Understanding Climate Projections, Compounding Impacts, and Implications for Adaptive Management

A briefing paper to help inform symposia discussions
Delta Independent Science Board
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In line with its legislative mandate to provide scientific oversight of adaptive management, the Delta Independent Science Board (Delta ISB) aims to stay informed on key issues impacting the Sacramento-San Joaquin Delta system. A critical need exists for Delta ISB members, the scientific community, and the public to deepen their understanding of the rapidly evolving science surrounding the ongoing and anticipated effects of climate change on the Delta region. This knowledge is essential for incorporating a range of potential climate futures into decision-making processes. While significant research on climate change has already been conducted in the region, it is crucial to remain up-to-date with the latest findings.

To address this, the Delta ISB will organize and host two symposia. The first will focus on 1) current climate projections for the region, the uncertainties associated with them, and the compounding effects of non-climate drivers. The second symposium will explore 2) how Delta organizations are integrating climate change considerations into their decision-making processes and the effects on Delta communities. The Delta ISB will host the first symposium in May 2025, and based on its outcomes, will plan a second symposium later in the year focused on the second goal.

To help shape the scope of the symposia, the Delta ISB has prepared this briefing paper, which synthesizes the latest science and research in the region, offering a foundation for discussions at the upcoming events.

These symposia will also contribute to addressing the Delta-wide management needs outlined in the 2022-2026 Science Action Agenda, particularly Management Need 6, which calls for research to "assess and anticipate impacts of climate change and extreme events to support successful adaptation strategies." The Science Actions within this management need emphasize the importance of understanding how rapidly changing conditions will affect water supply and quality, food web dynamics, invasive species, and overall management strategies. A comprehensive understanding of current climate research and its relevance to modeling efforts is necessary to address these critical management questions.

Methods:

This briefing paper was created using NoteBookLM, which facilitated the summarization of 50 key references identified as essential for planning the symposium. These documents were identified by the Delta ISB through public comments and a brief literature review (see Works Cited Section).

After importing the 50 references into NoteBookLM, the following questions were posed using the prompt: "In 500 words using an academic style of writing, please respond to this question based on the provided sources. Please write in paragraph form."

Current climate projections for the region and related uncertainties.

1. What are the important climate drivers for planning under future conditions (e.g., atmospheric rivers, warming, droughts, and wildfires)?
    a. What changes in these drivers are already being observed?
    b. What changes in the drivers of regional impacts are expected under future climate change?
2. What are state-of-the-science projections for the Delta region based on existing climate scenarios (e.g., sea level rise, precipitation and temperature changes, extreme events, eutrophication), and what are associated ranges of uncertainty?
3. What do we know about the potential for compounding impacts (e.g., extreme precipitation, sea level rise, warming and low-snow futures), along with sequential events (e.g., earthquakes and precipitation)?
4. How reliable are current downscaled climate products for regional application in the Delta region?
5. What if anything is missing for this information to be incorporated into existing models used for decision-support (e.g., what are the gaps between projections of climate models and projections needed to drive other models)? How do we address and prioritize what is missing?

How organizations in the Delta are incorporating climate change into their decision making

1. How are organizations in the Delta region integrating climate projections and future impacts of climate drivers into planning?
2. What types of uncertainties and projections are most useful and critical for decision-support? How can understanding of evolving impacts and risks help to build resilience in the region?
3. Are the current and previous efforts to address climate change in the region adequate for enhancing resilience of the Bay Delta system?

Part 1: Current climate projections for the region and related uncertainties

1) What are the important climate drivers for planning under future conditions (e.g., atmospheric rivers, warming, droughts, and wildfires)? What changes in these drivers are already being observed? What changes in the drivers of regional impacts are expected under future climate change?

Planning for future climate conditions requires understanding key climate drivers, including **temperature increases, shifts in precipitation patterns, sea level rise, and the growing frequency and intensity of extreme events** such as atmospheric rivers, droughts, and wildfires [CNRA, 2009; DSC, 2021]. These drivers interact in complex ways to create various hazards for communities, infrastructure, and ecosystems [DSC, 2021; IPCC, 2023].

Observed changes already include **increased average temperatures, alterations in temperature extremes, reduced snowpack, and rising sea levels** [CNRA, 2009]. These shifts are accelerating, with recent years marked by record-breaking extreme weather events, such as droughts, heat waves, and wildfires [CNRA, 2017]. For example, since DATE, the state has experienced the driest four-year statewide precipitation on record, as well as the smallest and second smallest Sierra snowpack on record [CNRA, 2017]. There has also been a noted decline in heating degree days and a rise in cooling degree days, indicating a warming trend [CNRA, 2009]. Changes in precipitation patterns include a downward trend in the Sierra Nevada snow fraction, and a shift from snow to rain [DSC, 2021]. **Drought conditions are becoming more frequent and persistent, exacerbated by a reduction in snowpack** [DSC, 2021; IPCC, 2023]. Wildfires are increasing in frequency, size, and devastation, with a particular rise in high-intensity fires [CNRA, 2017]. The historical spring runoff peak is also being reduced due to climate change [Dettinger & Cayan, 2014]. Furthermore, there is increasing variability in precipitation from year to year, and this "climate whiplash" complicates water storage efforts [PPIC, 2024].

