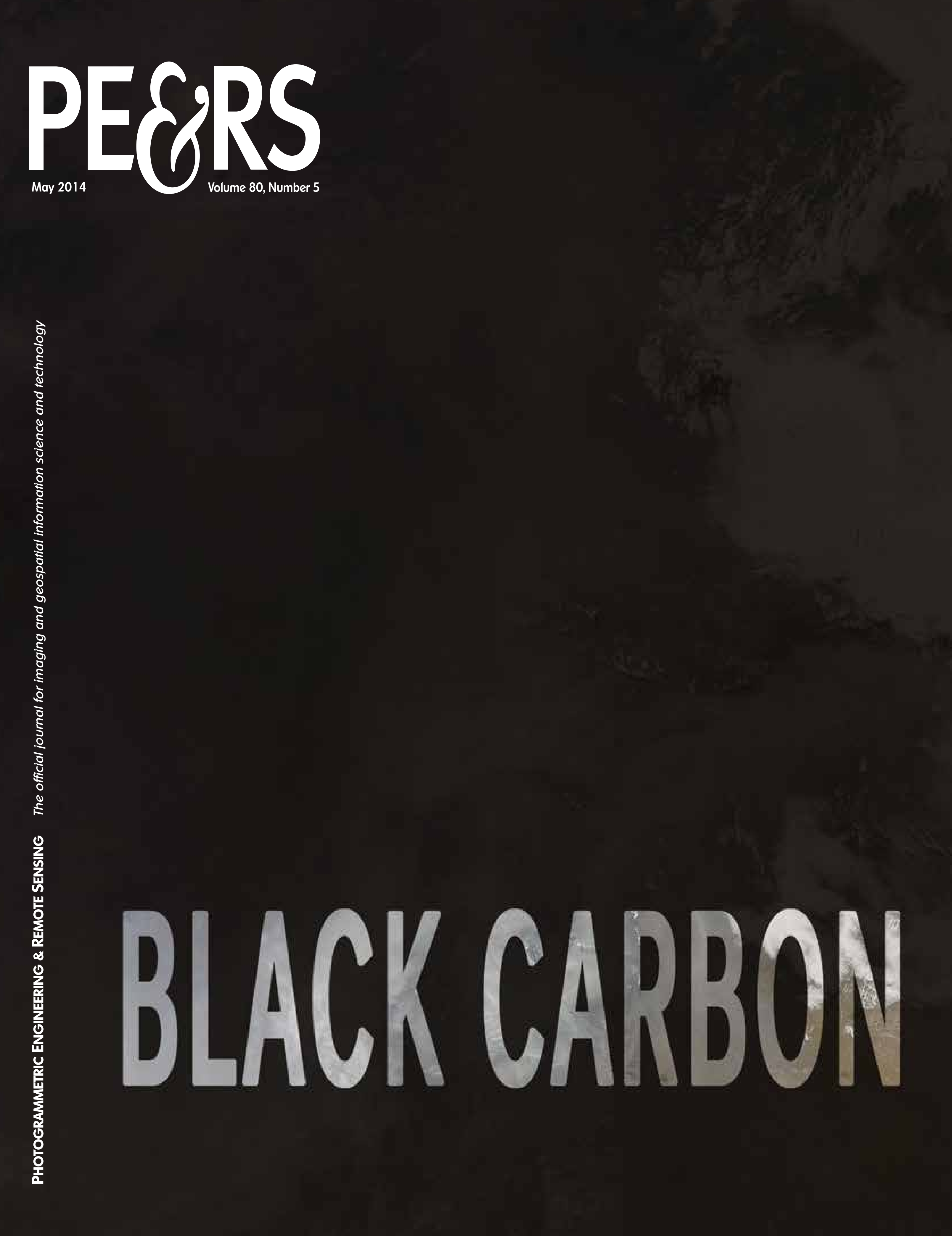
