THE WATER YEAR 2015 SNOW DROUGHT IN WASHINGTON STATE: WHAT DOES IT TELL US ABOUT FUTURE DROUGHT RISK?

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ABSTRACT

In many locations across the Washington State, the 2015 water year exhibited some of the lowest snow accumulations in the observational record. The low snowpack conditions, both in the Cascades and more broadly across the Northwest, set the stage for summer drought conditions that had negative impacts on water supplies, especially for agriculture, ecosystem health, and hydroelectricity production.

This paper presents data from SNOTEL stations throughout the Washington Cascades, illustrating the pervasiveness of low-snowpack conditions for the 2015 water year. Based on the SNOTEL records and observations of temperature and precipitation at meteorological stations in the region, it is clear that temperature was the driver of low-snowpack conditions, with a large proportion of the winter precipitation being delivered via atmospheric river events with high freezing levels.

Comparison of the seasonal temperature anomalies to future projections shows that the 2015 water year is a good analog for average temperatures around the mid-21st century. At the same time, aspects of the atmospheric circulation that helped contribute to the anomalous warmth and the paucity of cold storms resemble recognizable patterns of natural atmospheric circulation variability. The particular pattern evident in the 2015 water year (the Pacific North American pattern) is likely to continue to play an important role in the interannual variability of snowpack.

Information about future climate often focuses on changes that are tied to forcing from greenhouse gas emissions, and omit information about interannual circulation variability. Given that 2015 illustrates the important role that this variability can play in contributing to snow conditions, the paper recommends a more integrated approach when communicating to water managers about future 21st century snowpack conditions. (KEYWORDS: drought, climate change, Washington State, atmospheric river, 2015)

INTRODUCTION

Much of the western U.S. struggled with low snow conditions during the water year 2015 (October 1, 2014 – September 30, 2015; “henceforth WY 2015”). For the Washington Cascades, season-ending snowpack as measured by April 1 snow water equivalent (SWE) was low enough to break records, and many observation locations were snow free by April 1.

During the subsequent months, the resultant low-streamflow conditions challenged irrigators, ecosystem managers, and hydropower providers. The low streamflow set the stage for significant financial losses (e.g., agricultural losses in the hundreds of millions of dollars for Washington State; WSDA, 2015), and a state-wide drought declaration. A wide range of media outlets, resource managers, and policy makers were requesting information (and in some cases, arriving at conclusions) about the potential link between the 2015 drought conditions and anthropogenic climate change.

This paper explores the aspects of the temperature, precipitation, and atmospheric circulation that contributed to the low snowpack conditions in 2015. The temperature anomalies occurring in the Washington Cascades serve as useful analogs for future climate conditions, and provide a solid “talking point” for anticipating the future impacts of climate change on snowpack. However, the atmospheric circulation anomalies that were prevalent during the snow accumulation months (December-March) do not have an apparent link to anthropogenic climate change.

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The simultaneous contributions of forced change and natural variability to the snow conditions of 2015 highlight the shortcomings of typical techniques for communicating climate change information at the regional scale. The paper recommends a more integrated way to present and discuss information for projected future climate that better captures the role of natural variability, and could be more salient for managers who place a premium on decisions for year-to-year management of water resources. In addition, the paper recommends some future research avenues that would elucidate potential relationships between circulation variability and the regional scale and global-scale anthropogenic forcing of the climate system.

SNOWPACK OBSERVATIONS

Figure 1 shows the April 1 snow water equivalent (SWE) at a variety of SNOTEL sites and snow courses in Washington State. Of the 23 basins in Washington State for which basin-averaged SWE are calculated, 19 had April 1 SWE values below the 50% of their respective long-term median value; 13 had April1 SWE values below 25% (NRCS, 2015). For many basins and observational locations, 2015 established a new all-time low for April 1 SWE.

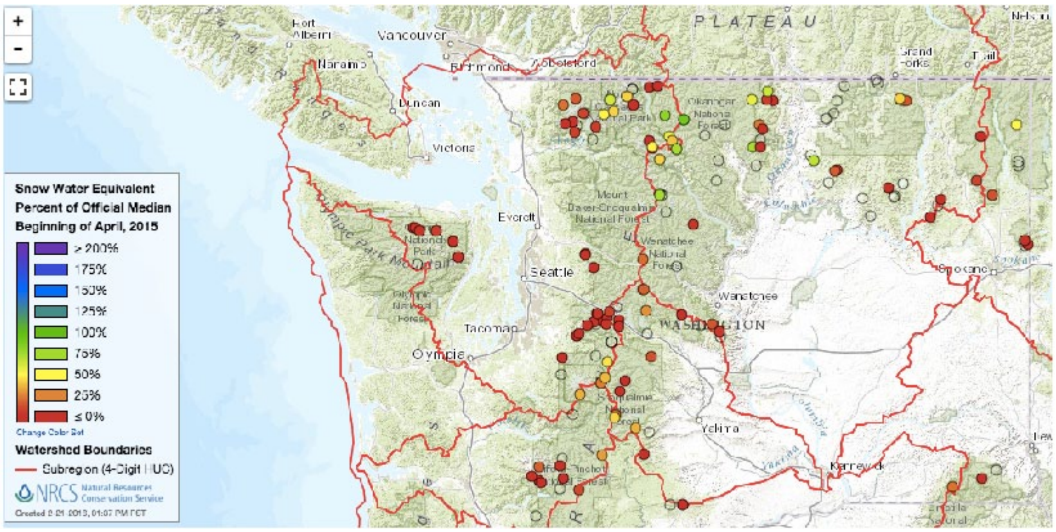


Figure 1A. April 1 SWE at SNOTEL and snow courses/aerial markers in Washington State. The panel shows April 1 SWE observations in terms of percentiles, compared to the period of record at that location. Data Source: NRCS

