is not so much to reflect on specific research outputs, but rather to provide an overview on the scientific advances concerning the Afro-alpine cryosphere and climate. The geographic focus-area of this paper is mainly along the eastern sector of Africa.

According to Diaz and Graham (1996), *"observed changes in freezing-level height are related to a long-term increase in sea surface temperatures in the tropics [...] tropical environments may be particularly sensitive because the changes in tropical sea surface temperature and humidity may be largest and most systematic at low latitudes."* To this end, Africa has a high representation of tropical high altitude sites (e.g. Mt. Kenya, Ruwenzori, Kilimanjaro), which hold potential paleoclimate records through various proxies; these could in turn provide indications of paleo-Indian Ocean surface temperatures and circulation patterns, particularly over the tropical regions. In addition, the eastern sector of Africa has an extensive latitudinal representation of high mountains from the Eritrean highlands in the north to the Cederberg (Western Cape, South Africa) in the south, thus providing potential opportunities to examine and monitor latitudinal shifts in high altitude climates.

Very importantly, most African Mountains are biological hotspots, host high levels of endemism, and offer refugia to endangered flora and fauna. A typical example is the Ethiopian Wolf, which only survives in small isolated populations across high mountain belts of Ethiopia, and which is said to be the rarest canid in the world. Ongoing climate change in the Ethiopian Highlands affects the wolf population both directly and indirectly. Finally, many of Africa's mountains are surrounded by arid to semi arid regions, making them tremendously valuable storehouses of water resources. It is thus imperative that we seek to understand the past and contemporary climate and hydrological changes in Africa's high mountain regions; such an endeavor should provide site specific data required for improving future climate/hydro forecasts, which currently rely mostly on Global Climate Models (GCMs). This paper focuses mainly on the Ethiopian Highlands, the Central East African Rift System and the Drakensberg in South Africa, however, starting first with a short remark on the Jebel Marra (*Figure 1*).

Jebel Marra

Jebel Marra is a mountain region of volcanic origin in northern Darfur, Sudan (12° 57′ N, 24° 16′ E), rising to 3070 m a.s.l. FAO apparently wrote a report on the climate of Jebel Marra in 1968. Although Abdalla and Babikir (1988) wrote a paper on the vegetation, soil and land use in Jebel Marra, there appears to have been no other recent scientific publications. Rainfall is said to have declined by 10 to 15% since the late 1960s, and given its valuable water resource in an otherwise very water-scarce environment, the area is politically sensitive. Much of the conflict in the Darfur is related, at least in part, to different ethnic groups moving towards the Jebel Marra to draw on its water resources.

Ethiopian Highlands

What do we know?

Hans Hurni was probably one of the first researchers to initiate a high quality, but rather short-term climatic monitoring in the Semien mountains of northern Ethiopia (Hurni, 1982). This work was undertaken during the 1970s to altitudes exceeding 3600 m a.s.l., but unfortunately was discontinued over the longer-term. Although over ten meteorological stations in Ethiopia are located in the Highlands, some reaching altitudes of 2800 m a.s.l., which at

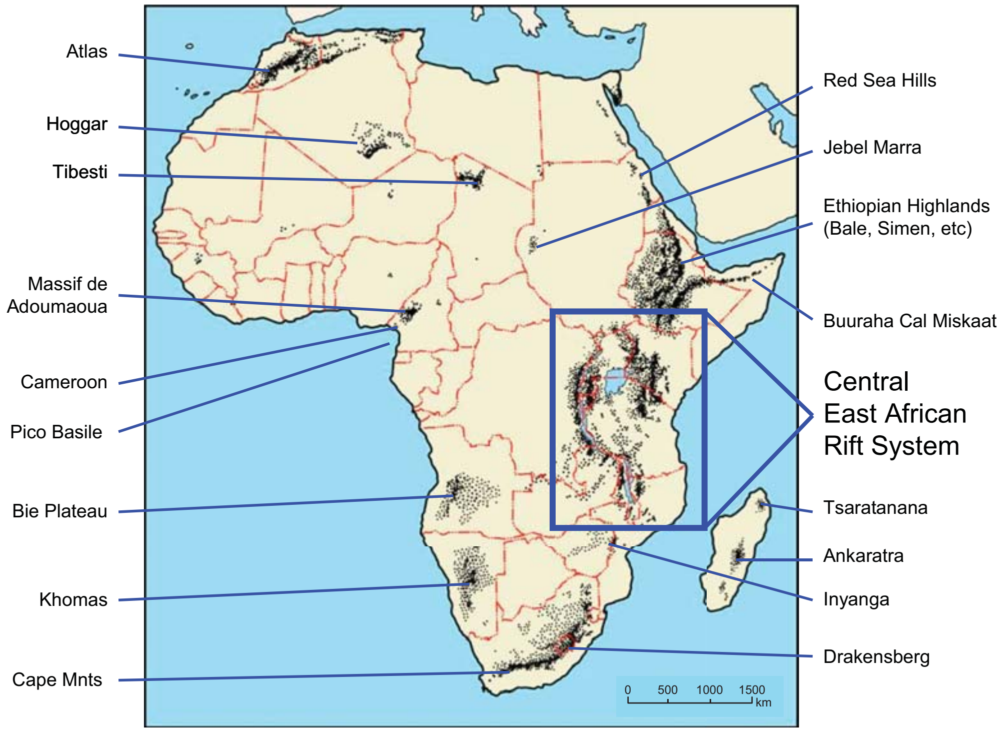

Figure 1: Mountain Ranges of Africa (Drafted by S. Grab)

a global scale is relatively high, we need to recognize that a high percentage of Ethiopia lies between 3000 and 4000 m a.s.l. Unfortunately, no long-term meteorological records exist for altitudes above 3000 m a.s.l. This epitomizes a concern relevant to much of Africa's high mountains, where valuable climate monitoring programmes are started up but not extended over time (i.e. decades rather than years).

Although Osman and Sauerborn (2002) published some long-term climate trends for the Ethiopian Highlands, these are based on lower altitude climate data. Some valuable rainfall data from the late 19th century exists from geographers who explored the region at that time. Considerable research has focused on Quaternary climate change, which is mainly based on proxy records (e.g. pollen). These climate change data are primarily reconstructed from sediment cores of high altitude lakes, especially from the Bale Mountains (e.g. Mohammed and Bonnefille, 1998). The reconstructions have produced some fantastic chronologies going through the Holocene. However, the temporal resolution of the paleoclimate reconstructions is rather limited.

A positive aspect is that historical documentary records reflecting past climates do exist. For instance, Simoons (1960) undertook a review on some historical documents reporting on past snowfall events in the Ethiopian Highlands. In my point of view, Simoons presented a very one sided approach, lacking in objectivity. Simoons discredits several past accounts on snow and argues that observers probably saw hail rather than snow. Nevertheless, Simoons found some interesting documents, which are worth further assessment. He quoted, for instance, that a 3rd century Axumite king who speaks of the Semien Mountains as *"difficult to access and covered with snow, where the year is all winter with hailstorms, frosts and snows into which a man sinks knee-deep"* (Simoons, 1960). Contemporary snowfalls are rare in Ethiopia and only light snowfalls are occasionally reported from the higher summits (> 4000 m a.s.l.). A further detailed analysis of past and contemporary snowfalls could improve the current understanding of historical climate change in the Ethiopian Highlands. In conclusion, there are documents about Ethiopia, which go back hundreds of years and which may contain valuable information about past climate change. We are now initiating a project to examine these documents.

What is required?

As mentioned above, one possibility is to reconstruct past climate changes based on documentary records, whilst another is via natural sciences using a variety of proxy data. Although there is no contemporary evidence for permafrost in the Ethiopian Highlands today, a key question is whether there was permafrost during the historical or more distant past? What was the timing of deglaciation within the different regions of Ethiopia? Although Henry Osmaston has undertaken extensive research in the Bale Mountains (e.g. Osmaston *et al.,* 2005), little is known about past glaciations across many of Ethiopia's other high mountain regions. To obtain long-term instrumental climate records, the installation of atmospheric and ground climate monitoring stations in high mountain regions is urgently required throughout Ethiopia. In addition, satellite based research should be encouraged and developed to monitor contemporary precipitation patterns and map cloud and snow cover.

Mount Kenya

What do we know?

Mount Kenya (Kenya) reaches an altitude of 5202 m a.s.l. and is located in the eastern part of the Central East African Rift System (*Figure 1*). As far as this mountain is concerned, we have a similar research history to that of the Ethiopian Highlands. In the early 20th century, geographers who explored the mountain provided excellent descriptive accounts on climate and glacier extent. Although these early records are descriptive, they contain valuable accounts on temperature and other weather phenomenon. These documented recordings are sometimes only for a single day, whilst a few were taken over a short period of four to five consecutive days at particular sites. Although limited, such records may be potentially valuable when comparing to contemporary climate conditions at the same localities.

Extensive work on alpine sedimentary chronologies (moraine and lake sediments) have been undertaken by such as Mahaney (1970s -1980s; e.g. Mahaney, 1982, 1984, 1988), Karlén *et al.* (1999) and Barker *et al.* (2001). The extracted sediment cores from high altitude lakes have yielded fantastic high resolution Holocene climate chronologies, and more specifically, indications on past glacial advances and moisture balances during the Holocene. Regular glacier surface area or mass balance reports on Mt. Kenya's remaining glaciers have been made since the 1980s, and is ongoing (e.g. Hastenrath and Kruss, 1992).

High mountain atmospheric and ground climate monitoring on Mt. Kenya was initiated by Winiger (1981), who set up a climate station at almost 4800 m a.s.l. Unfortunately, this was also a short-term project, primarily due to vandalism, which is a common problem to research undertakings in Africa. From the 1990s onwards, Global WMO/GAW stations were established at 3678 m a.s.l. and at 4200 m a.s.l. to monitor standard meteorological data, and since 2002, CO and O_3 are also monitored at the sites.

What is required?

It is necessary to ensure continued climate monitoring at the two WMO/GAW stations (3678 m a.s.l. and 4200 m a.s.l.). Although these two stations are currently running, we need to reestablish the 4700 m a.s.l. station near Point Lenana, adjacent to the Lewis glacier. The Lewis glacier is in its last phase of existence and it would be ideal to monitor the ongoing glacial retreat in conjunction with on-site climate dynamics. Important constraints, however, are vandalism and theft at the installations.

Kilimanjaro

What we know?

Kilimanjaro is also located in the Central East African Rift System, reaching 5895 m a.s.l. In the early 1900s, geographers began to explore Kilimanjaro, as was the case for Mt. Kenya. Again, documents containing excellent descriptive climate and glacier records were produced. Some of the early manuscripts provide comprehensive sketch maps of the Kibo crater area at the summit. For instance, some of the maps contain detailed site information on fumaroles in the region. Subsequent visits and remapping of the sites has provided good literature on neotectonic and glaciological changes in the summit region of Kilimanjaro (Thornton, 1865; Holdich *et al.,* 1900)

Unfortunately, Kilimanjaro has received very limited periglacial research attention, with only two or three papers published thus far (e.g. Hastenrath, 1973; Furrer and Freund, 1973). Knowledge on past or present permafrost and ground ice dynamics is absent. On a more positive note, there has been regular work on the glacial mass balance and glacial surface area extent. In addition, several reviews have been made based on sketch maps, tacheometry (late 1950s) and aerial photogrammetry, photos, and landsat images (1980s onwards) (e.g. Hastenrath and Greischar, 1997; Kaser *et al.,* 2004). Finally, Thompson *et al.* (2002) took ice cores from the summit area and produced a Holocene glacial chronology.

Since 2000, Hardy and his group have been continuously monitoring the climate at the northern ice field, which has assisted in the calibration of ice core data (e.g. Duane *et al.,* 2008). Chan *et al.* (2008) have shown that precipitation on the summit of Kilimanjaro is primarily connected with the Indian Ocean Circulatory Systems. If ice core records are available from the same area, we could possibly reconstruct past changes in the Indian Ocean Circulatory System based on our understanding from the contemporary work.

As far as the retreat of the Kilimanjaro ice is concerned, it has been common practice to assume that the rapid ice retreat is due to climate warming. However, recent work by Kaser *et al.* (2004) has demonstrated that the causes of ice volume reductions are somewhat more complex than merely ‘climate change’. Several factors such as precipitation dynamics, the ice mass geometry, radiation dynamics and geothermal activities have influenced recent decadal-scale mass balance changes on Kilimanjaro.

What is required?

As is the case for Mt. Kenya, we need to ensure that climatic and cryospheric monitoring continues on the Kilimanjaro summit and lower altitude zones. In addition, we need to establish the presence, distribution and characteristics of permafrost wherever it might occur. The following research initiatives have been identified for the near-future on Kilimanjaro:

1. To establish bore-hole temperature recording to 2 m depths for possible CALM sites (Circumpolar Active Layer Monitoring). A proposal has been submitted by David Palacios (Spain) and Stefan Grab (South Africa).

2. To record periglacial phenomena and processes.

3. To monitor geothermal activity and understand the role of geothermal heat sources.

4. To establish multicentury ice cap histories, as has been proposed by Georg Kaser.

Rwenzori / Virunga Mountains

What do we know?

The Rwenzori and Virunga mountains along the western Albertine Rift reach a maximum height of 5109 m a.s.l. at Margherita Peak. There have been regular commentaries on the glaciers, dominated by Heinzelin, Whittow and Osmaston in the 1950s-1960s. An apparent gap of scientific information occurred from the 1970s to mid 1990s, when an important review paper was written by Kaser and Noggler (1996). Ongoing work post 2000 has also placed increasing emphasis on the implications that climate/glacial changes have on mountain hydrology. Unfortunately, long-term climate data are not available. Some limited climate data are available from the Karisoke Research Centre (3100 m a.s.l.) from 1979 onwards, whilst Sabinyo (2500 m a.s.l.) and Kinigi (2200 m a.s.l.) have data for a few years only. As mentioned by Bagoora (1988), the problem with such stations is that they are located at much lower altitudes than the high mountains they are often meant to represent. The paucity of climate data has particularly limited zoological studies, such as for example those investigating gorilla mortality (Byers and Hastings, 1991). More recently, Italian researchers have established climate observatories at high altitudes in the central Rwenzori, which should hopefully assist in filling a major climate data gap. Given the scarcity of instrumental climate records, historical documents (early 1900s) are potentially very valuable resources that could help describe past environmental conditions and ascertain possible relative climate changes over the last century. Some examples:

> *Karisimbi is the highest peak….nearly always snow-covered…'*
> (Jack, 1913, p535)
>
> *'….and the snow-capped crest of Karisimbi, this last over 14,000 feet'.*
> (Philipps, 1923, p236/7)

What is required?

The Rwenzori require ongoing glacier and climate monitoring work to establish trends in glacial recession associated with climate variability/change. Periglacial phenomena and processes (e.g. permafrost?) are not well known in the Rwenzori and thus require attention. In addition, as is the case with other East African alpine zones, it would be advantageous to:

- Establish CALM sites (if permafrost is present).
- Establish additional atmospheric and ground climate monitoring at high altitudes (particularly for Karisimbi and other high volcanoes)
- Establish the status of previously installed weather stations in the Rwenzori.
- Establish historical climate change in the Rwenzori (last ca. 150 yrs).

Drakensberg – Maluti System

What do we know?

The Drakensberg are located along the border of Eastern Lesotho and KwaZulu-Natal province in South Africa, and reach a maximum altitude of 3482 m a.s.l. at Thabana Ntlenyana. Since the mid 1930s, over 70 publications have dealt with the periglacial and glacial geomorphology. Much of the debate has focused on whether there was Quaternary glaciation and/or permafrost during the Last Glacial Maximum. Recent work has confirmed both localized paleo-permafrost (Grab, 2002) and small-scale niche glaciation ca. 17000 yrs BP (Mills and Grab, 2005; Mills *et al.,* in press). Although there have been several short-term (usually less than 10 years data) climate assessments for the high Drakensberg (e.g. Grab, 1997; Nel and Sumner, 2008), the establishment of longer-term (10s of years) observatories is urgently required. Despite the absence of data, some detailed mountain climatological studies have been undertaken in the region (e.g. Tyson and Preston-Whyte, 1972; Freiman *et al.,* 1998).

Current research is focused on developing chronologies of historical climate change (last 160 years), based on documentary evidence, and satellite based climate studies on snowfall distribution patterns (e.g. Mulder and Grab, 2002). Annual rainfall trends and cold season severity have been compiled for the 19th century; findings suggest that the trends are not strongly linked with ENSO events (Nash and Grab, submitted; Grab and Nash, submitted). Preliminary findings for the Lesotho region suggest there was a 50-60% decrease in snowfall between the 1830s and the 1890s (Grab and Nash, submitted).

