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Executive Summary

The Sacramento-San Joaquin Delta (the Delta) serves a critical role in maintaining California's water supply, agricultural productivity, and biodiversity. However, these ecosystem services are threatened by global climate change and associated increases in the prevalence of droughts, floods, wildfires, and sea-level rise. To understand the latest climate science and its management implications for the Delta, the Delta Independent Science Board (ISB) hosted a two-day symposium in September 2025. The symposium highlighted how California's climate future will be shaped by more frequent wet and dry extremes rather than shifting averages. Even amid uncertainties in precipitation projections, the direction of change is unequivocal: a hotter and more variable climate is becoming the new norm.

The symposium underscored that the challenge lies not only in understanding climate risks but in embracing adaptive strategies that account for the accelerating pace of change. Over the past 5 to 10 years, there have been substantial improvements in sub-seasonal forecasting, characterization of rare atmospheric events with potential system-wide impacts, climate modeling, and understanding conditions surrounding future declines of mountain snowpack. These scientific advancements provide state and local agencies with more actionable information for managing water resources, reducing risk, and preparing for a future marked by greater climate variability and more extreme weather events.

Despite recent scientific advancements, several uncertainties hinder precise planning and operational guidance in the Delta such as drivers of precipitation change and infrastructure vulnerability to compounding and sequential hazards. As emerging research continues to address these uncertainties, symposium discussions highlighted how the Delta can achieve enhanced resilience against a volatile climate future by using flexible and forward-looking planning approaches, linking improved forecasts to management models, implementing multi-benefit mitigation strategies, and enhancing collaboration across regional and organizational boundaries. The symposium highlighted many advancements in science and management, but also potential disconnects between these two sectors that may hinder rapid implementation to address evolving climate challenges – this topic will provide the basis for a future ISB perspective piece.

Introduction

As global climate change intensifies, landscapes around the world are facing increasing stressors and shocks that threaten their stability and impact ecosystem processes across local and regional scales. California is undergoing fast-moving environmental changes as the state's climate continues to shift, resulting in increased prevalence of droughts, floods, wildfires, and sea-level rise. While these stressors have statewide impacts, risks are compounded in coastal regions like the Delta that experience climate pressures from the ocean (i.e. sea-level rise in the Pacific Ocean) and inland regions (i.e. flooding driven by changing precipitation regimes in the Sierra). Given the critical role the Delta serves in maintaining California's water supply, agricultural productivity, and biodiversity, there is a need to understand emerging climate science and the cascading impacts to water management, public safety, community resilience, and long-term planning throughout the region.

To support adaptive management of the Delta under uncertain climate futures, the Delta Independent Science Board (ISB) hosted a hybrid symposium (at the University of California – Davis on September 16-17, 2025) that brought together over 250 scientists, practitioners, and decision-makers to assess the latest climate science and its management implications for the Delta. With cross-disciplinary expertise and experience working in other large systems, such as the Chesapeake Bay, the Everglades, and the Mississippi River Delta, the Delta ISB offers a national perspective to the many issues facing the Delta region. These perspectives helped shape the symposium and this summary.

This summary is not a comprehensive review by the Delta ISB on the latest climate science and is not intended to capture everything presented at the symposium. Instead, it highlights key takeaways on the latest science and management implications that can help inform organizations working in the Delta on climate adaptation. The symposium was structured around the following sessions (see Appendix for links to recordings, slides and agenda):

1. **State of Science Keynote Presentations:** What have we known?
2. **Emerging Climate Science Panel:** What is latest cutting-edge science?

3. **State of Science Panel:** Is the latest science ready to be used in management?
4. **Integrating Science for Decision Support Panel:** How is science being integrated by organizations working in the Delta?
5. **Open Forum and Breakout Group Discussions:** What are the science needs?

This symposium summary synthesizes current understanding surrounding the state of climate science, how climate science has evolved over the past decade, major uncertainties, adaptation strategies, and management approaches that could be employed in the Delta.

State of Science

Keynotes and panel presentations summarized the current state of climate science, including observed and projected changes in key stressors and hazards under climate change. Since the Delta is impacted by climate-driven stressors across California and the world, these presentations focused on spatially broad climate science trends that present management implications for the Delta region. This section distills the following key climate science topics from both presentations and group discussions that are relevant to state and regional agencies:

1. What do we know?
2. How has science advanced in the past decade?
3. What are the major uncertainties?

What do we know?

This section was largely informed by Dr. Daniel Swain's keynote presentation titled "Climate change the Delta, and its watersheds: What we know, what we don't, & what surprises might be out there." Unless otherwise stated, all quantitative information in this section and the associated references can be found in the video recording of Swain's keynote presentation.

Warming Trends in California and Globally

Current global temperatures have risen 1.3 to 1.5°C (2.3 to 2.7°F) relative to the pre-industrial baseline, and California has warmed at least as quickly as the planet overall. Between 1895 and 2025, statewide average air temperatures increased by

about 1.4°C (2.5°F), with more intense warming observed post-2010. Increased rates of warming in recent years highlight the severity of current and future climate impacts. In the past decade, California experienced three of the hottest summers on record but, with projected warming of 2.5 to 3.0°C (4.5 to 5.4°F) by the end of the century, these temperature extremes could become the new normal.

Average rates of warming in California have accelerated by 0.5°F (0.3°C) per decade since 1974, but there is spatial and seasonal variation in warming, with the most pronounced changes occurring in inland valleys and higher-elevation watersheds. Within the Delta, climate model projections show less warming in estuarine environments that are moderated by the Pacific Ocean compared to inland regions (Figure 1 presented by Dr. Paul Ullrich in the "Emerging Climate Science" Panel). While increased warming in California inland and mountain regions (including the Central Valley, Sierra Nevada, and desert areas) is expected to result in localized impacts to these landscapes, hydrologic changes in headwater locations could lead to downstream shifts in ecosystem processes throughout the Bay-Delta watershed.