Future climate projections indicate that these trends will persist and intensify [CNRA, 2009; IPCC, 2024]. **Temperatures are projected to increase significantly by 2050 and 2100**, with higher-emissions scenarios resulting in more drastic increases [CNRA, 2009]. The state should expect overall hotter and drier conditions with a continued reduction in winter snow and an increase in winter rains [CNRA, 2009]. Although average annual precipitation may not change significantly, **longer dry spells interspersed with intense rainfall events are expected to become more common** [CNRA, 2009]. The state is expected to experience more extreme variability in precipitation [PPIC, 2024]. There is also a prediction that more precipitation will fall as rain rather than snow, further reducing snowpack and increasing the risk of floods [DSC, 2021; DSC, 2021]. **Sea levels are projected to rise**, threatening coastal areas and the Delta water conveyance system [CNRA, 2009]. The intensity of extreme weather events, including heat waves, wildfires, droughts, and floods, is also expected to increase [CNRA, 2009; CNRA, 2017]. The state's water supply system is already facing challenges, and these are expected to be exacerbated by increased temperatures and potential changes in precipitation patterns [CNRA, 2009].

There is anticipation of more frequent and larger floods and deeper droughts, and rising sea levels will pose a threat to the Delta water conveyance system and increase salinity in near-coastal groundwater supplies [CNRA, 2009]. Changes in the amount of runoff from each unit of precipitation are possible due to increased evaporation [Dettinger & Cayan, 2014]. In addition to changes in the average conditions, there will likely be a growing number of climate change-related extreme events such as heat waves, wildfires, droughts, and floods [CNRA, 2009]. There is an expectation that extreme temperatures currently estimated to occur once every 100 years could occur close to annually in most regions under a higher emissions scenario [CNRA, 2009]. **Peak inflows to the Delta are expected to increase by mid-century and by end-of-century** [DSC, 2021]. Overall, California is expected to experience hotter and drier conditions, with a continued reduction in winter snow and an increase in winter rains, as well as increased average temperatures and accelerating sea-level rise [CNRA, 2009]. The changing climate is expected to lead to more frequent and intense extreme events which will require a growing emphasis on climate change adaptation [CNRA, 2009].

2) What are state-of-the-science projections for the California Sacramento San Joaquin Delta region based on existing climate scenarios (e.g., sea level rise, precipitation and temperature changes, extreme events, eutrophication), and what are associated ranges of uncertainty?

State-of-the-science projections for the Sacramento-San Joaquin Delta region under various climate scenarios indicate significant changes in sea level, precipitation, temperature, and the frequency of extreme events, with associated ranges of uncertainty [DSC, 2021].

Sea level rise (SLR) is a major concern for the Delta, with projections varying based on emissions scenarios and time horizons [DSC, 2021]. By 2050, sea levels in the San Francisco Bay-Delta Estuary are likely (66% probability) to rise between **0.6 to 1.1 feet**, with an upper range (1-in-200 chance) projection of **1.9 feet** [DSC, 2021]. By 2100, sea levels are likely to rise between **1.2 to 3.4 feet**, with an upper range projection of **6.9 feet**. However, extreme rates of ice-sheet loss could result in sea level rise of up to 10.2 feet by the end of the century [DSC, 2021]. These projections are further complicated by land subsidence in the Delta, which can increase the relative rate of locally observed sea level change [DSC, 2021]. These changes will influence daily tides and peak storm water levels throughout the Delta [DSC, 2021]. Uncertainty in SLR projections stems from the complex feedback mechanisms of the climate system and the range of potential future emissions [DSC, 2021].

Changes in **precipitation patterns** are also expected. While average annual precipitation may not change significantly, the region is projected to experience more extreme variability with longer dry spells interspersed with intense rainfall events [Bouma-Gregson, 2024; DSC, 2021]. A greater proportion of precipitation is expected to fall as rain rather than snow, further reducing snowpack [Dettinger & Cayan, 2014]. This shift, combined with increased temperatures, is projected to result in changes to the timing and magnitude of runoff [Dettinger & Cayan, 2014; USGS, 2018]. Peak inflows to the Delta may increase by approximately 45% by mid-century and 80% by the end of the century [DSC, 2021]. These changes will increase the risk of both floods and droughts [DSC, 2021; Bosworth et al., 2024]. Uncertainty in precipitation projections comes from the variability of atmospheric processes and the difficulty of modeling changes in storm patterns [Dettinger & Cayan, 2014].

Temperature increases are another critical factor, with projections showing significant warming by 2050 and 2100 [DSC, 2021; Dettinger & Cayan, 2014]. The Delta's catchment winter temperatures are already about +2 °C warmer than the 20th-century average, analogous to average winter conditions projected for about 50 years from now [Dettinger & Cayan, 2014]. These temperature changes will impact water quality, increase evaporation, and alter ecological processes [Dettinger & Cayan, 2014, 10]. Uncertainty in temperature projections is related to the different emissions scenarios used in climate models and the limitations of climate models themselves [DSC, 2021].

Extreme events such as droughts, heat waves, and wildfires are projected to increase in frequency and intensity [DSC, 2021, Bosworth et al., 2024; CNRA, 2009]. Multi-year droughts are a characteristic feature of California's climate and can fundamentally alter water quality and ecosystem responses [Bouma-Gregson, 2024, Bosworth et al., 2024]. Droughts are defined as periods of below-average precipitation and resulting water shortages and can affect agricultural productivity, water supply, and ecosystems [DSC, 2021; Bosworth et al., 2024]. Rising temperatures, reduced snowpack, and changes in the timing of spring snowmelt will contribute to an increase in drought severity and frequency [DSC, 2021]. The risk of extreme temperature events is also increasing [DSC, 2021]. There is a possibility that extreme temperatures currently estimated to occur once every 100 years could occur close to annually in most regions under a higher emissions scenario [DSC, 2021]. Uncertainty in extreme event projections comes from the non-linear nature of these events and the limitations of models to accurately represent them [DSC, 2021; Bosworth et al 2024].

