

# REMOTE SENSING TECHNOLOGIES AND APPLICATIONS FOR MONITORING HIGH MOUNTAIN ENVIRONMENTS

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## ABSTRACT

*The first part of this paper will discuss typical data based problems in High Mountain areas and the applicability of Remote Sensing data in high mountain environment in respect to their limits (shadow, relief displacement, snow cover, clouds, etc.) itself. The general requirements for mapping purposes and topics of interest will be discussed in this part, too. In the second part of the paper different High Mountain Remote Sensing applications, the used methods and techniques will be presented. Mountain environments are likely to be among the most severely impacted ecosystems as a result of climate change. The applications will document case studies of different high mountains of the world (Alps, Andes and Himalayas), with different approaches, sensors and topics. Monitoring concepts of glacier investigations by means of terrestrial (laserscanner) and airborne/spaceborne sensors (aerial photographs, optical satellite images, radar data) are main research topics of the Institute for Geography and Regional Sciences and their partners in Graz. The case studies will document the mapping capabilities for topographic maps as well as the potential for hazard/landslides inventories.*

**Keywords:** High Mountain, Remote Sensing, Monitoring.

## 1. INTRODUCTION

Mountains are distributed across all over the world's continents. Mountain environments cover some 27% of the world's land surface, and directly support the 22% of the world's people who live within mountain regions (Messerli, B., Ives, J.D., 1997), but over 50% are directly or indirectly dependent on mountain resources (Secretariat of the Convention on Biological Diversity, 2003). The two key components which make mountains so important and sensitive are (1) altitude and (2) slope. With their elevation above the plains, the mountains trap an over-proportional fraction of terrestrial precipitation. With their steep and varied topography, and distinct altitudinal ecological zones, mountains support a high diversity of species and ecosystems and a large percentage of global endemic species. Mountainous areas throughout the world provide essential resources such as timber, minerals, recreational escapes, and a significant portion of the freshwater consumed by humans. They are rich sites for cultural diversity and for tourism. Mountains have a special role in showing the effects of climate change, too. Lowland people also depend on mountain environments for a wide range of goods and services, including water, energy, timber, biodiversity maintenance, and opportunities for recreation and spiritual renewal (UNEP World Conservation Monitoring Centre, 2002).

High Mountains are complex ecosystems characterized by - high relief energies (elevation differences), - steep relief (with dominance of gravitational processes), and - the existence of a significant altitudinal change of climatic conditions (resulting in the development of different ecological belts)" (G.K. Lieb, 2006). High Mountains are characterised by its remoteness (vertical and horizontal); are a „playground“ for „Global Change aspects“ and its impact on the environment; are characterized by high morphodynamic aspects; are extremely heterogenic and small structured; show a permanent change of vegetated and “non” vegetation areas; provide a permanent change in relief parameters, suffer from a lack of information (e.g. geodata); and can be strongly influenced by human activities (W. Sulzer, 2011).

## 2. REMOTE SENSING AND HIGH MOUNTAINS

Remote High Mountain areas of the world often suffer from appropriate geodata for investigating purposes. No or only few very roughly produced data bases are available. Remote Sensing therefore means a valuable tool for providing basic and specific thematic information. Typical data acquisition focused problems in High Mountain areas are (W. Sulzer, J. Gspurning, 2009):

- “Insufficient” analogue topographic maps (mainly low accuracy and obsolete...).
- Generally a lack of adequate geodata.
- Poorly documented analogue and digital datasets and in particular, incomplete or missing metadata. The biggest advantage of geo-spatial technologies results from the integrated use of data layers which has the

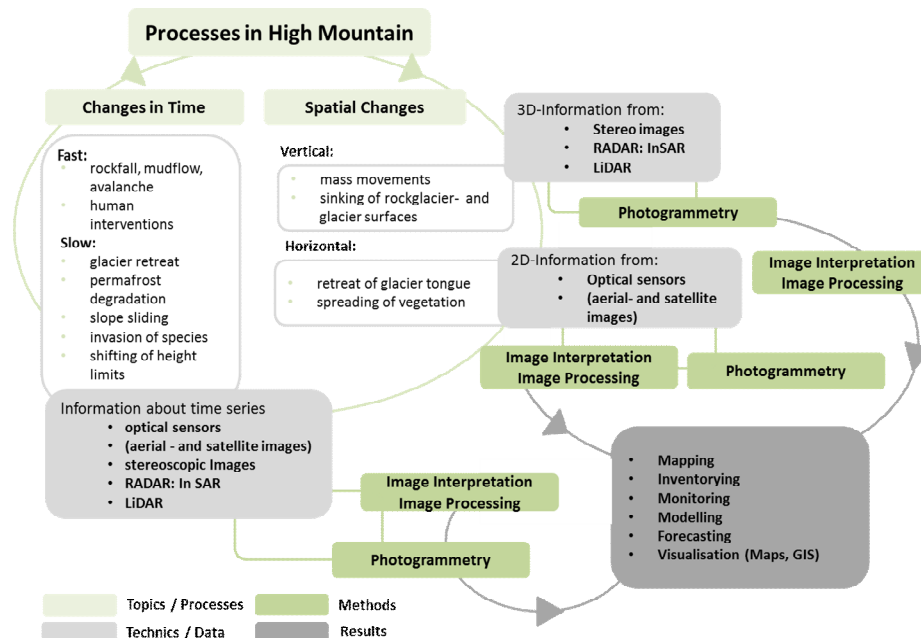
compatibility of data as a required precondition. In many cases, digital or analogue data sources lack even the essential information (projection parameters).

- Few themes covered and low spatial coverage because many of the alpine related geodata are derived from highly specialized studies undertaken for a distinct short term purpose and not for implementing information systems.
- Obsolete data because, for the most cases, it is nearly impossible to keep the databases updated for the entire investigation area.
- Proper resolution of datasets. Alpine areas are composed of small distinguishable landform units usually also characterized by a high value of relief energy; therefore modelling of alpine processes requires high resolution datasets (i.e., 1m - Digital Terrain Models/DTM's) which are seldom available.