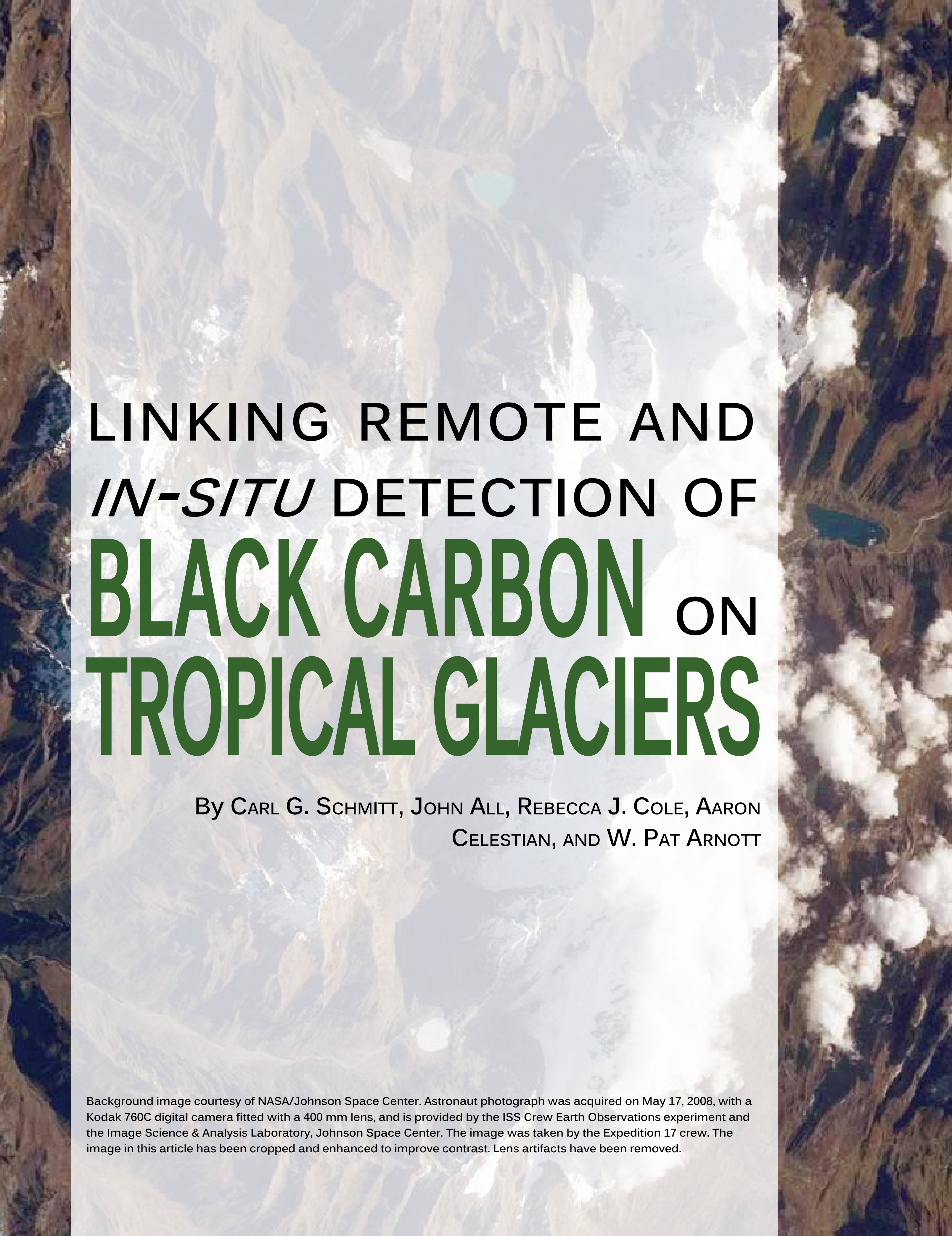
PE&RS

