Below is an itemized list of all comments in plain text and our responses in blue.

Anonymous Referee #1

The manuscript simulates End of Century (EOC) extremes and their effects on the water-energy balance in the Cosumnes river basin, using cutting-edge global climate and integrated hydrologic models (ParFlow-CLM). I really like the way the authors used to analyze the hydroclimatic changes by median WY, dry WY and wet WY (e.g., Figures 3-5). The manuscript is overall clearly written, and the results are well discussed.

We thank the reviewers for their positive comments and feedback and for acknowledging the quality and the significance of our work.

My first concern is the insufficient validation of the models' simulations in the historical period. Besides temperature and precipitation outputs, other watershed-integrated fluxes, and storages (e.g., ET, soil moisture, TWS and streamflow) should also be validated as much as possible using the observations, remote sensing data and reanalysis, to ensure the models' simulations reasonable. Only then will we believe the further analysis between future and historical periods is valid. In my opinion, the historical simulation of VR-CESM is not so good because the simulated dry, median, and wet water years are distinct from the PRISM (Figure A2).

The developed hydrologic model was previously compared to measurements in Maina et al. (2020): simulated ET was compared to remotely sensed ET derived from METRIC, soil moisture was compared to SMAP, snow water equivalent to SNODAS and a reanalysis by Bair et al., streamflow and groundwater levels variations were compared to ground measurements (4 stations were used to compare streamflow and 3 wells for groundwater levels comparisons). Comparisons with GRACE TWS are not meaningful given the size of this watershed (~7000 km^2) which is far smaller than the footprint of GRACE TWS (200,000 km^2). We have added details of the model validation below (Validation of the hydrologic model) and to appendix C of the revised manuscript.
We have also added the following lines to the revised manuscript, please refer to lines 341-365 (see below the text in italic).
"We specifically compared simulated and measured river stages at three stations located in the Sierra Nevada headwater, foothill, and the Central Valley. The annual averages absolute differences between measurements and simulations were between 0.4 and 0.8 m. We selected four wells in the Cosumnes watershed based on their availability of data to compare measured and simulated groundwater levels. These wells are sparsely distributed in the Central Valley. The absolute differences observed and simulated groundwater levels vary between 0.47 to 3.73 m. The highest absolute differences were attributed to the lack of a best estimation of groundwater pumping rates in the region. Nonetheless, the reasonable agreement between observations and simulated variables has allowed us to conclude that the model can capture these extreme dynamics. We rely on remote sensing data to assess the ability of our model to simulate key land surface processes (evapotranspiration, soil moisture, and snow dynamics). We compared the simulated SWE to SNODAS (The National Weather Service's Snow Data Assimilation, National Operational Hydrologic Remote Sensing Center, 2004) and a SWE reanalysis by Bair et al., (2016). Our comparisons indicated that the absolute differences between our SWE values and these data were equal to 3 mm on average. Moreover, the simulated key parameters controlling

the snow dynamics such as peak snow and timing of snow ablation were also in agreement with remotely sensed data for both dry and wet years (Appendix C). Absolute differences between the simulated ET and the remotely sensed ET from METRIC (Mapping Evapotranspiration at High Resolution with Internalized Calibration, Allen et al., 2007) were equal to 0.036 mm/s while the differences between the simulated soil moisture and the SMAP (Soil Moisture Active Passive, SMAP, 2015) soil moisture were 0.2."

This hydrologic validation was based on WY 2015-2017 in Maina et al. (2020), which used meteorological forcings specific to those years. In contrast, the climate model simulations were compared throughout the entire historical period because they represent 30 plausible realizations of the historical climate, since the simulations are only bounded by observed sea-surface temperatures and sea ice extents (a common practice in the climate modeling community known as AMIP protocols, https://pcmdi.llnl.gov/mips/amip/home/overview.html). Therefore, these simulations would not be expected to exactly recreate specific water years, due to internal variability in the atmosphere, but would be expected to recreate the distribution of water year types. We have clarified it in the revised manuscript, please refer to lines 190-201 (see below the text in italic).