The work on snow mapping will be used for risk assessment mapping and disaster risk reduction initiatives. Research at the University of Witwatersrand is investigating contemporary snowfall patterns in order to identify high risk areas for the population living in the Drakensberg, especially during catastrophic snowfall events. In addition, the distribution of long lasting snow patches is being compared against the distribution of active and fossil periglacial and glacial phenomena (e.g. moraine) so as to better understand the potential role of snow as a geomorphic controlling factor.

What is required?
Two primary future objectives are to:

1. Undertake high resolution / high precision paleoclimate verification. A programme to do cosmogenic dating and ostrachod work on recently discovered glacial moraine and paleo-lake sediments is now underway (Carr, Mills, Grab, Horne).

2. To establish permanent climate observatories.

Current African High Mountain Initiatives

The *'Global Change Research Network in African Mountains'* (GCRN-AM) was launched at Makerere University, Kampala, Uganda in July 2007, under the auspices of the *Mountain Research Initiative* (MRI), *Global Mountain Program*, *African Highland Initiative*, and a variety of other organizations and institutions. Makerere University is currently the 'home base' for the GCRN-AM. Four key working groups were established in Kampala, namely:

- Climate change
- Land use / land cover change
- Livelihoods / decision making
- Biological systems


Photo: iStockphoto.com

A follow up workshop was held in Addis Ababa (January 2008) to generate interest and formulate direction towards establishing high altitude observatory systems in Ethiopia. A similar initiative is now also underway to establish observatories in some of the southern African mountain regions.

Concluding Remarks

Geophysical research outputs and current needs are highly variable across the respective African mountain regions. Climate monitoring in most African high mountain areas is either absent or has lacked continuity; there are consequently only sporadic short-term data sets. The primary emerging requirements to fill the current geophysical research gaps are to:

- develop a database for past geophysical research outputs and current programmes.

- identify high priority monitoring sites within respective mountain regions.

- set-up regional monitoring networks and install standardized weather stations and borehole probes for links with GCOS (Global Climate Observing System) and GTN-G (Global Terrestrial Network for Glaciers) etc.

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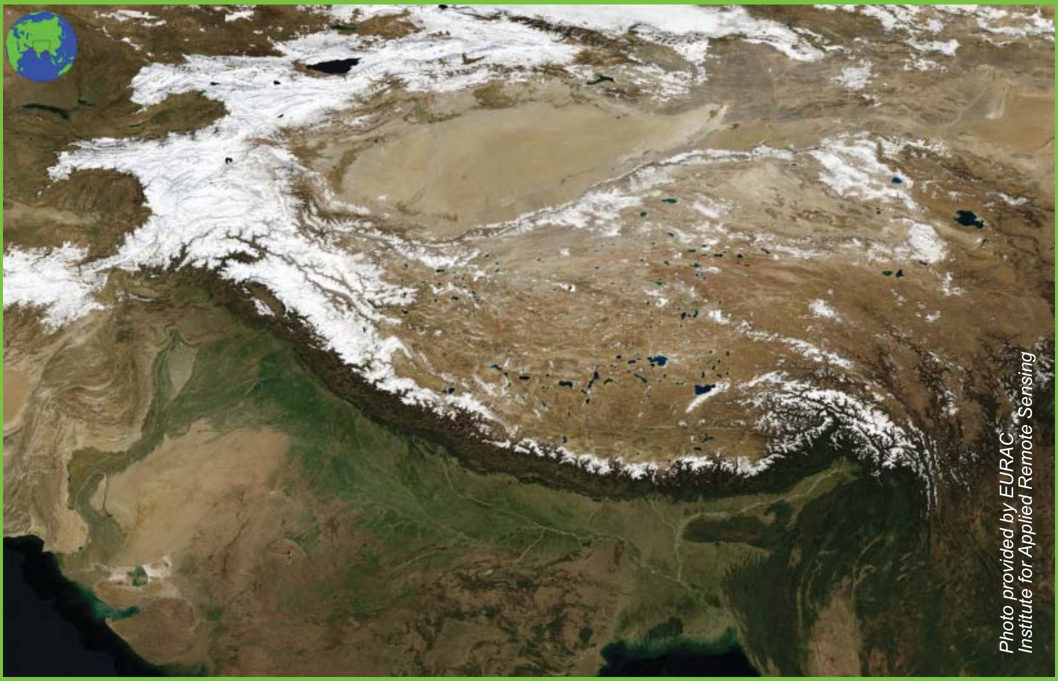

▲ *The Himalayas from Space.*

Hindu Kush & Himalayan Glacier Changes: Global Change Anomalies

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Abstract

Change detection on the glaciers of the Hindu Kush and Western Himalaya of Afghanistan and Pakistan is part of the Global Land Ice Measurements from Space (GLIMS) project being run by scientists at the University of Nebraska at Omaha (UNO) and their Steward collaborators from other universities. The UNO GLIMS Regional Center for Southwest Asia has undertaken tracking of glacier extents, snowlines, velocity fields, terminus positions, associated meltwater portals, lakes, white-ice stream locations, and debris-cover characteristics, primarily using ASTER satellite imagery as well as numerous other data sources. Lack of familiarity or general confusion in the literature with local naming conventions and more exact geographical locations of mountain chains have led us to a more definitive mapping of ranges using satellite imagery. In addition several decades ago one of us (JS) began investigations of glacial chronologies in the region that continues up to the present day in the Nanga Parbat, K2 and Shimshal Valley projects.

Glacier boundary changes in the recent past have been assessed in a series of case studies across the Hindu Kush and Western Himalaya with the result that many, if not most of the glaciers of Afghanistan are seen to be in strong down-wasting and back-wasting whereas in the higher Himalaya and Karakoram of Pakistan many glaciers are not changing greatly, although supraglacial and pro-glacial lakes may be on the increase in some places and surging seems to be increasing. Some 87 surge-type glaciers have been identified throughout the Karakoram region of Pakistan, India, and China, with 53 that have never been described previously. Anomalous climatic effects include increased precipitation, and downward trends in summer temperatures, perhaps due to increased cloudiness, which suggest that the Western Himalaya and

Karakoram are showing different response to global warming than elsewhere. Recent expositions of glacier change throughout the Hindu Kush, Himalaya, and Tibetan Plateau by many different groups indicate high variability caused in part by natural causes as well as incorrectly by non-standardized interpretations. These problems must be dealt with by new research protocols to deal with preprocessing, information-extraction and temporal-variability issues.

Keywords: Climate Change; Glaciers; Hindu Kush; Wakhan Corridor; Batura Glacier; Karakoram Mountains

Introduction

In the late 1990s the Global Land Ice Measurements from Space project (GLIMS) was set up in order to monitor world's glaciers. All over the world, countries were contacted and asked to work together in this project. Neither Pakistan nor Afghanistan, however, responded to a possible cooperation within the GLIMS Project. At that time, Afghanistan was dominated by Taliban, which had no interest in glaciers. The reasons for the original lack of interest in Pakistan are unknown but probably there were political or economic difficulties for them to ignore the initial inquiries from the US Government.

Today, Pakistan has interests in glaciers. Actually, two different agencies in the Pakistani government are dealing now with glaciers, the agricultural ministry and part of the climate change ministry. Most of the responsible people are older Pakistanis, who were trained around 25 years ago, so we now have new grant money from the US Agency for International Development (US AID) to bring additional educational efforts about glaciers and melt-water to young Pakistani scientists.

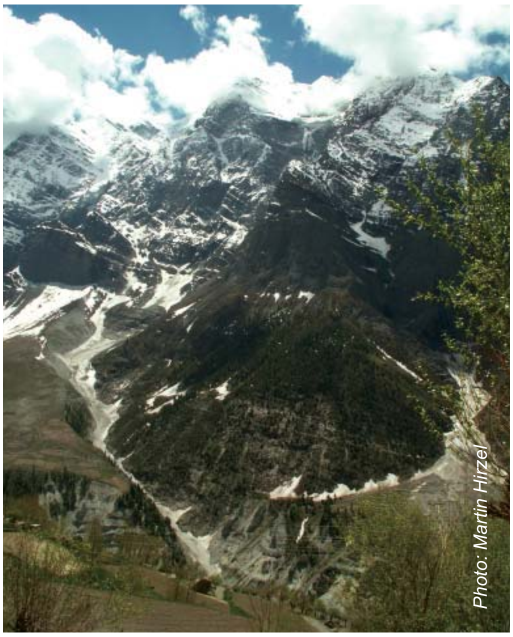
Photo: Martin Hirzel

▲ *Himalayan valley, close to Keylong, India*

As neither of the two countries had responded to the initial requests, the University of Nebraska at Omaha (UNO) finally took over the task to monitor the glaciers in the Western Himalaya and in the Hindu Kush. It therefore hosts the GLIMS Regional Center for Southwest Asia (Afghanistan & Pakistan). The UNO

GLIMS Project obtains its data from various sources. For instance, the project uses maps from the former Soviet Union or the United States Department of Defense (US DOD), as well as satellite images (e.g. from ASTER). The maps however strongly vary in their quality. This in turn leads to differences in the maps. The Soviet maps (1:50.000) of the early 1960s of Afghanistan, for instance, show a different extent of the Koh-i-Baba and Foladi glacier than the US DOD map (1:100.000) from the same time period. Such differences make it difficult to assess how the real state of the glaciers appeared in the past. Besides images and maps, field work data is included into the GLIMS Project too. Due to the changing political situations, field work was not always possible over the last 25 years, neither in Pakistan nor Afghanistan. Today, field work is possible in Pakistan. It is however impossible in Afghanistan due to the political instability within the country.

Although there are differences between the old maps, a comparison with the today's situation is feasible. Such a comparison shows that the Afghan glaciers are shrinking and that some of the small glaciers in Afghanistan have actually gone already. Satellite images support this general observation. Even though the glaciers are shrinking, the number of glaciers is increasing in some areas. As the glaciers melt down or down waste, and back waste, they become more in number but smaller in volume (e.g. Mir Samir glacier).

Wakhan Corridor

Umesh Haritashya took a closer look at the Wakhan Corridor, which is located in the North East of Pakistan. He was looking at 20 glaciers in the Wakhan Pamir Region and showed that all the 20 glaciers had been retreating from 1976-2003. Andy Bush was looking at the Wakhan Corridor too. He analyzed the surface air temperature and precipitation in this region for the period 1987-2006. The analysis shows that both the air temperature as well as the amount of precipitation decreased. The author's global climate model indicates the same results: down in temperature and down in precipitation.

In conclusion, the available data generally show negativity in rates of retreat for the Wakhan Pamir glaciers over


Photo: Martin Hirzel

▲ *View from Keylong, India, to the West.*

the last few decades. The rates of retreat can be quantified more easily then the down wasting. Nevertheless it can be stated that the glaciers are generally down wasting. Finally, the climate in the region became cooler and less precipitation is falling compared to a few decades ago. These changes of the very complicated climate in this region are probably due to orographic (rainshadow) effects.

Batura Glacier

Many data sources exist for the Batura Glacier in Hunza, Pakistan. For instance, several maps from different years (5 maps from 1966-1980) are available, as well as several satellite images (9 within the period 1973-2007). The Batura glacier's terminus was at the Hunza River in the 19th and early 20th century. The glacier however retreated 800 m away from the river until 1966. Over the last two decades, satellite images clearly show the predominant retreat of the white ice stream. From 1973-2004, it retreated about 2846 m. Surprisingly, the terminus is reacting differently. Between 1973 and 1992, it retreated by around 428 m. Since 1992, however, the terminus is advancing. From 1992-2007, we observed that it advanced about 87 m. The number of glacial lakes has increased as well. In conclusion, the white ice stream has been retreating in a great deal. There seems to be something going on, because the front has been reactivated and the glacier has been advancing again. This advancing is somehow odd. There is no explanation for this phenomenon yet, although we suspect increased winter precipitation from westerly wind sources. Is the renewed advance indicating an unusual new ice dynamics during global warming?

Batura glacier is not the only glacier advancing. From 1973-2004 several of the Batura and Hispar Mustagh Glaciers have been retreating. Quite a number of glaciers, however, have also been advancing during this period. Hence, the glaciers are not monotonically retreating in this part of the Himalaya at all. A similar picture can be found for the Karakoram Mountains.

▲ *Bhaga river close to Darcha, India.*

Karakoram Mountains

The Karakoram Mountains at the Indian, Pakistani and Chinese border host quite a few glaciers. Luke Copland analyzed the available images and data of the region. He identified 87 surge-type glaciers in the Karakoram of which 53 glaciers have never been reported before. Furthermore, Copland looked closer at these glaciers and illustrated that the Karakoram glaciers are characterized by a rapid terminus advance and high surface velocities. In addition, the glaciers generally have looped and contorted moraines and a rapid surface crevassing. What are the drivers for this rapid terminus advance? Copland suggests that it could be increased precipitation that augments the mass balance. This suggestion is supported by global climate models, which generally indicate an increase of precipitation, but also increased temperature. Another possibility for the glacier advances is increased basal melt water. Increased basal melt water has long been known to uncouple glaciers from their beds by hydrostatic water pressure, and is thus as a possible mechanism for glacier surge growth (Kamb *et al.,* 1985)

Compared to the Karakoram glaciers, the Indian glaciers are generally shrinking. So, the Karakorum and the Western Himalayan glaciers are behaving rather differently.


Photo: Martin Hirzel

▲ *Valley close to Udaipur, Himachal Pradesh, India.*

Conclusion

As we look at the glaciers, variable changes occur in the Hindu Kush – Himalaya region. In the Hindu Kush, the Wakhan Pamir and the Indian Himalaya, glaciers mostly are in retreat. On the contrary, the glaciers in the Pakistan Himalaya glaciers are mostly stable. Some of them are even advancing. In the Karakoram Himalaya, finally, more surges than anywhere in world are observed. Hence, preliminary results indicate considerable variability in glacier responses by region. These variable responses may be strongly climate controlled, although different from east to west, and north to south

Adequate assessment of glacier changes in the Hindu Kush - Himalaya - Tibetan Plateau requires consistent methodologies.

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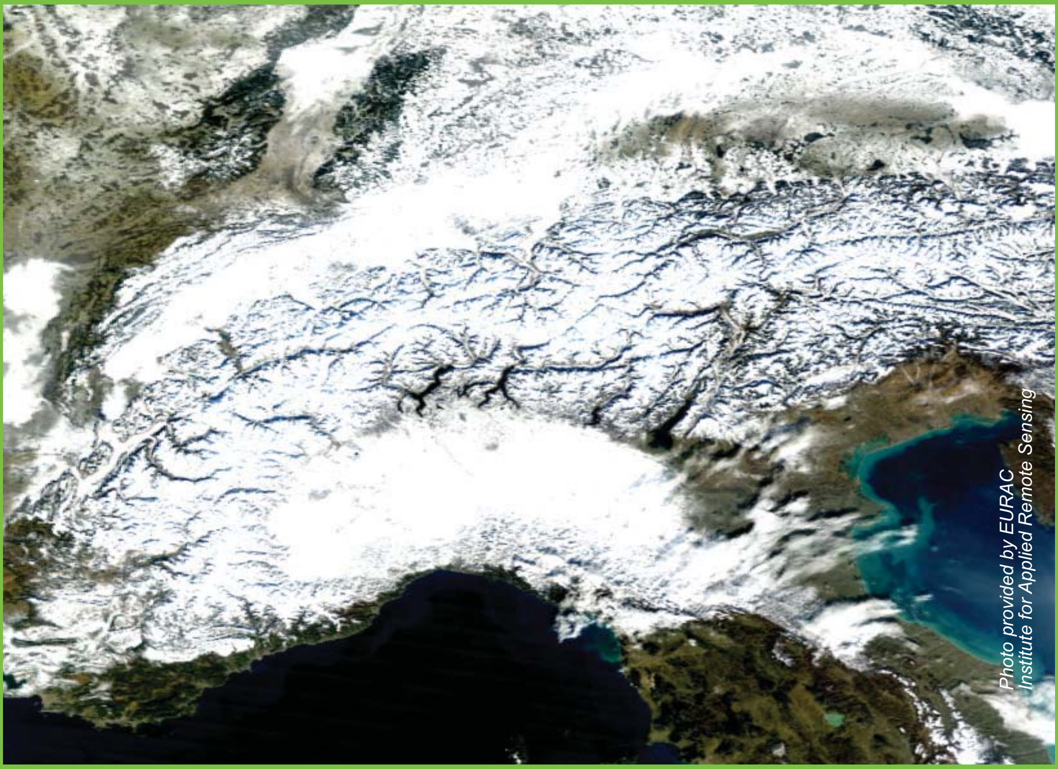

▲ *The Alps from Space.*

Climate Change, Impacts and Adaptation Strategies in the Alpine Space: Some Results from the INTERREG III B Project ClimChAlp

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Abstract

The IPCC-AR4 (Fourth Assessment Report), published in 2007, has stressed that the warming of the climate system is unequivocal, as is evident from several observations in different sectors and also has shown the following observed impacts on the global mountain areas: (1) a decrease of the snow cover and ice, especially from the year 1980; (2) a reduction of most of the mountain glaciers; (3) an anticipated reduction of the snow cover in the Spring. In particular, focusing on the European Alps region, the duration of snow cover is expected to decrease by several weeks for each °C of temperature increase at middle elevations; small glaciers will disappear, while larger glaciers will suffer a volume reduction between 30 and 70% by 2050. Also a larger number of Alpine large lakes will be formed as glaciers retreat with potential for glacier lake outburst floods. All these results show that the Alpine Space is a sensitive region to present and future climate change. In this contest the INTERREG III B – Alpine Space ClimChAlp (Climate Change, Impacts and adaptation strategies in the Alpine Space) project, which has just ended in March 2008, has aimed to develop transnational strategies for climate change risk prevention over the Alps and to develop recommendations to policy-makers on possible adaptation strategies based on the project results. In particular the ClimChAlp has produced a detailed review and analysis of the different scientific issues regarding the climate change and resulting natural hazards, the impacts of climate change on spatial development and economy for the Alpine region. Here a brief review of the assessment of the scientific results concerning the climate change and the impacts of climate change on the natural hazards carried out in the ClimChAlp project is presented.

