Grazer Schriften der Geographie und Raumforschung Band 41 / 2006 pp. 59 - 70

Regional Climate and Snow/Glacier Distribution in Southern Upper Atacama (Ojos del Salado) - an integrated statistical, GIS and RS based approach

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Abstract

The paper discusses the climatic, statistical, GIS-based and remote sensing approach of snow/glacier cover investigations of the Nevado Ojos del Salado region in South America. The climate conditions of the region, the interpretations of firn and glacier areas are investigated in respect to the exposure and height. The benefit and problems of statistical and GIS based snow distribution modelling are discussed as well as the techniques of Remote Sensing for snow cover classification. Examples and cases studies complete and document the complex topics, additionally.

KEYWORDS: Ojos del Salado, Snow/Glacier Distribution, GIS, Remote Sensing, Regional Climate

1. Introduction

Based on the results of several expeditions (field campaigns) into the High Atacama bounded by the area of San Pedro de Atacama in the north and the Ojos del Salado in the south the distribution of glaciations and perennial snow fields were discussed with special consideration to the climatic characteristics of the region. Within this paper the main geographic and thematic focus was set on the determination/acquisition and analysis of the actual distribution patterns and the probability of glaciations processes in the Nevado Ojos del Salado investigation area. For that reason a basic set of climate data taken from different studies, especially from D. Schmidt (1999), but also from the official sites of the Meteorological Survey of Chile has been established to describe the precipitation conditions in the investigation area. Additionally a first short field campaign to the area took place in February, 2003. In the next step this dataset has been enriched by the results of the analysis of multitemporal RS- data (SSE-OP, LANDSAT, ASTER etc.), which bring up additional information about snapshots of distribution patterns of perennial snow fields. In the model building phase multivariate statistical methods are used to extract the model relevant parameters (such as climatic, hydrological, land cover and terrain factors) out of the full featured dataset and quantify their influence on probability and distribution of patterns. In the implemented model these parameters were used to create virtual snapshots of intermediate states of glaciations and snowfield distribution and to simulate their behaviour. Finally the results coming from this combined approach were compared a new map edited by the Austrian Alpine Club (M. Buchroithner, 2004) covering the whole investigation area of the Ojos del Salado. The situation in this product (scaled 1:100.000) shows remarkable structures of snow and ice distribution.

1.1. Why snow/glacier investigations?

The variation of the snow and glacier cover as an important influence in high mountain regions on fauna, flora, climate, hazards and human activities (e.g. pasturing, ski tourism, water supply ...) has been studied for years. Snowfall is influenced by diverse climatic factors and in turn the snow cover affects the climate and the behaviour of glaciers. Therefore the spatial distribution of the snow cover is an essential factor the hydrological cycle and for climate change studies. Remote sensing techniques allow studying quantitatively the spatial distribution of snow and glacier for larger areas with high resolution. Limiting factors to use satellite data extensively are temporal resolution and the often-occurring cloud cover. Nowadays, new satellite sensors are acquiring data on a regular basis with spatial resolutions between 1 and 15 m. It has been shown, snow cover mapping from satellite data is possible by applying an extrapolation method within a Geographic Information System (GIS).

1.2. Investigation area

The area of interest is located at the border between Chile and Argentina in the Andean High Cordillera of South America at 27°10´ S latitude and 68°30´ W longitude. The area around Ojos del Salado (ca. 27° S) is part of

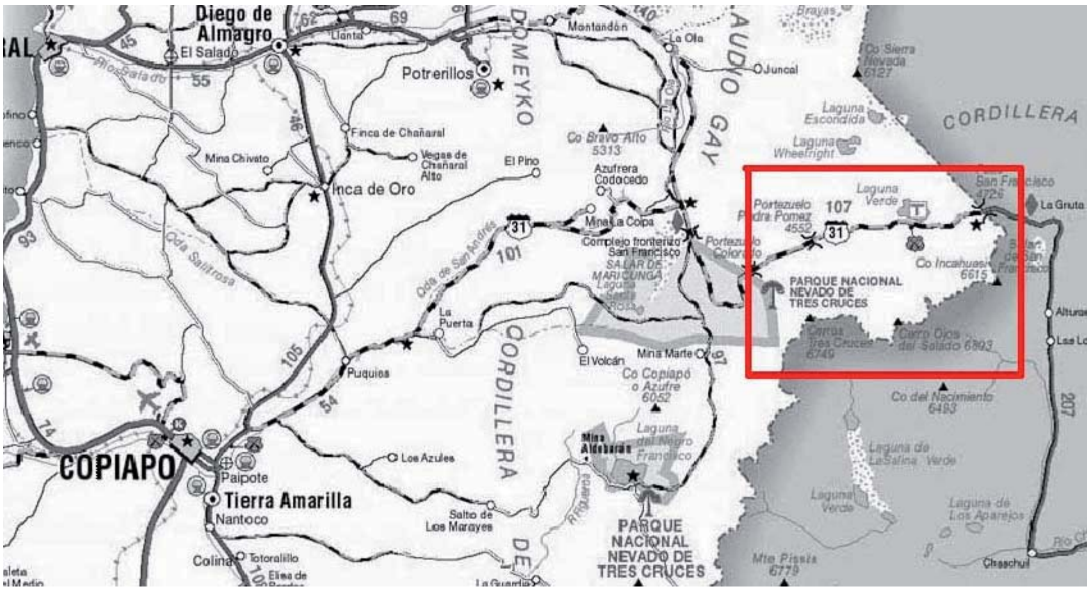

Figure 1: Location of the investigation area and topographic map (AV map).

the Circumpacific Ring of Fire with a series of volcanoes and the Ojos del Salado as the highest peak with a height of 6890m (V. Kaufmann and W. Sulzer, 1995). The landscape is volcanic origin and compromises a series of spectacular volcanoes. The volcanoes there rise throughout 1500 to slightly above 2500 m above a plateau at a height between about 4300 and 4700 m with the Laguna Verde, whereat a west-east extension is given.

Figure 1 shows the region of Topographic Map Ojos del Salado (AV Map), and lies approx. 250 street kilometers east of Copiapo. A main street from Copiapo through Paso San Francisco (near Laguna Verde) goes to Argentina. The elevation of the Altiplano approx. reaches 4000 meters.

