SPATIOTEMPORAL SWE VARIABILITY OF THE COLUMBIA RIVER BASIN

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ABSTRACT

Understanding the spatial and interannual variability of snowpack in montane regions such as the western U.S. is a key component of water management. Studies in this vein have typically focused on west wide analyses and found correlations with the El Nino Southern Oscillation and the Pacific Decadal Oscillation. However, smaller scale, subregional analyses may offer different insights into the spatiotemporal variability of snowpack which may be useful for water management at local scales as well as ecological assessments and planning. We consider March 1, April 1, and May 1 snow water equivalent at 243 sites within the Columbia River Basin over the years 1983-2012. A rotated principal component analysis is performed and resulting scores and loadings are correlated with a range of topographic and climatic variables. The first and second components of April SWE are strongly linked to latitudinal shifts in the jet stream. The second component is also correlated with the occurrence of Pineapple Express events. The third component is strongly correlated with interannual temperature and precipitation variability.
(KEYWORDS: SWE, interannual variability, spatial variability, principal component analysis, Columbia River Basin)

INTRODUCTION

Mountain snowpack across the Columbia River Basin (CRB) in a given year is often characterized as above normal, near normal, or below normal relative to climatology. While broad scale modes of climate variability such as the El Niño Southern Oscillation (ENSO) do indeed contribute to regional scale snowpack anomalies, these coarse descriptions forgo the detail necessary for many applications including water supply forecasting and ecological requirements. Studies of smaller scale variability of snowpack in this region have focused on April 1 snowpack (e.g. McCabe and Dettinger, 2002, and Cayan, 1996). Questions remain as to how snowpack variability in this region evolves over the spring season and what the primary drivers of the spatial and temporal patterns of snowpack variability are. The present study evaluates March 1, April 1, and May 1 snow water equivalent (SWE) data at SNOTEL sites and snow courses in the region to provide a sub-basin scale characterization of modes of SWE variability and their evolution over the spring season. These results are explained in the context of geographic and climatic variables.

DATA AND METHODS

SWE data from Natural Resources Conservation Service (NRCS) SNOTEL sites and snow courses was obtained for sites within the United States (U.S.) portion of the CRB for water years 1983-2012. SNOTEL data was quality checked following Lute and Abatzoglou [2014]. Snow course data was set to missing if the survey was done more than 10 days from the first of the month. 115 SNOTEL sites and 128 snow courses (243 total sites) were selected that had at least 75% complete records of March 1, April 1, and May 1 SWE.

Principal component analysis (PCA) is a powerful tool for distilling the variability in a dataset into its most important elements. This method has a long history in climatological research, including the study of snow variability (e.g. Cayan, [1996]; McCabe and Dettinger, [2002]). PCA can be sensitive to the choice of time period, domain, and to missing data. For this study, missing SWE data was infilled separately for each month. First, correlations were calculated between the available data for the given month at the target station and data for the same years and same month at all other stations. Then, the five stations with the highest correlations and that had data for all the years that the target station was missing were used to create a weighted estimate for each missing value at the target station. This infilling method avoids the assumptions that the nearest stations have the most similar climate and that station relationships remain static from month to month.

Infilled monthly SWE data was normalized and the regional average for each year was removed. PCA was

