Attribution and Characteristics of Wet and Dry Seasons in the Upper Colorado River Basin

REBECCA A. BOLINGER,* CHRISTIAN D. KUMMEROW, AND NOLAN J. DOESKEN
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

(Manuscript received 11 October 2013, in final form 8 July 2014)

ABSTRACT

Previous research has shown that the temperature and precipitation variability in the Upper Colorado River basin (UCRB) is correlated with large-scale climate variability [i.e., El Niño–Southern Oscillation (ENSO) and Pacific decadal oscillation (PDO)]. But this correlation is not very strong, suggesting the need to look beyond the statistics. Looking at monthly contributions across the basin, results show that February is least sensitive to variability, and a wet October could be a good predictor for a wet season. A case study of a wet and a dry year (with similar ENSO/PDO conditions) shows that the occurrence of a few large accumulating events is what drives the seasonal variability, and these large events can happen under a variety of synoptic conditions. Looking at several physical factors that can impact the amount of accumulation in any given event, it is found that large accumulating events (>10 mm in one day) are associated with westerly winds at all levels, higher wind speeds at all levels, and greater amounts of total precipitable water. The most important difference between a large accumulating and small accumulating event is the presence of a strong (≥4 ms⁻¹) low-level westerly wind. Because much more emphasis should be given to this more local feature, as opposed to large-scale variability, an accurate seasonal forecast for the basin is not producible at this time.

1. Introduction

The water supply for much of the southwestern United States begins as snowpack in the Upper Colorado River basin (UCRB). This water supply is sensitive to variability in snowpack and subsequent runoff, which are mostly modulated by variability in precipitation and temperature in the UCRB. A thorough understanding of the hydroclimatic variability in the UCRB is necessary in order to improve predictability. The Colorado Basin River Forecast Center (CBRFC) currently releases seasonal streamflow and water supply forecasts beginning in January (forecasting for the spring runoff and summer water demand seasons), but there is a greater desire from water managers and planners to have forecasts beginning in October of the previous year (i.e., the beginning of the water year). Franz et al. (2003) stated that earlier in the water year, the main source of forecasting uncertainty is meteorology. Later in the season (close to spring), meteorology has less of an impact, as existing conditions (i.e., snowpack) increasingly play a larger role in forecasting streamflow and water supply.

Many studies have attempted to identify what drives variability in the region. Hurkmans et al. (2009), Kim et al. (2006), and Hidalgo and Dracup (2003) have found that warm season precipitation in the UCRB is more strongly correlated with the El Niño–Southern Oscillation (ENSO) than cold season precipitation. Similarly, Aziz et al. (2010) used singular value decomposition to conclude that ENSO and the Pacific decadal oscillation (PDO) are not the primary drivers for snowpack variability in the basin. Other studies have found the opposite: Mo et al. (2009), Timilsena et al. (2009), Hunter et al. (2006), and McCabe and Dettinger (2002) all found correlations between the basin’s winter variability and ENSO/PDO. Additional studies have found that other oceanic regions, aside from the eastern tropical Pacific (ENSO) and the northern Pacific (PDO), were better correlated with the basin’s variability (Nowak et al. 2012; Aziz et al. 2010; Switanek et al. 2009). Some studies have

* Current affiliation: NOAA/Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan.

Corresponding author address: Rebecca A. Bolinger, NOAA/Great Lakes Environmental Research Laboratory, 4840 S. State Rd., Ann Arbor, MI 48108.

E-mail: becky.bolinger@noaa.gov

DOI: 10.1175/JCLI-D-13-00618.1

© 2014 American Meteorological Society
shown that UCRB climate is dominated by variances on decadal-to-multidecadal time scales (Nowak et al. 2012; Ault and St. George 2010).

Using 100 yr of precipitation and temperature data provided by the Parameter-Elevation Relationships on Independent Slopes Model (PRISM) Climate Group (see section 2), this study confirms a correlation between UCRB variability and the ENSO and PDO ocean regions (see Fig. 2). Although significant (at the 90% confidence interval), these correlations are not very strong (typically less than 0.4). Additionally, an EOF analysis shows that ENSO and PDO only explain around 10% of the variance in the basin. Most of the basin’s variability is dominated by a strong year-to-year signal.

