PRECIPITATION MODIFICATION AROUND LARGE DAMS IN OROGRAPHIC ENVIRONMENTS: THE CASE OF CASCADE RANGE AND SIERRA NEVADA

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Abstract

This study explored the potential impact of artificial reservoirs in the Cascade Ranges and Sierra Nevada Mountains where orographic precipitation is dominant. The underlying hypothesis is that an additional and man-made source of moisture, such as an artificial reservoir and irrigated landscapes, can modify the pre-dam state of orographic process on the windward side or the convective process on leeward side of the mountain. Four blocks of dams (two from Cascade Ranges and two from Sierra Nevada) and six individual dams were considered in this study. Long term precipitation, relative humidity (RH), and dew point temperature (DPT) data were used. Patterns of climatologic RH, DPT, and precipitation percentiles (computed from a 30+ year record) were analyzed. Finally these results were compared for the post-dam period for the selected dams. The results show that artificial reservoirs on both sides can impact the local climatology. Atmospheric moisture content on the leeward side was generally seen elevated in the post-dam era with no significant change in precipitation. On the other hand, extreme precipitation (95th percentile) was found to be amplified by an average of 5 mm/day on the windward side; while an average 5 mm/day decrease was observed on the leeward side during the post-dam era. Understanding local feedbacks from artificial reservoirs and other anthropogenic activities on climate is crucial for water resources management, reservoir design and operation. The results presented in this study support the hypothesis that the impact of artificial reservoirs in an orographic environment is different on either side of a terrain formation.

Keywords: Orography, artificial reservoirs, precipitation, humidity, Sierra Nevada, Cascade Ranges

1. INTRODUCTION

Dam construction and operations for the purpose of irrigation, flood control, water supply, and power generation, are some of the most ubiquitous anthropogenic activities that potentially contribute to changes in local and regional environmental conditions, including climate (*Costa et al., 2003; Cotton and Pielke, 2007; Biemans et al., 2011*). The number of dams around the world, which is probably more than 800,000 (*Lehner and Döll, 2004; ICOLD, 1998*), can be considered an important but often less-studied driver for climate and weather at the local to regional scale (*Degu et al., 2012, Hossain et al., 2012*). Hereafter, 'dams' are used interchangeably with the word 'artificial reservoirs'. Although recent studies have shown the impact of these dams on climate and local storm distribution (*Woldemichael et al., 2012; 2013*), the scale and extent of their impact is not completely understood over a variety of geophysical settings (*Degu et al., 2011; Yigzaw et al., 2012*).

Local weather formation is often affected by geographical location and topography (*Houze, 2012; Smith, 2006; Raupach and Finnigan, 1997; Alpert, 1985*). Orography is a major factor in creating climate variation on different spatial and temporal scales (*Roe, 2005*). The presence of a barrier in the form of high mountains usually increases the chances of precipitation (i.e., orographic precipitation) on the windward side if there is adequate advection of moisture. Local convective processes can be amplified and produce a heavy precipitation as a result of such topographical features. The leeward side has a considerably lesser chance of experiencing precipitation (*Smith, 2006*). Beyond its simple presence, the mountain barrier height and its horizontal extent can also impact the precipitation process (*Colle, 2004; Manabe and Terpstra, 1974*).

Different studies have been completed on major topographic formations around the world. In the Himalayas, a formation which extends to 2400 kms in length, the relation between orography and precipitation formation has been well documented by *Barros et al. (2006).* Using a numerical model, the impact of mountains on the climate (and vice versa) during the orographic process is explored for monsoon and winter periods. Their finding states that when monsoon winds that are southeasterly wind meet a barrier against the north-south ridge, the upwind area gets more precipitation than the downwind area at scale as small as 10 km. The other formation with orographic effect is the Alps with an approximate stretch half that of the Himalayas. Heavy precipitation results in the Alps due to orographic effect (*Medina and Houze, 2003; Massacand et al., 1998; Haiden et al., 1990*). A climatology analysis of this region by *Frei and Schaer (1998)* shows the spatial distribution of precipitation over the Alps so that precipitation is enhanced on the foothills and inner valleys. It is likely that the frequency of these heavy precipitation events is to increase in the future as a result of climate change (*Frei et al., 1998*). A detailed study on orographic precipitation process in the Alps is provided by the Mesoscale Alpine Program (MAP, http://www.map.meteoswiss.ch/). A comprehensive study of orographic precipitation systems around the world can be found in *Smith (2006)* and *Barros et al. (2006)* for the case of the Himalayas.

Precipitation in the west coast of US (Sierra Nevada and Cascade Ranges) is highly affected by orographic process as well (e.g. *Houze and Medina, 2004; James and Houze, 2005*). Though extreme precipitation in the west coast is associated with atmospheric rivers (ARs) (*Dettinger, 2011; Ralph and Dettinger, 2011; Ryoo et al., 2011*), orography plays the important role in enhancing precipitation in the Sierra Nevada and Cascade Ranges. Without these topographic features ARs could extend a longer stretch in land (*Dettinger, 2011*). As the amount of the moisture from the Pacific decreases, precipitation occurs at low altitude rather than snow formation at the peaks (*Dettinger, 2011*). The controls for precipitation formation during growing season (April-September) of the west coast are orographic and convective. The orographic control is terrain driven and stronger on the windward side. The convective control, which is driven more by differential surface heating, is less sensitive to terrain and stronger on the leeward side.

In an era of increasing climate awareness, the relationship between topography (orographic precipitation formation) and large dams has not been studied in detail. There are around 75,000 dams in the US alone with a height greater than 2m (Graf, 1999). Based on the data available from Global Reservoir and Dam database (GRanD) (Lehner et al., 2011), many of these dams are concentrated on large mountain ranges (Figure 1). Mountains allow the natural topographic relief to maximize volumetric storage for surface water. The relative abundance of dams on each side of a mountain is perhaps an indication of the conventional mindset to water resources development, which is to *capture water where it is easily available (i.e. windward side) or provide supply where regions are drier (i.e., leeward side).* Folsom and Oroville Dam of California are examples of windward dams that regulate surface water flows from the Sierra Nevada Mountain. Weber dam in Nevada is one example of dam on the leeward side of Sierra Nevada that is used for water supply, irrigation and hydropower generation in very dry climates.

The presence of dams can potentially impact the local precipitation and flood pattern (*Pizarro et al., 2013*). The study of *Woldemichael et al. (2012 and 2013)* investigated the land-atmospheric interaction with the presence of artificial reservoirs in Sierra Nevada and Cascade Ranges. The results from the study have shown that there is in fact an increase in extreme precipitation due to the artificial reservoirs. A key information from these two modeling studies is that the artificial reservoir considered on the leeward side of Cascade Ranges (i.e., Owhyee dam) has influenced the extreme precipitation more than Folsom dam, which is on the windward side of Sierra Nevada. Thus, understanding the potential interaction between large dams and precipitation in orographic environments can improve water resources management in a changing climate and under increasing pressures from urbanization and population growth. A numerical modeling study by *Woldemichael et al. (2012)* also reports that artificial reservoirs near the Sierra Nevada Mountains can trigger an increase in extreme precipitation driven by post-dam land use and land cover changes in the surrounding regions. Other studies (for example: *Yang et al., 2011; Yigzaw et al., 2013; Gregory et al., 2006; Scanlon et al., 2005*) have also shown the impact of LULC changes and other anthropogenic activities on hydrological and meteorological processes. More importantly, such an investigation can help the engineering community to better understand the meteorological and hydrological impacts that dam design and construction have on the windward and leeward sides of a mountain.

