SATELLITE-MONITORED SNOW COVER IN WESTERN NORTH AMERICA: A COMPARISON OF WATER YEAR 2015 TO MEDIAN CONDITIONS

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ABSTRACT

Snow covered area (SCA) is readily monitored via satellites, and can illustrate complex spatial patterns of accumulation and melt that cannot be captured via point measurements. Along with its important relationship to total water supply, snow also insulates surface soil horizons, provides protection for plant root systems during freezing events, and can delay the onset of soil drying and the fire season. Traditional snow course and snow pillow measurements illustrated that the water year of 2015 saw snow levels that were substantially below normal in much of western North America. However, the determination of a 'normal' SCA pattern (and the subsequent determination of what is abnormal) for a region requires the processing and analysis of vast amounts of spatial data, and is often not logistically feasible. Using emerging technologies for processing massive spatio-temporal data, we calculated the near-term (2000-2015) normal monthly snow covered area at 500 m spatial resolution for more than 4.2 million km^2 to illustrate how the water year of 2015 departed from typical conditions in the eight major hydrologic basins of western North America. Over the 96 months/basins available for analysis, 27 new monthly minimums for SCA were recorded in the water year of 2015. The most severe departures from the near-term normals were in the more coastal and southern basins. (KEYWORDS: Remote sensing, snow covered area, climatology, snow drought)

INTRODUCTION

Snow accumulation and melt are a critical source of water for domestic, industrial, and recreational uses in western North America (Mote et al., 2005). Along with its importance as a water supply, snow also insulates surface soil horizons and provides protection for plant root systems during freezing events (Schaberg et al., 2008). Additionally, extensive snow cover can delay the onset of soil drying and the beginning of the forest fire season (Flannigan et al., 2009).

Snow depth and snow water equivalent (SWE) have been monitored at specific locations for many years in the United States (through the US Department of Agriculture SNOTEL program) and through Provincial programs in Canada (e.g. the British Columbia River Forecast Centre) and provide critical information on water availability. The water year of 2015 (October 2014 - September 2015) had exceptionally low snowfall in western North America by most measures from these agencies. United States SNOTEL summary reports indicated that all western states, including Alaska, experienced below normal April 1, 2015 SWE levels, with Arizona, California, Nevada, Oregon, Utah and Washington all averaging below 50\% of normal across all measurement locations (http://www.wcc.nrcs.usda.gov/snow/). In British Columbia, automated snow pillow sites indicated that the vast majority of the province experienced below normal April 1 SWE levels, with significant areas, particularly the southern coast mountains, at less than 50\% of normal (BC River Forecast Centre, 2015). At the most extreme, the April 1 SWE levels in California's Sierra Nevada mountains appear to be the lowest in the past 500 years (Belmecheri et al., 2015). These low snow levels likely contributed to the multi-year drought conditions in California, drought conditions in Washington, Oregon, and British Columbia during the summer of 2015, and an early onset of forest fires in BC and Alaska (Westerling et al., 2006). The water year of 2015 has been associated with exceptionally warm temperatures globally. At the time, the calendar year of 2014 was the warmest year on record (Dang, 2015), and this record was surpassed by a wide margin in 2015 (https://www.ncdc.noaa.gov/sotc/global/201513).

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Snow coverage is highly variable in space (Luce and Tarboton, 2004), and although the network of point measurements of snow depth and SWE is continually expanding, point snow measurements cannot capture the complex spatial patterns of snow accumulation and melt, and their relation to topography and landcover, that can be illustrated through remote sensing. Snow covered area (SCA) has been monitored via remote sensing in the visible-infrared spectrum for more than 35 years via a long lineage of imaging satellites, including (but not limited to) the range of Landsat and GOES (Geostationary Operational Environmental Satellite) satellites, AVHRR (Advanced Very High Resolution Radiometer), and more recently the MODIS (MODerate resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imaging Radiometer Suite) instruments.