Previous studies have also tried to improve long-term predictions of streamflow in the region. Franz et al. (2003) detail the ensemble streamflow prediction (ESP) forecasts used by the National Weather Service (NWS) River Forecast Centers (RFCs, CBRFC included). The ESP forecasts combine a soil moisture accounting model with a snow model and a streamflow routing algorithm. Starting with current basin conditions, a range of historical temperature and precipitation values are input into the model to produce an ensemble of possible streamflow scenarios. Werner et al. (2004) found that adding ENSO conditions to the model did not improve forecasts for the UCRB. Other studies have found only weak to no lag correlations between the UCRB hydroclimate and ENSO/PDO indices (Hurvans et al. 2009; McCabe and Dettinger 2002).

Some older studies have focused on more local, synoptic-scale statistics of winter season precipitation in the region, without regard to ocean indices. Rasmussen (1968) found that winter storm periods over the UCRB were generally associated with 500-hPa southwesterly flow, while northerly 500-hPa flow was more dominant during dry periods. Similarly, Changnon et al. (1993) found an overall higher number of 500-hPa southwest troughs and a lower occurrence of dry ridge patterns during wet snowpack years over the Rocky Mountains. Although both studies identified a statistical relationship between the 500-hPa pattern and the region’s winter precipitation, neither study focused in on specific storms or attribution.

Until now, the majority of studies have focused on identifying statistical relationships between the regional climate variability and large-scale climate drivers and using those statistical relationships as a basis for predictability. With the lack of any clear indicators that these statistical relationships can actually be utilized to improve seasonal forecasting, further research must be done. First and foremost, there is still a need to identify the primary causes of variability in the UCRB in order to improve upon seasonal predictability.

The objectives of this study are 1) to identify the primary contributors to winter seasonal precipitation in the basin and 2) to improve our understanding of the local drivers that modulate wet seasons versus dry seasons. The former is accomplished by focusing on monthly precipitation statistics and how they impact seasonal variability. For the latter, a detailed case study of one wet winter and one dry winter is presented. Event statistics for 10 seasons are also analyzed.

This paper is organized as follows. Section 2 describes the data and methodologies used. Section 3 analyzes the subseasonal characteristics by looking at monthly contributions and identifying differences between wet years and dry years. A wet and dry year case study (with similar ENSO/PDO conditions) is thoroughly detailed in section 4. In section 5, several key physical characteristics are analyzed for 10 winter seasons, and conclusions are presented in section 6.

2. Basin data and variability

a. Data

The UCRB, with an areal size of about $2.6 \times 10^5$ km², is located in the western United States. For this study, the entire basin will be analyzed as one basin average and will also be separated into its eight subbasins (Fig. 1, top): Upper Green (UG), Yampa-White (Y-W), Upper Colorado (UC), Gunnison (Gun), Dolores (Dol), San Juan (SJ), Dirty Devil (DD), and Lower Green (LG) basins.

Precipitation and temperature data from the PRISM dataset (PRISM Climate Group 2013) are used for the UCRB. The PRISM dataset is described in detail by Daly et al. (1994). The monthly data are available at 4-km gridded resolution from 1895 to the present. This study will analyze 100 yr of monthly data, 1911–2010. PRISM data are derived from in situ observations and have been shown to capture the magnitude and variability of precipitation over the UCRB reasonably well (Smith and Kummerow 2013).