Paper presented Western Snow Conference 2015
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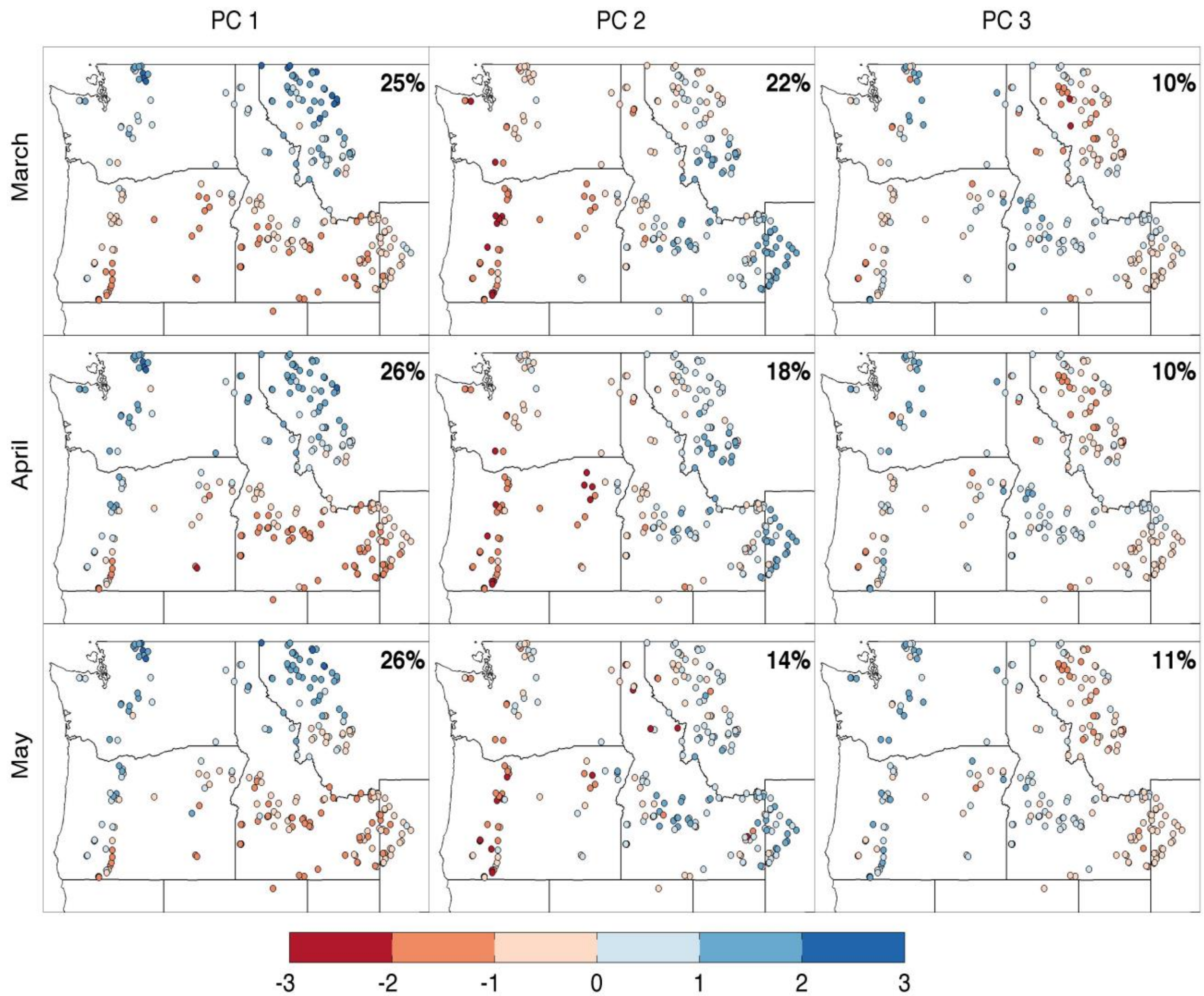

Figure 1. Spatial loadings of PCs 1, 2, and 3 of March, April, and May SWE. The percent of variance explained by each PC is indicated in the upper right of each plot.

performed on the SWE data for each month individually. PCA effectively separates the dataset into a matrix of time elements (scores) corresponding to each year in the dataset and a matrix of spatial elements (loadings) corresponding to each station in the dataset. Component loadings were rotated using the varimax method [Barnston and Livezey, 1987], which preserves temporal orthogonality. Parallel analysis [Ledesma and Valero-Mora, 2007] indicated that three components should be kept for March and April, and five for May. Our analysis focuses on the first three components for each month.

Spatial analysis of rotated PCA (RPCA) loadings included finding correlations between loadings and station elevation, latitude, and longitude, and March, April, and May climatological monthly temperature and cumulative precipitation at each station (from PRISM). Temporal analysis considered correlations between temporal scores and winter (Oct-Mar) means of the Multivariate ENSO Index (MEI, Wolter and Timlin, [1993]) and Oct-Mar, Oct-Apr, and Oct-May, means of the Pacific North American (PNA) pattern. Correlations with the number of Pineapple Express events landfalling between 32N-55N between October and each month of interest for water years 1995-2012 (*Dettinger et al.*, [2011], personal communication) and yearly Oct-Mar regional mean temperature (Tavg) and cumulative precipitation (Ppt) (from the National Climatic Data Center) were also evaluated. All correlations were considered significant at alpha=0.05. Finally, we created composite 500mb geopotential height anomaly plots for years with scores > 1 and for years with scores < -1. Significance of height anomalies was evaluated using a bootstrap resampling method with 1000 samples and alpha equal to 0.05. Composite anomalies of

250mb zonal and meridional winds were evaluated in the same manner. This paper will focus primarily on April 1 RPCA results.

