Got Snow?

The Need to Monitor Earth’s Snow Resources

Got Snow?

The Need to Monitor Earth's Snow Resources

National Aeronautics and Space Administration

www.nasa.gov

Acknowledgments

This publication was produced at the National Snow and Ice Data Center within the Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder.

Writing, editing, and design

Editor: Agnieszka Gautier
Writers: Matthew Sturm, Michael Durand, David Robinson, and Mark Serreze
Publication design: Agnieszka Gautier

Processed Chlorine-Free

FSC www.fsc.org 100% From well-managed forests FSC® C000000

Printing notes

Printed with vegetable-based inks at a facility that is Forest Stewardship® Council certified; uses 30 percent recycled chlorine-free paper that is manufactured in the U.S.A. with electricity offset by renewable energy certificates.

Table of Contents

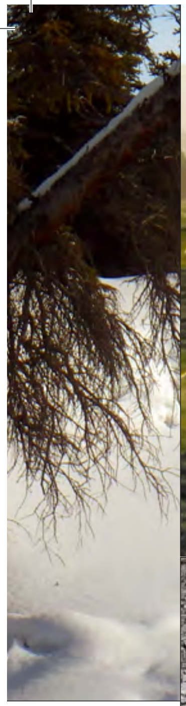
Executive Summary

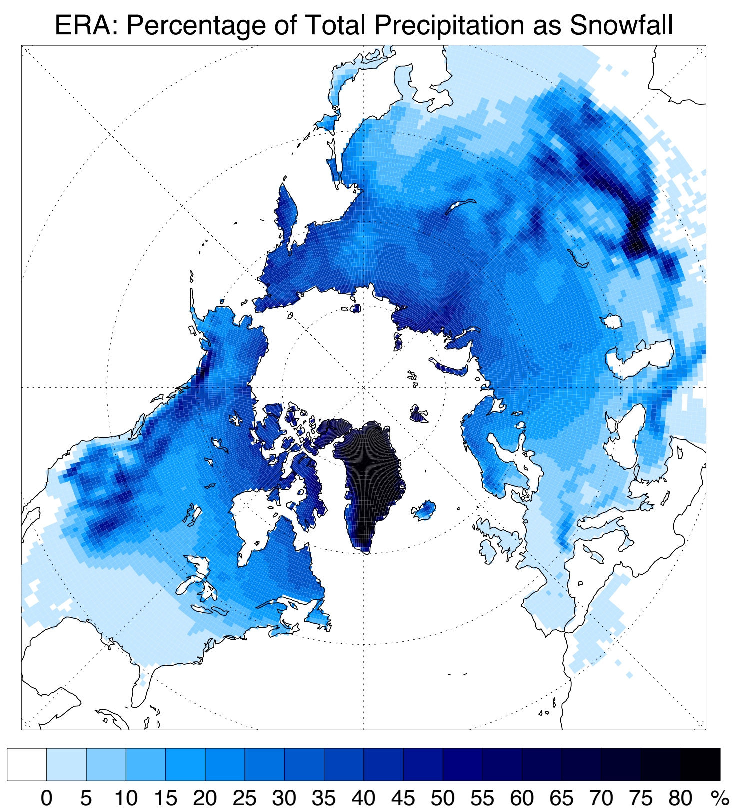
Snow is life. It is the water we drink and the food we eat. Mountains collect and store snow in winter. Spring snowmelt brings water to crops and people downstream, and it feeds reservoirs that generate electricity. Even before snow melts, however, its white blanket helps drive essential climate processes that cool the planet. Changes in snow, both in quality and quantity, have consequences.

Significant shifts in snow accumulation, timing, and melt are underway. Still, the quantity of snow stored across the prairies and tundra, in the mountains, on sea ice, and in the forests remains difficult to measure, frustrating attempts to understand how and why this precious resource is changing.

Remote sensing provides the means of measuring these changes, but developing the needed technologies will require investments and a sustained effort. The time to make these investments is now, before snow-related water and climate issues become critical.

To begin, we need to conduct a series of comprehensive, community-wide field experiments that span a range of snow types and in which we deploy multiple remote sensing technologies. This will enable informed choices about how to best combine sensors, data assimilation techniques, and modeling approaches. Here we describe a practical framework for moving forward.

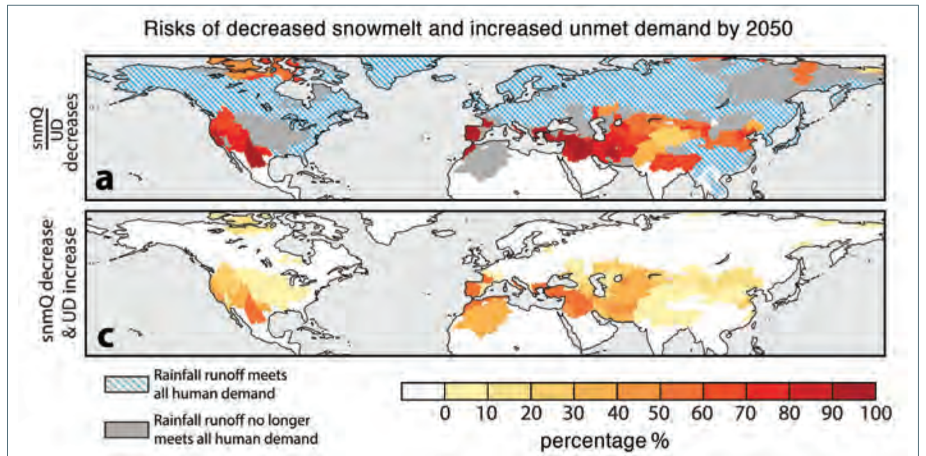




In the Northern Hemisphere, 57 million square kilometers of land may be seasonally covered with snow, while adding ocean surfaces increases the number to 90 million square kilometers. Land where 40 percent of precipitation falls as snow is about 15 million square kilometers in area. Credit: Andrew Slater, NSIDC

The Importance of Snow

More than one-sixth of the world's population (1.2 billion people) relies on seasonal snowpack and glaciers. In California, more than 70 percent of water from the San Joaquin River, which originates from Sierra Nevada snow, is used to irrigate the Central Valley. Although only two percent of U.S. cropland is in the Central Valley, it produces about 300 crops and nearly half the nation's fruits and nuts. Mountain snowpacks are like frozen reservoirs. A third of California's water supply, and nearly three-quarters of the water in the western United States depends on these frozen reserves.