For the wet year and dry year case study, daily data from the Natural Resources Conservation Service’s (NRCS) National Weather and Climate Center (NWCC) Snow Telemetry (SNOTEL) network (NRCS NWCC 2013) are used. The subbasin-averaged snowpack is calculated from every SNOTEL site’s snow water equivalent data. Accumulation days are identified as days when the snowpack is greater than on the previous day. Accumulation days for the basin are calculated by taking the difference in one day’s basin-averaged snowpack from the previous day’s basin-averaged snowpack. This is used to determine the fundamental differences between the two seasons. Surface and pressure level
variables from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim; Dee et al. 2011) are used for synoptic analysis during the case study.

b. Basin variability

Correlations between UCRB October maximum temperature and October sea surface temperature (SST) are shown in Fig. 2 (correlations for precipitation discussed but not shown). SST data are taken from the Hadley Centre (Rayner et al. 2003), and to eliminate smaller-scale variability. SSTs are spatially averaged using a 10° latitude by 10° longitude moving window. All of the individual subbasins show nearly identical correlation patterns in the ENSO and PDO regions for both temperature and precipitation. UCRB temperatures are negatively correlated with the ENSO region (e.g., warmer-than-average SSTs, El Niño, are associated with cooler-than-average UCRB temperatures), while UCRB precipitation shows positive correlations.

UCRB temperature also shows positive correlations around 35°N in the Pacific Ocean, wrapped around a negative correlation maximum south of Alaska (i.e., the PDO region). The cool phase of the PDO (where temperatures at 35°N in the Pacific are warmer than average) is associated with warmer-than-average temperatures and less-than-average precipitation. When ENSO and PDO are in phase, they act to enhance the effects over the UCRB, which has previously been shown.

As was noted in the introduction, although correlations shown in Fig. 2 are significant, they are not particularly strong, with magnitudes no greater than 0.4. Figure 3 shows the comparison between the UC subbasin’s October maximum temperature and October SSTs over the area of highest correlation in the PDO region. Though the relationship is clear, there is still significant scatter—for example, there are many times when the UC’s temperature is below average, even when the SSTs in the North Pacific are above average.

Analysis of correlations for the months November through June and lag correlations were also performed (not shown). The results indicate that the fall months show the strongest correlation between UCRB variability and ENSO/PDO, with weak to no correlations during the winter and spring months. Additionally, the only significant lag correlation in the ENSO/PDO region is evident for the October–November time period (with a one-month lag).

Overall, the basin variability’s connection to largescale variability does not fully answer the question of what drives the variability of the basin. The following sections shed more light on the UCRB’s variability.

3. Subseasonal characteristics

To better analyze the mechanisms that control the variability of the UCRB, it is important to understand each month’s impact on the season as a whole and how that changes for wet or dry seasons. Monthly and seasonal percent of average precipitation is calculated for each subbasin, with statistics shown for wet and dry seasons in Figs. 4 and 5. In this section, dry refers to precipitation less than 90% of average, and wet refers to precipitation greater than 110% of average.
When looking at each month’s contribution to the seasonal total (Fig. 4), March and April are the largest contributors for the northern subbasins (UC, Gun, UG, and Y-W). October is the largest contributor to the seasonal total for the southern subbasins (Dol, LG, DD, and SJ). When combined with the correlations, this is an important result. For the northern subbasins, the largest contributing months are during a time (in the spring) when there is very little correlation (and no lag correlations) between precipitation and large-scale forcings (such as ENSO or PDO). Therefore, a long-term prediction at the beginning of the season would have little skill. There could, however, be more skill for the southern subbasins, where October is the largest contributing month, and October climate also has the strongest correlation to large-scale forcings.

For all of the subbasins, June contributes the smallest percentage to the seasonal total (and usually little to no snow accumulation; Fig. 4). During the winter months, each subbasin varies in the smallest contributing month. In general, February is the least sensitive to variability, so it contributes much more to dry season totals and much less to wet season totals. The southern subbasins exhibit much higher variability throughout all the months.

Looking at Fig. 5, for most of the subbasins, spring months are generally wet during wet seasons. February is the least sensitive month to wet seasons, and can be either wet or dry. During dry seasons, October is usually drier than average for most of the subbasins. Additionally, October can be dry during a wet season. The occurrence of a wet October is much more common in a wet season than a dry one, therefore a wet October could be a good predictor for the season as a whole. Overall (especially for the southern subbasins) there is a higher frequency of occurrence of dry months. Therefore, the occurrence of a dry month does not necessarily aide in the prediction of a dry or wet season.