Anthropogenic activities (e.g. LULC change and artificial reservoirs) make the land-atmosphere interaction even more complex by impacting meteorological and hydrological variables. Artificial reservoirs increase the evaporation from open surface and evapotranspiration from irrigated lands. At the same time LULC changes that are associated with these artificial reservoirs can affect the latent heat, albedo and other parameters which are important in the process of precipitation formation. Clear understanding of the end-result of these interactions may be difficult. However it is nevertheless critical to investigate the complex feedback among meteorological and hydrological processes in the presence of artificial reservoirs, as failure of these structures or improper discharge of flood can be catastrophic for downstream areas.

This study explores the underlying hypothesis that the additional and man-made moisture that is available near a dam, in a region that is already conducive to orographic precipitation, is likely to modify the precipitation pattern during the post-dam period. An associated question that arises from such a hypothesis is *if there is indeed an impact on precipitation and other variables, which side (windward or leeward) is likely to experience the more detectable alteration and why?* To answer this question, the cases of Cascade Ranges and Sierra Nevada mountains have been selected because of their extensive presence of large dams. The fact that the weather formation of these areas is orographic helps easily identify the windward/leeward side. This, in addition to the large number of dams available, is one of the reasons the specific study area is selected. Central Valley of California is a good example where inter-basin water transfer is implemented between Sacramento and San Joaquin river basins (US Bureau of Reclamation; USBR, 2008). Such practice can be implemented in areas where there is unbalanced water distribution, such as windward and leeward areas.

2. STUDY AREA

The study area selected is the mountain ranges in the Western US specifically on Cascade Ranges and Sierra Nevada Mountains (Figure 1: upper panels). This area has very distinct topographical features ranging from coastal plains to mountains. There are different mountain ranges in the US. Among these Appalachian, Cascade Ranges, Rocky Mountains, and Sierra Nevada are the most dominant types in terms of their contribution to local to regional weather circulation and storm formation. The contrast of coastal and mountainous areas in west coast creates a perfect condition to study orographic processes (e.g. *James and Houze*, *2005*).

The major cause of precipitation in the Western US Mountain ranges is the North Pacific Ocean high pressure systems (National Atmospheric and Oceanic Administration: *NOAA, 1985*). There usually exists a difference in the relative humidity between the coastal and inland areas, particularly over California. The relative humidity over inland areas increases significantly from summer to winter. This distributional change in the relative humidity is also affected by mountain barriers such as the Sierra Nevada and Cascade Ranges. These mountains obstruct the flow of moisture coming from the North Pacific high pressure systems. With the dissipation of wind over the mountain tops (especially Sierra Nevada), there is lesser precipitation on the leeward side (*NOAA*, 1985). In the Western US, the majority of the dams are on the western side from the Cascade Ranges and Sierra Nevada Mountains. There is sparse distribution on the leeward side of these mountain ranges. These leeward dams have been built for multiple purposes, among which irrigation and power generation are dominant (*Degu et al., 2012*).

3. DATA AND METHODOLOGY

Four blocks of dams were selected over the Cascade Ranges (CR) and Sierra Nevada (SN) Mountains (two from CR and two from SN; Figure 1). The block represented a ‘cluster’ of dams within a selected mountain range. The basis for the selection of these blocks is the Köppen climate classification and annual average precipitation. Geographic distribution data that is available in GRanD (*Lehner et al., 2011*) was used to identify the leeward or windward side dams (Figure 1- upper panels and Table 1). A climatologic wind rose diagram for the growing season (April-September), derived from 30 years of atmospheric reanalysis wind direction data at the 850 mb pressure level, was earlier derived by *Degu et al. (2012)*. These wind rose diagrams were used to identify the predominant wind direction around the selected dam locations.

In *Degu et al. (2011)*, it was reported that the influence of dams may extend up to a radius of 100 km due to the nature of winds during the growing season. Since most of the data used for analysis is ground and point-based data, selecting a single station meant that it can potentially represent different neighboring dams rather than a unique one in the area. Therefore, it was more reasonable, in our opinion, to select 'blocks' of dams on the basis of other criteria like climate classification rather than analyze an individual dam or individual point ground station. Our approach also helped in handling the difference in construction year of individual dams. According to the National Inventory of Dams (http://geo.usace.army.mil/nid/) most of the dams in the US were constructed after 1950. Therefore, it is logical to compare trends of average quantiles starting from 1950 for both windward and leeward sides. In addition to the block of dams, individual dam pairs were selected on both sides of the mountain to support the study objectives. From Cascade Ranges, Howard A. Hanson and Keechelus dams and Green Peter and Pelton dams were chosen as pairs. In Sierra Nevada, Little Grass and Grizzly Valley dam were selected. The pairs are shown in a windward-leeward pattern in Figure 1. Table 1 shows the selected pairs of dams and their location on the mountain side relative to wind direction.

Data on precipitation was taken from the Global Historical Climatology Network Data (GHCND) that is archived by NOAA's National Climatic Data Center (NCDC, available on the website http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). The number of stations used for averaging over a selected block ranged from a minimum of 3 to a maximum of 30 precipitation measuring stations. Relative humidity (RH) and average dew point temperature data (DTP) were available from NCDC through the international research institute for climate and society (IRI) of

Colombia University (available online at http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.DAILY/.FSOD/).

Instead of a point measurement, a satellite data with high spatial resolution can potentially yield a better understanding of climatology in areas with artificial reservoirs. The drawback of using satellite data is that there is no long temporal data measurement record prior to 1979 (for example Tropical Rainfall Measurement Mission-TRMM provided data from 1997 on) and the spatial resolution of data available is coarse to analyze the local climate variations (sub-100km). However, the satellite precipitation product from the PERSIANN-CCS (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System; Hong et al., 2004) has a spatial resolution of 0.04 degrees (~ 4km) and hourly temporal scale, which is the finest currently available starting from the year 2003. This data was used to explore the spatial distribution of precipitation against the relative location of artificial reservoirs.

The analysis period was the growing season (April-September). Precipitation in the Western US occurs mostly during winter season. Winter events are a result of large scale (synoptic) process in Western United States beginning from October to March (Lareau and Horel, 2012). Conversely, the objective of this study is to understand the local-regional (10-100 km) impact of artificial reservoirs due to isolated local-mesoscale convection systems that are known to occur on both sides of the mountains according to our analysis of precipitation records since 1900 A.D. Such events are more likely to occur during the growing season and triggered by locally available moisture, for which, large reservoirs and associated LULC activity often represent a major source. Hence, our assumption is that an analysis during the growing season should be the first step in a dam attribution study in orographic environments. Although the growing season in California can vary from 225 to 300 days (*Western Regional Climatic Center: WRCC, 2012*), a period of 180 days (April-September) improves representation of the higher elevation areas of the Sierra Nevada which has growing season period as low as 50 days.