Changes in water quality, specifically **eutrophication**, are also of concern, particularly during drought conditions [Bouma-Gregson, 2024; Hartman et al 2024]. Reduced freshwater inflows and increased water temperatures can lead to an increase in nutrient concentrations and create conditions favorable for harmful algal blooms [Bouma-Gregson, 2024, Bosworth et al 2024; Hartman et al 2024; IEP 2022]. The cyanobacteria *Microcystis* has become more prevalent in the Delta since the late 1990s [Bouma-Gregson et al 2024]. Uncertainty in eutrophication projections stems from the complex interactions between hydrology, nutrient cycling, and biological processes [Bouma-Gregson et al 2024].

These projections collectively indicate a future of significant environmental change in the Delta. The ranges of uncertainty associated with these projections underscore the need for flexible and adaptive management strategies [DSC, 2021].

3) What do we know about the potential for compounding impacts (e.g., extreme precipitation, sea level rise, warming and low-snow futures), along with sequential events (e.g., earthquakes and precipitation)?

The potential for compounding impacts and sequential events presents significant challenges for the future, particularly in regions like California and the Sacramento-San Joaquin Delta. Climate change is increasing the likelihood of multiple hazards occurring simultaneously or in quick succession, and the impacts of these events can be greater than the sum of their individual effects [NCA Chpt 2; NCA Compounding Events; IPCC, 2023].

Compound events are broadly categorized as multivariate (co-occurring hazards), temporally compounding (successive hazards), spatially compounding (hazards occurring in multiple connected locations), preconditioned (hazards superimposed on long-term trends), and complex (non-climatic stressors that exacerbate climate hazards) [NCA Compounding Events].

Climate change is increasing the chances of compound events [NCA Compounding Events]. For instance, the risk of concurrent heatwaves and droughts is expected to increase [IPCC, 2023]. Co-occurring hot and dry conditions will become more frequent, increasing the risk of extreme wildfires, as well as affecting agriculture, water resources, and freshwater and marine ecosystems [NCA Chpt 2].

The combination of **increasing drought risk and extreme precipitation** can lead to extreme wildfire seasons followed by heavy precipitation, increasing the risk of post-fire hazards like debris flows, landslides, and flash floods [NCA Chpt 2]. In addition, **more frequent extreme La Niñas** would simultaneously elevate the risk of western US droughts and back-to-back severe Atlantic hurricanes [NCA Compounding Events].

Sea level rise is expected to compound the impacts of coastal storms and flooding. Higher average sea levels can result in higher storm surges, more extensive inland flooding, and increased erosion along the coastline [NCA Coastal Effects; CNRA, 2009]. Even if storm intensity or frequency does not change, storms will impact the California coast more severely due to higher sea levels [CNRA, 2009]. Additionally, compound flood events are commonly due to the joint occurrence of heavy precipitation, high river flows, elevated groundwater levels, soil saturation, and elevated ocean water levels [NCA Coastal Effects]. The combination of rising sea levels, storm surge, and heavy precipitation will increase the risk of coastal flooding and can also lead to saltwater intrusion into groundwater aquifers [CNRA, 2009; NCA Water; NOAA Sea Level Rise].

Warming temperatures exacerbate the effects of other climate drivers. For instance, warming temperatures will lead to a greater proportion of precipitation falling as rain rather than snow, reducing snowpack and increasing the risk of floods [Dettinger & Cayan, 2014; Huang & Swain 2022]. This "double whammy effect," where both the volume of precipitation and the fraction that becomes runoff increases, can lead to unexpectedly large increases in runoff volume [Huang & Swain 2022]. Furthermore, there is evidence of multiple intense "rain on snow" events that correspond temporally with event-maximum runoff peaks [Huang & Swain 2022]. **Warming can also lead to more intense atmospheric river events and subsequent severe flood events** [Huang & Swain 2022].

Low snowpack conditions, driven by warming temperatures and a shift from snow to rain, will further compound drought impacts. This will reduce water availability during the dry season and increase the risk of wildfires and ecological stress [Dettinger & Cayan, 2014]. The increased frequency of drought under climate change is also likely to enhance other stressors with a variety of synergistic interactions [Herbold et al 2022].

Sequential events such as earthquakes followed by heavy precipitation can also lead to cascading impacts. For example, an earthquake can destabilize slopes, increasing the risk of landslides and debris flows during subsequent heavy rainfall events [CNRA, 2009]. Similarly, a prolonged drought followed by extreme floods can cause already weakened riparian species to succumb to bank erosion, increasing the risk of levee failures [IEP MAST, 2022].

These cascading impacts of compound and sequential events can overwhelm adaptive capacity and substantially increase damage [IPCC, 2023]. The interconnected nature of many systems means that the failure of one system can trigger cascading failures in others [DSC, 2021; DWR Climate Change Vulnerability Ass]. For example, more drought, fires and intense rainfall events can produce more mud- and landslides which can disrupt major roadways and rail lines [CNRA, 2009]. Sea-level rise is also likely to cause more frequent storm-related flooding of airports, seaports, roads, and railways in floodplains [CNRA, 2009].

It's important to note that there are **uncertainties** associated with projecting compound and sequential events. These events are rare, and the short observational record limits the ability to quantify historical changes and evaluate the ability of climate models to simulate them [NCA Chp 2; NCA Compounding Events]. However, despite these uncertainties, there is broad agreement that compound events are a growing threat, necessitating integrated planning and management strategies to reduce risks [NCA Compounding Events].

4) How reliable are current downscaled climate products for regional application in the Delta region?