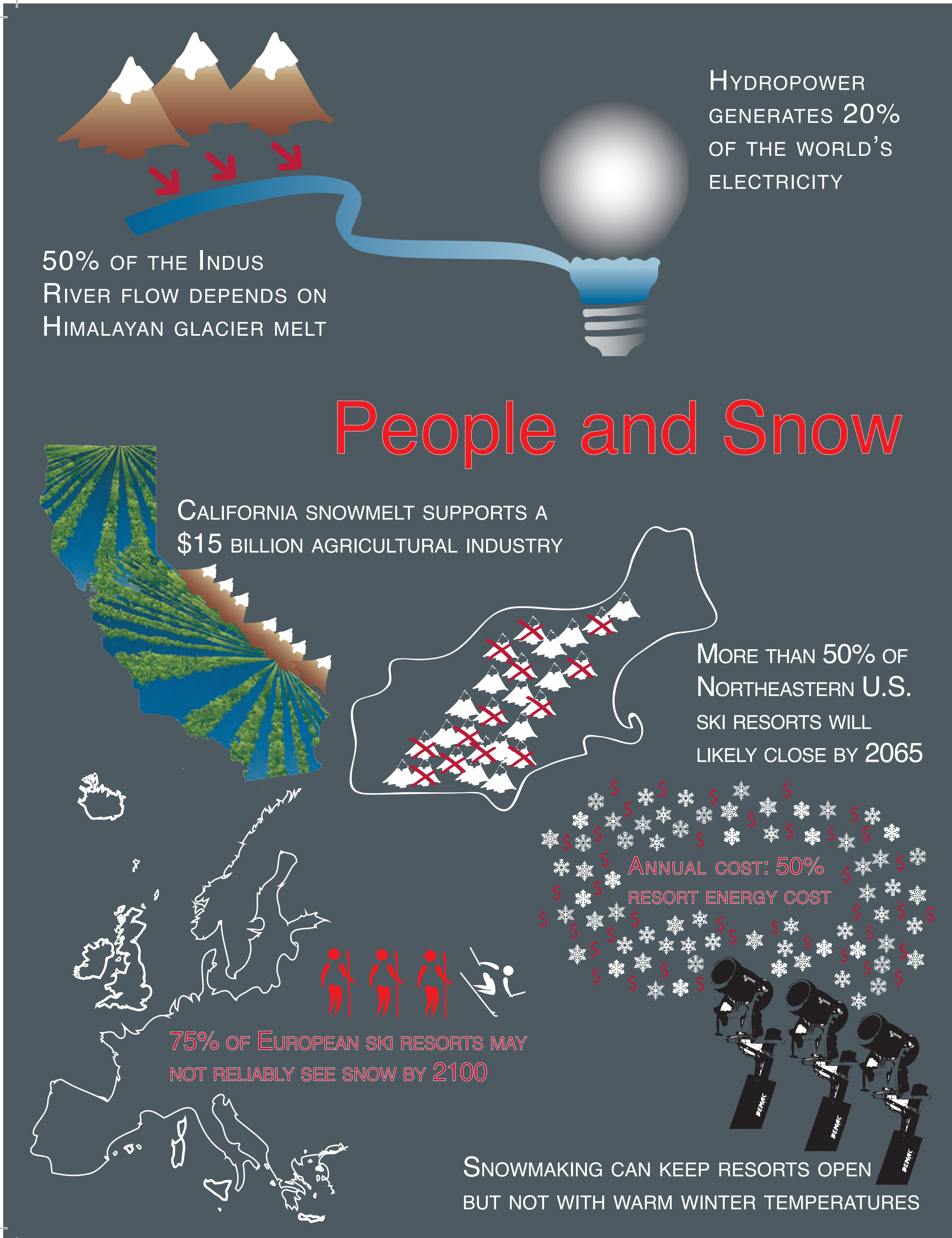
These maps show the risks of decreased March-August snowmelt supply and increased unmet demand by 2050. The top image shows the risks of decreased snowmelt only. Blue lines indicate areas where future rainfall runoff is sufficient to meet present human water demands. Grey areas, which are projected to be snowmelt dependent, indicate regions that shift from sufficient to insufficient rainfall runoff and do not meet water demand. In the bottom image, the risks of decreased snowmelt and increased, unmet demand are joined. Credit: Mankin, J. S. et al., 2015.

Snow is also good business. During the 2009-2010 winter season, snow-related tourism and recreation brought in a $12.2 billion dollar profit in the United States.

More difficult to monetize is the role of snow in Earth's climate system. Snow, being so white, reflects up to 80 percent of the sun's energy, acting to cool the planet. Loss of snow will result in Earth absorbing more sunlight, accelerating the warming that is already underway.

Since 1967, a million square miles of spring snow cover has disappeared from the Northern Hemisphere, an area the size of Argentina. Changes in global snow cover are altering global food production patterns, reducing hydropower generation, and forcing the closure of ski areas. Over the past 50 years, the ski season in parts of British Columbia has been shortened to one fourth its previous duration. At Lake Tahoe, spring arrives two and a half weeks earlier. The same is true of Barrow, Alaska, the northernmost town in the United States.

Changes in snowfall amounts and timing are altering water discharges. Earlier spring runoff tends to prolong droughts. Due to California's multi-year drought, largely a result of reduced snow, farmers have extracted water from aquifers, causing the land to sink by 30 feet or more in places.



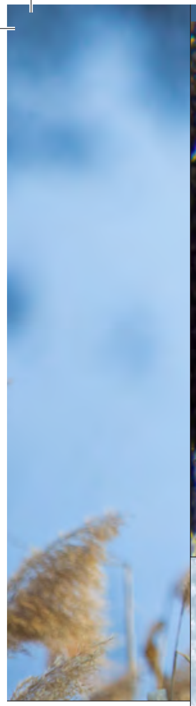
Critical Snow Changes, Critical Snow Questions

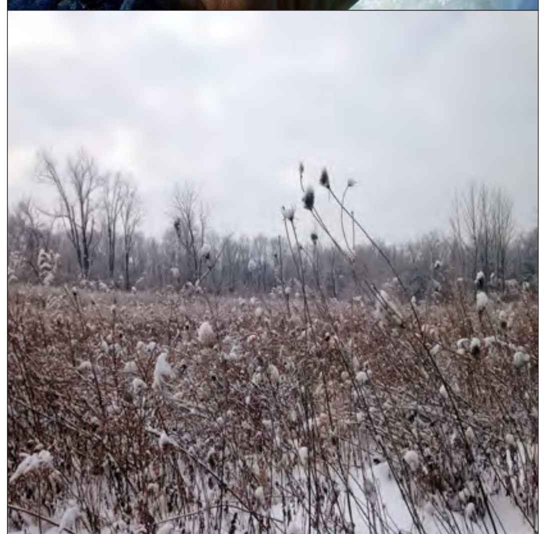
Industry, agencies, and decision-makers need accurate snow information to respond to altering climate and water availability. They need to predict future snow resources. To provide reliable and useful predictions, these four features need to be measured both locally and globally:

