

Incorporating decadal climate variability information in the operation and design of water infrastructure

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ABSTRACT

The high thermal and mechanical inertia of the oceans results in slow changes in sea surface temperatures (SSTs). Changes in SSTs, in turn, can impact atmospheric circulation including water vapor transport, precipitation, and temperatures throughout the world. The Pacific Decadal Oscillation (PDO), the tropical Atlantic SST gradient variability, and the West Pacific Warm Pool are patterns of natural climate variability that tend to persist over decadal time periods. There are current efforts to produce decadal climate predictions, but there is limited understanding if this information can be used in water resources management. Understanding the current state of decadal climate variability (DCV) phenomena and the probability of persisting in that state may be useful information for water managers. This information could improve forecasts that aid operations and short-term planning for reservoir management, domestic and industrial water supplies, flood risk management, energy production, recreation, inland navigation, and irrigation. If conditions indicate a higher likelihood of drought, reservoir managers could reduce flood storage space and increase storage for conservation purposes. Improved forecasts for irrigation could result in greater efficiencies by shifting crops and rotational crop patterns. The potential benefits of using a forecast must be balanced against the risk of damages if the forecast is wrong. Seasonal forecasts using DCV information could also be used to inform drought triggers. If DCV indices indicate that the climate has a higher probability of dry conditions, drought contingency plans could be triggered earlier. Understanding of DCV phenomena could also improve long-range water resources planning. DCV can manifest itself in relatively short-term hydrologic records as linear trends that complicate hydrologic frequency analysis, which has traditionally assumed that hydrologic records are stationary.

Key words: Decadal climate variability, Drought management, Nonstationary flood frequency analysis, Reservoir management

HIGHLIGHTS

- Knowledge of the current phase of decadal climate variability (DCV) indices and the probability of persisting in that state may be useful information for water managers for seasonal forecasts.
- DCV information could inform the allocation of flood storage and conservation storage spaces in reservoirs, but the potential use of DCV information depends on the risk if the forecasts are wrong.
- Analysis of DCV phenomena could help explain trends and breakpoints in nonstationary flood frequency analysis.

INTRODUCTION

Climate is a major driver of hydrologic conditions and varies on multiple time scales from sub-seasonal to decadal and centennial. This paper focuses on decadal climate variability (DCV) and its impacts on water resources

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management. DCV can be defined as quasi-oscillatory variability that occurs at approximately 8- to 20-year periods (Mehta, 2017, 2020). There are many potential water sectors affected by DCV, including reservoir management, flood and drought risk management, domestic and industrial water supplies, irrigation, energy production, recreation, and inland navigation (Mehta, 2017). DCV's manifestation in relatively short-term hydrologic records as linear trends can confound hydrologic frequency analysis, which has traditionally assumed that hydrologic records are statistically stationary. DCV and its hydrologic effects also confound the attribution of observed anomalies to natural variability or climate change, which can confuse adaptation planning in the short, medium, and long term. Therefore, it is very important to understand and, if possible, predict DCV effects on impacted sectors to inform water resources management in the short, medium, and long term. Empirical data analysis and simulations with climate models in the last 20–25 years have improved the understanding of DCV and have also stimulated decadal climate prediction efforts (see Mehta (2020) for a comprehensive review of the state of the DCV science and prediction). The goals of this paper are to familiarize the water resources management community with DCV and to evaluate the potential use of DCV information for the operation and design of water infrastructure. Although the examples illustrated here are from the United States, they are potentially applicable to other parts of the world.

BACKGROUND ON DCV

Natural processes in the Earth's climate system can cause internally generated climate variations at a variety of regular or irregular periods due to interactions among atmosphere, oceans, land surface, and snow and ice. Heat from the oceans is the major source of atmospheric motion. The specific heat capacity of sea water is approximately four times larger than air, and the density of sea water is approximately 1,000 times greater than air. Therefore, the oceans can absorb and retain much more heat than the atmosphere because the total heat capacity is the product of mass (density \times volume) and specific heat capacity. It is estimated that the upper two meters of the world's oceans contain as much heat as the entire global atmosphere. Therefore, the ocean to atmosphere heat transfer is the major source of heat for the atmosphere.

Changes in sea surface temperatures (SSTs) can impact atmospheric circulation including water vapor transport, precipitation, and temperatures throughout the world. SST changes can cause changes in jet stream location and strength, and thereby cause changes in storminess and precipitation (rain, snow) over the planet's oceans and land areas. The high thermal (heat capacity of sea water) and mechanical (density of sea water) inertia of the oceans cause very slow currents and waves, and very slow changes in temperatures, including SSTs. This slow change is in marked contrast to much faster atmospheric winds, waves, and temperature changes. In this way, SST changes over a few seasons to a few decades can cause changes in water vapor and heat (temperature) transports, and storminess over continents.

El Niño, for example, is a periodic warming of SSTs in the eastern tropical Pacific Ocean. The Southern Oscillation refers to an oscillation in surface air pressure between eastern and western Pacific regions. The two together are referred to as El Niño-Southern Oscillation (ENSO). La Niña is a periodic cooling of the eastern tropical Pacific Ocean (Philander, 1990; Glantz *et al.*, 1991; Rasmusson, 1991; Glantz, 2001). ENSO is the major pattern of natural climate variability on seasonal to interannual time scales. ENSO events happen irregularly at around 2- to 7-year intervals. Figure 1 shows a time series of SST in the Niño 3.4 region, with warmer SSTs being El Niño events. ENSO attributes, such as the frequency and intensity of El Niño and La Niña events, undergo decadal variability.

Other SST variability patterns – the Pacific Decadal Oscillation (PDO), the Tropical Atlantic SST gradient (TAG for brevity) variability, the West Pacific Warm Pool (WPWP) SST variability – have approximately decadal (8–20 years) periods. The PDO is a pattern of decadal–multidecadal variations that span the Pacific Ocean such