Monitoring the environment of mountainous areas is of great importance for the mountainous area itself, but also for the adjacent lowlands. Since access of mountainous areas is difficult, remote sensing is a valuable alternative to intensive fieldwork and the gathering of data required for GIS analyses. High Mountain areas are regions, which are especially suitable for providing surface information by means of Remote Sensing. Remote Sensing techniques provide useful tools for spatial and especially for height related interpolation of local – field based acquired information (F. Buchroithner 1995; B. Shrestha 2007). Due to their contactless and spatial extent, aerial photographs and satellite images get an increasing importance for many mountain related topics (LULUC, change detection, hazards, monitoring, etc.). The knowledge of the possibilities and limitations of remote sensing and the careful evaluation of remotely sensed image data are inevitable for the meaningful, effective and financially feasible application of these techniques.

Furthermore, the applicability of geodata in High Mountain environments has system limitations. The requirements for analysing, mapping and monitoring purposes are listed below (W. Sulzer and J. Gspurning, 2009):

- Availability of high-resolution spatial and temporal data
- GIS and remote sensing toolboxes (which have to be adopted or newly created)
- A suitable data basis for processing (rectification, image/GIS analyses and presentation; e.g. (digital) topographic maps, DEM, fieldwork)
- Suitable weather/atmospheric conditions and season
- Suitable sensors (geometric/spectral/radiometric/temporal resolution)
- A skilled user for geodata processing, analyses and presentation (necessary skills include image processing/GIS, knowledge about natural and cultural environment, and cartographic skills).



**Figure 1.** Selected processes in the High Mountains and their investigation by means of Remote Sensing (M. Nutz, 2007, changed and added)

For investigation of High Mountain dynamics remote sensing data are available since about 40 years, with different geometric, spectral resolution and temporal resolution. To apply scientific investigations in High Mountain environments, especially generation of spatial information with large extent, Remote Sensing techniques have been proofed as a sustainable tool. Remote Sensing delivers data in different scales, which are needed to understand the complex processes in the High Mountain environment. By means of a simultaneous view of large regions,

relationships can be recognized (N.J. Schneevoigt, L. Schrott, 2006). By means of Remote Sensing data, mapping and times series can be achieved as well as further modelling; the current situation (mapping) or the changing (monitoring) of the landscape can be investigated, respectively its development can be modelled, too.

Some Examples of applications in the high mountains are glacier- and permafrost monitoring within a global climate change and hazard research initiative, mapping and monitoring of mass movements for hazard management or habitat mapping and – monitoring protected areas (e.g. Natura 2000 areas). Modelling of scenarios of the past and/or future is part of all mentioned applications. The natural landscape changes in the high mountains are a.o. tectonic and climate induced (e.g. earthquakes, heavy rainfall evidences, glacier retreatment, a.s.o.). Gravitational processes are causing on the one hand erosion and on the other hand accumulation. Higher temperatures affect in- and decreasing habitats and uplifting of height limits. Spatial changes detected by means of remote sensing can be horizontal and vertical (A. Kääb, 2005). The dimension time gets its importance from different velocity of the events.

### 3. CASE STUDIES OF HIGH MOUNTAIN REMOTE SENSING

#### 3.1 Glacier Monitoring – case Study of Pasterze Glacier in Nationalpark Hohe Tauern (Austria)

The leading topic of this case study is the spatio-temporal reaction of glaciers to the changing climatic conditions. Pasterze glacier is used as an example of pronounced shrinking of a glacier since 1850. The glacier retreat is monitored by traditional as well as modern methods (with special focus on Remote Sensing).

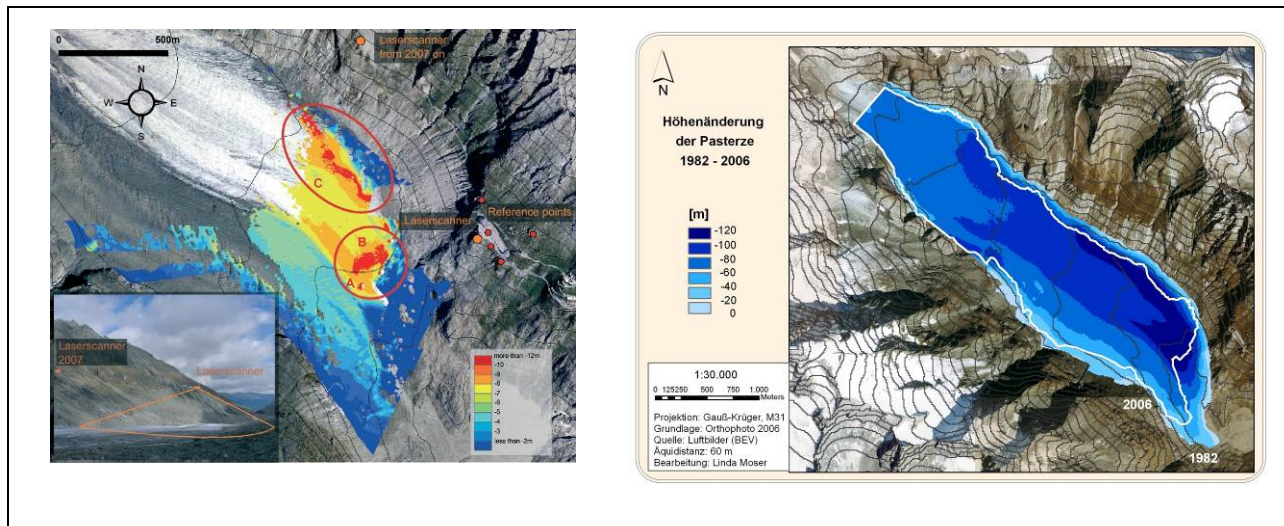
Remote Sensing techniques for glacier monitoring can be applied in different spatial, spectral and temporal dimensions and scales. A. Kääb (2005) describes the spatial dimension as a point (1D), area (2D), surface incl. height information (2,5D) and “real” height information (3D). The spectral dimension can be monospectral, multispectral and hyperspectral, and the temporal dimension documents whether the data is available for one time, two times or for multiple times. Passive and active sensors will be applied for glacier monitoring, which are mounted as well as on airborne, satellite systems and even on terrestrial platforms. Digital Elevation Models (DEM) and height measurements on glaciers are the key factors for volume estimations. Volume changes, changes in mass balance of a glacier can be recognised as an indicator for climate changes. The velocity on the glacier surface can be measured by means of aerial photographs and satellite images and with differential radar interferometry.