Both Figs. 4 and 5, and the correlations statistics, point to the greater importance of October over the other months. October has a stronger correlation to ENSO and PDO (which can be predicted to a certain degree of accuracy over a longer time period). As October is the largest contributing month to the southern subbasins’ seasonal precipitation total, the predicted ENSO/PDO phases for October could give a better idea of what might happen over the southern subbasins. Additionally, the occurrence of a wet October greatly increases the possibility of a wet season overall for all of the subbasins.

4. Case study

The statistics have shown that large-scale climate variability and basin variability are correlated, but the connection isn’t clear or robust. To further examine this,
two seasons with similar ENSO and PDO signals are examined. Though the large-scale climate indices are similar for the two seasons, the basin’s response is very different. The time series in Fig. 6 show that the 2002 (top, a dry year) and 1997 (bottom, a wet year) winters were very similar in the ENSO region. Both seasons start with slightly below-average SSTs, increasing to the ENSO cold phase in the winter months. By the spring, both seasons were in the warm phase of ENSO. Their PDO time series (not shown) also share similarities. Both seasons start in the PDO cold phase and end in the warm phase by the end of the summer. Their springs are

Fig. 4. For each subbasin, each month’s percent contribution to the seasonal total for average years (gray bars), dry years (maroon bars), and wet years (blue bars).

Fig. 5. For each subbasin, number of occurrences of wet (blue) and dry (red) months during dry seasons (left bars) and wet seasons (right bars).
slightly different, as the 1997 season is in the warm phase by May, while the 2002 season stays in the cold phase through the spring.

Correlations statistics between SST and the basin show that the cold ENSO phase in the fall is generally associated with negative standardized precipitation index (SPI; see appendix for more details) and above-average temperatures. The cold phase of the PDO would act to enhance this relationship. Table 1 shows the monthly SPIs and departures from average temperature for the month. (Values are normalized.)

<table>
<thead>
<tr>
<th>Month</th>
<th>SPI 1997</th>
<th>SPI 2002</th>
<th>Temp 1997</th>
<th>Temp 2002</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>+0.59</td>
<td>-0.66</td>
<td>-0.87</td>
<td>+1.17</td>
</tr>
<tr>
<td>November</td>
<td>+1.00</td>
<td>+0.38</td>
<td>+0.82</td>
<td>+2.25</td>
</tr>
<tr>
<td>December</td>
<td>+0.37</td>
<td>-0.23</td>
<td>+0.97</td>
<td>-0.89</td>
</tr>
<tr>
<td>January</td>
<td>+1.32</td>
<td>-0.99</td>
<td>+0.55</td>
<td>-0.00</td>
</tr>
<tr>
<td>February</td>
<td>-0.20</td>
<td>-1.59</td>
<td>-0.67</td>
<td>-1.11</td>
</tr>
<tr>
<td>March</td>
<td>-1.44</td>
<td>-0.44</td>
<td>+1.80</td>
<td>-1.06</td>
</tr>
<tr>
<td>April</td>
<td>+1.23</td>
<td>-0.79</td>
<td>-1.85</td>
<td>+2.51</td>
</tr>
<tr>
<td>May</td>
<td>+0.50</td>
<td>-1.36</td>
<td>+0.96</td>
<td>+0.86</td>
</tr>
<tr>
<td>June</td>
<td>+0.60</td>
<td>-1.08</td>
<td>+0.47</td>
<td>+2.66</td>
</tr>
</tbody>
</table>

SNOTEL snowpack data are used to look at the daily statistics of each season. From the beginning of the water year to the last day of snowmelt season, the 1997 snowpack period lasted 295 days, and the 2002 snowpack period lasted 253 days. Although, the 1997 snowpack period only had 14 more accumulation days than 2002 (accumulation day defined as one day’s snowpack greater than the previous day’s, in section 2). Focusing on the distribution of just the accumulation days (Fig. 7), accumulations less than 2.5 mm are the most common for both seasons. However, those lowest accumulations account for more than 80% of all the accumulation days in 2002, and less than 60% of the accumulation days in 1997. The 1997 accumulation season has a much higher frequency of higher accumulations than 2002.