"The atmospheric model used for these simulations is the Community Atmosphere Model (CAM) version 5.4 with the spectral element dynamical core, with an atmospheric dynamics time step of 75 seconds, an atmospheric physics time step of 450 seconds, a prognostic treatment of rainfall and snowfall in the microphysics scheme (Gettelman and Morrison, 2015) and run under Atmosphere Model Intercomparison Project (AMIP) protocols (Gates, 1992). Under the AMIP protocols, the atmosphere and land-surface components of the Earth system model are coupled and periodically bounded by monthly observed sea-surface temperatures and sea-ice extents. Although this configuration does not exactly recreate historical water years and events, it is expected to reasonably simulate the distribution of water year types. Also, it should be noted that the model only projects future conditions, within the envelope of plausible future conditions of the RCP8.5 scenario and its assumptions of greenhouse gas emissions, sea-surface temperatures, and sea ice extents and would not be expected to exactly forecast individual water years."

Validation of the hydrologic model

We compared temporal variations of streamflow at 3 stations, one each located in the Sierra (uplands), at the intersection between the Sierra and the Central Valley, and in the outskirts of Sacramento (see Figure R1). Four wells in the watershed (see Figure R1a) have reasonable, publicly-available records of groundwater levels and were used to check the ability of the model to reproduce water table depth variations.

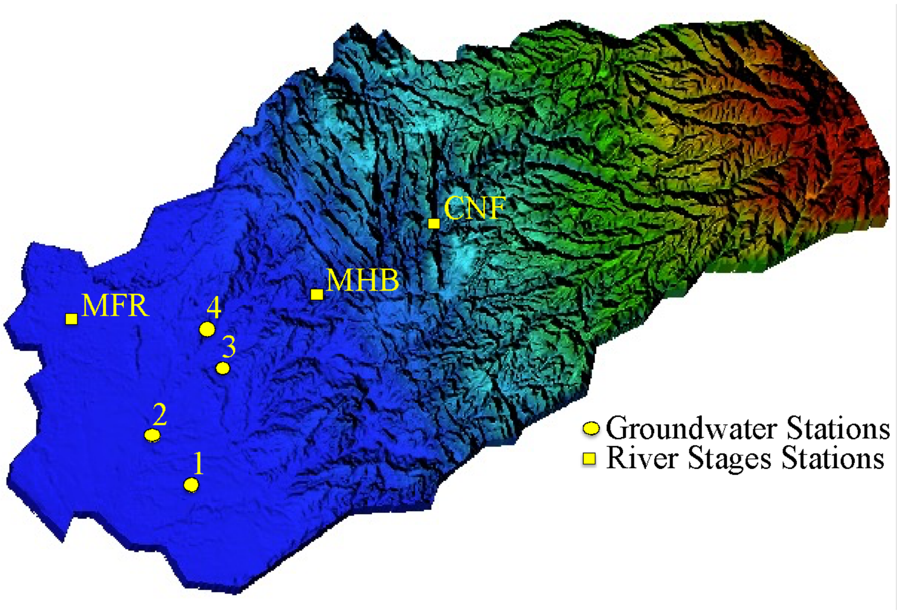

Figure R1a: The Cosumnes watershed geology and the locations of the 3 streamflow gauges (CNF, MHB, and MFR) and 4 groundwater wells (stars).

Figure R1b depicts the comparisons between simulated and measured river stages at the 3 stations indicated in figure R1a. Absolute errors (L1) in m and relative errors (L2) are shown in Table R1a. Differences between simulated and measured streamflow vary between 0.4 and 0.8 m (Table R1a) indicating that the model is able to reproduce the river dynamics.