Within the long-term project “Alpchange” (since 2001) new methods of glacier monitoring were applied on Pasterze glacier. Some of the results of laserscanning campaigns, Differential –GPS and as well as airborne and spaceborne Remote Sensing data will be presented. Measurements with terrestrial laserscanning on the tongue of the Pasterze glacier were applied since 2001, each year. The results (**Figure 2**, left) show shrinking areas on the part of the glacier with bare ice (C); with (A, B) effects of different ablation situations on the glacier. On the debris covered glacier the subsidence is less than in the bare ice area.

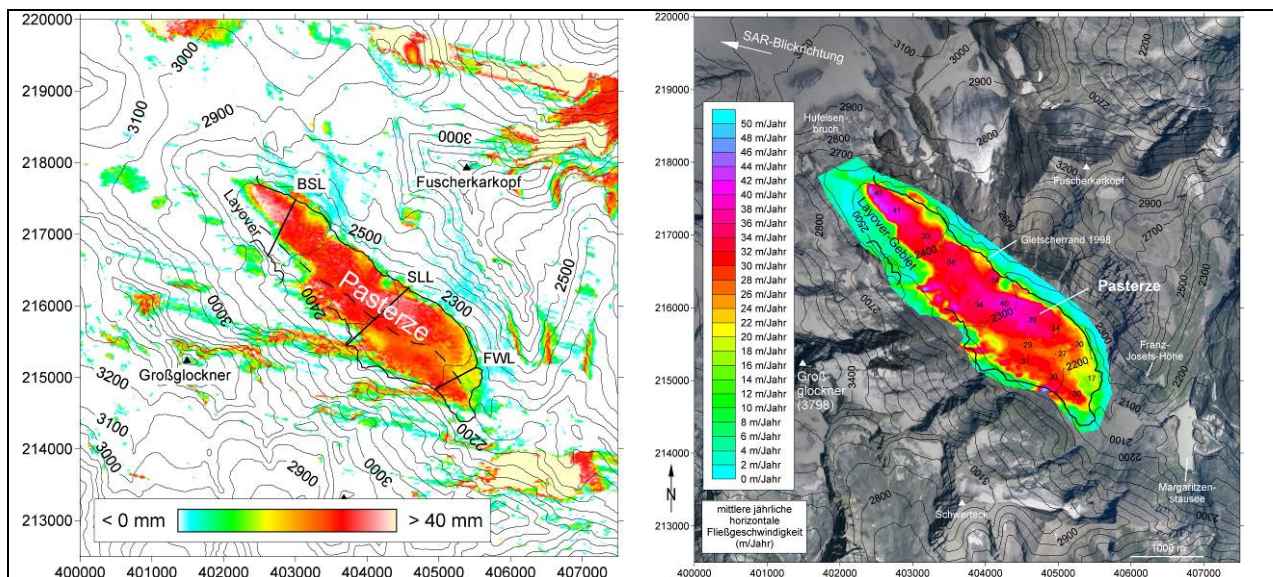
DGPS measurements (Avian et al 2007) were applied a) to map the exact delineation of the glacier, b) to measure the velocity of the glacier along a profile, c) to map the borderline between the debris covered and bare ice areas and d) to acquire Ground Control Points for laserscanning. The comparison of traditional tachymetric field methods of glacier measurements with modern methods shows that there are no controversial data for the results. The combination of different methods achieves a general advantage for the glacier monitoring (W. Sulzer and G.K., Lieb, 2009). GPS shows exact results for 3D information (e.g. lines and points), Laserscanning results in a spatial information with similar accuracy. Tachymetric field methods have still the achievement of detailed measurement of surface movements and achieve additional information’s for the modern methods. Due to the heavy workload of terrestrial laserscanning the method was applied only at the tongue of the glacier. Aerial stereoscopic images are still in use to get height information of the total glacier surface (**Figure 2**, right). The acquisition time of the aerial photographs is the third week of September, so this fits perfect to the end of the mass balance year of the glacier (just before the first winter snow falls).

V. Kaufmann et al. (2008) investigated the Pasterze glacier velocity by means of ERS-1/2 differential SAR-Interferometry (DINSAR). SAR Images from the summertime were used for the analyses. One of three image pairs of the ERS Tandem Mission on the lower part of Pasterze glacier shows sufficient coherence to generate a good interferogram. For the investigation period in August 1995 maximal velocity vectors of 30-40mm/day could be recognized (**Figure 3**).





**Figure 2.** Left: Height differences from laserscanning campaigns in the period 2004/2005 on the Pasterze glacier (M. Avian et al., 2007); Right: Height differences from aerial photogrammetry in the period 1982/2006, white line marks the glacier extent from 2006 (L. Moser, 2008)