In the 2002 season, there were only two days when snowpack accumulation was greater than 10 mm; these occurred in November, the only positive SPI month in the October–June season (Table 1). In the 1997 season, for the period of October–April, most of the months had more than one day with accumulations greater than 10 mm; the only months that didn’t have multiple large
accumulation days were February and March (the only negative SPI months, as seen in Table 1).

The daily statistics for the two winters suggest that a wetter-than-average season will have an increase in frequency of large accumulation days, as opposed to more snowy days in general. Because large accumulation days define the difference between wet and dry seasons, it is important to know what causes large accumulations in the basin. Heavy basin snowfall requires three components: upward vertical motion, instability, and a source of moisture. The upward vertical motion, or lift, comes from the rising air that is forced upward because of orographic influences. This lifting mechanism can become even stronger in the presence of unstable air, which is needed for larger accumulating events. This unstable air (warmer air below colder air) can be provided in several different ways, including frontal passage or the passage of a baroclinic trough. What exactly provides the instability for an individual heavy storm over the basin is not easy to predict on a short time scale (i.e., one week), thus adding to the extreme difficulty of seasonal prediction for the area. The moisture for the basin is most often provided by maritime polar (mP) air masses that travel from the northern Pacific across the western United States. These air masses are modified as they pass over the complex terrain of the western United States, so the amount of moisture available when they reach the basin is variable with each system. Also, the exact position of fronts and surface lows associated with the air mass can cause widely varying results in the basin. Closer examination of specific storms will provide more information.

The days of 26–27 January 1997 were two of the largest accumulation days in the 1997 winter season, with a two-day total accumulation of 32 mm. Before the start of this event, a surface low moved southward, staying on the northern fringes of the UCRB, while a weak surface high pressure set up over the southern part of the basin (Fig. 8, top left). The pressure gradient over the basin would have resulted in westerly flow across the basin and a very strong high pressure region across the U. S. Midwest would have blocked the surface low from quickly moving away from the basin. The two-day storm totals show widespread precipitation over much of the western United States, with the heaviest amounts in northern California and dry conditions over Washington (Fig. 8, top right). Surface analysis does not show evidence of the passage of a strong cold front, and 500-hPa heights were mainly zonal over the region. As such, it is difficult to determine the storm’s major source of instability over the basin.

The days of 27–28 January 2002 exhibited a similar synoptic setup to the 1997 storm. A surface low pressure center settled over eastern Wyoming, with a weak surface high pressure over the southern part of the basin (Fig. 8, bottom left). With the pressure gradient and location of fronts around the basin, a similar westerly flow would have resulted across the basin. But the two-day total snowpack accumulation over the basin was less than 4 mm. Precipitation totals show that precipitation was not as widespread or as intense (Fig. 8, bottom right). Frontal passage had also not occurred during this time period, but the 500-hPa heights do show a large trough to the west, bringing southwesterly flow into the basin (unlike the zonal flow from the 1997 example).

Although the orographic component was present for both of the storms, the accumulations for the 2002 storm were much less. It is difficult to determine with certainty the reasons for this, but there are a couple of possibilities. In the reanalysis (Fig. 8, left), pressure gradients appear to be somewhat stronger in the 1997 storm. This could mean that the 2002 storm did not have a strong enough westerly component to generate the upward motion needed for larger accumulations. Additionally, the southwesterly flow aloft could have brought in warmer air than what was at the surface, acting to stabilize the region. Another possibility is that the modified mP air mass over the area for the 1997 storm could have had more moisture associated with it. The entire western region received less precipitation in the 2002 example, suggesting that the air mass itself was not as strong of a moisture source. Also, the presence of the strong high pressure in the eastern United States could have played a role in making the 1997 storm’s duration longer.

Perhaps the low pressure center in the 2002 example
was allowed to pass by too quickly for larger accumulations to occur.

The basic synoptic setup of the two storms is very similar, but minor differences changed the overall results, leading to very different snow accumulations over the basin. Looking at the other storms in 1997, there is much diversity in the synoptic-scale patterns that resulted in larger accumulations. Essentially, no two storms were the same. More in-depth investigation into the local details that could impact the strength or intensity of any given event over the basin is necessary and will be examined in the next section.