Downscaled climate products offer a valuable approach to understanding regional climate change impacts, yet their reliability for application in the Sacramento-San Joaquin Delta region is complex and requires careful consideration [DSC, 2021]. **Global Climate Models (GCMs)**, which provide estimates of future climate conditions, often operate at a spatial resolution too coarse for detailed vulnerability assessments [DSC, 2021]. To address this, statistical downscaling techniques like **Localized Constructed Analogs (LOCA)** are used [DSC, 2021]. LOCA uses quantitative relationships between large-scale climate stressors and local conditions to generate finer-scale projections [DSC, 2021]. For the Delta region, GCM simulations have been downscaled using LOCA, incorporating coarse-scale GCM projections of variables like temperature and precipitation, and fine-scale physiographical and meteorological features [DSC, 2021]. However, despite these advancements, challenges and uncertainties remain.

One significant challenge lies in the **selection of appropriate projections and scenarios** due to the large uncertainties inherent in modeling and analysis assumptions [DSC, 2021]. Different GCMs and emissions scenarios (such as RCP 4.5 and RCP 8.5) can lead to a wide range of projections, making it difficult for planners and decision-makers to determine the most likely future climate conditions [DSC, 2021]. To address this issue, a "decision scaling" approach is used, which evaluates system performance by stress-testing it against changes in key climate variables [DSC, 2021]. This method helps in understanding a system's sensitivities to climate stressors such as temperature, precipitation, and sea level rise [DSC, 2021]. While downscaled climate models provide valuable inputs, the uncertainty in the projections is still considerable [DSC, 2021]. For example, precipitation is one of the least certain aspects of climate models, particularly at regional levels, due to the models' inability to resolve complex local interactions such as orographic intensification and rain shadowing [DSC, 2021]. This uncertainty is particularly relevant in the Delta, where precipitation trends vary considerably across subregions [DSC, 2021].

Furthermore, downscaled climate data has limitations in representing the dynamic and complex interactions within the Delta region, as climate models may not capture the full range of local processes and interactions [DSC, 2021]. For instance, although air temperatures are projected to increase across the Delta, localized effects based on variations in topography and proximity to the coast may cause spatial variations in projected temperature changes [DSC, 2021]. Similarly, while the models may show a slight increase in average annual precipitation, the magnitude of these changes is small relative to historical year-to-year variability, which makes it difficult to detect a strong signal in recent data or future projections [DSC, 2021]. These uncertainties underscore the need for decision-makers to consider the full range of possible climate futures when making adaptation and planning decisions [DSC, 2021]. **It is critical to apply sensitivity analyses** to climate projections to understand how the system may respond under a variety of possible changes to key climate variables [DSC, 2021].

In summary, while downscaled climate products provide a necessary tool for regional climate assessments, they should be used with caution, and with a full understanding of their limitations [DSC, 2021]. They are most effective when used in conjunction with methods like decision scaling and sensitivity analyses to evaluate a range of possible climate futures and understand how sensitive the Delta region is to various climate stressors [DSC, 2021]. The inherent uncertainties in climate models, particularly in regional projections of precipitation, necessitate an approach that incorporates a range of potential outcomes, rather than relying on a single projection [DSC, 2021].

5) What if anything is missing in order for this information to be incorporated into existing models used for decision-support (e.g., what are the gaps between projections of climate models and projections needed to drive other models)? How do we address and prioritize what is missing?

A number of gaps and limitations exist in current climate models and their application to decision-support systems [Rising et al 2022]. These include a lack of representation of key processes and feedbacks, uncertainties in projections, and difficulties in downscaling and applying global models to local scales [Rising et al 2022]. Addressing these gaps is essential for improving the accuracy and reliability of climate information used for decision-making [CNRA, 2017].

Gaps in Climate Models

Representation of key processes:

- **Clouds and convection:** Climate models often have inadequate representations of clouds and moist convection, which are critical for accurately simulating the water cycle and its response to climate change [Stevens & Bony 2013]. In particular, models struggle to capture the observed relationships between tropical clouds and circulation, which impacts the accuracy of cloud feedbacks and climate sensitivity estimates [Hill et al 2023]
- **Ocean circulation:** Models have difficulty reproducing past changes in thermohaline ocean circulation, which are influenced by subtle temperature and salinity differences. They may not accurately capture the observed cold blob in the North Atlantic, for example [Rahmstorf et al 2024].
- **Ice sheets:** Ice sheet models have limitations in their mathematical representations of ice dynamics [OPC, 2017]. They also poorly represent the meltwater-buffering capacity of firn, which could affect the timing of ice shelf hydrofracturing in models [OPC, 2017].
- **Land surface processes:** Models need to include more explicit and faithful representations of surface and groundwater processes, water infrastructure, and water users, including the agricultural and energy sectors [Milly et al 2008]. Treatments of land cover change and land-use management should also be routinely included [Milly et al 2008].
- **Decomposition:** There are uncertainties in the algorithms controlling decomposition, which affect estimates of fuel loading, with implications for wildfire projections [Hanan et al 2022]. Woody fuel decomposition and the interactions with fire are not well studied [Hanan et al 2022].

Feedbacks and Interactions:

- **Eddy feedback:** Current climate models underestimate the positive feedback between transient eddies and large-scale flow anomalies, leading to weak signal-to-noise ratios in ensemble mean predictions [Hardiman et al 2022].
- **Coupled processes:** Climate models struggle to capture the coupled dynamics of ice-atmosphere-ocean-Earth systems [OPC, 2017]. Models also do not fully represent interactions between climate change and variability, demographic shifts, economic insecurity and political processes [Rising et al 2022].
- **Compounding events:** Models have limitations in simulating compound events and their impacts [NCA Compounding Events; Rising et al 2022].

Compound, sequential, and concurrent extremes can lead to lower thresholds for substantial impacts, but are often missing from analyses [Rising et al 2022].