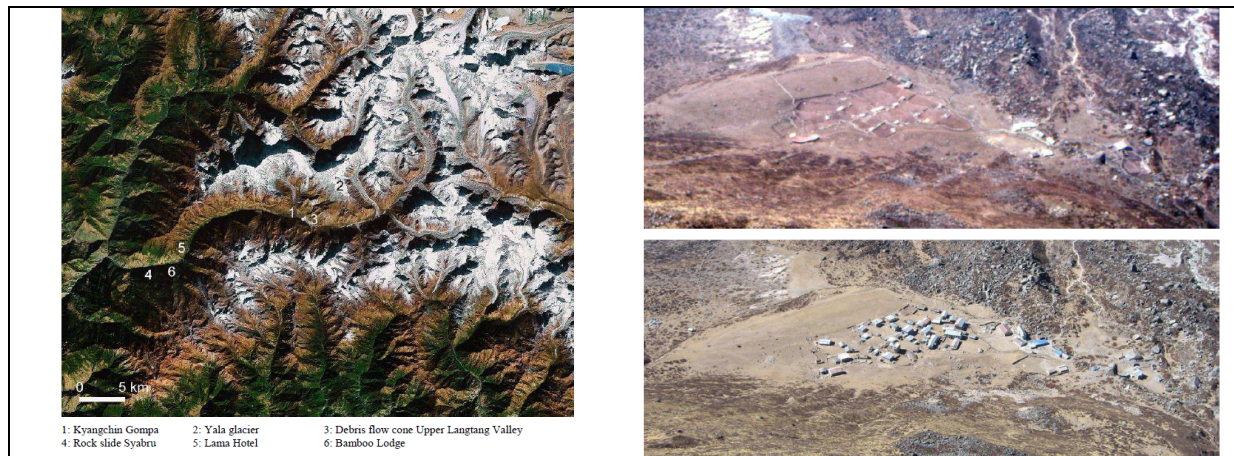


**Figure 3.** Left: Geocoded differential SAR interferogram of the image pair 20.8.–21.8.1995, Right: Mean horizontal velocity of the Pasterze glacier, generated from a one day lasting ERS-1/2 Interferogram for the period 20.8.1995–21.8.1995, (V. Kaufmann et al, 2008).

### 3.2 Monitoring of a high mountain environment - case study of Langtang Nationalpark (Nepal)

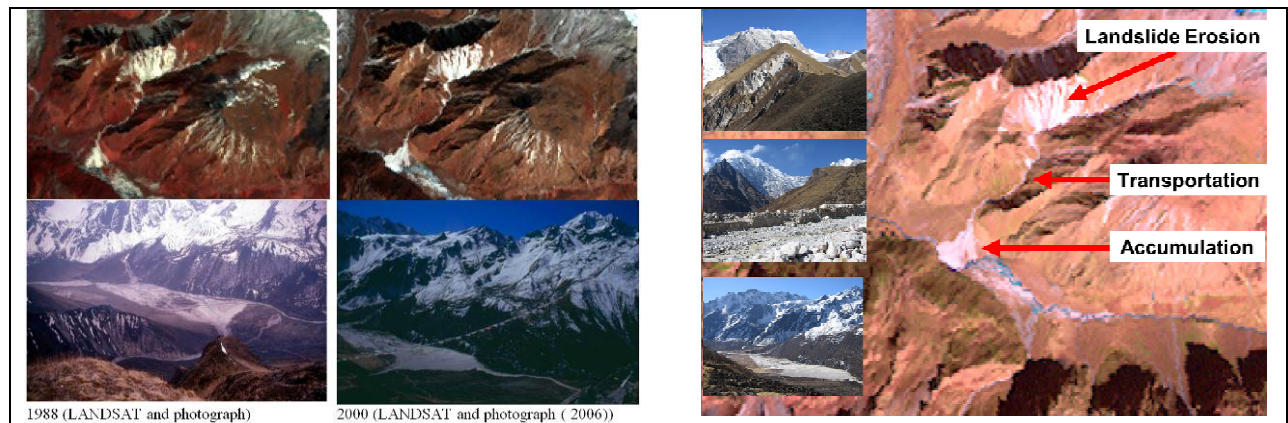
The case study (W. Sulzer, 2010) of the Langtang Valley (Nepal) has the objective of documenting the natural and cultural development of the high alpine landscape during the last two decades. The study is a result of 4 field trips to this region during this period. The study will focus on the following indicators: the political situation, tourism, vegetation and land use, glacier and rockfalls. Langtang Himal is located about 60 km north of Kathmandu, the capital city of Nepal. The Langtang Valley is surrounded by the High Mountain ranges of Langtang Himal and Jugal Himal. Langtang Himal, with peak altitudes of about 6,500 to 7,200 m, forms the northern and eastern divides, bordering Nepal and Tibet (China). Jugal Himal, with peak altitudes of about 6,800 m, forms the southern divide.





**Figure 4.** Left: Langtang Valley in an overview (numbers refer to case studies in the text, basic: LANDSAT-Mosaic); Right: Kyangchin Gompa 1988 (top) – 2006 (bottom) (1 in Figure 4/left, Photograph: W. Sulzer)

**Figure 4** (left) gives an overview about the studies in the Langtang Area; **Figure 4** (right) documents the changes in Kyangchin Gompa between 1988 and 2006. The original alpine pasture settlement (with a small gompa and cheese factory) had only one lodge (half rounded building in the left corner) in 1988. This increased to 5 lodges in 1992 and 10 accommodations in 2006. However, only 2 of them were open in March 2006. While all the lodges were full in 1997, they accommodated only 8 tourists in a 4 day period in 2006. The absence of tourists has the effect that many buildings/lodges are not busy in March and are open only during the high season. If tourists do not return in the coming years, it is doubtful whether most of the new buildings will be preserved in their tourism functions.