A 30 year moving window was used to derive the precipitation quantiles associated exceedance probabilities such as 50% (P50), 10% (P90), 5% (P95), and 1% (P99). A point to note is that only 180 days of growing season data from the total of 365 days per year was used in all statistical computations reported hereafter. In essence, the exceedance probabilities are thus representative for the growing season only. Our preliminary analysis showed that a 30 year period moving average yielded the most stable estimates of precipitation quantiles that are not sensitive to a longer data length. A rainfall threshold of 1 mm/day was used to define a day with rain. Data was analyzed for both pre and post-dam periods to identify any potential shift in the precipitation patterns after dam construction on the windward and leeward side of the mountain.

For block of dams, in-situ stations that are closest to the selected dams were used for pair of dams selected. For precipitation pattern analysis, 8 such stations were available (one near each dam). For analysis of RH and DPT, there were only 6 stations with continuous measurement (Figure 1, lower panel). The minimum length of data on precipitation was 57 years (29 years for pre-dam period and 28 years for post-dam period). For RH and DPT, the minimum length of data was 14 and 11 years, respectively, and available only for the post-dam period.

4. RESULTS AND DISCUSSION

A Mann-Kendall (Mann, 1945; Kendall, 1975) trend test was done for temperature, dew point temperature, and relative humidity. The trend for each parameter was done using the growing season data for the entire length of data available. The purpose of this test was to understand how the parameters considered have changes (increased or decreased) at an individual station and over the study area. Figure 2 shows the trend test done for these parameters at a 5% significance level. Most of the trends were observed on the windward side for dew point temperature (DTP), temperature (TP), and minimum relative humidity (RH); while on the leeward side the more trends are observed for maximum relative humidity. The specific trends are individually discussed in the following paragraph of this section. Two sets (CR-A Windward/Leeward; CR-B Windward/Leeward; SN-A Windward/Leeward; SN-B Windward/Leeward) of percentiles (P50, P90, P95, and P99) were analyzed for each block of dams and individual pairs. For block of dams shown in Figure 1, the precipitation percentiles are shown in Figure 3 and Table 2 in a summary form for the assumed pre- and post-dam periods. The percentile representing P50 shows no change in the post dam period. This is also consistent with findings of *Degu et al. (2011)* and *Groisman et al. (2005)*, who have found less impact on the mean than the extremes. Therefore, P90 and higher percentiles are the subsequent focus for detection of changes in precipitation patterns.

Trend lines were fitted to the percentiles time series using least-square regression. Since the percentiles were computed over a 30 years moving window, comparison of the trend line slope provided an insight on the temporal rate of change in extreme precipitation occurrence. The trend fitted to the percentile time series for the block of dams selected revealed that there is no distinctive trend observed on either side of the terrain. On the other hand, our result supports the argument that artificial reservoirs have impacted extreme precipitation regardless of their location relative to a mountain. In Figures 3, slope comparison of extreme precipitation (P95, P99) shows there is relative difference on the increase of the extreme on the windward and leeward side. A trend that can be observed from the perspective of the study’s objective is that there is a decrease in extreme precipitation on the leeward side; while there is an increase in these extreme values on the windward side (Table 2). Though no strong conclusion can be drawn, the result of Table 2 also shows that there is an indication that the impact of artificial reservoirs is amplified by orographic controls more than convective controls for areas affected by same terrain formation. Since the study period pertained to the growing season, the contribution of local convective systems is more for precipitation than synoptic (large scale weather) processes.

Available relative humidity and dew point temperature results are shown in Figure 4 and 5, respectively. As seen on Figure 3, there is an increase in relative humidity (both maximum and minimum) except in some area of the windward side of Sierra Nevada. It is also evident that larger change is observed in maximum relative humidity than the minimum RH. In Figure 5, an increase in dew point temperature was observed on both windward and leeward sides. However there was a relatively higher increase slope on the leeward side. The increasing trend in dew point temperature and relative humidity can be related to the presence of artificial reservoirs in the region that could be supplying extra moisture for the local and regional land-atmosphere interaction process.

The spatial distribution of PERSIANN-CCS precipitation data is shown in Figure 6. The result shows the yearly average values for the month of July in each year. It can be assumed that the result depicts the local features well as the specific period is characterized by lesser impact from large scale fronts both from the pacific and Rocky mountains. The result shows that more precipitation is observed on the leeward side than the windward side for the area considered in this study during the growing season. Though it cannot yet be justified that there is direct physical evidence between artificial reservoirs on the leeward side and the precipitation events, one can still make the claim that these reservoirs can contribute to the precipitation process through evaporation and evapotranspiration of its impounded water.

The percentiles for individual pairs of dams are shown in Figure 7 for selected dams on windward and leeward side. It can be seen again that the extreme precipitation (P90 to P99) were more affected than the median (P50). There was an increase in precipitation percentile (except for P99 in the case of Keechelus and Grizzly Valley dams) in all leeward areas near dams. Slope comparisons of percentiles for pairs of dams show that there is a steeper slope (of the trend line) in the post dam periods for the leeward dams than the windward dams. Ross and Conconully dams however yielded a different pattern. The precipitation formation process is likely different for these two dam locations requiring a more in-depth synoptic study. Recent numerical modeling studies by *Woldemichael et al. (2012 and 2013)* report that artificial reservoirs near the Sierra Nevada Mountains and Cascade Ranges can trigger an increase in extreme precipitation driven by land use and land cover changes in the surrounding regions. The two studies focused on Folsom dam (windward side) and Owhyee dam (leeward side). For Folsom dam, the study found an increase of 4% in the 72 hour probable maximum precipitation (PMP). Owhyee dam, which is on the leeward side of Cascade Ranges, the PMP was found to increase by 8%.

Figures 8 and 9 show that there have been a systematic observational increase in RH and DPT near dams on the leeward side. One potential cause for this trend could be the relative position of the dam itself. Leeward side of a mountain in orographic environments is significantly drier than the windward side. Thus the ‘background’ (pre-dam) level of humidity is sufficiently low in magnitude and variability on the leeward side for the additional moisture contribution by dams (lake and LULC) to be detected clearly from observations.

The daily mean dew point temperature for the selected dams on the leeward and windward sides is shown in Figure 9. An increase in the dew point temperature was observed for dams on both sides of the mountain range. However, as the precipitation process on the leeward side is as a result of convective process (as oppose to orographic on the windward side), the results presented for the dew point temperature show that the presence of reservoirs on the leeward side seem to alter the moisture availability more than on the windward side (Figure 9). Again, the likely argument for such a trend, among many factors, is what has been discussed in the preceding paragraphs.

5. CONCLUSION AND RECOMMENDATION

Based on the results that are presented in this study, there is a clear indication that impact (contribution) of artificial reservoirs in local-regional climate can be affected by its topographic position. As the topographic formation dictates weather formation and climate classification on a larger scale, it will be important to look in to specific dams and their impact by implementing physically-based atmospheric models. The two processes in which precipitation is formed over the study area during the growing season are orographic and convective processes. Orographic process is dominant on the windward side; while the convective process is stronger on the leeward side of the two terrain formations (Sierra Nevada and Cascade Ranges). The orographic process seems to amplify the impact artificial reservoirs have on extreme precipitation on the windward side. On the other hand, the dams on the leeward side appear to have increased the local humidity and hence impacted more the convective precipitation process.