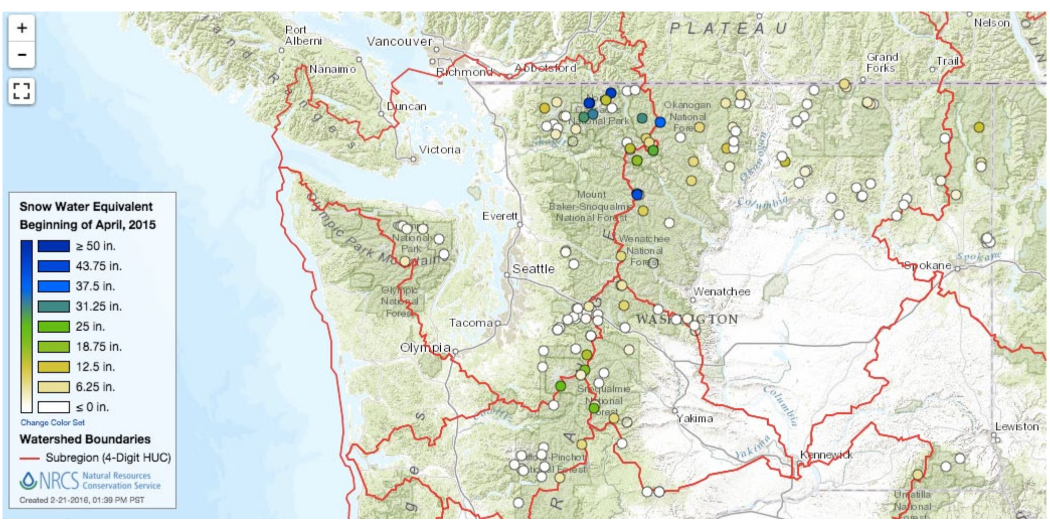


Figure 1B. The panel shows absolute SWE depths, in inches of SWE. Almost all stations exhibited snowpack well below their respective historical median values (red circles in 1A), and many stations had no snowpack by April 1 (white circles on 1B). Data Source: NRCS

Figure 2 shows six illustrative SNOTEL records from the Washington Cascades for WY 2015. From south the north, the six stations are: Lost Horse (elevation 5120 ft), Paradise (5130 ft), Stevens Pass (3950 ft), Stampede Pass (3850 ft), Park Creek Ridge (4600 ft), and Harts Pass (6490 ft). The SNOTEL stations roughly capture the latitudinal range of the conditional across the Washington Cascades. They also represent a mix of elevations, ranging from the stations near the passes (~4000 ft) to the highest SNOTEL in the state (Harts Pass).

With the exception of Harts Pass, nearly all the SNOTEL stations experienced remarkably low snowpack conditions. Lost Horse and Stampede Pass had no snow remaining by April 1; Stevens had approximately 25% of its median April 1 SWE value; Paradise had approximately 30% of its median April 1 SWE value; and Park Creek Ridge had slightly less than 50% of its median April 1 SWE value. Notably, all the SNOTEL stations received within 20% of their average accumulated precipitation for the October 1 – April 1. This disparity between accumulated precipitation and snow accumulation indicates the important role of temperature: although sufficient moisture was available at throughout the latitudinal and elevational range of the SNOTEL network, warm conditions caused much of the precipitation to fall as rain instead of snow.