5. Event statistics

a. Accumulations

In the previous section, a discrepancy between the number of large accumulating events was found between the wet and dry winters (Fig. 7). This raises a couple of questions. First, is there typically a greater number of large accumulating events in wet winters compared to dry winters? If so, is the number of large accumulating events in a wet winter typically an order of magnitude greater than the number of large accumulating events in a dry winter? This is important to note, because an order of magnitude difference between wet and dry winters would point to the likelihood of some larger-scale, persistent pattern that could be predicted. A smaller difference between wet and dry winters would suggest more randomness.

In Fig. 9, the number of small, medium, and large accumulating events for 10 yr of basin-averaged SNOTEL accumulation data are plotted. The magnitudes of each category were chosen by analyzing Fig. 7, which clearly shows that the majority of accumulating events are less than 2.5 mm (small events). The previous section found the largest discrepancy between a wet and dry winter for events greater than 10 mm (large events). Therefore,
medium events would populate the rest of the accumulating events in a winter (2.5–10 mm).

The three driest winters in the 10-yr period are 2002, 2004, and 2006, all of which have the smallest numbers of large accumulating events (2, 5, and 5, respectively). The three wettest winters (2005, 2008, and 2009) have the largest numbers of large accumulating events (11, 11, and 8, respectively). The number of small and medium accumulating events varies from year to year and is not always consistent for dry winters or wet winters (although it is generally more common to have a greater number of medium accumulating events in a wetter winter). Figure 9 further proves that it is the number of large accumulating events that determines how wet or dry a winter is.

While it is clear that large accumulating events are important, it is not clear that this is a predictable factor. The difference between a dry winter and wet winter is less than 10 events, less than an order of magnitude. Therefore, it can be assumed that the number of accumulating events in a given winter is more random and less due to any larger-scale patterns that would likely result in a greater discrepancy between the wetter and drier winters.

The next logical step is to determine what factors are the catalysts for the life of a large accumulating event. As the large accumulating events set apart the wet seasons from the dry seasons, the factors that drive these events need to be acknowledged. In the following paragraphs, two important contributing factors, wind and moisture, are examined by event size.

**b. Wind velocities**

Wind speed and direction could both impact accumulating events over the basin. Wind direction can be important for several reasons: moisture advection, temperature advection, and orographic lift. The wind speed will affect the intensity of the advection and lift. ERA-Interim wind speed and direction are analyzed at the high level (300 hPa), midlevel (between 500 and 700 hPa), and low level (between 750 and 850 hPa, depending on the elevation of the grid point in the basin). Daily values are categorized based on the previously determined large, medium, and small accumulating event dates for 2001–10.

At high and midlevels, the predominant wind directions for large, medium, and small accumulating events are from the west, southwest, and northwest. Large accumulating events tend to have a higher occurrence of southwesterly flow, while medium and small accumulating events have higher occurrences of northerly flow. This differentiation is likely due to more moisture and warmer temperatures being advected into the basin for the large accumulating events, while winds from the north will be colder and drier. Low-level wind direction is shown in the top panel of Fig. 10, which shows a much greater divergence between the characteristics of large and small accumulating events. Low-level easterly winds are quite common for small accumulating events but rarely ever occur during a large accumulating event. Conversely, westerly winds are very likely in a large accumulating event (occurring 80% of...
the time) but happen much less often for a small accumulating event (30% of the time).

Because the westerly component is the most frequently occurring direction at all levels (especially for large accumulating events), wind speed is analyzed only for events with winds from the west, southwest, or northwest. As would be expected, higher wind speeds at the high and midlevels are more common for large accumulating events. As shown in the bottom panel of Fig. 10, low level wind speeds for small accumulating events are most often 2–6 m s$^{-1}$, while large accumulating events are most often 4–8 m s$^{-1}$. At the low levels, it’s evidenced that 71% of all large accumulating events are associated with a strong (greater than 4 m s$^{-1}$) westerly wind, while only 14% of small accumulating events have a strong westerly wind.