RESULTS

Spatial Analysis

The first three components of March SWE, April SWE, and May SWE accounted for 55.8%, 54.4%, and 51.3% of the total variance, respectively. Spatial loading patterns of April PC 1 feature negative values in the lower latitudes and positive values in the upper latitudes. March PC 1 and May PC 1 displayed similar spatial patterns. A significant negative correlation was found between April PC 1 and elevation, and a significant positive correlation was found between April PC 1 and latitude (Figure 2).

April PC 2 was characterized by a roughly longitudinal continuum with negative loadings in the west and positive loadings in the east. March PC 1 and May PC 1 had similar patterns. Significant positive correlations were found between April PC 2 and both elevation and longitude, while a significant negative correlation was found with station climatological winter temperature (Figure 2). We note that elevation and longitude themselves are strongly correlated over the domain.

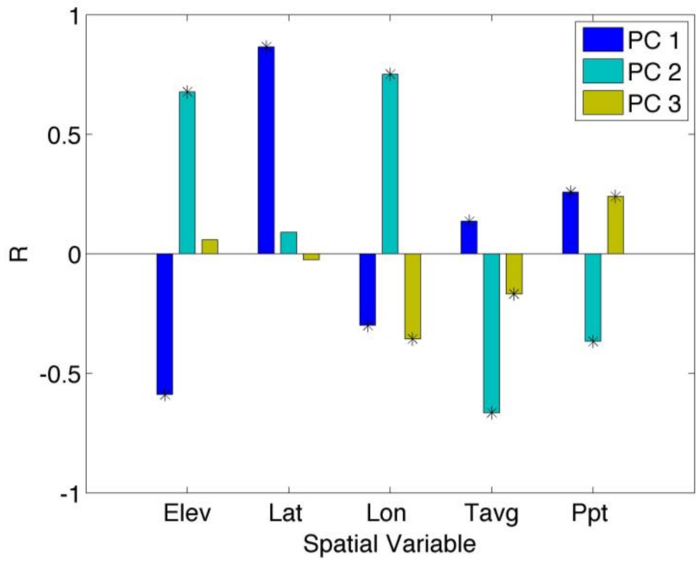

Figure 2. Correlations of April loadings with site elevation, latitude, longitude, and April mean temperature and cumulative precipitation.

Relative to the first two components, the spatial pattern of PC 3 is less coherent. Generally, high loadings are found in the west and low loadings are found in the east, particularly in the Rockies. The spatial patterns for March PC3 and May PC 3 are similar. No strong correlations were found with April PC 3 loadings.