Keywords: Alpine Region; Climate Change; ClimChAlp

Introduction

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007a) stated clearly that warming of the climate systems is unequivocal. Since the 1970s, several variables that affect the climate have changed strongly. A number of this variables directly affects the Alpine Space, e.g. rainfall intensity, snow cover and glacier extents, extreme high temperatures and in general the atmospheric surface temperatures. Global mean surface atmospheric temperatures have been rising over the last 100 years with 0.074 ± 0.018°C/decade. During the last 50 years, however, temperature increase was even stronger with 0.128 ± 0.026°C/decade. In the 1850-2006 temperature data set (IPCC, 2007a) the 12 warmest years of the whole data set are the most recent ones. Global mean surface atmospheric temperature change from the period 1850-1899 to period 2001-2005 accounts to +0.76 ± 0.19°C (IPCC, 2007a).

According the IPCC (2007b) the Alpine Space (*Figure 1*) is one of few identified hotspots in which the vulnerability to future climate change is likely to be high by 2050. Future climate projections show that snow cover will be reduced at low altitudes, glaciers will retreat and permafrost will melt at high altitudes. In the future, Alps could be one of the European areas to experience strongly increasing year-to-year variability in the summers and thus a higher incidence of heat waves and droughts (IPCC, 2007b). Hence, climate change will affect a socio-economic and ecological system such as the Alpine Space. Today, the Alpine Space is already at a critical level and vulnerable to natural disasters, demographic pressures and environmental impacts. In the next 100 years, climate change will destabilize this vulnerable system even more. As a consequence, the Alpine population will be confronted with more natural and economical hazards. For instance, the risk for floods may increase or tourism will be affected by a decreased snow cover. Both examples are not linked to one country only. Hence climate warming is a transnational problem, which needs transnational solutions and coordinated adaptation measures.

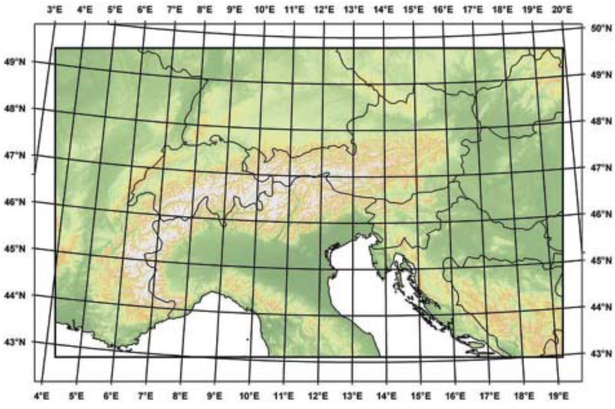


Figure 1: The Alpine Space (Source: ALP-IMP project, www.zamg.ac.at/ALP-IMP/).

Table 1: The ClimChAlp project development.

June 2004:	Idea for project and first written contact
November 2004:	Presentation of first draft at conference in Rosenheim
July 2005:	Workshop in Augsburg with scientists and designated project partners
July - December 2005:	Elaboration of project and assembly of partnership
December 2005:	Application for project
February 2006:	Approval of project
March 2006:	*Project Start* - Kick off meeting
May 2007:	“Midterm Conference” (Bolzano)
March 2008:	Final Meeting (Laufen, Germany)
31 March 2008:	*End of Project*

ClimChAlp Project

In the last years the ClimChAlp project (Climate Change, Impacts and adaptation strategies in the Alpine Space), an INTERREG III B - Alpine Space Project tried to tackle some of these environmental concerns regarding the Alpine Space. This project aimed at supporting the political decisions regarding protection and natural disasters prevention due to climate change in the Alps. In particular ClimChAlp tried to develop transnational strategies on risk prevention of climate change and possible adaptation measures over the Alpine Space in order to contribute to the sustainable development in the Alps in sectors such as spatial planning, natural hazards and socio-economic activities (www.climchalp.org). The project started in March 2006 and ended in March 2008 (*Table 1*). All the Alpine countries (Austria, France, Germany, Italy, Liechtenstein, Slovenia and Switzerland) have been participating in this project.

To fulfill these objectives during the ClimChAlp an assessment of the state of the art of the research on the Alpine region has been carried out in order to provide recommendations for policy-makers concerning measures for minimizing the effects of climate change. In more detail an assessment of climate change in the Alps based on historical climate and climate related data and climate model scenarios has been carried out. Also a validation of global and regional models for the Alpine Space has been carried out during the project. Finally, the impacts of climate change on natural hazards have been also examined and monitoring instruments have been assessed. Furthermore, the project analyzed the consequences of climate change on spatial development, economic activities for possible adaptation measures.

During ClimChAlp possible management tools for the Alpine Space have been analyzed and a Flexible Response Network has been proposed in order to optimize reaction possibilities considering changing intensities of natural hazards. This network has to be considered as a starting point for new INTERREG projects, such as AdaptAlp (Adaptation to climate change in the Alpine Space). Scientific reports for the Alpine Space have been finalized at the end of ClimChAlp concerning the:

- Analysis and validation of climate observations data-sets and climate model projections data-sets.
- Assessment of natural hazards adaptation to climate change.
- Analysis of socio-economic impacts (socio-economic Implications of Climate Change for Tourism, Transportation and Agriculture).
- Flexible Response Mechanism.

At the end a Strategic Paper has been developed including recommendations to the policy-makers for managing impacts of climate change.

Here I present a brief review of the assessment of the scientific results concerning the climate observations and the climate scenarios and the impacts of climate change on the natural hazards carried out in the ClimChAlp project.

Alpine Temperature

The ClimChAlp assessment of the scientific literature has shown clearly that the surface atmospheric temperature observations in the Alps are converging towards a general temperature increase. This warming trend seems to have accelerated during the last decade (*Figure 2*), and is confirmed also by an increase of the heat summer days and a decrease in freezing days. Looking at historical data, warm periods have been detected in the Alps from about 1780 to 1810, 1890 to 1945, and from the 1970s onward. In addition, the data have shown that 1994, 2000, 2002 and 2003 have been the warmest years in the Alps within the last 500 years. In general, the mean Alpine temperature has increased up to +2°C for some high altitude sites over the 1900-1990 period. This increase is more than double of the mean global temperature of about +0.78°C in the last 100 years. The Alps are among the areas warming much faster due to climate change (ESFR ClimChAlp, 2008a).

Alpine Precipitation

Despite the precipitation measurements are more difficult to carry out in the Alps, especially at high altitudes, precipitation records have shown for the period 1901-1990 an increase of winter precipitation by 20-30%

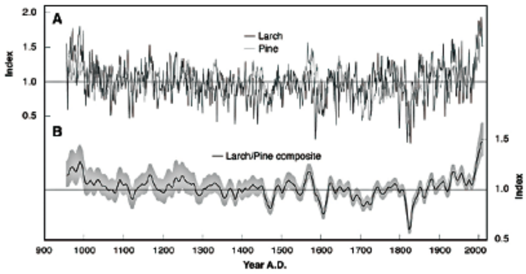


Figure 2: Comparison of two RCS (Regional Curve Standardization) records from ring alpine network: one from Switzerland (composed of four Larch chronologies) and one from Austria (Pine) (Source: Figure 6.8. – ALP-IMP Final report, 2006).

in the Western Alps and a decrease of autumn and winter precipitation in the southern part of the Alps. The precipitation data have shown also a very large inter-annual and inter-seasonal variability. Precipitation data of the Western Italian Alps have shown strong fluctuation, but no significant trend. This is true for the mean annual precipitation, the precipitation intensity as well as for the percentage of dry days per year. In general it is difficult to detect a signal of climate change on the precipitation data in the Alpine Space, due to strong local fluctuations of the patterns (ESFR ClimChAlp, 2008a).

Alpine Glaciers

The Alpine glaciers have lost about 30-40% in glacierized surface area and about 50% in ice volume between 1850 and 1975 (Haeberli and Beniston, 1998). Another 25% of the remaining volume disappeared between 1975 and 2000, and additional 10-15% in the first five years of this century (Haeberli *et al.,* 2007). More dramatic changes took place in some periods: during the decade 1980-1990 glacier mass losses increased by more than 50% respect to the 20th century mean value (*Figure 3*). Due to a large local/regional variability (Haeberli *et al.,* 2000; North *et al.,* 2007) the apparent homogeneous trend of glaciers retreat breaks over shorter time periods (years to decades): for example, an advancing period has been observed in the Alps during the 1970-1980, which is consistent with other regions in the World (Hoelze *et al.,* 2003). This glacier retreating trend has been observed trough the mass balance analysis of some alpine glaciers in the period 1965-2005 (North *et al.,* 2007), in which an acceleration of loss of glacier volume from the middle eighties is shown (*Figure 3*). During the summer heat wave of 2003 the Alpine glaciers melting reached a record: a mean specific mass loss of -2.5 m water equivalent, which is eight times the annual mean of the period 1960-2000 (ESFR ClimChAlp, 2008a).

Alpine Snow Cover

In most of the Alpine Space the snow pack is declining. One reason for declining snow pack is that precipitation falls as rain rather than snow, especially in fall and spring. Furthermore, snow melt occurs faster and sooner in the spring. Snow pack is therefore less and hence soil moisture is less as summer arrives. As a result, declining snow pack will increase the risk of drought in summer,

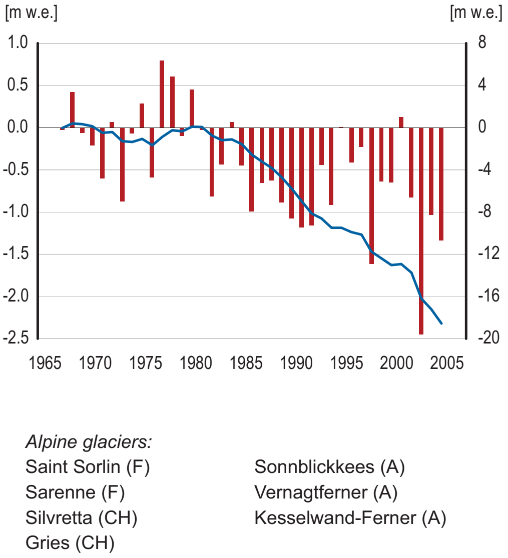
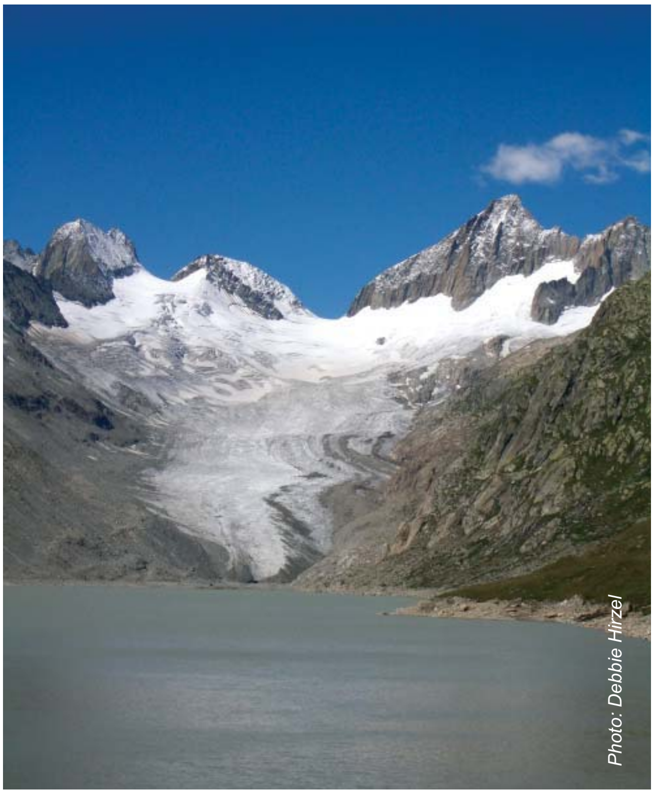


Figure 3: Annual (left y-axis) and cumulated (right y-axis) mass balance of nine alpine glaciers for the period 1967-2005, in m. w.e. (Source: Figure 33 – North et al., 2007).

also in the Alpine region. For instance, spring snow cover at the northern hemisphere shows 5% stepwise drop during the 1980s (IPCC, 2007a,b). In southern Germany, for example, the data have shown a trend toward less lasting snow cover: the number of days with snow cover has decreased markedly at lower altitudes (30-50%) and moderate altitudes (10-20%) and has decreased less than 10% on high ground (Hennegriff *et al.,* 2006). A decrease in snow cover duration has a strong impact on tourism (ESFR ClimChAlp, 2008a).



▲ *Alpine Glaciers lost 10 to 15% of their volume during the first five years of this century. Oberaargletscher with Oberaarlake, Switzerland*

Alpine Permafrost

The area in the Alps covered by permafrost is comparable in extent to the glacierized area, but its long-term evolution is much less well known. Boreholes observations have shown that permafrost temperatures are now rising at high rate, but this can be influenced by snow cover conditions in early wintertime (Vonder Mühll *et al.,* 1998; Haeberli and Beniston 1998). A fast warming of 0.5-0.8°C during the last century in the upper decameters of Alpine permafrost has been confirmed by some borehole measurements (Harris *et al.,* 2003). Permafrost degradation is likely to be in the future a critical factor for natural hazards such as rock falls, mudslides and debris flows, and interactions with other phenomena such as hanging glaciers exist (ESFR ClimChAlp, 2008a).

Global and Regional Climate Models for the Alpine Space

In general, Global Climate Models (GCMs) are not appropriate for direct applications on a spatial scale such as the Alpine Space. In order to study this area, the results of GCMs have to be downscaled to regional level. Hence, there is a need for adequate Regional Climate Models (RCMs). During the ClimChAlp project, GCMs and RCMs simulations for different spatial scales have been validated, with a focus on the Alpine Space. The RCM climate scenarios provide the essential climate information for im-

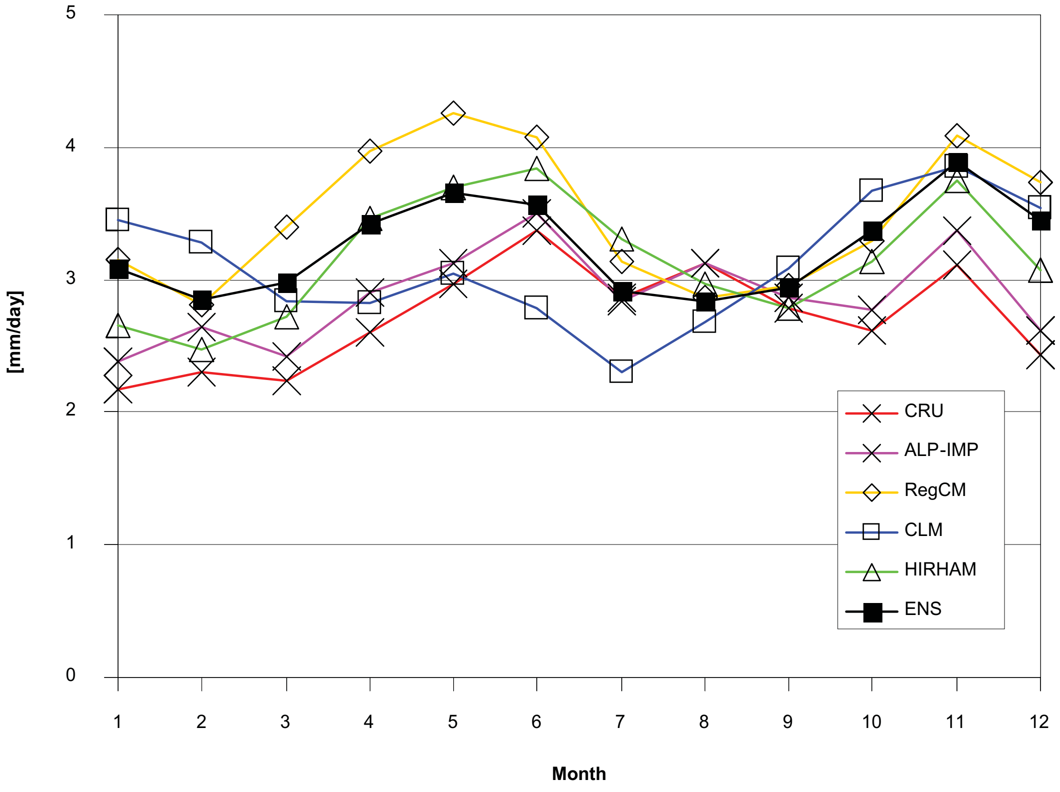


Figure 4: Observed and simulated annual cycle of mean precipitation averaged over the Alpine Space for the period 1961- 1990 (ENS – ensemble mean over the RCMs) (Source: Figure 3.9 - ESFR ClimChAlp 2008a).

pact studies concerning, for instance, natural hazards under possible future climate change conditions. The analysis of the output of some GCMs and a systematic validation of several RCMs (RegCM, REMO, HIRHAM, CLM, MM5 and ALADIN) for the Alpine Space shows that the horizontal resolution of these models is not adequate to simulate, for example, the precipitation events occurring in the Alps. Most models have a resolution of 10-20 km, which is not sufficient for the Alpine region. Hence, the resolution of RCMs for the Alps must be increased in order to improve the assessment of changes in the magnitude and frequency of climate extremes on regional scale. Despite the horizontal resolution still large for the Alpine Space, the RCMs can reproduce the monthly mean temperature, but they tend to overestimate the precipitation for most of the year (*Figure 4*). The validation and the analysis of these different

RCMs showed that there is no single best RCM for the Alpine Space. Hence climate model projections on the Alps must be improved in the near future (ESFR ClimChAlp, 2008a).