Comparisons between current observations and the long term normal SWE is common for point-scale snow course and snow pillow data; however, the logistical difficulties in obtaining and processing large amounts of spatial snow cover data means that there are few examples where the 'normal' patterns of SCA have been determined (e.g. Brown, Derksen, and Wang, 2010; Zhou, Aizen, and Aizen, 2013). Knowledge of the typical monthly cycle of SCA would allow for the identification of trends and anomalies in SCA over time and allow us to put exceptional years, such as the water year of 2015, into a historical context.

New cloud-based technologies, specifically designed for manipulation of vast amounts of spatial data, have emerged that make these types of temporal analyses simpler. Google Earth Engine is a cloud-based remote sensing data repository and computation platform intended for rapid, global scale geospatial analysis. In this study, we used Earth Engine to analyze large spatial datasets in ways that were not previously feasible. Our specific objectives were to 1) Determine and map the near-term SCA normals and water year 2015 in the major basins of western North America at 500 m spatial resolution; and 2) Use these normals to place into context the SCA for the drought water year of 2015.

METHODS

Snow covered area, from the MODIS instrument on board NASA's Terra satellite, was used to quantify snow cover for each of the major Pacific-draining river basins of North America on a monthly time step (Figure 1). Basin boundaries were obtained from the Commission for Environmental Cooperation (http://www.cec.org/Page.asp?PageID=924&ContentID=2866); smaller coastal watersheds were merged and then manually divided into three regions: North Coastal (north and west from the southern end of the Alaska panhandle), Mid-Coastal (from the north side of the mouth of the Columbia River to the Alaska panhandle) and South Coastal (everything south of the Columbia River).

The 500 m resolution MODIS binary snow cover product used in this analysis (MOD10A1) has been shown to be approximately 93% accurate globally (Hall and Riggs, 2007), however, accuracy is likely influenced by forest coverage. The snowcover classification employed in the MOD10A1 product includes an adjustment in the classification threshold in areas with normalized difference vegetation index (NDVI) values greater than 0.1 (Klein and Hall, 1997); however, this adjustment is based on an assumption of snowcover under forest canopy, which may not always be accurate (Rittger, Painter, and Dozier, 2013).

The daily return period of the MODIS instrument on board NASA's Terra satellite allows for enough observations to overcome the significant amount of cloud cover that can be seen in western North America, particularly in the winter months. Monthly median binary SCA from MODIS-Terra was calculated using the Google Earth Engine JavaScript playground (https://earthengine.google.org/#intro). Google Earth Engine's parallel, cloud-based computing allowed for pixel-by-pixel calculations and mapping of the entire area of interest. This process would be logistically difficult using more common geoprocessing techniques on a local workstation.

The monthly median SCA was calculated for each 500 m pixel for the visible (non-obscured) pixels for the entire period of record (2000 to 2015) and for each individual year. Though 15 years of data is too short of a period to truly calculate an SCA normal, the data do provide an indication of the typical recent conditions and a smoothed picture of the snow cover cycle. We refer to this 15 year median as the near-term normal, and we produced high resolution maps and calculated basin scale statistics of the monthly cycle of SCA in this time period. We used these basin level statistics to investigate the range in interannual variability and assess how the water year of 2015, which by most other measures was a very low snow year, related to more typical SCA conditions.