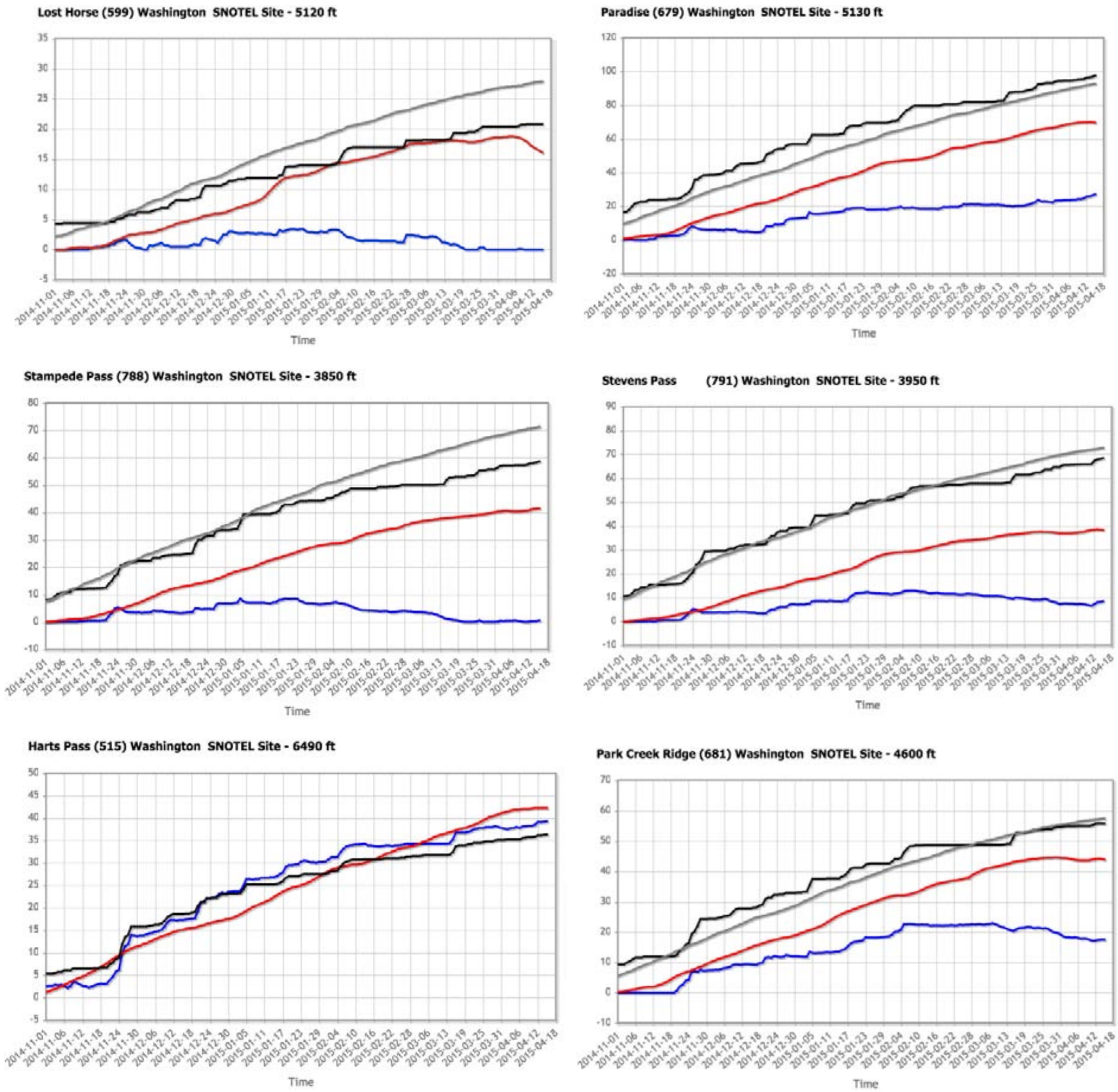
REGIONAL TEMPERATURE AND PRECIPITATION OBSERVATIONS

To place the temperature and precipitation anomalies observed at the SNOTEL stations into a broader context, data from the Washington State climate divisions are shown in Figures 3 and 4.

The warm conditions during the winter presided over the entire region, and were not isolated to high elevations. Figure 3 shows the magnitude of the monthly temperature anomalies. In all Washington climate divisions, all the months during the typical period of snow accumulation (December – March) exhibited warm anomalies relative to the 20th century mean. For January, February, and March, these anomalies were exceptional, exceeding +5°F in some of the Western Washington lowlands areas and ranging from +6-9°F in the Cascade regions. It was the warmest January-March within the observational record for Washington State.

Precipitation (Figure 4), by comparison, was close to the 20th century average. Most climate divisions exhibited weak dry anomalies for monthly precipitation. Looking across the December-March period, the deviations were within 20% of the long-term average rainfall..

Overall, the regional-scale meteorological observations are consistent with the observations at the SNOTEL sites – the lack of snow was a symptom of pervasive warm conditions, as opposed to a lack of precipitation.



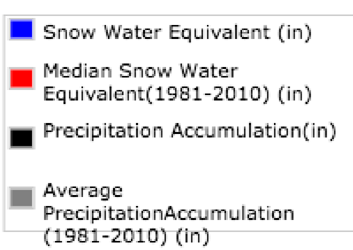


Figure 2. Example SNOTEL records from Lost Horse, Paradise, Stampede Pass, Steven Pass, Park Creek Ridge and Harts Pass. Blue indicates SWE; red indicated the median SWE, derived from historical observations; black indicates the accumulated precipitation; and gray indicates the average accumulated precipitation. Note that each graph has a different scaling on the y-axis. Data Source: NRCS.