**Figure 5.** Documentation of erosion in the region of the landslide area (W. Sulzer, 2011)

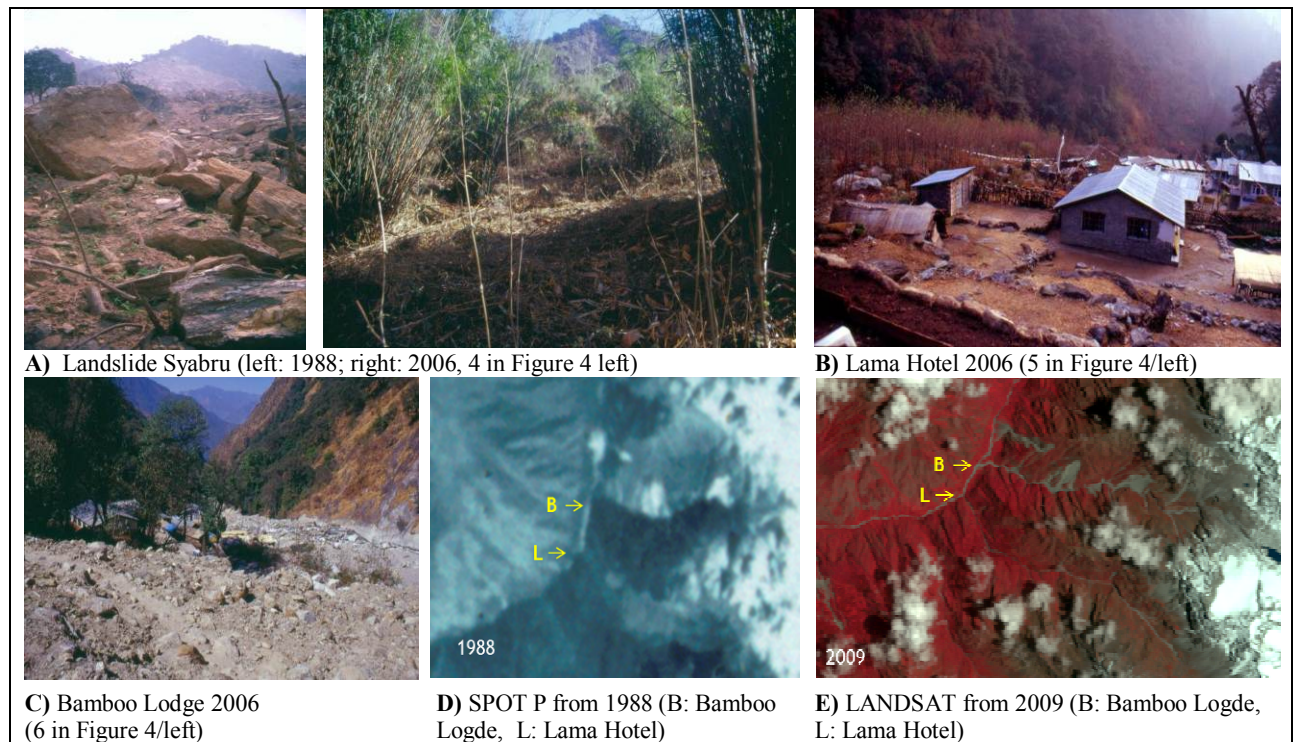
As mentioned in **Figure 5**, the accumulation area of the landslide is dominated by active erosion gullies and a significant fan in the main valley. In the period between 1988 and 2006 this fan increased downwards, as documented by pictures and satellite images.

A significant concentration of landslides and mudflows can be found in the lower part of the Langtang Khola valley. That part of the valley, which is deeply entrenched by the river and has the highest relief energy, shows many landslide and mudflow deposits. Four examples in the High Himalaya area (**Figure 6.**) and one example in the Nepalese Midland (**Figure 9**) are pointed out in the following:

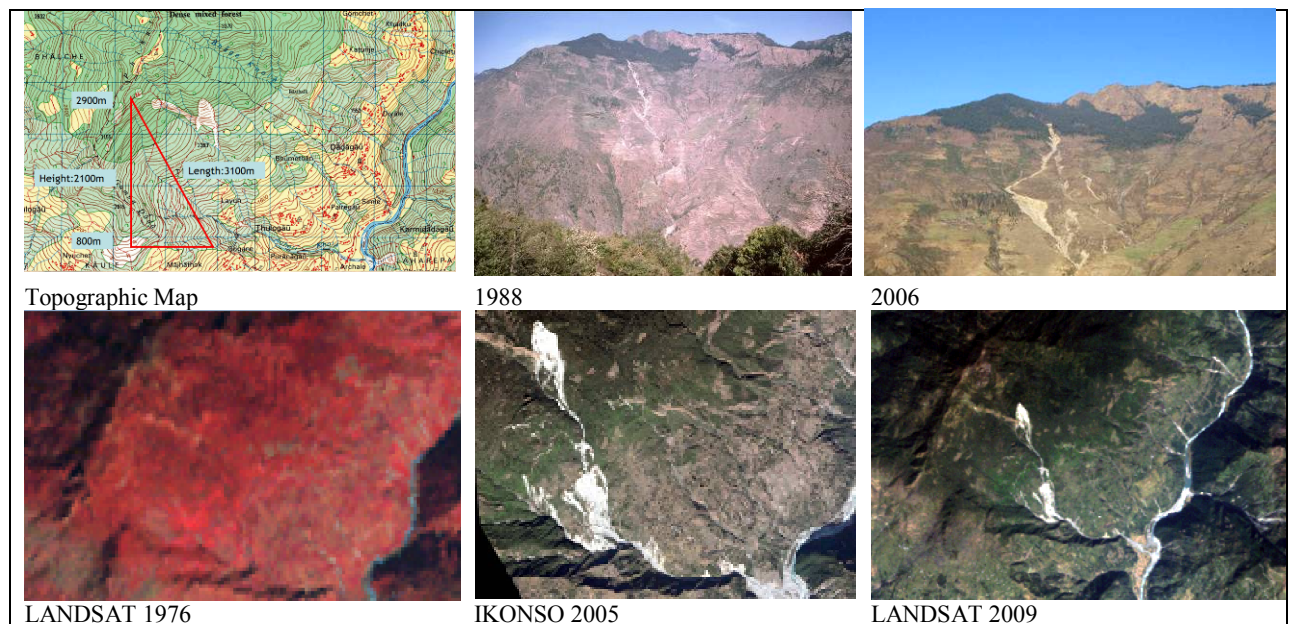
- **(A) Landslide/rockfall north of Syabru** on the way to the Langtang Valley: In 1986 a rockfall occurred onto the trekking path. By 2006 vegetation had once again covered the area.
- **(B) Lama Hotel:** On 2 June 2001 an enormous mudflow (roots in the NE side valley) destroyed 2 lodges. Although further small mudflows occur during the monsoon period, the vegetation reaches a height of 3-5m.
- **(C) Bamboo Lodge:** In August 2005 a large mudflow reached the Langtang Khola valley and endangered the tourism infrastructure. Further mudflows threaten to fill up the valley during heavy rainfall and destroy the lodges located in the valley.
- **(D) / (E):** SPOT image from 1988 und LANDSAT image from 2009.



- **(F) Trisluli Khola landslide:** An impressive landslide occurred near Betrawati, where a height difference of 1,800m can be measured within a distance of 6 km. The development can be documented and measured by means of Remote Sensing images (**Figure 7**).