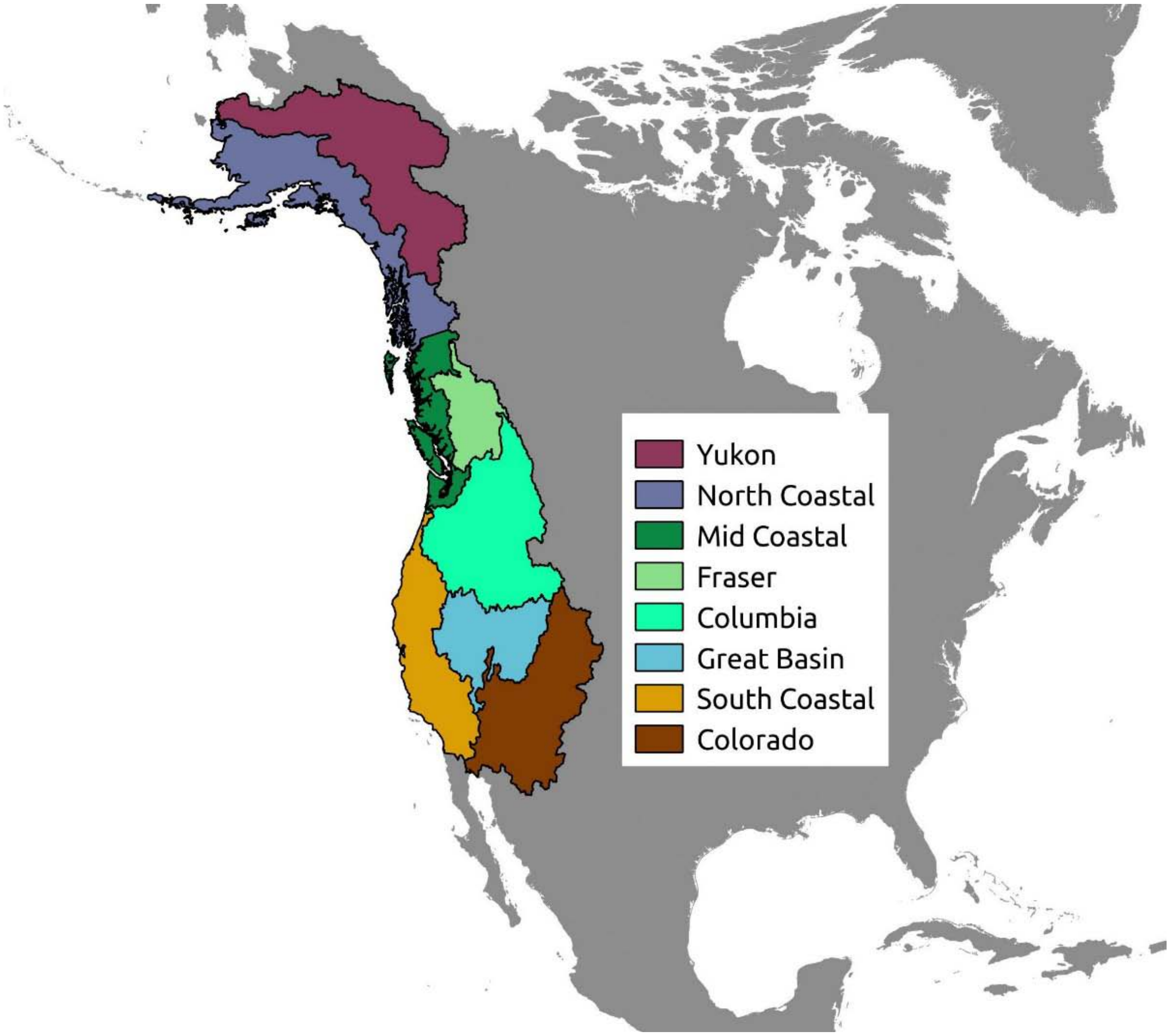

Figure 1. The major Pacific-draining basins of North America. Data obtained from http://www.cec.org/Page.asp?PageID=924&ContentID=2866.

RESULTS AND DISCUSSION

Monthly median and water year (WY) 2015 is shown by basin in Figure 2. The summer snowcover seen in the North and Mid Coastal, and to a lesser extent, the Yukon, Fraser and Columbia basins, is indicative of glacier coverage. In addition, a large portion of the Yukon River basin and a small portion of the North Coastal region does not experience daylight during much of December and January, hence those results may be slightly less reliable. We give the percent coverage for these regions based only on the visible areas. To place the near-term normal in a longer term context, the 2000 to 2015 time period has generally been associated with the cold phase of the Pacific Decadal Oscillation (PDO, Mantua and Hare (2002)) particularly in the decade from 2000 to 2010 (https://www.ncdc.noaa.gov/teleconnections/pdo/). The cold phase of the PDO is generally weakly positively (negatively) correlated with snow levels at low (high) latitudes in western North America (Mote, 2006).