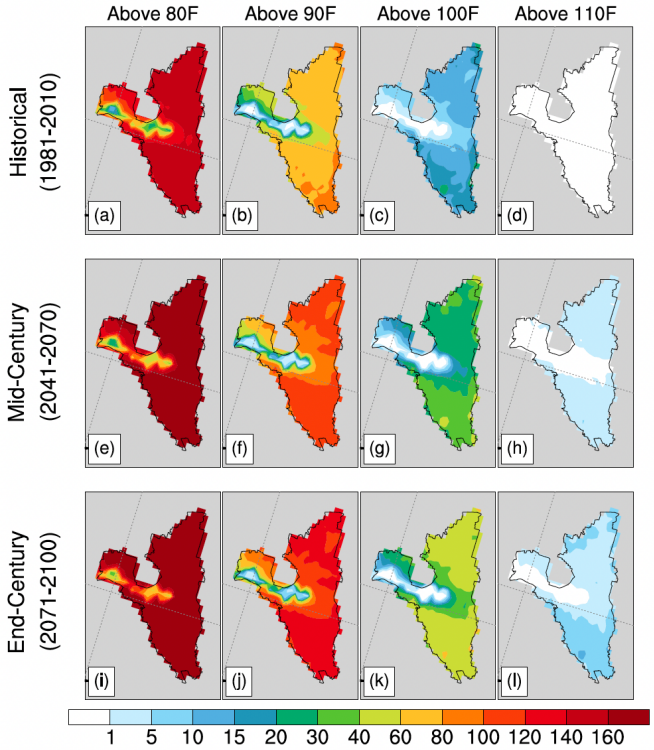


Figure 1. Map displaying the average number of days per year that the maximum daily temperature in the Sacramento-San Joaquin Delta was higher than threshold in the historical record (a-d) and in future mid-century (e-h) and end-century (i-l) climate model projections. This figure was presented by Dr. Paul Ullrich in the "Emerging Climate Science" Panel.

Loss of Snowpack and Shifts in Runoff

Increased rates of warming in California mountain regions are diminishing California's snowpack, which is historically the state's largest natural water reservoir and critical to maintaining both human and ecosystem processes in the Delta. Historically, snowmelt gradually feeds rivers, streams, and reservoirs into the summer months, providing water during the time when demand is greatest. However, warmer winters increase the fraction of precipitation falling as rain rather than snow, which reduces natural storage capacity and increases winter flood risk. By 2050, the average annual snow-water-equivalent is expected to decrease by 1.5 million acre-feet (stated by Dr. Ben Hatchett in the "Emerging Climate Science" Panel). California's seasonal water balance, as well as traditional engineered surface water storage systems and operating regimes, were designed around historical patterns of snow accumulation and melt, resulting in substantial management challenges with climate-driven shifts in precipitation regimes.

While warmer winters are expected to increase rain-driven runoff, the most extreme runoff events may follow warm storms that deposit heavy rainfall on existing snowpacks, called rain-on-snow events. Rain-on-snow events produce rapid snowmelt, extreme runoff, and destructive floods at lower elevations. As the mid-elevation regions warm, the frequency and magnitude of rain-on-snow-driven flood events are projected to increase, particularly in the southern Sierra Nevada mountains. Flooding in these regions is not only expected to impact annual water availability but could drive substantial riverbed sediment mobilization and disrupt ecosystem processes in the Sacramento and San Joaquin river systems.

Increasing Hydroclimate Variability

Rising temperatures are altering fundamental atmospheric and hydrologic processes in nonlinear ways, so that small changes in temperature can induce abrupt or disproportionate changes outside of what one would expect if changes followed a straight-line trend (Clausius-Clapeyron relationship; Figure 2). As the air warms, it essentially acts like an "expanding atmospheric sponge," soaking up and storing more moisture during dry periods and releasing more rainfall during storms, particularly higher rates over short durations. At the same time, this greater **"atmospheric thirst"** or evaporative demand can increase rates of evaporation when there is water available. These opposing forces are increasing the likelihood

of rapid transitions between intense wet and dry periods, a pattern often described as **“hydroclimate whiplash.”**

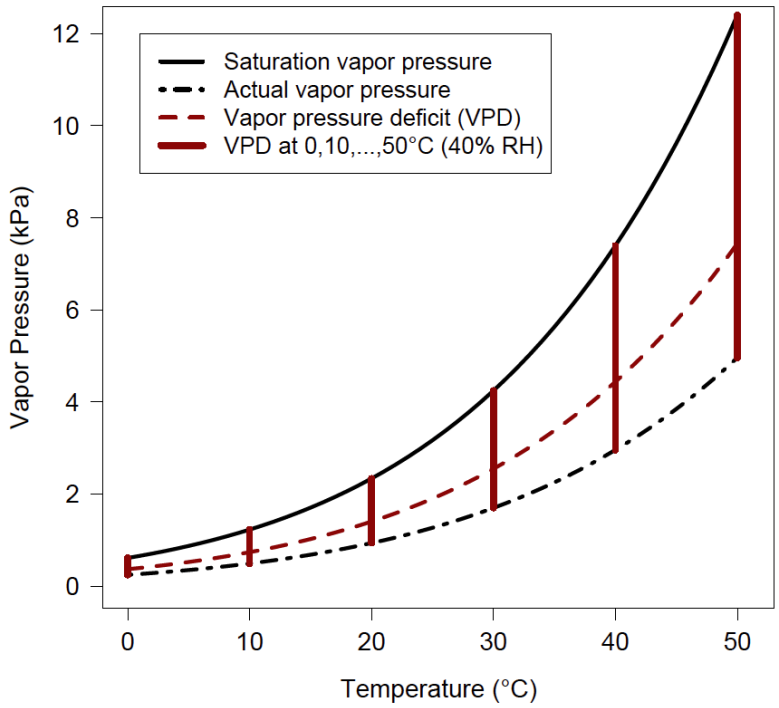


Figure 2. Graphical representation of the nonlinear relationship between temperature and saturation vapor pressure. Linear increases in temperature result in exponential increases in the moisture-holding capacity of the atmosphere.

California has always experienced large swings in precipitation from year to year, but new scientific assessments show that these swings are becoming more pronounced in a changing climate. There is a widespread agreement among climate modelers, as expressed in the symposium, that a significant increase or decrease in annual precipitation across California before the end of the century is highly unlikely. However, how this water arrives in California is expected to change significantly, with symposium presenters indicating that there could be an increase in precipitation delivered through atmospheric rivers (ARs; Box 1) matched approximately by a decrease in non-AR precipitation (Figure 3). These atmospheric rivers may become less frequent overall but are expected to be stronger and may occur in clusters with a few weeks or months between their arrivals. These clusters of strong atmospheric rivers can increase runoff and flood risk, overwhelming reservoirs, rivers, levee systems, and urban water infrastructure, as well as increasing the risk of local pluvial flooding throughout large portions of the Delta.

Box 1. Definition of atmospheric rivers

Atmospheric rivers are narrow corridors of highly concentrated atmospheric water vapor. When this atmospheric water vapor collides with CA's topography, such as the Sierras or other mountain ranges, it rises, cools, and then falls as extreme amounts of rainfall. The amount of precipitation generated from an atmospheric river can be several times greater than the flux of water from Earth's major rivers. In California, atmospheric rivers are one of the primary sources of winter storms.