**Figure 6.** Mudflows and landslides in the lower Langtang Valley (explanations in the text; Photographs: W.Sulzer)



**Figure 7.** Development of the landslide near Betrawati in the Trisluli Khola valley (F), (Photographs: W.Sulzer)

The first three (A-E) examples represent landslides of natural origin, which occurred largely without human influence. The main triggers are the high relief energy, the geological-tectonic situation and intensive monsoon precipitation. In the Nepalese midland (**Figure 7, F**) natural preconditions for landslides are strengthened by intensive land use (pasturing, farming, road construction, forest clearing etc.).

This case study intends to provide a short overview of the changes that have occurred in the Langtang National Park area over the past two decades. The examples presented make no claim to being, complete, they are intended rather to provide an incentive for further investigation of the area and research theme.

### 3.3 Cerro Aconcagua Satellite Map (Argentina)

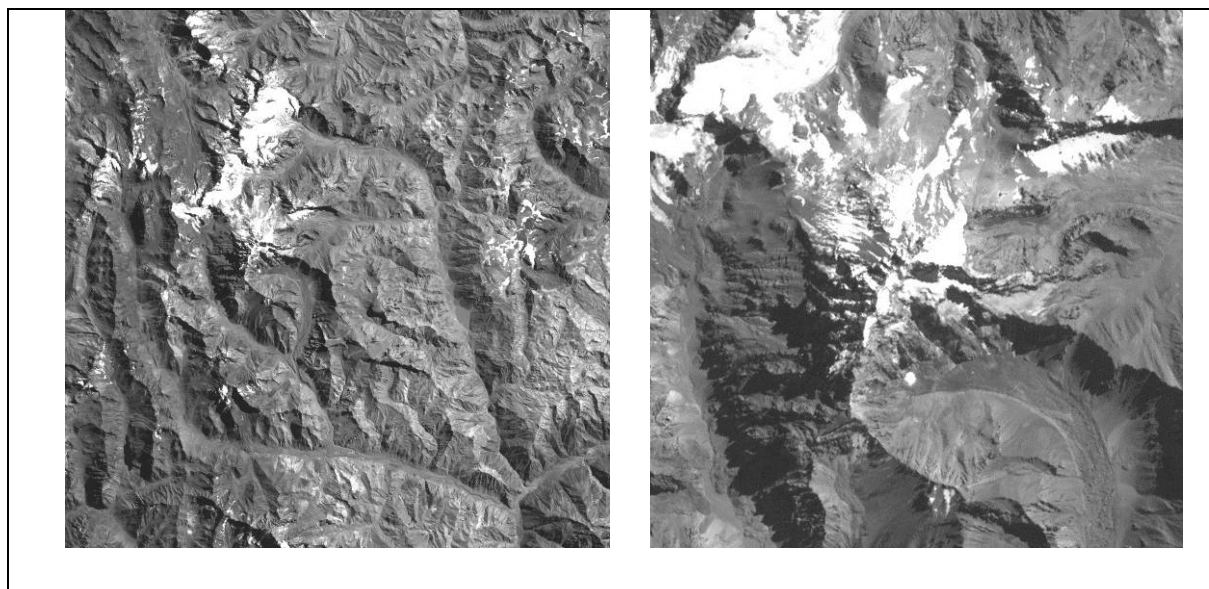
This case study discusses the integration of various Remote Sensing based data (SRTM, LANDSAT and ASTER) for generating a topographic/tourist map (combine image line map) of Mt. Aconcagua (Argentina). Due to the lack of appropriate official topographic maps (1:50.000) Remote Sensing data are the only source which can provide adequate topographic and thematic information. The investigation area is located in the midst of the Central Andes in the Aconcagua Provincial Park (Argentina) with Mt. (Cerro) Aconcagua (6962m) is the highest mountain in South America and reaching out up to Argentinean-Chilean-Bolivian Border. The aim of the project is to provide a satellite based image map of the entire Aconcagua Mountain region in scale 1:100.000 (R. Kostka, W. Sulzer and M. Wurm, 2006).

One main factor for the use of remote sensing data is the availability of data, low or no costs and their common applicability for typical high mountain research tasks. Due to the limits of GIS suitable parameters and due to the low quality of the maps there was no possibility for further contour line digitizing for generating a DEM of the investigation area. Topographic maps are available with scale: 1:500 000, 1:250 000, 1:100 000 and 1:50 000 in Chile and at scale 1:50.000 and 1:100.000 for Argentina. During the process of scanning, geocoding and mosaicing the severe problem was to unify the different geodetic systems of the two countries.

The only solution getting appropriate information for the map was to use pure satellite image data. This can be achieved only by a multi-temporal and multi-sensoral approach. Different image data will provide different kind of map information:

Feature	Source
• Image information:	• ASTER/LANDSAT
• Contour lines:	• DEM: ASTER/SRTM/LANDSAT
• Vegetation cover:	• LANDSAT/ASTER
• Glacier/Lakes:	• LANDSAT/ASTER
• Traffic network:	• GPS/LANDSAT/ASTER/MAPS
• Perspective views:	• DEM/LANDSAT/ASTER