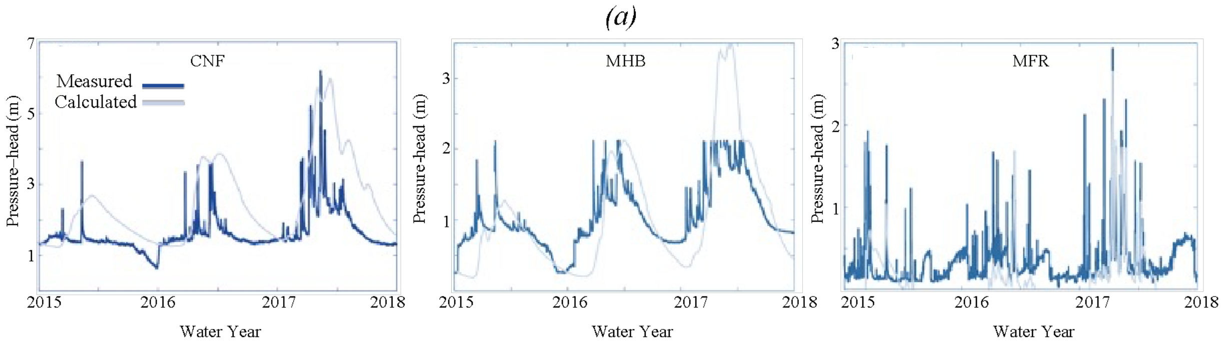

Figure R1b: Comparisons between measured and calculated river stages (i.e., pressure-heads simulated by ParFlow-CLM). Measurements' locations are indicated in Figure R1a.

Measurements	L_1 *(m)*	L_2 *(-)*
River Stages (CNF)	*0.8*	*0.5*
River Stages (MHB)	*0.4*	*0.36*
River Stages (MFR)	*0.57*	*1.06*
Groundwater Levels (Well 1)	*3.73*	*0.05*
Groundwater Levels (Well 2)	*1.63*	*0.02*
Groundwater Levels (Well 3)	*0.476*	*0.0077*
Groundwater Levels (Well 4)	*1.08*	*0.016*

Table R1a: Differences between measured and calculated surface and groundwater levels. L1 is the absolute error and R2 the relative error.

Comparisons between simulated and calculated groundwater levels (here referred to as the pressure-heads at the bottom of the domain) shown in figure R1c indicate that the model has reasonable agreements with measurements. As shown in table R1a, the error varies between 0.47 to 3.73 m depending on the station. Mismatches between simulated and observed groundwater levels at wells 1 and 2 are likely due to an inaccurate estimation of pumping in these areas. The temporal variations of the groundwater levels show an impact of withdrawals but because these withdrawals are hard to estimate the model does not correctly reproduce these trends.

(b)

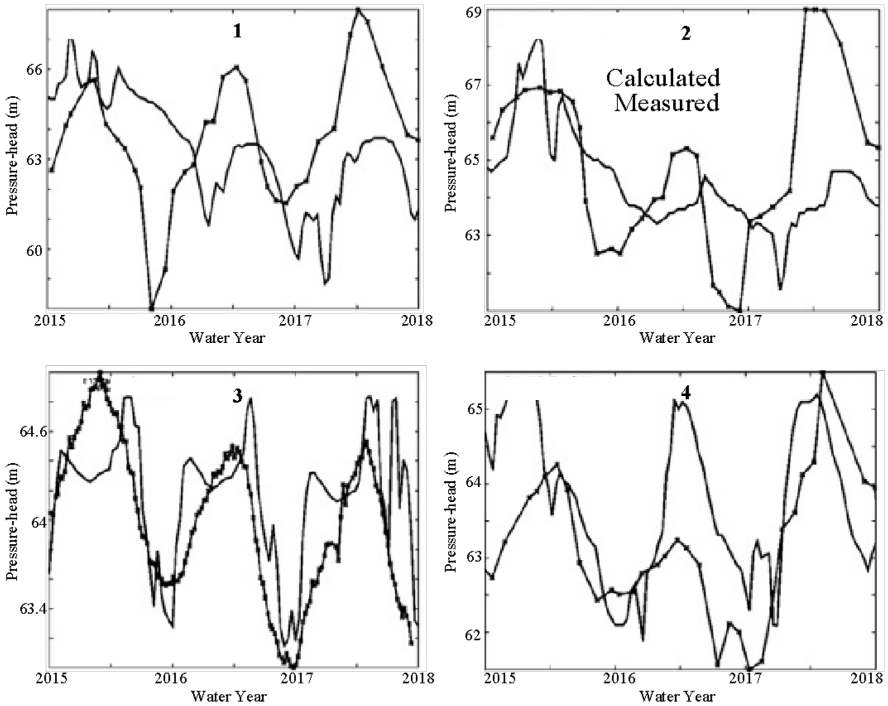

Figure R1c: Comparisons between measured and calculated pressure-heads at the bottom of the domain. Measurement locations are indicated in Fig. R1.