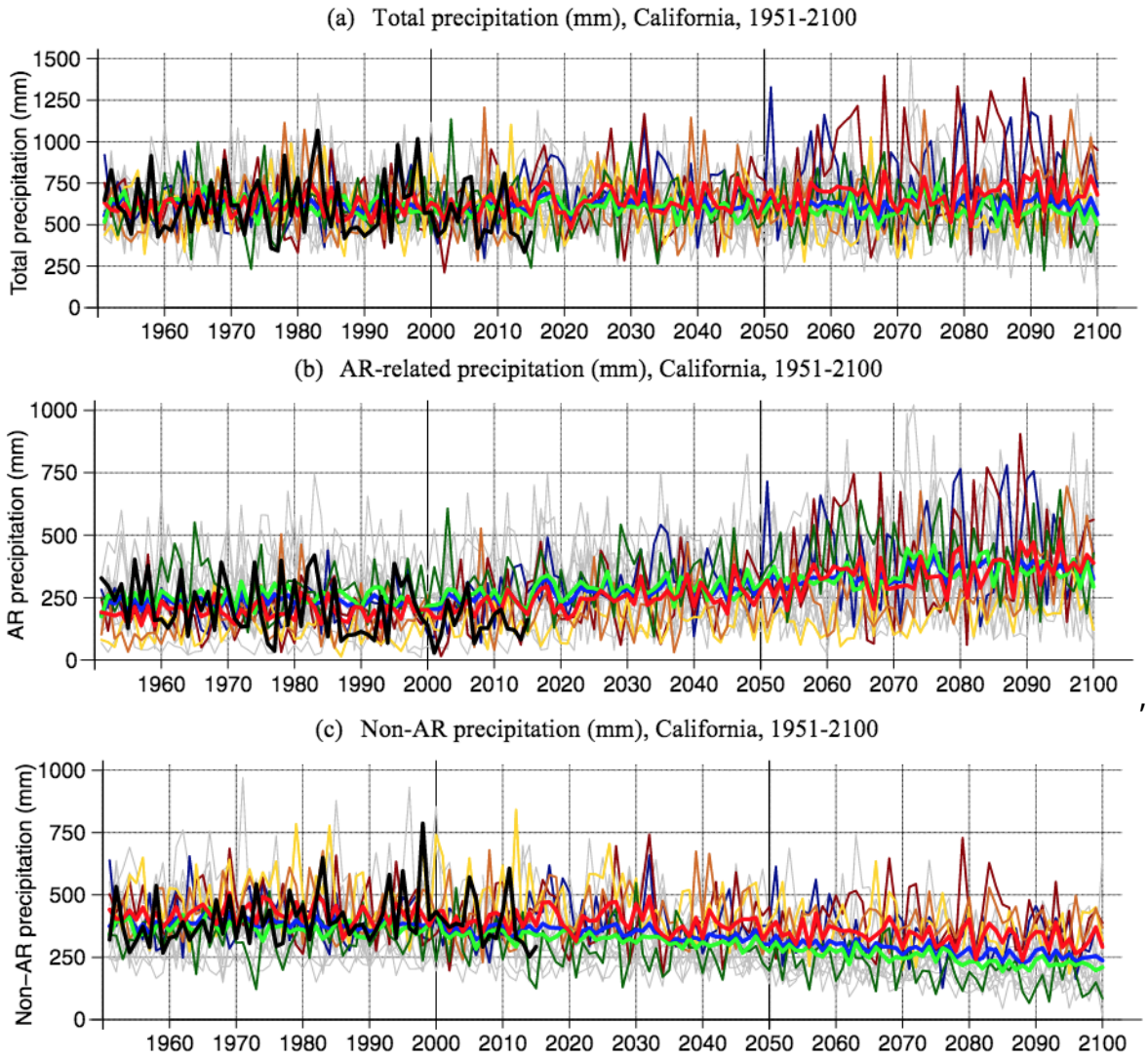


Figure 3. Total California precipitation (a), as well as precipitation from atmospheric rivers (ARs; b) and non-atmospheric river storms (non-AR; c). All lines represent results from global climate models, expected the thick black line that represents observed precipitation data. Total precipitation remains constant, while there is a 20% increase in AR precipitation and a 20% decrease in non-AR precipitation from 1951 to 2100. All graphs were presented by Dr. Mike Dettinger during the "State of Science" Panel.

These changes underscore an emerging theme: California's climate future will be shaped less by gradual shifts in average conditions and more by growing variability and volatility between wet and dry periods – increasing the prevalence of extreme floods and droughts. Climate trends show an increase in drought severity from 1895 to 2024, but a simultaneous increase in the risk of a California megaflood over this same time. California megaflood scenarios were originally modeled by the United States Geological Survey (USGS) in ARkStorm (Porter et al., 2011 included in Further Reading), but recent updates to this scenario incorporate climate change (ARkStorm 2.0; Huang & Swain, 2022 included in Further Reading) and indicate that the likelihood of catastrophic events comparable to the Great Flood of 1862, which is the largest recorded flood in the western United States, has doubled. In a changing climate, relying on historical trends is no longer sufficient for predicting future precipitation. As this variability in wet and dry extremes continues to grow, it is becoming increasingly clear that incorporating emerging climate science into storm forecasting is essential for effectively managing statewide water resources, reservoirs, ecosystems, agriculture, flood risk, and drought preparedness.

Fire, Watersheds, and Ecosystem Impacts

Increased prevalence of dry periods reshapes water management across the state of California, but also exponentially increases wildfire extent and severity in the coast and Sierra mountain ranges. These climate-driven increases in wildfire intensity are further reshaping California's hydrology, as burned watersheds exhibit greater runoff, reduced canopy interception, increased soil erosion and sediment loads in streams and rivers, and degraded water quality. Post-fire flooding and debris flows pose additional hazards to reservoirs, water treatment facilities, and downstream communities. These interactions create compounding challenges for water supply reliability, ecosystem function, and public safety in the Delta.

Accelerating Sea Level Rise

Sea level rise, along with continued hydrologic changes in inland and mountain regions, escalates climate-driven flood risk in coastal regions like the Delta. Rates of global sea level rise have roughly doubled over the last 30 years due to melting ice sheets and thermal expansion of the world's oceans. This water expansion is driven by increased global temperatures and absorption of excess heat by oceans – accounting for about half of observed sea level rise since 1900. For the San

Francisco Bay–Delta, additional factors may lead to higher-than-average relative sea level rise, such as gravitational effects related to Antarctic ice mass loss, which causes a decrease in sea level near Antarctica and increase in sea level rise in the northern hemisphere. Rising seas increase the hydrostatic pressure on critical water conveyance and flood control systems and infrastructure adjacent to tidal waters and agriculture throughout the region. Together, these hydrologic changes increase the risks of levee overtopping and failure, salinity intrusion into the Delta, storm surge and wave impacts, and chronic tidal flooding in coastal communities.

How has the science advanced?

This section highlights several climate science advancements over the past 5 to 10 years, which were discussed during the "Emerging Climate Science" Panel and can be found in the panel recording unless otherwise stated. Over the past decade, scientific research has advanced understanding of how climate variability and change are shaping extreme events, water availability, and system-wide risks. In particular, progress in sub-seasonal forecasting, improved characterization of rare high-impact events, growing recognition of rapid-onset hazards such as flash droughts and hydroclimate whiplash, advances in climate modeling (including the use of artificial intelligence [AI]), and clearer insights into the emergence of low-to-no-snow conditions are transforming the basis for climate-informed planning and decision-making. Together, these advances provide more actionable information for managing water resources, reducing risk, and preparing for a future marked by greater climate variability and more extreme weather events.