Uncertainty:

- **Climate sensitivity:** There are discrepancies between estimates of climate sensitivity derived from models and those based on observed warming, due in part to the pattern effect, which is the process whereby climate sensitivity depends on the geographic pattern of surface warming [Rugenstein et al 2023].
- **Downscaling and Local Variability**: Climate models often operate at a scale that is too coarse to address local or regional water resource concerns [Milly et al 2008]. Translating climate information from global models to local scales can be challenging [NCA Water]. There are gaps in understanding community-level impacts of projected changes in extreme events [NCA Climate Trends].

Gaps in Data

- **Monitoring data**: There is a lack of long-term groundwater monitoring wells [NCA Water]. Also, limited information exists on dynamic changes to vegetation strata following fires [Hanan et al 2022].
- **Paleoclimatic records**: Expanded collection and understanding of paleoclimatic records is needed [Dettinger & Cayan, 2014].
- **Land surface data:** A complete inventory of all land holdings, with accompanying information about habitat types and sensitive species, is needed to understand the vulnerability of managed lands to climate change [DWR Vulnerability Assessment].
- **Observed VLM:** Higher-resolution assessment of Vertical Land Movement (VLM) rates are needed, as this can impact sea level rise projections [NOAA Sea Level Rise].

Addressing and Prioritizing What is Missing

Improve models:

- **Increase model complexity and resolution:** Increase the level of process detail, better representing surface and groundwater processes, water infrastructure, and water users, and consider land cover and land-use changes [Milly et al 2008; Stevens & Bony 2013]. Use higher-resolution simulations that better resolve processes related to clouds, convection, and ocean circulation [Milly et al 2008; Stevens & Bony 2013].

- **Address model biases:** Quantify model biases in surface warming trends, and determine if models compensate for biases through erroneous ocean heat uptake rates or aerosol forcings [Rugenstein et al 2023]
- **Integrate feedbacks:** Improve the representation of feedback processes such as eddy feedback in models [Hardiman et al 2022]. Improve how models represent the interactions among climate change, variability, and societal processes [Rising et al 2022].
- **Represent compounding events:** Improve models' representation of compound events and their impacts [NCA Compound Events; Rising et al 2022].
- **Incorporate parameter uncertainty:** Represent parameter uncertainty by using probability distributions over parameter values [Rising et al 2022].
- **Improve water system modeling**: Improve the representation of groundwater in water system models [DWR Adaptation Plan 2020].

Collect data:

- **Enhance monitoring**: Expand monitoring programs to better track and understand the development, spread, and decline of droughts [Dettinger & Cayan, 2014]. Collect data on land holdings and their vulnerability to climate change [DWR Vulnerability Assessment 2019]. Collect data on vegetation strata following fires [Hanan et al 2022].
- **Expand Paleoclimatic records**: Improve knowledge and use of paleoclimatic records [Dettinger & Cayan, 2014].
- **Improve VLM Data**: Utilize satellite-based advanced Interferometric Synthetic Aperture Radar (InSAR) analysis to provide higher spatial resolution measurements of VLM rates [NOAA Sea Level Rise].

Improve communication and collaboration:

- **Interdisciplinary Collaboration:** Foster collaboration between climate scientists, economists, and social scientists [Rising et al 2022]. Develop frameworks that incorporate the diverse perspectives of different stakeholders [NCA Water].
- **Knowledge sharing:** Improve the sharing of knowledge and expertise across disciplines [Rising et al 2022]. Ensure that climate scientists provide results in a form that can be readily incorporated into economic analysis [Rising et al 2022].

- **Transparent communication of uncertainty:** Separate variability from uncertainty when presenting model-based information [Rising et al 2022]. Clearly state model limitations and represent unmodeled risks [Rising et al 2022].
- **Stakeholder engagement**: Engage with users and stakeholder groups regarding their specific planning and decision contexts [NOAA Sea Level Rise].

***Prioritization**:*

- **Vulnerability assessments:** Conduct assessments to integrate risk with the likely sensitivity and response capacity of natural and human systems that are at risk of experiencing climate change consequences [CNRA, 2009].
- **Decision scaling:** Apply "decision scaling" approaches to evaluate the performance of systems by stress testing the system to better understand its sensitivities to changes in key climate stressors [DSC, 2021; DWR, 2019].
- **Address key data gaps:** Prioritize the collection of essential data for vulnerability assessments [DWR, 2019; CNRA, 2009]. Identify and fill knowledge gaps related to climate adaptation, and evaluate the most effective strategies [CNRA, 2009].
- **Iterative Approach**: Use iterative approaches to incorporate new climate information, and update management practices and goals accordingly [CNRA, 2017].
- **Focus on actionable science**: Translate scientific advances into actionable science that is useful for decision making [NOAA Sea Level Rise].

Utilize multiple approaches:

- **Combine modeling and non-modeling approaches**: Combine model-based quantification with non-model-based qualitative assessments [Rising et al 2022].
- **Use ensembles:** Employ ensemble modeling to capture the range of uncertainty and improve projections [OPC, 2017]. Use ensembles to test the sensitivity of policy relevant conclusions to model error, and stochastic behavior [Rising et al 2022].
- **Develop alternative methods:** Explore methods such as "tales of the future" to incorporate deep uncertainties, and to encapsulate physically realistic and plausible futures [Rising et al 2022].

By addressing these gaps and prioritizing the collection of data, improving models, and engaging in collaborative research, we can better understand the impacts of climate change and develop more effective and resilient adaptation strategies [NCA Water].

Part 2: How organizations in the Delta are incorporating climate change into their decision making

1) How are organizations (state agencies and other groups) in the Delta region integrating climate projections and future impacts of climate drivers into planning?