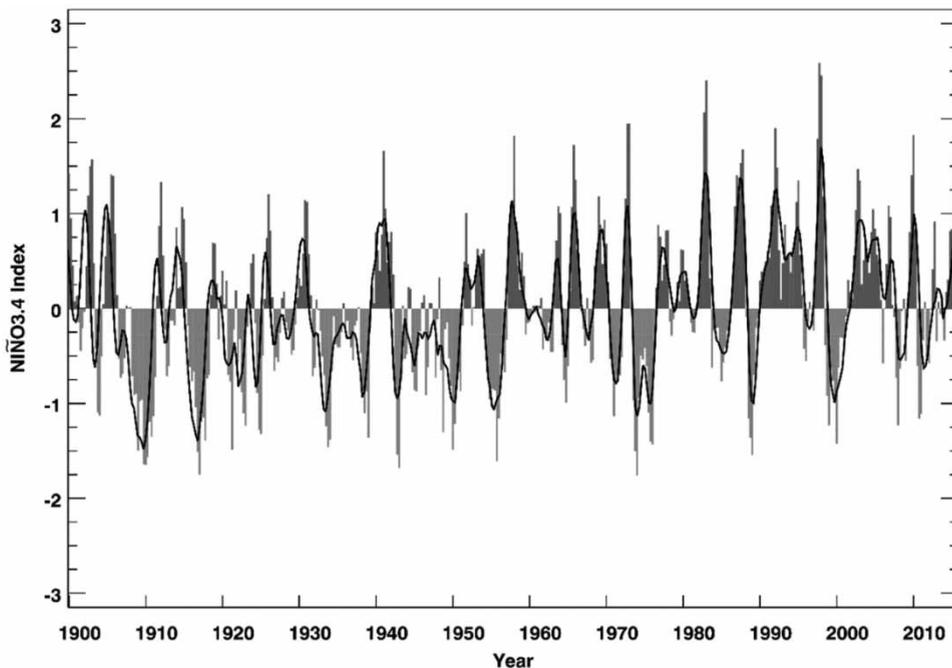


Fig. 1 | The 3-month average (Dec–Jan–Feb, Mar–Apr–May, Jun–Jul–Aug, Sep–Oct–Nov) Niño3.4 SST index (bars) from January 1900 to November 2015 and its 4-season running-average smoothed version (line).

that there are SST anomalies of one sign (positive or negative) in the tropical–subtropical Pacific and of the opposite sign in the mid-latitude Pacific (Mantua *et al.*, 1997). The PDO index time series is shown in Figure 2. In the positive or warm PDO phase, the SSTs in the tropical–subtropical Pacific and along the North and South American coasts are warmer than average, and those in the mid-latitude central and western Pacific are cooler than average. In the negative or cool PDO phase, the SSTs in the tropical–subtropical Pacific and along the North and South American coasts are cooler than average, and those in the mid-latitude central and western Pacific are warmer than average. Figure 2 shows that the PDO index from 1,900 to 2015 has undergone variability at a variety of periods from interannual to multidecadal, but the smoothed index clearly shows the prominence of decadal–multidecadal variability.

The TAG index is derived by averaging SST anomalies in a tropical North Atlantic box (5°–20°N, 30°–60°W) and a tropical South Atlantic box (0°–20°S, 30°W–10°E) and subtracting the latter from the former (Mehta, 1998; Rajagopalan *et al.*, 1998). The time series of the TAG index is shown in Figure 3. Empirical orthogonal function–principal component analysis of tropical Atlantic SST anomalies also reveals this SST pattern as the dominant pattern of tropical Atlantic SST variability. The TAG index varies at interannual to decadal and longer timescales as shown in Figure 3. The Atlantic Multidecadal Oscillation (AMO) Index is defined as a coherent pattern of variability in North Atlantic SSTs and is formed by averaging SST anomalies from the Equator to 80°N. The AMO index shows dominant variability at a period of 60–80 years and minor variability at a period of 10–12 years (Folland *et al.*, 1986, 2001; Schlesinger & Ramankutty, 1994).

The WPWP SST variability is yet another DCV phenomenon (Mehta, 2020). The western waters of the equatorial Pacific and the eastern Indian Ocean have the warmest seawaters in the world. The WPWP index from 1900 to 2015 has a clear warming trend, but the de-trended index shows variability over decadal time scales.

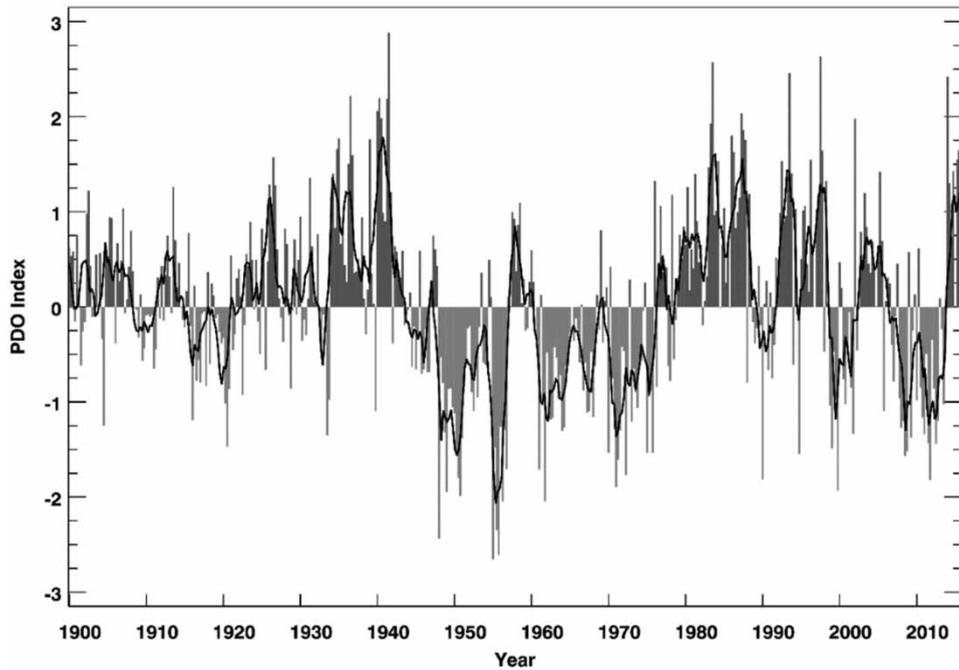


Fig. 2 | The 3-month average (Dec–Jan–Feb, Mar–Apr–May, Jun–Jul–Aug, Sep–Oct–Nov) PDO Index.