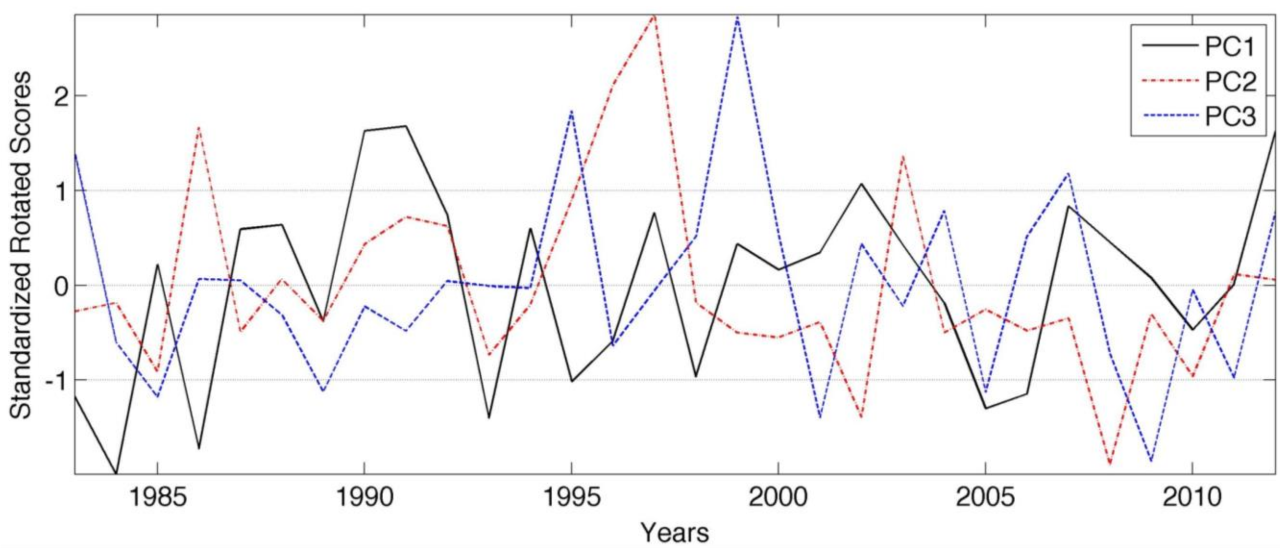

Figure 3. Time series of standardized temporal scores of April 1 SWE.

Temporal Analysis

No significant correlations were found between April scores (Figure 3) and ENSO (Figure 4), likely because the signature ENSO dipole in the western U.S. generally affects the CRB somewhat uniformly (all above or all below normal), thus our subregional analysis, with yearly means removed, would not detect this. PC 1 was significantly negatively correlated with the PNA. PC 2 was significantly positively correlated with the number of PE events and moderately correlated with regional temperature and precipitation. PC 3 had the strongest correlations with regional temperature and precipitation.

Geopotential height composites of years with April PC 1 scores >1 (Figure 5a) revealed a significant high pressure band across the North Pacific, indicating a poleward shift in the jet stream during these years. This is complemented by the composite wind field for the same years, which shows enhanced westerly flow above the high and mostly westerly to northwesterly flow into the CRB. The PC 2 composite showed a negative height anomaly across the Pacific further off shore, suggesting an equatorward shift in the jet stream. This is reinforced by anomalous westerly winds below the negative height anomaly. A high pressure center over the west coast of the U.S. indicated above average temperatures and anticyclonic flow which pulls relatively warm moist air into the region. The PC 3 composite was characterized by a significant low pressure center roughly above the Gulf of Alaska, bringing warm moist air to most of the region while likely creating slightly cooler and stormier conditions in the western portion of the CRB.

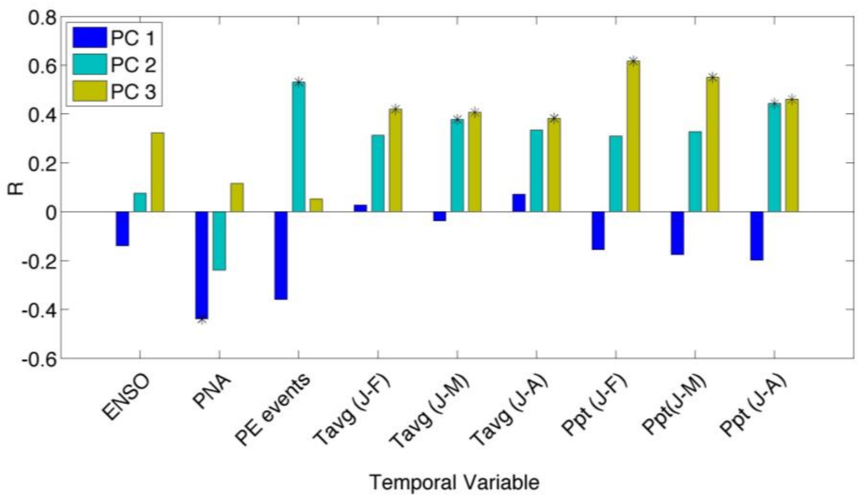

Figure 4. Correlations of April scores with ENSO, PNA, the number of PE events, mean regional Tavg and cumulative Ppt for Jan-Feb, Jan-Mar, and Jan-Apr.