2. Climatic conditions with respect to snow/glacier

This section is about the climatic conditions with regard to the distribution of firn and glaciers. In addition to regional aspects this section also refers to the conditions of local climate as the latter play an important role in the snowdrift as well as in the ablation.

2.1. Data and methodology

Aside from papers of D. Schmidt (1999) and M. Richter (2002), also relevant articles of M. Vulle (1996) and H. Veit (1991) were available as data base. Precipitation maps of H. Aravana and K. Wolcken (1985) could be used, but at large they provide only a rough overview of the location of the Arid Diagonal, on the south edge of which the investigation area is situated.

In addition to the interpretation of all climate data it was methodically important to evaluate the snow and glacier distribution in situ in the course of a field trip in February 2005. Two peaks have been climbed then (Incahuasi, 6620 m, Tres Cruces Norte, 6030 m), from where the current glacier distribution across vast parts of the investigation area could be evaluated. An important task was the comparison of the areas with firn and ice displayed in the "Alpenvereinskarte" 1:100.000 Ojos del Salado with the digital photos which have been taken.

2.2. Location of the investigation area and general climatic traits

The area around Ojos del Salado (ca. 27° S) is part of the Circumpacific Ring of Fire with a series of volcanoes and the Ojos del Salado as the highest peak with a height of 6890 m. The volcanoes there rise throughout 1500 to slightly above 2500 m above a plateau at a height between about 4300 and 4700 m with the Laguna Verde, whereat a west-east extension is given. In this part of the Andes glaciation begins again, but only in a small dimension and the glacier decline is prominently pronounced in this area (A. Rivera 2002). There can't be named a definite snow line like in the Alps. It is remarkable that also relatively high volcanoes as the Incahuasi (6620 m) are unglaciated, other ones like the Tres Cruces Norte (6030 m) have perennial firn fields. This will be described in detail below. The next more important glacier is on the Tronquitos at 28° south latitude.

Due to the small amount of precipitation with a total of about 300 to 500 mm it seems reasonable to define the area on the south edge of the so-called Arid Diagonal (B. Messerli et al. 1998), which in the north begins in the area of Calama, continuing over the Llullaillaco (24° S) with its core zone and thereby crosses the main crest respectively in the following it continues along the eastern foot of the Andes in Argentina. Furthermore, the changing character of precipitation from north to south is essential: While in the north the maximum precipitation falls during summer, it is the other way round in the south. These winterly snowfalls are now essential for glaciation.

2.3. The climatic conditions in detail

The temperature conditions are well documented thanks to data of the meteorological network of D. Schmidt (1999) and first results of the meteorological station on the Llullaillaco at a height of 6739 m, whereat the temperatures have to be estimated about 2 to 3 K lower as they are in the graph because of the slightly more southern latitude (about 3 to 4° difference of latitude). The three selected stations provide a good overview of the temperature conditions which are to be expected to have an annual fluctuation of about 7 to 8 K, which is likely to be around 10 K only in basin locations like on the Laguna Verde. The diurnal fluctuation depends much more on the topographic location and on peaks like on Llullaillaco it achieves about 6 to 8 K in summer with low wind speeds and about 4 to 5 K in winter (R. Lazar, 2005), while in valley and basin locations diurnal amplitudes of 15 K and more can be expected. Thus the number of days with freeze-thaw cycles is very high and frost patterned grounds are quite characteristic. The absolute minimum values in winters with snow cover can fall to -30 °C in valley and basin locations which are situated at high elevation; the lowest value on the Llullaillaco has been recorded in May 2004 at -32°C.

Concerning the precipitation distribution, winter precipitation is predominant in contrast to the north (around San Pedro de Atacama), as the results of the used stations near by our investigation area (La Laguna and El Indio at about 30° south latitude) are showing. According to H. Veit (1991) about 80 % of precipitation falls between May and September, whereat winterly snowfalls are very unreliable and thus the station El Indio at a height of 3840 m recorded only 100 mm in some years, in other years which have been influenced by El Niño sometimes there also have been recorded values up to 800 mm. This is a typical characteristic of dry summer subtropical climate. As in turn the area around Ojos del Salado lies 3° more northern, the percentage of summerly convective precipitation probably has to be estimated higher than recorded by the two stations. For the area of Laguna Verde (4450 m) an extrapolated annual cycle has been determined, considering precipitation measurement losses due to high wind speeds (for snow falls they can amount to more than 50 %). According to this, annual amounts of precipitation of about 350 to 400 mm can be expected, which even can increase with increasing height. A maximum zone of precipitation is to be expected at a height of about 5500 m (about 500 mm), as the cloud base lies very high especially in the summer term. In accordance with the data from the core zone of the upper Atacama which runs approximately through the Llullaillaco, those expected 500 mm do accord quite well. This value was the premise for the growth of at least small glaciers.

The exceptional position of Ojos del Salado concerning the seasonal structure of precipitation stands out well (B. Messerli et al., 1998). As a result of satellite image interpretation, the number of days with winterly snow cover is very high (over 80 % of interpreted cases), while the relative frequency of convective cloudiness has declined from 60 to 80 % in the north to about 40 to 50 % in the investigation area.

In addition to sunshine of course wind plays an important role in the glacier distribution, whereat the west winds definitely outweigh. Even in summer with low pressure gradients the west wind drift mostly is predominant, especially at the level of 500 hPa. Particularly combined with winterly snowfalls, considerable drifts can occur in

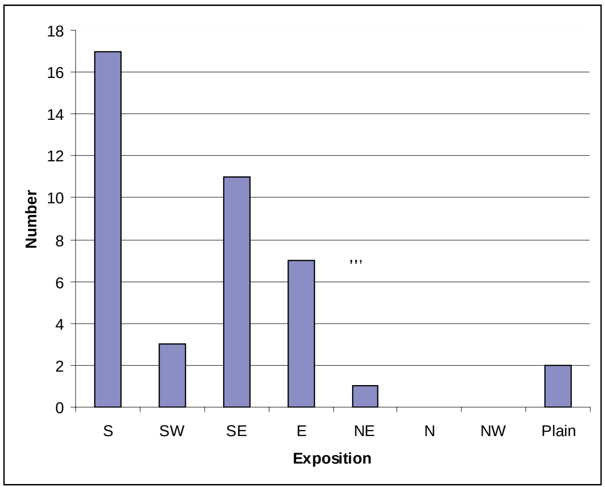

Figure 2: Distribution of firn/glacier in the Region of Ojos del Salado.