May 2014 Volume 80, Number 5

PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING *The official journal for imaging and geospatial information science and technology*





LINKING REMOTE AND *IN-SITU* DETECTION OF BLACK CARBON ON TROPICAL GLACIERS

By Carl G. Schmitt, John All, Rebecca J. Cole, Aaron Celestian, and W. Pat Arnott

Background image courtesy of NASA/Johnson Space Center. Astronaut photograph was acquired on May 17, 2008, with a Kodak 760C digital camera fitted with a 400 mm lens, and is provided by the ISS Crew Earth Observations experiment and the Image Science & Analysis Laboratory, Johnson Space Center. The image was taken by the Expedition 17 crew. The image in this article has been cropped and enhanced to improve contrast. Lens artifacts have been removed.

Remote Sensing Challenges in Mountainous Regions

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Remote sensing technology is advancing at a dizzying pace as ever more accurate sensors and analysis techniques emerge. However, while this cornucopia provides us with seemingly unlimited tools, there is still the need for ground reference data and other ancillary data so that the radiative transfer state variables translate into biophysical variables of interest. The American Climber Science Program (ACSP) is on the cutting edge of this process as we explore some of the harshest areas on Earth – from Central American mountain rain forest to the summit of Mt. Everest - and gather data that is integrated through remote sensing to create holistic understandings of these environmental systems. The ACSP is an integrated research program designed to facilitate field data collection opportunities for scientists in regions that are difficult to access. Scientists and climbers come together for expeditions to collect in situ data for scientific projects and to share their enthusiasm for the mountains. Research expeditions are also designed to provide opportunities for non-scientists to learn about scientific practices as well as to instruct future scientists on safety in mountain regions.

The ACSP's central tenet is integrated research and our expeditions are formed of scientists and students from diverse disciplines. Each participant leads their individual project and also assists in data gathering for all of the expedition studies. We gather a variety of ground data: from spectroradiometer readings to glacier particulate composition and quantity to interviews of local yak herders on grazing patterns. This information is then integrated and regionalized using remote sensing data to help inform local resource management and conservation efforts in coordination with various stakeholders. At the end of the day, we seek out research projects with maximum societal benefit and scientific innovation.

John All collecting ground reference data above the Khumbu Valley in Sagarmatha National Park, Nepal.

Over the next year, we will be periodically sharing ACSP work from Central America, Africa, the Himalayas, and the Andes as *PE&RS* Highlight articles. More information can be found about the ACSP at www.climberscience.com or www.mountainscience.org and we invite collaborators in all disciplines.

Our first example will be from the ACSP Cordillera Blanca expeditions in Peru. In association with the American Alpine Club, the Peruvian Ministry of the Environment, Huascaran National Park, and several Peruvian Universities, the ACSP has conducted research expeditions where, among other things, we have sampled anthropogenic pollutants deposited on glaciers. These pollutants can lead to increased glacier melt rates and the article which follows discusses the issues involved in using remote sensing techniques to detect these pollutants.

INTRODUCTION

A substantial proportion of humanity depends on glaciers or seasonal snow melt for their water supply (Barnett et al., 2005). Tropical glaciers are a key water supply for many cities and a great deal of agriculture; however, these glaciers are receding at an alarming rate (Rabatel et al., 2013). Global climate change is leading to increasing temperatures globally; higher tropospheric temperatures are one of the prime factors leading to glacier melt, especially at lower latitudes. An additional anthropogenic impact on glaciers is increased levels of pollution in the atmosphere. Atmospheric pollutants such as black carbon particles can be deposited on glacier surfaces through precipitation processes or through 'dry deposition'. Black carbon on glacier surfaces increases the rate of melting due to absorption of light that would otherwise be reflected (Painter et al., 2013). Although studies have shown that the albedo impact of black carbon on glaciers is significant, the actual extent of black carbon deposition on tropical glaciers has yet to be investigated.

Remote sensing of black carbon on tropical glaciers can give us a better understanding of the extent of the problem. However, there are a number of challenges for determining glacial black carbon concentrations from remote sensing and in-situ measurements of black carbon can greatly enhance the accuracy of derived indices. In this article we discuss the remote sensing challenges as well as some techniques for solving them using ground data collection.