Composite height anomalies for years with April PC 1 scores less than -1 (Figure 5b) feature a broad zonal negative height anomaly across the Pacific indicating a equatorward shift in the jet stream that is reinforced by enhanced zonal flow below the negative height anomaly. Both height and wind anomalies fade over the continental U.S., however this pattern likely results in a southward shift in storm tracks across the western U.S. Composite height anomalies for negative scores of April PC 2 show a positive height anomaly across the Pacific, indicating poleward movement of the jet stream. This pattern brings west to northwesterly flow into the CRB. Years with negative scores for PC 3 were characterized by a significant high pressure center over the Gulf of Alaska, creating anticyclonic flow which brings cold and dry air from western Canada into the CRB.

DISCUSSION

Synthesizing the analyses above, we find that April PC 1 is shaped by latitudinal shifts in the jet stream such that in years with positive scores, the jet stream shifts poleward, delivering moisture further north than usual. The dependency on the latitudinal position of the jet stream shapes the north-south pattern in the PC 1 loading map and is corroborated by the positive correlation between PC 1 and latitude. PC 1 was also significantly correlated with the PNA, however additional research is needed to clarify in what way the PNA contributes to PC 1.

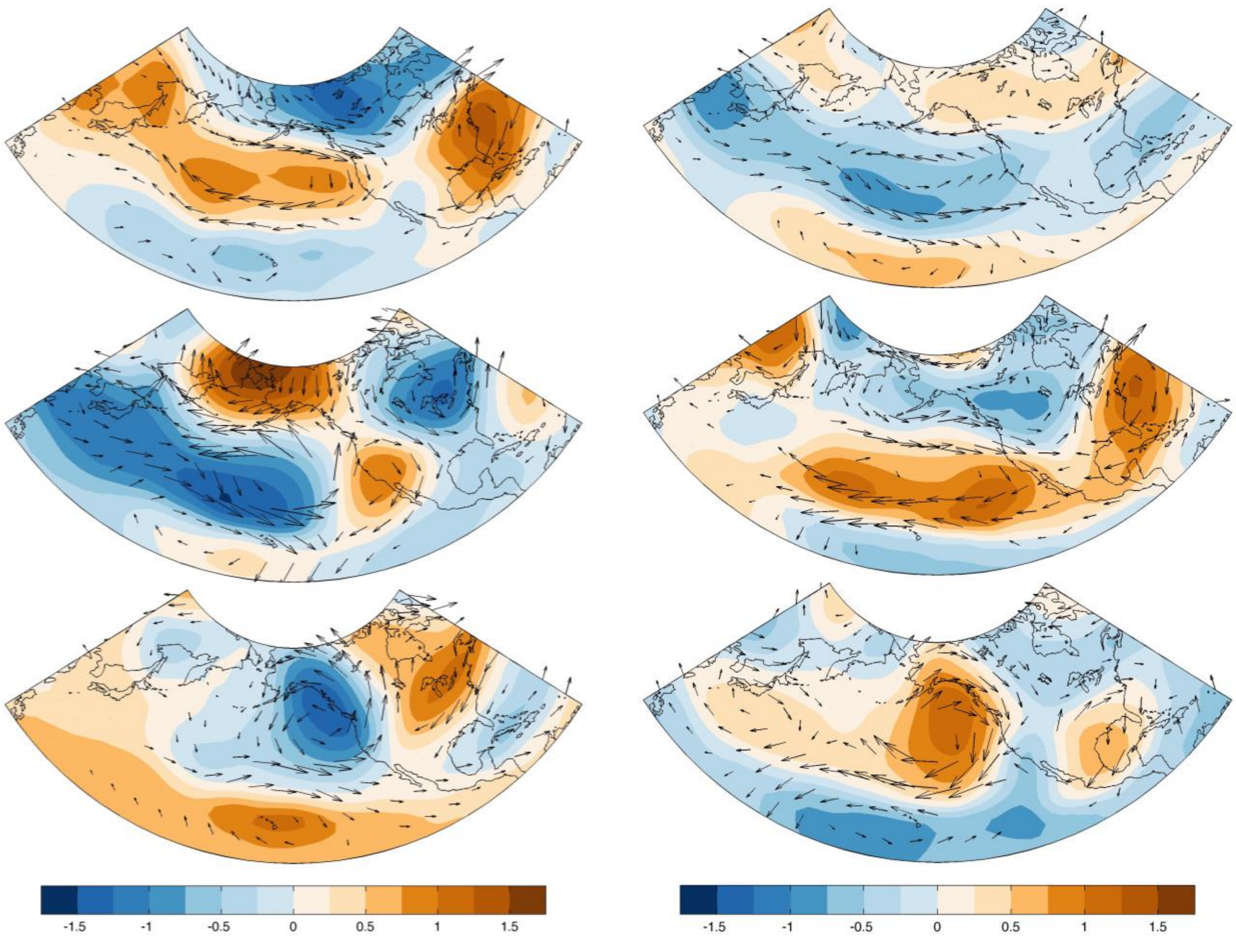

Figure 5. Composite standardized anomalies of 500mb heights for years with April scores > 1 (a) and < -1 (b). Vectors represent composite standardized anomalies of 250mb winds. Only significant vectors are plotted. Subplots represent PCs 1, 2, and 3.

PC 2 was tied to the number of Pineapple Express events each winter. These events, a subset of Atmospheric Rivers, bring large amounts of warm moist air and can contribute a substantial portion of annual precipitation [*Dettinger et al.*, 2011]. PC 2 was also weakly correlated with regional precipitation over multiple time frames, supporting the PE finding. The composite maps reveal the importance of the latitudinal positioning of the jet stream over the Pacific as well as a high pressure center over the west coast during years with positive scores. This combination shifts the jet stream further south in years with positive PC 2 scores and creates warm conditions over the western half of the CRB, limiting snowfall potential. Climatologically cooler areas (i.e. the eastern portion of the CRB) may be cool enough to capitalize on the increased moisture availability due to westerly and southwesterly flow while maintaining a high snow to precipitation ratio.

