Orographic Atmospheric Phenomena in Patagonia: A preliminary survey

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Abstract: The southern Andes create a variety of atmospheric phenomena, but these have not been well studied. In this paper, we describe our preliminary observations and modeling of a few of these phenomena including: the sharp vegetation gradient on the eastern slopes, orographic triggering of roll convection, foehn wall and short lee-wave trains, liquid clouds capping ice clouds, "bullet" clouds, and isotopic fractionation of water vapor..

Keywords: Andes, Patagonia, mountain waves, orographic precipitation, ice clouds, roll convection, isotope fractionation

1. TERRAIN DETAIL

Until recently, the terrain of South America was available in the GTOPO30 data set, or in classified military datasets. The GTOPO30 data set, besides having only 1km resolution, was rather poor in quality in this region. Now, with the 90m Shuttle Radar (SRTM) data, the situation is much improved. While the SRTM data is not perfect, most "holes" can be filled using available software, and errors in very steep terrain (e.g. in Torres del Paine) can be reduced by smoothing to, say 200m resolution. As most mesocale meteorological models require only 500m to 2000m terrain fields, the smoothed SRTM fields are very suitable.

2. SATELLITE MONITORING

The cloud fields associated with the Southern Andes can be monitored using existing environmental satellites; especially GOES, Terra and Aqua MODIS and Landsat. GOES gives continuous coverage, but with poor resolution and look angle. MODIS gives high quality multi-spectral views twice each day Landsat has a poor 18 day return time but a good 30 meter spatial resolution. The USGS Landsat 5 and 7 archives contain the order of 100 images for each path/row in the southern Andes region. The MODIS and Landsat archives contain many clear-sky images that can be used to map snow and vegetation, as well as cloudy images. Here we give a few examples.

Using cloud compositing techniques, it possible to obtain nearly cloud-free MODIS images for each 16-day period during the year. From these images, using surface reflectivities in the red and near IR, we can compute a vegetation index (NDVI). In Figure 1, we show the annual average vegetation index, draped over a smoothed SRTM DEM. The domain extends from about 41 to 50S latitude. The most obvious features are: a) the strong west-to-east decrease in vegetation associated with the Andes rain shadow; and b) the north and south Patagonian Ice Sheets (deep blue).

Using the multi-spectral capabilities of MODIS, we can gain a 3-D view of orographic clouds. In Figure 2 we show a cloud-top layer draped over SRTM terrain. The height of the layer is deduced from the emission temperature while the color on the drape represents reflected light in MODIS bands. Several features are worth noting: 1) the well-defined foehn wall where the orographic clouds "plunge" over the lee slopes; 2) the dominance of ice (Blue) in cloud tops but with occasionally higher liquid clouds; 3) downstream convective roll clouds and cirrus jump clouds.

Using Landsat images, one can obtain a more detailed view of orographic clouds. In Figure 3, we show a sharp foehn wall cloud in the vicinity of Lago Argentina. Peaking out from the downwind cloud edge is the southern Patagonian Ice Sheet and its descending valley glaciers. Figure 4 shows a similar situation in the same area, but the foehn wall is followed by a short train of lee waves. The lee wave clouds appear rough, suggesting that they include turbulent BL air, or that they are rotors. The author has a collection of time-lapse movies of foehn wall and lee wave clouds from the southern Andes.

Figure 5 shows a typical MODIS image of clouds over a larger domain during a precipitation event in southern Chile. The following features are evident: 1) Upstream over the Pacific Ocean, open cell convection dominates with a typical cell size of 100km; 2) Dense clouds over the mountains with a more stratiform appearance in the south and a more convective appearance in the north; 3) generally clear skies in the lee slopes in Argentina, but with long convective roll clouds. These rolls appear to be generated by lateral lake-plateau circulations in the glacial lake terrain of SW Argentina. The author has time-lapse movies of these rolls.

In several Landsat images of SW Argentina, diffuse high clouds are evident with a peculiar "bullet" shape. These clouds are narrow, aligned with the wind, and have rounded upwind noses. They form east of the southern Andes over the steppe. An example is shown in Figure 6. A photograph of bullet clouds taken from the airport at Calafate, Argentina is shown in Figure 7. The generation mechanism of these clouds is unclear. They may be associated with individual mountain peaks upstream. On the other hand, vertical motion patterns with wind-aligned phase lines cannot propagate vertically; so a pure mountain wave explanation seems unlikely.

3. WATER VAPOR FRACTIONATION

Associated with the wet-dry contrast across the southern Andes (Figure 1) and the prevailing westerly airflow, there is an isotope fractionation of water vapor as it crosses the mountains and the heavier isotopes of water condense out. A recent study in the equivalent northern latitudes of Oregon (Smith et al., 2005) used the isotope gradient to estimate the drying ratio across the Cascades to be 43%. Data by Stern and Blisniuk (2003) suggests a similar fractionation may occur in the southern Andes. A recent broader scale sampling program allows comparison with a predictive model of isotope ratio. In Figure 8, we show the predicted rainfall isotope pattern from the LT model (Smith and Barstad, 2004) using regional wind climatology. Figure 9 compares the predicted and observed isotope ratios. The slope in Figure 9 is sensitive to the cloud delay times; here chosen to be 500 seconds.