Improved sub-seasonal forecasting (near-term, 2–3 weeks) for extreme events

As highlighted by Dr. Benjamin Hatchett, one important area of development is the substantial advances in sub-seasonal climate forecasting, particularly at lead times of approximately two to three weeks for extreme events such as atmospheric rivers. Forecasting at these timescales has improved markedly, providing decision-makers with actionable information well beyond traditional weather forecasts. This extended lead time is especially critical for water and reservoir management, as it allows operators to distinguish between upcoming dry periods when retaining water is advantageous, and periods when additional storm activity may require pre-emptive releases to reduce flood risk. Improved sub-seasonal forecasts also enhance emergency preparedness for heatwaves, heavy rainfall, and storms,

enabling earlier coordination among agencies and more effective risk reduction strategies. **These scientific gains highlight the growing importance of translating forecast information into operational decisions through improved communication, partnerships, and co-production between scientists and practitioners.**

Better understanding of rare events (e.g., atmospheric rivers) driving system-wide changes

As described by Dr. Dan Cayan, scientific understanding of rare, high-impact atmospheric events has improved considerably, revealing their critical role in shaping long-term hydroclimatic conditions. Research increasingly shows that the rarest events such as extreme atmospheric rivers can drive flooding and strongly influence water availability over decadal timescales. These events serve as a critical bridge between short-term weather variability and long-term climate change, linking episodic extremes to persistent system-wide changes. Improved characterization of the frequency, intensity, and drivers of atmospheric rivers has clarified their contributions to water resources as well as their associated flood hazards. **This growing body of work underscores that long-term planning cannot rely solely on historical averages, but must explicitly account for low-probability, high-consequence events that disproportionately shape regional hydroclimate outcomes.**

Recognition of flash droughts, hydroclimate whiplash, and wildfire connections

As indicated by Dr. Mike Hobbins, **flash droughts,** defined by their rapid onset and intensification, have emerged as a critical but challenging hazard because they unfold faster than most existing decision-making and management cycles. Unlike traditional droughts, flash droughts can develop within weeks, leaving little time for mitigation or response. Recent scientific advances have improved recognition of these events and begun to clarify their underlying mechanisms, including land surface water availability and anomalous temperature-driven evaporative demand. Importantly, researchers are now studying the strong linkages between flash droughts, hydroclimate whiplash (rapid transitions between wet and dry extremes), and heightened wildfire risk. **These interactions pose compounding threats to water supplies, ecosystems, and public safety, emphasizing the need for integrated monitoring systems that couple groundwater and surface water**

hydrological models and predictive tools that can anticipate rapid climate transitions before impacts fully materialize.

Enhanced climate model reliability and assessment, including the potential benefits of artificial intelligence

As described by Dr. Paul Ullrich, climate modeling capabilities have advanced significantly, leading to a clearer understanding of where models perform well and where uncertainties remain. Notable improvements have been made in representing regional and local-scale processes, which are essential for translating large-scale climate change impacts into actionable regional implications. At the same time, discrepancies between modeled and observed climate behavior, such as differences in projected versus observed Pacific Ocean trends, have highlighted the need for continued model evaluation and refinement. Emerging approaches that integrate AI offer promising opportunities to enhance model performance, identify patterns in complex datasets, and improve representation of poorly resolved processes. While AI is not a replacement for physical understanding, its integration into climate science is increasingly viewed as a complementary tool that can accelerate insight, reduce uncertainty, and support more reliable climate assessments for planning and decision-making. In addition, physics-informed machine learning and AI models provide an approach for leveraging some of the benefits of AI while still incorporating physical understanding.

Understanding the timing of transition to low-to-no-snow conditions

As highlighted by Dr. Alan Rhoades, recent research has substantially improved constraints on the emergence of low-to-no-snow conditions in mountain regions and associated implications for water resources, ecosystems, and downstream communities. The transition to a sustained new normal state of low-to-no-snow conditions is occurring approximately 20 years earlier in the southern hemisphere and at lower levels of warming compared to the northern hemisphere – elucidating what low-to-no-snow emergence may look like in California in the future. While the estimated timing of low-to-no-snow emergence in California has become more robust, uncertainties remain in the spatial patterns of these hydrologic changes in a warming climate. Intense rainfall and rain-on-snow are expected to create more punctuated runoff events, particularly if global warming exceeds 2.5°C. However, climate models suggest that the flood hazard from these runoff events will shift

from the northern to southern portions of California and result in water resource management implications that vary by region.

What are the major uncertainties?

Despite the notable scientific advances described above, substantial uncertainties remain in the quantitative assessment of how climate change will manifest across California and the Delta. While the broad direction of change is clear, these uncertainties complicate the task of translating climate projections into precise planning and operational guidance. Symposium discussions identified six areas where scientific understanding remains materially incomplete and emerging research is actively reshaping the basis for regional planning:

- Pacific Decadal Oscillation (PDO) and El Niño–Southern Oscillation (ENSO) Behavior Under Warming
- Dynamic Versus Thermodynamic Drivers of Precipitation Change
- Recurrence Potential of Medieval-Scale Megadroughts
- Infrastructure Vulnerability to Compounding and Sequential Hazards
- Ecosystem Tipping Points and Post-Transition Consequences
- Limits of Models and Decision Frameworks

These six areas are described in depth in the sections below.

Pacific Decadal Oscillation and ENSO Behavior Under Warming

One of the most consequential uncertainties discussed at the symposium, which was highlighted in the keynote presentation by Dr. Daniel Swain, concerns how large-scale Pacific Ocean circulation patterns, specifically ENSO and the PDO, will evolve as greenhouse gas concentrations continue to rise. For decades, the prevailing expectation from global climate models was that warming would produce an El Niño-like mean state (‘positive’ phase) in the tropical Pacific, implying greater warming in the eastern tropical Pacific relative to the west. However, observed Pacific sea surface temperature trends through 2025 have displayed the opposite signal, with a persistent La Niña-like (‘negative’ phase) pattern characterized by anomalously cool eastern Pacific waters. This represents a significant discrepancy between model projections and observations, with direct implications for California's precipitation.

Recent studies found that multidecadal trends in the PDO and associated annual precipitation in California were dictated by internal climate processes, as well as underrepresented external climate forcings. Existing climate models underestimate the sensitivity of regional ocean–atmosphere patterns to anthropogenic aerosol and greenhouse gas emissions. However, recent studies (Klavens et al., 2025; linked in Further Reading) revealed that these external climate processes are responsible for the three-decade-long, unpredicted negative phase of the PDO. In a negative phase, atmospheric circulation patterns shift to promote high pressure systems over California and associated dry conditions. Without properly accounting for greenhouse gas emissions in PDO predictions, current climate models may be underestimating the persistence and magnitude of future drought risk in California.