A series of research expeditions have been conducted in the Peruvian Andes over the past three years by the American Climber Science Program (ACSP) and some of the data collected was used as ground truth to reference remote sensing measurements on glaciers (Schmitt et al., 2013). Observations from the ACSP expeditions as they relate to the uncertainties in remote sensing measurements of black carbon in glaciers will be discussed, as well as preliminary results that could be used to guide future observations.

Glacier Measurements by the American Climber Science Program

The ACSP has conducted several research expeditions in the Cordillera Blanca Mountains of Peru. Research projects carried out by the ACSP include the measurement of light absorbing impurities, including black carbon and dust, on the glaciers of the region and experimental spectoradiometer readings on the glaciers (Figure 1). A detailed description of the black carbon research including the collection, processing, and analysis techniques used is given in Schmitt et al. (2013). Briefly, snow samples were collected by volunteer climbers and scientists while climbing 14 different mountains in the region (Figure 2). In camp, the melted snow was passed through filters, which captured impurities for further analysis. A total of 250 filter samples were collected in the three expeditions. Analysis was done by measuring the heat absorption capacity of the particles on the filters. Filters were individually illuminated by a broad band light source and an infrared thermometer was used to monitor the temperature of the filter. The increase in temperature of the filter is directly related to the heat absorptive capacity of the particles on the filter. Results of the filter measurements indicate that there is a significant amount of plain dust in some regions while other areas include significant black carbon as well.

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Research Motivation

When a region with glaciers is experiencing warming, even if precipitation patterns remain constant, the water availability for the region will change. Initially, runoff from glaciers will increase as melting increases, but eventually the glacier area will be reduced sufficiently that the increased melting will be offset by the increased water loss due to evaporation, sublimation, or absorption into newly exposed ground surfaces. The highest level of runoff is referred to as "peak water" (Baraer et al., 2012). Once the highest levels of runoff have been passed, water flow levels decrease, usually to levels significantly below the pre-warming flow rates. Surface water flow rates are then driven more by precipitation; and as a result, dry season water flows can be substantially reduced while wet season flows may not be

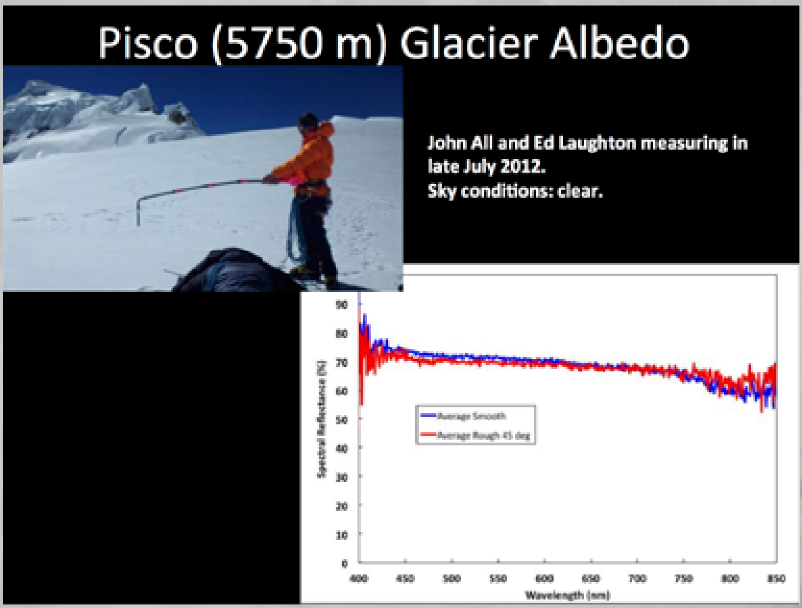

Figure 1. We have tested various techniques for gathering ground spectroradiometer data that can be compared to remotely sensed information.

Figure 2. Dr. John All gathering snow samples at over 5000 meters in the Ishinca Valley.