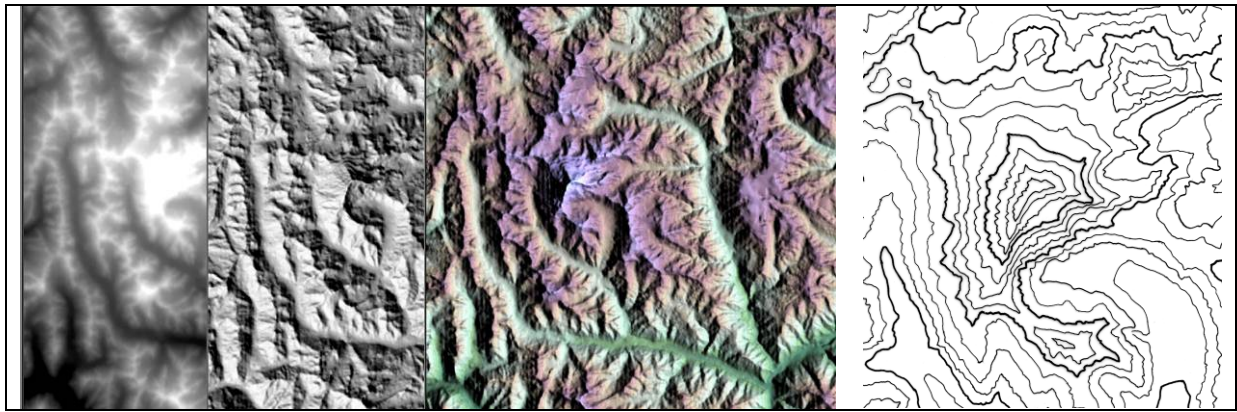
**Image Representation:** The geometric basic for the map sheet is a georectified LANDSAT TM image of 1999. The rectification quality (RMS Error) meets the requirements of a map with scale of 1:100.000. The determining factor for using this satellite scene is the high radiometric quality and low snow cover. Additional LANDSAT TM and ETM+ scenes (1975, 1986, 1987, 1989, 1999, and 2000) and ASTER images (2002 and 2004) are used to provide actual and detailed information about glacier/snow and vegetation distribution. ASTER data, especially, are very suitable for morphological and situation details, due to their higher spatial resolution.



**Figure 8.** ASTER Satellite images for the whole region (left) and subset from the Cerro Aconcagua (right)

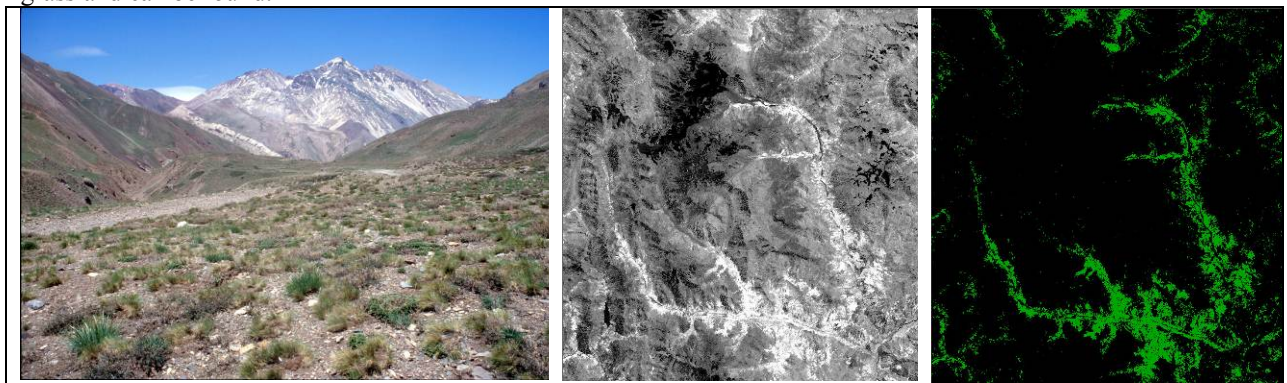
**Contour Lines:** For a DEM generation a combined analyze of multitemporal and multisensoral DEM's were used (more information in R. Kostka, W. Sulzer and M. Wurm (2006). Therefore, different ASTER DEM's (to fill up and reduce the aerial extent of "zero-data-values"), a digital elevation model from stereoscopic LANDSAT ETM+ data and the available SRTM elevation model with a resolution of 100m were generated. In a raster to vector and contour line conversion provide a contour line map with an equidistance of 50m. Smoothing and cartographic improvements provide a 100m equidistance, finally. The accuracy of the contour lines is within the limits of a map in scale 1:100.000.





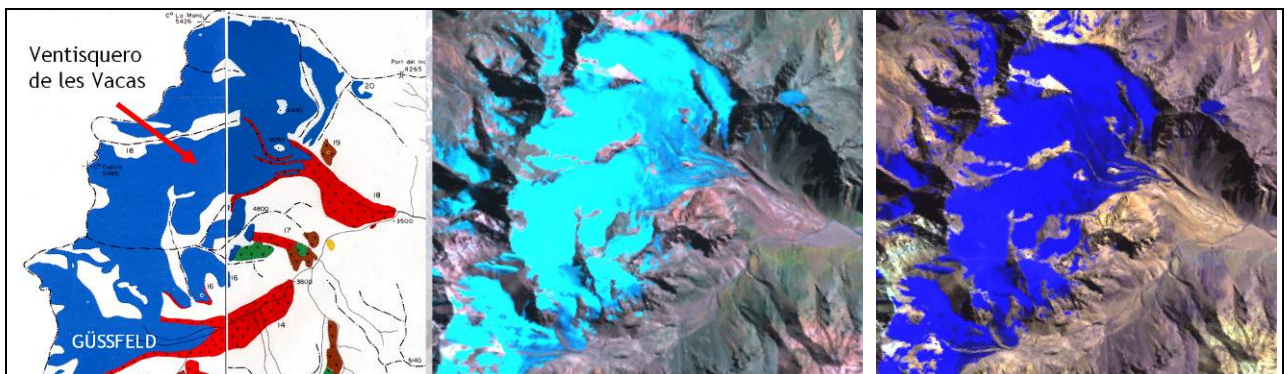
**Figure 9.** DEM - Contour line Generation

**Vegetation Cover:** ASTER and LANDSAT ETM+ data can be used to obtain information about glacier and snow distribution (with a multi seasonal approach) and by means of a digital landuse classification a vegetation layer can be generated. The Aconcagua region is dominated by an alpine vegetation environment, where only in lower parts grassland can be found.



**Figure 10.** Vegetation cover (left: spare alpine vegetation in the Horcones Valley, middle: Vegetation index; right: vegetation mask for the map)

**Glacier/Lakes:** Glacier and lakes can easily be classified by their clear spectral reflectance in the LANDSAT Images. The only difficulty shows the differentiation of a snow cover on the glacier with snow cover in the surroundings. This problem was solved with a multi-seasonal approach.