eastern exposures. The annual cycle of wind can be exemplified with a graph, whereat the maximum in winter is to be estimated with 8 to 10 m/s on the Laguna Verde at 4450 m, in crest and peak locations it is clearly more than 10 m/s. It can happen also in summer that alpinists are not able to reach the Ojos del Salado because of severe storm, but the mean values probably are around 5 to 7 m/s. These values correspond quite well to the observations made in the course of the field trip in February 2005. In general an afternoon maximum is characteristic in the diurnal cycle of wind speed, as the pressure differences between Pacific coast and continental Argentinean side increase.

2.4. Interpretations of firn and glacier areas according to exposure and sea level

Based on the Alpenverein Map from M. Buchroithner (2004), an interpretation of the firn and glacier fields (minimum size about 10 ha) has been done, which resulted in a clear predominance of south, southeast and east exposures (Figure 2). This corresponds very well to the wind data as described above. The effect of exposure seems to slightly exceed the effect of wind, as the south exposure is in the fore with 16 cases. Lower limits have been determined by a further interpretation, they fluctuate between 5200 and 6400 m (maximum in the range between 6000 and 6200 m, 10 cases). This graph (Figure 3) also shows

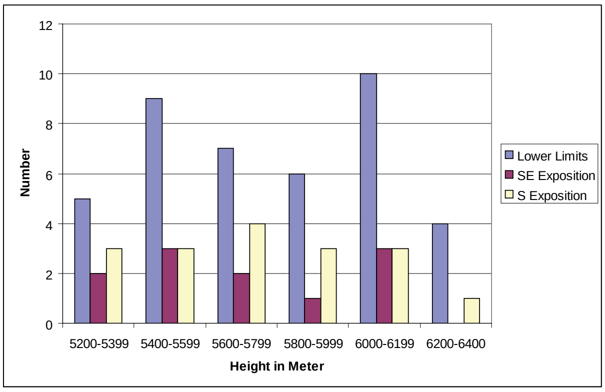

Figure 3: Distribution of firn/glacier in respect to the exposition.

an evaluation of the respective firn or glacier field considering the local climate. The results from the field trip in February 2005 have been used for this purpose. According to that, the cases recorded on the map in a height from about 5600 m above sea level are real, while the other 17 cases are at least problematic or improbable. Possibly they are artefacts or firn fields, which have been formed as a result of exceptional snowfall events and wind conditions. Furthermore, some firn furrows are noticeable, which also could be found during the field work in February 2005. They are missing in places where firn and ice areas could be expected due to the local climate. Incahuasi, Cerro Mulas Muertos and Cerro Vicuñas are good examples for this. There are some small areas on the Incahuasi (6620 m), but their total extent is very low, and it is also noticeable that there is no ice in the wind-protected crater.

3. Statistical, GIS and RS based approach

3.1. Benefits and problems of snow distribution modelling

With respect to many of the scientific snow distribution and glacier mass balance related papers there are mainly three reasons, why distribution modelling should be done:

- Snow coverage distribution, snow pack consistency and snow cover partitioning on different watersheds strongly influence the water balance of a region so snow cover mapping produces knowledge.
- In the second case, snow cover modelling with GIS- or statistical tools is a practicable way of data acquisition if serious alternatives are not really available. Especially in wide area research scenarios situated in pathless high mountain terrains.
- Because of snow pack distribution, redistribution and variability is high on almost every level of scale, the spatial resolution and length of time series of snow related data in most cases are very poor;
- Last but not least snow distribution modelling is proven a feasible way of data generation for the evaluation of geodata collected in other ways.

Snow distribution patterns schematically are controlled by several distinct factors. First of all the amount of precipitation (as rain and in snow like form) in general and its dependency on the high mountain terrain is an important factor (B. Sevruk, 1997; A. Barros and D.P. Lettenmaier, 1994; A. Basist et al., 1994; F. Blumer, 1994). Furthermore the distribution of snow in alpine relief is heavily influenced by mass displacement induced by avalanches or air flow and wind freight. In the opposite of these “allocating components” some snow conserving factors steering the perennial outlasting of the snowfields have to be taken into account (D. Marks et al., 2002).

Accepting these presumptions means that a snow cover modelling process has to keep in mind at least four data layers (precipitation, height, and wind influence and conservation tendencies). Usually the acquisition of the relevant geodata requires a relatively dense network of data logging/control stations which is very difficult to set up in an extreme mountainous environment like the investigation area.

As mentioned above, suboptimal circumstances can cause serious problems during the analyses, so – among other objectives - this paper tries to avoid these problems by employing a geostatistical approach. Unlike other approaches, the introduced method focuses on a database compiled from 2 different sources, snow field data from distribution pattern empirically found in the investigation area. Additionally remotely sensed data collected from LANDSAT and ASTER spaceborne systems were used to derive DTM-related information as well as to identify all-the-year snow fields. Based on this collection of geoinformation (spatially linked to the midpoint of 10 x 10 m raster cells covering the whole investigation area between 6996320/542300m and 7004500/548900m; UTM 19J - WGS84), the study attempts to detect regularities lying under the data and to establish a model for predicting snow field distribution patterns (G. Liston, 1999).

For modelling in a first basic approximation a multiple regression procedure was used, which has the significant advantage of describing usable models by predicting one dependent variable from a set of independent (steering) parameters, being well introduced in the scientific community and working very well with many variables and many cases, even in standard PC environments. Furthermore regression analysis output can be used to quantify the quality of this description by calculating residuals and model error with ease.

As in most cases of snow field research campaigns also for the Ojos area the following parameters might take influence on distribution pattern:

- In a direct manner (that means as factors of distribution): Precipitation, snowfall, airflow and relief curvature.
- In an indirect manner (that means as factors of re-distribution): Avalanches, wind freight and terrain exposition.
- In a conserving manner (that means as factors preventing the melting of snow): Temperature, height above sea level, snow density and snow chemistry.