During years with high April PC 3 scores, we can expect a snowpack anomaly pattern reminiscent of the PC 3 loading pattern. PC 3 was significantly positively correlated with winter temperature and precipitation interannually, meaning that the PC 3 loading pattern occurs mostly in warm and wet years. Such years might typically be expected to result in a pattern more similar to PC 2, where the high elevation snowpack benefits from additional moisture whereas low elevation snowpack suffers from increased temperatures. However, the interpretation of PC 3 is complicated by the significant low pressure anomaly over the Gulf of Alaska. This low effectively creates cooler and stormier conditions in the western portion of the basin and pulls warm air up into the eastern portion of the basin, shifting the conditions in favor of snowpack in the west.

CONCLUSIONS

A rotated principal component analysis of March 1, April 1, and May 1 SWE found that spatial loading patterns for the first three PCs were relatively consistent from month to month and were often characterized by either a north-south or east-west spread. Further research is needed to determine whether the drivers behind these patterns are the same from month to month. April PC 1 was linked to latitudinal shifts in the jet stream just off shore which push storm tracks north in positive years. PC 2 was correlated with interannual precipitation variability and the occurrence of Pineapple Express events. PC 2 was also associated with a shifting jet stream and anomalous high pressure over the west coast during positive years. This winter saw a ridging pattern over the west coast for more than two months and snowpack departures from normal were similar to the PC 2 loading pattern, lending some confidence to the applicability of our results to years outside the period studied here. April PC 3 was strongly linked to interannual temperature and precipitation variability and anomalous pressure over the Gulf of Alaska, which results in unusual northerly flow into the region. Although PC 3 only accounts for 10% of April 1 SWE variability and is thus more difficult to interpret, further evaluation of links to temperature and precipitation, as well as other climate metrics may improve our understanding of this less coherent component.

While many studies of western U.S. snowpack variability have identified ENSO as a major driver (e.g. *McCabe and Dettinger*, [2002]), our analysis finds that at smaller scales, intra-regional variability is informed by other factors, such as the PNA and Pineapple Express events. More nuanced understanding of subregional snowpack variability and its relations to broader climate can improve water supply forecasting, particularly at local scales. This analysis can also inform ecological flow requirement planning, forest fire risk evaluation, and wolverine habitat vulnerability assessment.

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