Our study indicates that the hypothesis, that the position of dams relative to orographic environment dictates the impact on precipitation patterns, appears to have merit for further consideration. The importance of understanding relationship between anthropogenic activities and modification in local-regional climate can lead to newer approaches in future water resources systems design (of dams, irrigation systems) and management (of demand for power, food generation etc.). A local feedback as opposed to a global climate change approach can result in a sustainable dam design and operation. In an era where the unpredictable nature of flood events has increased due to climate change, customization of design parameters using local feedbacks should be considered important for the engineering and decision making communities.

Future studies should use numerical models on pairs of dams located on both sides of the mountain along the prevailing wind direction over orographic environments. What is evident from the studies of *Woldemichael et al. (2012 and 2013)* is that a physical investigation of the impact of artificial reservoirs in an orographic environment is best understood through modeling of the atmospheric processes than analysis of point station data. The point data used in this study can only be indication of changes. Better water resources management and operation approach may be achieved in regions where construction of newer dams is the primary solution for economic and social development. The fact that there is an indication of increase in precipitation, relative humidity, and dew point temperature on the leeward side is an encouraging finding to justify an intensive numerical model analysis of storms in the larger region.

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Table 1: Pair of dams selected for analysis on dams in orographic environment.

Block	Dam Name	Year constructed	Relative location
CR-A	Howard A Hanson	1962	Windward
	Keechelus	1916	Leeward
CR-A	Green Peter	1967	Windward
	Pelton	1957	Leeward
SN-A	Little Grass	1961	Windward
	Grizzly Valley	1966	Leeward

Table 2: Summary of moving average precipitation for the selected blocks of dams. The period 1900-1949 represents a pre-dam period; while 1950-1982 represents the post-dam period. Shaded rows indicate a potential impact by dams.

Block	Quantile	Precipitation (mm/day)			
		Windward		Leeward	
		Period			
		1900-1949	1950-1982	1900-1949	1950-1982
CRA	P50	7	7	4	4
	P90	25	25	13	13
	P95	33	34	18	18
	P99	56	56	31	32
CRB	P50	6	7	4	4
	P90	24	27	13	13
	P95	33	36	18	18
	P99	56	61	34	31
SNA	P50	9	9	5	5
	P90	38	40	22	22
	P95	51	53	32	30
	P99	84	87	58	53
SNB	P50	7	7	4	4
	P90	28	31	17	14
	P95	37	42	25	21
	P99	60	67	48	40

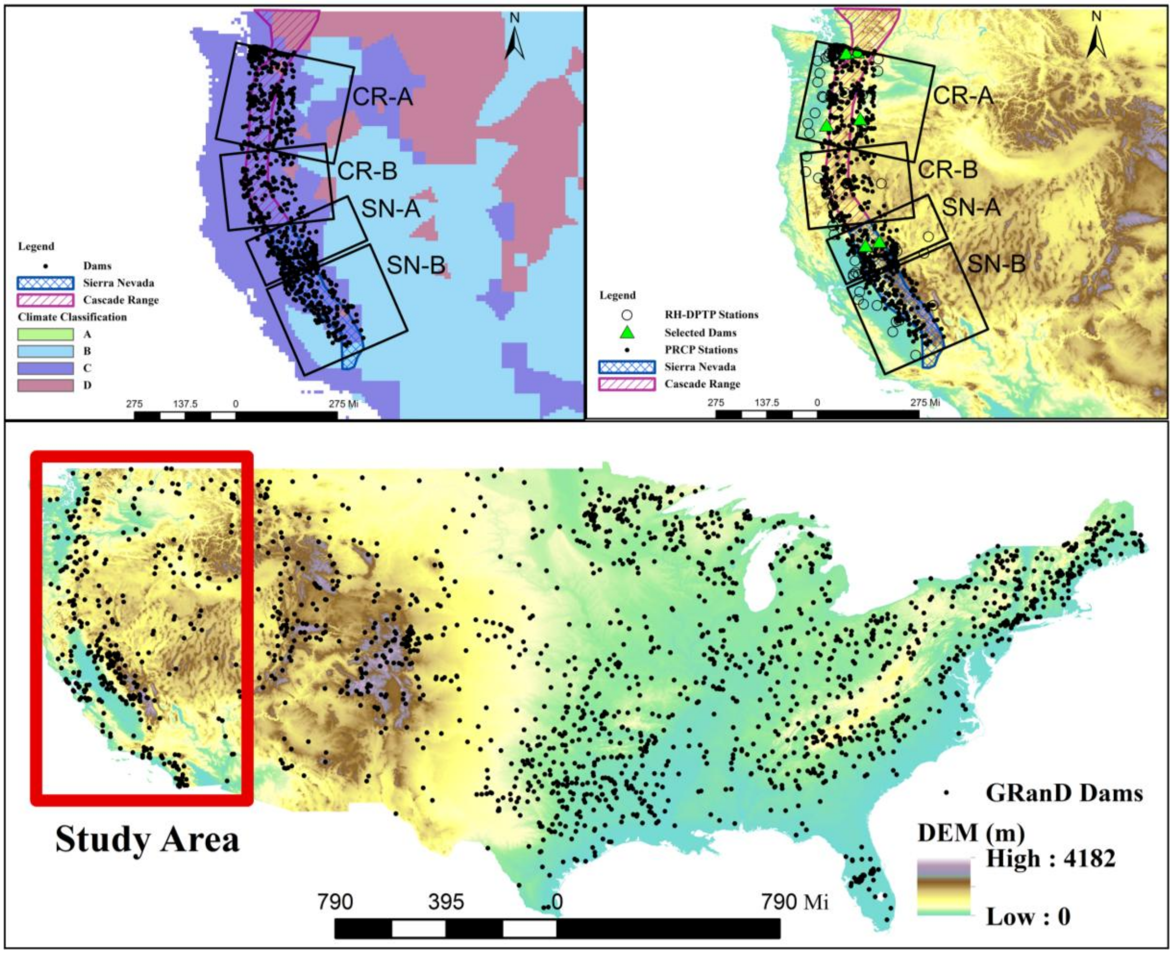

Figure 1: Location of large dams in the GranD database (*Lehner et al., 2011*) of the US (lower panel); study area topography, selected dams and upwind directions (upper panels).