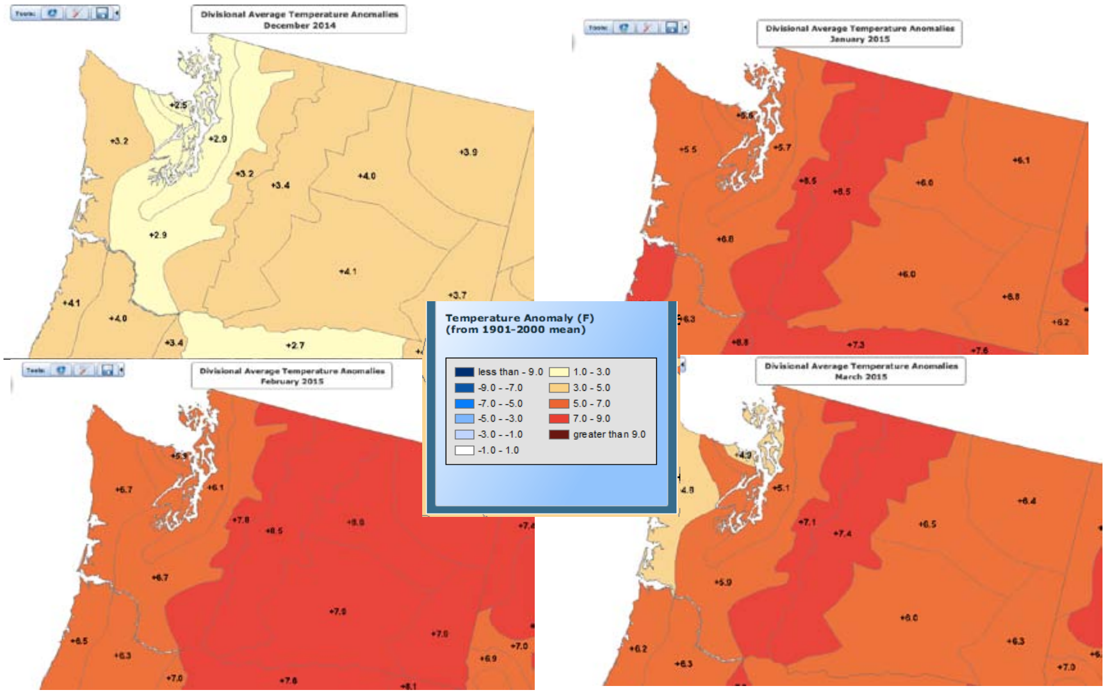


Figure 3. Monthly temperature anomalies (in °F) in Washington State for December 2014 (upper left), January 2015 (upper right), February 2015 (lower left), and March 2015 (lower right). Anomalies are calculated for each Climate Division, relative to the 1901-2000 average. Data Source: NOAA, Climate Divisions.

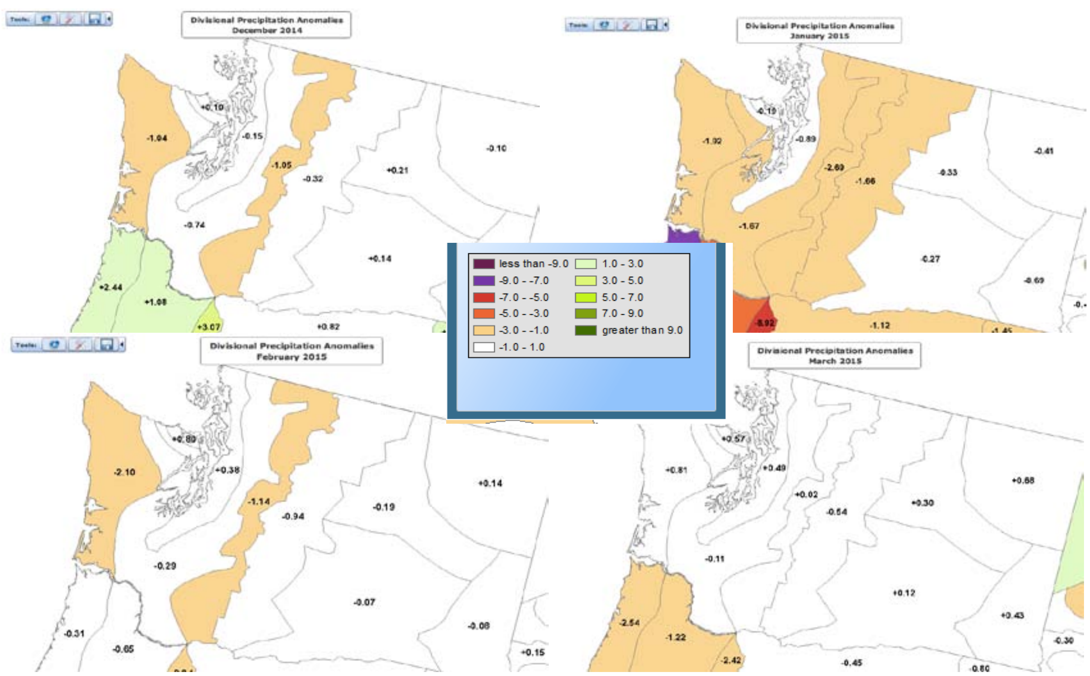


Figure 4. Monthly precipitation anomalies (in inches) in Washington State for December 2014 (upper left), January 2015 (upper right), February 2015 (lower left), and March 2015 (lower right). Anomalies are calculated for each Climate Division, relative to the 1901-2000 average. Data Source: NOAA, Climate Divisions.