As already mentioned in this paper, because of the ruggedness and the in hospitability of the terrain the acquisition of most of these parameters unfortunately is almost impossible. Therefore three groups of parameters have been used to substitute the missing steering factors. Most of the models input were replaced by terrain based parameters taken from an ASTER – DTM covering the investigation area. The distribution probability of the snow pattern is mainly derived from Satellite images; in more detail, a mesh with 10m to 10m distance from one intersection to each other is laid over the Ojos del Salado site representing the sampling (determination) points for height (in meters), aspect (classified in north-, south- and west/east-ori-

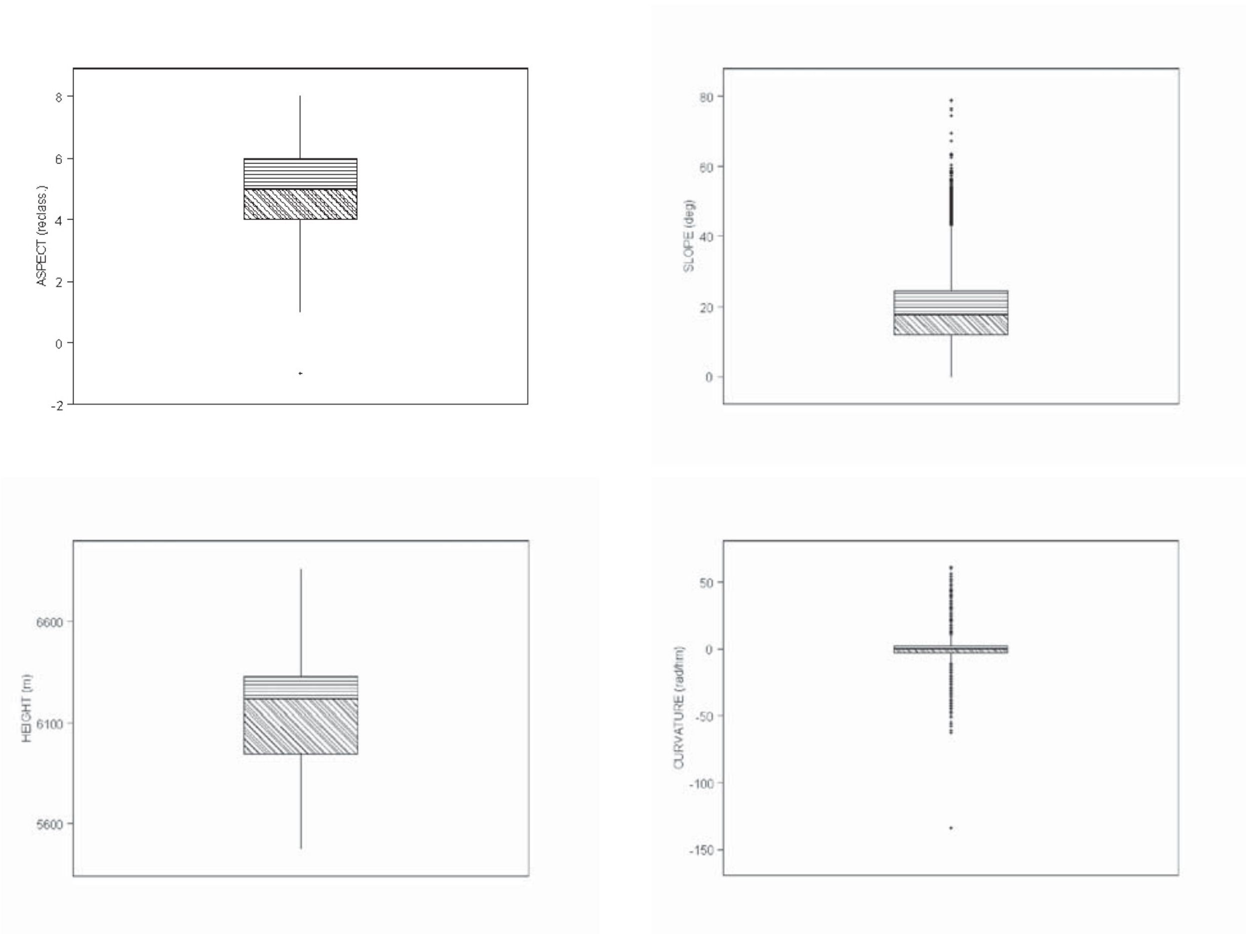

Figure 4: Distribution of aspect (a), curvature (b), height (c) and slope (d) within the undoubtedly snow covered raster cells.

ented regions), slope in degrees and curvature (measured in rad per hectometres). Additional information (i.e. dominating wind direction and wind speed) has been collected empirically during several field campaigns. The box-plots in Figure 4a) to d) are showing the descriptive measurements for the DTM-derived parameters of the sampling points lying undoubtedly within the snow-covered areas (about 150.000 out of 540.000 cell midpoints).

The results documented in the figures can be summarized in some remarkable findings: It is quite obvious, that only the parameters aspect and height show a strictly limited distribution with a strong concentration of raster

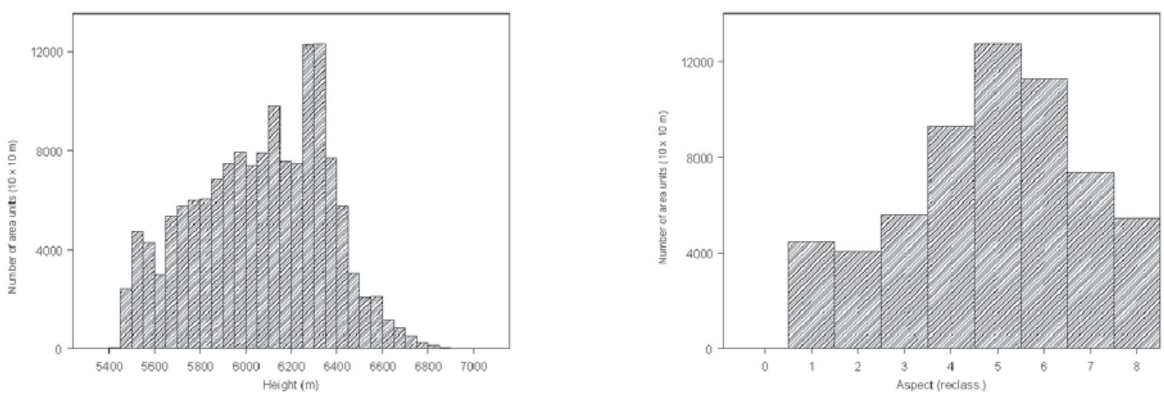

Figure 5: Distribution (and weighting) of factors height (a) and reclassified aspect (b).