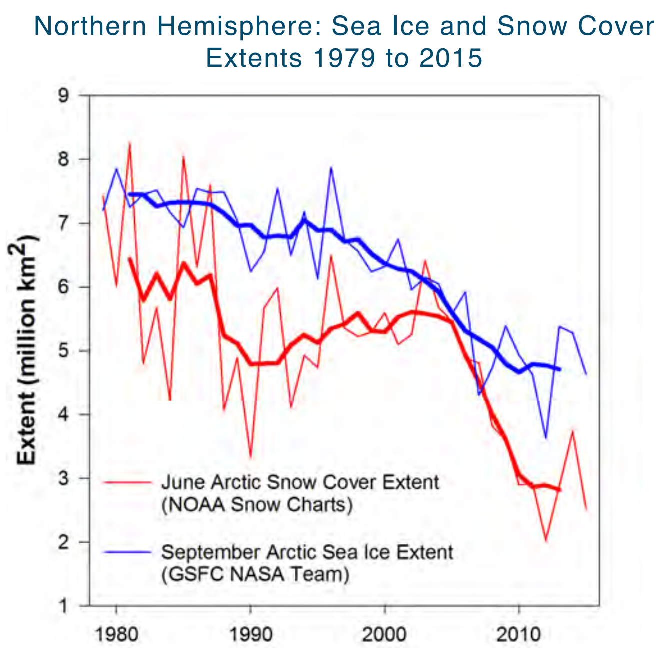
1. The areal extent and location of the snow (square miles)
2. How long the snow lingers (days)
3. The depth and water equivalent of the snow (inches)
4. How the snow is changing

Since the 1970s, much of Earth has been mapped for extent of snow cover albeit at coarse spatial resolution. Largely based on instruments that work in the optical wavelengths, these data clearly document a sharp decline in June snow cover extent (see graph on page 12).

The water equivalent of snow is also changing rapidly, but remote sensing capabilities are not yet adequate. Improving our ability to reduce the unknown is essential for water managers, farmers, stakeholders, climate modelers, and the public. Accurate knowledge of trends could warn us of impending problems.







This graph shows sea ice and snow cover extents for the Northern Hemisphere from 1979 to 2015. The thick lines are 5-year running means. Snow cover extent is for June (red) while the sea ice extent is for September (blue). Although both experienced overall declines, the June snow cover decline exceeded September sea ice decline. Image adapted from Derksen and Brown 2012.

The Challenge of Monitoring Snow

Why have adequate snow remote sensing capabilities not yet been developed?

1. The remote sensing products need to have extremely high resolution for application to local water resource and flooding issues, while also supporting global coverage.

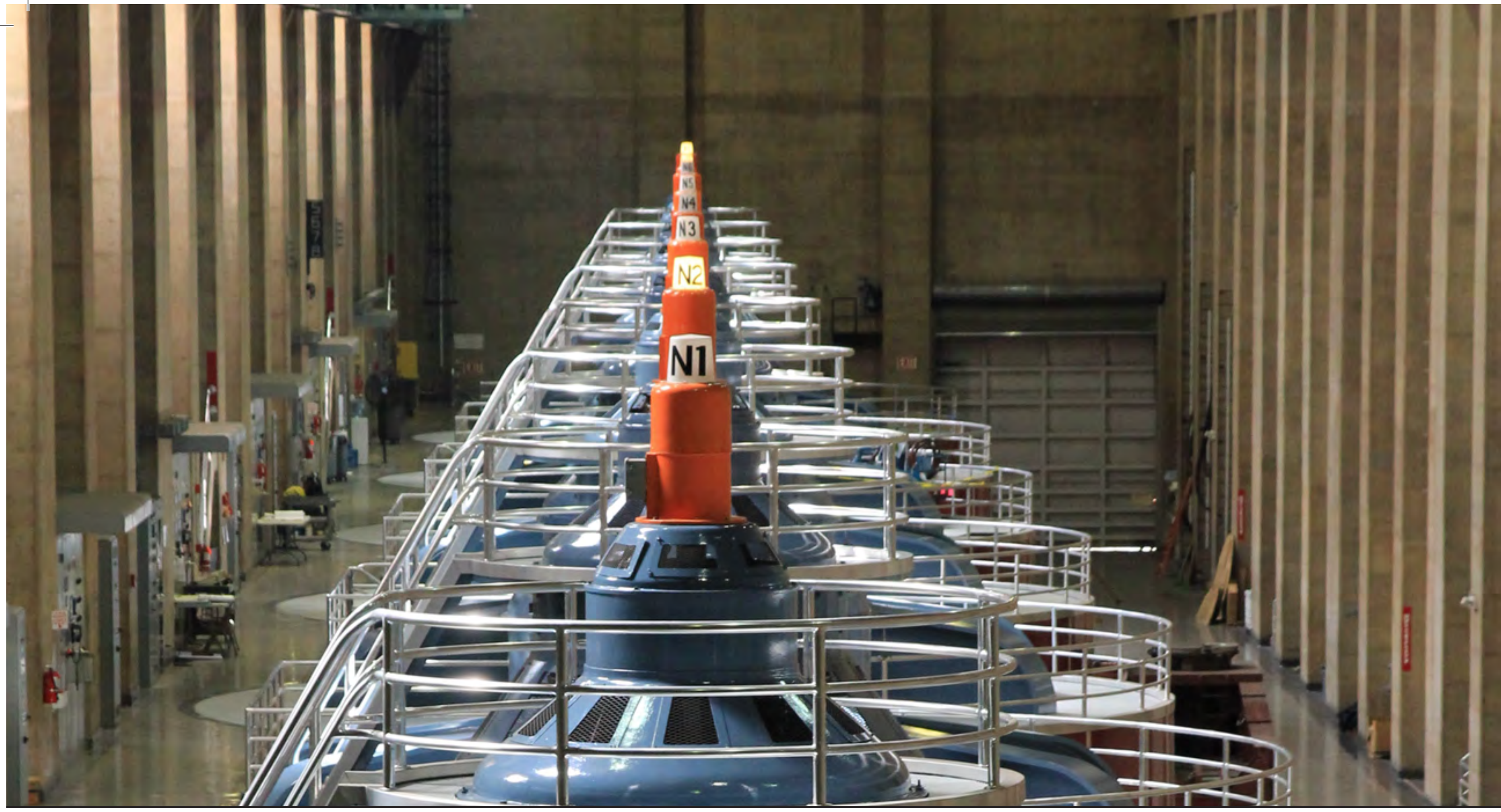
2. Necessary information often requires penetrating the snow surface and probing the properties of the full snowpack depth.

3. It is difficult to collect surface observations at the spatial and temporal resolutions needed to properly calibrate retrievals of snow properties from remote sensing. Snow water equivalent (SWE) is the most critical metric for water resources. Snow contains 40 to 95 percent air. Obtaining an accurate measure of SWE requires either measuring snow mass or determining both the snow's density and its depth (depth times density equals SWE).