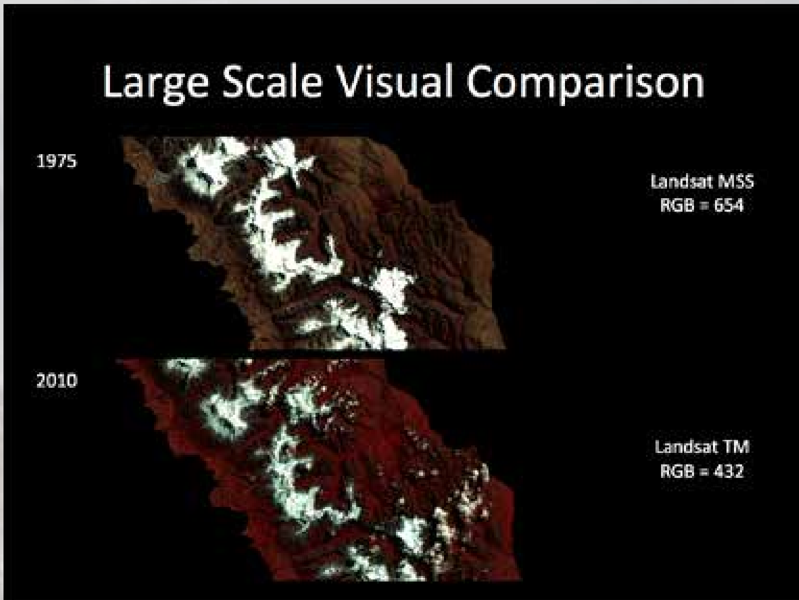

Figure 3. A comparison of Landsat images from 1975 and 2010 showing glacial retreat in the Cordillera Blanca.

as significantly impacted. As an example, in the Cordillera Blanca mountain range in Peru, it is anticipated that dry season discharge rates in some valleys will be reduced by up to 70% compared to pre-warming flow rates (Baraer et al., 2012). The change in surface water flow has substantial implications for maintaining sustainable water supplies for societal needs (Figure 3).

The process of melting leading to changes in river flow rates could be accelerated if the temperature change coincides with an increase in black carbon deposited on glacier. Albedo changes mean that glaciers with high amounts of black carbon would melt faster, resulting in peak discharge rates being reached sooner than without black carbon. River flow reduction would come sooner as glacier area and volume are reduced more rapidly due to added black carbon. These events have clear implications for human use of increasingly scarce water resources. Better predictive tools for factors affecting glacier melt rates are urgently needed for planning for climate change adaptation.

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The Effects of Black Carbon on Glaciers

Black carbon particles are generally produced through incomplete combustion of fossil fuels or biofuels. Sources of black carbon include smoke from cook stoves, diesel engines, and biomass burning. Black carbon particles in and on snow and ice reduce solar albedo. Black carbon particles efficiently absorb solar radiation, which leads to localized increased temperature, which in turn accelerates sublimation or melting. Simulations have shown that the effect of black carbon on glacier surfaces can lead to glacier recession even when temperature and precipitation records suggest that glaciers should be advancing (Painter et al., 2013).

While there are numerous reasons why it is difficult to use remote sensing for black carbon measurement on snow (Warren, 2013), a number of these uncertainties are less significant for glacier studies. The albedo of snow and ice packs can be calculated using radiative transfer techniques and these calculations clearly show that snow albedo is reduced by black carbon. With 30 ng/g of black carbon (a typical North American snow value), the albedo of snow is decreased between 2.5-6.0% (Warren and Wiscombe, 1985). The uncertainties are due to the assumptions necessary in the radiative transfer models, but some of these uncertainties are reduced when only tropical glaciers are considered.

Figure 4: Dark layers of accumulated impurities are indicated on the crevasse wall. ACSP director, John All, is approximately two meters in height for scale.