	SNODIS	CURVATURE	ASPECT	SLOPE	HEIGHT
SNODIS	1.00000000	-0.01011243	0.08804082	-0.01924859	0.11851963
CURVATURE	-0.010112433	1.000000000	0.001532933	0.016679795	0.017184265
ASPECT	0.088040821	0.001532933	1.000000000	0.044633296	0.035063358
SLOPE	-0.01924859	0.01667980	0.04463330	1.00000000	0.12562809
HEIGHT	0.11851963	0.01718427	0.03506336	0.12562809	1.00000000

Table 1: Correlation coefficients between the most important model variables (SNODIS describes the observed snow distribution).

cells within the interquartile range; so in the case of the factor height there can be found a clear accumulation between 5900m and 6300m. Furthermore most of the positive tested sampling points (i.e. 92%) can be characterized as orientated SE (4), S (5) or SW (6). Contrary to this, both slope and curvature seem to be relatively high dispersed. With respect to all tested samples especially a wide range of the curvature value is given, in the lower quartile as well as in the upper quartile.

In the next processing step these results from the analysis of the satellite imagery and empirical observations were used to calculate the "probabilities of appearance" and derive weighting factors for the development of a distribution model. Based on this thought and according to their distribution the variables height (between 5550m and 6600m; see Figure 5a) and aspect (SE, S, SW; see Figure 4b) are ascribed the most overall importance.

To avoid the influences of strong direct or indirect interactions the covariances/correlation coefficients between the variables of the model have been calculated. As shown in Table 1 most of the variables considered indicate not even a weak interdependency; this fact confirms the thesis that the factors used in the model are independent from each other. Furthermore it seems to be clear, that height and aspect can be used as primary steering parameters.

According to Table 1 variable slope (weak interdependency with height) was chosen as the third weighting factor; this variable shows a high concentration of samples between the inclination of 5 deg and 35 degrees, a skewness (Fisher's G) of 6.911643e-001 and a kurtosis value (Fisher's G2) of 7.667204e-001. From all parameters taken

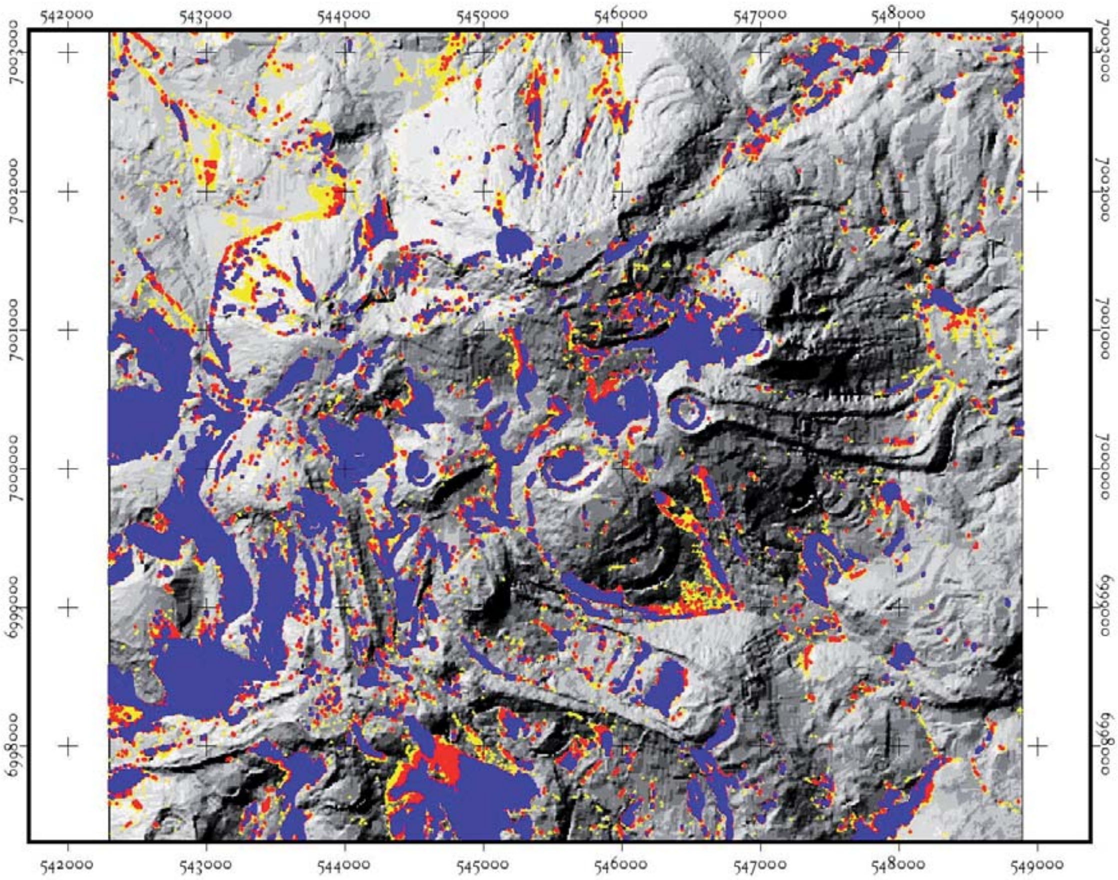

Figure 6: Distribution of perennial snow fields (zone 1 = blue, zone 2 = red, zone 3 = yellow). Projection parameters of the basemap: UTM 19J, WGS 84.

into account curvature seems to provide the smallest contribute to the distribution of perennial snow fields. So this parameter has been least weighted in the modelling procedure.