Organizations in the Sacramento-San Joaquin Delta region are proactively integrating climate projections and the anticipated impacts of future climate drivers into their planning frameworks through a multifaceted approach encompassing comprehensive regional initiatives, targeted state agency actions, sector-specific adaptations, and overarching cross-cutting strategies [DSC, 2021; DSC, 2025] . This integration is driven by the increasing recognition of climate change as a fundamental challenge to the Delta's ecological integrity, water supply reliability, infrastructure resilience, and the well-being of its communities [DSC 2021, 2025]. A central framework for this integration is the **Delta Adapts: Creating a Climate Resilient Future initiative led by the Delta Stewardship Council (DSC)** [DSC 2021, 2025]. This comprehensive regional effort involves a two-phase process: a Climate Change Vulnerability Assessment (CCVA) and an Adaptation Plan [DSC, 2025] . The CCVA meticulously analyzes regionally specific climate risks and vulnerabilities, considering a spectrum of climate scenarios and future time horizons, thereby providing a robust scientific foundation for adaptation planning [DSC, 2021]. The subsequent Adaptation Plan outlines concrete strategies and actions for various levels of governance and land management to mitigate identified climate vulnerabilities across critical sectors such as flood risk reduction, ecosystem health, agriculture, and water supply reliability [DSC, 2025]. Delta Adapts aligns with state-level climate guidance and leverages the best available climate data and analytical tools [DSC, 2021].

Numerous state agencies play pivotal roles in embedding climate considerations into their planning. The **Department of Water Resources (DWR)** actively provides climate datasets and tools, including the Cal-Adapt platform, to support informed decision-making in areas like groundwater management and local water planning [CNRA, 2017; DWR Adaptation Plan 2020]. DWR also collaborates closely with the DSC on initiatives like Delta Adapts, ensuring consistency in data and analytical approaches, particularly concerning flood risk [CVPP 2022]. Furthermore, DWR is committed to incorporating future climate extremes into its Flood Investment Strategy and employs advanced techniques like decision scaling to assess the vulnerability of the State Water Project to hydrological risks driven by climate change [CNRA, 2017; DWR Climate Adaptation Plan, 2020; DWR Decision Scaling for Hydrological Risk 2019]. The **Central Valley Flood Protection Board (CVFPB)** integrates climate change analyses into its Central Valley Flood Protection Plan (CVFPP) to better understand and manage escalating flood risks [CVPP, 2022]. This includes developing tools to assess social vulnerability to flooding, aligning with the equity considerations emphasized in Delta Adapts [CVPP, 2022].

Sector-specific integration highlights the granular application of climate projections. In **flood management**, organizations are incorporating climate change into risk assessment models, floodplain management practices, and the design and maintenance of levee systems [DSC, 2025]. Nature-based solutions for flood mitigation and ecosystem services are also gaining traction [DSC, 2025]. **Water management** planning now accounts for projected changes in temperature, precipitation, snowpack, and sea-level rise, influencing reservoir operations and water supply reliability assessments [DWR Decision Scaling for Hydrological Risk, 2019; DSC, 2021]. In **ecosystem restoration**, state agencies like the California Department of Fish and Wildlife (CDFW) are incorporating climate science and projected impacts on flora and fauna into conservation planning efforts, such as Habitat Conservation Plans [CNRA, 2017;]. The Delta Conservancy prioritizes projects that demonstrate resilience to climate change impacts and embrace science-based adaptive management [Delta Conservancy, 2017]. Even sectors like **transportation** are engaging, with Caltrans conducting vulnerability assessments using climate projections and integrating climate considerations into project development and regional transportation plans [CNRA, 2017].

Underpinning these diverse efforts are crucial cross-cutting strategies. **Adaptive management**, a systematic process of monitoring, evaluating, and adjusting management actions based on new knowledge and changing conditions, is a cornerstone of climate adaptation in the Delta [CNRA, 2009; Delta Conservancy, 2017; DSC, 2025]. Collaborative partnerships among federal, state, regional, and local agencies, tribes, non-governmental organizations, and the public are essential for effective climate action, with the DSC serving as a key convener [DSC 2021, 2025]. Finally, a significant emphasis is placed on **equity and addressing the**

needs of vulnerable communities, as highlighted by Executive Order B-30-15 and the social vulnerability analyses within Delta Adapts [CVPP, 2022; DSC 2021, 2025]. This involves actively engaging with community-based organizations and tribes to ensure that adaptation strategies are inclusive and responsive to the unique challenges faced by the most susceptible populations [DSC, 2025]**.**

In conclusion, the integration of climate projections and future impacts into planning within the Delta region is a dynamic and evolving process. It is characterized by comprehensive regional initiatives like Delta Adapts, dedicated efforts from state agencies across various sectors, a commitment to adaptive management and collaboration, and an increasing focus on equitable outcomes for all Delta communities. This multi-layered approach underscores the seriousness with which organizations in the region are confronting the challenges posed by a changing climate [CVPP, 2022].
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2) What types of uncertainties and projections are most useful and critical for decision-support? How can understanding of evolving impacts and risks help to build resilience in the region?

Drawing on the sources and our conversation history, several types of uncertainties and projections are most useful and critical for decision-support in the Delta region, and understanding evolving impacts and risks is crucial for building resilience.
Useful and Critical Uncertainties and Projections for Decision-Support:
•**Regional Downscaled Climate Projections:** While global climate models provide broad trends, **downscaled projections that offer information at regional and sub-regional levels are more useful for local planning** [CNRA, 2009; DSC, 2021; NCA Water]. These can inform shoreline and land use planning [CNRA,2009] and help understand specific regional climate risks and vulnerabilities in the Delta [DSC, 2021]. However, decision-makers often struggle with selecting projections due to the large uncertainty [DSC, 2021].

- **Probabilistic Projections:** Rather than relying on single scenarios, **probabilistic approaches to sea-level rise projections and other climate impacts can inform decisions by conveying the likelihood of different outcomes** [OPC, 2017] . Understanding the probability of certain consequences under different future climate scenarios is a key aspect of moving towards a "vulnerability assessment approach" [CNRA, 2009].