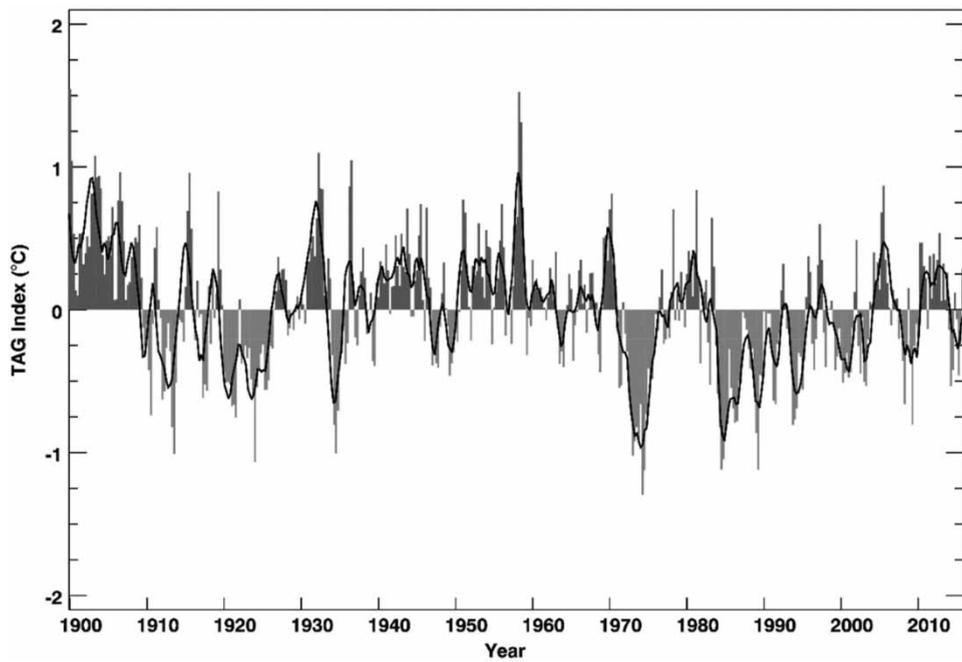


Fig. 3 | The 3-month average (Dec–Jan–Feb, Mar–Apr–May, Jun–Jul–Aug, Sep–Oct–Nov) TAG.

These DCV phenomena influence variability in hydrology throughout the world. Different phases of these DCV indices have been associated with wet and dry periods on land. In North America, for example, different phases of the PDO and AMO have been associated with dry or wet periods (Enfield *et al.*, 2001; McCabe *et al.*, 2004, 2008; Schubert *et al.*, 2004a, 2004b; Mo *et al.*, 2009). Water managers may be able to use the phases of these DCV indices and their observed correlations with continental hydrometeorology to support their decision-making, as, for example, in reservoir management and the operation of irrigation systems that depend on reservoir systems.

DECADAL CLIMATE PREDICTABILITY

The thermal and mechanical inertia of the oceans is a potential source of climate predictability. There are empirical and dynamic modeling methods to estimate the probability of future climate conditions. Empirical methods use observed data such as SSTs. The observed data are a relatively short time series compared to the decadal time scale and is a shortcoming of empirical methods (Mehta, 2020). Dynamic methods use Earth System Models (ESMs) to simulate future climate.

Coupled Model Intercomparison Projects Phase 5 (Taylor *et al.*, 2012) and Phase 6 (Eyring *et al.*, 2016), conducted under the World Climate Research Program in the last 10 years, included coordinated decadal climate hindcasts (retrospective forecast of past decades) and forecasts by approximately 30 complex climate models from many countries. Also, the Near-Term Climate Prediction Project of the World Meteorological Organization is now operationally producing worldwide decadal climate forecasts available from the U.K. Meteorological Office. The results showed some skill in predicting North Atlantic temperature. There is less prediction skill in the North Pacific temperatures (Kirtman *et al.*, 2013; Meehl *et al.*, 2014). One source of predictability is volcanic eruptions that influence SSTs and are one of the sources of decadal SST hindcast skill in the year(s) following significantly large eruptions (Mehta *et al.*, 2013, 2019).

Some of the major problems with decadal climate prediction include the following: (1) relatively short time series of instrument-based global ocean observations, especially sub-surface observations, for understanding, model initialization, and comparison with prediction; (2) an insufficient understanding of fundamental physics of DCV; (3) an insufficient theoretical understanding of possible behaviors of geographically varying, complex and non-linear dynamical systems with mixed initial and boundary values; and (4) global climate models displaying less than satisfactory skill in simulating climate in general and DCV in particular (Meehl *et al.*, 2009, 2014; Mehta *et al.*, 2011).

Models of non-linear dynamical systems are sensitive to initial conditions. The initial conditions for the global climate cannot be known with certainty. Ensembles of multiple simulations with different initial conditions are one method to handle this uncertainty. Multi-model ensembles using predictions from different ESMs are an approach to the initial condition and model uncertainty (Kirtman *et al.*, 2013).

Decadal climate patterns such as the PDO and TAG tend to persist over time. This persistence has the potential to provide information about the climate in the next season or year. Many of the studies involving the impacts of DCV on hydrometeorology are based on the phase of the DCV phenomena, whether positive or negative. These phases tend to persist from year to year. The transition probabilities can be estimated from the observed record by whether the index remains in the current state or transitions to an alternative state. These probabilities are uncertain since they are estimated from a limited sample size and assume stationarity. Table 1 shows the observed transition probabilities for the PDO from 1 year to the next. Table 2 shows the transition probabilities for the TAG index. The PDO shows more persistence than the TAG. The negative or positive state of the index may be associated with wet or dry local conditions, and the transition probabilities may provide some guidance if conditions will continue into the next year.

Table 1 | Phase transition probabilities for the PDO from 1 year to the next year.

Phase	Positive	Negative
Positive	0.72	0.28
Negative	0.20	0.80

DCV AND WATER MANAGEMENT OPERATIONAL DECISIONS

Use of forecasts in reservoir management

Water resources managers must often balance competing uses of water, such as municipal and industrial water supply, irrigation for agriculture, support of navigation on rivers, energy production, recreation, water quality, and support for the aquatic environment. This section will examine the potential use of DCV information for reservoir management. Reservoir management decisions include the allocation of storage between flood and conservation purposes and the allocation of water among multiple conservation purposes. The section will also look at the policy for using climate forecasts by the U.S. Army Corps of Engineers (USACE), a major water manager in the United States.

The flood control pool is used for flood storage to store water during floods to reduce flood damages downstream. The conservation pool, or multipurpose pool, is for additional seasonal flood storage and for the storage of multiple purposes including hydroelectric power, irrigation, navigation, municipal and industrial (M&I) water supply, downstream water quality, recreation, and support for the environment including fish and wildlife. The inactive capacity is used to maintain a minimum pool and to store sediment. The reservoir operator must allocate reservoir storage into flood storage space and conservation storage and to balance the multiple purposes.

The capacities of the flood storage and conservation storage may vary during the year depending on the flood season. Flood storage may increase in the anticipation of seasons with more runoff and flooding, while conservation storage may increase for additional water for other purposes during the summer. Reservoir rule curves show how reservoir storage should be divided between conservation storage and flood storage throughout the year. An example of a reservoir rule curve for Oroville Dam in California is given in [Figure 4](#). Major floods occur in winter and spring due to snow melt and rain on snow events. Water levels are reduced in fall to prepare for the winter flood season. For Oroville, the size of the flood storage space is based on the observed precipitation that has occurred in the watershed during the autumn and the winter. The flood storage space is increased or decreased based on the accumulation of snow in the basin and the anticipated volume of spring runoff, but the refill begins on the same date each year. [Figure 5](#) shows another reservoir rule curve for Shasta Dam in California. The volume of the flood storage space is the same at the beginning of the flood season. The refill rate for the reservoir and beginning time can vary based on the observed inflows to the reservoir.