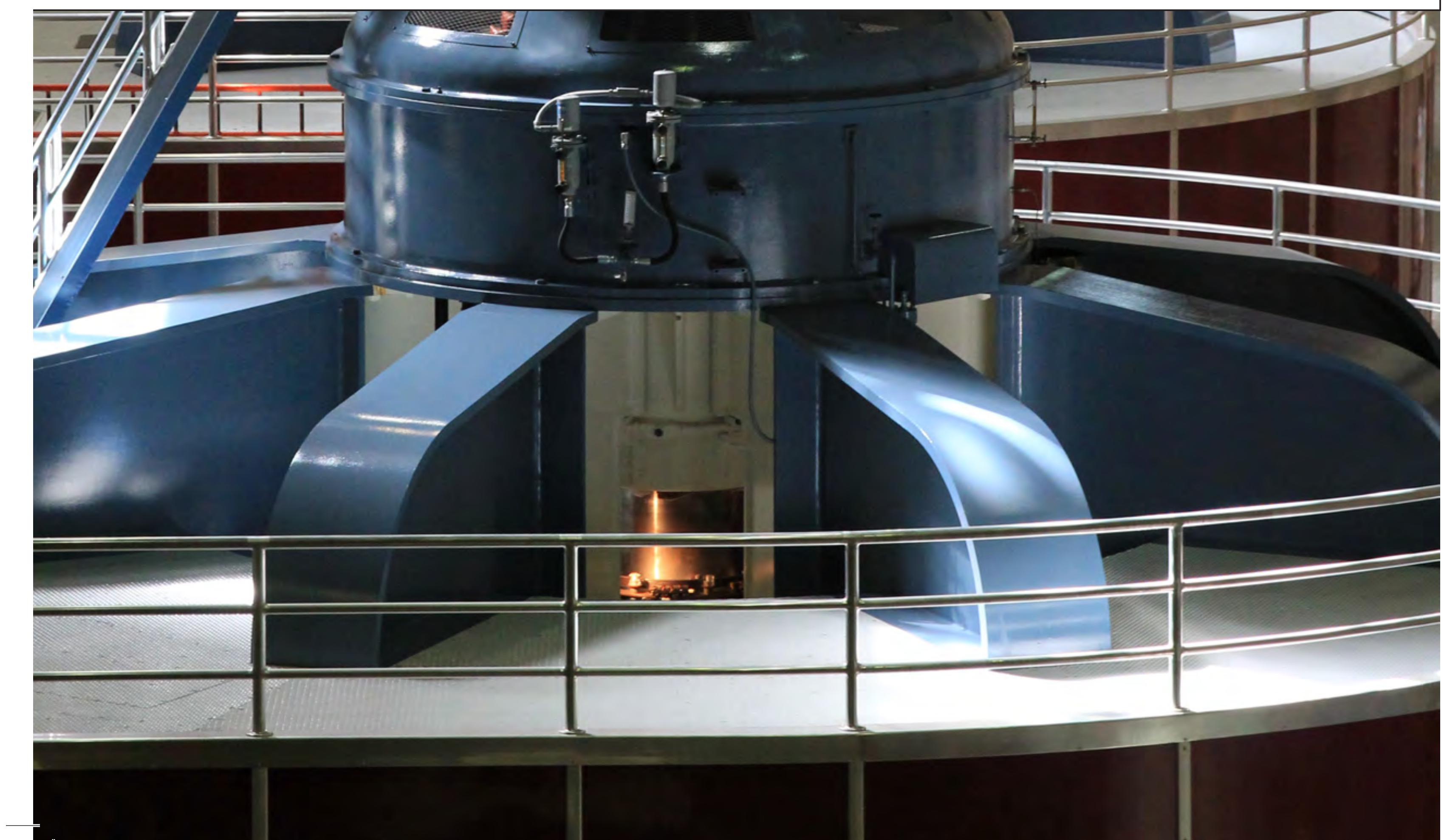
Microwave measurements can estimate SWE. However, accuracy has proven elusive, in part because microwaves respond to water and ice present in the soil beneath the snow. Moreover, microwave signals are very sensitive to any liquid water within the snow, which is always present during the melt period. Thus, microwave remote sensing instruments become "blind" during the melt period.

Another challenge is that snow depth and SWE fluctuate throughout winter. The shallow, low-density snow cover of October has little in common with the deep, dense snow at winter's end. Brief weather events like high wind, rain-on-snow, or warm sunshine can alter snow conditions in hours. Hence, it is not enough to have few and infrequent measurements.

But there is good news. Snow scientists around the world agree that if current sensors are used in clever and synergistic ways, the needed information could be provided. Getting to that point, however, requires ramping up the research effort, and funding a targeted series of field and laboratory studies to identify and develop the best sensor combinations, and the optimal way to use them. The U.S. and international science communities have been working together to design and implement a strategy for improved snow remote sensing that we are confident will succeed.



As a low-cost, non-polluting energy generator, hydroelectricity is a coveted power source. Low water flow, however, means less electricity. For instance, the California drought has cost the Hetch Hetchy Power System, which powers much of San Francisco, about $15 million. On average, the system generates 1.6 billion kilowatt hours of energy each year. Its turbines produce $7.7 million worth of energy to sell to irrigation districts and another $8.3 million on the open energy market. In 2015, there was only enough to power the city, and to sell $1 to $2 million to irrigate districts.



What We Need to Know About Snow

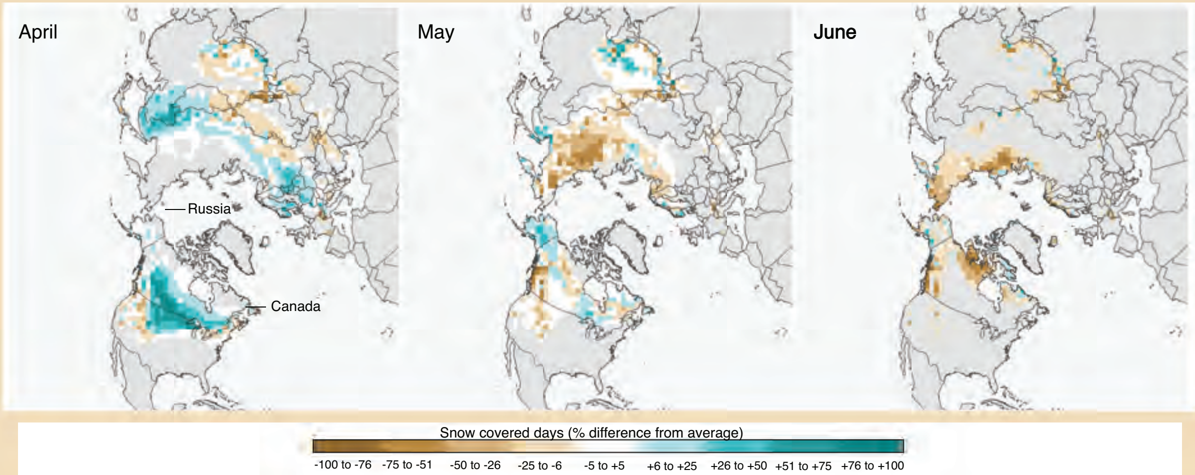
Knowing SWE is key for water conservation and allocation, and for assessing wildfire risk. Current remote sensing technologies for SWE include the attenuation of gamma rays emitted by the soil under snow, passive or active microwave emissions, and various methods of assessing snow depth, which is then multiplied by a known or assumed density. At coarse spatial scales (50 km blocks), SWE can be determined from detecting subtle changes in Earth's gravity. Unfortunately, none of these technologies has reached a state of operational readiness and reliability.