- **Scenario Planning (Planning and Bounding Scenarios):** Developing both "planning scenarios" (what is most likely to happen in the near- to mid-term) and "bounding scenarios" (how bad could things get in the long term) can help frame important problems in coastal risk assessment and management [NOAA, 2022] . Evaluating how proposed projects would work under a variety of future scenarios is also encouraged [PPIC, 2024].
- **Decision Scaling:** This "bottom-up" analysis approach helps understand how complex systems (like water supply) behave in response to changes in key climate variables (temperature, precipitation, sea-level rise) [DSC, 2021; DWR Climate Adaptation Plan, 2020; DWR Decision Scaling for Hydrological Risk, 2019]. It allows decision-makers to understand which climate variables exert the greatest effect on future system performance, informing future decision-making and monitoring [DSC, 2021]. DWR has used decision scaling to assess the State Water Project's hydrologic vulnerability [DWR Climate Adaptation Plan, 2020] .
- **Near-Term Projections (e.g., 30-year horizons):** For certain decision types, especially those related to the lifespan of buildings and infrastructure, shorter time horizons are most relevant [NOAA, 2022] . These projections can inform initial designs and the adaptations required [NOAA, 2022].
- **Extreme Water Level Probabilities:** Understanding the probabilities of extreme water levels, considering sea-level rise and storm events, is crucial for assessing current and future vulnerabilities of coastal communities and infrastructure [DSC, 2021; NOAA, 2022].
- **Projections Incorporating Deep Uncertainty:** Recognizing that for many impacts, robust probability distributions do not exist ("deep uncertainty") is important [Rising et al 2022]. Exploring deep uncertainties through scenarios and vulnerability assessments can help in planning even when probabilities are unknown [Rising et al 2022].
- **Visualization and Mapping Tools:** These tools can help build more resilient communities and ecosystems by facilitating the assessment of vulnerabilities and risks at appropriate scales [CNRA 2017]. NOAA's SLR Viewer, for example, provides maps of high tide flood thresholds [CNRA 2017] .

How Understanding Evolving Impacts and Risks Helps Build Resilience:

- **Identifying Vulnerabilities:** A key research need is to develop statewide climate impact vulnerability assessments [CNRA, 2009]. Understanding what, where, when, and how climate impacts are increasing vulnerability is crucial for policy-makers [CNRA, 2009]. This includes assessing community and ecosystem vulnerability using decision-support tools [CNRA, 2017].

- **Developing Adaptation Strategies:** Once vulnerabilities are identified, adaptation strategies can be formulated to reduce risks [DWR Climate Adaptation Plan, 2020]. This includes considering a range of adaptation options and their costs and benefits [CNRA, 2009].
- **Prioritizing Actions:** Understanding the most significant risks and vulnerabilities allows for the prioritization of limited resources in implementing adaptation strategies [CNRA, 2009]. The "Corridors of Clarity" concept suggests focusing on the strongest and most direct paths between policy decisions and outcomes to overcome uncertainty paralysis [Polasky et al 2020].
- **Implementing Flexible and Adaptive Approaches:** Given the uncertainties, flexible and adaptive approaches are recommended to prepare for uncertain climate impacts [CNRA 2017]. Adaptation pathways provide an analytical approach for exploring and sequencing possible actions based on alternative future developments [DWR Climate Adaptation Plan, 2020; PPIC, 2024]. Adaptive management, an iterative process of monitoring and adjusting, is essential [OPC, 2017].
- **Integrating Climate Considerations into Planning:** Climate change should be considered in all core functions of government [CNRA, 2017]. This includes integrating climate resilience and hazard avoidance into local government general plans and policies [CNRA, 2017].
- **Enhancing Community Resilience:** Understanding risks at the community level and engaging residents, especially vulnerable populations, in planning processes is vital for building grassroots resilience [CNRA, 2017]. Strengthening community social networks can also build climate resilience [CNRA, 2017].
- **Learning and Improving:** Monitoring the changing climate conditions and the outcomes of resilience efforts through metrics is important for accountability and for making course corrections as needed [CNRA, 2009; CNRA; 2017; CVPP, 2022]. Periodically reviewing adaptation effectiveness and updating strategies based on new information is crucial [CNRA, 2009; DWR Climate Adaptation Plan, 2020; OPC, 2017].
- **Considering Compounding Events:** Understanding how multiple climate hazards can occur simultaneously or sequentially to create greater overall impact is essential for effective resilience planning [DWR Vulnerability Assessment, 2019; NCA Coastal Effects, 2023; NCA Compounding Events, 2023].

- **Addressing Equity and Social Justice:** Since climate change exacerbates existing inequities, efforts to build healthy and equitable communities need to be central to adaptation strategies [CNRA 2017; CVPP 2022; IPCC 2023]. Understanding the vulnerabilities of specific social groups is crucial for developing effective and just responses [CNRA 2017; EPA, 2021; IPCC, 2023].

In summary, the most useful uncertainties are those that are acknowledged and integrated into decision-making processes, driving the need for flexible and adaptive strategies. The most critical projections are those that are regional, probabilistic, and explore a range of future scenarios, including the consideration of deep uncertainties. Understanding the evolving impacts and risks, particularly vulnerabilities across different sectors and communities, is fundamental to developing targeted, effective, and equitable adaptation measures that build long-term resilience in the Delta region.

3) Are the current and previous efforts to address climate change in the region adequate for enhancing resilience of the Bay Delta system?