Snow Albedo

At visible wavelengths, ice is nearly non-absorbing, which means that spectral albedo is controlled by the absorbing particles mixed in with the glacier ice. It also means that the albedo of snow over dark surfaces can be influenced by the dark surface below. During the 2012 ACSP expedition, samples were collected in a crevasse to identify changes in contaminant levels over time. The crevasse wall showed intermittent dark layers which were often separated by a meter or more of cleaner ice (Figure 4). Even if these dark layers were optically perfectly absorbing, they would likely have little influence on the spectral albedo.

Black carbon and dust in snow and ice cause the greatest reductions in albedo when the effective ice particle size is large (Warren and Wiscombe, 1980). Gardner and Shart (2010) show calculations of snow pack albedo using different assumptions of particle size and impurity levels. The uncertainty due to lack of knowledge of effective particle size is substantial. This issue is mitigated somewhat for tropical glaciers. In the tropics, the temperature does not vary as significantly as in mid-latitudes. With more predictable temperatures, the evolution of ice particle size is more easily predictable. To test this, snow pits have been excavated during ACSP expeditions. Observations showed that typical particle sizes were similar in different years at the same location and that particle sizes were uniform (2-5 mm) with respect to depth (down to 1.2 meters below the surface).

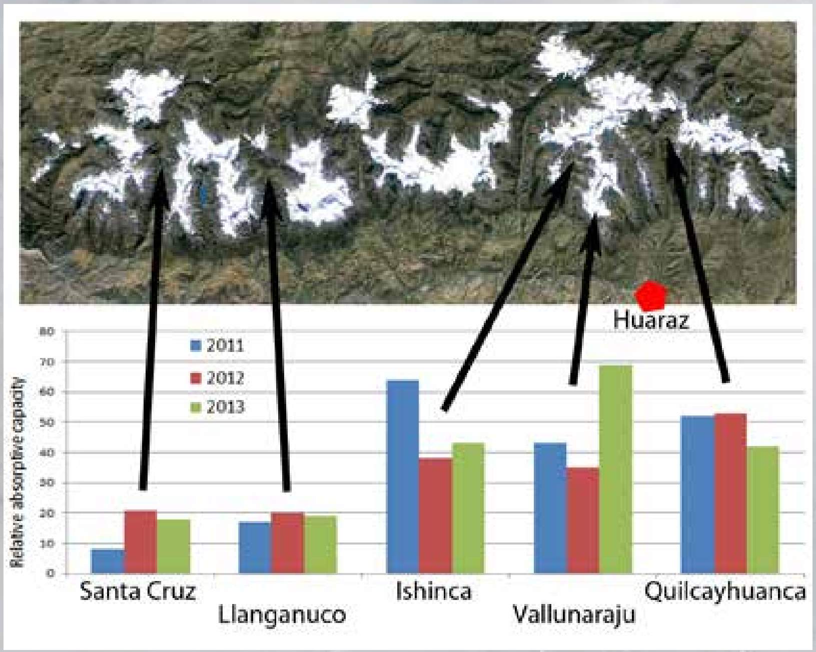

Figure 5: Map of the Cordillera Blanca mountain range. The relative concentration of light absorbing particles for each of the three expeditions is shown below. Huaraz, the largest city in the region is indicated. Note that the most polluted glaciers are nearest to Huaraz.

Conclusions

While remote sensing detection of black carbon in annual snow packs is complex, a number of complicating issues are mitigated when considering tropical glacial ice measurements versus snow measurement and using extensive field data collection. Glaciers are thick, which means that sub-glacier absorbing features will not play a role in albedo. Due to consistent temperature in the tropics, the effective ice particle sizes that make up glacial ice can be more easily predicted. Low level clouds such as diamond dust or ice fog which can lead to uncertainties in the arctic regions are far less likely to be issues above tropical glaciers.

