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FIRST CLOUD-FREE LANDSAT TM IMAGE MOSAIC OF HIELO PATAGONICO SUR, SOUTHWESTERN PATAGONIA, SOUTH AMERICA

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First cloud-free Landsat TM image mosaic of Hielo Patagónico Sur, southwestern Patagonia, South America

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ABSTRACT: A new mosaic of Hielo Patagónico Sur, an icefield of 13,000 km^2 in area located in the southwestern Patagonia, South America, is presented. The mosaic has been assembled with three scenes acquired by Landsat 5 satellite on 12 March 2001. An outstanding characteristic of this new mosaic is that shows for the first time since the initiation of Landsat missions almost 30 years ago the entire icefield of 372 km in length totally free of clouds. The TM image mosaic in Universal Transverse Mercator projection has been georeferenced to notable features in the field, mapped with differential GPS and tied to the argentine geodetic network. The mosaic was used to delineate the drainage area of the icefield contributing water to Río Santa Cruz basin. It was also used to monitor the variations of major outlet glaciers which calve into the fiords of Pacific and into freshwater Patagonian lakes. Finally, the comparison with Landsat TM mosaic of early 1986 allowed to quantify the retreat of glaciers with termini on land, directly related to climatic change.

RESUMEN: Se presenta un nuevo mosaico del Hielo Patagónico Sur, el campo de hielo de 13.000 km^2 de superficie ubicado en la Patagonia suroccidental, América del Sur. El mosaico ha sido confeccionado a partir de tres escenas tomadas por el satélite Landsat 5 el 12 de Marzo del 2001. La característica excepcional de este nuevo mosaico es mostrar por primera vez desde el inicio de las misiones Landsat hace casi 30 años todo el campo de hielo de 372 km de longitud totalmente libre de nubes. El mosaico de imágenes TM en proyección Universal Transversa Mercator ha sido georeferenciado a rasgos notorios de terreno mapeados con GPS diferencial, y vinculados a la red geodésica argentina. El mosaico fue usado para delinear el área de drenaje del campo de hielo que contribuye agua a la cuenca del Río Santa Cruz. También fue utilizado para monitorear las variaciones de los principales glaciares de descarga, que desprenden en los fiordos del Pacífico y en los lagos de agua dulce de la Patagonia. Finalmente, la comparación con el mosaico Landsat TM de inicios de 1986 permitió cuantificar el retroceso de los glaciares con término en tierra, vinculados directamente al cambio climático.

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INTRODUCTION

Campo de Hielo Patagónico Sur, usually called "Hielo Patagónico Sur" (HPS) is a classic icefield on our planet (Williams, 1986), located in southwestern Patagonia, South America (Fig. 1). With 13000 km^2 in area the HPS is by far the largest ice body within the Southern Hemisphere, excluding Antarctica. The icefield extends between Chile and Argentina for 372 km along the meridian 73° 30' west, from 48° 15' to 51° 40' south. Due to the very low precipitation rates in Patagonia, which range around 200 mm a^{-1}, the HPS has an outstanding importance for the semiarid Patagonian regions as the major freshwater resource.

The acquisition from space of optical images over HPS has been very much limited due to unusually frequent cloud cover over the icefield region which is affected by strong westerly winds. The first almost complete coverage of HPS without clouds was taken from Salyut-6 spacecraft on 10 March 1978 (Williams, 1987). Unfortunately this superb hand held photograph (Fig. 2) taken with Hasselblat camera by Soviet cosmonauts G.M. Grechko and Y.V. Romanenko was of limited use for glaciological purposes due to its obliqueness. Few early Landsat Multispectral Scanner (MSS) and Return Beam Vidicon (RBV) images of HPS of glaciological interest are listed in the chapter "Glaciers of South America-Glaciers of Chile and Argentina" (Lliboutry, 1998) of the "Satellite Image Atlas of Glaciers of the World".