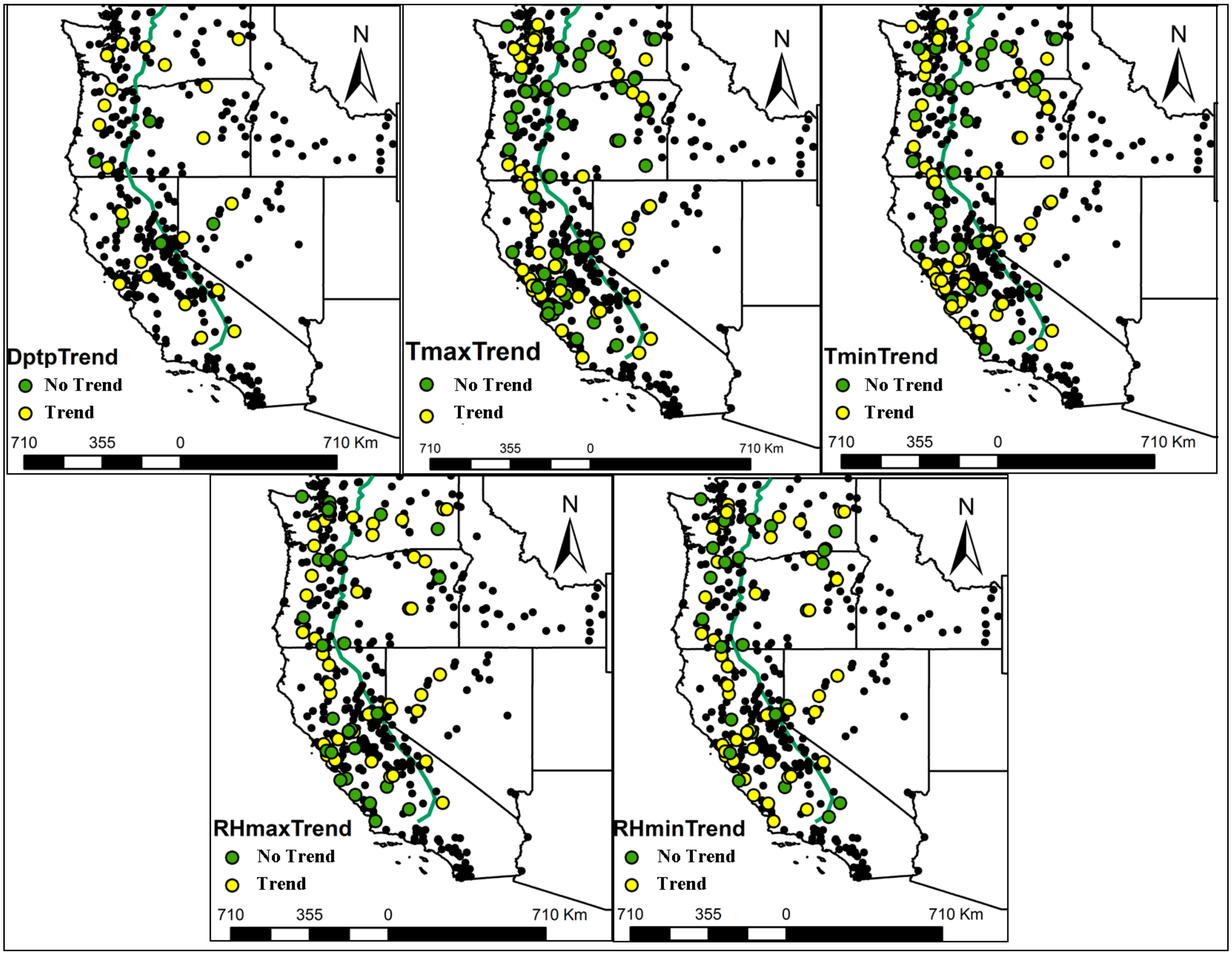

Figure 2: Mann-Kendall trend test for different parameters at 5% significance level. Dew point temperature (DPT), maximum temperature (Tmax), minimum temperature (Tmin) (upper three panels); relative humidity (RH) (lower two panels).

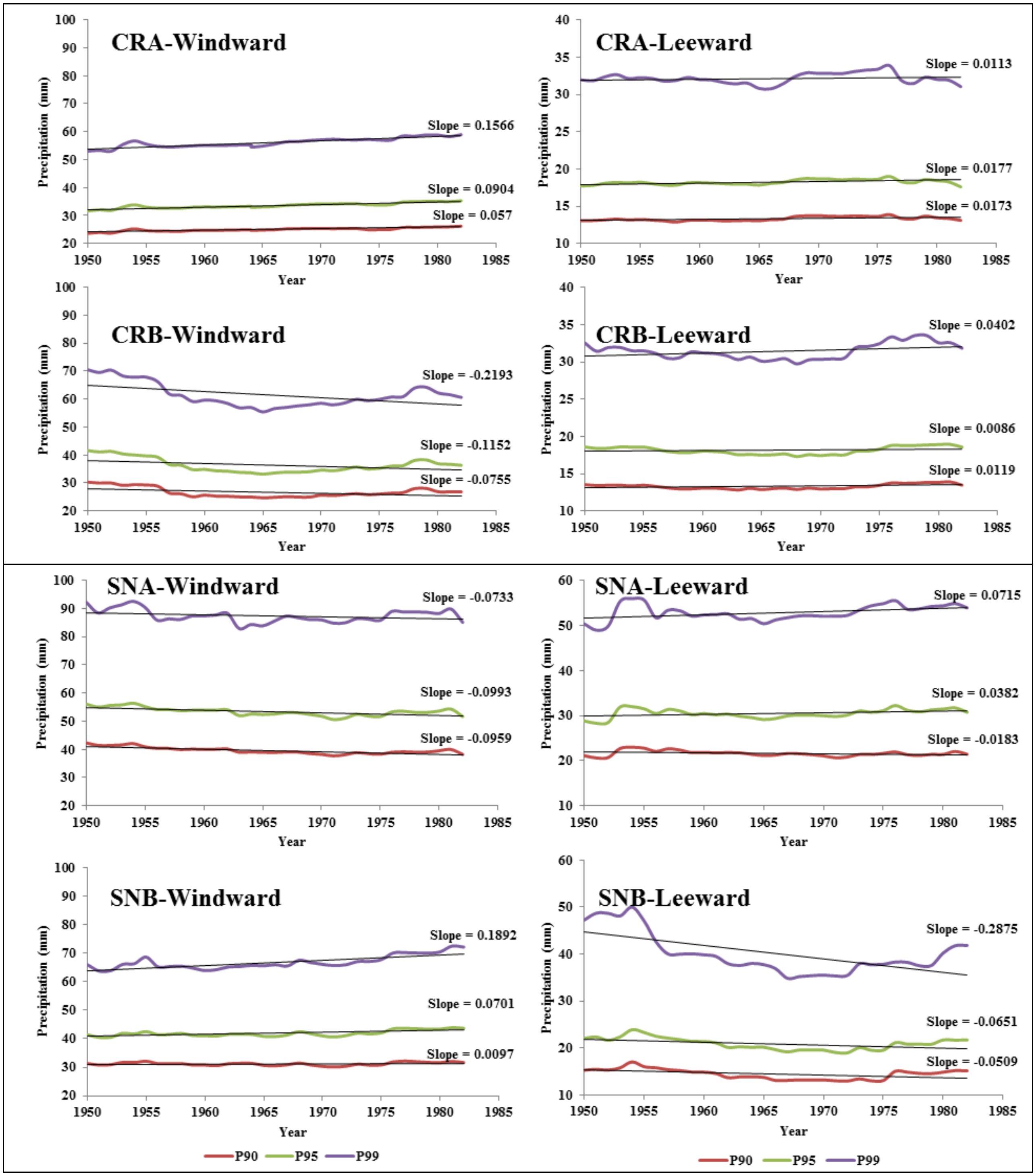

Figure 3: Time series of precipitation over selected block of dams for the period of 1950-1982 (post-dam period).