For ecology, knowledge of snow depth is critical. Deep snow is an effective insulator, keeping the ground warmer than the air above. Snow protects plants from winter kill, but its insulating effects can also accelerate permafrost thawing. Deep snow poses challenges for large herbivores like elk, moose, and caribou by inhibiting their mobility and grazing. Snow depth can be measured remotely using airborne (and perhaps satellite) scanning lasers and altimeters, or using photogrammetric methods by differencing elevations of snow-free and snow-covered surfaces.

For climate, the extent and reflectivity (albedo) of snow is crucial. Most natural Earth surfaces (like soil and vegetation) absorb about 80 percent or more of solar energy, which results in warming, while fresh snow absorbs only about 10 percent, which helps in cooling. Less snow leads to more solar energy absorbed, further promoting warming and less snow in a feedback loop. Extent and reflectivity can be monitored remotely from aircraft or satellite, one technology in which we already have reasonable skill.

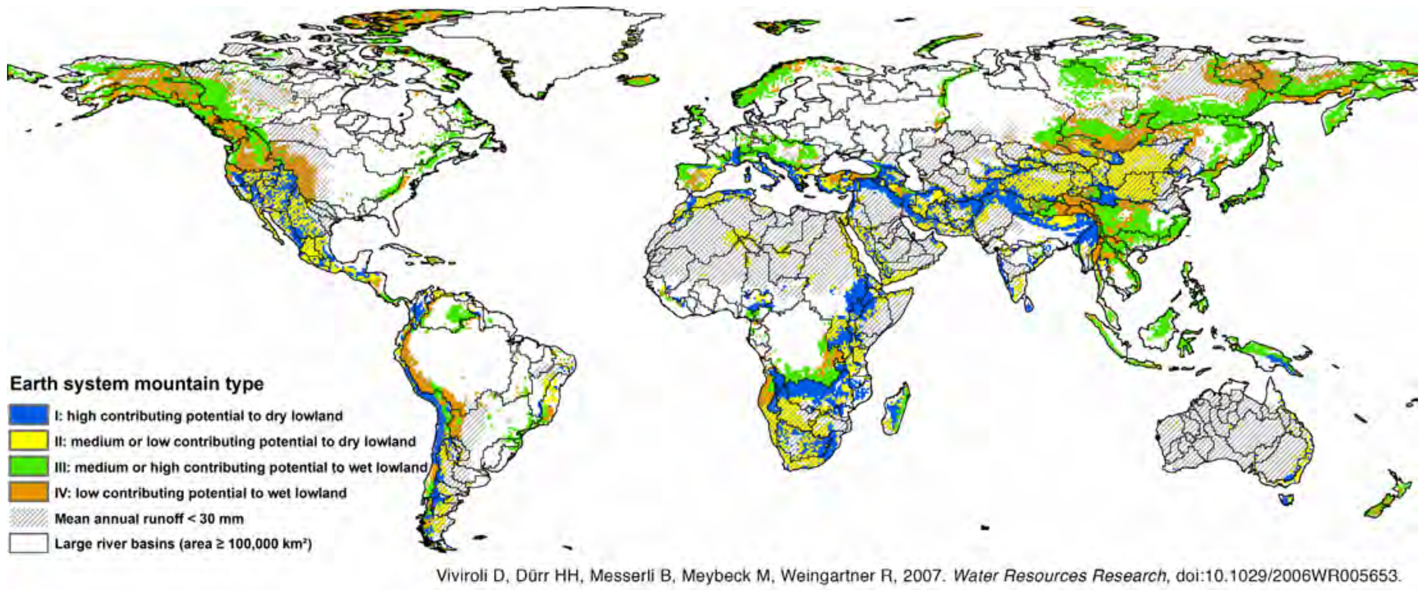
Other important attributes of the snow cover remain difficult or impossible to measure, such as snow contaminants, like soot and nitrate, snow strength (important for avalanche forecasting and military traffic ability assessments) and snow permeability (important for crop and soil ventilation beneath snow). However, combining existing and future remote sensing technologies with improved models may also allow us to infer these things, and to improve snow knowledge for hydrology, ecology, and climate.

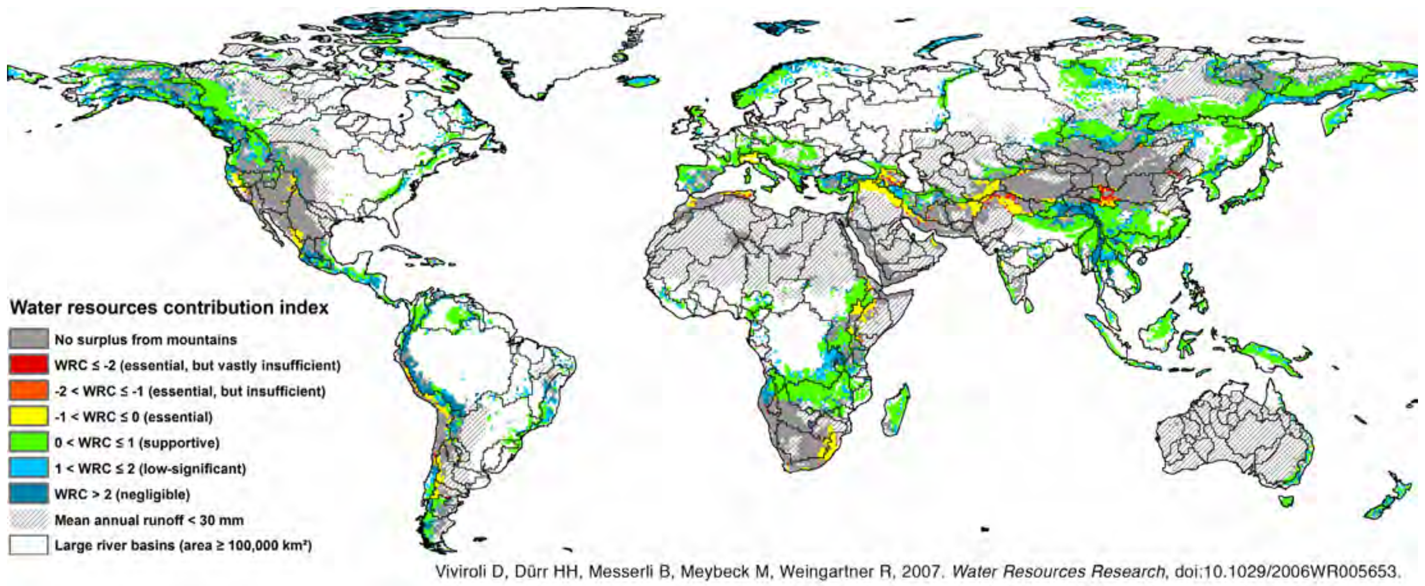
Spring 2013 Snow Cover Days Anomaly Maps



Areas that experienced up to 100 percent fewer snow-covered days than the long-term average (1981 to 2010) appear in brown, and areas that experienced up to 100 percent more snow-covered days than the long-term average appear in blue-green. Credit: NOAA's Climate.gov Web site, based on data provided by Dave Robinson and Tom Estilow, Rutgers Snow Lab.