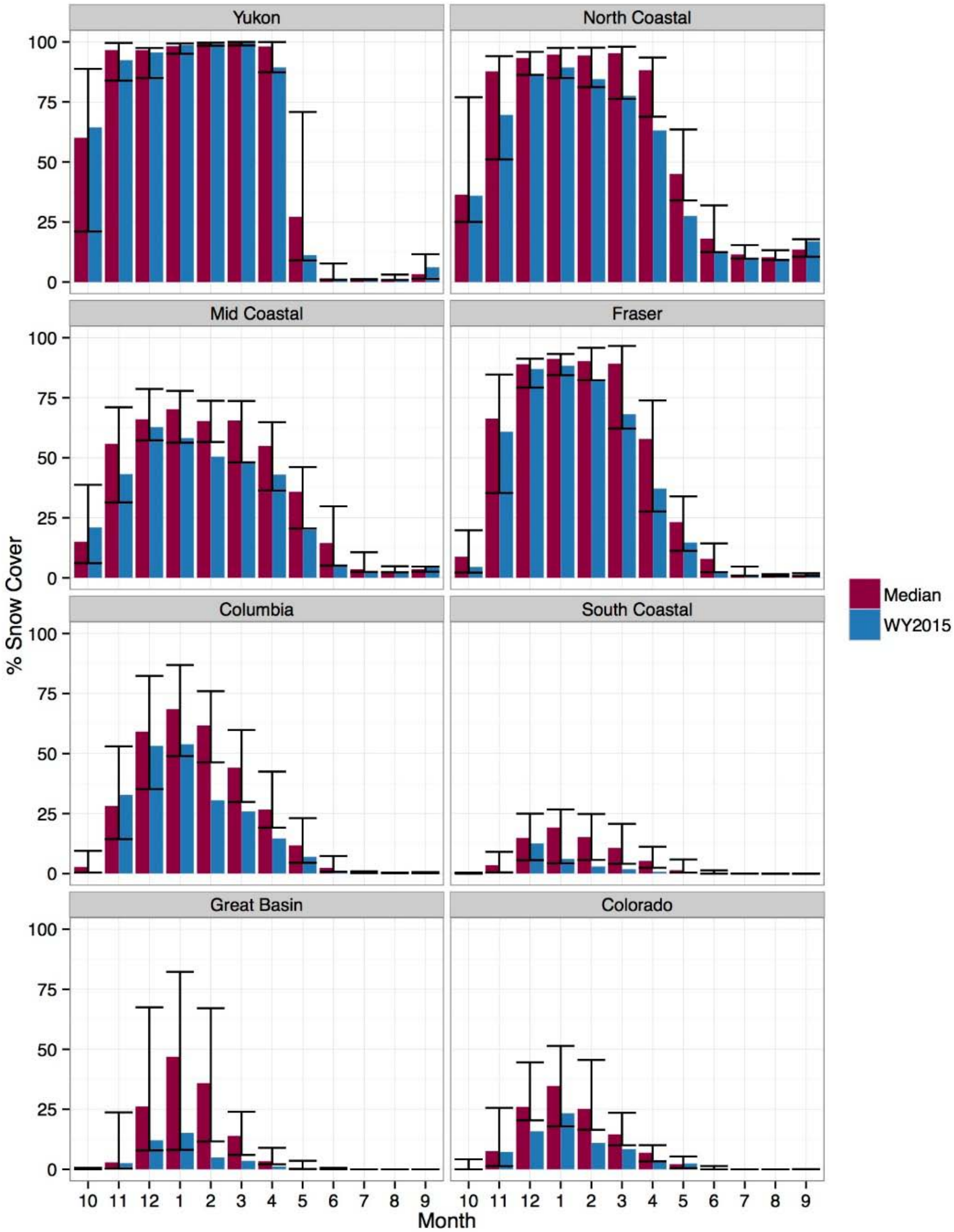

Figure 2. Median and water year 2015 cycle of snow covered area for the major Pacific-draining watersheds of North America. Error bars indicated the maximum and minimum observed SCA (prior to 2015) for each basin.