Based on some of the assessed regional climate projections, small scale hydrological model simulations have been conducted in selected river basins of the Alps in order to identify possible climate change signals. These hydrological simulation results have evidenced the need to couple suitable precipitation/runoff models with adequate RCMs in order to assess potential future risks of extreme events in the Alpine Space. At global and regional scale climate change is expected to strongly influence the hydrological cycle with consequences also for extreme events (intensity and frequency). A potential increase in average daily precipitation is likely to produce an increased number of floods and disastrous mud avalanches within the Alpine Space. The ClimChAlp project has shown clearly that the available RCMs applied on small river catchments in the Alpine Space do not simulate quite well all relevant processes for extreme precipitation events. Therefore, a different type of RCMs is needed to resolve the small catchments' scale in the Alpine Space (ESFR ClimChAlp, 2008a,b).

Alpine Floods

The observations on the Alps have shown an increase in the frequency of extreme floods over the past 20 years in the Alps, compared to the 20th century mean. But this flood increase seems to remain within the natural range of variability. In Southern Germany, the KLIWA project has evidenced that the frequency of winter floods increased since the 1970s with the exception of Southern Bavaria (north edge of Alps). In the future, according to various scenarios, an increase of winter floods and decrease of summer low waters is expected, as well as an earlier flood peak due to snow melting (ESFR ClimChAlp, 2008b).

Alpine Debris Flows

No trends have been observed in Alpine debris flows. The available studies evidenced a decrease in the occurrence of debris flows: for example the debris flows frequency in the Swiss Alps has reached the lowest level in the last 300 years


Photo: Debbie Hirzel

▲ *In most Alpine areas snow pack and snow cover duration are decreasing. This will increase the risk of droughts in summer.*

and also has decreased since the mid 1970s in the French Alps. The simulations show a decrease of debris flows events for a future warmer climate over the Alps. However, the frequency could increase in particular areas of the Alpine Space depending on local situations and driving parameters (ESFR ClimChAlp, 2008b).

Avalanche

A change in avalanche hazards in connection with climate change is uncertain. In general, it is assumed that the possible change would follow the snow cover evolution. A decrease in avalanche hazards is likely at low and medium altitudes. Yet, heavy precipitation events might counterbalance this trend by triggering general avalanche situations (ESFR ClimChAlp, 2008b).

Alpine Glacial Hazards

The glacial hazards can be affected by climate change in two ways: firstly, hanging glaciers could loose stability, secondly, the number and size of proglacial lakes could increase as a consequence of glacier retreat and ice temperature increase (ESFR ClimChAlp 2008b).

Alpine Mass Movements

An increased number of rock falls were observed at high altitude during the 2003 heat wave. The degradation of permafrost in steep slopes is a major factor for the reduced stability of rock walls and the rock fall pattern. Increased precipitation might lead to more frequent and extended slope instabilities in the future. In particular, the changes of intense precipitation could impact the shallow landslides (trough the surface water runoff and stream actions), while the changes of long-term precipitation could impact the deep landslides (trough underground water action). On the other hand, the possible future decrease of summer precipitation may have a positive effect by reducing the deep and shallow landslides activity (ESFR ClimChAlp, 2008b).


Photo: Maria Emilie Lichem

▲ *Changing temperatures and decreasing snow cover will have strong impacts on the tourism sector.*

Conclusions

One of the aims of the ClimChAlp project has been the assessment of the status of the scientific research on climate change and impacts of climate change on the natural hazards in the Alpine Space. Several research gaps have been evidenced during the project (ESFR ClimChAlp, 2008a,b), such as the following:

- A need for homogenization of the existing climate data sets on a transnational level and an enhancement of the transnational cooperation and information exchange;
- A need for higher horizontal resolution regional climate models;
- A need for development of better methods for correcting uncertainties in model projections;
- A need for maintaining the existing glacier observation networks, which can provide input data for water availability, landscape and tourism issues;
- A need for improvement of the snow cover observation networks through new methods (remote sensing and snow cover/climate coupled models);
- A need for better monitoring of permafrost and related parameters (air temperature and snow cover pattern) both in steep and gentle slopes (essential for inputs for permafrost models);
- A need to increase the research on the effects of climate change on mountainous forest vegetation (the potential role of forests as protection against natural hazards in a changing climate);
- A need to improve the precipitation-runoff models;
- A need to continue the study of the potential future evolution of debris flow and torrential floods in the Alps.

The scientific studies assessed in ClimChAlp demonstrate that the Alpine Space is one of the areas in Europe most sensitive to climate change. Hence, adaptation to climate change will be necessary to address unavoidable impacts, but it will need strongly adequate observational data and future scenarios' data. Finally, the scientific community involved in the Alpine research needs to be strongly linked to the Alpine stakeholders and decision-makers in order to elaborate both short- and long-term risk management plans and response actions for the Alpine Space.

Acknowledgements

The author is grateful to all ClimChAlp Partnership and in particular to the *Lead Partner Bayerisches Staatsministerium für Umwelt, Gesundheit und Verbraucherschutz, Referat Klimaschutz, (Bavarian State Ministry of the Environment, Public Health and Consumer Protection, Munich, Germany)*. A special mention to Dr. Paolo Angelini of *Ministero dell'Ambiente e della Tutela del Territorio e del Mare (Italian Ministry for Environment, Land and Sea, Rome, Italy*), ClimChAlp WP5 Leader, and all other colleagues that contributed to the Climate Change Assessment Report and Natural Hazards Report during the ClimChAlp project.

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▲ *View on Bucura Lake, Retezat Mountains, Romania.*

Lakes as Witnesses of Global Change in Mountains

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Abstract

This paper addresses the role of high mountain lakes in global change processes. High mountain lakes, of which most were formed during the last glaciation, are abundant in the mountain areas around the globe. Since they have a common origin, large similarities can be found between high mountain lakes throughout the world. These similarities allow to compare local influences of global phenomena, such as climate change. I show in this paper, why mountain lakes are especially suitable to trace global change phenomena. Furthermore, I present some indicators and signals that can be used to gain information from past climate changes and from past human activities.

Keywords: High Mountain Lakes; Global Change

Introduction

There are no easy and straightforward answers to apparently simple questions regarding the current global climate change, such as: is there a problem? Is this natural or anthropic variability? What is the extent and severity of the problem? Is that fluctuation an early warning of more severe changes to come? When did (will) the problem first become serious? What were conditions like previously? Are there underlying trends or cycles? Do current trends reinforce or counteract natural trends? What is the rate of change? In fact, in order to assess actual and future impacts of current global change, there is a need to combine knowledge and observations. On the one hand, assessments have to include state of the art knowledge and amalgamate them into sufficiently complex models able to make projections on future conditions and reconstruct past situations. On the other hand, observations allow for contrasting current knowledge, either by means of space for time comparisons, which provide analogues and the range of variance we can expect, or by means of time series, instrumental or based on natural records, which allow the following of the pace of changing trends and frequency of events. Each approach has its own limitations, namely, either over-simplification or over-complexity of modeling, the lack of dynamic constrains of space and time and the lack of generality of local time series. Thus, the interaction between modeling and observational approaches is essential to avoid the associated risk to each individual approach. There are places in the earth system where applying this combined approach for observing and evaluating global change is particularly worthwhile, one of them are mountain lakes (Catalan *et al.,* 2006).

Why Are Mountain Lakes Excellent Observatories for Global Change?

Lakes collect information far beyond their own limits: from atmospheric depositions to catchment processes. From an environmental point of view, lakes are a landscape added value. Indeed, variability in climate and deposition interact with catchment characteristics (bedrock, soils, vegetation) and through the hydrological network this variability is reflected in the loads to the lake of silt, nutrient, major ions and organic matter. Eventually lake dynamics respond to these loads, direct deposition and weather forcing. Interestingly, at the end a record of this lake dynamics is kept in lake sediments.

Mountain lakes are abundant, because many of them originated during the last glaciation through the ice action in the mountains. As a consequence of this common origin, high mountain lakes are among those ecosystems with larger similarities throughout the planet, latitudinal and continental differences are mitigated to a certain extent by the altitude where they are located. Lakes within the alpine belt, above tree-line, are particularly comparable. Usually, there is low local human impact beyond cattle raising in some particular areas.

Alpine lakes are relatively simple systems compared to other freshwater ecosystems. Catchments are relatively small, scarcely vegetated and commonly on crystalline bedrocks. Lakes are morphologically simple, though they are relatively deep compared to their surface area. These general characteristics determine that they contain valuable recorders of atmospheric forcing (Psenner and Catalan, 1994). In addition, most physical, biogeochemical and ecological first principles easily apply to their dynamics, thus being particularly amenable for modeling (Wright *et al.,* 2006).

Ecosystem variability in mountain lakes fundamentally arises from three main sources, namely, catchment bedrock nature, the altitudinal gradient and lake size differences. Bedrock characteristics determine major water chemical features, such as acid neutralizing capacity, pH, and total salt content. These features particularly influence algal and plant species distributions, and in extreme cases, such as very acidic waters due to sulfur oxidation, all kinds of biota (Catalan *et al.,* 2009). Within areas of similar bedrock, major changes occur with increasing elevation. The altitudinal gradient includes multiple environmental factors (Körner, 2007). Temperature decreases (ca. 5.5°C km^{-1}), atmospheric pressure declines, clear sky radiation, and UVB proportion increase with increasing altitude. These changes result in a number of related changes in vegetation, soil development, growth period length and ice cover duration. Finally, lake size effects are particularly relevant concerning the availability of light at the deepest part of the lakes. As lakes are usually highly oligotrophic and poor in dissolved organic carbon and silt, light penetration is high and in shallow lakes littoral characteristics extend to the whole bottom of the lake, making a substantial difference for the ecosystem organization compared to deep lakes where a part of the bottom is not covered with algal biofilms (Buchaca and Catalan, 2008).

Combining the distinct mountain lake features (e.g. abundant and globally distributed, covering altitudinal gradients and sensitive to atmospheric forcing changes) we may realize that they are excellent observatories for the on-going global changes. These observatories provide three types of valuable information: sites for monitoring time series on on-going changes; space for time analogues for comparison and understanding of the changes and past for future analogues to evaluate the significance of the current rate of change and future projections. Hereafter, I am going to use mostly examples from the Limnological Observatory of the Pyrenees. Similar case studies could be provided from other lake districts in other mountain ranges and, hopefully, this Mountain Lake Observation approach will be extend to a larger number of mountain areas in the world.

The Limnological Observatory of the Pyrenees

The Limnological Observatory of the Pyrenees consists in four programmes of observations covering respectively lake, catchment, lake district, and paleo-dynamics. The Lake Redon station provides a long-term monitoring of a mountain lake and comprises an automatic weather station, atmospheric deposition measurements (major elements, trace metals, persistent organic pollutants), water column temperature, water chemistry, sediment fluxes and plankton community monitoring. Hydrological and catchment biogeochemistry monitoring is carried out at Sant Nicolau Valley in the Aigüestortes i Estany de Sant Maurici National Park, and it includes meteorological variables, deposition, discharge, water level, water chemistry, macroinvertebrates and epilithon. A third programme consists on large surveys to a selected number of lakes among the more than 1000 lakes larger than 0.5 ha existing in the Pyrenees. Finally, a fourth programme includes the study at high resolution of sediment records covering historical and Holocene periods.

Mountain Warming

In Europe, the combination of short time series (a few years) of automatic weather station data with statistical downscaling and spatial extrapolation techniques allow for accurately reconstruct air daily data during the last 200 years at remote mountain sites based on records of low land weather stations distributed throughout Europe (Agustí-Panareda and Thompson, 2002). According to these extrapolations, in the Pyrenees (Lake Redon) there has been a warming trend of about 1.5°C since the beginning of the 20th century (Catalan *et al.,* 2002). The tendency existed through the century but it accelerated from some particularly cold years onwards. Although the warming tendency appears in most of the months, temperature increase in early summer and autumn is particularly noticeable.

High resolution studies of the sediment record in the lakes have revealed some early responses to this warming tendency (Catalan *et al.,* 2002). In Lake Redon, two planktonic diatom species have increased following autumn patterns. *Fragilaria nanana* and *Cyclotella pseudostelligera* followed September and October temperature, respectively. Plankton succession studies have corroborated that the two species successively grow during these two months, which indicates that the relationship was not a spurious correlation. If, instead of regarding single species, we consider trends in communities (e.g. diatom assemblage principal components) or general state variables (e.g. chlorophyll), it appears that there is a high correlation at long-term scales (century), but a remarkable hysteresis in the response to climate fluctuations of the same magnitude but shorter duration (decade). These results underline the importance of the long-term studies, in order to assess ecosystem responses to climate change. This kind of studies have been carried out in a few flagship sites in several mountain ranges (Battarbee *et al.,* 2002). However, other studies indicate that these are not “one lake” stories. Deployment of thermistors in lakes at different altitudes in several mountain ranges have shown that there is a large short-term coherence in lake surface temperature within regions. Therefore, although each lake may respond differently to similar physical forcing, general tendencies may be common throughout mountain lake districts (Livingstone *et al.,* 1999).

References from the Past

Are there references of recent abrupt ecosystem changes in the past? There is no need to go far back in time. At mid Holocene, a deep change took place in dominant landscape vegetation in the Pyrenees that scarcely took a millennium (Reille and Lowe, 1993). A cooling of 4-5°C during the warmest month of the year occurred in a few centuries, with a decrease of more than 700 degree-days in growing period for plants. These changes caused the replacement of forest dominated by deciduous trees (*Tilia, Ulmus, Quercus, Acer, Corylus*) by present beech (*Fagus*) and silver fir (*Abies*). The magnitude of temperature changes, occurring during a few centuries, was similar to some of the projections for the next several decades. Therefore, large landscape changes in vegetation can be expected, although the pace and way of change are extremely difficult to predict and, probably, will be mediated by local contingencies.

Climate change effects are not limited to summer temperature variations. In mountains, the altitudinal gradient is well reflected in the ice cover duration in lakes. In that aspect, the ice cover duration is a reference to normalize altitude among mountains at different latitudes (Catalan *et al.,* 2009). In mountain lakes, ice cover duration influences annual plankton succession. Chrysophyte cysts are excellent sediment recorders of the inter-annual variability in plankton succession, as many chrysophyte species are found at different stages of the phytoplankton ice-free period succession. They have been used to reconstruct altitudinal anomalies, which in this case may be interpreted as changes in the winter-spring climate that determine ice cover duration (Pla and Catalan, 2005). Holocene reconstructions in the Pyrenees have shown a coherent climatic signal with Greenland ice core and Irish speleotherm data, indicating that there is likely a general hemispheric forcing of mountain lakes determining a large fraction of their inter-annual variability.