Focusing on the two individual storms that were analyzed in the previous section (26–27 January 1997 and 27–28 January 2002), wind direction and speed are studied at all levels before, during, and after the events. The 2002 event shows slightly higher low-level wind speeds, but the 1997 event shows a southwesterly component at one point during the event, while the 2002 storm only shows a westerly direction after the event. Also noteworthy, the 1997 event shows the highest upper-level wind speeds before the event, while in 2002, the highest upper-level wind speeds occur after the event. Although outside the scope of this study, this may suggest that the specific timing of certain wind velocities at different levels may be important for overall accumulations over the basin.

c. Total precipitable water

Also important to the generation of an accumulating event is the moisture available in the region. ERA-Interim total column water vapor [hereinafter referred to as total precipitable water (TPW)] is analyzed for every year from 2001 to 2010. Based on the assumption that a wetter year may have more days with a greater moisture content in the atmosphere, Table 2 shows the number of days in each winter where the maximum daily, basin-averaged TPW was greater than 11 mm. Interestingly, there appears to be no correlation between the number of days with higher atmospheric moisture content and how wet or dry the overall season was. For example, 2008 (a wetter winter) had 41 days with higher TPW, 20 days less than the total for 2002, which is the driest winter of all 10 winters shown. This may suggest that storms during a wet season are more efficient at capitalizing on the higher moisture content.

Similar to the wind analysis, Fig. 11 shows TPW for large, medium, and small accumulating events. The majority of small accumulating events are associated with 4–12 mm of TPW, while the majority of large accumulating events have slightly higher moisture (8–16 mm of TPW). While this does show that large accumulating events tend to have more moisture than
small accumulating events, the results are less diverse than what was seen with the wind analysis. Both the yearly and event-specific TPW analyses suggest that events are not as sensitive to moisture variability.

6. Conclusions

Based on the vulnerability of the water supply in the west coupled with limited supplies and large water demands, it is becoming increasingly important to better understand and predict the variability of water in the Upper Colorado River basin. Many studies have already investigated the statistical relationship between the region’s variability and large-scale climate variability. This study expands on this knowledge by examining each month’s contributions to wet and dry seasons and analyzing the physical characteristics of wet and dry seasons and specific storms.

A detailed investigation of the subseasonal characteristics in each subbasin yielded several interesting results. For the northern subbasins, March and April are generally the largest contributors to the seasonal total, while October is usually the largest contributor for the southern subbasins. The southern subbasins exhibit more variability (monthly and seasonally) than the northern subbasins. Overall, February shows the least variability, regardless of if the season is wet, dry, or average.

Both SST correlations and the monthly analysis point to the importance of October. For the southern subbasins, October precipitation is the largest contributor to the seasonal total, and October is also more strongly correlated with ENSO/PDO. Additionally, a wet October increases the likelihood of a wet season. Smith and Kummerow (2013) have already found October to be an important month for the hydroclimate of the UCRB. When cold season precipitation falls as rain instead of snow (more likely to happen early in the season, like October), the seasonal total could be wetter than average but overall runoff will be reduced because of lower peak snowpack. The results for October do show that it could provide some information about the rest of the season (particularly after a wet October), but the correlations are still not strong enough to solely depend on statistics for an accurate prediction. Additional research can be done in the future to further verify the importance of October and its possible usefulness in seasonal prediction.

A case study looked in depth at the 1997 and 2002 seasons—both showed similar ENSO and PDO conditions, but 1997 was a wet season, while 2002 was dry. The ENSO and PDO conditions (both mainly in the cold phase during the winter), could increase the possibility of warm and dry conditions across the basin (based on correlation analysis). The majority of the months during the 2002 season were warmer and drier. Although there were warmer-than-average months during the 1997 season, most of the months were wet.