In the last processing step after completing the model the probability values were calculated and - for a more transparent visualization – reclassified into three zones of snow cover appearance. Zone 1 consists of areas for which the used parameters indicate the existence of perennial snow fields with the utmost probability. Zone 2 includes all areas (resp. sampling points) where the coincidence with snow fields is very probable. The sampling points lying within the last mapped zone 3 are characterized by the fact that occurrence of snow fields is possible but with a smaller degree of probability as in zones 1 and 2. Figure 6 gives a more detailed spatially overview over the described results.

Compared with the findings presented at the symposium 2005 (which were partly based on a preliminary study and which were finally characterized by a lack of variability explained by the regression model used) the results produced by the current approach are much more reliable. In other words: Zone 1 and 2 show a high degree of matching with all kinds of sources (maps as well as RS - products). Even in zone 3 there is a wide accordance in many regions of the investigation area. But otherwise also still unexplained discrepancies can be found indicating that the model used now still needs some refinement.

3.2. Remote Sensing Techniques for Snow Cover Classification (SCC)

For three decades, satellite remote sensing instruments have measured snow properties from drainage-basin to continental scales (H. Haefner et al, 1997: J. Dozier and T.H. Painter, 2004; D. K. Hall and J. Martinec, 1985). Snow-covered areas derived from multispectral measurements in the visible and near infrared parts of the spectrum, were among the earliest geophysical measurements from satellites. The earliest remote sensing of snow properties focused primarily on mapping the snow extent with multispectral sensors, such as the LANDSAT (MSS, TM, ETM+), and NOAA. They were able to detect a growth in grain

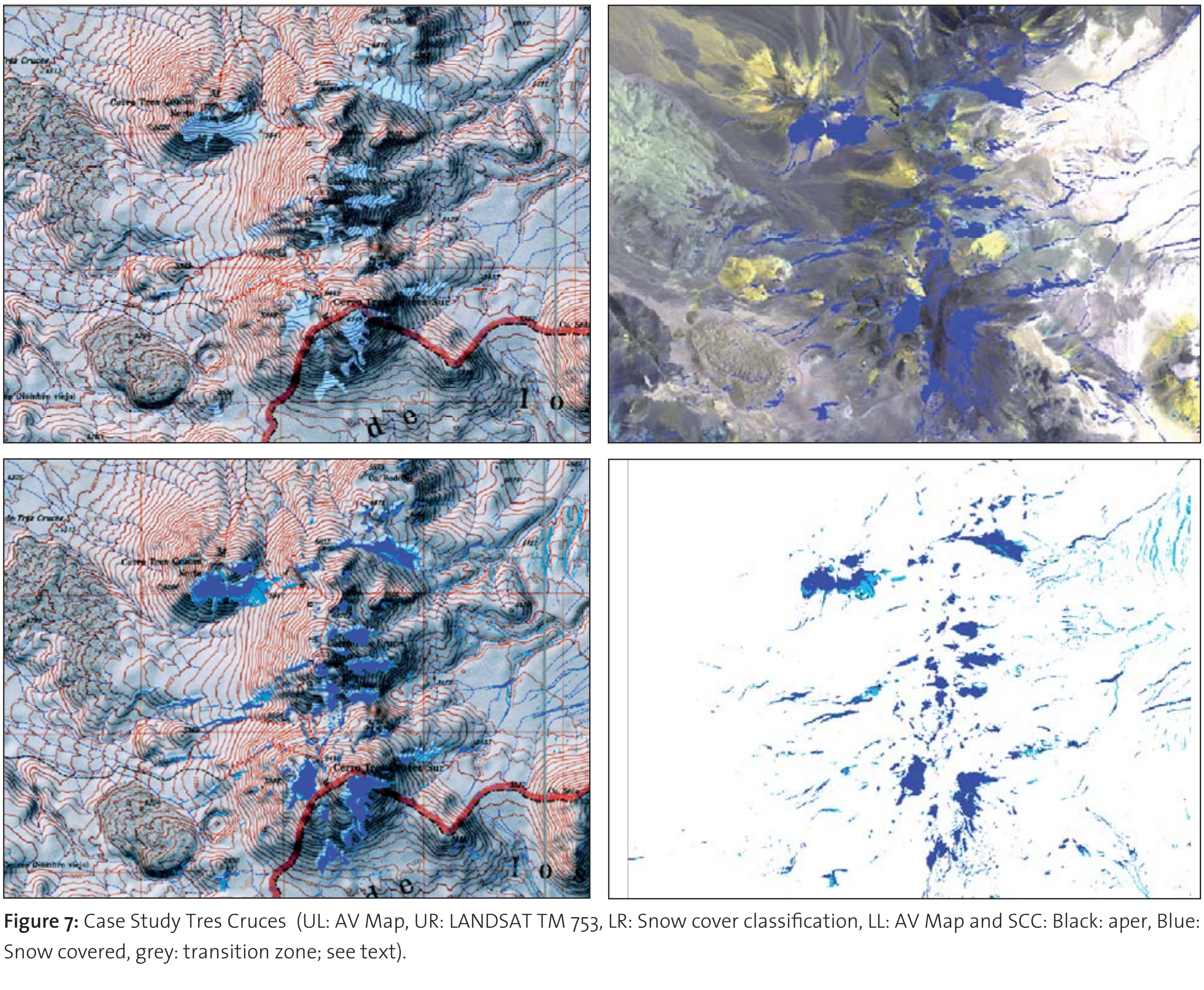

Figure 7: Case Study Tres Cruces (UL: AV Map, UR: LANDSAT TM 753, LR: Snow cover classification, LL: AV Map and SCC: Black: aper, Blue: Snow covered, grey: transition zone; see text).