**Figure 11.** Glacier Layer (left: glacier inventory map, middle: LANDSAT TM image; right: glacier/snow layer for the map)

**Traffic Network:** The traffic network in the Aconcagua region is focused on the main valley which has an important function between Argentina and Chile. Additional GPS recording during the field work supply the image analyses.



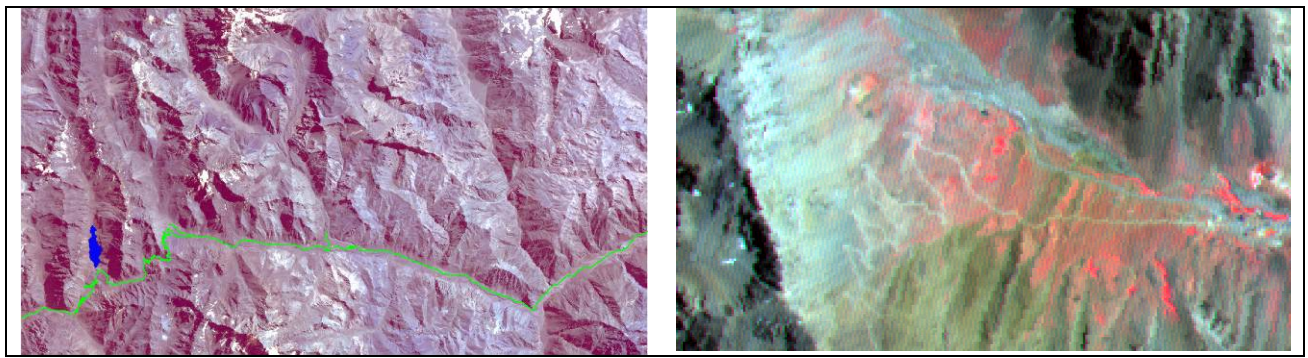


Figure 12. Traffic Network (left: Road from LANDSAT, right: road to Christo Retendor ASTER data)

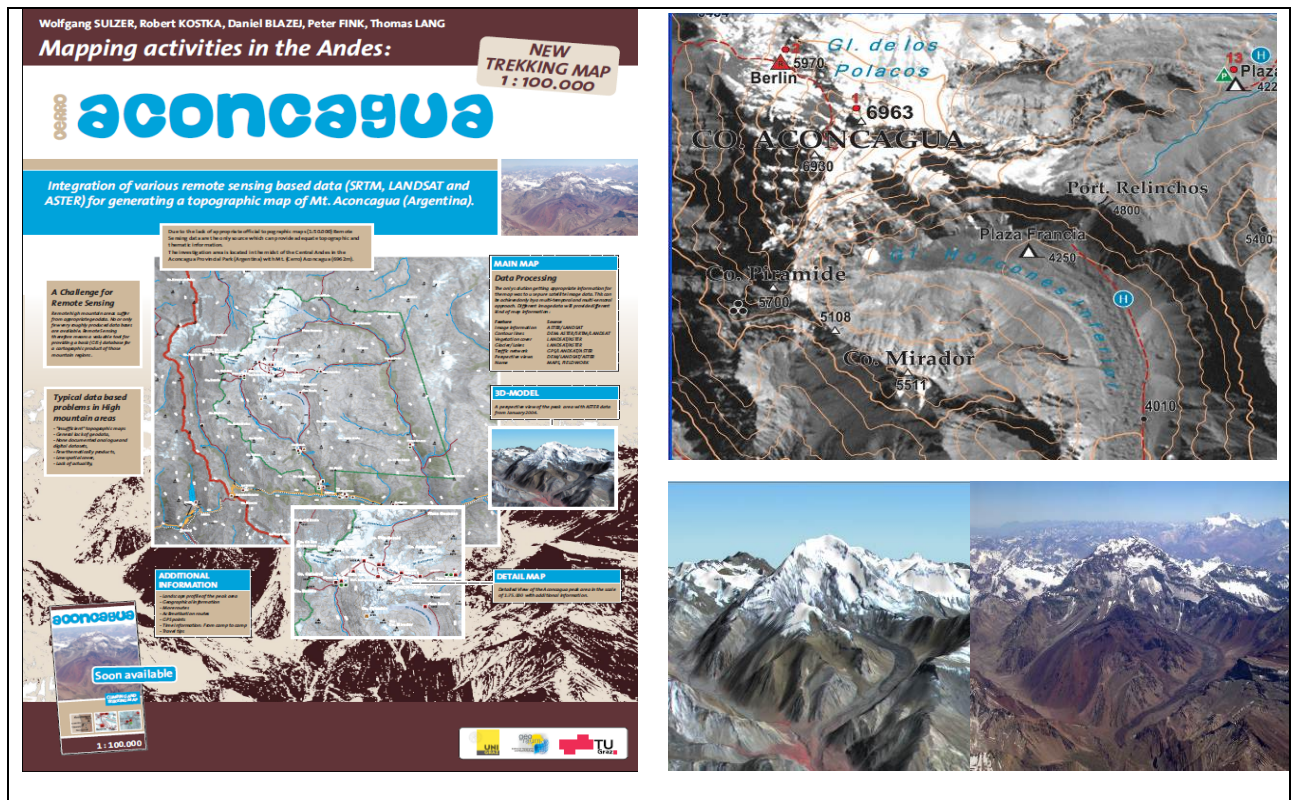


Figure 13. Cerro Aconcagua Trekking Map (left), Detail of an satellite image map (right up) and perspective view of a glacier surge of the Horcones Inferior glacier (right down: photograph of 1/2006 by Deutscher/Hirschmugl; right: perspective view with ASTER data of 1/2004).

## 4 CONCLUSIONS

Remote Sensing data and their analyses provide valuable efforts for the treatment of High Mountain environment topics. In general the Remote Sensing techniques obtain results by means mapping, inventorying, monitoring, modelling, forecasting and visualisation including collateral information and data within a georeferenced GIS environment. The presented case studies document only a small perspective of the potential applications of Remote Sensing in the High Mountains. Further studies and applications can be recognised in the Proceedings of High Mountain Remote Sensing Cartography (HMRSC) symposium series, which are available on the Homepage of the Institute for Geography and Regional Sciences (<http://geographie.uni-graz.at/>).

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