Dynamic Versus Thermodynamic Drivers of Precipitation Change

In the "Emerging Climate Science" Panel, Dr. Paul Ullrich discussed long-standing uncertainty in the relative contributions of thermodynamic and dynamic processes that drive future precipitation change. The thermodynamic component, which is driven by the well-understood Clausius-Clapeyron relationship, is consistent across models and observations and underlies high confidence in projections of more intense extremes at both wet and dry ends of the distribution. By contrast, the dynamic component remains far more uncertain and includes changes in the large-scale atmospheric circulation patterns that govern storm tracks, updraft within a storm, the position of the jet stream, and the frequency and duration of blocking events (Box 2). Current climate models show little agreement on the direction or magnitude of dynamic changes over California, including shifts in the position of the North Pacific High, changes in the intertropical convergence zone, and variations in the vertical distribution of moisture that influence how much precipitation falls west of the Sierra Nevada and supplies freshwater to the Bay-Delta watershed (Box 2). These dynamic uncertainties make it difficult to project long-term mean precipitation totals with confidence, even with increasing confidence in the type and magnitude of extreme events in a changing climate. At the symposium, panelists acknowledged that the mean precipitation signal for California overall remains statistically indistinguishable from zero across the current generation of downscaled projections, but there is a clear signal toward

more frequent extreme wet years, a pattern consistent with intensification of atmospheric river events.

Box 2. Definitions of thermodynamic terminology

- **Updraft:** The vertical column of rising air that can increase storm growth and intensity
- **Blocking events:** a high-pressure atmospheric system, that may or may not be combined with a low-pressure system, that disrupts the normal flow of the Jet Stream and drives extreme precipitation in mid-latitude regions
- **North Pacific High:** A semi-permanent, subtropical area of high pressure in the North Pacific Ocean
- **Intertropical Convergence Zone:** region where the northeasterly and southeasterly trade winds converge – commonly forming a continuous band of clouds or thunderstorms near the equator

Recurrence Potential of Medieval-Scale Megadroughts

In the "State of Science" Panel, Dr. Dan Cayan referred to paleoclimate evidence from tree ring chronologies, including submerged conifer stumps documented in Tenaya Lake and other Sierra Nevada areas, that confirms California experienced medieval megadroughts: droughts of multi-decade duration that occurred during the Medieval period (spanning the years 800 to 1350). These drought events represent severe and persistent dry spells far exceeding anything in the modern instrumental record. What remains poorly understood is the precise atmospheric and ocean–atmosphere mechanism that sustained such droughts for 60 to 70 years or more. These durations far exceed the typical interannual or even decadal oscillations of ENSO and the PDO. As discussed at the symposium, the lesson ordinarily drawn from the Holocene record is that California's hydroclimate is ultimately capable of recovery from extended dry periods, driven by the same variability that produces wet anomalies. However, the emerging evidence that PDO phase may now be partly driven by external climate forcings (i.e. aerosols and greenhouse gas emissions) raises the possibility that the boundary conditions governing drought persistence have changed. Current climate models cannot fully explain the mechanisms that sustained Medieval megadroughts, which limits confidence in assessments of whether anthropogenic forcing could increase the likelihood of their recurrence.

Infrastructure Vulnerability to Compounding and Sequential Hazards

Significant uncertainty surrounds the vulnerability of the Delta's aging and complex infrastructure to compounding and sequential hazards, as discussed by Dr. Stefan Talke in the “State of Science” Panel. While individual stressors (e.g., sea level rise, extreme flooding, land subsidence, seismic activity) can each be assessed in isolation, the difficulty lies in characterizing the joint probability and cascading consequences of multiple stressors occurring in close temporal proximity. For example, as discussed by symposium participants, an earthquake that weakens levee foundations need not coincide with a major flood to cause widespread failure: a significant storm event within 18 months of a seismic event could cause compromised infrastructure to fail before repairs are completed.

In the Delta, sea level rise vulnerability assessments are complicated by vertical land motion or subsidence. Subsidence exhibits spatial variability across the Delta, with land surface elevations decreasing by 2 to 13 millimeters per year. Landscape vulnerability assessments that simultaneously account for sea level rise and land surface elevation changes (“relative sea level rise”) may more accurately capture risk, but these highly location-specific differences are poorly captured in regional-scale models. Developing assessment frameworks that incorporate these compound and sequential risks remains a critical scientific and engineering need to reduce uncertainty.

Ecosystem Tipping Points and Post-Transition Consequences

Considerable uncertainty surrounds the timing, nature, and downstream consequences of ecosystem regime shifts under continued warming. In the “Emerging Climate Science” Panel, Dr. Paul Ullrich indicated that by approximately mid-century, the forests of the Sierra Nevada will be exposed to a climate regime more characteristic of present-day Southern California chaparral and shrublands. The transition from conifer-dominated forest to shrub-dominated landscape is expected to occur rapidly and discontinuously, most likely triggered by a large-scale wildfire event, bark beetle infestation, or a combination of stressors acting in succession. While the direction of this transition is projected with reasonable confidence, the consequences for watershed hydrology, sediment delivery, carbon stocks, water quality, and downstream Delta conditions remain insufficiently studied. As noted during symposium discussion, the scientific community has

devoted considerable attention to documenting the characteristics of this ecological tipping point, but comparatively little work has examined what the system will look like after it is crossed. Given the nonlinear nature of ecosystem transitions and the long lead times required for management responses, this represents a gap with important consequences for long-term Delta planning.

Limits of models and decision frameworks

There are important uncertainties related not only to the climate system but also to the models and decision frameworks used to translate climate information into operational guidance. Hydrologic and water-operations models often rely on historically-based sequences that are modified to approximate climate change, an approach that underrepresents unprecedented combinations of events, such as extreme storms occurring in combination with high antecedent soil moisture or simultaneous drought and heat extremes. While high-resolution downscaling, large ensemble simulations, and emerging AI tools are improving representation of regional processes, they cannot fully eliminate uncertainty stemming from structural model limitations or from deep uncertainty in future socio-economic pathways.

There is still limited understanding of how best to couple physical projections with social, institutional, and economic dynamics that shape real-world adaptation. Existing planning cycles, permitting timelines, peer-reviewed publication timelines, and funding mechanisms can be substantially longer than the time required for new science to alter risk assessments, creating potential misalignments between evolving knowledge and risk mitigation implementation. These institutional uncertainties interact with physical uncertainties to influence which adaptation pathways are feasible, when, and for whom. Taken together, these uncertainties underscore the importance of embracing adaptive, scenario-based planning frameworks rather than point-estimate forecasts. They also reinforce the need for continued investment in observational networks, model development, and targeted process studies to narrow the range of plausible futures and support more robust, risk-informed decision-making across the region.