There was only a minimal difference in the number of snow accumulation days between the seasons; however, 1997 had a much greater frequency of large accumulation days (greater than 10 mm). This result supports a previous study that concluded the basin’s water balance was more dependent on large accumulating and longer-duration winter storm events (Rasmussen 1968). A qualitative analysis of a 1997 storm with the largest 24-h accumulation of the season (at 19 mm) showed a slow-moving surface low along the northern part of the basin, with fronts surrounding the basin to the east and to the north and a surface high to the south. The prevailing flow across the basin was westerly. A similar synoptic pattern was found during the 2002 season, but minor differences resulted in a much lower accumulating storm (less than 4 mm). When evaluating the synoptic conditions for several other larger accumulating storms during both seasons, diverse results could be found. Modification of air masses, precise positioning of troughs and fronts, and the speed and intensity of the troughs could ultimately affect the amount of accumulation over the basin. Therefore, an event-based analysis of key physical factors that could impact an event was performed.

The event-based analysis showed that low-level wind direction is one of the most important factors that could impact the amount of accumulation in a precipitation
event over the basin. Low-level westerly winds are needed for a large accumulating event to occur. Easterly winds will result in a smaller accumulating event. Figure 10 showed that 71% of large accumulating events have a strong, low-level westerly wind (compared to only 14% of small accumulating events). The event-based analysis also highlighted the connections between upper-level wind direction, wind speed, and TPW with event accumulations; however, these connections were not as strong. The conclusions that can be extrapolated from the event-based analysis are as follows: 1) large accumulating events are most impacted by the presence of a strong, low-level westerly wind; 2) since a wet season is defined as having more large accumulating events, a wet season would require an increased frequency of synoptic conditions that are favorable for the onset of strong, low-level westerly winds; and 3) because low-level winds are regularly modified by more local or mesoscale variations (more so than upper-level winds, which are dominated by synoptic-scale variability), it would be extremely difficult to forecast, long term, how many large accumulating events could possibly occur.

Areas of further research could include other local or synoptic drivers of accumulating events, including the overall speed and intensity of troughs and cold fronts, the relative location of low or high pressure centers outside of the basin, and the evolution of physical characteristics before and during accumulating events. It also seems necessary to use these smaller-scale processes to complement the connections the basin has with large-scale variability. Ideally in the future, one could combine the correlations with SST and the basin’s relationship with synoptic and smaller-scale components to come up with a more reliable prediction.

Basin variability has proven to be complex and diverse. Large-scale climate variability (i.e., SST), although present, is not the primary contributor to basin variability and is not recommended for use as a predictor. Additionally, the basin’s sensitivity to much smaller scale factors leads to the conclusion that accurate seasonal prediction is not realistic at this time.

Acknowledgments. The authors wish to thank the two anonymous reviewers for their valuable comments. This research is funded by a grant from NOAA’s National Integrated Drought Information System.

APPENDIX

SPI and Z Score

The correlation and EOF analyses (referenced in sections 1 and 2), were performed by calculating a SPI and a temperature Z score for the UCRB (and a temperature Z score for SST). SPI results are also shown in Table 1. The use of SPI and temperature Z score in these instances is preferable for the use of statistical analysis of variability, because both variables (T and P) are normalized.

A standardized precipitation index is calculated for each 4-km grid point in the UCRB. SPIs are calculated by taking the 100 yr of precipitation data (which follow a gamma distribution) and normalizing them into a Gaussian distribution (McKee et al. 1993). A cumulative distribution function is then calculated, and from that an index is created (similar to a Z score) which ranks precipitation from around −3 (extremely dry) to +3 (extremely wet), with 0 representing the 50th-percentile ranking. This study analyzes the one-month SPIs from October to June (marking the beginning of the water year and capturing critical snow accumulation and snowmelt time frames). Each 4-km grid point within a subbasin is averaged together for one subbasin average. All of the 4-km grid points in the UCRB are also averaged together for one basin average.

A temperature Z score is calculated for maximum temperatures at each 4-km grid point in the basin. Z scores are calculated by computing the 100-yr average for each individual month, removing the average from that specific month, and dividing by the standard deviation. As with the SPI, subbasin averages and one entire basin average are calculated.

REFERENCES


PRISM Climate Group, cited 2013: PRISM Climate Group, Oregon State University. [Available online at http://www.prism.oregonstate.edu.]