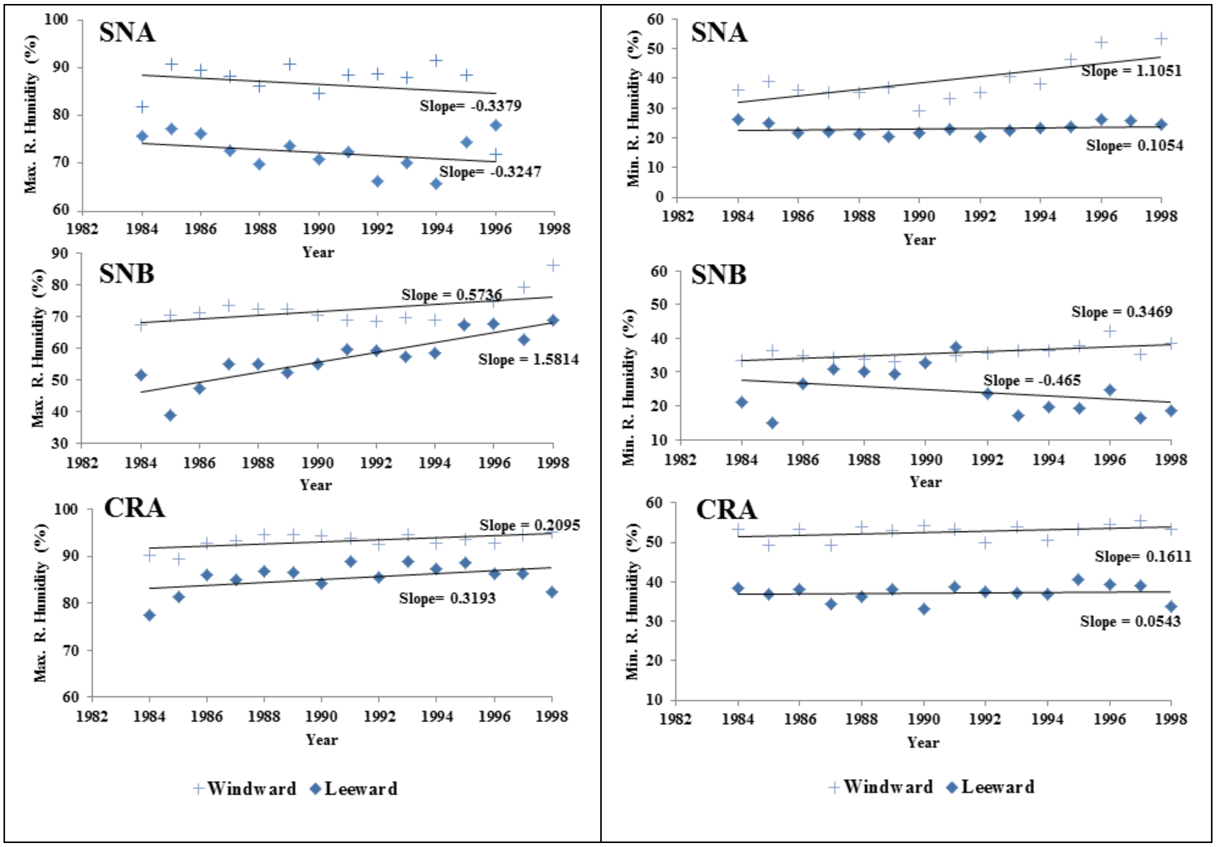

Figure 4: Maximum relative humidity (left panel) and minimum relative humidity (right panel) over selected areas in Sierra Nevada and Cascade Ranges.

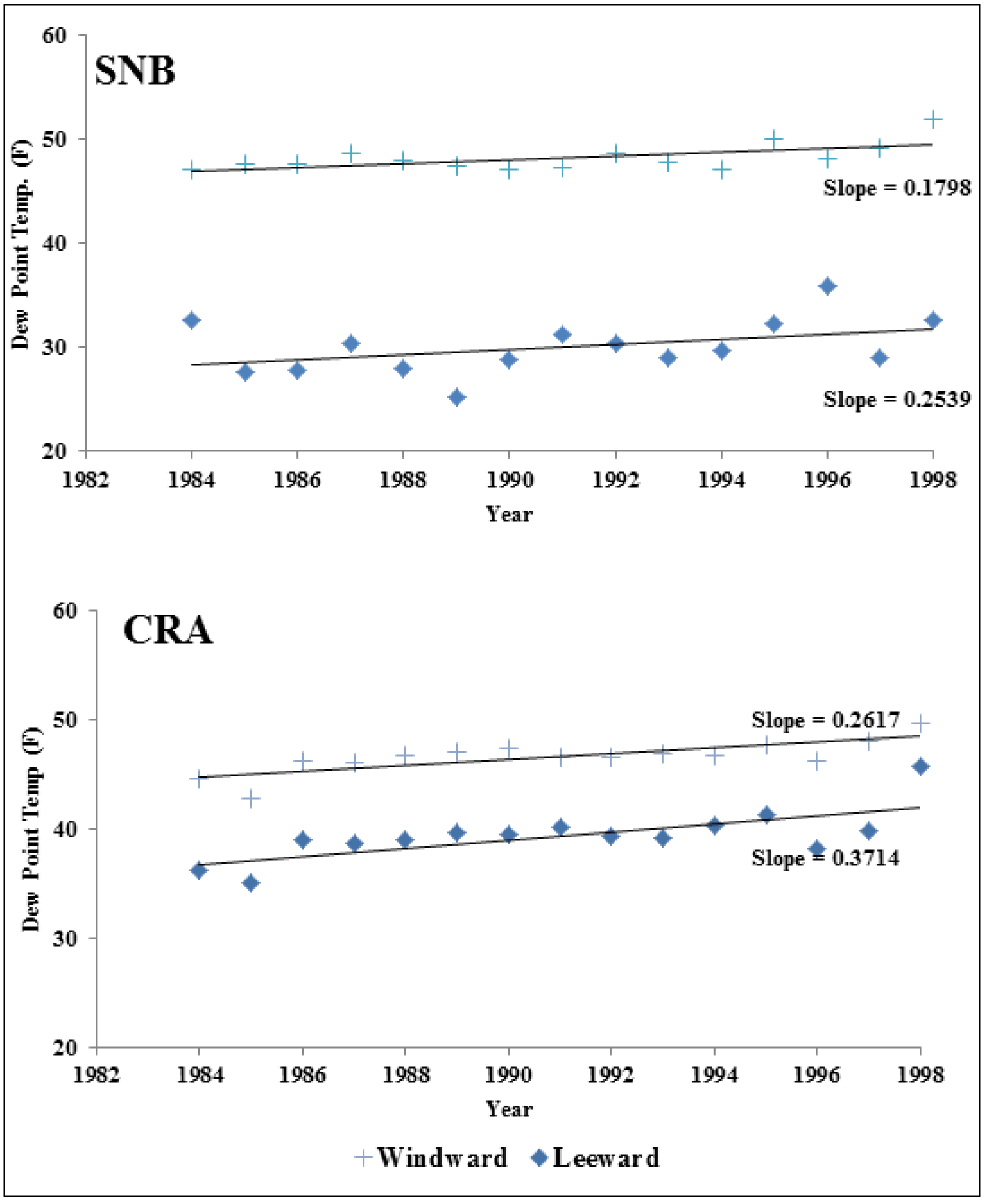

Figure 5: Dew point temperature over selected areas with dams in Sierra Nevada and Cascade Ranges.