Information on DCV along with the current and predicted ENSO state may indicate that there is an increased likelihood of dry or wet conditions currently and in the next couple seasons. Information that there is a higher

Table 2 | Phase transition probabilities for the TAG index from 1 year to the next year.

Phase	Positive	Negative
Positive	0.55	0.45
Negative	0.53	0.47

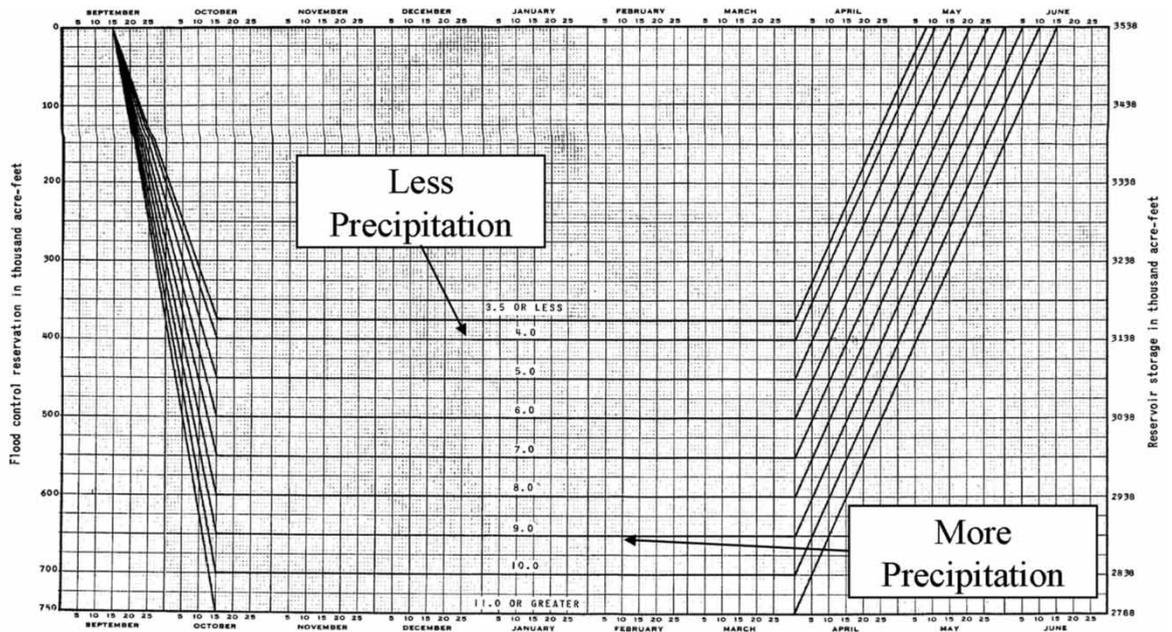


Fig. 4 | Reservoir rule curve for Oroville Dam in California (USACE, 2005).

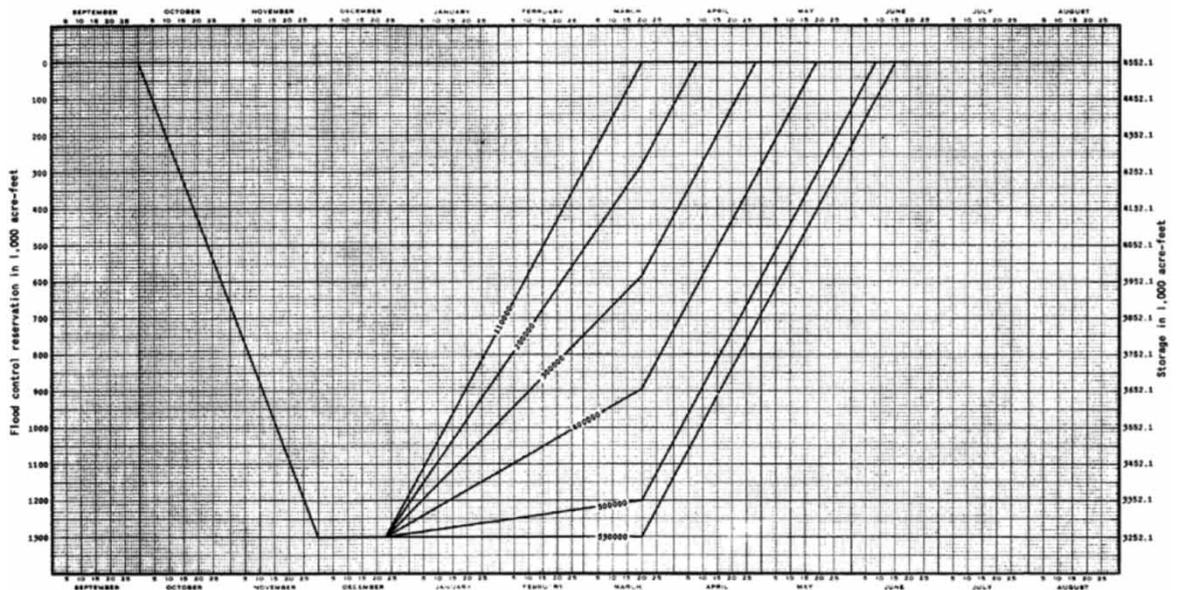


Fig. 5 | Reservoir rule curve for Shasta Dam in California (USACE, 1977).

probability of dry conditions could possibly be used to decrease flood storage to provide more water for conservation purposes or refill the reservoir early to ensure a full supply during summer. Hamlet & Lettenmaier (1999) said that the use of PDO and ENSO information could extend the lead time of streamflow forecasts for the

Columbia River basin by about 6 months over current forecasting practices based on snowpack in the basin. Hamlet *et al.* (2002) stated the use of these forecasts during conditions associated with higher streamflows would provide greater flexibility for fall hydropower generation without threatening other uses.

The U.S. Army Corps of Engineers Engineer Manual on Management of Water Control Systems (EM 1110-2-3600), released in October 2017, specifically addresses the use of climate forecasts in reservoir operations. The Engineer Manual (EM) acknowledges some usefulness of climate forecasts.

6.3.3.1. Long-term (monthly, seasonal, or annual) weather forecasts can be useful for planning purposes and for developing reservoir runoff forecasts several months in advance.

However, the EM says the patterns associated with DCV are limited in their usefulness for long-range forecasts.

6.3.3.2. Some of the commonly discussed large-scale weather patterns are limited in their ability to be incorporated into long-range forecasts, such as the Arctic Oscillation, PDO, and AMO.

The EM acknowledges that ENSO can have impacts on climate in the United States.

6.3.3.3. The ENSO cycle, however, has been demonstrated to having distinct impacts on various regions of the continental United States based on both the phase (warm versus cold) and intensity. These correlations are greatest from late fall into early spring with the general correlation during an El Nino event being cooler and wetter along the southern tier states and warmer and drier from the Pacific Northwest into the Northern Rockies. The opposite impacts are often observed within these regions during a La Nina episode.