REGIONAL CIRCULATION PATTERNS

Figure 5 shows the monthly geopotential heights and geopotential height anomalies for the 500-hPa surface for December 2014 - March 2015. These maps characterize the atmospheric circulation patterns that maintained the anomalously warm conditions during the months of typical snow accumulation. The 500-hPa level is considered to be the “steering level” for storms; the troughs (negative geopotential height anomalies) and ridges (positive geopotential height anomalies) found at this level of the troposphere are valuable diagnostics for thinking about the advection of air masses and the paths of storm systems. In addition, areas of strong geopotential height anomalies also correspond to temperature anomalies. Positive (negative) geopotential height anomalies denote relatively warmer (colder) temperatures, both at and below the particular geopotential surface.

While December exhibited relatively weak anomalies on the 500-hPa surface in the vicinity of and upstream from the Pacific Northwest, the subsequent winter months were dominated by strong positive anomalies (ridging) along the West Coast. The strong ridging acted to block storms from entering the Northwest, deflecting them north or south.

The persistent winter ridge pattern, as well as the upstream and downstream troughing over the North Pacific Ocean and the North American East Coast, respectively, bear a strong resemblance to the positive polarity of the Pacific North American pattern (PNA; Wallace and Gutzler, 1981). The PNA index values (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/norm.mon.pna.wg.jan1950-current.ascii.table; based on the modified pointwise method) for January, February, and March are +1.15, +0.92, and +0.64, respectively. The positive conformation of the PNA is associated with above-average temperatures in the Northwest, and relatively lower spring snowpack (Abatzoglou, 2011). The positive polarity of the PNA has been more prevalent during recent winters, contributing to a trend toward warmer winter conditions (Liu et al., 2015).