4. CONCLUSIONS

In spite of its interest and importance, little research on Patagonian orographic effects has been carried out (but see Cook et al., 2003). In this note, we point to some of the interesting physical problems that could be studied in Patagonia. While the lack of local infrastructure is a problem, the new availability of remote sensing data, isotope data and new modeling techniques makes progress possible. It would provide an ideal site to test theories and models and to compare with corresponding mid-latitude Northern Hemisphere phenomena.

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REFERENCES

Cook K. H., X. Yang, C. M. Carter, and B. N. Belcher, 2003: A modeling system for studying climate controls on mountain glaciers with application to the Patagonian icefields. *Climatic Change*, **56**, 339-367.

Smith, R. B. and I. Barstad, 2004: A linear theory of orographic precipitation., *J. Atmos. Sci.*, Vol. **61**, 1377–1391.

Smith, R. B., I Barstad, L. Bonneau, 2005: The Oregon Climate Transition. *J.Atmos. Sci.*, **62**, 177-191.

Smith. R. B., and J. Evans, 2005: Water vapor isotope fractionation by the southern Andes. [In preparation].

Stern, L. A., and P. M. Blisniuk, 2002: Stable Isotope composition of precipitation across the southern Patagonian Andes. *J. Geophys. Res.*, **107**, D23, 4667.

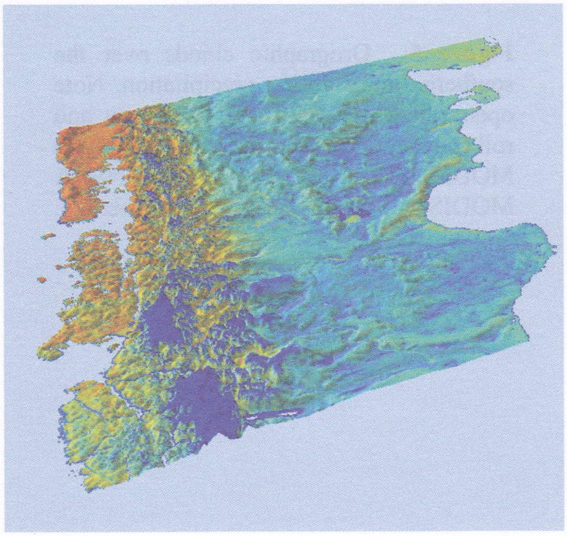

Figure 1: Southern Andes Average NDVI from a MODIS time series is draped over a degraded SRTM DEM. View from the south. Dense vegetation is red, sparse vegetation is pale blue and snow is deep blue (Data from NASA; image analysis by the Yale Center for Earth Observation).

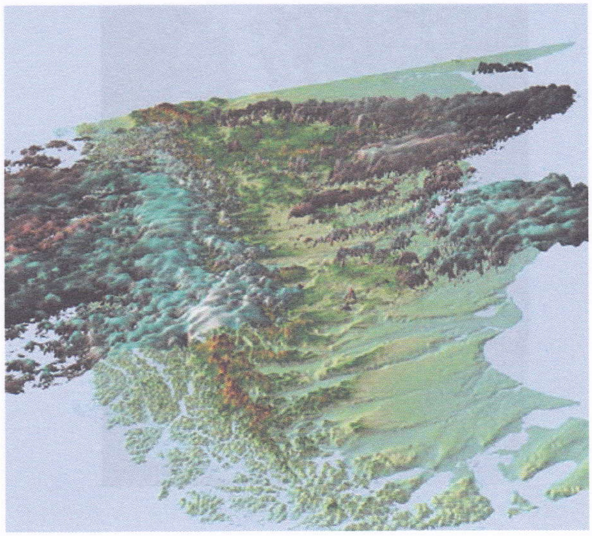

Figure 2: Satellite view of orographic clouds during precipitation in Patagonia on 29 October 2004. Airflow is from left to right. The terrain is from SRTM, degraded to a 1km resolution, and viewed here from the south. The cloud height is derived from the thermal channel (#31) of Aqua-MODIS . The cloud color is a MODIS 1,2,7-RGB false color composite. Ice clouds appear blue.

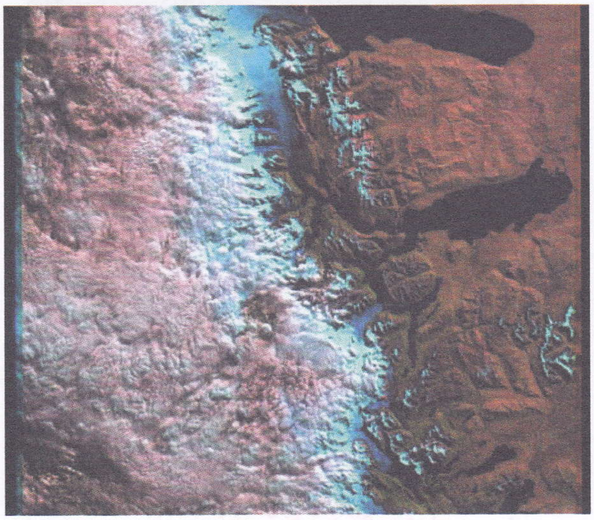

Figure 3: Foehn Wall near Lago Argentina; Landsat 7, April 8, Path 231 Row 95 (from USGS website).