How can we use the science to adapt?

Several themes arose during presentations and discussion about how emerging climate science can be incorporated into adaptive management. Foremost, the increasing volatility of California's hydroclimate, often characterized as hydroclimate whiplash, suggests the need to increase attention on managing for extreme conditions, rather than average conditions based on historical trends. The hydroclimate changes include increased aridity and amplification of the winter high precipitation season. With expected precipitous change and compounding stressors, potential adaptive management responses include flexible and forward-looking planning, tighter links between mid-term climate forecasts and management models, and restoring natural processes in the upper watershed to mitigate risk in the Delta.

The symposium participants discussed some of the federal, state, and local agencies that are already using current climate science to inform planning and operations. Nonetheless, many participants saw opportunities for improvement in ensuring that the best available science was being used across diverse agencies and programs. Further, they wanted to see climate science result in management actions with community engagement in generating and evaluating adaptations and responses before crises occurred. Participants emphasized that, while there remain important scientific uncertainties, these should not preclude action on improving system resilience. It was acknowledged that not all future socio-ecological risks can be avoided but adaptive management can lessen impacts, promote faster recovery from adverse events, and create a more resilient Delta system.

Flexible and forward-looking planning

Under the theme of flexible and forward-looking planning, approaches were suggested that leveraged new data, modeling, and decision support tools. A major idea was to use scenario planning and stress-testing for major decisions. Scenario planning leverages alternative futures for comparison, making it an effective tool for addressing concerns about changing conditions and compounding events. Stress testing, in contrast, involves systematically varying system variables and evaluating performance metrics to define acceptable and unacceptable performance across a wide range of future conditions. The decision-scaling

approach being used by the Department of Water Resources (DWR), which Romain Maendly presented during the “State of Science” Panel, is an example of this method. DWR creates and tests scenarios by systematically varying precipitation and temperature and then examines how reliably key water supply and ecological indicators stay within ranges defined as acceptable or desirable. Participants emphasized that stress tests should include performance evaluation over a change in low flows rather than only mean or high flows. A specific technique mentioned was the use of synthetic stochastic weather generators and adjusted historical records to incorporate variability and climate change impacts. Broadening the range of conditions used in hydrologic models and addressing the issue of under-sampling of extreme events would advance traditional probabilistic approaches.

Other approaches were discussed that included the use of evidence-based adaptive management and dynamic adaptive planning. Both approaches involve identifying adaptation strategies and testing them against acceptable thresholds of system behavior. Testing occurs through monitoring or modeling system changes and identifying management triggers for specific actions or changes in management strategies. The two approaches differ in that dynamic adaptive planning generally encourages aligning major decisions with long-term goals (e.g., 20-year time horizons are used by DWR), while adaptive management may have short or long cycles and incorporates triggers for minor and major decisions. In dynamic planning, a planner has a strategic vision of the future, commits to short-term actions, and establishes a framework to guide long-term actions. Such approaches may require more resources to plan, conduct, and model, but often do not require additional data or fundamentally different models. Because some adaptation measures take decades to plan and build, participants recommended looking out to long-time horizons. After 2050, projected climate trends are expected to accelerate sharply, with extreme impacts expected before the end of the century, making long-range planning essential.

Several examples of new science that could serve as water resource management triggers were presented in the symposium presentations. One was the Evaporative Demand Drought Index (EDDI), which is a robust measure of drought and can serve as an early warning for late-summer low flows, flash droughts, and enhanced fire risk. Another was the potential to use OpenET at the watershed scale to better

quantify land-air water flux through evaporation and transpiration across regions. Flash droughts are defined as phenomena that occur "too fast for [the] decision cycle" of management, but developing methods for early prediction and recognition can help mitigate associated negative impacts.

Linking improved near-term forecasts to management models

The integration of near-term forecasts has substantially improved water management and decision-making in small watersheds, offering potential scaling opportunities for the Delta. An example mentioned by multiple presenters at the symposium was Forecast Informed Reservoir Operations (FIRO). FIRO was cited multiple times as a "big advance" that integrates improved mid-term weather and water forecasts (particularly of atmospheric rivers) into dam operations to more flexibly balance water management and flood control, informing whether to store water for drought or release it for flood control. Weather forecasting for projections of just over two weeks has improved substantially, enabling better planning and risk mitigation for extreme events. Symposium participants also raised the idea of using advances in deep learning (AI tools that extract patterns from data) and large-sample hydrology (big data statistical exploration) to conduct streamflow forecasting and other short-term forecasts. They suggested that new tools should be considered since deep learning models sometimes outperform traditional models that use equations to mimic physical processes or fit statistical models based on current hypotheses of system behavior. Hybrid methods that leverage both deterministic models with AI appear to have great promise – particularly when rapid predictions are required.

Flood-Managed Aquifer Recharge (FloodMAR) was also identified as a key resilience strategy that aims to increase groundwater as a rainfall reservoir (“groundwater banking”) by capturing floodwater for groundwater recharge. This approach has been linked to FIRO, as FIRO offers similar flood risk mitigation by retaining more water in reservoirs and has broad benefits of reducing the mismatch between water demand and supply during dry periods, and can potentially serve as a cold-water input to create fish refugia. Both FIRO and FloodMAR provide adaptive capacity for a future that receives more rainfall in extreme storms including atmospheric river events and experiences diminished snowpack. The idea of groundwater banking as a complement to surface reservoirs offers additional water

security benefits, as underground storage is not influenced by the higher rates of evaporative loss that may be expected in a warmer future.

Multi-benefit risk mitigation approaches

Another theme that resonated with many symposium participants was increasing the attention paid to mitigation options that provide multiple benefits, specifically climate-informed interventions that would create benefits regardless of the specific future climate. Wetland restoration was a primary example of a positive approach which, when implemented in the upper watershed or headwaters, can mitigate flood risk while also creating ecosystem benefits (e.g., habitat for smelt and salmon) and promoting carbon sequestration. Other projects were discussed that enhance Delta levees for flood control while also creating habitat on the water side and increasing recreational access (i.e. boating). Practices to reduce or reverse Delta subsidence, including rice farming and wetland restoration, were discussed as projects which can preserve peat soils, stop or reverse soil carbon emissions, and increase levee resilience against sea level rise and extreme events if sited appropriately. In addition to these land conversion strategies, wildfire mitigation tools like Pyrecast can help manage fire risk during dry periods, which offers potential co-benefits to water supply, habitat, and carbon stocks. There is large potential for multi-benefit risk mitigation in the Delta and greater watershed, but the breadth of these management actions requires collaboration and coordination across disciplines, organizations, and spatial boundaries.