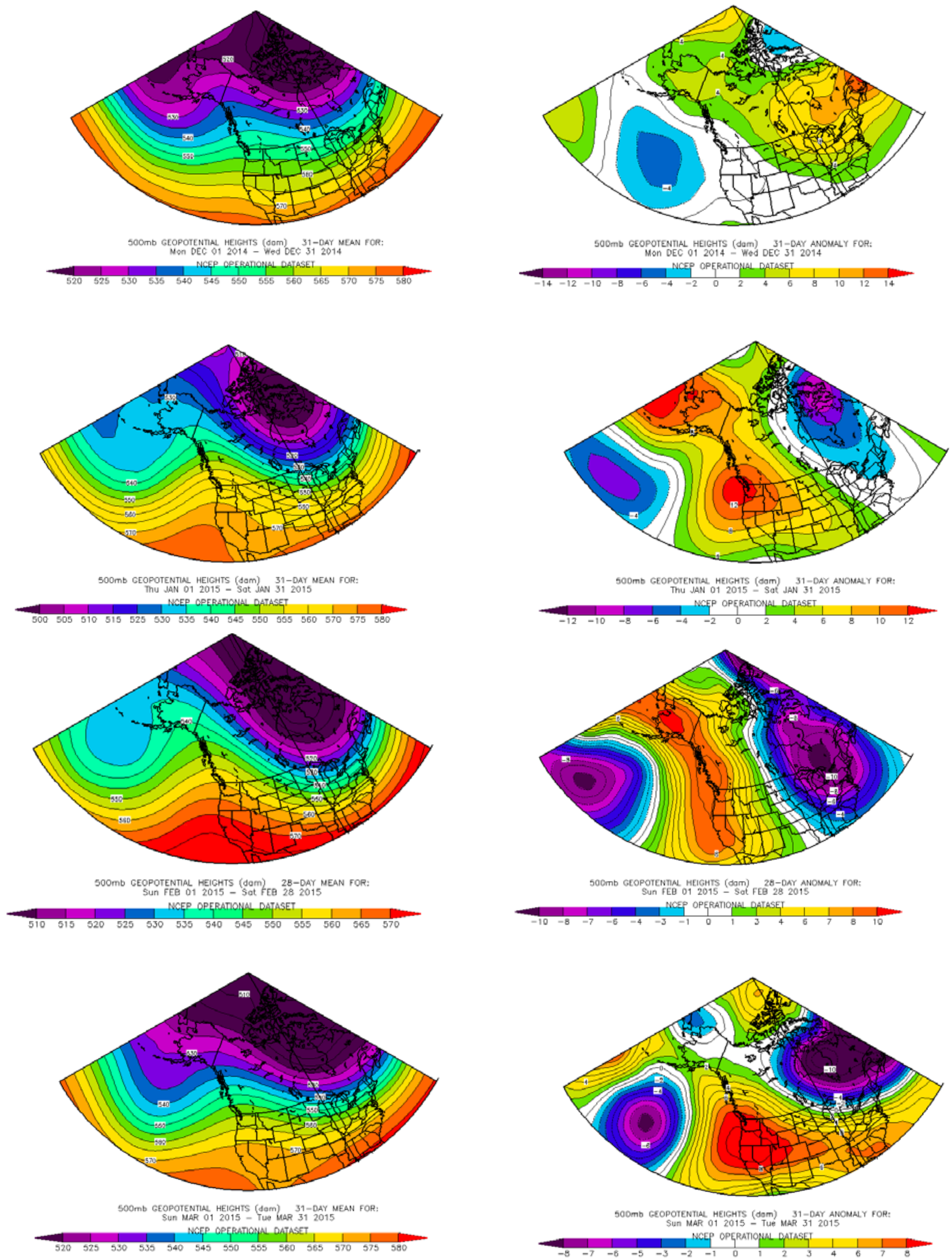


Figure 5. Maps of 500-hPa geopoential heights (left) and geopototential height anomalies (right) for December 2014 (top row), January 2015 (second row), February 2015 (third row), and March 2015 (bottom row). Data Source: NCEP.

INDIVIDUAL STORM EVENTS

Much of the material presented above focuses on the monthly and seasonal aspects of the snow accumulation season in WY 2015. To get a better sense of the individual storms that delivered precipitation to the region, it is useful to also examine imagery for the daily and weekly weather.

From two coastal stations (Quillayute, KUIL, and Hoquiam, KHQM), a set of heavy rainfall events were identified: December 8-10, December 20, January 4-5, January 23, February 5-7, March 15, and March 25. Data were accessed Weather Underground (www.wunderground.com). Two stations were chosen in an effort to capture large regional precipitation events that would affect the bulk of the north-south extent of the Cascade range. Coastal stations were chosen to avoid topographic effects (e.g., rain shadowing) that are common when viewing the daily precipitation observations for the stations farther inland, especially those within the Puget Sound.

The heavy rainfall events account for a little more than half of the accumulated rainfall during the December-March period (52% for Quillayute; 58% for Hoquiam). Examination of the corresponding satellite imagery (Fig. 6) of integrated water vapor illustrates the visual characteristics of an atmospheric rivers (Ralph et al., 2004; Neiman et al., 2008). An identifiable stream of water vapor connects the tropics to the coast of the Pacific Northwest. Although these storm events are responsible for a large volume of precipitation, the freezing levels are likely to be well above most of the elevational range of the Cascades. Evidence for this can be seen in several of the SNOTEL records (Fig. 2), where large jumps in the accumulated precipitation occur on dates during these heavy rainfall events, but the snow accumulation remains flat.

CONSIDERATION OF FUTURE REGIONAL CLIMATE PROJECTIONS

The warm temperatures experienced in the Washington Cascades during the snow accumulation months of WY 2015 (+5-7 °F compared to the 1901-2000 mean for the average of December-March period for the climate divisions in Washington State), are similar to the temperatures for an average year in the mid 21st century. (Fig. 7, left panel). Unlike the case for projected changes in temperature, the projected changes in precipitation, are likely to be considerably smaller than the historically observed interannual variability (Fig. 7, right panel). This is the case for both annual temperature and precipitation (shown in Fig. 7) and wintertime temperature and precipitation (not shown). Since this year-to-year variability is expected to continue in the future, the changes in annual or seasonal rainfall are unlikely to “stand out” in the coming decades; the region will continue to experience relatively wet and dry years and relatively wet and dry winters. Although we should not expect every water year in the mid-21st century to exhibit a dry anomaly equal to the 2015 observations, the magnitude of the 2015 anomaly is relatively small and falls well within the range of what should be expected.

Despite the fact that the seasonal temperature and precipitation experienced in 2015 are reasonable proxies or analogs for near-average conditions by the mid-21st century, the snowpack conditions for April 1, 2015 were more similar to the average snowpack conditions projected for the late 21-st century. Projected changes in April 1 SWE for Washington State are projected to be approximately -40% around mid-century and between -56% and -70% by the end of the century (Snover et al., 2013), relative to average conditions in the 20th century.

The difference in future time periods for the “best analogs” for the seasonal temperature and snowpack highlight the important impact that sub-seasonal circulation variability can have on hydrologic conditions. The persistent blocking associated with the positive PNA pattern prevented relatively colder storms from reaching the Pacific Northwest. As a result, most of the seasonal precipitation was delivered during atmospheric river events with high freezing levels. This situation exemplifies how circulation variability can enhance the snowpack anomalies that we might expect from examining seasonal temperature anomalies alone. Given that this circulation variability is considered to be natural, and largely unchanged by large-scale forcing from greenhouse gases, 2015 speaks to the importance of having an integrated view of forced and natural variability in making statements about future hydrologic conditions at the seasonal and annual timescales.