Despite the remarkable correlation between altitude and duration of the ice cover, there are some local differences due to the seasonality in the characteristics of the atmosphere within the altitudinal range covered in some mountains. For example, for the Alps it has been estimated that a warming of about 6°C would produce a decline of the duration of the ice cover close to 150 days at an altitude of 2000 m, while at 3000 m a.s.l. the change would be little more than 100 days (Thompson *et al.,* 2005). However, the biological effects may not mirror this physical difference. Quite the contrary, it is likely that the biological effects would be larger at 3000 m a.s.l. than at 2000 m a.s.l. The reason is that at 3000 m a.s.l. the warming would imply that the ice cover will persist less than 190 days (Catalan *et al.,* 2009). This fact will produce exceptional changes in the communities that live in the lakes, as 190 days has been identified as an ecological threshold above and below which the communities of many organisms tend to differ greatly. As at the elevation of 2000 m a.s.l. the ice cover shortening will not imply crossing any ecological threshold, it is likely the communities change less. This is a general point to consider in climate change, locally or regionally. Biological effects may be larger regardless lower physical changes, if the latter imply crossing an ecological threshold.

Global Change Is More than Climate

Global change is more than climate; it includes a polyhedric amalgam of changes (Catalan, 2008). The increase in atmospheric carbon due to the use of fossil fuels is at the centre of what has been called global change because it represents a systemic change in the planet. Climate is affected globally and the biogeochemical dynamics of the biosphere are also implicated as a whole. Nevertheless, today’s global change includes several other processes. Some of these may be classified as systemic, such as the increase in other greenhouse gases, the reduction of the ozone layer and the duplication of circulating reactive nitrogen. However, most of the changes due to human activity have also become global, due to their progressive accumulation and extension over many territories. Among these cumulative changes there are the overexploitation of resources, erosion, acidification, eutrophication, biosphere toxification, urbanization, and enhancement of species dispersion. These pressures have led other global change components such as changes in ecosystem functioning, loss of biodiversity, increase in invasive species and emerging diseases. Mountain lake dynamics reflect part of these changes, particularly those related to atmospheric changes including long-range transport of pollutants.

Numerical models and geological records reveal that at geological time scales large fluctuations in atmospheric CO_2 content have been avoided by regulatory mechanisms on which climate and CO_2 consumption by silicate rock weathering play a central role (Kump *et al.,* 2000). Greenhouse effects of atmospheric CO_2 levels will influence air temperature and atmospheric moisture, which in turn will regulate weathering rates. However, the typical time scales of the feedback mechanism remains controversial. Increase in alkalinity, and thus increase in atmospheric CO_2 trapping, has been observed during the last decades in several mountain lakes from the Alps and the Pyrenees where water chemistry monitoring has been maintained (Mosello *et al.,* 2002). In addition, pH reconstructions using diatoms have shown a correlation between pH and air temperature before acid deposition periods, which were disrupted with the onset of acid rain in the 1950s (Psenner and Schmidt, 1992). All these observations suggest a fine tuning between CO_2 increase, warming and rock weathering including short temporal scales. Weathering of silicate rocks is a net CO_2 consumption. However, its effect on reversing present CO_2 increase has been estimated in about 10,000 years, once fossil fuels have exhausted (Lenton and Britton, 2006).

Spheroidal carbonaceous particles (SCP), soot particles, produced during carbon and oil combustions can be identified in top sediments of lakes from any mountain in the world (Rose *et al.,* 2002). Even in extremely remote places such as the Spitsbergen Island in the Arctic Ocean, there is a deposition record. Obviously, the SCP fluxes are orders of magnitude different between the latter and lakes closer to emission sources (e.g. Piedmont-Ticino alpine lakes), however, the temporal patterns are similar everywhere, at least within Europe, with a marked and sudden increase during the 1950s and a peak in the 1970s. The decrease indicated the successful application of a cleaner combustion technology (Rose *et al.,* 1999).

Linked to combustions and long-range particle transport are polycyclic aromatic hydrocarbons (PAHs). Mountain lakes are also excellent witnesses of their production and spreading. In Europe, the Tatra Mountains were particularly affected by large deposition fluxes, about ten-fold higher than in any other mountain range in Europe (Fernández *et al.,* 2003). PAHs transport to remote areas depends on particle deposition and therefore is under the influence of climatic variations. Whereas fish possess mixed-function oxygenase systems that rapidly metabolize PAHs, these enzymes are poorly developed in some invertebrates and, as a consequence, they have a lower rate of metabolic degradation. Low PAH concentrations in fish do not necessarily imply that they are not receiving significant pollutant fluxes and that they are free of stress. In Lake Redon (Pyrenees), the contents of PAHs in the food web organisms included in the diet of brown trout were investigated (Vives *et al.,* 2005). The preferential habitat and trophic level of the component species were assessed from the signature of stable isotopes ($\delta^{13}C$ and $\delta^{15}N$). Most of the organisms exhibit PAH distributions largely dominated by phenanthrene, which agrees with its predominance in atmospheric deposition, water, and suspended particles. Total PAH levels are higher in the organisms from the littoral habitat than from the deep sediments or the pelagic water column. Fish exposure to PAH, therefore, may vary from lake to lake according to the relative contribution of littoral organisms to their diet. The reasons why PAH concentrations are higher in littoral organisms still need to be elucidated.

The oldest atmospheric pollution arriving to mountain lakes is that of heavy metals. Regarding the Pyrenees, lake sediments revealed heavy metal pollution since the onset of intensive mining and smelting in old Roman times (Camarero *et al.,* 1998). In a sediment core from Lake Redon a surface peak of lead concentration that was ca. 10-fold higher than the background level was found. This peak is attributed to the mining activities in the area since the beginning of this century, on the basis of the similarity between the isotopic composition of lead in the sediments and lead in the ores from the mines. Although lead pollution due to the combustion of gasoline was expected to be present, no evidence could be deduced from the lead isotope ratios of sediment due to the masking effect of lead from mines. More interestingly, a second peak appeared in a deeper layer, with a maximum lead concentration of ca. 17-fold higher than the background level. The date of this peak is ca. 658 AD. Coincident isotopic signatures revealed that lead in both peaks must have the similar origin. Non-documented mining and smelting at a relative large scale should have then taken place in the surrounding mountain area during post-Roman times. The rise of anthropogenic lead in sediments started around 670 BC, in good agreement with the accepted chronologies for lead pollution at a large European scale (Shotyk *et al.,* 1998).

The comparison of the concentration of heavy metals in contemporary and pre-industrial sediments obtained from sediment cores of a number of lakes across the European mountains allows assessing the present day status of regional pollution (Camarero *et al.,* 2009). The analyses showed that the concentration of trace metals and metalloids is significantly high in the modern sediments of these relative remote, pristine lakes, comparable to those found in moderately polluted sediments.

However, the matter related to atmospheric pollution affecting mountain lakes that perhaps has attracted more interest in recent times, by unexpected, has been the increasing accumulation with the altitude of some compounds. In the last decade, it has been observed that some persistent organic pollutants such as the semi-volatile organochlorine compounds (OCs) are transferred from tempered areas, where they were produced and used, to cold distant points without significant dilution (Breivik *et al.,* 2002). The natural processes of volatilization and absorption along with the atmospheric transport give rise to their accumulation in ecosystems and organisms at high latitudes (Wania and Mackay, 1993). Interestingly, it has been demonstrated that there is also a tendency for accumulation of some compounds in altitude due to decreasing temperatures with elevation (Grimalt *et al.,* 2001). The patterns of deposition of these compounds probably will be under the influence of the climatic change in the immediate future, since its retention in the zones of fresh water after the atmospheric transport depends on local weather conditions (Carrera *et al.,* 2002; Van Drooge *et al.,* 2004; Meijer *et al.,* 2006). The analysis of OCs in muscle of fish from high mountain lakes shows that part of their variability depends on fish age and lake altitude. The interesting point is that the degree of dependency decreases with the vapor pressure of the compound (Vp), thus the distribution of OC with Vp < $10^{-2.5}$ are mostly determined by these two variables (Vives *et al.,* 2004). OC accumulation in fish is higher than predicted from theoretical absorption and solubilization enthalpies, which implies that there is an additional temperature-dependent amplification mechanism (Grimalt *et al.,* 2001).

Despite their remoteness, high mountain lakes have been also affected by some direct anthropic alterations. In early times, lakes were mainly affected by deforestation and erosion related to pasturing activities. In recent times, direct alterations are related to hydropower exploitations (Catalan *et al.,* 1997) and lake stocking with fish (Miró and Ventura, 2004). Abrupt changes in water level, as a result of impounding, affect all the littoral biota and particularly the survival of macrophyte populations (Gacia and Ballesteros, 1996). The introduction of fish, due to their establishment as top predators may affect and, eventually, suppress some species typical of these high altitude sites (Bradford *et al.,* 1998; Knapp *et al.,* 2001). Fish were not able to reach naturally most of the alpine lakes, because of the existence of steep slopes and subterranean parts in the streams flowing from the lakes. Therefore, the actual presence of fish in many lakes can only be attributed to artificial stocking. Documentary evidence indicates fish stocking as early as the 15th century, both in the Tyrolean Alps and Catalan Pyrenees. These early initial introductions were done with individuals of autochthonous species, which were fished from nearby streams and were restricted to the lowest lakes due to their easiest access. The purpose was food supply of local communities. In addition, they were used as a complementary economic resource. The traditional practice drastically changed during the second half of the 20th century, when widespread introductions related with leisure fishing activities took place and stocks of allochthonous species were used.

We may conclude that mountain lakes are excellent witnesses of current global change. Warming, toxification, species invasion, land use changes, etc. are on-going components of this change that are particularly relevant in mountains and of which mountain lakes can offer reference conditions from the past and sentinel ecosystems at present.

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▲ *Mountain Pine partly covered with snow.*

High Altitude Plant Life in a Warm, CO_2-enriched Atmosphere

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Abstract

High altitude ecosystems cover a comparatively small fraction of the European landscape but exert major influences on large forelands through hydrological teleconnection. Here, I present some mountain geostatistics and discuss responses of high elevation forests and alpine vegetation to a warmer, CO_2-enriched atmosphere, nitrogen deposition and land use. Climatic warming will directly affect trees and thus, the high altitude tree limit, because of the close aerodynamic coupling of tree crowns with the atmosphere. In contrast, climatic warming will exert smaller effects on low stature vegetation, and these effects will largely act via snow cover duration. Elevated CO_2 does not lead to higher productivity in alpine vegetation, but may select for certain responsive taxa at the loss of others. In contrast, nitrogen deposition, at rates close to current front range fluxes, induces a major transformation of alpine vegetation. Consequences of land use changes, particularly in the upper montane belt, may exceed the impact of all previously mentioned drivers to an extent that hydrology is significantly affected. Such effects had never been quantified in economic terms, and need urgent attention at catchment scale in light of the projected shortages in both water and electric energy. All these environmental changes will also affect biodiversity, but neither the extent of such changes nor the ecosystem scale consequences are easy to assess, given the overwhelming significance of geodiversity at high elevation. Many of these changes are small and subtle, and do not necessarily meet the requirement of 'early warning'. The changes in and near the treeline and in snow bed communities are possibly among the few cases, where plants do show rapid changes.

Keywords: Climate Change; Treeline; Mountain Regions; Mountain Ecology

Introduction

In mountain areas, the elevational change in life conditions becomes rather unpredictable above the high elevation treeline, because exposure, slope and topography exert a dominating influence on the actual climatic conditions experienced by organisms. Nevertheless, there is one prominent biogeographical boundary in mountains, the relatively abrupt transition from montane forests to the treeless alpine belt: the climatic treeline. Upright plants such as trees and tall shrubs show temperatures, which closely match air temperature. In contrast, the small stature alpine vegetation above the treeline is dominated by plants, which are nesting themselves in a modified, aerodynamically decoupled microenvironment very different from surrounding ambient conditions. Under solar radiation this compact vegetation accumulates heat and

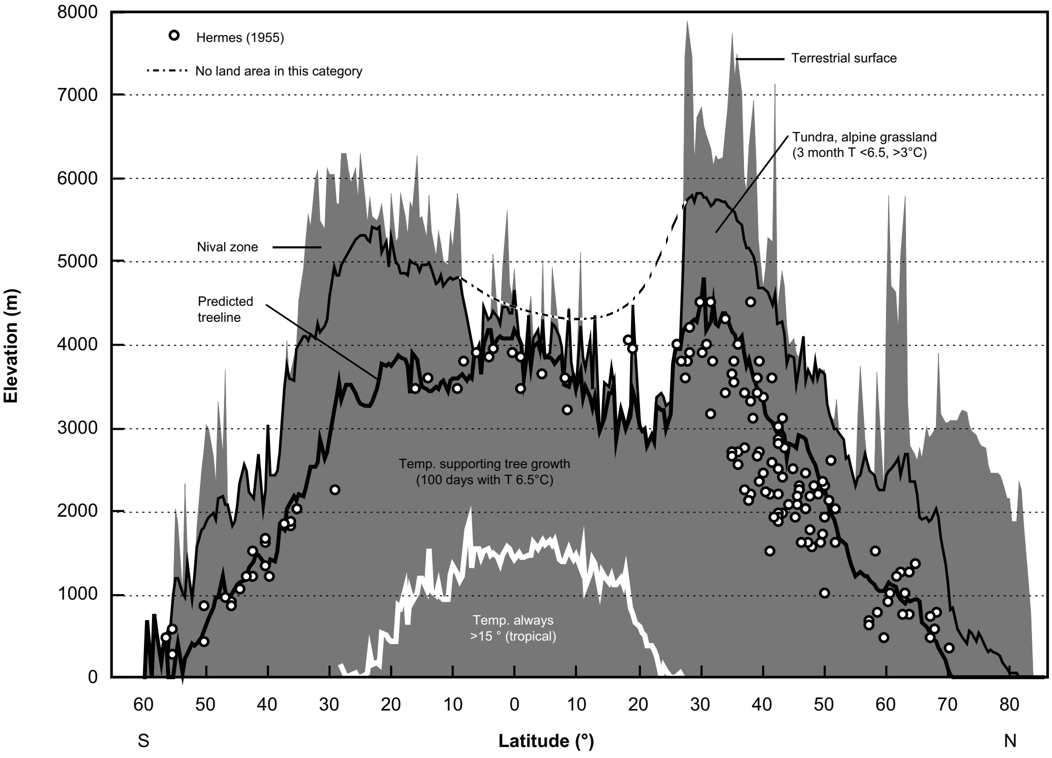

Figure 1: The global latitudinal distribution of maximum elevation of land area (shaded area), the snowline and the climatic treeline. The treeline position has been modeled using a thermal threshold (>90 days with temperatures of 6.5°C), with the data points from Hermes (1955) illustrating actual treeline positions. The discrepancy between actual and predicted treeline (particularly in the northern hemisphere temperate zone) is largely explained by anthropogenic treeline depression.

thus is much warmer than standard meteorological data would suggest. The ability to "engineer" such micro-environments is the reason why plants can live at altitudes much higher than treeline.

Given its significance as a bioclimatic reference line, I will first address the treeline phenomenon, a demarcation of life seen across the globe. Above a region-specific elevation, trees are unable to live. What are the true thermal limits of trees and what are the causes that constrain trees to such limits? In a second part, I will discuss the possible responses of the alpine vegetation to atmospheric change and land use. Finally, I will address the significance of high elevation biota for landscape-wide carbon storage.

Temperature Dependence of the Treeline

The temperature of tree crowns is closely coupled to air temperature. The smaller the foliage, the closer this coupling is. Under direct solar radiation, conifers are always operating closer to air temperature than broad-leaved trees (Leuzinger and Körner, 2007). Conifers at treeline are experiencing temperatures close (within 2 K) to what a weather station would report (Körner, 2008).

Trees depend on temperature like any other plant, but the capacity of trees to decouple themselves aerodynamically from ambient air conditions is very limited, whereas small stature plants do decouple quite strongly. In terms of early indicators for climate change and of warming in particular, trees at treeline are the first ones to translate the change into a biological signal.

Temperature data loggers have been installed around the world in order to identify the critical temperature that permits trees to live. The results showed that, on average, trees are not growing in areas with a growing seasonal mean temperature below 6.6 ± 0.8°C (Körner and Paulsen, 2004). This borderline temperature, which has a surprisingly small uncertainty, is valid throughout the world. It works for the Alps, for the Altai, Northern Scandinavia, Kilimanjaro or the snowy mountains in Australia, even though these areas are situated in very different climatic regions. In Northern Sweden, the growing season lasts around 10 weeks, in the tropics it is close to 52 weeks. Nevertheless, the difference in growing season temperature between these treeline sites is only 1 K. Hence, this dramatic difference in the length of the growing season changed the treeline temperature only very little. When water is not restricting tree growth, temperature is the overarching driver of treeline position.

Data from different regions in the world support the modeled treeline position using this thermal threshold (*Figure 1*). Obviously, some points deviate from the modeled isotherm, especially in the northern hemisphere. The most likely reason is the frequent anthropogenic depression of the treeline, especially in Europe. Nevertheless, the 6.6 ± 0.8°C prediction is pretty close to where the climatic treeline can be found today.