Since the inception of Landsat satellite series to the present only two image mosaics covering the entire icefield could be assembled. The first one, hereafter called Landsat Thematic Mapper (TM) 1986 mosaic, was produced with images of 14 January 1986 (Naruse and Aniya, 1992). However, this mosaic presents some clouds over the central part of the icefield, in the region of Cordón Mariano Moreno and Glaciar Viedma. Since the launch of Earth Resource Technology Satellite (ERTS 1) or Landsat 1 in July 1972, for the first time the full extent of HPS without clouds could be covered by optical images on 12 March 2001. Almost 30 years have elapsed since the initiation of earth monitoring from space until a series of optical images could be acquired, showing the full extent of HPS including its outlet glaciers and contiguous glacier areas, free of clouds. This clearly demonstrates the difficulties in remote sensing of ice-covered regions with optical sensors. It is interesting to note that these unique cloud-free TM scenes were acquired only few months before the Landsat 5 was discontinued. Although the remote sensing with Synthetic Aperture Radars (SAR) on board of European Research Satellites (ERS) initiated in early 1990's provided high resolution multitemporal images of HPS, the radar images are of limited use for

glaciological research due to the terrain distortion, because no digital elevation model (DEM) is available for the entire icefield.

In this paper we present the first completely cloudless mosaic of Hielo Patagónico Sur assembled with Landsat TM optical images acquired on 12 March 2001. The three scenes used for the mosaic assembly are: Path 231/Row 94, Path 231/Row 95 and Path 231/Row 96. They were processed by the ground receiving station "Estación Terrena Córdoba" located in Córdoba, Argentina, of Comisión Nacional de Actividades Espaciales (CONAE).

GEOREFERENCE AND MOSAICKING

The Landsat TM 1986 mosaic has been assembled with two and a quarter scenes acquired on 14 January 1986 (Naruse and Aniya, 1992). The geometric correction of this mosaic was performed with an aid of Carta Preliminar de Chile at 1:250,000 scale published by Instituto Geográfico Militar of Chile, and is described in Aniya et al. (1996).

The most recent mosaic, hereafter referred to as Landsat 2001 mosaic, was assembled with three images acquired on 12 March 2001. The false color composite of the 2001 mosaic results from combination of bands 3 (0.63-0.69 μm), 2 (0.52-0.60 μm) and 1 (0.45-0.52 μm) (RGB). These band combination provides more realistic colors of snow-ice cover, rock outcrops, water and vegetation. All processes involved in production of Landsat 2001 mosaic were performed with GEOMATICA® software on PC platform. To produce the mosaic it was necessary to create an empty image database. Its geometry and coordinates are in Universal Transverse Mercator (UTM) projection, zone 18 F, referred to WGS-84 ellipsoid. The UTM is an excellent projection for regions extending predominantly north-south (Snyder, 1987), therefore ideal for the north-south elongated HPS. The original georeference information contained in the header files of all three images, which could have made mosaicking a simple and straightforward process, could not be used because of severe coordinate blunders. Furthermore, the original raw images were projected on World Reference System 1980 (WRS-80) ellipsoid. For consistency reasons we have decided to resample all images on WGS-84 ellipsoid. This resampling does not introduce any geometric deformation because the WGS-84 ellipsoid is by definition of the same size as WRS-80 (Snyder, 1987). The TM images were georeferenced to characteristic and conspicuous features such as lake coastlines, islands and rivers, mapped in the field with kinematic differential Global

Positioning System (GPS). As most GPS data were differentially processed a sub-meter accuracy was achieved. The GPS lines used for georeference of the mosaic are distributed unevenly at the central-eastern and northeastern parts of the icefield, i.e. in the vicinity of Upsala and Moreno glaciers and along the eastern shore of Lago San Martin/O'Higgins. They are a result of field measurements carried out after the mid 1990's in support of different projects. All GPS field surveys were tied to "La Gerónima" geodetic point, located nearby the southern arm of Lago Argentino (see Fig. 3). This point is part of the Argentine geodetic network known as "Posiciones Geodésicas Argentinas 1994" (POSGAR '94, 1997), officially adopted by Instituto Geográfico Militar (IGM) of Argentina in 1997. Using these GPS data as ground control source the seven TM bands of each image were coregistered by applying a first order polynomial model and nearest-neighboring resampling method. This method was selected because introduces smaller distortions to information contained in pixel values. Due to the lack of GPS ground control lines the southernmost image (Path/Row 231/096) was tied to the mosaic by using more than 25 tie-points located on the overlap stripe.