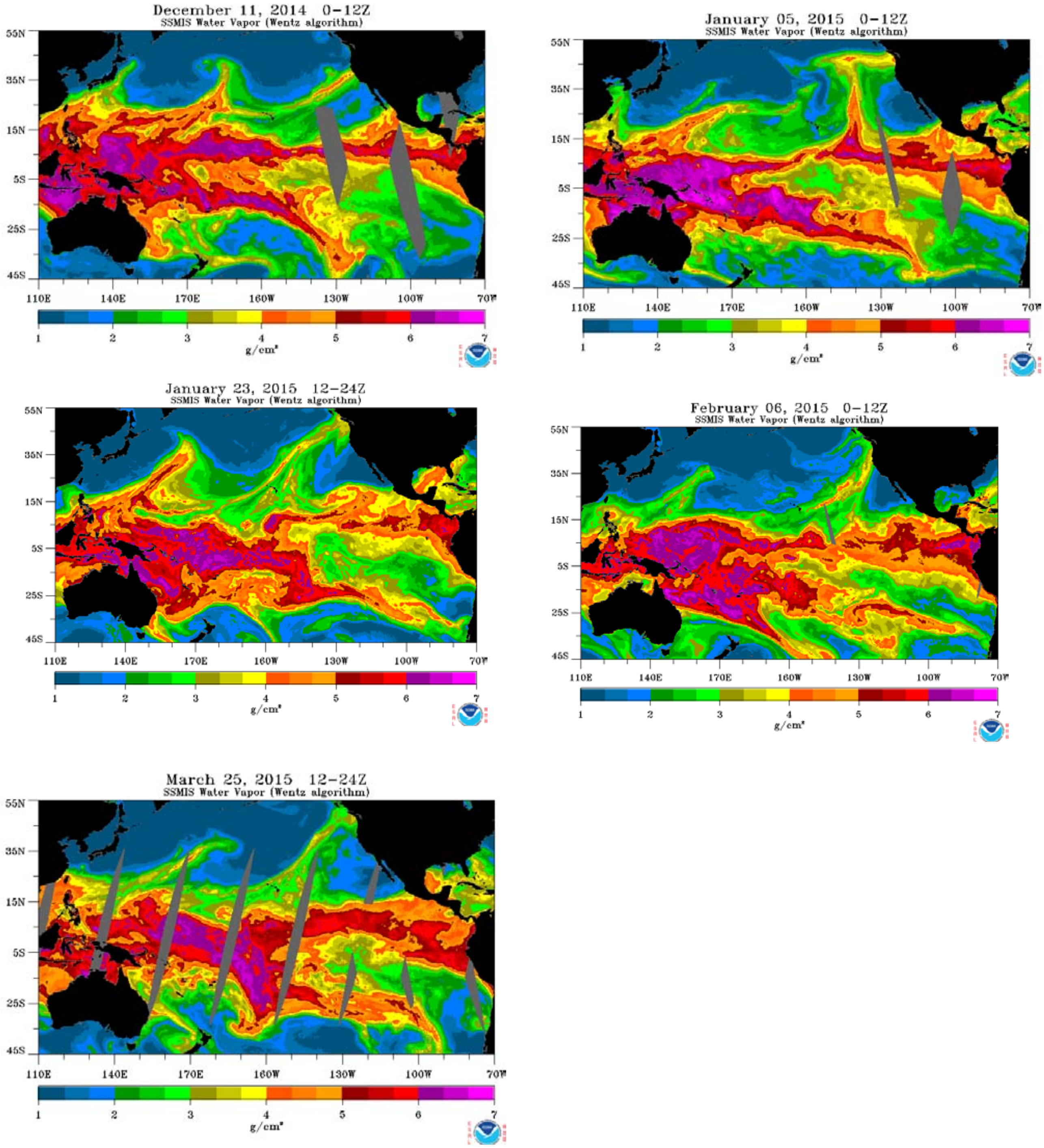


Figure 6. Integrated Water Vapor of Satellite Imagery showing Atmospheric River events. Images show the southwesterly flow of moisture into the Pacific Northwest during a subset of events when heavy precipitation was observed along the Washington Coast. Data Source, NOAA/ESRL/PSD