Treelines in a Warmer Climate

As temperature is the main natural variable controlling treeline position, one could expect, due to global warming, that trees at the treeline are growing faster and are moving

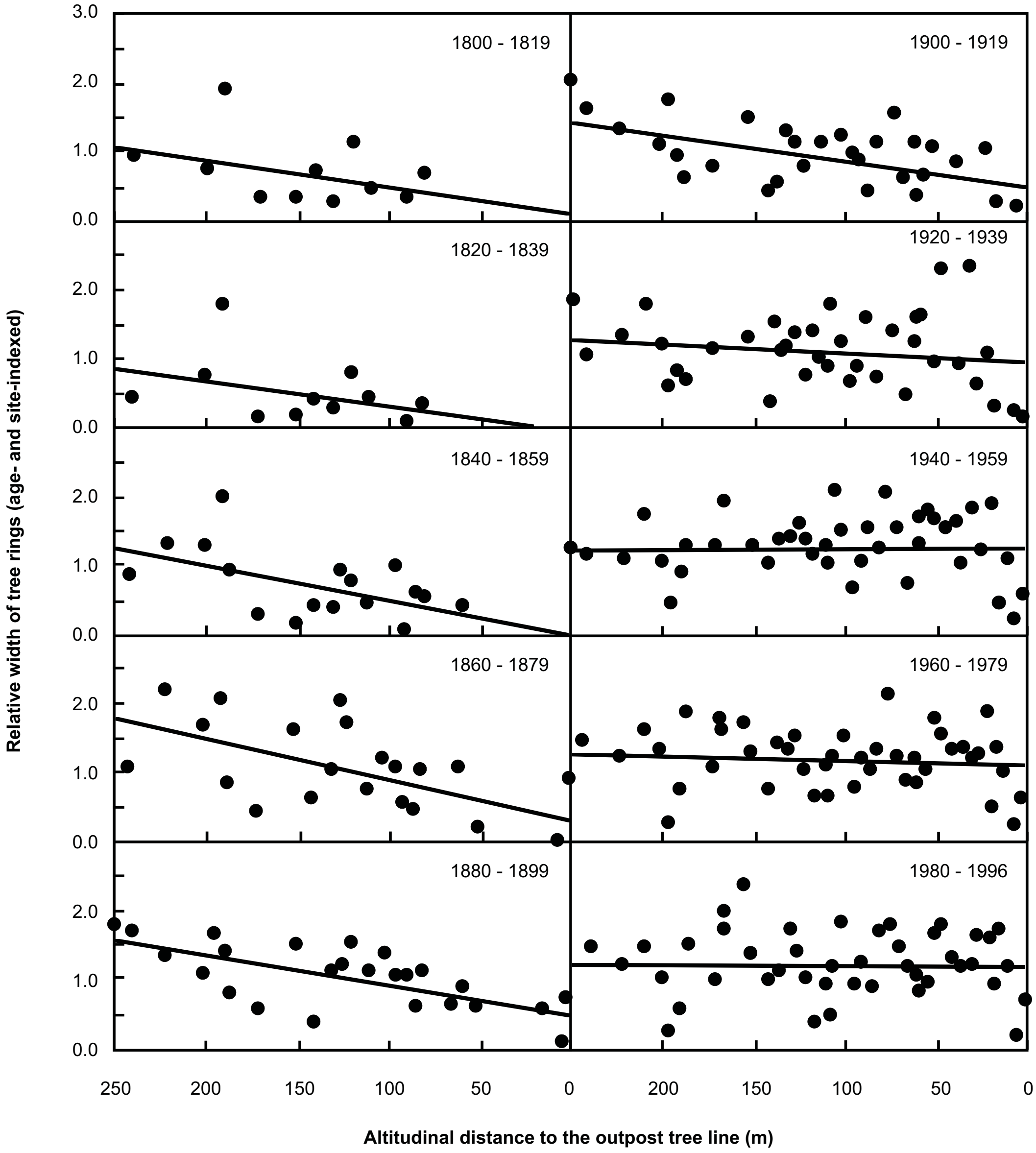

Figure 2: *Radial stem increment in relation to time period and altitudinal distance to the outpost treeline. Each point is the mean value of all age detrended ring with data of all trees at the same distance to the outpost treeline (Source: Paulsen et al., 2000).*

upslope into new terrains. Gehrig-Fasel *et al.* (2007) surveyed forest cover in the Central Alps and found that most of the current increase in forest cover has to do with land use change. 96% of the additional forest area observed in the Central Alps is infilling of open land, originating from former land use. Only 4% of the current tree encroachment into open land seems to be due to a slight upward migration into new terrain. Such an expansion of the montane forest will be very slow. There will be periods with "exploratory excursions", drawbacks due to extreme events, stationary phases, but eventually we have to expect a slow advance. In contrast, growth signals of existing trees (tree rings) in response to the last century's climatic warming are already very pronounced at treeline (e.g., Rolland *et al.,* 1998, Paulsen *et al.,* 2000).

Paulsen *et al.* (2000) analyzed trees, which were growing directly at the treeline as well as a few hundred meters below the tree limit (*Figure 2*). This procedure allows to decouple the analysis from the absolute altitude in order to permit a comparison between different regions. At the end of the little ice age, the slope of annual radial stem increment plotted against distance to the treeline is steep, indicating a sharp decline in tree growth towards the climatic tree limit. In the first half of the 19th century, trees at the treeline hardly grew. As years passed by, the trend-line of the data gets flatter and flatter. Today, the ring width does not show any difference between trees at the tree limit compared to trees 200-300 meters below. In conclusion, there was a massive increase of vigor at the treeline during the last 150 years. The increased growth started already around 1850 for trees between 55-100 m below the treeline. After 1900, also the trees between 30-50 m below the treeline started to grow more. Halve a century later, after 1950, the trees located at the limit (0-20 m) followed. Today, the growth rates are nearly the same over the respective elevations. This is a very clear and strong evidence that tree growth became stimulated by recent climatic warming.

Tree Growth at the Treeline

What is the mechanism that is constraining growth at the treeline? In simple terms, plant growth is a two step process, and each of these steps responds to environmental constraints: For a plant to grow, it first needs the substrate (building material) to do so. In essence, this means producing sugar via photosynthesis (source activity). In a second step, sugars must be invested in structural tissue (meristematic activity, i.e. sink activity). Which of the two processes is limiting growth, the acquisition or the investment of carbon?

Photosynthesis is not substantially constrained at treeline conditions. At 0°C, photosynthesis still runs at one third of its full capacity (Körner, 2003). No flowering plant, however, has ever been found to grow at 0°C or below. The colder it gets, the less photosynthesis (source activity) plays the critical role as a limiting factor. It rather is the sink activity, which is the important variable in this case. At temperatures below 5°C (a temperature, which permits half of maximum leaf photosynthesis), the formation of new cells and tissues ceases (cell division and cell differentiation). As a result, trees face a discrepancy between the ability to acquire carbon and to invest carbon as temperature drops. As a consequence, trees are accumulating more sugar, starch and lipids as one approaches the treeline (Hoch and Körner, 2003). The concentration of non-structural carbohydrates (NSC) in high altitude pines in Mexico, the Alps and Sweden increases with elevation. In no case, the NSC pool was found depleted at the growth limit of trees. Trees at the low temperature limit are fully packed with reserves and are obviously not carbon limited. Follow-up studies in China (Shi *et al.,* 2006, 2008) and Bolivia (Hoch and Körner, 2005) and several unpublished data sets confirmed that there is no lasting carbon limitation at the treeline, irrespective of the tree species that forms the treeline.

The work in Bolivia was on *Polylepis tarapacana* at the Volcano Sajama, 18° S. The Sajama region is the worlds' highest place with trees higher than 3 m. In this region, trees are growing up to 4810 m a.s.l. In Tibet, trees higher than 3 m grow up to around 4700 m a.s.l. At such elevations, the oxygen and carbon dioxide partial pressure reach only about half of that at sea level. So trees at such a high elevation not only experience low temperatures but also a drastically reduced availability of CO_2, which is only partly compensated by the greater diffusivity of the thinner air. Although trees generally grow slower as one approaches the treeline, there is no case reporting carbon reserve depletion, including the highest location on earth where trees can grow.

If a warmer climate does facilitate faster growth, we also should find a warmer year to produce more growth. However, trees produce shoot buds in the previous season, so the size of the shoot (the number of nodes) is predefined in the previous year, and we should see longer shoots in the year following a particularly warm summer. This is exactly what Krnoul and Körner (unpubl.) observed in the year 2004, which followed the heat wave summer 2003 in the southern part of Europe (*Figure 3*). The normal difference in annual shoot length growth of *Pinus cembra* between low sites and treeline disappeared from 2003 to 2004. So the warmer climate clearly stimulated tree growth in the recent past, both in terms of ring width as well as in terms of shoot extension growth.

▲ *Treelines are generally located at an altitude with a mean temperature of 6.6°C. Mountain Forest, Puschlav, Switzerland*

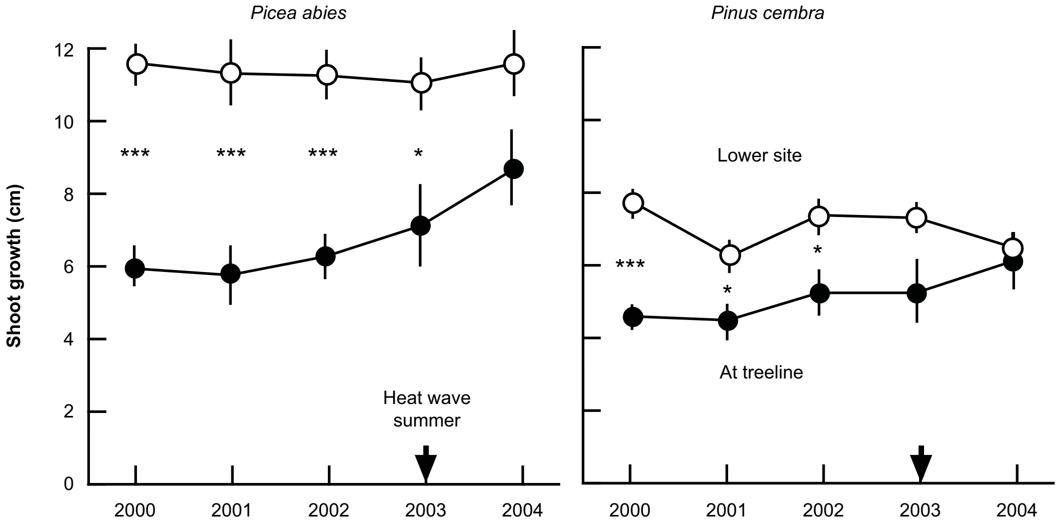

Figure 3: Shoot length growth in Pinus cembra in the Central Alps at treeline and several hundred meters below treeline. Note the greatly enhanced shoot extension in 2004, following the 2003 heat wave (M. Krnoul and Ch. Körner, unpublished data).

Alpine Vegetation and Global Change

Given that rising temperatures clearly stimulated tree growth at high elevation, one might expect all other high elevation plant species to profit from warmer conditions as well, and there should be upslope migration. However, there are lots of constraints to shifts in species ranges. One important constraint is the unpredictability of the alpine environment. While mean temperatures rise, low temperature extremes might not. The lengthening of the growing season because of earlier snowmelt cannot be utilized by all species. Many alpine species control their phenology by temperature-independent photoperiod signals (Körner 2006). This prevents the break of dormancy during warm spells in winter, before the risk of sharp freezing events is over. Plants at lower elevations have similar problems. So many plants insure themselves against such failure due to 'misleading' temperatures by photoperiod control, i.e. by applying an astronomic calendar for sprouting and flowering. This way they do not get stimulated by warm temperatures at the wrong time (Keller and Körner, 2003). Opportunistic species that follow in their development the seasonal course of temperature are located at safe sites such as snow beds. When the snow disappears, they start growing immediately. Roughly half of the Alpine flora belongs to this opportunistic group.

Another reason why a warmer climate may not always lengthen the growing season at high elevation is increased snowpack. Since warmer air masses carry more moisture, heavier snowfall has been observed at high elevation. Particularly heavy late winter snowfalls have been observed recently in the Alps during the warmest years on record.

Nevertheless, changes in species diversity have been observed. For instance, Grabherr and Pauli (1994) documented the arrival of new species on summits during recent decades. Bahn and Körner (2003) showed that some plant species from lower altitudes are migrating up the slope and now contribute to a formerly species-poor snowbed flora in the alpine belt. These changes were quite dramatic over a period of only 13 years. A French group evidenced a general upward shift of species abundance peaks in the montane belt (Lenoir *et al.,* 2008).

Direct Influence of Elevated CO_2 on Alpine Biota

While temperature is a potential growth 'facilitator', CO_2 concentration is a direct driver of carbon incorporation by plants, and it was expected that alpine biota should be partially sensitive to rising CO_2. However, there is now compelling evidence that atmospheric CO_2 enrichment has no 'fertilizer' effect on alpine plant growth. Perhaps this is so because resources other than carbon are limiting, or because CO_2-driven soil moisture savings (stomatal responses) have no effect because soil moisture is not a limiting resource at those elevations. In a four year CO_2 enrichment experiment on alpine grassland, Körner *et al.* (1997) demonstrate that biomass production was not affected at all (*Figure 4*). Newer studies using Free Air CO_2 Enrichment (FACE) support this finding (E. Hiltbrunner, N. Inauen, Ch. Körner, unpublished data). Hence, it is unlikely that alpine plants will profit directly from CO_2 increase through a stimulation of photosynthesis. A FACE experiment at treeline (Davos, Switzerland) revealed no stimulation of pine after 6 years of treatment (Handa *et al.,* 2005, 2006) but faster growth in larch, a signal, which became smaller in recent years (T. Handa, pers. com.).

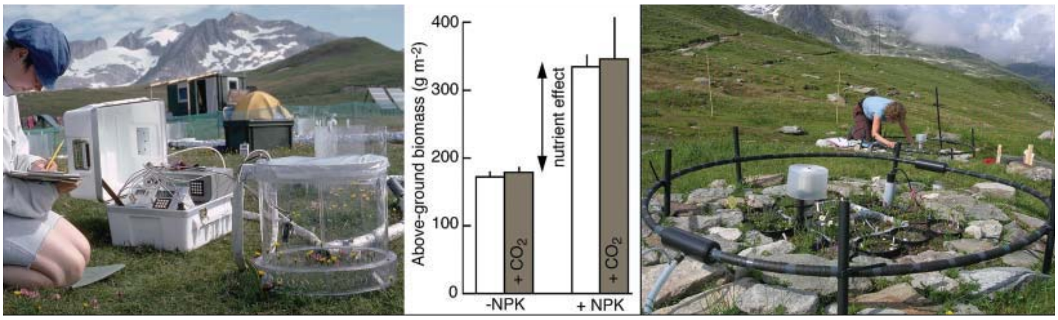

Figure 4: 4 years of CO_2 enrichment of alpine grassland at 2500 m a.s.l. (left) had no effect on plant biomass production, irrespective of whether the vegetation received mineral fertilizer (45 kg NPK ha^{-1} a^{-1}) or not. Newer data in glacier forefield vegetation (right) using free air CO_2 enrichment (FACE) yielded similar data (for references see the text).

Effects of Nitrogen Depositions

In contrast to CO_2, vegetation is very sensitive to another component of atmospheric change, the loading of the atmosphere with soluble nitrogen compounds and greater N deposition, which enhances plant growth. While 45 kg N ha^{-1} a^{-1} doubled plant biomass (*Figure 4*), even a much smaller nitrogen addition of 15 kg N ha^{-1} a^{-1} added to the current natural background of 3-4 kg N ha^{-1} a^{-1} over two years, leads to a 53% increase in biomass on calcareous soil (E. Hiltbrunner, unpublished data). This example is showing that atmospheric changes other than those in temperature may have dramatic effects on alpine plants. Glacier forefields are rich in slow-growing plant species. Many of these species are 'designed' to grow slow and to occupy the same spot for several decades or even centuries. If such plants co-occur with other, more vigorous species that are able to respond to enhanced nitrogen deposition, the competitive situation changes completely at the likely disadvantage of the slow growing species (Heer and Körner, 2002).

Impacts of Land Use Change

Mountains are the water tower of the world. Depending on definition, 12-25% of the global area is covered by mountains, and half of mankind depends on the water that comes from these areas. How will a change in high altitude land cover affect hydrology? The quality of mountain catchments depends strongly on soil stability. Soil stability, on the other hand, depends totally on the plant cover. Then plant cover itself is only stable if it is composed of a diverse mixture of species. Some species out of this mixture might resist extreme situations in which other species might fail. Hence, there is a link between biodiversity, plant cover, soil stability, and in the end, the inhabitability of the mountain valleys. Changes in high altitude vegetation may affect both slope stability and hydrology.

In many parts of the world precipitation increases with elevation (like in the Alps), but not so in the tropics and subtropics where precipitation declines drastically above the daily condensation layer at medium elevations (cloud forests). In temperate zone mountains the runoff fraction of precipitation clearly increases with elevation, but the type of land cover may affect the partitioning of water between evapotranspiration and runoff.