Across basins and months, the Yukon River was the only basin that experienced a typical snow cover cycle for the 2015 water year, with October, January, August and September above median SCA for the basin. September 2015 was the only month with at least half of the basins (Columbia, Fraser, Mid-Coastal, and Yukon) above median levels, though the median SCA during this month is low for all basins. Water year 2015 resulted in below median snow cover levels for the majority of the time in all other basins and all other months, with only May in the

Colorado River, November in the Columbia River, October in the Mid Coastal region, and August in the South Coastal region above median levels (note that the median for August in the South Coastal region is essentially 0% coverage). In total, 27 new minimums were experienced in all basins over the 96 months/basins analyzed in water year 2015 (Table 1). February 2015 experienced the most new minimums, with all but the North Coastal region and Yukon River basins experiencing new minimum SCA during this month.

Table 1. Months during WY 2015 that were below the previous minimum SCA for the observed period (2000 to 2014).

	Month											
Basin	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Colorado River			X		X	X						
Columbia River					X	X	X			X	X	
Fraser River					X					X	X	
Great Basin					X	X	X					
Mid-Coast					X	X		X	X	X	X	
North Coast			X				X	X	X	X		
South Coast					X	X	X	X				
Yukon River												

As a whole, the South Coastal region and Great Basin appear to have the most significant departures from normal, corresponding with the historic drought levels in the state of California. Despite the fact that these basins have low median SCA fractions during the winter months, even during normal winters, snow melt from the Sierra Nevada mountains (in the Great Basin) is critical to the water supply of the state of California (Belmecheri et al. 2015). Though the Mid- and North Coastal regions do not appear to have as large of departures as the southern regions, in certain months they experienced absolute decreases of more than 6\% below the previous minimums for the WY 2015. In the North-Coastal region, this represents a decrease of more than 46000 km^2 (for May 2015) and in the Mid-Coastal region this represents more than 15000 km^2 (for February 2015). The large expanse of snow-free land area in the North and Mid-Coastal regions illustrates the sensitivity of coastal zones along the rain-snow temperature threshold. Mapping of the March 2015 snow cover overlaid upon the median (2000-2015) March snow cover for Southwest British Columbia (BC) and Northwest Washington (Figure 3) illustrates this decrease in more detail in the Mid-Coast region. Vancouver Island shows a marked difference in snow cover, while the southern Coast Mountains on BC's mainland, are generally higher relief, contain more alpine areas, and do not display as large of a difference in total snow cover. Loss of snow cover in forested areas is critical ecologically, leading to loss of insulation for tree roots from late season freezes, drying of fuels for potential forest fires, and changes in food availability for forest-associated animals. The level of spatial detail shown in Figure 1 (which is also available for all months for the full region), opens up potential for many different types of spatial analysis, including correlation between snow cover and fire start locations, and vulnerability assessments of tree die-off or tree disease mapping.