ParFlow-CLM also simulates the key land surface processes governing the transfer of water and energy at the land-atmosphere-soil interface: evapotranspiration, snow dynamics, and soil moisture. In Maina et al., (2020a), we conducted rigorous comparisons between the ParFlow-CLM simulated land surface processes and remotely sensed estimates of these variables. Table R1b shows the correlation coefficient between ParFlow-CLM results and the various datasets compared.

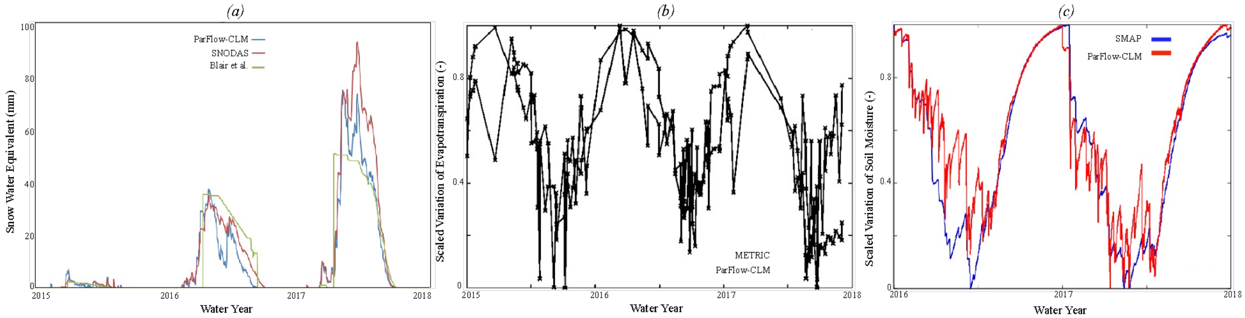

Figure R1d: (a) Comparisons between domain-averaged total snow water equivalent obtained with ParFlow-CLM, SNODAS and Bair et al., reconstruction, (b) Comparisons between actual evapotranspiration obtained with ParFlow-CLM and METRIC (c) Relative variation of soil moisture obtained with ParFlow-CLM and SMAP. Note that the time series of (c) is shorter because of the availability of SMAP data

Satellites based products	*L1 (m)*	*L2 (-)*	*Pearson Correlation Coefficient*
SWE SNODAS (mm)	*3.09*	*3.77*	*0.97*
SWE Bair et al., (mm)	*3.80*	*2.69*	*0.84*
Soil Moisture SMAP (-)	*0.217*	*3.07*	*0.94*
ET METRIC (mm/s)	*0.067*	*1.40*	*0.6*

Table R1b: differences between measured and remotely sensed evapotranspiration (METRIC), soil moisture (SMAP), and snow water equivalent (SNODAS and Bair et al., 2016)

The authors may argue the historical simulations are acceptable, because a global climate and integrated hydrologic models are used (more complex and larger simulation domain). However, one can use a finer-resolution hydrological model (e.g., VIC, SWAT, and many others) driven by statistically or dynamically downscaled regional climate model outputs to obtain more reasonable (maybe more accurate from the perspective of validation) simulations in this river basin (7000 km2), and to do further analysis like the authors did in this study. Please explain why the global climate and integrated hydrologic models are more suitable for this case study?

We set up our modeling framework by taking into account the:

- Californian atmospheric dynamics.
- Impacts of groundwater dynamics and lateral flow on the hydrology and the land surface processes of the region.
- Dependance of the groundwater dynamics in the valley to the snow dynamics in the Sierra Nevada.

These considerations are critical for a better understanding of the impacts of a changing climate on Californian hydrology.

ParFlow-CLM is an integrated hydrologic model that solves the transfer of water and energy from the bedrock to the canopy. Parflow uses the Richards equation a physics-based equation that solves the subsurface flow in three dimensions and therefore accounts for deeper and lateral flow. Previous studies have demonstrated that the lateral flow is very important to the surface and land energy dynamics (Maxwell and Condon, 2016). On the contrary, VIC does not simulate this lateral subsurface flow and only solves overland flow based on an additional routing model. It also employs a series of physics-based equations contrary to SWAT.

When simulating the evolution of California's climate, the interaction between dynamical and thermodynamic responses has important, and sometimes, offsetting effects on critical storms that drive annual precipitation and snowpack totals in the Sierra Nevada, such as atmospheric rivers. Payne et al. (2020) show that thermodynamic responses to climate change enhance atmospheric river characteristics (e.g., Clausius-Clapeyron relationship), whereas dynamical responses diminish atmospheric river characteristics (e.g., changes in the jet stream and storm track landfall location). Therefore, we argue that it is critical to account for both the dynamical and thermodynamical effects of climate change, which we do through the use of VR-CESM.

We did not perform statistical downscaling because leveraging variable-resolution Earth system model capabilities, such as VR-CESM, enables dynamical downscaling internally within an Earth system model which limits traditional multiple model bias propagation (e.g., bias from a global climate model forcing imposed on a regional climate model simulation that in turn would also generate biases), allows for more consistent teleconnection responses, enables upscale/downscale effects to influence the broader climate, etc. As a result, we think this study adds a "unique" data point to the literature regarding changes in end-century hydrology in California as it is a distinctly different methodology than previously explored regional climate model based dynamical downscaling efforts and/or bias-corrected statistically downscaled global climate model efforts.

Below is a table (Table R1c) with a number of commonly-used hydrologic models and their advantages and limitations when simulating the hydrology of California. Only Hydrogeosphere and ATS have similar advantages as ParFlow-CLM and represent best the Californian hydrology of interest to this study. Because these models use similar equations and the coupling approaches use, we expect their results to be the same. Moreover, these models all share the resolution limits imposed by high computational expense. We have added this information to the revised manuscript, please refer to lines 280-296 and the text below in italic.

"ParFlow has many advantages in comparisons to other hydrologic models. Compared to other hydrologic models (MODFLOW (Harbaugh, 2005), FELFOW (Trefry and Muffels, 2007), SWAT (Soil and Water Assessment Tool) (Neitsch et al., 2000), SAC-MA (Sacramento Soil Moisture Accounting Model)), ParFlow has the advantages of accounting for land surface processes such as snow dynamics and evapotranspiration and their interactions with the subsurface which are crucial for studying the hydrology of California. ParFlow also solved the subsurface flow by accounting for variably saturated conditions, an important feature for calculating groundwater recharge and the connection between the groundwater and the land surface processes, which is not the case for the aforementioned models. While some hydrologic models have a better representation of the land surface processes (Noah-MP (Niu et al., 2011), VIC (Variable Infiltration Capacity Model Macroscale Hydrologic Model) (Liang et al., 1994)), these models do not have a detailed representation of the subsurface flows. Because the surface flow is important in the region and it establishes the connection between the headwaters and the valleys, its good representation is essential for projecting changes in hydrology. Compared to other integrated hydrologic models (CATHY (Catchment Hydrology) (Bixio et al., 2002), MIKE-SHE (Abbott et al.,

1986)), ParFlow has the advantages of solving a two-dimensional kinematic flow equation that is fully coupled to the Richards equation.”

Hydrologic Model	**Land Surface**	**Surface**	**Subsurface**	**Limitations when simulating Californian hydrology**
MODFLOW (Harbaugh, 2005)/FELFOW (Trefry and Muffels, 2007)	No	No	Yes (diffusivity equation)	These models do not integrate land surface processes (such as snow dynamics) and their interactions with the subsurface critical to the Californian hydrology.
SWAT (Soil and Water Assessment Tool) (Neitsch et al., 2000)	Yes	Yes	Yes	The model is based on HRU (hydrologic response units). The model isn’t physics-based, therefore, it doesn’t account for the two-way interaction between the land surface and the subsurface processes.
SAC-MA (Sacramento Soil Moisture Accounting Model)	No	Yes (Rainfall-Runoff)	Yes (Water Budget)	The model doesn’t simulate snow dynamics and evapotranspiration. A water budget equation is used to simulate the groundwater dynamics which doesn’t account for the lateral flow and unsaturated zone flow.
Noah-MP (Niu et al., 2011)	Yes (water and energy balance)	Yes (a routing scheme can be used to derive surface flow)	Yes (percolation)	Although this model physically solves the land surface processes including evapotranspiration and snow dynamics, it doesn’t account for the two-way interaction between the land surface processes and the subsurface. Lateral and unsaturated zone flows are not represented.

VIC (Variable Infiltration Capacity Model Macroscale Hydrologic Model) (Liang et al., 1994)	Yes	Yes (Rainfall-Runoff)	Yes (percolation and water budget)	Although this model physically solves the land surface processes including evapotranspiration and snow dynamics, it doesn't account for the two-way interaction between the land surface processes and the subsurface. Lateral and unsaturated zone flows are not represented.
Hydrogeosphere (Aquanty, 2015)	Yes (water and energy balance)	Yes (2D diffusive wave equation)	Yes (3D Richards equation)	This model has similar advantages as ParFlow-CLM and could be used to model the hydrology of California.
CATHY (Catchment Hydrology) (Bixio et al., 2002)	Yes (there is a version coupled to Noah-MP)	Yes (1D Saint Venant Equation)	Yes (Mass balance equation)	The mass balance equation is not as robust as the Richards equation for describing the variably saturated flow in the subsurface and recharge processes. In addition, the original model doesn't solve land surface processes.
MIKE-SHE (Abbott et al., 1986)	No	Yes (diffusivity equation)	Yes (Darcy equation and a 1D Richards equation)	The main limitation of this model is the lack of land surface processes and the Darcy equation used to describe subsurface flow doesn't account for the unsaturated flow.
ATS (Advanced Terrestrial Simulator) (Coon et al., 2016)	Yes (water and energy balance)	Yes (2D diffusivity equation)	Yes (3D Richards equation)	This model has similar advantages as ParFlow-CLM and could be used to model the hydrology of California.
ParFlow-CLM (Kollet and Maxwell, 2006)	Yes (water and energy balance)	Yes (2D diffusivity equation)	Yes (3D Richards equation)	

Table R1c: Advantages and limitations of the most used hydrological models

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Anonymous Referee #2

In this work, the authors present global climatic and hydrologic models to simulate the extremes and their impacts on the water-energy balance over California. The paper is well written and with high relevance to the hess journal. Please see some suggestions I kindly ask the authors to address:

We thank the reviewer for their positive comments and feedback and for acknowledging the quality and the significance of our work.

1) The title of the paper is “Projecting the impacts of end of century climate extremes on the hydrology in California.”. The title of the paper is a bit strong since it recommends that the whole hydrological-cycle has been modeled for the State of California and also for a time-window reaching the end of the century. Many authors struggle to simulate only one part of the hydrological-cycle of California (e.g., rainfall-runoff model, as for example in Yin et al., 2021; while many similar studies exist in literature). For such a promising title, a strong literature review should be performed to include similar studies for all hydrological-cycle variables and to show how the proposed model is more advanced.

We acknowledge that the title could be misleading since we are only simulating a watershed in California although the watershed is representative of the state’s hydrology. We propose to change the title to “Projecting end of century climate extremes and their impacts on the hydrology of a representative California watershed”.

While we didn’t simulate the hydrology over the entire 30-years at the end of the century (2070-2100), we selected three years that represent the spread of hydroclimatic conditions in this end-of-century period by choosing the driest, median, and wettest years from the climate simulations. We believe that the study mentioned by the reviewer has a different scope from ours as it seeks to forecast discharge a week ahead of time for use in rainfall-runoff and machine learning models. To better understand how the hydrology will evolve over long timescales in response to climate change it is important to represent the transfer of water and energy from the bedrock to the canopy. This is especially important in California where the subsurface hydrology downstream (i.e., groundwater dynamics) strongly depends on the land surface processes occurring upstream (i.e., snowmelt). ParFlow-CLM has been shown to capture these critical processes in many sites.