Land use change leads to both abandonment to intensification. For instance, never before in the recent history, have the Swiss Alps seen sheep numbers as high as they currently are (400.000). The reason is that classical agriculture with cattle became unprofitable. Many people who worked in the agricultural sector changed to other types of work outside this sector (e.g. tourism). They, however, often keep some sheep and flock them into large herds over summer. These herds graze the mountains, largely not shepherded, all by themselves. Through this uncontrolled pasturing some areas get eroded, others are not used and are lost to shrub encroachment. In contrast, when properly shepherded, grazing can have a beneficial effect, does not affect soil stability and improves hydrological yields. Controlled grazing may in fact reduce evapotranspiration by up to 10%. Converted into runoff at 2000-2500 m elevation, this corresponds to an increased electric energy yield of roughly 150 \$ ha^{-1} a^{-1}, a sum potentially bigger than government subsidies for maintaining mountain agriculture (Körner *et al.,* 1989). Sustainable grazing regimes thus provide a triple-win situation. Firstly, there is higher biodiversity in open mountain terrain compared to shrubland. Secondly, the potential for food production is retained. Thirdly, short grass yields more water and hydropower. Such land use effects may be far more pronounced than the effects of climatic change (Körner, 2000).

Extent of the Mountain Area and Carbon Storage

Whenever climatic influences on mountain biota are discussed, one needs to bear in mind that the area of land declines rapidly, as one moves upslope (Körner 2000). Any discussion of species migration in response to climatic warming would have to account for this reduction of land area with elevation. Any upslope migration of taxa will inevitably lead to ‘crowding’ and competitive exclusion, simply for space reasons. In Europe, only about one percent of land area is above the treeline. Nevertheless, this is the area, where all major rivers have their origins. Hence, we are talking about an extremely small but very influential area. Because of this relatively small area, carbon sequestration in high mountain terrain is quite marginal. While montane forests do store a lot of carbon on a hectare basis, their areal extent is very limited. *Figure 5a* shows that it would be great to have more of the forests around 1400-1600 m a.s.l. These forests store even more humus carbon than lowland forests (*Figure 5b*). However, because of their larger area, lower elevation forests represent by far the biggest carbon pool, although these data refer to Switzerland, a very mountainous country.

Conclusion

The most sensitive parts of a mountain landscape to climatic warming are the treeline and summit biota. We should nevertheless not expect a rapid change of treeline position rather than a rapid increment of vigor within the treeline ecotone. Plant species that grow above the treeline often employ photoperiodic control of their phenology, and rather than profiting from warming they will be running into problems if the snow duration changes. Not all species will be able to follow (escape) the expected climatic changes by migration. Many will stay, where they are and may become overgrown by new invaders. Noticeably, clonal plants have an ability to occupy a piece of land for centuries or even millennia, irrespective of climate change (Steinger *et al.,* 1996).

The stability of steep mountain slopes depends on biodiversity and other factors, land use in particular. While most of the global change debate related to mountains is focusing on climatic warming, land cover transformation and changes in runoff regimes driven by both climate change and land use change deserve far greater attention. Furthermore, high elevation pasture land may gain significance when extreme summer drought events such as the one in Europe in 2003 will occur more often (Schär *et al.,* 2004) and impact the lowlands, with the highlands offering some refuge for herds.

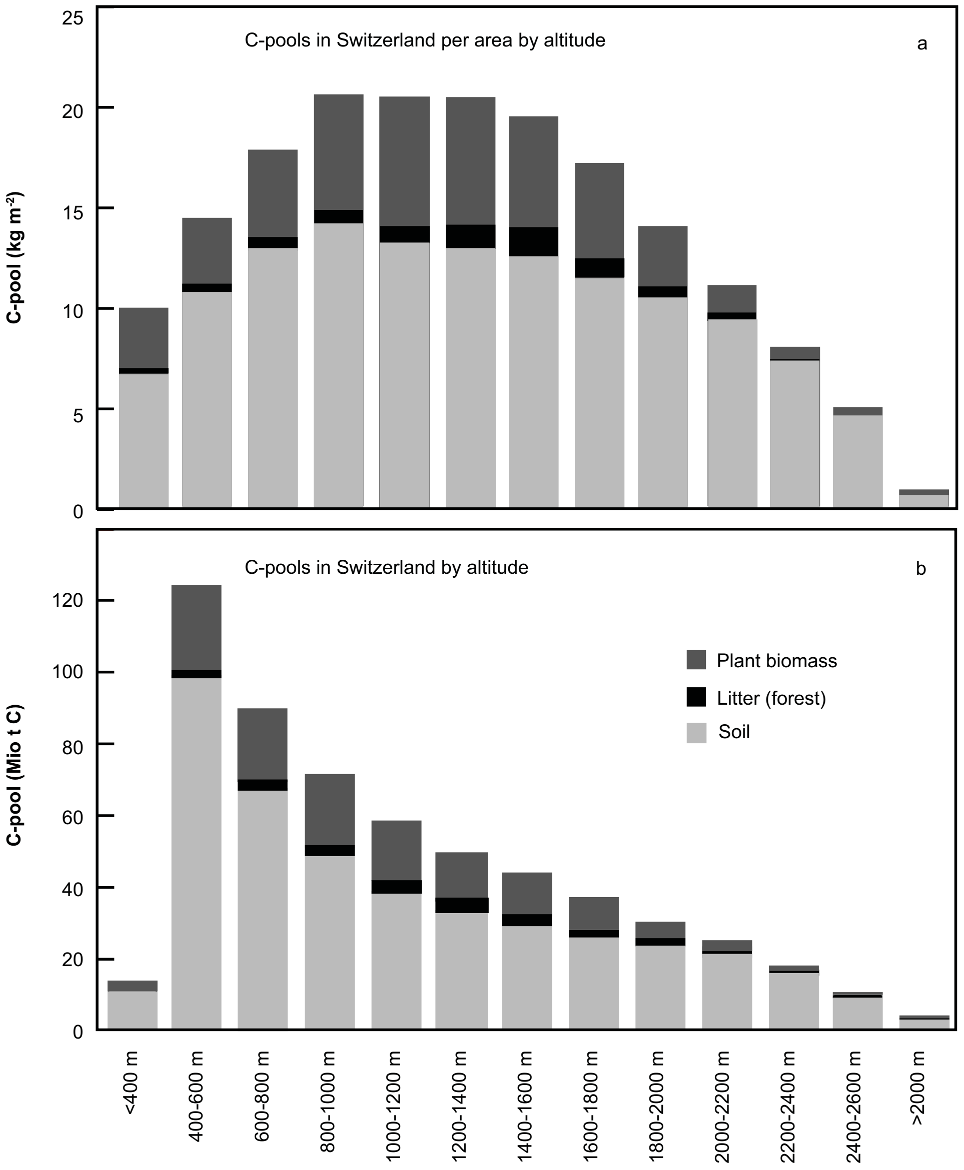

Figure 5: The elevational change of forest carbon storage in form of plant biomass carbon, litter carbon and soil humus carbon in Switzerland. (a) C stocks per unit of land area, (b) the actual stocks per 200 m elevation belt in Switzerland (Source: Paulsen, 1995).

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▲ *Snow as important water storage. View on Sertigtal, Davos, Switzerland*

Climatic Change and Alpine Impacts

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Abstract

The Alps are one of the principal sources of water for many European rivers, notably the Rhine, the Rhone, and tributaries of the Po and the Danube; in this respect, the Alps have often been referred to as the "water tower of Europe". They are also regions that feature high biodiversity; and they are also a locale where there are concurrent and often competing interests between environmental and economic concerns.

The European Alps already today exhibit strong warming trends, well above the global average warming recorded in the course of the 20th century. As climate is expected to get warmer in coming decades, the Alpine environment will experience significant impacts that will have major repercussions for socio-economic activities in this highly populated and industrialized mountain region of the world.

The paper will make a brief survey of regional climate model results applied to the Alps, and what future climate may look like by 2100 under the IPCC A2 high greenhouse-gas emissions scenario. The consequences of strong warming and seasonal shifts in precipitation will be assessed in terms of mountain ecosystems, cryosphere, and hydrology. Any changes in climate that impact water resources in the Alps will thus have significant impacts on the use and management of water, not only within the boundaries of the mountains themselves, but also in the populated lowlands downstream. Finally, an estimation of shifts in extreme events and their possible additional impacts will be addressed.

Keywords: Climate Change; Alps; Hydrology; Water Tower; Cryosphere

Introduction

The European Alps are located at a unique geographical position. They are sitting in the centre of Europe and their climate is influenced by air masses coming from the borders of Europe. From the south, Saharan and Mediterranean air masses transport a rather large amount of heat and moisture towards this mountain region. Furthermore, moisture rich air reaches the Alps also from the Atlantic area. Polar air masses, on the other hand, bring cold air and rather dry air. Finally, continental, dry air masses from the east influence the alpine climate too. In conclusion, various air masses are competing in the Alpine area. A changing climate, whether it is past or future, is not just a matter of changing temperature, but also a matter of changing frequency of the appearance of some of the different air masses. These air masses are responsible for the precipitation regimes and other atmospheric circulation patterns. If the yearly contribution of the different air masses changes, then the Alpine climate will adjust to these changes. Over the last 20-25 years some rather subtle changes have been taking place in the Alpine domain. The polar and continental regimes, for instance, reduced their influence, at least in Switzerland. On the other hand, the Atlantic and southern regimes occurred more often. Furthermore, it has been observed that the warming signal in the Alps is much stronger than on the global scale. All these observations indicate, that some change is taking place, which may or may not be linked to global warming patterns.

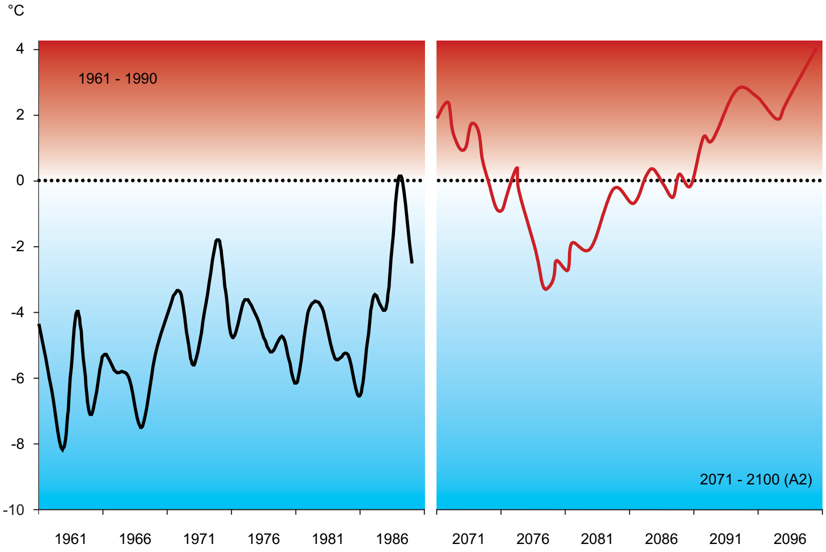

Figure 1: Winter temperatures (January) at Säntis, Switzerland (2500 m a.s.l). Left: measured data from the reference period 1961-1991. Right: Model simulation for the period 2071-2100, based on IPCC A2 high emission scenario (Source: Beniston, 2004).

Evolution of Climate in the 21st Century

Looking forward into the 21st century, most of the work is based on the IPCC reports (2007). Towards the end of the 19th century, the little ice age finished. Since then, we lived in a quite warm period. During the last 100 years, global temperature was generally above the global mean over the last thousand years. Future projections indicate a rise in global temperature of up to 6°C, depending on the emission scenario. Climate is responding strongly to high emissions and less to lower emissions. Whatever the emission pathway at the end of the 21st century will be, we are committed to warming. Even low emissions will lead to a rate and amplitude of warming. The rate and the amplitude are far greater than anything that has been seen over the last thousand years and probably throughout the whole Holocene.

Heat Days in Geneva

How does that translate down to the local level? Beniston (2005) has been looking at heat days in Geneva, Switzerland, in more detail. From 1961-1991, the 25°C threshold was exceeded around 40 days per year. The author modeled the regional climate at Geneva. For a high emission scenario, the IPCC A2, the model predicts a doubling of the number of days per year that would exceed 25°C by the end of the century (2071-2100). Looking, however, at the 35°C threshold, the picture looks different. In the reference period (1961-1991) 1-2 days per year exceeded the 35°C threshold. The model predictions towards the end of the century indicate, however, that around 10-14 days per year will experience a maximum temperature above 35°C. Such a threshold has implications for human health, crops and animals, ecosystems and hydrology. It is the type of situation that was experienced during the 2003 heat wave in Europe, where temperatures beyond 35°C persisted for over 2 weeks in many parts of Europe. This is the kind of event that we are likely to see at least on summer out of two in the future.

Temperature at Säntis

Global warming affects mountains in various ways. *Figure 1* shows the winter temperatures (January mean) measured at the Säntis, Switzerland, (2500 m a.s.l.) during 1961 and 1991. The figure clearly shows the very strong warming already during this period. In the early 1960s, the temperatures were around -6°C, rising to -2°C towards the end of the 1980s. This corresponds to 3-4°C of warming over the observed 30 years. The model projections (high emission scenario A2) for the period 2071-2100 show even higher temperatures rises. The modeled temperature increases by 4-5°C compared to 1961-1990. This will have major impacts on the Alpine environment and the Säntis, since the average number of days that will be above the freezing point increases very substantially. In the reference period (1961-1991), the Säntis observatory measured a January mean temperature that exceeded slightly the freezing point only once, in 1983.

In the future climate, barring the colder period, which the simulation predicts around 2080, January will be generally above the freezing point at the level of 2500 m a.s.l. (*Figure 1*). This warming could have significant consequences for early year runoff. It might, for instance, spark the vegetation cycle of some of the opportunistic plant species. In conclusion, very subtle changes in temperature may cause major changes in other elements of the natural environment. This may simply be the case when the very important ecological threshold, the 0°C line, is crossed.

Precipitation in the Alpine Domain

Changing climate does not just lead to changing temperatures, but also to alterations in the precipitation patterns, for instance. Many models are suggesting that the seasonal precipitation pattern will change, even though the simulations are highly inaccurate in terms of getting the amounts of precipitation correctly. Nevertheless, these simulations are an indication of processes that are likely to happen in the future. Today, we are already seeing a number of such processes in some parts of the Alps. The models suggest a likely increase in wintertime precipitation by around 20%. Summertime precipitation, on the other hand, will decrease by around 30%. For spring and autumn, the models predict changes of a few percent only. In spring, precipitation will increase, whereas in autumn less precipitation will occur. The absolute amounts of precipitation differ from one model to another. The sign of change is nevertheless constant throughout the models. The more the Mediterranean regime will influence the Alpine region, the stronger the seasonal shift will be (more precipitation in winter, less during summer). The Mediterranean climate is basically a climate with a very long dry season from late spring to autumn and a mild, rainy season during wintertime.

Impacts on the Alps

How will changing temperatures and altering precipitation regimes impact the Alpine domain?

General Impacts

Ecosystems will certainly respond in different ways. Some of the ecosystems are already responding today, others will adapt in coming decades. As precipitation patterns change, the hydrological system will definitely change as well. Seasonality will change, e.g. in terms of peak runoff. One of the major impacts will occur in the mountain cryosphere. Snow and ice will only respond with increased melting if sustained temperatures above the freezing point will take place at high altitudes at which we do have snow and ice today. Additional impacts will occur on other systems than the ecology, hydrosphere or cryosphere. The socio-economic system, for instances, will have to deal with declining permafrost cohesion of soils and other unstable soils. Natural hazards will certainly be one of the key issues that also will impact upon several socio-economic sectors. Some of the events are going to affect infrastructure and communication routes, leading to high costs for mountain communities. Hence, insurance costs will increase, for instance.

Changing precipitation and cryosphere patterns, especially the impacts of changing snow amount and the changing seasonality of the winter season, is going to have an impact on the hydro-sector. Dams are likely to fill earlier on in the season compared to today. This will make the utility manager think about how to deal with the new seasonality. One element, which is highly important in economic terms, is the ski industry (OECD, 2007). We see already in today's climate that mild and snow free winters have a strong impact on the economy. The mild European winter of 2006/2007 had immediate economic consequences for low and mid altitude ski stations in Switzerland.

Changing temperature and precipitation regimes will directly affect the agricultural sector. In a highly subsidized agricultural economy, like in Switzerland and many other parts of the industrialized world, economy will probably help to buffer the side effects on agricultural yields.

To conclude, disrupting natural systems leads to a number of impacts in economic and also social terms on quite a range of sectors as we know them today. This is definitely the case for a highly and densely populated mountain area such as the Alps.