The bottom line of the EM is a warning not to reduce flood storage space based on seasonal climate forecasts or climate indices:

6.3.3.4. However, it should be noted that not every event within the ENSO cycle has the same characteristics or intensity, so the water manager should be cautioned not to reduce the level of flood risk management based solely on long-range weather forecasts or climatic indexes. These forecasts can inform the water manager of the possibility of those conditions; however, an unjustified use of such forecasts may, in the long run, result in inaccurate regulation of project facilities, and under extreme conditions, impact the projects' authorized functional use. (USACE, 2017a)

A major concern is the uncertainty of the climate system and the impacts in the basin and the potential consequences if conditions turn out different than forecast. The potential benefits of using climate information and the reliability of the information will need to be demonstrated and evaluated before they will be adopted by USACE reservoir managers.

There are efforts underway in USACE and other water management agencies to evaluate the potential use of forecasts in reservoir management. For example, a project is underway in California to evaluate forecast-informed reservoir operations (FIRO) for Lake Mendocino. The preliminary viability assessment of FIRO was concerned with the following questions.

- If FIRO is implemented, will operation improve reliability in meeting water management objectives and ability to meet environmental flow requirements, and to what extent?
- If FIRO is implemented, will operation adversely affect flood risk management in the system? If so, where and to what extent can that be mitigated?
- What meteorological and hydrological forecast skill is required to enable FIRO to be implemented? Is current forecast skill adequate to support FIRO, and what improvements would be needed to enable the full implementation of FIRO? (FIRO, 2017)

These questions could also serve as a guide for evaluating the use of climate forecasts, including DCV information, in reservoir management.

Case study 1: drought contingency planning and Apalachicola–Chattahoochee–Flint River Basin

Another potential application of DCV information is informing drought management. A drought contingency plan is triggered when certain conditions are met. Some indicators of drought are below normal precipitation, lower than average reservoir inflows, and low reservoir levels. The potential use of DCV information for reservoir drought contingency planning will be considered in this section. The case study will be the Apalachicola–Chattahoochee–Flint River Basin, which is located in the southeastern United States in Georgia, Alabama, and Florida. The USACE operates several dams and reservoirs in the basin:

- Buford Dam and Lake Sidney Lanier
- West Point Dam and Lake
- Walter F. George Lock and Dam and Lake
- George W. Andrews Lock and Dam and Lake George W. Andrews
- Jim Woodruff Lock and Dam and Lake Seminole

The reservoirs serve multiple purposes. Lake Sidney Lanier and West Point Lake contain flood storage space to store flood waters. Generally, water is stored during high-flow periods in the winter and spring and is released during the dry summer and fall. Hydropower generation occurs at all the dams except George W. Andrews Lock and Dam. In addition, there are other hydropower dams on the Chattahoochee River operated by private companies. There is a navigation channel on the Apalachicola and Chattahoochee Rivers. The ACF basin provides water supply to many municipalities, including the city of Atlanta. Lake Lanier and downstream of Buford Dam are major sources of M&I water supply. The USACE projects also release minimum flows that provide water quality benefits. In addition, USACE dams release flows to benefit the aquatic environment, fish, and wildlife and to support fish spawning. Finally, the lakes provide significant recreation benefits, which are degraded when reservoir elevation falls below certain levels. During normal flow periods, the ACF basin can meet these multiple needs, but during drought not all water management objectives can be met.

The water control plan for the ACF must balance the needs of these multiple purposes. The ACF projects are operated as a coordinated system to the maximum extent possible rather than as independent, individual projects. [Figure 6](#) shows the composite storage for the basin and the action zones within the conservation storage. The zones are described as follows:

Zone 1: If all the lakes are in Zone 1 or above, the river system would operate in a fairly normal manner. Releases can be made for hydroelectric power, water supply, and water quality. If system composite conservation storage is in Zone 1, releases can be made in support of a navigation season (January to April or May). Drought contingency operations cease when levels return to the composite action Zone 1 in accordance with the Drought Contingency Plan.

Zone 2: Hydroelectric power generation is supported at the same or a reduced level. Water supply and water quality releases are met. Minimum flow targets are met. If system composite conservation storage is in Zone 2, releases can be made in support of a navigation season (January to April or May).

Zone 3: Hydroelectric power generation is supported at a reduced level. Water supply and water quality releases are met. Minimum flow targets are met. If system composite conservation storage is in Zone 3, navigation is not supported. Drought contingency operations are triggered when levels drop to Zone 3.

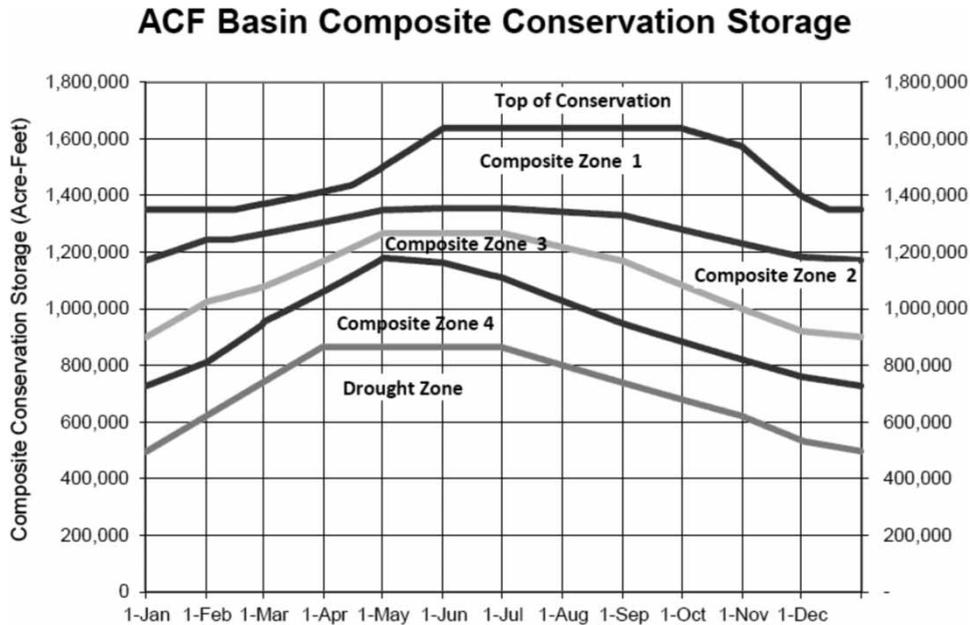


Fig. 6 | ACF basin composite conservation storage (USACE-SAM, 2017).

Zone 4: Hydroelectric power demands will be met at a minimum level and might occur for concurrent uses only.