Field measurements such as those conducted by the American Climber Science Program can help to validate remote sensing measurements. The Cordillera Blanca mountain range contains approximately 500 square kilometers of glacier area, down 20-30% since1970 (Rabatel et al., 2013). Light absorbing particles may have played an important role in the reported glacial loss. Figure 5 shows the relative concentrations of light absorbing particles based on ACSP measurements. These results indicate that there are substantially more light absorbing particles including black carbon on the glaciers near Huaraz, the largest nearby city. ACSP measurements on glaciers further from Huaraz showed that most of the light absorbing particles in glacial ice were dust particles. This would suggest that remote sensing studies should initially consider glaciers in reasonable proximity to large population centers, as the signal might be significantly stronger and easier to detect.

The ACSP plans to expand its measurements of glaciers to different regions in the coming years. Regions which are likely highly impacted by pollution from cities as well as from biomass burning, such as in the Amazon basin, will be targeted. This research will be conducted in collaboration with the Pollution and its Impacts on the South American Cryosphere (PISAC) Initiative (www.mce2.org/pisac), an international collaborative group of scientists whose goal is to investigate key sources and impacts of black carbon and co-pollutant emissions in the Andean and Patagonian regions.

Acknowledgements

We would like to thank the American Alpine Club for their support of the ACSP expeditions. We would also like to thank Ellen Lapham for her unwavering support of ACSP Peru expeditions and thanks to all of the volunteers who have made these expeditions a success. The authors also thank Leslee Schmitt for editing the manuscript.

References

Baraer, M., B. G. Mark, J. M. McKenzie, T. Condom, J. Bury, K-I. Huh, C. Portocarrero, J. Gomez, 2012. Glacier recession and water resources in Peru's Cordillera Blanca, *J. Glaciology*, **58**, 134-150, doi:10.3189/2012JoG11J186.

Barnett, T. P., J. C. Adams, and D. P. Lettenmaier, 2005. Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, **438,** 303-309, doi:10.1038/nature04141.

Bond, T. C., et al. 2013. Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res. Atmos.,* **118**, doi:10.1002/jgrd.50171

Gardner, A. S., and M. J. Sharp, 2010. A review of snow and ice albedo and the development of a new physically based broadband albedo parameterization, *J. Geophys. Res.*, **115**, F01009, doi:10.1029/2009JF001444.

Painter, T. H., M. G. Flanner, G. Kaser, B. Marzeion, R. A. VanCuren, and W. Abdalati, 2013. End of the Little Ice Age in the Alps forced by industrial black carbon, *Proceedings of the national academy of sciences*, doi: 10.1073/pnas.1302570110.

Rabatel, A., B. Francou, A. Soruco, J. Gomez, B. Caceres, J. L. Cabellos, R. Basantes, M. Vuille, J. E. Sicart, C. Huggel, M. Scheel, Y. Lejeune, Y. Arnaud, M. Collet, T. Condom, G. Consoli, V. Favier, V. Jomelli, R. Galarraga, P. Ginot, L. Maisincho, J. Mendoza, M. Menegoz, E. Ramirez, P. Ribstein, W. Suarez, M. Villacis, and P. Wagnon, 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. The Cryosphere, 7, 81-102 doi:10.5194/tc-7-81-2013.

Schmitt, C. G., A. Celestian, J. All, M. Rucks, J. Cave, W. P. Arnott, R. Cole, 2013. Sampling of light absorbing particulates on the glaciers of the Cordillera Blanca, Peru. Proceedings of the Glacial Flooding and Disaster Risk Management Conference. Huaraz, Peru, July 13-22, 2013.

Warren, S. G., and W. J. Wiscombe, 1985. Dirty snow after nuclear war, *Nature*, **313**, 467-470.

Wiscombe, W. J., and S. G. Warren, 1980. A model for the spectral albedo of snow. I: Pure snow. *J. Atmos. Sci.*, **37**, 2712-2733.

Warren, S. G., 2013. Can black carbon in snow be detected by remote sensing? *J. Geophys. Res.* **118**, 779-786, doi: 10.1029/2012JD018476.

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Background image courtesy of NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC. Dense smog settled over the North China Plain on February 20, 2011. The featureless gray-brown haze is so thick that the ground is not visible in parts of this photo-like image taken at 11:35 a.m. by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite.