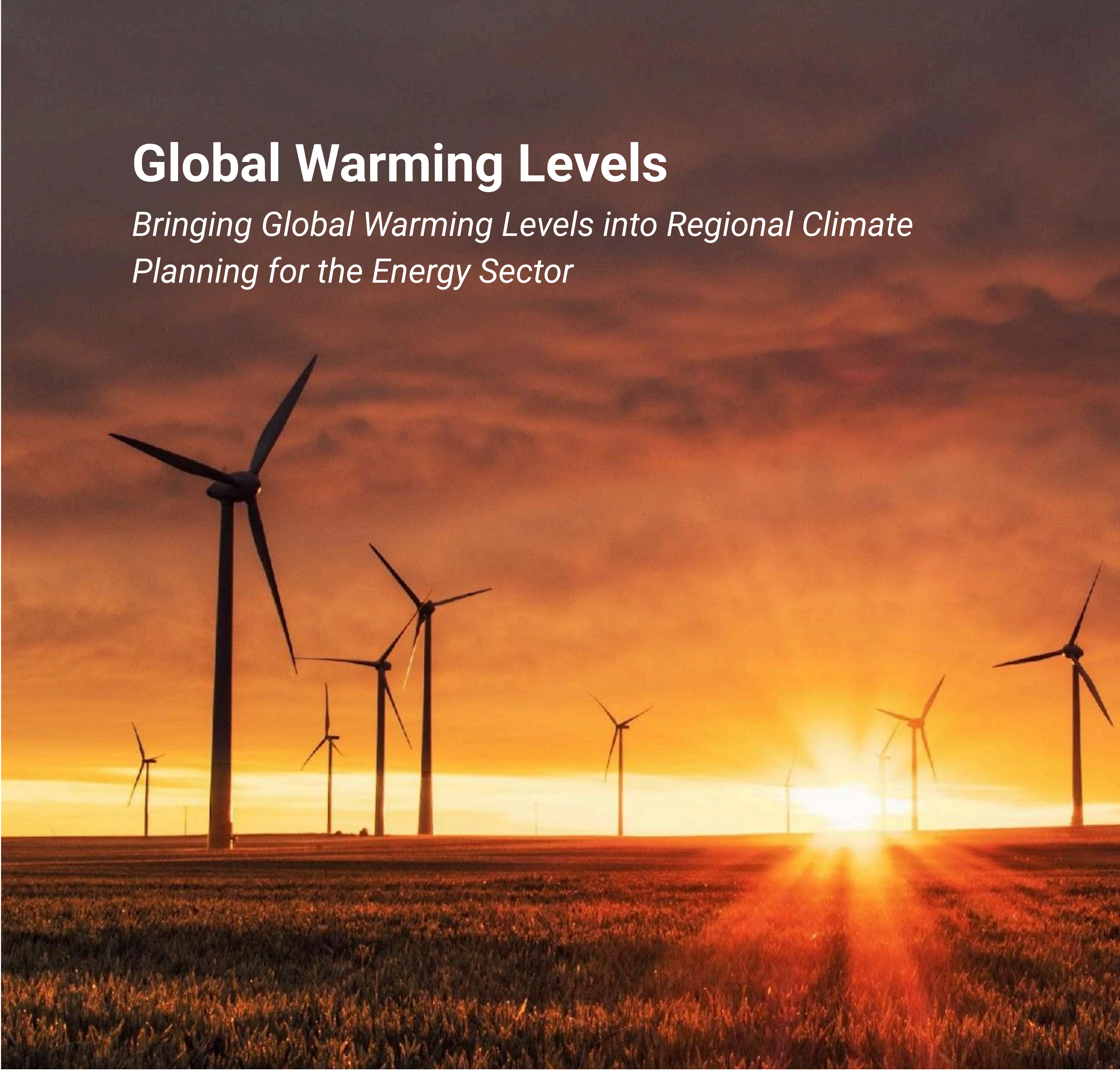
Global Warming Levels

Bringing Global Warming Levels into Regional Climate Planning for the Energy Sector



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Cal-Adapt
Supporting California's Energy Resilience, Reliability, and Planning

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Executive Summary

As climate change accelerates, local communities require scientifically sound localized climate data to build resilience against extreme hazards like heatwaves, droughts, and intense precipitation. However, regional climate planning has traditionally been hindered by a lack of common climate analysis approaches and rapidly evolving climate modeling frameworks. In addition, the transition from Coupled Model Intercomparison Project Phase 5 (CMIP5) to CMIP6 introduced new emissions scenarios (Shared Socioeconomic Pathways - SSP) and a **"hot model problem"**: where several advanced models project overly high global climate sensitivities. These factors create significant uncertainty regarding *when* specific warming thresholds will be reached, making long-term regional planning and cross-generational report comparisons highly complex and tedious.

To mitigate these challenges, the international scientific community has increasingly adopted the **Global Warming Level (GWL) approach**. Rather than asking what a region will look like in a specific year (e.g., 2050), the GWL framework assesses what a region looks like at specific increments of global warming (e.g., 1.5°C or 2.0°C above pre-industrial levels).

While highly effective at the international level, transitioning the GWL framework to regional planning presents distinct trade-offs:

Benefits of GWLS	Challenges to Regional Adoption
Bypasses the "Hot Model" Problem: Aligns simulations by warming thresholds rather than specific years, isolating the regional climate signal from global model sensitivity biases.	**High Data & Computational Burden:** Requires calculating unique crossing windows for every individual climate simulation based on globally averaged surface temperatures.
Scenario Agnostic & Interoperable: Combines data across different emissions scenarios (e.g., SSP 5-8.5 and SSP 3-7.0) and allows direct comparison between CMIP5 and CMIP6 outputs.	**Rigid Framework:** Standard half-degree international targets do not always align with rigid, legally mandated local planning horizons (e.g., a mandate for the year 2040).
Maximizes Data Utilization: Unlocks a broader pool of computationally intensive downscaled datasets by utilizing models that would otherwise be filtered out in time-based frameworks.	**Baseline Inconsistencies:** Creates ambiguity when trying to compare traditional time-based historical reference periods with GWL-based future states.

To bridge the gap between international climate science and practical local planning, **Cal-Adapt** has developed a suite of innovative tools and methodologies designed to make regional GWL implementation seamless:

- **Reduced Computational Burden:** By providing pre-computed global temperatures per Global Climate Model (GCM), Cal-Adapt enables users to execute quick GWL data slicing without heavy backend processing.
- **Customizable Thresholds:** Enables planners to depart from rigid half-degree increments and define custom GWLs tailored to specific local risk tolerances and decision-making frameworks.
- **Methodological Alignment:** Defines historical reference periods using a GWL-compatible approach, ensuring statistical consistency across datasets.
- **Bridges GWLs and Time:** Features an IPCC-aligned GWL timing estimation tool, allowing practitioners to transition seamlessly between warming levels and specific calendar time-horizons.

Cal-Adapt operationalizes the GWL framework for regional climate planning, enabling scientifically robust, scenario-agnostic analyses that remain consistent across generations of climate projections, reduces biases associated with differing model climate sensitivities, and aligns adaptation decisions with international climate targets such as the Paris Agreement. Realizing the full potential of GWL planning will require coordinated investment across the climate adaptation community.

To accelerate adoption and strengthen regional climate resilience, practitioners should:

1. **Build capacity** through training on GWL tools, methods, and operational workflows.
2. **Equip decision-makers** with the knowledge needed to understand the value of GWL-based planning and identify when GWL-based approaches are more appropriate than traditional time-based approaches and vice versa.
3. **Invest in implementation** by providing the resources needed to integrate GWL-based analyses into regional planning and decision-making where they provide the greatest operational benefit.

Key Takeaways

1. The GWL approach avoids models that project too high warming, creates scenario-agnostic planning results, and ties back to international planning targets. However, implementing a GWL approach for regional climate planning is not straightforward: requiring additional data processing, rigidity for practical planning, inflexible reference periods, and unclear approaches to connect back to time-based planning targets.
2. Cal-Adapt reduces the technical barriers to adopting a GWL framework through an innovative suite of open-source tools and methods that make this advanced climate framework practical for regional decision-making. Rather than requiring users to perform complex climate data processing, Cal-Adapt delivers pre-computed global temperatures per GCM to enable instant GWL-based analyses, customizable GWL targets, standardized GWL-based reference periods, and flexible IPCC-based timing estimates that bridge GWLs with conventional planning timeframes.
3. Cal-Adapt equips practitioners to fully realize the advantages of the GWL framework by enabling analyses that incorporate a broader ensemble of climate simulations and reducing biases associated with the CMIP6 "hot model problem" (Figure 1). Achieving widespread adoption will require coordinated investment in both capacity and implementation. Cal-Adapt's tools, guidance, and user engagement will accelerate institutional support, ultimately enabling climate planning that is more resilient, flexible, and actionable.

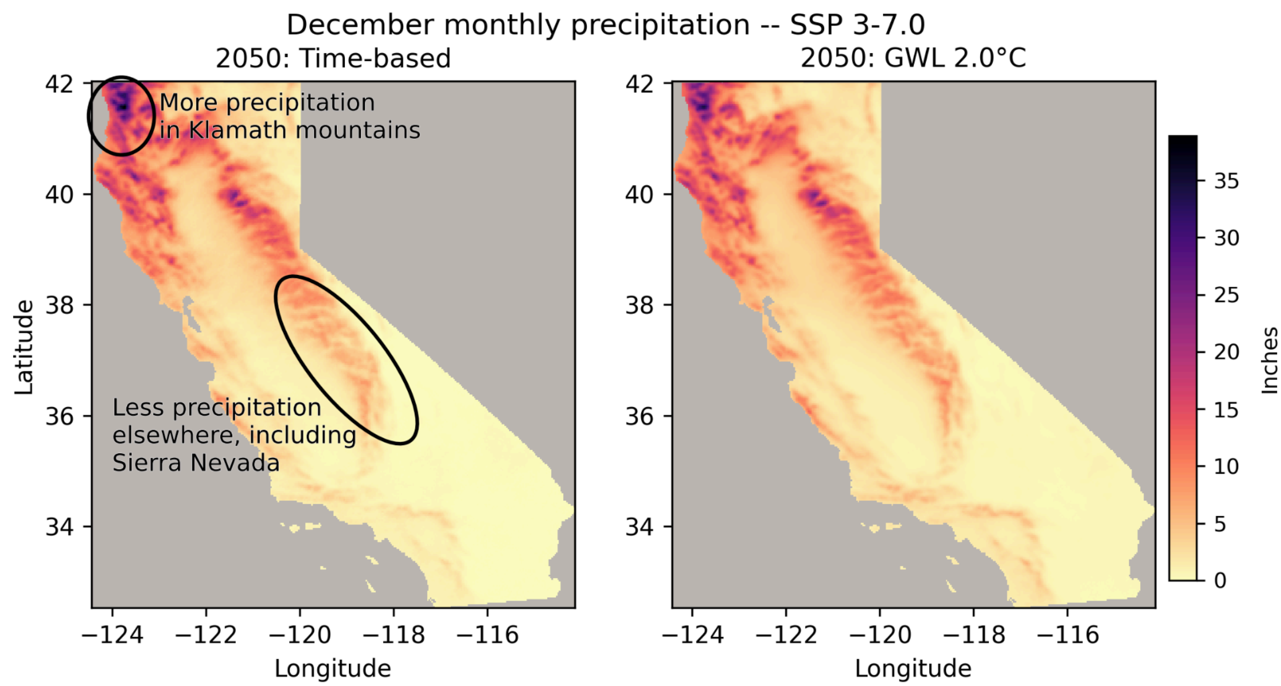

Figure 1: Example of the difference in monthly precipitation when using a time-based (left) vs GWL (right) approach.

Introduction & Motivation

As the climate continues to warm, communities are forced to face extreme climate hazards including multi-day heatwaves, prolonged droughts, and intense precipitation events. These climate hazards impact public health, damage infrastructure, and strain resources and systems. Regions, however, are impacted differently, posing challenges that must be identified and addressed at the local scale to build resilience [1]. In recent years, the practice of developing hazard mitigation and adaptation plans has grown significantly [2]. These plans provide communities with a framework to build climate resilience in the face of a warming and more volatile climate, with novel solutions designed for and used by their communities. To ensure decisions are appropriate for the respective region, regional planning must be grounded in scientifically sound methodologies using modern climate data. The careful process of gathering tailored regional insights from raw climate data remains a barrier to use, as use-focused guidance, regulations, and policy-driven standards vary.

Indeed, the need for a common set of approaches for climate analyses is growing. These approaches must provide common methods to be applied locally for state-level regulatory contexts while also fitting into the growing internationally recognized benchmarks for climate treaties [3]. The Paris Agreement, adopted in 2015, set the target of keeping global temperature change to less than 2°C of warming, preferably below 1.5°C [4]. These global temperature targets helped drive subsequent Intergovernmental Panel on Climate Change (IPCC) reports to focus on quantifying global impacts at each of these targets [1]. Integrating these targets into regional planning can help create consistency across spatially varying climate resilience planning efforts.

In addition to a growing need for cohesive approaches, climate modeling continues to advance in complexity. The most recent phase of the Coupled Model Intercomparison Project (CMIP6) introduced significant progress, such as higher spatial resolution and improved representation of Earth system processes, but also exposed disagreement amongst models and uncertainty surrounding the magnitude of future warming [5]. While CMIP6 expanded the number of available climate models from about 50 in CMIP5 to more than 65, some of these models produced higher-than-likely warming projections, raising concerns about how these models should be interpreted and used in climate impact assessments. This so-called **"hot model problem"** adds uncertainty across the CMIP6 ensemble about how quickly warming targets will be reached [6] (Figure 2). Furthermore, CMIP6 also replaced the Representative Concentration Pathways (RCPs) used in CMIP5 with Shared Socioeconomic Pathway (SSP) scenarios, which combine greenhouse gas emissions with different assumptions on future land use, technology, population growth, and economic development, allowing climate projections to more accurately reflect the societal factors that influence both future emissions and climate risk [7-8]. The choice of SSP scenario is critical because each scenario follows a different warming trajectory, ranging from temperature stabilization due to rapid emissions reduction (SSP 1-1.9) to accelerated warming under high emissions (SSP 5-8.5)[1], significantly determining both the magnitude of future warming and when a specific GWL is reached.

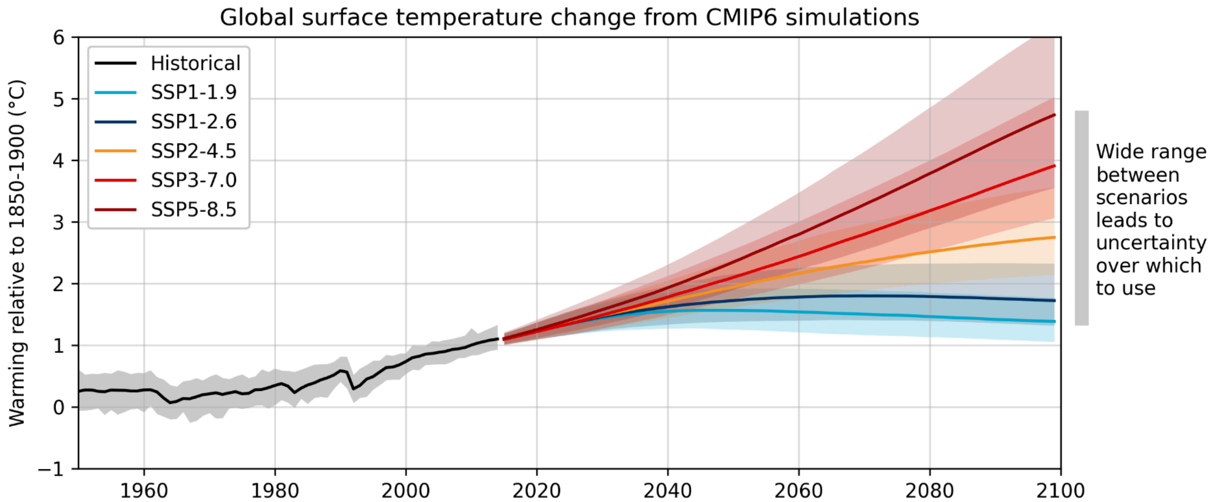

Figure 2. CMIP6 global temperature change relative to the 1850-1900 pre-industrial period across the 5 SSP scenarios used for planning. Solid lines represent the multi-model mean for each SSP, while the shaded range provides 90% (*very likely*) confidence intervals. For a traditional time-based approach, the choice of scenario becomes increasingly critical after approximately 2030. In a GWL approach, the choice of scenario becomes agnostic – reducing scenario uncertainty. Adapted from IPCC Figure SPM.8 [1].

The Global Warming Level (GWL) Approach was developed to address the challenges in utilizing these complex systems. It supports the growing need for aligning scientific analysis of climate change impacts with international climate treaties, the hot model problem, and the need for scenario-agnostic planning, which led the international scientific community to develop and adopt a new method to quantify global and regional climate impacts. The GWL approach provides an alternative framework to assessing climate impacts by prioritizing a specific degree of warming as an anchor point for assessment. Instead of asking the question: *What do climate impacts in California look like in 2050?* GWLs ask the question: *What do climate impacts in California look like under 2˚C of warming?* **GWLs enable regional climate change results to tie back to international planning targets, avoid the hot model problem, and create scenario-agnostic planning results, allowing for consistency across generations of climate reports and plans.**

GWLs are largely adopted and incorporated into climate planning at an international level but the adoption of GWLs into regional planning continues to face many challenges [3]. The rest of this paper will address these specific challenges, along with the key benefits, and describe Cal-Adapt's approach to the GWL framework for regional planning.

[1] Ahead of the CMIP7 climate models release, the CMIP6 high emission levels of SSP 5-8.5 have been deemed implausible based on recent emissions trends, climate policy, and renewable costs [12], reinforcing the premise that a single SSP scenario should not be utilized for regional climate assessment.

Benefits of GWLs in Regional Climate Planning

In addition to compatibility with widely recognized global climate targets, GWLs offer practical and scientific benefits for regional climate analysis, including:

1. **Avoiding uncertainty from the "hot model problem" in CMIP6 models**
2. **Scenario-agnostic planning**
3. **Increased sample size**

A GWL approach separates the regional climate change signal from uncertainties about global climate sensitivity [8], avoiding the CMIP6 "hot model problem", as the models show a strong consensus on how the climate hazards change due to warming.

The method is premised on the fact that climate change impacts at a given GWL are projected to be approximately the same regardless of when that GWL is reached. In other words, the timing of when a GWL is reached is less important than the impacts at the warming level itself: many climate impacts on human and natural systems are expected to be similar under a 2°C warmer world, regardless of *when* 2°C occurs. By characterizing the climate state at increments of global warming, such as 2°C or 3°C above pre-industrial conditions, this framing emphasizes that climate models share a strong consensus on how climate hazards are likely to manifest as warming increases, but if and when each increment of global warming will be reached ultimately depends on society's choices in the coming years [9]. This approach of climate analyses around a common GWL rather than a specific year reduces the influence of "hot models" (Figure 3), resulting in more robust and reliable future climate impact assessment.

A GWL approach is scenario-agnostic and allows for interoperability across generations of emissions scenarios (i.e., between CMIP5 and CMIP6). In other words, regional impacts calculated at 2°C of warming using CMIP5 models can be directly compared to impacts calculated at 2°C using CMIP6 models without having to compensate for how the emissions scenarios have changed [11]. This benefit is also forward-facing: a GWL approach will be compatible with future CMIP model efforts, such as the upcoming CMIP7 suite of models. The longevity of a GWL approach is particularly useful in a policy and regulatory context, where planning requirements are updated on different reporting cadences to remain timely and consistent across generations of climate simulations.

The combination of avoiding uncertainties around "hot models" and including multiple scenarios inherently enables the use of more climate data overall. Climate models that have high climate sensitivities still produce skillful projections of regional impacts. Under a time-based planning framework, a single emissions scenario is typically chosen, and analysis is limited to simulations that follow that scenario, which may include unrealistic warming. Under a GWL framework, these simulations can be fully utilized rather than being filtered out. This means planners can develop a playbook of adaptation strategies for incremental GWLs (e.g. 1.5°C, 2°C) without having to commit to considering a single emissions scenario.

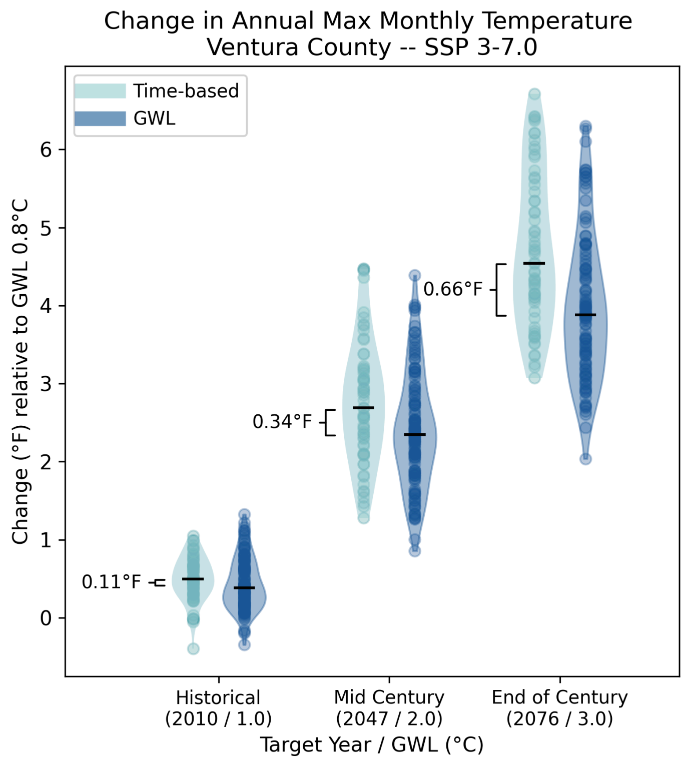

Figure 3. Difference in maximum annual daily temperature impact distributions in Ventura County, CA when using a time-based (light blue) vs GWL (dark blue) approach at several GWLs.

Challenges of Adopting GWLs in Regional Climate Planning

While the benefits of a GWL approach in regional climate planning are numerous, practical challenges remain that can prevent local practitioners from implementing a GWL framework. The GWL methodology is more complex and data-intensive than a traditional time-based planning approach [13]. Rather than simply extracting the same future time period from every simulation (e.g., 2030-3060), a GWL analysis requires additional steps.

1) The 30-year period centered on the target warming level must be identified separately for each simulation because every model crosses a given warming level at a different time.
2) Data is then extracted per simulation and re-aligned to the common warming level.

This realignment step is crucial, but creates a data management challenge, as each simulation contributes a different 30-year slice. Furthermore, determining when each simulation crosses the specific GWL requires the globally averaged surface temperature from each climate simulation [14], adding computational and data requirements that are not needed in conventional regional climate analysis. Additional methodological details are provided in the Appendix.

The rigidity of common GWL planning targets can also be a limiting factor in adopting the approach. Half-degree increments of GWLs (i.e., 1.5°C, 2°C) are globally recognized targets [4], but regional planners often work around specific time-horizons that may not fit neatly into this framework [13]. Thus, translating between global targets and specific regional warming impacts may not be straightforward. For example, if a local agency is mandated to plan around a specific mitigation horizon of 2040, there may not be an obvious GWL selection (Table 1)[2]. Similarly, operational climate planning often requires characterizing change against specific recent-historical reference periods, such as the commonly used 1981-2010 baseline climatological period. Without additional guidance, it can be unclear how to correctly compare conditions in a time-based reference period with a GWL-based future period.

Planning Horizons	GWL	Best Estimate Year for GWL
Historical Baseline	1.0°C	2010
Near-Term Planning	1.5°C	2031 (SSP 3-7.0)
Mid-Century Planning	2.0°C	2047 (SSP 3-7.0)
Mid-Late-Century Planning	2.5°C	2062 (SSP 3-7.0)
Long-Term Planning	3.0°C	2075 (SSP 3-7.0)

Table 1. Translating common GWL planning targets to planning horizons and approximate best estimate year for when a GWL is reached across the SSP 3-7.0 multi-model mean.

Cal-Adapt's Approach: Operational GWLs for Regional Climate Planning

Cal-Adapt operationalized the GWL framework for regional planning by developing an open-source suite of tools, standardized methods, and practical guidance to make GWL-based analyses easier to produce, integrate, and interpret into existing planning workflows through:

- Pre-computed global temperature per GCM to enable fast access to custom GWLs, thus reducing the compute burden on users.
- Ability to identify and utilize custom GWLs to match specific planning needs.
- Referenced historical periods defined by GWL to enable comparisons of climate impacts relative to meaningful recent conditions.
- A planning-ready timing-to-GWL translation tool grounded in IPCC-based GWL timing estimates.

[2] Using Cal-Adapt's tool to translate between time-based targets and GWLs, 2040 is approximately 1.8°C.

Cal-Adapt's scientific and technical solutions pave the way for aligning regional climate results to international planning targets, avoiding the hot model problem, and creating scenario-agnostic planning results for consistency across generations of climate reports in time. Cal-Adapt allows planners to realize the benefits of a GWL framework while retaining the flexibility to work within existing operational planning systems they are accustomed to when using time-based analysis. As the climate planning community increasingly adopts GWL-based approaches, continued investment in practitioner training, open-source tools, and implementation support will be essential for more robust regional climate resilience planning.

Flexible Historical Reference using GWLs

Future climate change impacts are often quantified relative to a historical reference period to provide context for the magnitude of change. For example, *the change in the frequency of extreme days between 2050 and 2010*. Computing the difference between a future and historical climatology as a "**delta signal**" is helpful both to reduce systematic model biases[3] and to frame future climate conditions in a meaningful context.

Although GWL-based climate impacts are often calculated relative to pre-industrial conditions (i.e., relative to 1850), a 150+ year-old reference point is not necessarily a useful framing for regional climate planning. In operational adaptation planning and risk assessment, practitioners often need changes calculated relative to present-day conditions or a more recent period of observations. While defining a historical reference period by a specific range of years (e.g., 1981-2010) is common practice, it creates an inconsistency when the future climate is defined by a GWL. In this case, the delta signal is calculated between two fundamentally different reference frames: one based in time and one based around an amount of global warming. Because individual models warm at different rates [9], a time-based historical reference period does not correspond to the same level of warming across simulations (Figure 4 right). To ensure the delta signal is consistent and directly comparable among models, both the historical reference period and the future period should be defined using GWLs (Figure 4 and Figure 5). Indeed, as shown in Figure 5, comparing conditions using two different approaches leads to uncertainty in the actual amount of warming. Users should always follow the same approach (time-based or GWL) for both the historical and future periods to ensure consistency and minimize uncertainty. Implementing this approach in practice requires identifying the appropriate GWL associated with a particular historical reference period.

[3] A climate model that has high climate sensitivity in the historical period will also have a high climate sensitivity in a future period. A delta signal, which includes the same parent model in both the historical and future period, negates the high climate sensitivity bias, leaving only the change signal.

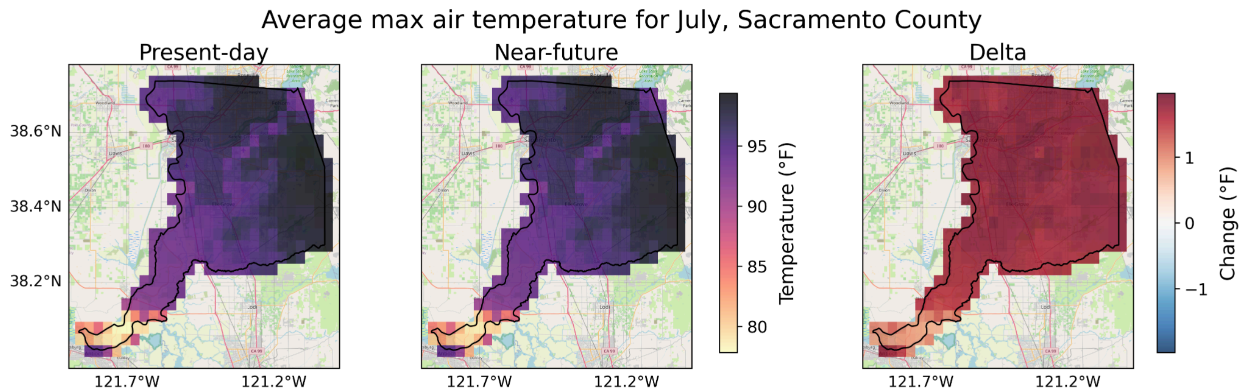

Figure 4. Maps of average July max temperature for Sacramento, CA for present-day (1.2°C GWL) and near-future (2.0°C) conditions. The delta signal provides key additional context for the change conditions: Sacramento County is projected to have hotter July summer days.

To promote fast access to historical reference GWLs, Cal-Adapt has pre-identified 3 common historical reference periods to serve the needs of practitioners:

- 0.8°C GWL, which approximately corresponds to the 1983-2012 historical period
- 1.0°C GWL, which approximately corresponds to the 1991-2020 historical period.
- 1.2°C GWL, which approximately corresponds to the 1998-2027 historical period.

How selecting GWL reference periods can influence results	
Consistent Periods: Comparing conditions at **2.0°C** of warming to conditions at **0.8°C** of warming *creates a consistent change signal* (a difference of 1.2°C of global warming) across simulations and scenarios. This ensures that results focus on the change signal and comparative impacts.	**Inconsistent Periods**: Comparing conditions at **2.0°C** of warming to time-based reference of 1980-2010 results in *comparing a different amount of warming* in each simulation. In this example, one model has warmed by 1.1°C, while the other has warmed by 1.6°C, adding additional uncertainty to the amount of change to local impacts.

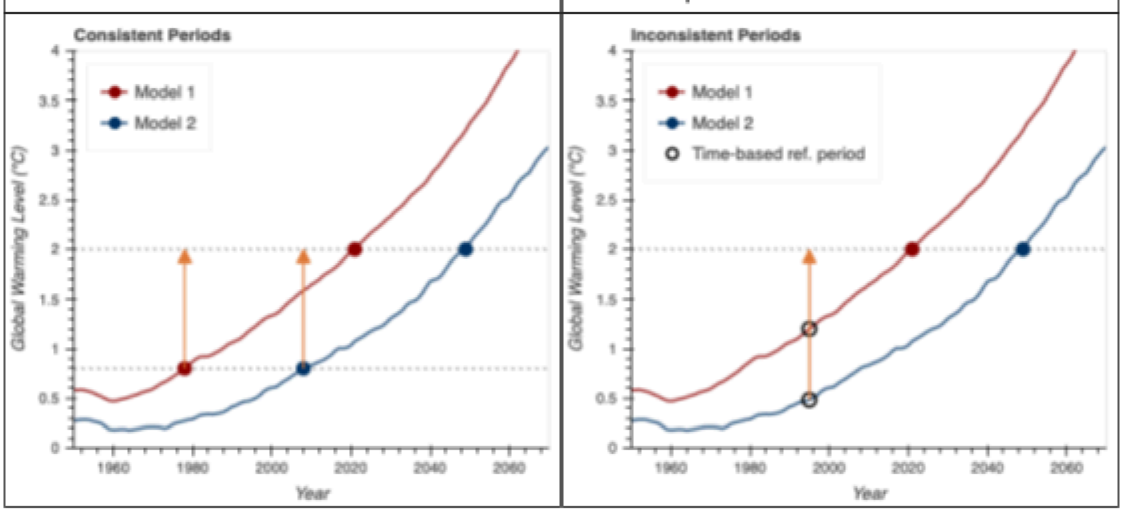

Figure 5. Cross-comparison of historical reference periods of a time-based approach vs. GWL, highlighting the need for consistent approaches (e.g. GWL reference period for a GWL approach).

Many Cal-Adapt tools utilize 1.2°C GWL as the default historical reference GWL period to represent present-day conditions. Practitioners may, however, elect to use an alternative historical reference level befitting their planning needs.

Planning-Ready Timing to GWL Translation

One of the largest barriers to using a GWL framework for practical planning is the lack of an explicit timeline connected to GWLs. In other words, saying "*I need extreme heat targets at 1.5°C warming*" is not as obvious as "*I need extreme heat targets at 2030*". Practitioners often need to connect climate risk to existing planning processes and institutional goals built around specific future planning horizons. Thus, any functional implementation of a GWL planning framework should require a robust method for estimating when each GWL will be reached and the flexibility to define GWL targets that can fit into existing planning processes.

Consistent with the IPCC AR6 report that accompanied CMIP6, Cal-Adapt does the heavy lifting for practitioners and estimates GWL timing using the IPCC's best-estimate warming trajectories [1]. These warming trajectories were generated using a combination of specialized climate models and long records of observational constraints on global climate sensitivity. The resulting dataset provides the best scientific consensus on when each level of global warming will be reached under each CMIP6 SSP scenario [13]. This approach is strongly recommended over a more simplistic estimate of averaging GWL crossing years from each simulation to obtain the approximate timing, as the "hot model" bias is reintroduced into the calculation, which can lead to an earlier, unrealistic timing estimate.

Alternative Planning Approach

While the translation tools built by Cal-Adapt are a crucial feature to fit into existing processes, they can also be used if a user decides to fully switch to the GWL framework. Rather than seeking to understand what is going to happen in 2040, a user develops plans for when the GWL is 1.5°C, 2.0°C, or 3.0°C. This enables the development of plans focused on the impact of global warming *independent* of the timing of these events. For example, seeing the current trajectory, a community might activate their 1.5°C plan and have the 2.0°C plan ready to go. In 5 years, if the projections are more aggressive or warming has increased faster than anticipated, a community could activate that 2.0°C plan earlier than expected. Regardless, the plan is available and reflective of the impacts under global warming and is easily implemented with Cal-Adapt's tools.

Operational Workflows for GWL-Based Planning

Cal-Adapt provides operational workflows that integrate GWLs into existing planning processes while maintaining a direct connection to planning timelines. The workflows separate the analysis of climate impacts from estimates of when those impacts are anticipated to occur, allowing practitioners to update timing assumptions as scenarios evolve without having to regenerate climate impact datasets. Depending on the planning objective, a practitioner can follow one of two complementary workflows:

I Need to Estimate GWL Timing for My Impact Assessment

Use this workflow when planning is organized around warming thresholds such as 1.5°C, 2.0°C, or another GWL, including custom levels.

Objective: The objective of a "GWL-based" workflow would be to assess the impacts associated with a specific GWL and determine when those impacts are likely to occur. Operational steps are outlined in Figure 6.

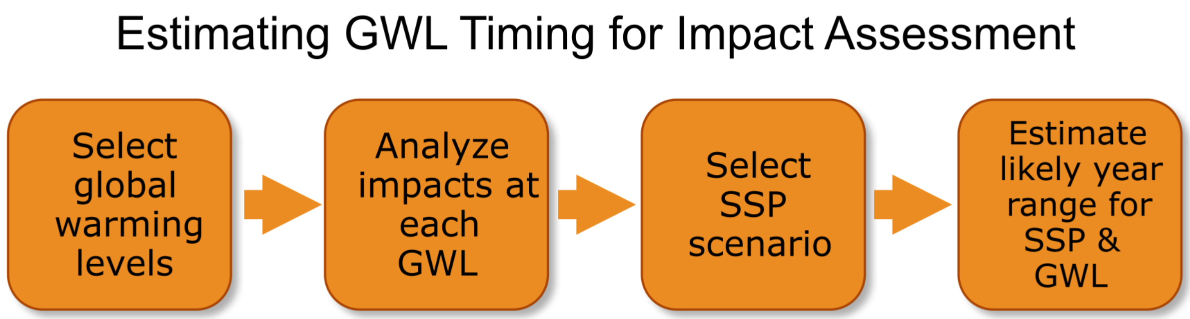

Figure 6. Cal-Adapt's operational workflow for planning around a GWL. A practitioner first identifies one or more target GWLs, then aggregates the data and analyzes regional climate impacts at each GWL. To obtain timing estimates, select the SSP scenario most relevant to your objective. The most likely range of years is identified using the IPCC warming trajectories.

Results: A scenario-agnostic assessment of climate impacts paired with scenario-specific timing estimates. If emissions assumptions or IPCC timing estimates are updated, only the timing estimates would need to be revised; the climate impact analysis remains unchanged.

I Need to Plan Around a Target Year Using GWLs

Operational planning processes often require planning for a specific target year that may not correspond neatly with one of the standard GWLs (e.g. 1.5 °C, 2.0 °C, etc), such as 1.75°C. Use this workflow when existing planning processes require information for a specific planning horizon, such as 2040, 2050, or 2070.

Objective: The objective of a "time-based" workflow would be to produce GWL-based climate analysis that aligns with a specified planning year. Operational steps for this workflow are outlined in Figure 7.

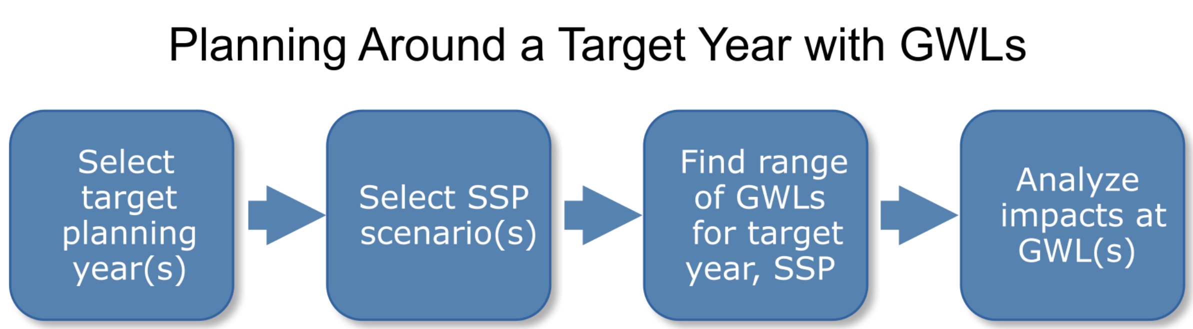

Figure 7. Cal-Adapt's operational workflow for planning around a target year with GWLs. A practitioner first selects their planning target year and the SSP scenario for estimating the timing of warming to connect to GWLs. The IPCC warming trajectories are then used to identify the most likely range of GWLs reached at the target year. Retrieve the data at the corresponding GWL to analyze regional impacts that are identified using your target year.

Results: Climate projections retain the scientific advantages of a GWL-framework (i.e., reduced hot-model bias and utilizing a larger pool of climate simulations), while remaining directly applicable to planning processes built around any time-based target planning year.

Together, these workflows allow practitioners to move seamlessly between time-based and GWL-based planning. Practitioners can continue planning around familiar target years, while benefiting from the improved scientific consistency of a GWL framework.

Recommendations

Using GWLs allows regional climate planning to take advantage of the latest scientific insights and methods developed for global climate assessments. Although the GWL framework requires additional data processing and a shift away from time-based planning targets, these challenges are outweighed by the practical benefits when incorporating multiple climate models. Defining both historical and future climate conditions with GWLs reduces inconsistencies between climate model sensitivities, makes more efficient use of the available climate model ensemble, and supports planning that can be updated as the climate changes.

Cal-Adapt takes the guesswork out for practitioners: The specific workflows, tools, and guidance that Cal-Adapt has developed provide the flexibility to overcome key challenges in computing and communicating GWL-based climate impact analysis. Because adoption of the GWL approach is still relatively new, there are remaining opportunities to develop best practices and refine approaches for utilizing GWLs in specific planning processes, particularly around capturing uncertainties and integrating results with near-term planning and local observational records. Collectively, this area of research represents a valuable opportunity for the advancement of regional climate planning capabilities.

Ready to bring Global Warming Levels into your Regional Climate Planning?
The following resources are available via Cal-Adapt[4]:

1. Guidance
    a. Global Warming Levels
    b. Climate Models and Projections
    c. Using Climate Projections in the Analytics Engine
    d. Typical Meteorological Year 8760s
2. Cal-Adapt Data Explorer Tools
    a. Climate Metrics Map
    b. Data Download Tool
    c. Renewables Visualizer

[4] https://cal-adapt.org

Fully customizable analyses using the GWL approach can be generated via the *Cal-Adapt Analytics Engine*:

3. Jupyter Notebooks
   a. Warming Level Methods
   b. Vulnerability Assessment
   c. Threshold Tools
   d. Custom Climate Profiles
   e. Basic Data Access

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Appendix: Efficiently Aggregating Regional GWL Data

Cal-Adapt produced an innovative approach to enable a fast operational process with GWLs by pre-computing GWL timing once so that regional climate data can be retrieved on demand for any GWL. This approach reduces the more computationally intensive calculations to a one-time operation and enables efficient aggregation of GWL data for rapid data exploration and experimentation. This methodology can be broken down into two steps (Figure 8):

1. **Pre-calculating a GWL "lookup" table.** The first essential step for implementing a GWL approach is identifying the year that the globally averaged surface temperature reaches the target threshold for each climate simulation. This is done by first calculating each simulation's average annual global surface temperature in the pre-industrial reference period, which is taken as 1850-1900 to maintain consistency with methods in IPCC AR6. For the remaining years in each simulation (i.e. 1900-2100), a 20-year running average of global temperature relative to the reference period is used as the global warming level for that simulation. By pre-computing and saving this time series for all CMIP6 simulations, the GWL crossing year for any simulation can quickly be found by identifying the first year that is above the target warming level.

2. **Dynamically selecting data from regionally downscaled simulations**. To analyze climate conditions at a given warming level, a window of years centered on the crossing year is taken from each simulation. In the case of regionally downscaled simulations derived from global climate simulations, the GWL window is identified using data from the original global simulation, then the corresponding years of data are selected from the downscaled simulation. These windows of data come from a different range of years for each simulation but are re-aligned with each other for GWL-based analysis.

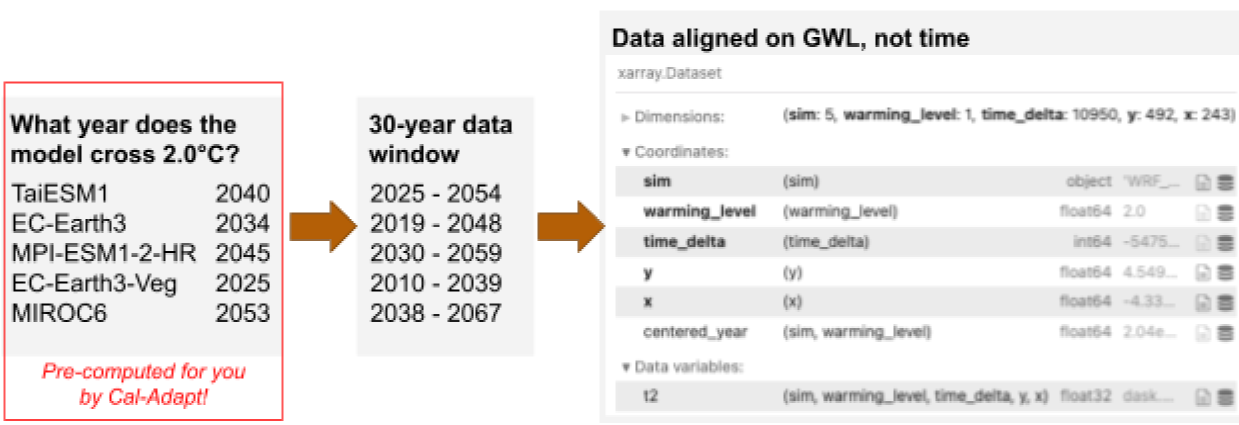

Figure 8. The process of GWL fast data retrieval. Cal-Adapt has pre-calculated a GWL look-up table per model, so that the GWL crossing year for any simulation and any GWL can be quickly identified to prepare data retrieval. Using the pre-identified crossing years, when a user asks for GWL data the tool dynamically selects a data window around the crossing year and returns data that is aligned on the GWL.