Institutional and Collaborative Strategies

A key discussion point, particularly among the modelers present at the symposium, was the potential benefit of shared resources or improved communication among researchers and decision makers. Strengthening partnerships between academia and government was seen as a path to making the best available science actionable and usable by agencies and organizations, including water management districts. Agency scientists were interested in learning from each other, and some have interest in using the same or similar climate change scenarios to better understand related risks. Mitigation strategies could be improved by expanding monitoring networks and remote sensing observations used to measure the impact of adaptation strategies, though these efforts require long-term investments and

funding streams. An optimistic viewpoint and recurring theme expressed by panelists was that some of the most devastating effects of climate change in the Delta could be ameliorated with greater coordination and collaboration between agency efforts in the watershed and Delta if informed by a more holistic system perspective of the science, adaptive management, and modeling.

What can be done differently?

Symposium presentations and breakout discussions highlighted meaningful ongoing activities within the Delta and California to incorporate climate science into planning and management. The Delta Stewardship Council developed Delta Adapts, a climate change initiative that includes a vulnerability assessment and an adaptation plan focusing on four thematic areas: flood risk reduction, ecosystems, agriculture, and water supply. The State of California is also advancing its adaptation strategy through the Fifth Climate Change Assessment, which provides a scientific foundation for understanding risks and vulnerabilities across the state and is designed to inform planning and investments at all scales. Some key strengths of those Delta-focused and statewide efforts were adoption of formal, structured decision-making approaches to manage uncertainty and the use of scenario-based planning.

To complement established management efforts, participants offered ideas for changes in planning and adaptation strategies. The themes of the proposed changes were to shift towards flexible, data-driven, and integrated adaptive management to handle extreme hydroclimatic variability. Participants also noted the need for future discussions about the many social dimensions of climate change, including how climate models are used and implemented at multiple levels of governance. Beyond modeling, participants noted a need to engage with communities to design adaptive pathways and create incentives for forward-looking planning.

Table 1 summarizes the suggestions made during the symposium for potential changes to concerns and uncertainties raised. Several of the suggestions highlight tools developed to enable climate-informed management. A lesson from these projects was that creating shared resources and tools with an end-user focus could build upon these examples. The suggested new directions collectively represent the

core principles of the adaptive management cycle, requiring enhanced monitoring efforts, measuring the success of adaptations, and performing "after-action reviews" to refine future strategies. A dynamic approach to managing uncertainty and a proactive approach to reducing uncertainties are crucial because the trends and impacts, though relatively flat until 2050, are expected to rapidly increase thereafter.

Table 1. Existing Management Efforts and Suggested Adaptation Strategies. This was based on presentations, plenary discussion, and breakout groups at the symposium.

Existing Management Effort	Suggested Adaptation Strategy
Traditional Climate Planning (Reliance on Averages): Planning often relies on historical averages ("the mean") or limited realizations of different scenarios, resulting in insufficient evaluation of extreme events and preparation for non-stationary conditions.	**Embrace Extremes and Scenario-Neutrality: Avoid using the average for management** as **extreme events are the new normal.** Implement **bottom-up stress testing approaches** to define acceptable and unacceptable system performance across the policy-relevant state space, focusing on changes in **low flows and high flows** rather than mean flows.
Water Operations Modeling (CalSIM3): As implemented by the Bureau of Reclamation's, CalSIM3 (a water resource planning model), currently relies on a historical time series that is "perturbated" to adjust for climate, a method acknowledged to poorly represent non-linear effects and extreme events and hydroclimate whiplash.	**Decouple and Advance Modeling:** Gain the ability to decouple CalSIM from the historical record and explore alternative hydrology. Use techniques such as synthetic stochastic generators or adjusted historical records to better capture variability. Furthermore, improve efficiency by adopting better coding alternatives (e.g., rewriting older macro-based inputs).

Existing Management Effort	Suggested Adaptation Strategy
Traditional Reservoir Operations: Dam operations traditionally rely solely on fixed historical data and rules to balance flood control and water supply.	**Integrate Real-Time Forecasting:** Given the enhanced skill of advanced weather forecasts (particularly atmospheric rivers), and ability for near real-time data assimilation in models, there are opportunities to align management with forecasts such as FIRO to make dam operations more flexible and adaptable.
Flood Control and Water Storage: Efforts focus on localized control and storage, but struggle with the "mismatch between demand and supply" during extremes.	**Develop Multi-Benefit Storage Solutions:** Some participants indicated that new storage is needed to replace the loss of snowpack as a major water reservoir. FloodMAR was an example of an integrated strategy that combines flood control with groundwater recharge, capturing high-flow water for drought preparedness and avoiding high evaporative losses.
Localized Restoration: Agencies are investing in restoring freshwater-managed wetlands for the dual purpose of subsidence reversal and carbon sequestration but may not be achieving maximum benefits.	**Quantify and Optimize Benefits of Nature Based Solutions:** Conduct research to better understand benefits of environmental restoration approaches including wetland restoration in headwaters (upstream of the Delta), and reducing methane emissions from wetland systems to maximize net carbon sequestration. Scientific study is needed to accurately project the degree to which subsidence can be halted or reversed with different land use practices.

Existing Management Effort	Suggested Adaptation Strategy
Insufficient Data on Water Use: There is an acknowledged gap in understanding how much water is being taken out of the system by people and evaporative loss.	**Adopt Advanced Monitoring and Data Tools:** Better quantify water consumption, particularly Evaporative Transpiration (ET). Specific suggestions were to scale up efforts like OpenET to the watershed scale for comparisons across regions. Use tools like EDDI for early warning of drought and low flows.
Siloed Planning and Inconsistent Funding: Funding for multi-benefit projects is often inconsistent (bond-based funding) and planning operates in "silos" separated by organizational or spatial boundaries. Without coordinated actions at the watershed scale, there is challenge in integrating models for multi-objective management.	**Improve Coordination and Institutional Frameworks:** De-silo studies and practices to share resources and design for multiple project benefits. Improve cross-agency coordination to integrate model results in a way that is informative for multi-objective management. Secure ongoing, long-term funding streams to support monitoring and maintenance, moving beyond inconsistent bond-based funding.
Science-to-Operations Disconnect: Science and operational modeling efforts often suffer from a disconnect with management practices. This disconnect results in climate tools and model outputs that lack an end-user focus or provide data that is not easily accessible, interoperable, or usable by practitioners	**Improve Access and Relevance for End Users:** Improve access to and transparency for modeling efforts, making it easier for end users to learn about and understand these resources. Tools would be created with an end-user focus, ensuring the outputs of models are configured to be the inputs that end users require. Strengthening partnerships between academia and practitioners could improve science-to-operations knowledge transfer. Using storytelling can make the science personal and actionable for communities and decision-makers.