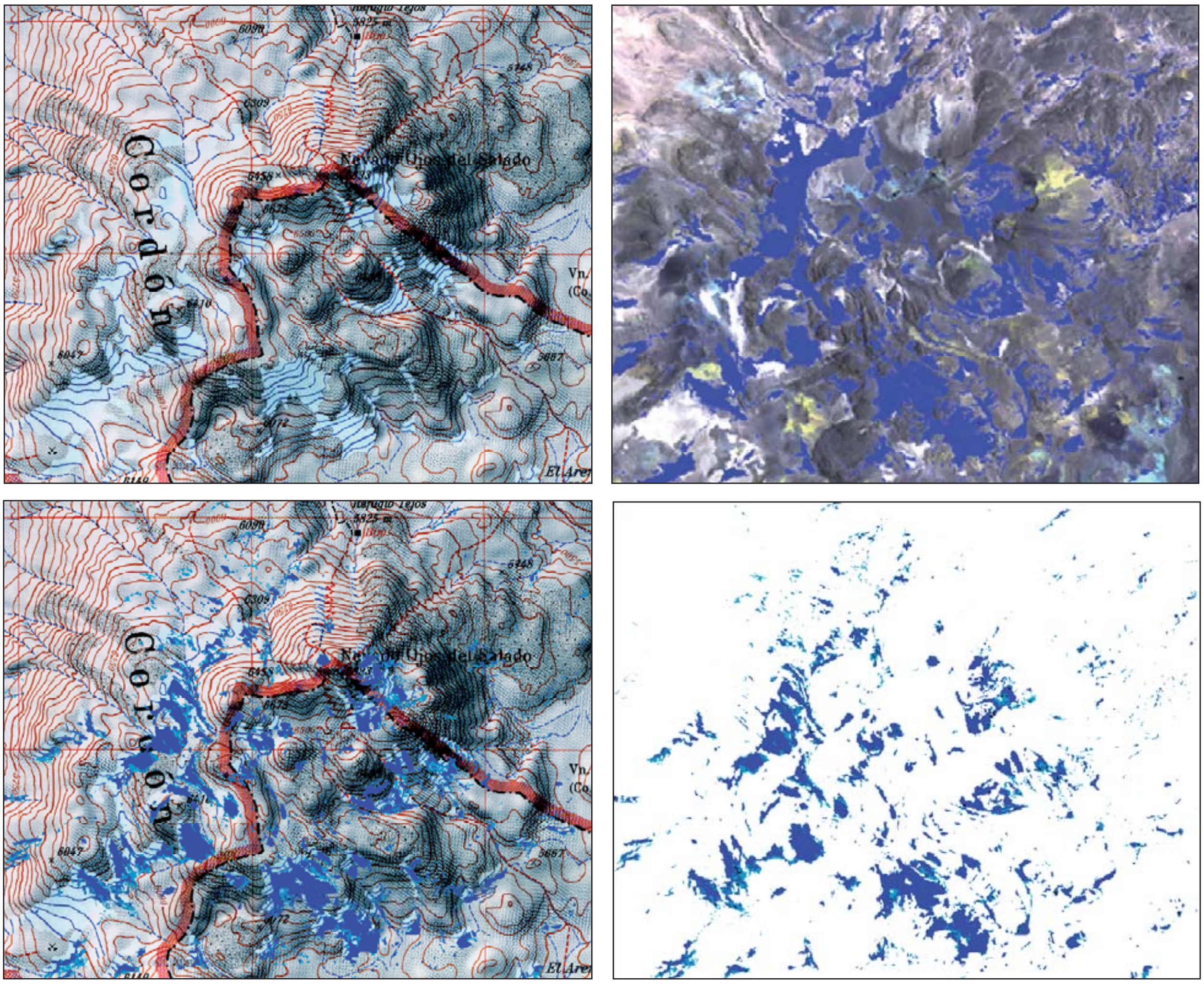

Figure 8: Case Study Ojos del Salado (UL: AV Map, UR: LANDSAT TM 753, LR: SCC: black: aper, blue: snow covered, grey: transition zone; see text, LL: AV Map and SCC).

size and a decrease in snow water equivalent. The MODIS (Moderate-Resolution Imaging Spectrometer) instrument represents a standard snow map product (Hall et al. 1995 and 2002; A.G. Klein et al., 1998, X. Zhou, H. Xie and J.M.H. Hendrickx, 2005).

Mapping of snow and estimation of snow characteristics from satellite remote sensing data require to distinguish snow from other surface cover and from clouds and compensate for the effects of the atmosphere and rugged terrain (comp. J. Dozier, 1989).

So far, RS data have been extensively used to map the snow areas and to measure the surface Albedo. They were also used to get information on the snow type. In the visible part of the solar spectrum, the snow reflectance is mainly dependent on the concentration of pollutants. Tile near-infrared reflectance is dependent on the snow grain geometry- that is, its shape and size (M. Fily et al., 1997).

Principal measurement techniques are dealing with the measurement of reflected solar radiation (visual and near-infrared band), the measurement of thermal radiation (passive microwave radiometry) and, the measurement of return signal from active radar systems (SAR, SLR, etc., J. Sokol et. al, 1999). Basic remote sensing parameters are Albedo (visible part of spectrum), the surface temperature (infrared part of spectrum), the brightness temperature (microwave part of spectrum, passive) and the Radar backscatter coefficient (microwave part of spectrum, active).

Effects of physical conditions on measurement method are:

- Visual and infrared radiometry:

- cloud cover inhibits surface observations
- snow cover (high albedo) dominates the signal
- water and wet ice/wet snow reduces the albedo
- sensitive to temperature: thin ice, leads
- not sensitive to other ice properties