Global Mountain Types and Water Contribution



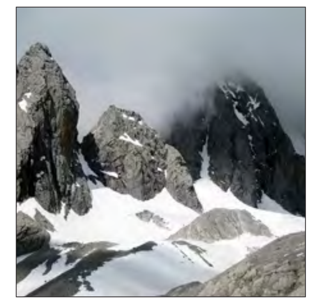


These global maps show Earth's mountain types (above) and water contribution (below). Areas with an annual runoff of less than 30 millimeters are subject to increasing uncertainty and therefore displayed in hatch marks. Credit: Viviroli D, et al., 2007. doi:10.1029/2006WR005653

Location, Location, Location...

The technical challenges of snow remote sensing are formidable, and cannot be achieved from a "universal" solution or single sensor. However, by dividing the world's snow covers into four types, we can use a "divide and conquer" strategy, matching the appropriate tools to each snow type. In increasing order of remote sensing difficulty, there are four regional types of snow:

- **Prairie and tundra snow.** Thin snow over sparse vegetation and flat terrain, with deeper dunes and drifts due to wind.
- **Mountain snow.** Deep snow in steep and highly varied terrain: extreme spatial heterogeneity.
- **Sea ice snow.** Thin snow over mostly flat ice floes, but also over rubble ice; in both cases the underlying ice greatly complicates interpreting the remote sensing signal.
- **Forest snow.** Tree canopies can overwhelm the signal from the snow on the ground below the trees.

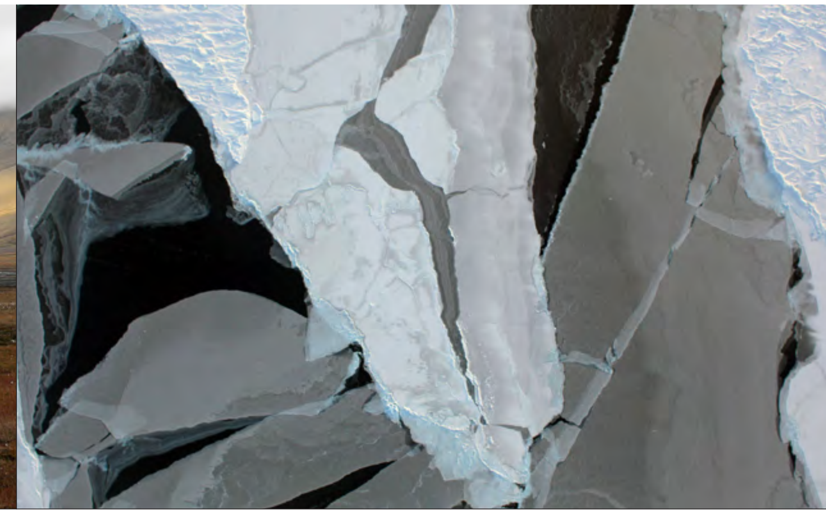



Prairie and tundra snow

Prairie and tundra cover over 32 million square kilometers, or about 21 percent of the land surface area of the planet. The generally thin (20 to 60 cm) snow cover in these areas lasts weeks to as much as nine months of the year. With current technology, we are unable to determine whether the dramatic decrease in June snow extent (see graph page 12) is due to earlier melt because of less SWE, due to higher spring temperatures, or a combination of both.


Mountain snow

Mountain snow tends to be deep, up to ten meters in maritime ranges, and thus often exceeds the saturation limit for microwave-based methods for determining SWE. Steep slopes, widely varying exposure, and substrate ranging from rock to organic soil also confound microwave signals. Airborne lidar and photogrammetric techniques, with their high resolution, show promise but the trade-off is limited spatial coverage, precluding measurement over large areas. In mountain snow, measuring both the SWE and albedo is critical so as to understand how the timing of melt is changing.




Sea ice snow

At their respective mid-winter peaks, sea ice in the Northern and Southern Hemispheres covers a combined 35 million square kilometers, and the ice is usually covered by snow. The dramatic decline of summer Arctic sea ice is well known, but the decline of snow on sea ice has been equally rapid (a loss of between 37 and 56 percent). Snow on sea ice governs both ice thickness and ice albedo. We need to know snow depth and its reflectivity to model the ice. Unfortunately, snow microwave remote sensing is complicated because there is little microwave contrast between sea ice and overlying snow. Salt brine at the snow-ice interface introduces additional difficulties. We need spatially and temporally continuous, high-resolution observations to better understand why snow on sea ice is declining.


Forest snow

The boreal forest (taiga) is Earth's largest terrestrial ecosystem, covering about eleven million square kilometers with snow cover that lasts six to nine months a year. An estimated four million square kilometers of forest in the mid-latitudes have related snow properties. These forest snow covers play a crucial role in global biogeochemical and ecological cycles. Studies have linked snow accumulation in mid-latitude forests to forest health. Throughout forests, rising temperatures and earlier spring snowmelt have increased the frequency of forest fires. Our ability to measure snow in forests has been limited because existing remote sensing technologies cannot see snow through tree canopies. This makes forest snow the most challenging for remote sensing.

The Way Forward

The United States and international snow science communities advocate adopting the following path as the way forward to more effective snow remote sensing.

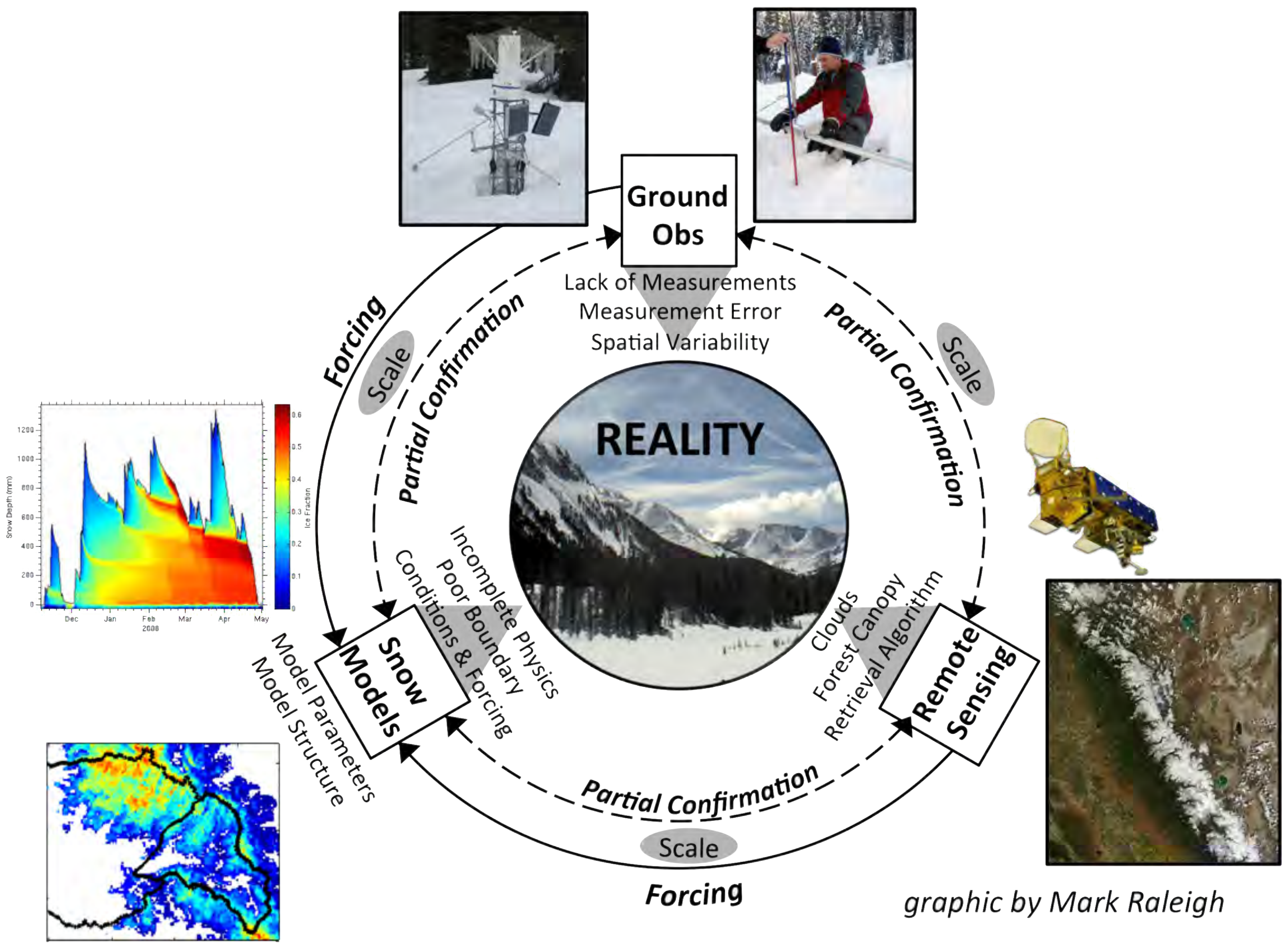
1. Launch a focused set of field campaigns, including extensive surface-based observations, to evaluate how to best combine different remote sensing technologies. These activities will allow scientists, stakeholders, and decision makers to evaluate trade-offs between technologies for each kind of snow. It will galvanize the community into concerted action.