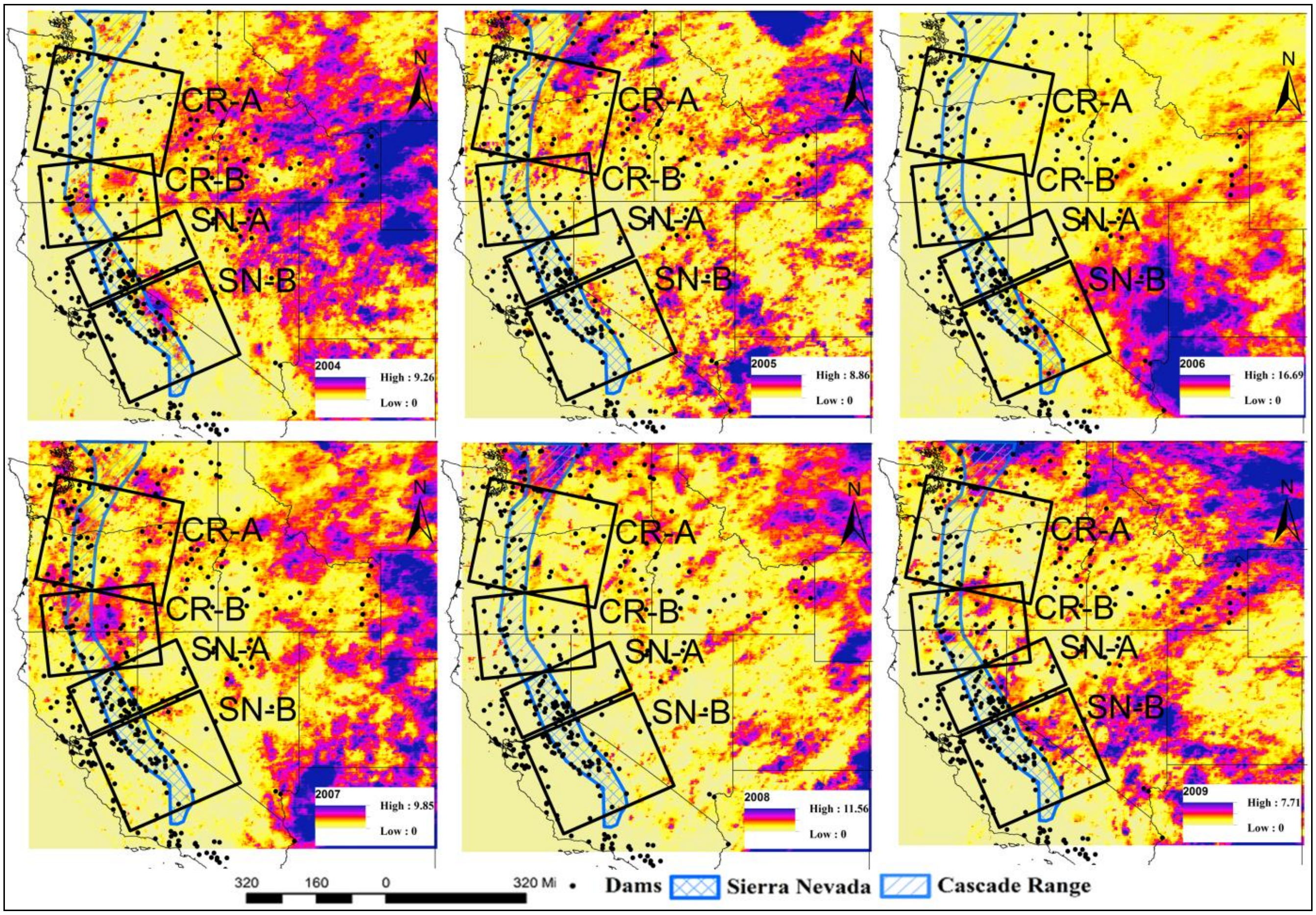

Figure 6: Monthly average precipitation (mm/day) product from PERSIANN-CCS for the month of July (2004-2009). Each panel represents a specific year.

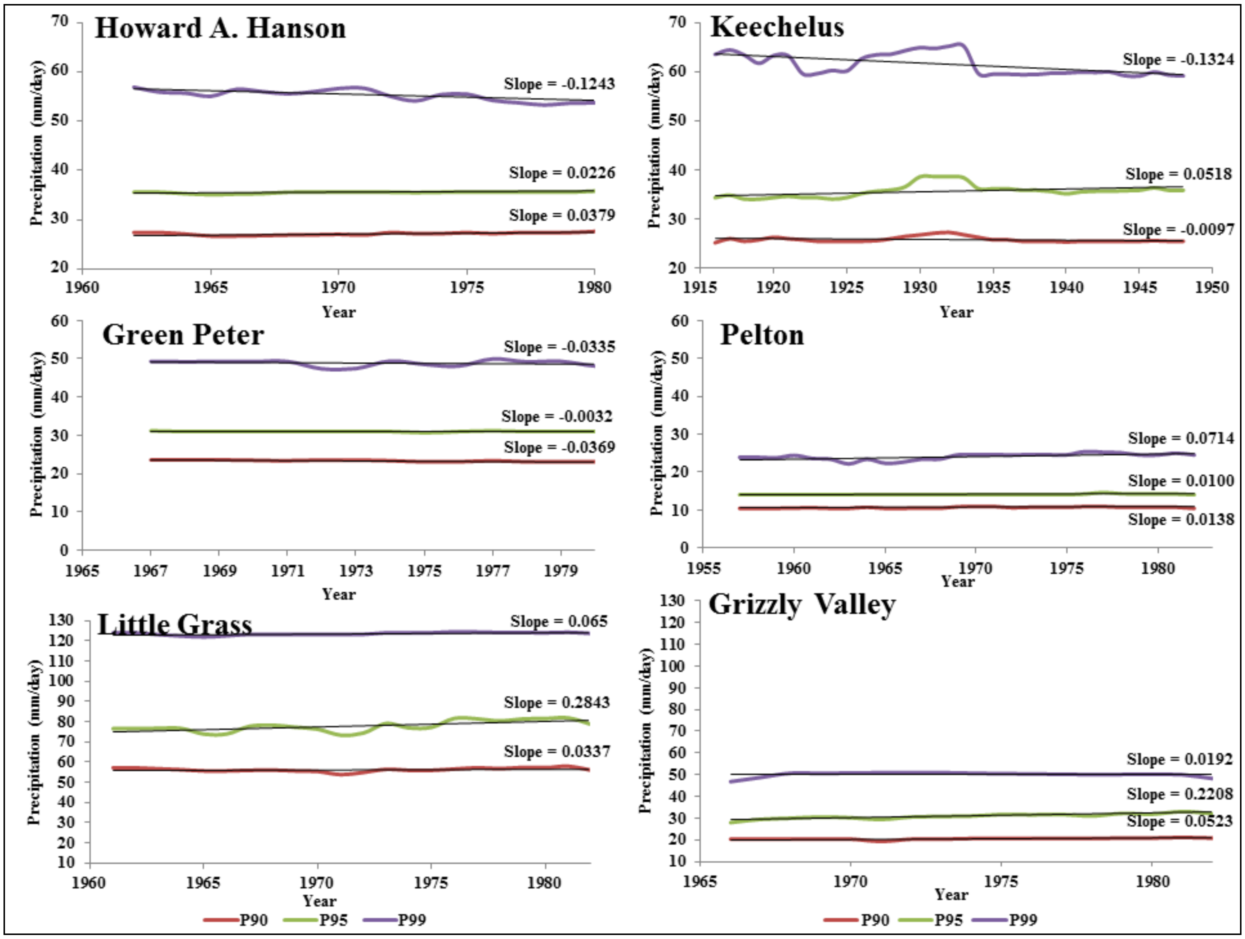

Figure 7: Precipitation percentile (P90, P95, and P99) for selected dam locations on windward side (left panels) and leeward side (right panels) of Cascade Ranges (upper two panels) and Sierra Nevada (lower panel) in post-dam period.