After completing the georeference and mosaicking an accuracy check was made by comparison to 1:100,000 quadrangle map series given in Transverse Mercator (Gauss Krüger) projection published by IGM of Argentina. A total of 15 points were selected on different topographic maps and their coordinates transformed to UTM projection, compared to those derived from Landsat 2001 mosaic. It was found after analysis that coordinates of features measured in the field with differential GPS differ on average about 150 m from those obtained from maps. As the coordinates measured in the field with differential GPS are very accurate it is assumed that the above discrepancy might be attributed to probable errors of topographic maps. In areas where GPS lines are not available the comparisons yield differences of up to 300 m. However, on average the errors are estimated in the order of 150 m, i.e. equivalent to about five pixels on TM image.

Figure 3 shows the Landsat 2001 mosaic with superimposed drainage areas of 48 major HPS glaciers as determined from Landsat 1986 mosaic by Aniya et al. (1996). Only the names of the largest glaciers are written on the mosaic. The red line indicates the drainage area of HPS which contributes to the Río Santa Cruz basin. The section indicated with red dashed line corresponds to the ice divide in the flat region of the central high part of the icefield plateau named "Meseta de los cuatro glaciares", as inferred by Skvarca et al. (1995).

Fig. 1. Location map of Hielo Patagónico Sur (HPS), Chile-Argentina, southwestern South America.

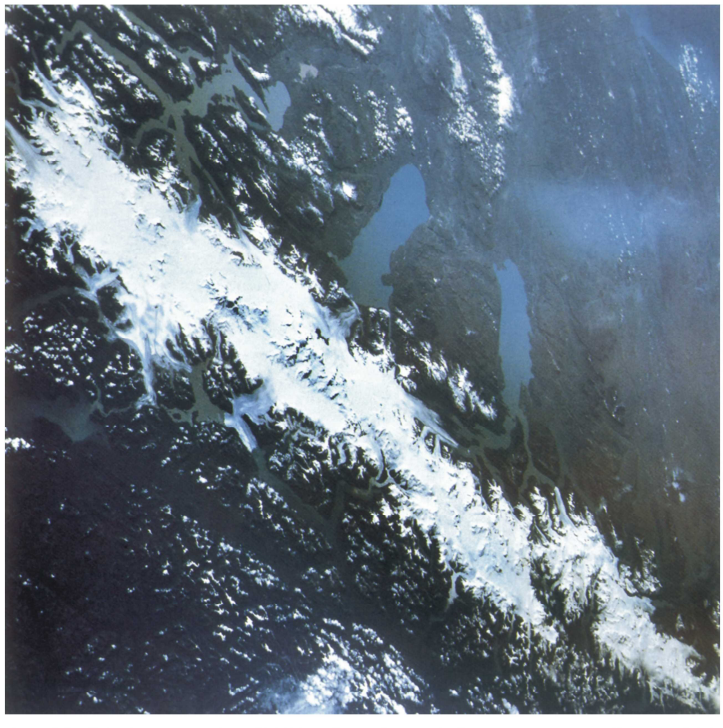

Fig. 2. Hand held photograph of HPS taken from Salyut-6 spacecraft on 10 March 1978 (Published by courtesy of the Institute of Geography, Russian Academy of Sciences)