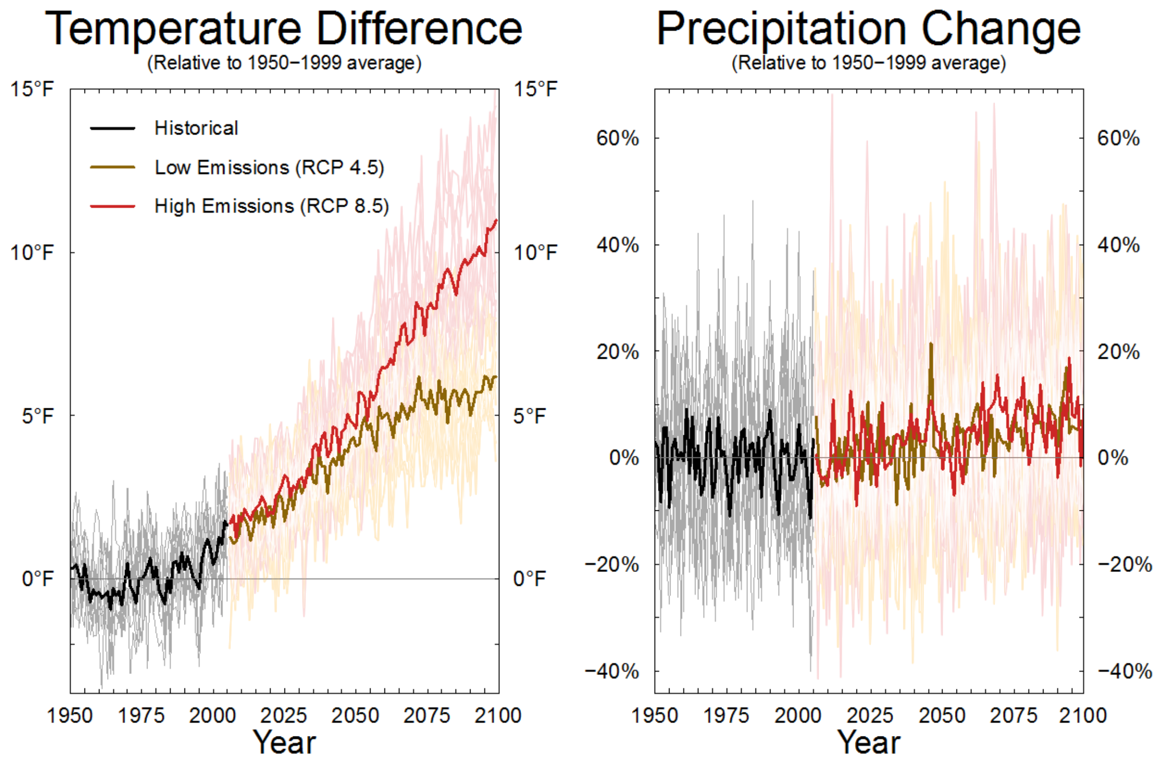


Figure 7. 21st Century projections for annual future temperature (left) and precipitation (right) for the Puget Sound region. All temperature estimates are simulated by climate models, as described in Mauger, et al. (2015). Historical conditions are shown in gray, with the multi-model average in black. Future projections are shown with two different emissions scenarios: one scenario assumes reductions in global greenhouse gas emissions are achieved (yellow), the other is a “business as usual” scenario that assumes continued growth in future emissions (red). The multi-model averages of these two scenarios are shown with a bolder line. Data Source: Mauger et al., 2015.

THOUGHTS ON COMMUNICATING FUTURE HYDROLOGIC CONDITIONS

As established in the previous section, there remains a significant range in potential snowpack outcomes for a given future seasonal temperature and accumulated precipitation amount. That range reflects the wide collection of circulation patterns that could occur while still being consistent with a specified average seasonal temperature and accumulated precipitation. In short, the WY 2015 illustrates how natural circulation variability is an important secondary player to seasonal-mean temperature and accumulated precipitation in determining actual hydrologic conditions within a water year.

Incorporating the role of natural variability into actionable information for water managers (or more simply, understandable information for the general public) may represent a change in “conventional wisdom” regarding discussions of future climate. Climate service providers often present information about projected future seasonal temperature, accumulated precipitation, or snowpack changes in terms of a 30-year mean derived from an ensemble of models. Using 30-year averages among an ensemble of models effectively removes biases that might be associated with any single model, isolating the change or “signal” associated with greenhouse gas emissions at the global scale, removing any “noise” from internal or natural climate variability at the regional scale. These results are often distilled into a single value (or range of values) corresponding to units of temperature change, or percentage changes in precipitation or April 1 SWE. However, this method of presenting information about future hydrologic change masks the role that natural circulation variability will play in contributing to actual future hydrologic conditions at the regional scale during a single water year.

To address this issue, climate service providers working at the regional scale should present annual timeseries of multiple, individual climate models for temperature, precipitation, and snowpack. The greater level of detail afforded by a collection of annual realizations from individual models will enable a probabilistic view of potential water year outcomes. Individual models and individual years with particularly large deviations from the ensemble mean conditions can be used as examples of future conditions where natural circulation variability acts to undercut or amplify the forced changes.

The simulations of individual water years from individual models should be a complement to the multi-model ensembles focused on 30-year climatological averages, rather than a substitute or replacement. These simulations can be treated as future extremes on the time scale of a water year, and may be more useful for informing future planning in cases where hydrologic conditions within a particular water year are disproportionately important to management outcomes (e.g., changes in hydropower production on an annual basis may be more important to revenue planning than a change in the 30-year average of hydropower production).

FUTURE RESEARCH

The recommendation for providing greater detail when presenting projections of future temperature, precipitation, and snowpack is, in some ways, a "stop gap" measure. It would be ideal to have greater insight into the ways that seemingly natural patterns of circulation variability may (or may not) change in response to greenhouse gas forcing. For the PNA, there are some examples of this work, exploring potential changes in frequency, magnitude, and in the location and orientations of centers of action (Allen et al., 2014). For other aspects of the regional circulation, there has also been some initial work regarding the location an strength of the jet stream (Salathé, 2006). At the hemispheric scale, there is a vigorous discussion regarding the detectability of potential changes in the meridional character of tropospheric circulation (Wallace et al., 2014) and what the future expectation we should have for a potentially "wavier" jet stream. Greater understanding of the potential connection between large-scale forcing and regional scale climate variability will improve our ability to interpret the range of potential future hydrologic conditions for water resource managers.

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Data Sources and Imagery

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