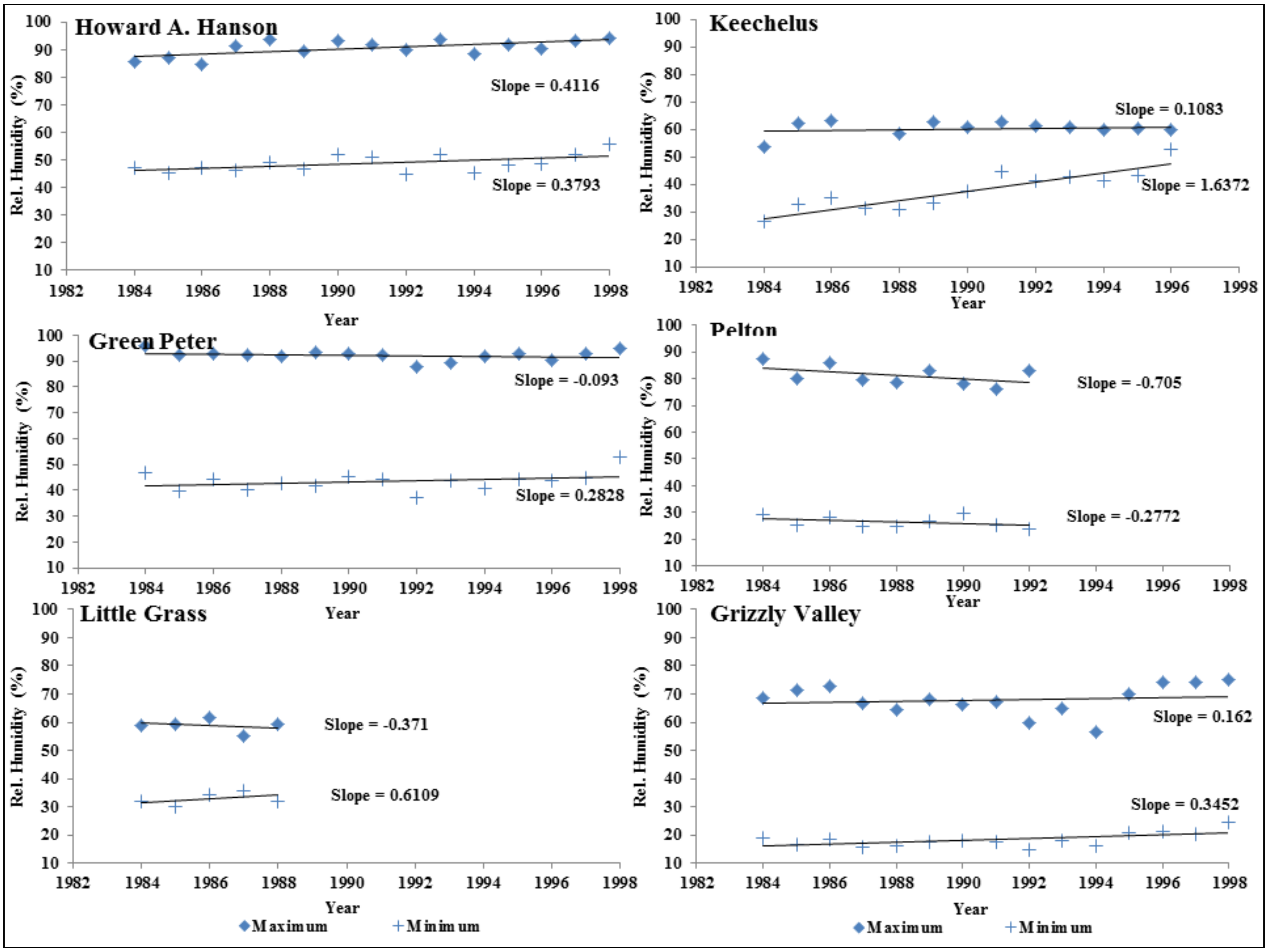

Figure 8: Mean daily relative humidity and their slope for dams on windward side (left two panels) and leeward side.

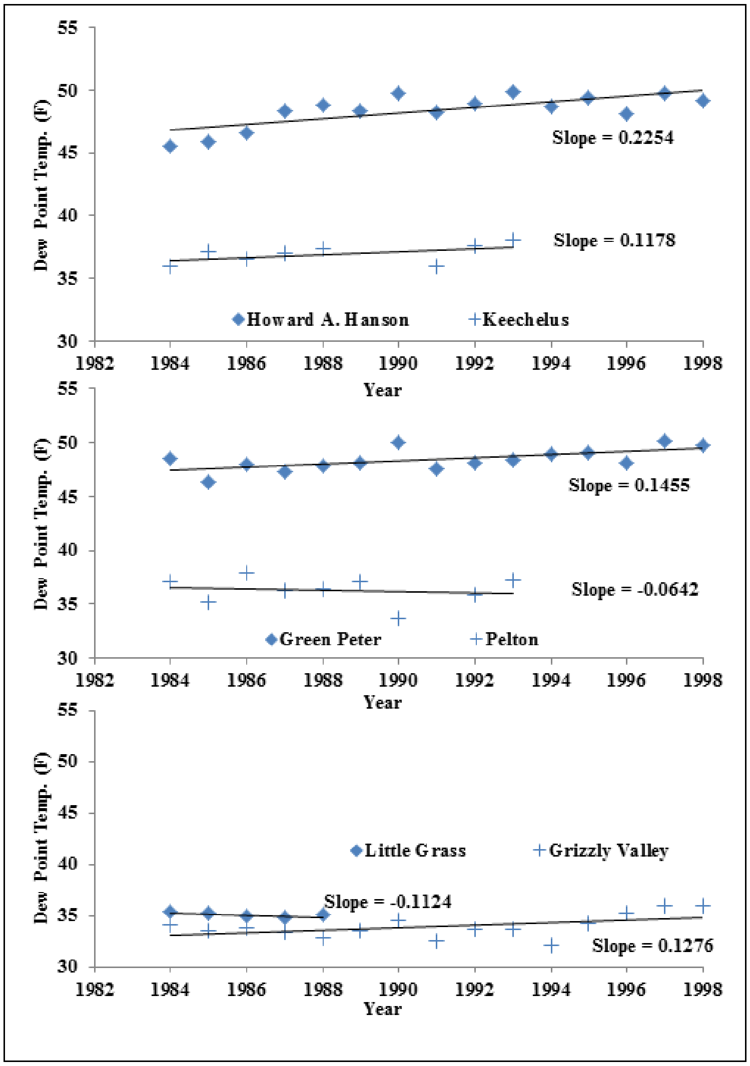

Figure 9: Daily mean dew point temperature comparisons for windward and leeward dams.