Based on the information in the sources, it appears that while there have been significant efforts to address climate change in the Bay Delta region, **they are likely not yet fully adequate for enhancing the resilience of the system** [CVPP, 2022; DSC, 2025] . The sources highlight ongoing vulnerabilities and the need for accelerated and more comprehensive action [DSC, 2021; CVPP, 2022].

Here's a breakdown of why:
Ongoing Vulnerabilities: The Delta remains highly vulnerable to climate change impacts such as sea-level rise, changes in precipitation patterns, increased flooding, extreme heat, and drought [CNRA, 2017; DSC, 2021]. The Delta Adapts Climate Change Vulnerability Assessment (CCVA) extensively details these vulnerabilities across ecosystems, water supply, infrastructure, and communities [DSC, 2021]. For example, significant land area is projected to be exposed to flooding by mid and end-of-century [DSC, 2021].

Initiatives and Planning Efforts: Several plans and initiatives are in place to address climate change:

- **Delta Adapts:** This comprehensive regional approach includes a vulnerability assessment and an adaptation plan aimed at building climate resilience in the Delta and Suisun Marsh [DSC 2021, 2025;

CVPP, 2022]. It identifies strategies across flood risk reduction, ecosystems, agriculture, and water supply reliability [DSC 2025].

- **California Climate Adaptation Strategy (2009) and Safeguarding California Plan (2017 Update):** These statewide strategies acknowledge the Delta's vulnerability and outline actions for adaptation, including improving water and flood management systems, enhancing ecosystems, and planning for sea-level rise [CNRA 2009, 2017] The Safeguarding California Plan highlights the need to reduce Sacramento-San Joaquin Delta climate change vulnerability [CNRA 2017].
- **Central Valley Flood Protection Plan (CVFPP) Update:** This plan responds to increasing flood risks and incorporates climate change impacts, emphasizing nature-based solutions and multi-benefit projects to build resilience [CVFPP 2022]. It also considers social and economic factors contributing to community vulnerability [CVFPP 2022].
- **DWR Climate Adaptation Plan:** DWR outlines a five-step approach aligned with UNESCO's CRIDA for the State Water Project (SWP) to adapt to climate change impacts like reduced snowpack and sea-level rise [DWR Climate Adaptation Plan 2020]. DWR is also coordinating with the Delta Stewardship Council's Delta Adapts process [DWR Climate Adaptation Plan 2020] .
- **Delta Levees Investment Strategy (DLIS) and EcoRestore:** These initiatives aim to reduce the likelihood and consequences of levee failures and restore critical habitat in the Delta and Suisun Marsh to increase resilience [DWR Vulnerability Assessment 2019].
- **Adapting to Rising Tides (ART) program:** The San Francisco Bay Conservation and Development Commission (BCDC) prepares climate vulnerability assessments and adaptation tools for the San Francisco Bay Area [CA Natural and Working Lands Climate Smart Strategy, 2021].

Focus Areas of Adaptation: Efforts span various sectors:

- **Flood Risk Reduction:** Strategies include levee improvements, nature-based solutions for flood mitigation (e.g., wetland restoration), improved emergency preparedness, and optimized reservoir operations [DSC, 2025].

- **Ecosystem Restoration:** Actions focus on restoring and connecting habitats, implementing functional flows, reversing land subsidence, and protecting native species to enhance ecosystem adaptability [DSC, 2025].
- **Agriculture:** Strategies include promoting climate-smart farming practices, efficient water use, and diversification of agricultural activities [DSC, 2025].
- **Water Supply Reliability:** Efforts aim to reduce reliance on the Delta through conservation, expanded storage, modernized conveyance, improved reservoir operations, and updated water quality standards [DSC, 2025].
- **Governance and Collaboration:** Fostering collaboration among agencies and stakeholders is recognized as crucial for successful adaptation [DSC 2021, 2025].

Limitations and Areas for Improvement:

- **Funding Gaps:** Implementing the recommended adaptation strategies, such as levee improvements and ecosystem restoration, requires significant funding, and a substantial gap likely remains [DSC, 2025].
- **Scale and Pace of Implementation:** The urgency of climate change impacts necessitates an acceleration of the pace and scale of multi-benefit project implementation [CVFPP, 2022].
- **Uncertainty:** Despite advancements in climate science, uncertainties in projections remain, making it challenging to predict the exact timing and intensity of impacts [DSC 2021, 2025]. This underscores the importance of adaptive management [CNRA, 2017; Delta Conservancy, 2017; DSC, 2025].
- **Coordination and Integration:** While collaboration is emphasized, continued efforts are needed to improve coordination among different state, federal, and local agencies and to align policies across sectors [CVFPP, 2022] Integrating climate considerations into all levels of planning and decision-making is also crucial [DSC, 2025].
- **Equity Considerations:** Ensuring that adaptation efforts address the needs of socially vulnerable communities and promote equity remains a critical aspect needing further integration [CNRA, 2017; DSC 2021, 2025]. The Delta Adapts plan specifically considers social vulnerability [DSC, 2025].
- **Adaptive Management:** While the concept of adaptive management is recognized [CNRA 2017; Delta Conservancy, 2017], its consistent and effective implementation across all efforts is vital for responding to evolving conditions and new information [DSC 2025].

- **Understanding Flood Dynamics:** A comprehensive, climate-informed understanding of flood dynamics in the Delta is still being developed [DSC 2025].

In conclusion, while significant planning and initial actions are underway to address climate change in the Bay Delta region, the scale and urgency of the impacts suggest that current efforts may not yet be fully adequate to ensure the long-term resilience of this complex system. **Accelerated implementation, increased funding, enhanced coordination, a stronger focus on equity, and a commitment to adaptive management based on the best available science are all crucial for building a more resilient Bay Delta system in the face of a changing climate** [DSC 2021, 2025; CVFPP, 2022].

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Purple Text Denotes citation is not cited in the text

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