2. Craft different remote sensing solutions for different types of snow, specific to the practical challenges posed by each type.

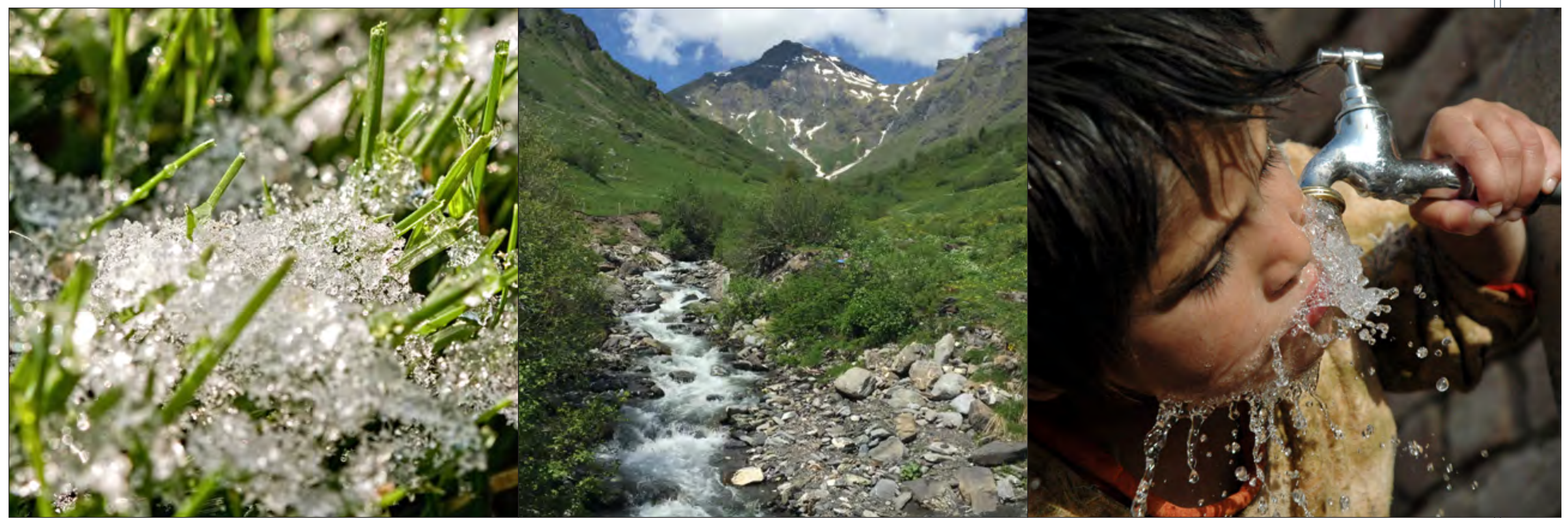
3. Use both aircraft and orbital sensors to achieve both high resolution and widespread coverage.

4. Combine the advantages of emerging technologies (e.g., lidar, altimetry, gravity) with existing technologies, and with historic records, in order to achieve higher accuracy.

5. Acknowledge the limitations of remote sensing and fill gaps (e.g., snow cover under trees) by developing and adopting an integrated data assimilation, modeling, and observation framework. This three-legged system is shown schematically in the figure below.



graphic by Mark Raleigh



Conclusion

Snow is a key component of the global climate and directly impacts billions of people. Our planet's snow cover is changing. We are unable to monitor and understand these changes using ground-based measurements alone and hence must rely on remote sensing. Currently no single instrument we possess is adequate. An international network of snow science communities has been working to develop a path forward. These communities have the requisite knowledge and skills to start now and make major strides—if empowered and funded to do so. As laid out in this document, the path includes:

1. Considering location as an essential input for inferring snow from remote sensing.

2. Testing promising sensors across many snow types and learning how best to use them in combination with older sensors.

3. Developing a framework to ingest remote sensing data, ground-based data, and modeling tools to produce a comprehensive product that is space- and time-filling, and which can "infer" attributes of snow that may be impossible to sense remotely.

4. Addressing the trade-off between specificity (high resolution) and coverage.

5. Putting in place a transparent and objective way to choose the best technology for space-borne deployment, should such an opportunity present itself.