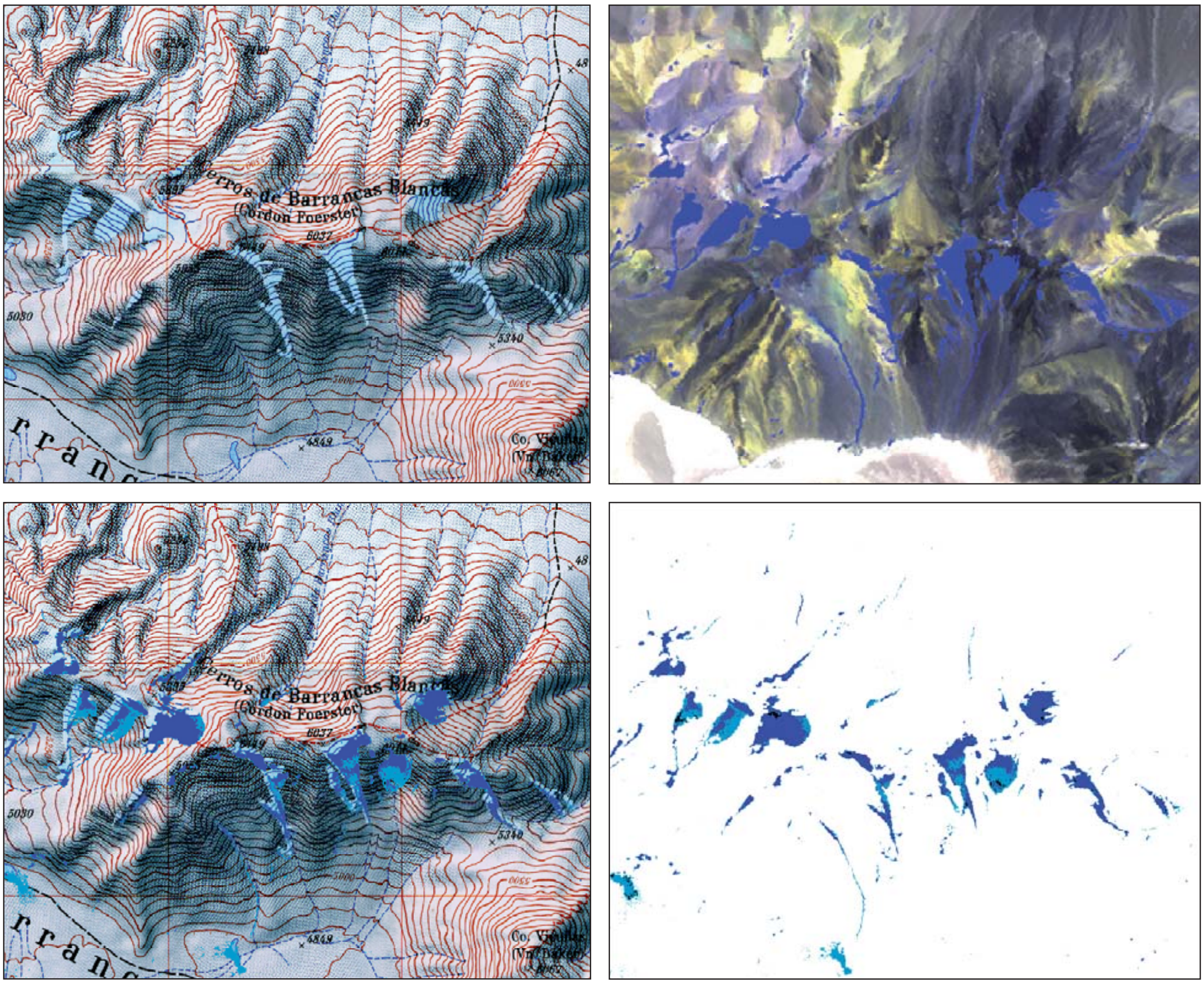

Figure 9: Case Study Cerros de Barrancas Blancas (UL: AV Map, UR: LANDSAT TM 753, LR: SCC: black: aper, blue: snow covered, grey: transition zone; see text, LL: AV Map and SCC).

- Passive microwave radiometry and active radar systems:
  - independent of cloud and light conditions
  - penetrate snow during dry/cold conditions
  - sensitive to ice properties: salinity, crystal structure, surface roughness
  - sensitive to water and moist in snow

The seasonal depletion and spatial distribution of the snow cover in alpine regions is monitored most effectively by multispectral remote sensing satellites (D.W. Cline, et al., 1998; D. Brander et al., 2000; N.P. Molotch et al., 2001; T. Caroll et al., 2003; J. Dozier and T.H. Painter, 2004).

3.3. Case Study LANDSAT - Snow Cover Classification (SCC)

A.G. Klein and B. L. Isacks, (1998) used in addition to a geomorphological mapping, Landsat TM to determine the area of the Central Andes covered by glaciers and snow cover and (1999) spectral mixture analysis of LANDSAT Thematic Mapper images applied to the detection of the transient snowline on tropical Andean glaciers.

The study region of Ojos del Salado LANDSAT TM was used, too, to determine the area covered by glaciers and snow cover. These areas were determined using a snow cover classification. Amongst a times series of several years, the less snow covered scene were selected for the case study. As most of the images were collected during the dry winter months, the snow cover shown in the images should be near its annual minimum. In this case it was scene from the year 2002, which correlates with the field mapping and represented snow cover distribution of the AV map of Ojos del Salado, too.

For the knowledge-based classification a set of training areas has been selected for the feature classes:

- snow covered, (S)
- transition zone (50% snow covered) (T) and

- aper (snow free) (A).

In order to achieve better classification accuracy, individual training sets (LANDSAT, photographs, topographic map have been selected for various illumination conditions.

4. Conclusion

The results show very well the prominent dependence on exposure and wind conditions for the distribution of firn and ice areas, so that most of these areas are on southern and eastern slopes. Surprisingly, there are no perennial firn fields and glaciers on some peaks and their slopes despite their favored exposure and wind protection. Furthermore, the continuing glacier decline even in this part of the Andes could be determined during the field work, whereas the former Rebitsch glacier south of Eremitaño (northwest of Laguna Verde) has only relic ice today and it has lost much of its former extent. Generally it can be said that even the highest peak, Ojos del Salado, is glaciated only in a small dimension due to little precipitation. Many of the areas displayed on the maps are rather perennial firn fields. There hasn't been found moving ice with crevasses during the inspections on Incahuasi and on Tres Cruces Norte. Slope glaciers thus seem to be restricted to only a few volcanoes.

Systematic, periodical and precise snow cover mapping supported by GIS Remote Sensing and statistical technology, and the organisation of the results in a snow cover map or snow cover information system forms the basis for a wide range of applications.

On the practical side, these applications can be related to the monitoring of seasonal and yearly alterations of the snow cover under the presently existing climatic conditions, to simulate and forecast runoff, to map the regional distribution of the water equivalent, and to document the recession process of the snow cover during the melting period in its relation to geoecological features on high mountain environments. To improve this approach, the input data, especially the climatic parameters must deliver more precise, spatial well distributed data. After this step – a sufficient differentiation between snow/perennial snow and glaciers can be achieved.

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