Water supply and water quality releases are met. Minimum flow targets are met. If system composite conservation storage is in Zone 4, navigation is not supported.

Drought Zone: Hydroelectric power will only be met as a result of meeting other project purposes. Water supply and water quality releases are met. Minimum flow targets are met but are reduced to their lowest level. If system composite conservation storage is in the Drought Zone, navigation is not supported and the emergency drought operations are triggered. (USACE-SAM, 2017)

In the Southeastern United States Gulf Region, La Niña conditions are associated with below normal precipitation (Ropelewski & Halpert, 1989) and below normal streamflow (Dracup & Kahya, 1994). In addition, several studies have found a link between decadal climate patterns and streamflow in the region. Tootle *et al.* (2005) showed that the AMO may influence La Niña impacts on streamflow in the Southeast United States. Stevens & Ruscher (2014) examined precipitation in the ACF basin and found that the southern part of the basin is primarily influenced by ENSO conditions, while the northern part of the basin is influenced more by the AMO and the PDO. Johnson *et al.* (2013) analyzed stream flow in the ACF basin and determined that the phase of the AMO modulated the impacts of La Niña. During La Niña years, the streamflow was about 50% lower during the positive phase of the AMO compared with the negative phase of the AMO. Singh *et al.* (2015) examined the baseflows of the Flint River. They found that during positive phases of AMO and PDO, La Niña conditions were associated with severe drought and a greater decrease in baseflow levels in the Flint River. This research has shown that DCV influences drought in the ACF basin. The current DCV conditions could be used to influence when the drought zone is activated, but a thorough assessment of using the DCV information in reservoir operations would first need to be conducted. The assessment would determine the benefits and costs of using the DCV information on each purpose under scenarios both when the DCV information provides a timelier drought trigger or

not. This assessment must then be reviewed with stakeholders to determine if the change in operations is acceptable.

The use of DCV information in stakeholder decisions

In addition to reservoir managers, the stakeholders who use this water may also be able to use DCV information to improve their decision-making. Electrical energy production affected by river flows includes hydropower and thermal energy plants cooled by river flows. Knowledge of current decadal climate patterns, such as whether there is a higher probability of dry or wet conditions, could help schedule hydropower production. In the Columbia River basin, forecasts using ENSO and PDO information could support increased autumn hydropower generation during wet conditions associated with higher streamflows (Hamlet *et al.*, 2002). Potential power transfers from the Pacific Northwest to California could be predictable based on forecasts using ENSO and PDO (Voisin *et al.*, 2006).

Agriculture is another potential application. Climate information may allow farmers to adapt management decisions such as fertilizer applications and crop selection to upcoming weather conditions (Mjelde & Hill, 1999; Hill & Mjelde, 2002; Meza *et al.*, 2008). A study of farmers in the Missouri River Basin on the use of DCV information in crop selection and irrigation decisions found that the benefit of using DCV information could be substantial (Fernandez *et al.*, 2016).

DCV information could support inland navigation and shipment decisions. Firms may ship their products either domestically or for export using inland navigation. They need to decide when and where to ship and what mode of transportation to use. During low-flow periods and channel restrictions, barge spot rates increase. During severe droughts, the channel may close. Drought forecasts using climate information may improve shipping decisions. Other firms include barge companies and their competitors. Barge companies may be required to reduce loads or change barge configurations during low-flow periods leading to higher unit costs and shipping rates (Olsen *et al.*, 2005). The competitors to the barge industry include railroad and trucking companies. During channel closures or restrictions, the volume of their freight may increase as shippers move to alternatives. Drought forecasts could help these firms deploy their assets.

In addition, forecasts of dry conditions could help channel operators plan their dredging resources in advance. Drought forecasts may inform dredging decisions. Dredging is often performed during droughts to maintain channel depths. Channel operators could plan for increased dredging volumes by staging dredges or awarding additional dredging contracts in the anticipation of drought conditions.

DCV, NONSTATIONARITY, AND WATER RESOURCES PLANNING

Another potential use of DCV information is in water resources infrastructure planning. Water managers often use future economic benefits to evaluate the future performance of projects. In the United States, for example, 'the Federal objective of water and related land resources project planning is to contribute to national economic development consistent with protecting the Nation's environment, pursuant to national environmental statutes' (USWRC P&G, 1983). Future economic benefits are estimated using hydrologic frequency distributions fitted to the observed record of river flows. The observed record includes low-flow periods and wet periods of various frequencies, intensities, and durations.

Past practice assumes that the past observed record will be representative of the future. Global warming may cause very different conditions than were observed in the past. This concern has focused attention on trend analysis to determine if hydrologic conditions are changing. The U.S. Army Corps of Engineers, for example, has adopted guidance to consider climate change in project planning (USACE, 2018) and for the detection on non-stationarities in hydrologic records (USACE, 2017b). The procedures can detect abrupt changes or more gradual

trends, but are not able to detect ‘the potential presence of Long-Term Persistence (LTP) in the discharge time series that are related to oscillations in climate regime over a wide range of temporal scales’ (USACE, 2017b). The presence of a trend is often associated with what period of record is used, since there may be episodic wet and dry periods in the observed record (Matalas & Olsen, 2001). Both abrupt changes and gradual trends could be associated with natural DCV patterns. Understanding of the underlying climate processes and DCV patterns may better distinguish trends and attribute the trend to decadal climate shifts or another factor. Kundzewicz *et al.* (2019) reviewed the links between climate variability indices and floods across the globe and found relationships in different regions. Salas *et al.* (2018) provide a review of techniques to address nonstationary extreme events and the challenges in using them.

For flood risk reduction projects, future benefits are estimated from the likelihood of future flooding and the damages that would occur under different flood magnitudes and with alternative flood risk reduction measures. The current engineering practice to determine the likelihood of future flooding is to fit a frequency distribution to the observed record of flood flows. In the United States, the Water Resources Council in the 1970s developed uniform guidelines for U.S. Federal agencies to follow and adopted the log-Pearson Type 3 distribution for flood frequency estimation. The Guidelines for Determining Flood Flow Frequency have been recently revised and published as Bulletin 17C (England *et al.*, 2019). Bulletin 17C says that the problem of multidecadal episodic wet and dry periods is a lingering problem for flood frequency analysis.

‘In certain locations, flood records may indicate apparent nonrandomness and exhibit strong multi-decadal trends or wet and dry cycles that are not explained by land use change, water management, or climate change. Such records are particularly challenging and this is one of the most vexing problems in flood frequency analysis. The Work Group did not evaluate methods to account for nonrandomness and/or multidecadal trends in flood frequency. Additional work in this area is warranted, as it is a seriously unresolved problem. If multidecadal trends of this sort are identified through appropriate statistical tests and data analysis, it is recommended that the underlying physical mechanisms be investigated to gain hydrological understanding (Lins & Cohn, 2011). How to adjust such a record for flood frequency is an unresolved problem.’ (England *et al.*, 2019)

The problem of multidecadal wet and dry periods and their effect on flood frequency analysis will be illustrated with the example of the Red River of the North.