Existing Management Effort	Suggested Adaptation Strategy
Reactive and Limited Scope Planning: Decisions often ignore compounding risks (e.g., climate + seismic + subsidence), rely on a limited local scope, and lack preparation for sudden transitions and tipping points.	**Expand Scope and Integrate Risks:** Integrate compounding risks into assessment to improve mitigation strategies. Incorporate upstream watershed management (e.g., mountain meadow restoration) as a fundamental part of Delta solutions, recognizing that headwaters directly influence downstream water flow, quality, and timing. Storm sequencing, coincident high flows between tributaries or tide levels, wildfire and flood, drought-levee failure-salinity intrusion were among some of the compounding events highlighted.

What is next?

Building on the momentum generated by the symposium, the Delta ISB communicated its key takeaways through presentations at Delta Stewardship Council meeting, the California Natural Resources Agency Speaker Series, and the State of the Estuary Conference in October 2025, broadening awareness of climate-related science needs across scientific, management, and policy communities. Information gathered during the symposium helped shape the science needs in the Sacramento-San Joaquin Delta Report, released in October 2026, for California's Fifth Climate Change Assessment. Led by the Delta Stewardship Council in partnership with the Delta Protection Commission and Delta Conservancy, the report marked the first climate assessment prepared specifically for the Delta region (see Further Reading).

One of the key takeaways from the symposium for the Delta ISB is that cutting edge climate science is relevant for robust decision making, but is slow to be incorporated. As a follow up to the symposium, the Delta ISB will be investigating what more can be done with the science, how to facilitate more system-level thinking, and how science is adopted and integrated into practice. Based on the outcome of this investigation, the Delta ISB may work on a perspective piece for peer review publication.

Appendix – Materials from the Symposium

- **Meeting Notice/Agenda**
- **Recordings**
- **Presentation Slides**
- **Science Gap Priority Matrix**
  These were the top 3 science gaps or needs identified by the five breakout groups. This is also presented in table view here.
- **Survey Results**
  See what participants said they learned during the symposium.
- **AI Generated Summary of Select Documents: Overview of Climate Science in the Sacramento-San Joaquin Delta**
  This document was created using NoteBookLM to summarize what is known about climate change prior to the symposium.
- **Panelist and Speaker Profiles**

Public Comments

After the symposium, the Delta ISB received written public comments that built on the discussion at the symposium, and highlighted work not part of the symposium.

Table 2. Public Comments received following the Emerging Climate Symposium

Date	Commenter	Subject
10/13/2025	California Water Research	Failure of CMIP6 models to capture decadal scale variability in the Pacific Highlighted an article by Jacobson and Seager (2025), Pacific Decadal Variability and Its Hydroclimate Teleconnections in CMIP6 Model
11/12/2025	California Water Research	Modeling of 1500s megadrought using a stochastic weather generator Highlighted an article by Gupta et al. (2025), Exploring Water System Vulnerabilities in California's Central Valley Under the Late Renaissance Megadrought and Climate Change

Date	Commenter	Subject
3/19/2026	California Water Research	Presented a draft and summary of, Accelerated North Pacific Warming and the Kuroshio-Oyashio Extension: A Literature Synthesis

Further Reading

State of Bay-Delta Science: This is an ongoing synthesis and communication effort led by the Delta Science Program. The 2025 edition featured seven articles exploring extreme climate and weather events and their impacts on the Bay-Delta and its watershed. Individual chapters address heatwaves, droughts, atmospheric rivers, wildfires, and related governance and climate adaptation considerations. Many of the presenters at the symposium authored these articles.

California's Fifth Climate Change Assessment: The fifth assessment will contribute to the scientific foundation for understanding climate-related vulnerability throughout California. The latest edition includes a report focused on the Delta, prepared by the Delta Stewardship Council, Delta Protection Commission, and the Sacramento-San Joaquin Delta Conservancy.

Delta Adapts: Since 2018, the Delta Stewardship Council has led a two-part climate initiative called "Delta Adapts," which takes a comprehensive, regional approach to climate resiliency that cuts across regional boundaries and commits to collaboration across state, local, and regional levels.

Article: Human emissions drive recent trends in North Pacific climate variations: This article by Jermey Klavans et al. (2025) highlights how climate models have historically suggested an El Niño-like trend in the tropical Pacific under climate change, meaning they predicted greater warming in the eastern tropical Pacific compared to the west. However, real-world observations through 2025 have shown a La Niña-like trend, which is the opposite of what many models predicted. This discrepancy raises significant uncertainty about future atmospheric circulation change.

Maven's Notebook Feature: Climate change, the Delta, and its watersheds: What we know, what we don't, & what surprises might be out there: This feature summarizes the keynote presentation by Dr. Daniel Swain at the Emerging Climate Science Symposium.

Maven's Notebook Feature: Climate change and the future of the Delta: This summary highlights the October 2025 California Natural Resources Secretary Speaker Series, which included a presentation by Dr. Jayantha Obeysekera on key takeaways from the Emerging Climate Science Symposium.

Maven's Notebook Feature: Bridging the gap between new climate science and water planning in California: Dr. Jayantha Obeysekera was interviewed by Maven's Notebook and shared his perspectives on the need to implement new climate science, barriers to implementation, and how agencies can integrate the latest climate projections in water resource management and planning in California. This interview also included some high-level takeaways from the Emerging Climate Science Symposium.

Report: ARkStorm: The United States Geological Survey (USGS) Multihazards Demonstration Project by Porter et al. (2011) modeled an extreme winter storm scenario like the California megaflood in 1861-1862, and the secondary hazards to follow (i.e. landslides and flooding). The assessment of these impacts is intended to be used by planners, policymakers, and managers to inform emergency preparedness and enhance resiliency.

Article: ARkStorm 2.0: Building upon the original ARkStorm scenario, this article by XingYing Huang and Daniel Swain (2022) discusses two separate megastorm scenarios capable of causing a megaflood. One of these scenarios is drawn from historical climate (around 1996 to 2005) and the other from a hypothetically warmer future (around 2071 to 2080 in the "high warming" emissions scenario).

Understanding Decision-Making Under Deep Uncertainty - A Summary and Synthesis of Information Learned through a Seminar Series: The Delta Independent Science Board (Delta ISB) has reviewed the scientific tools and concepts that can increase the capacity to anticipate and adapt to growing uncertainty of future conditions in the Bay-Delta system. These tools and concepts are often classified as "decision-making under deep uncertainty" (DMDU). This report provides a summary based off a seminar series on the tools that can reduce Deep Uncertainty, defined as unpredictable events or system variability that cannot be well characterized with existing data, models, and understanding. Often, there is little or no agreement among interested parties on how systems are likely to behave or the probabilities

of occurrence of such events, including the duration, sequence, and co-occurrence of events.

Other useful articles on approaches to reduce uncertainty:

- Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world by Marjolijn Haasnoot et al. (2013)
- Managing the Risk of Uncertain Threshold Responses: Comparison of Robust, Optimum, and Precautionary Approaches by Robert J. Lempert and Myles T. Collins (2007)