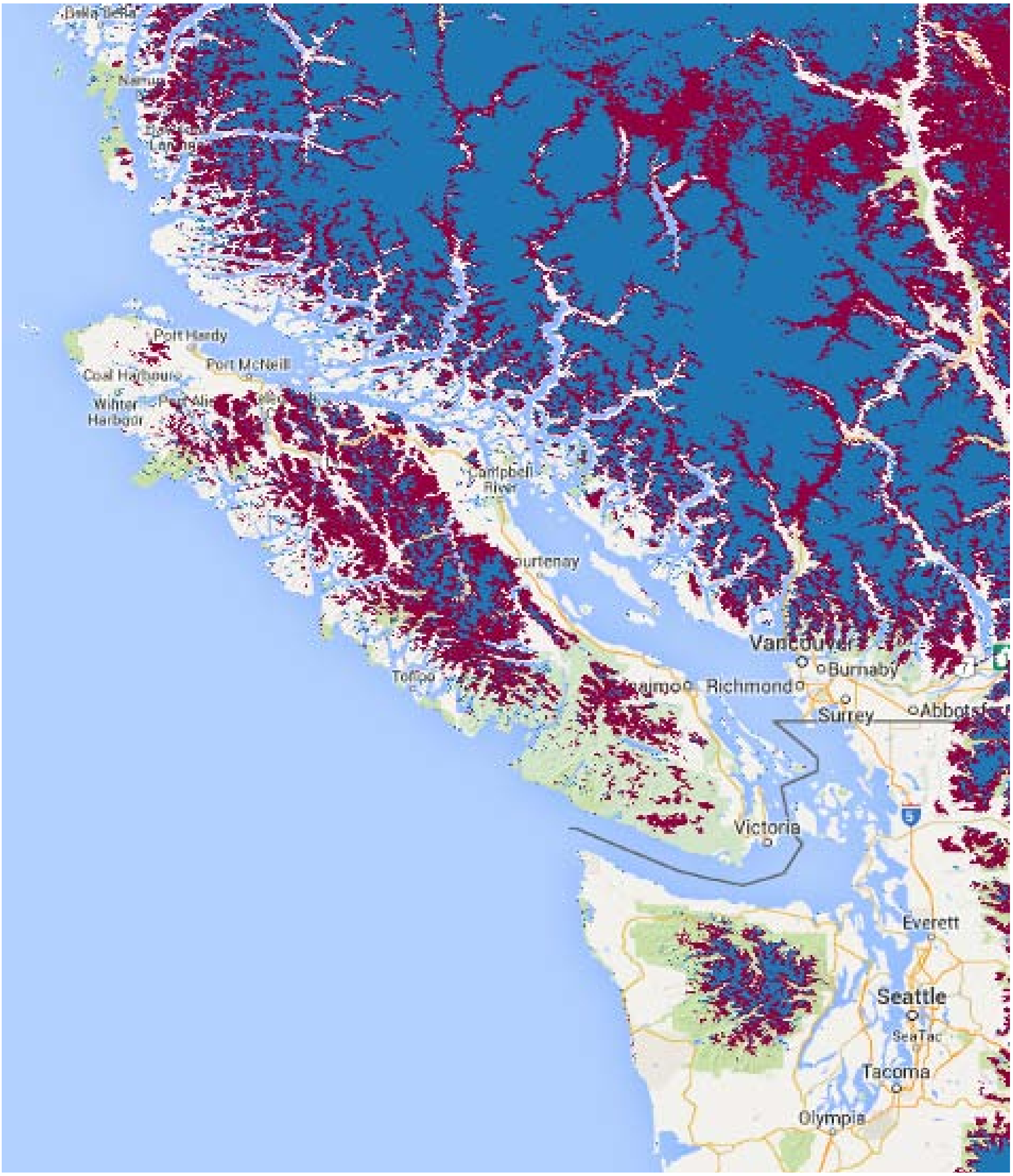

Figure 3. March 2015 snow cover overlaid upon the 2000-2015 March median snow cover for Southwest BC and Northwest Washington at the native 500 m resolution of the MOD10A1 snow cover product. Base map from Google.

CONCLUSIONS

The water year of 2015 saw new minimums in snow covered area over many months across several drainage basins of Western North America. The new minimum SCA levels experienced in the water year of 2015 contributed to a stressed water supply in many regions of western North America, and contributed to ongoing drought in California. Along with the implications for water supply, snowcover has other important functions that were likely impacted in 2015 and may be repeated in future years as the climate changes. Persistent snowcover delays the onset of fuel drying and impacts fire danger; additionally, mid-winter snowcover can insulate soil and root systems from short term freezing.

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