Captions

Cover page: Hoar frost surfaces on a snowpack. Credit: Matthew Sturm

Page 6: Mt. Cook snow thaws into this rushing river in the National Park in New Zealand. Credit: Tony Fernandez

Page 7: (left to right) In 2012, extreme flooding in Pakistan left 14 million people homeless. In this image, a boy drinks clean drinking water provided by UK aid. Credit: Viki Francis; Sprinklers irrigate corn in Texas, U.S.A. Credit: Kay Ledbetter; The Hoover Dam and Lake Mead as seen from the new bypass bridge. Credit: Paul Gorbould

Page 8: (header) Snowfall settles around Smoke Creek, Brooks Range, Alaska. Credit: Matthew Sturm; (top down) Alfalfa grows quickly in California's Central Valley as long as it gets plenty of water. Credit: Ken Figlioli; Sunset falls on a farm in the Alps before a thunderstorm. Credit: Markus Jaschke; The bottom of Lexington Reservoir during the California drought. Credit: Christopher Hynes; The toe of the Pastoruri Glacier lies in the Peruvian Andes. It is one of the few glaciers left in the South American tropics. Credit: Karinna Paz

Page 9: The Alabama Hills are a range of hills and rock formations near the eastern slope of the Sierra Nevada in the Owens Valley in Inyo County, California, United States. This image shows the extent of the California drought as the snowpack on these mountains at this time of years typically stretches out to the valley floor. Credit: C. Edward Brice

Page 11: (left to right) A scientist measures standing water levels in the snowpack during snowmelt at Council, Alaska. Credit: Elizabeth Sturm; Snowmelt percolates out of the snowpack and freezes into icicles along the banks of the Niukluk River in Alaska. Credit: Matthew Sturm; Hoar frost forms on bushes in Fairbanks, Alaska. Credit: Matthew Sturm

Page 12: (header) Wheat sticks out of a snowpack in Jermuk, Armenia. Credit: Raffi Youredjian; (top down) Snow flakes settle on a camera bag. Credit: Matthew Sturm. A man holds a hoar-frosted grass blade in his hand. Credit: Matthew Sturm; Snow covers a prairie field in Ohio. Credit: Michael Durand; Overflow ice forms steep banks along the Sadlerochet River, Alaska. Credit: Matthew Sturm

Page 13: Snow covers lasting leaves on a tree. Credit: Jean-Marc Linder

Page 14: Inside the Hoover Dam, turbines turn to generate hydroelectricity. Credit: Perry Quan

Page 15: (left) Under a setting sun, this 2014 aerial photograph shows the length of the Black Canyon. The Colorado River, trapped by the arch of the Hoover Dam, fills to form Lake Mead, which lies on the border between Nevada and Arizona. Credit: Tim Felce; (right) Taken September 2009, this images shows low water levels in Lake Mead. Las Vegas obtains 90 percent of its water from here. Credit: Raquel Baranow

Page 17: The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite has captured this natural-color image of snow cover in the Colorado Rockies. The Californian Sierra Nevada are to the left. Credit: NASA

Page 18: (top, left) Snow dusts the peaks off of Trail Ridge Road in the Rocky Mountain National Park in Colorado. Credit: Matthew Shipp; (top, right) In autumn, tundra colors in Svalbard turn rust and red. Svalbard is a Norwegian archipelago between mainland Norway and the North Pole, and continues to be the northernmost inhabited area. Credit: Billy Lindblom; (bottom, left) Snow settles on Yulong Snow Mountain, in Lijiang, Yunnan, China. Credit: Cheryl Leong Ee Li; Snow lingers in the summer in the Berner Oberland Mountains of Switzerland. Credit: Els/flickr

Page 19: (top, left) Arctic sea ice can take many forms, as seen in this image from a recent NASA Operation IceBridge aerial survey. Varying thicknesses of sea ice appear, from thin, nearly transparent layers to thicker, older sea ice covered with snow. Credit: NASA; A polar bear breaks through thin Arctic sea ice in the Arctic Ocean. Credit: Patrick Kelley, U.S. Coast Guard; (lower, left) Deep snow covers the Krokskogen forest floor in Norway. Credit: Randi Hausken; The forest canopy thins in winter in the Frankfurt Am Main Neu-Isenburg Forest, Germany. Credit: Michael Fingerle

Page 21: (left to right) After a light snow dusting, ice crystals form in this grass. Credit: Laura Gilmore; Snowmelt feeds this stream high in the Swiss Alps. Credit: Scott Jungling; A child drinks water from a water pipe in Afghanistan. Credit: Imal Hashemi

References

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, 438(7066), 303-309, doi:10.1038/nature04141.

Berghuijs, W., R. Woods, and M. Hrachowitz (2014), A precipitation shift from snow towards rain leads to a decrease in streamflow, Nature Climate Change, 4(7), 583-586, doi:10.1038/nclimate2246.

Brown, R., and D. Robinson (2011), Northern Hemisphere spring snow cover variability and change over 1922–2010 including an assessment of uncertainty, The Cryosphere, 5(1), 219-229, doi:10.5194/tc-5-219-2011.

Derksen, C., and R. Brown (2012), Spring snow cover extent reductions in the 2008–2012 period exceeding climate model projections, Geophysical Research Letters, 39, L19504, doi:10.1029/2012GL053387.

Flanner, M., K. Shell, M. Barlage, D. Perovich, and M. Tschudi (2011), Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008, Nature Geoscience, 4(3), 151-155, doi:10.1038/NGEO1062.

Koster, R. D., S. P. Mahanama, B. Livneh, D. P. Lettenmaier, and R. H. Reichle (2010), Skill in streamflow forecasts derived from large-scale estimates of soil moisture and snow, Nature Geoscience, 3(9), 613-616, doi:10.1038/ngeo944.

Lettenmaier, D. P., D. Alsdorf, J. Dozier, G. J. Huffman, M. Pan, and E. F. Wood (2015), Inroads of remote sensing into hydrologic science during the WRR era, Water Resources Research, 51(9), 7309-7342, doi:10.1002/2015WR017616.

Liston, G. E., and C. A. Hiemstra (2011), The changing cryosphere: Pan-Arctic snow trends (1979-2009), Journal of Climate, 24(21), 5691-5712, doi: 10.1175/JCLI-D-11-00081.1.

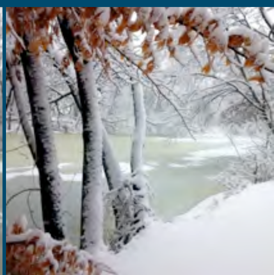
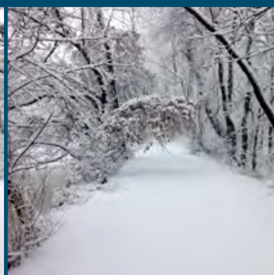
Mankin J. S., D. Viviroli, D. Singh, A. Y. Hoekstra, and N. S. Diffenbaugh (2015), The potential for snow to supply human water demand in the present and future. Environmental Research Letters, 10(11), 114016, doi:10.1088/1748-9326/10/11/114016.

McKay, G., and D. Gray (1981), The Distribution of Snow, in Handbook of Snow, edited by D. M. Gray and D. H. Male, pp. 153-190, Pergamon Press, Toronto.

Pierce, D. W., and D. R. Cayan (2013), The uneven response of different snow measures to human-induced climate warming, Journal of Climate, 26(12), 4148-4167, doi:10.1175/jcli-d-12-00534.1.

Sturm, M., and R. A. Massom (2009), Snow and sea ice, in D. Thomas and G. Diekmann (editors): Sea ice, 2nd edition, New York and Oxford, Wiley-Blackwell, 153-204.

Viviroli, D., H. H. Dürr, B. Messerli, M. Meybeck, and R. Weingartner (2007), Mountains of the world, water towers for humanity: Typology, mapping, and global significance, Water resources research, 43(7), W07447, doi:10.1029/2006WR005653.


www.nasa.gov