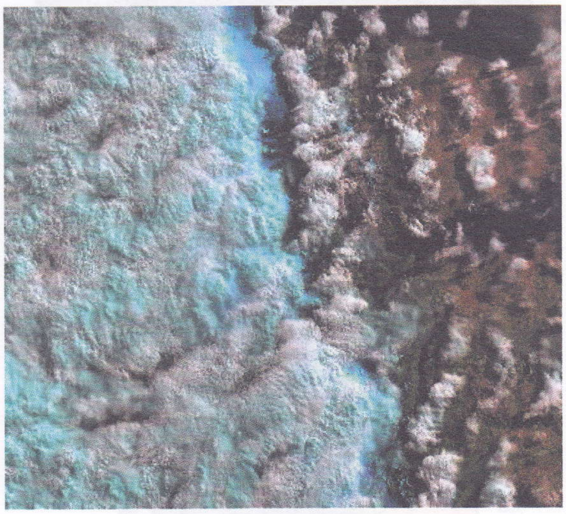

Figure 4: Foehn Wall and lee waves near Lago Argentina; Landsat 5, Feb 13, 1997, Path 231 Row 95 (from USGS Website).

Figure 5: Orographic clouds over the southern Andes during precipitation. Note open cell convection over the ocean and roll convection over the steppe. Aqua MODIS, JD = 323 2002 (from NASA MODIS Atmosphere Website).

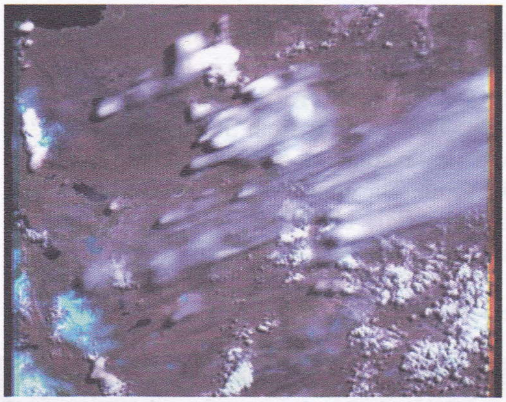

Figure 6: Bullet clouds over SW Argentina; Landsat 7, December 7, Path 230, Rows 92,93.

Figure 7: Bullet clouds seen from Calafate, Argentina (view SW), January 9, 2005, 10AM.

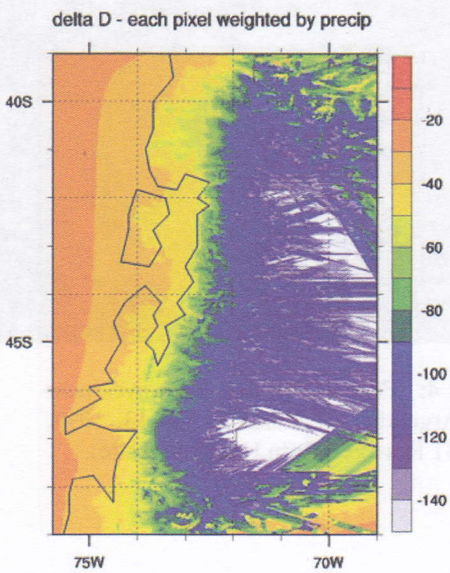

Figure 8: Normalized hydrogen isotope ratio computed from LT and Rayleigh fractionation. Cloud delays are assumed to be 500 seconds.

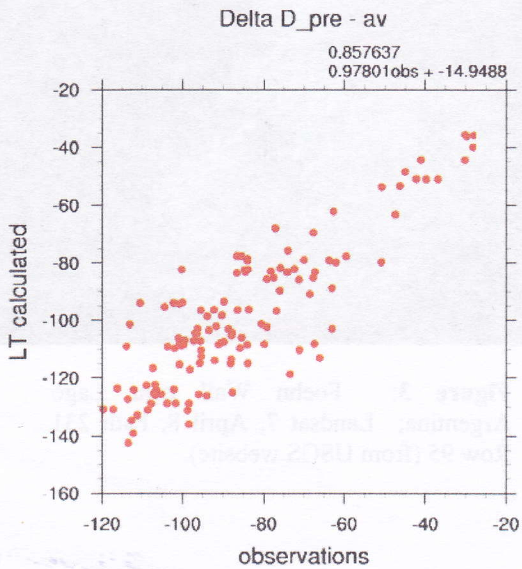

Figure 9: Predicted isotope ratio versus data from stream water; including Stern and Blisniuk's data and the author's samples from summer 2005.