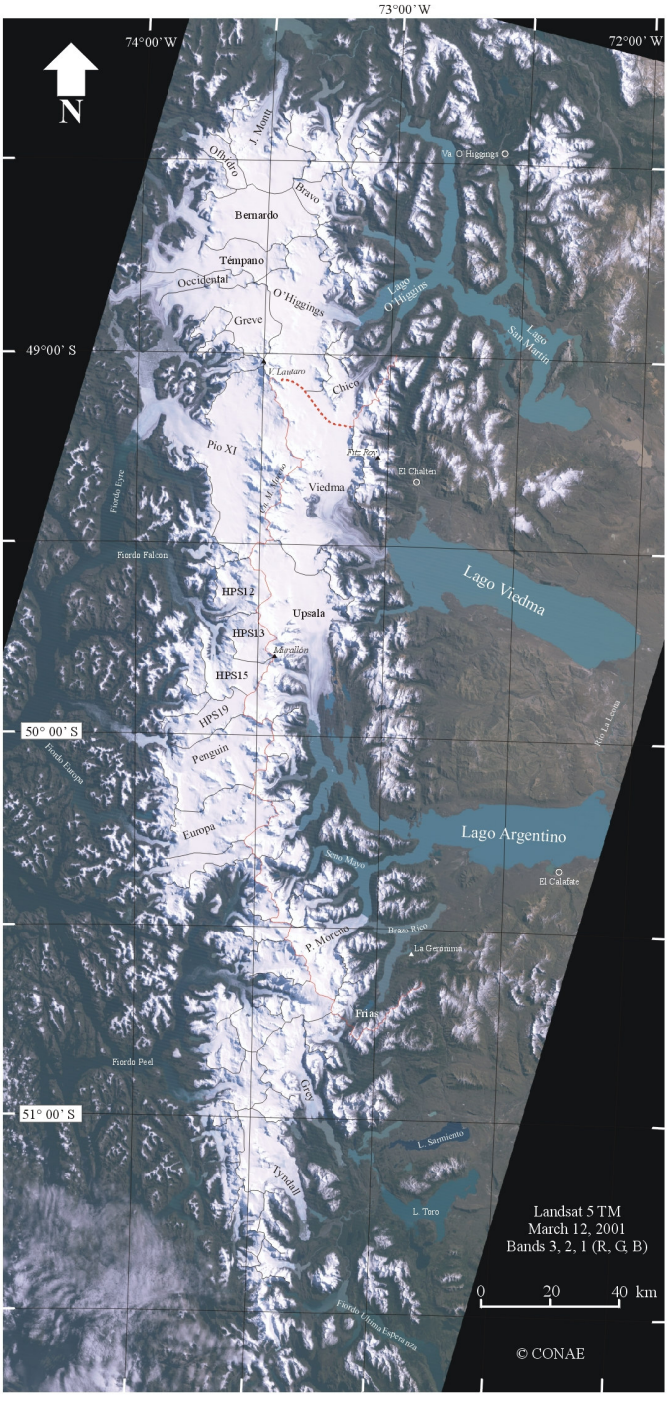

Figure 3. Landsat TM mosaic of Hielo Patagónico Sur assembled with images acquired 12 March 2001.

DISCUSSION AND RESULTS

HPS and contiguous glacier drainage areas

To calculate the icefield drainage area which contributes water through melting and calving to the Río Santa Cruz basin we have utilized basically the areas given in the HPS glacier inventory of Aniya et al. (1996). Only 9 of the 48 inventoried glaciers flow towards the east into Lago Viedma and Lago Argentino, which discharge through Río La Leona and Río Santa Cruz, respectively, into the Atlantic Ocean. According to Aniya et al. (1996), the drainage areas of these nine individual glaciers, excluding the exposed rock are: Glaciar Upsala (902 km^2), Glaciar Agassiz (50 km^2), Glaciar Onelli (84 km^2), Glaciar Spegazzini (137 km^2), Glaciar Mayo (45 km^2), Glaciar Ameghino (76 km^2), Glaciar Moreno (258 km^2) and Glaciar Frías (48 km^2). The nine glaciers yield a total area of 1600 km^2. For Glaciar Viedma, the second largest glacier of HPS we have adopted the area of 978 km^2, given in Skvarca et al. (1995). The criteria Aniya et al. (1996) used in their inventory was based on contiguity of glaciers to the icefield and the size of drainage basin. In their inventory were excluded small cirque, slope and valley glaciers which are disconnected to the icefield. However, these areas measured from the Landsat 2001 TM mosaic add another 599 km^2 of ice to the Santa Cruz river drainage basin. In conclusion, about 3177 km^2 of HPS and contiguous glaciers contribute to water discharge of Río Santa Cruz, as a result of melting and calving (Skvarca, 2002). The red line marked on Landsat 2001 mosaic, which extends from Lago del Desierto in the north to Glaciar Frías in the south, indicates the ice divide and watershed of Río Santa Cruz upper basin (Fig. 3). In the flat central region located in the northern part of HPS called "Meseta de los cuatro glaciares" the ice divide is only inferred and therefore indicated with dashed line, as defined by Skvarca et al. (1995). The definite ice divide between Viedma, Chico and O'Higgins glaciers should be possible to determine with interferometry, coherence provided.