Hydrology in More Detail

The Swiss Alps are often referred to as the water tower of Europe. From the Swiss Alps, rivers are flowing towards the north, south and the east. Around two third (67%) of the water that falls on the Swiss Alps eventually runs through the Rhine and its tributaries into the North Sea. 18% goes through the Rhone into the Mediterranean Sea. 10% of the precipitation takes the way via the Ticino and the Po into the Adriatic Sea. Even a small contribution (5%) leaves Switzerland via the Inn River into the Danube and finally reaches the Black Sea.

The source region of the rivers, which are feeding the different regions of Europe, is located in fairly limited radius in the Central Swiss Alps (Gotthard Region). One can easily imagine that a disturbance of the climatic conditions will result in significant impacts, not only within the Alpine Domain, but even more in the downstream areas. A disturbance will have greater impacts on the densely populated lowland areas that are depending on the water resources (e.g. for hydropower, the agriculture in the Rhone valley or the industry


Photo: Debbie Hirzel

▲ *Changing temperatures and altering precipitation regimes will certainly impact Alpine ecosystems as well as the mountain cryosphere.*

in the Rhine valley). Highly industrialized economies several hundreds of kilometers away from the Alps are highly dependent on the major resource that water represents. Therefore, any disruption at the origin of the major rivers at the very small area in the Central Swiss Alps may have massive impacts far downstream.

Snow is a major factor that influences hydrological regimes. Snow during the winter season represents water storage in solid form that will be released into the water systems in spring and the early summer. Snow is one of the essential components that determines the seasonal character and the amount of water that runs off into major rivers.

In the Alps, the winter season will become milder, but more precipitation is likely to fall. *Figure 2* shows the modeled snow duration with a local temperature rise of 4°C and a precipitation increase of 10%. The darker colors in the map indicate that the low land plateau from Geneva through to Zurich and beyond will see very little snow in the future. Maybe a couple of days per year, maybe not even that. In the mountains, roughly above 2000-2500 m a.s.l. snow cover will last almost as long as today. One might see, paradoxically, even more snow at elevations above 3000 m a.s.l., simply because the predicted increase in winter precipitation will fall out as snow at high elevations.

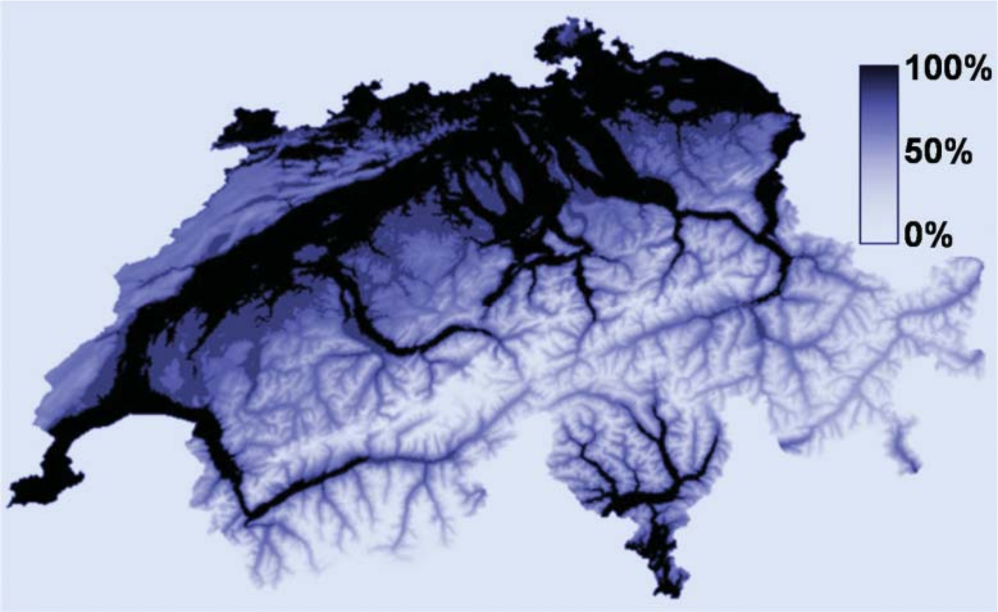

Figure 2: Map of Switzerland illustrating the reduction in snow volume that can be expected following an increase of 4˚C in DJF minimum temperatures, compared to contemporary climate (Source: Beniston et al., 2003).

As seasonality, snow duration, precipitation and other climate variables change, the runoff pattern of the Swiss rivers will change as well. Today, runoff strongly increases around May for rivers in the catchment areas like Rhine or Rhone (*Figure 3*). Highest runoff is generally registered in July and it decreases afterwards again to a rather low winter level. This is a typical signal of snow thawing, which is releasing large quantities of water fairly rapidly. As the snow tends to disappear towards the summer, the runoff will be mainly dependent on convective shower activities at the end of the summer. As we go into the autumn much of the precipitation will be stored again as snow for the next season and river runoff decreases. *Figure 3* also presents regional climate model predictions on the future runoff pattern. The predictions point toward a greater runoff in the winter. The reason is that more precipitation will occur during the winter and most of it will fall down as rain, at least at elevation below 1200-1500 m a.s.l. During the summer, the rivers carry only very low amounts of water, because the summer will be a very dry season. Furthermore, most of the snow that will be left of the snow packs in the Alps will have been melted well before the beginning of the summer. As a result, this will lead to very major changes in the runoff pattern of rivers.

We have already lived through in the past that may become more frequent in the future, as projected by these model simulations. An example of critical flood situation is the Rhine in 1995, which overflowed its banks practically from Basel to Rotterdam. This hazard

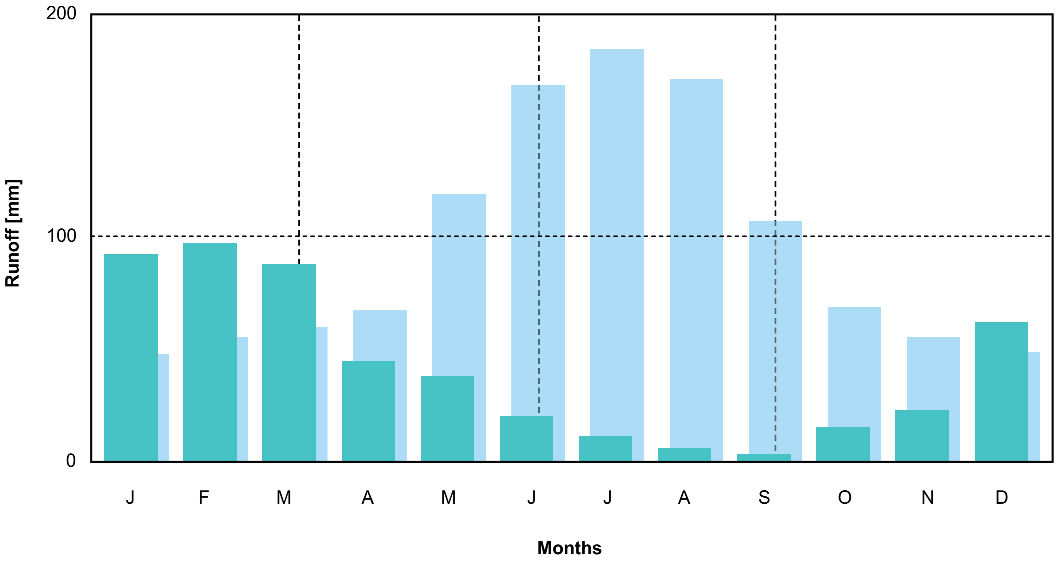

Figure 3: Changes in surface runoff by 2100 for the Rhône/Rhine catchment areas. Runoff as it is today (blue) and as the model predicts for the year 2100 (grey) (Source: Beniston, 2004).

was associated with early snow melt in February in the Alps coinciding with quite strong precipitation in South Western Germany. The combination of these two factors led to a catastrophic event. Another example, this time of extreme drought, occurred in August 2003, during the European heat wave. Even though the 2003 summer will be remembered as an extremely hot season, it was also an extremely dry year, with precipitation deficits that began 6-8 months prior to the peak heat wave period of August 2003. The precipitation deficit, leading to dry soils, is one explanatory factor for the intensity and persistence of the heat wave.

With a changing precipitation pattern, the distribution of heavy precipitation events (>50 mm/day) will also change. In the period 1961-1990, most of the events had been registered in the summer (~18 events/year). In spring, the number of events was about half of the summer ones. In winter, only very few events occurred. With ~11 events/year, autumn is in between summer and spring. The HIRHAM regional climate model suggests a shift of events from summer to spring. In the period 2071-2100, the number of yearly heavy precipitation events will probably double for spring and halve for the summer period. In winter and autumn, only a few more events will occur compared to the current state.

Heavy precipitation events in spring do, however, not imply flooding directly. In spring, the snow line is lower than during summer. Hence, more precipitation will fall as snow instead of rain. This solid precipitation leads to a retention of water and the probability for flooding decreases.


Photo: Guido Hirzel

▲ *Transporting 67% of the water that falls on the Swiss Alps, the Rhine and its tributaries are of major importance for the downstream areas. Rheinfall, Neuhausen am Rheinfall, Switzerland.*

Conclusions

Today, we are looking at very rapid global changes. Not only the climate is changing, but also other sectors of the natural environment, like vegetation, undergo dramatic transformations. The changes today are very rapid and will go on even faster in the future. In the northern parts of the Alpine zone, the climate will transition towards a more Mediterranean-type climate. Such a transition will be associated with warm and moisture rich winters and hot and dry summers. Heat waves and the two extreme events of precipitation, drought and heavy precipitation, are likely to increase. Therefore, the risk for natural hazards will augment over the coming decades. As the number of extreme natural events increases, the risk, however, is not likely to increase in a linear way. Some effects of extreme events may be counterbalanced by other processes. For instance, a shift of heavy precipitation events from summer towards spring and winter, results in the storage of water as snow. This in turn leads to a smaller risk for flooding.

Not only is the socio-economic environment affected. There are major impacts on the natural environment too, like on glaciers, snow, water, ecosystems, forests, etc. Wherever the natural environment is disrupted, socio-economic activities of humans will be affected directly or indirectly.

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Conference Programme

INTERNATIONAL CONFERENCE ON
MOUNTAINS AS EARLY INDICATORS OF CLIMATE CHANGE
Padua University, 17-18 April 2008

Thursday 17 April
Palazzo Bo, Aula Magna“Galileo Galilei”

Inaugural Session
15.30-18.00

Opening Remarks	
Giuseppe Zaccaria	Deputy Dean University of Padua
Gaetano Leone	Deputy Director - UNEP Regional Office for Europe
Agostino Da Polenza	President Ev-K2-CNR Committee
Guido Sacconi	President Commission on Climate Change EU Parliament
Giuseppe Cavaretta	Director Earth and Environment Departement CNR
Paolo Angelini	Italian Ministry of Environment Land and Sea
Alfredo Guillet	Italian Ministry of Foreign Affairs
Oscar De Bona	Regional Ministry for Mountains – Veneto Region
Roberto Marcato	Councillor, Province of Padua
Anna Milvia Boselli	Municipality of Padua

Opening Lesson	
Richard Armstrong	Climate change, snow cover and glaciers

Friday 18 April
Palazzo Bo, Aula “Archivio Antico”

Session 1
9.00-13.30

Chair: Gaetano Leone - Deputy Director UNEP Regional Office for Europe		
9.00	Liisa Jalkanen	GAW mountain observatories in detection of atmospheric change
9.40	Sandro Fuzzi	Atmospheric composition change and climate in high mountain areas
10.20	Riccardo Valentini	Global change and ecosystem services: an outlook on forests and mountain regions
11.00	*Coffee Break*	
11.30	Patrick Wagnon	Glacier evidences of climate change in the tropical Andes
12.10	Stefan Grab	Climate Change in the African Mountains
12.50	John Jack Shroder	Himalayan Glacier Changes and Global Change Anomalies
13.30	*Session 1 Conclusions*	

Session 2
14.45-18.05

Chair: Gaetano Leone - Deputy Director UNEP Regional Office for Europe		
14.45	Sergio Castellari	Climate change, impacts and adaptation strategies in the Alpine Space: Results from the INTERREG III B project ClimChAlp
15.25	Jordi Catalan	Lakes as witnesses of Global Change in Mountains
16.05	Christian Körner	High altitude plant life in a warm, CO_2-enriched atmosphere
16.45	Georg Kaser	Studying Changing Mountain Glacier - Why and How?
17.25	Martin Beniston	Climatic Change and Impacts on the Alpine Environment
18.05	Shardul Agrawala	Climate Change and Winter Tourism: From Risks to Opportunities (10min video transmission)
18.15	*Session 2 Conclusion*	

Acronyms and Abbreviations

ABC	Atmospheric Brown Cloud
AGAGE	Advanced Global Atmospheric Gases Experiment
ClimChAlp	Climate Change, Impacts and adaptation strategies in the Alpine Space
DJF	December, January, February
ENSO	El Niño - Southern Oscillation
FACE	Free Air CO_2 Enrichment
FAO	Food and Agriculture Organization
GAW	Global Atmosphere Watch
GCM	Global Climate Model
GHG	Greenhouse Gas
GLIMS	Global Land Ice Measurements from Space
GLOF	Glacier Lake Outburst Floods
GPP	Gross Primary Production
IPCC	Intergovernmental Panel on Climate Change
MB	Mass Balance
MEI	Multivariate ENSO Index
NAO	North Atlantic Oscillation
NCO-P	Nepal Climate Observatory-Pyramid
NEE	Net Ecosystem Exchange
NSC	Non-structural Carbohydrates
OC	Organochlorine Compound
OECD	Organization for Economic Cooperation and Development
PAHs	Polycyclic Aromatic Hydrocarbons
RCM	Regional Climate Model
SCA	Snow Covered Area
SCP	Spheroidal Carbonaceous Particles
SEB	Surface Energy Balance
SOGE	System for Observations of halogenated Greenhouse Gases in Europe
SST	Sea Surface Temperature
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

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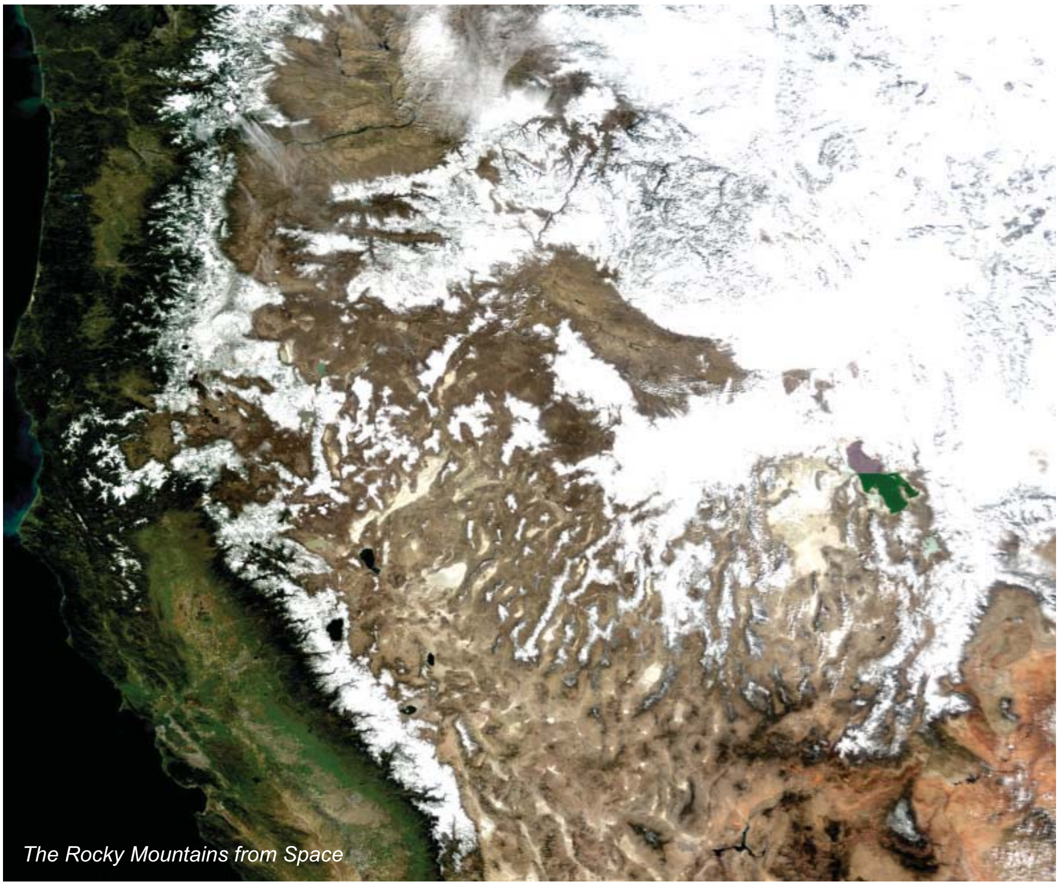

The Rocky Mountains from Space

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