Case study 2: impact of DCV on flood frequency analysis: Red River of the North

The Red River of the North has flooded several times since 1997. Large floods occurred in 1997, 2009, and 2011. The Fargo, North Dakota and Moorhead, Minnesota metropolitan area have suffered flood damage in these events. The Corps of Engineers conducted a feasibility study to investigate flood issues in the Fargo–Moorhead metropolitan area and to identify flood risk management measures that could be implemented (USACE-MVP, 2011a). One of the requirements of a feasibility study is to estimate the future benefits of proposed flood risk reduction alternatives and compare them with the cost of the alternative to estimate annual net benefits and the benefit–cost ratio. To estimate future flood damage, reduction benefits require an estimate of the probability and magnitude of future flooding.

Figure 7 shows the annual average daily flow and the annual maximum daily flow for the Red River at Fargo. The record shows that the recent decades have been wetter than the earlier record. The increase in streamflow raised questions about the stationarity of the record and what methods could be applied in developing a flood frequency distribution. The study team organized an expert elicitation panel to evaluate the apparent non-

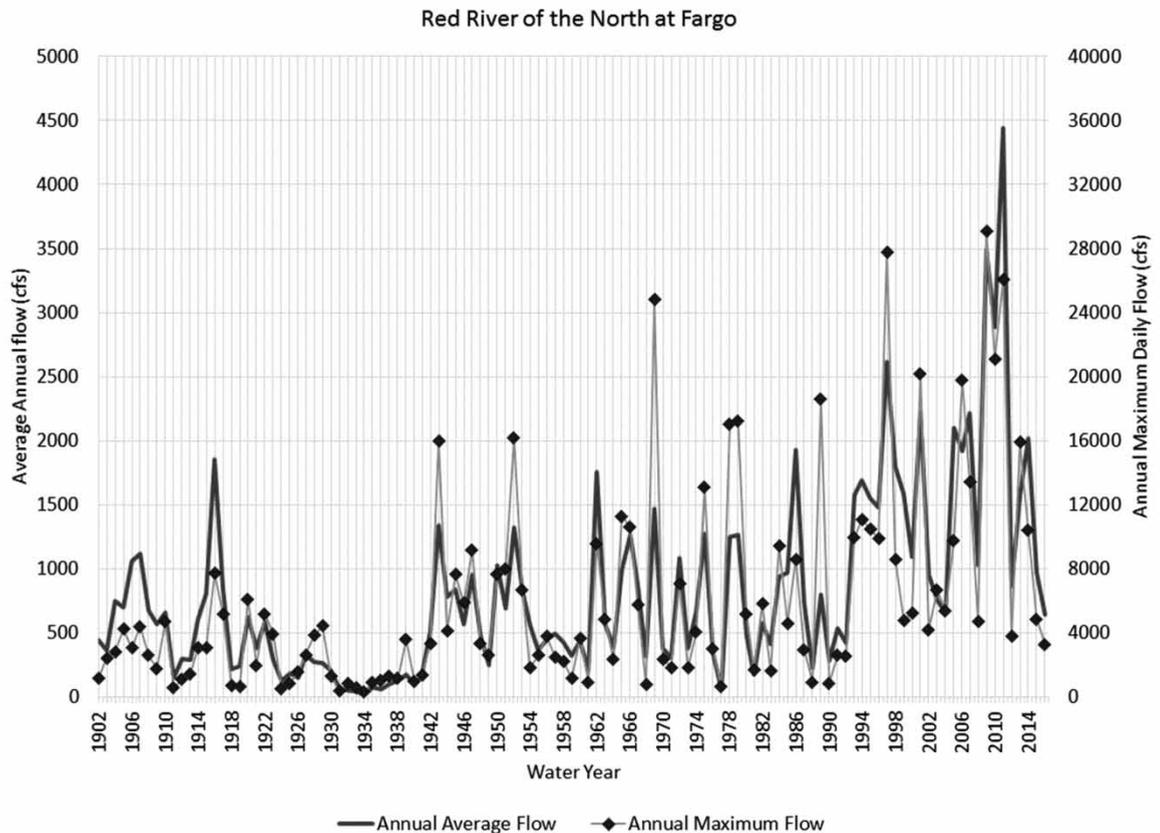


Fig. 7 | Annual average flow (left axis) and annual maximum daily flow (right axis) for the Red River of the North at Fargo, North Dakota.

stationarity. The panel concluded that there was insufficient evidence that the more recent wet period was due to anthropogenic global warming. The historical record indicated that major floods occurred in 1882 and 1897 and there were major floods and wet periods prior to the 19th century. The panel concluded that the flow period could be divided into an earlier dry period and the current wet period. A Pettit test was conducted on the unregulated peak flows and the year 1941 was the break point with the highest statistical significance. A change point test conducted by Villarini *et al.* (2009) on regulated flows showed a significant step change at 1942 (USACE-MVP, 2011b).

One flood frequency distribution was estimated for the dry period and one for the wet period, and then combined to form a composite distribution. For the period 1902–1941, the regulated 1% flood was 9,500 cubic feet per second (cfs), while for 1942–2009, the regulated 1% flood was 34,700 cfs. Using the full period of record plus the historic floods in 1882 and 1897, the regulated 1% flood was 33,000 cfs (Mueller & Foley, 2014). Each period had less variance than the variance of the full record (USACE-MVP, 2011b). It is uncertain how long the current wet period will last until a possible shift to a drier period. USACE used the probability of occurrence of being in a dry period as 35% and of being in a wet period as 65%. This estimate was based on the dry period occurring about 35% of the time during the period of record. These probabilities were used to form the combined distribution (Mueller & Foley, 2014).

The following questions are addressed by this case study: Does decadal climate information provide any insights into the flow record of the Red River of the North? Are different dry and wet periods associated with different climate patterns? Is there any evidence about how long the dry and wet periods last before shifting to a different regime?

Decadal climate patterns are associated with annual and seasonal conditions, rather than with individual weather events. However, Figure 7 shows that large floods generally occur in wet years and major floods are not likely in dry years. An exception is the large flood that occurred in 1969, a year with only medium annual flow. The correlation between the annual maximum flow and the annual average flow is 0.86.

Figure 8 shows the annual average streamflow, the annual average precipitation, and the annual maximum temperature as deviations from the long-term average value. Indices for the PDO and the TAG are also shown. For the full period of record, streamflow, precipitation, and temperature have almost no correlation with the PDO and TAG indices. If we focus on the dry period before 1941, the streamflow record shows the low flows. The PDO pattern is generally positive throughout this period. The TAG is negative in the 1920s, then shifts to generally positive in the late 1920s and 1930s. In this case using this particular statistical analysis, the recent wet period in the 1990s and 2000s does not seem to be associated with either the PDO or the TAG index.