In addition, the Landsat 2001 mosaic was used to monitor changes occurred in fifteen years of the major HPS outlet glaciers Pío XI, O'Higgins, Viedma, Upsala and Moreno, in comparison to Landsat 1986 mosaic (Skvarca and De Angelis, 2002). Both Landsat TM image mosaics were also used to quantify the variations of 34 glaciers with termini on land distributed around the icefield, which respond directly to climate. A consistent and substantial decrease of 19.2 km^2 has been detected from 1986 to 2001. Of the thirty four monitored glaciers, thirty three have receded during the last 15 years (Skvarca and De Angelis, 2002).

CONCLUSIONS

A mosaic, composed with three Landsat TM images acquired on 12 March 2001, has been assembled and georeferenced to selected features mapped in the field with GPS. The outstanding characteristic of this mosaic is that it shows for the first time, since the inception of Landsat missions in 1972, the full extent of Hielo Patagónico Sur without clouds. The Landsat 2001 mosaic provides and important information for glaciological studies of HPS related to detection of glacier variations and ice field extent by comparison to early Landsat images and Landsat 1986 mosaic. This mosaic was also used to define the drainage area of the icefield which contributes to Río Santa Cruz basin and to quantify for the first time variations of those HPS glaciers with termini on land. A consistent glacier retreat was detected between 1986 and 2001: of the thirty four land termini glaciers monitored around Hielo Patagónico Sur all but one have receded during the recent 15 year time interval.

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REFERENCES

ANIYA, M., H. SATO, R. NARUSE, P. SKVARCA and G. CASASSA. 1996. The use of satellite and airborne imagery to inventory outlet glaciers of the Southern Patagonia Icefield, South America. *Photogrammetric Engineering & Remote Sensing*. Vol. 62, Nº 12, 1361-1369.

NARUSE, R. and M. ANIYA. 1992. Outline of Glacier Research Project in Patagonia, 1990. *Bulletin of Glacier Research*, 10, 31-38.

LLIBOUTRY, L. 1998. Glaciers of South America-Glaciers of Chile and Argentina. Satellite Image Atlas of Glaciers of the World. R. S. Williams, Jr. and J.G. Ferrigno, Eds. *U.S. Geol. Survey Profess. Paper 1386-I*, 109-206.

POSGAR '94. 1997. www.igm.gov.ar/subcom_geod/posgar.doc

SKVARCA, P. , H. ROTT and M. STUEFER. 1995. Synergy of ERS-1 SAR, X-SAR, Landsat TM imagery and aerial photography for glaciological studies of Viedma Glacier, Southern Patagonia. VII Simposio Latinoamericano de Percepción Remota", Puerto Vallarta, México, Nov. 5-10, 1995. *Memorias SELPER*, 674-682.

SKVARCA, P. and H. DE ANGELIS. 2002. 15 year changes of southern Patagonia icefield glacier, Argentina-Chile, detected from Landsat TM mosaics. *Proceedings*, 29th International Symposium on Remote Sensing of Environment (ISRSE-29), April 8-12, 2002, Buenos Aires, Argentina (on CD-ROM).

SKVARCA P. 2002. Importancia de los glaciares del Hielo Patagónico Sur para el desarrollo regional. *In:* M.J. Haller, Ed. Geología y Recursos Naturales de Santa Cruz. *Relatorio del XV Congreso Geológico Argentino*. El Calafate, V-1: 785-798. Buenos Aires.

SNYDER, J.P. 1987. Map Projections-A Working Manual. *U.S. Geological Survey Professional Paper 1395*, pp. 383.

WILLIAMS, R.S. Jr. 1986. Glaciers and Glacial Landforms. *In* Short, N.M. and R.W. Blair, Jr. Eds, *Geomorphology from space, A global overview of regional landforms*. NASA SP-486, 521-596.

WILLIAMS, R.S. Jr. 1987. Background to the Soviet glaciological studies from the Salyut-6 orbital station. *Polar Geography and Geology*, Vol. 11, No. 1, 1-11.

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