CONCLUSION

The ENSO, the PDO, the TAG variability, the AMO, and the WPWP are patterns of natural climate variability. The phases of the PDO, TAG, and WPWP tend to persist over decadal time periods. During the past couple of decades, empirical data analysis and climate model simulations have improved the understanding of DCV. There are also international efforts to produce decadal climate hindcasts and forecasts.

There is still a great deal of uncertainty involving decadal climate information associated with both the future ocean climate pattern and the impact on local hydrology. The use of DCV information in reservoir management depends critically on the risk if the forecasts are wrong. In reservoirs with flood storage space, there is a danger of increased flood damages if a flood occurs when drought conditions are forecast. Another consideration is that reservoir water management plans are developed to balance the objectives of multiple stakeholders. The beneficiaries of a forecast may not be the same stakeholders who bear the risk of a wrong forecast. For example, a forecast of drought conditions may imply that reservoir managers should store more water and reduce flood storage. The increased storage would benefit water supply, navigation, hydropower, and irrigation stakeholders. However, if a flood occurs, the damages may increase to downstream residents who may be flooded. The need to balance the risk of wrong forecasts with the forecast benefits applies to other water resources decisions beside reservoir management including energy production, agriculture, and inland navigation.

Seasonal forecasts using DCV information could be used to inform drought triggers. If DCV and ENSO indices indicate that the climate has a higher probability of dry conditions, drought plans could be triggered earlier. In drought plans, there is concern about balancing conservation uses of the limited water and not about filling flood storage space. However, some stakeholders may be adversely affected by early triggering of drought plans.

Understanding of DCV processes could also improve hydrologic frequency analysis when there are trends in the observed record. Different DCV patterns may be associated with wet or dry periods in the hydrologic record. For example, conditions may be in a wet period due to natural DCV which show up as an increasing trend in the observed record. This trend may likely be reversed when there is a future phase shift. In the case study described in this paper, the trend could not be attributed to the PDO and the TAG, which implies the trend is due to some other factor.

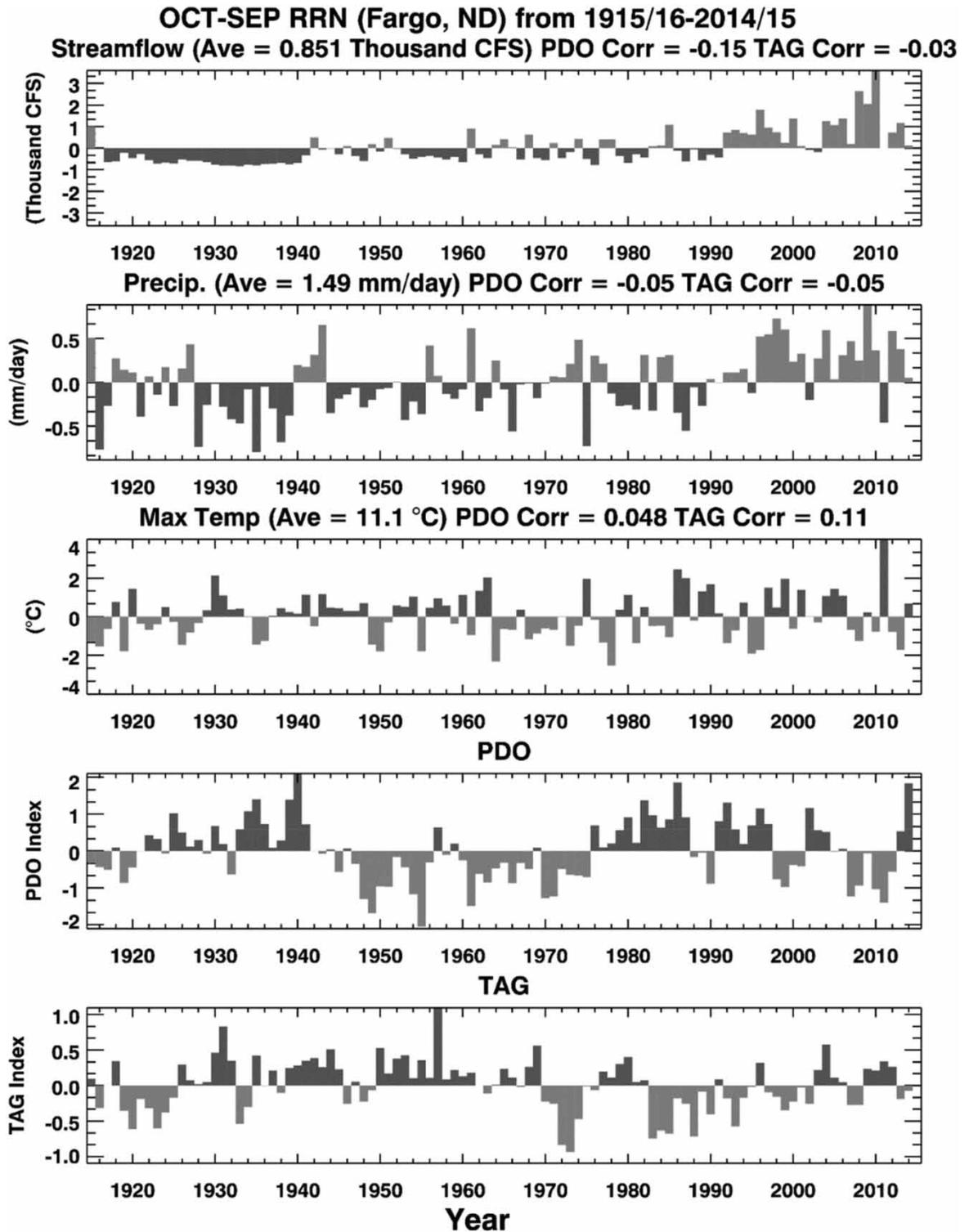


Fig. 8 | Annual average streamflow, annual average precipitation, and temperature for the Red River of the North (RRN) basin and the PDO and TAG indices.

There has been much progress in the understanding of DCV in the last few decades. Future research may provide a better understanding of the predictability of DCV patterns and the uncertainty of these predictions. Future research should also be conducted on how DCV forecasts can be used in water resources management and other fields. Bayesian analysis and other analytical techniques that consider the probabilistic nature of the forecasts and their uncertainty may be appropriate. Water managers and climate scientists should develop and continue collaboration to evaluate how this information could better inform the operation and design of water infrastructure.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories https://waterdata.usgs.gov/nwis/inventory/?site_no=05054000&agency_cd=USGS& and www.crces.org.

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