To justify how our hydrologic model differs from others, we provide a table below (Table R1c) with the most used hydrologic models and their advantages and limitations when simulating the hydrology of California. Only Hydrogeosphere and ATS have similar advantages as ParFlow-CLM. We also argue that Parflow-CLM can best represent the Californian hydrology of interest to this study due to these unique advantages over other models. Because the equations and the coupling approaches used by these models are similar, we expect their results to be the same.

We have added this justification to the revised manuscript, please refer to lines 280-296 and the text in italic below.

"ParFlow has many advantages in comparisons to other hydrologic models. Compared to other hydrologic models (MODFLOW (Harbaugh, 2005), FELFOW (Trefry and Muffels, 2007), SWAT (Soil and Water Assessment Tool) (Neitsch et al., 2000), SAC-MA (Sacramento Soil Moisture Accounting Model)), ParFlow has the advantages of accounting for land surface processes such as snow dynamics and evapotranspiration and their interactions with the subsurface which are crucial for studying the hydrology of California. ParFlow also solved the subsurface flow by accounting for variably saturated conditions, an important feature for calculating groundwater recharge and the connection between the groundwater and the land surface processes, which is not the case for the aforementioned models. While some hydrologic models have a better representation of the land surface processes (Noah-MP (Niu et al., 2011), VIC (Variable Infiltration Capacity Model Macroscale Hydrologic Model) (Liang et al., 1994)), these models do not have a detailed representation of the subsurface flows. Because the surface flow is important in the region and it establishes the connection between the headwaters and the valleys, its good representation is essential for projecting changes in hydrology. Compared to other integrated hydrologic models (CATHY (Catchment Hydrology) (Bixio et al., 2002), MIKE-SHE (Abbott et al., 1986)), ParFlow has the advantages of solving a two-dimensional kinematic flow equation that is fully coupled to the Richards equation."

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				for the lateral flow and unsaturated zone flow.
Noah-MP (Niu et al., 2011)	Yes (water and energy balance)	Yes (a routing scheme can be used to derive surface flow)	Yes (percolation)	Although this model physically solves the land surface processes including evapotranspiration and snow dynamics, it doesn't account for the two-way interaction between the land surface processes and the subsurface. Lateral and unsaturated zone flows are not represented.
VIC (Variable Infiltration Capacity Model Macroscale Hydrologic Model) (Liang et al., 1994)	Yes	Yes (Rainfall-Runoff)	Yes (percolation and water budget)	Although this model physically solves the land surface processes including evapotranspiration and snow dynamics, it doesn't account for the two-way interaction between the land surface processes and the subsurface. Lateral and unsaturated zone flows are not represented.
Hydrogeosphere (Aquanty, 2015)	Yes (water and energy balance)	Yes (2D diffusive wave equation)	Yes (3D Richards equation)	This model has similar advantages as ParFlow-CLM and could be used to model the hydrology of California.
CATHY (Catchment Hydrology) (Bixio et al., 2002)	Yes (there is a version coupled to Noah-MP)	Yes (1D Saint Venant Equation)	Yes (Mass balance equation)	The mass balance equation is not as robust as the Richards equation for describing the variably saturated flow in the subsurface and recharge processes. In addition, the original model doesn't solve land surface processes.
MIKE-SHE (Abbott et al., 1986)	No	Yes (diffusivity equation)	Yes (Darcy equation and a	The main limitation of this model is the lack of land surface processes

			1D Richards equation)	and the Darcy equation used to describe subsurface flow doesn’t account for the unsaturated flow.
ATS (Advanced Terrestrial Simulator) (Coon et al., 2016)	Yes (water and energy balance)	Yes (2D diffusivity equation)	Yes (3D Richards equation)	This model has similar advantages as ParFlow-CLM and could be used to model the hydrology of California.
ParFlow-CLM (Kollet and Maxwell, 2006)	Yes (water and energy balance)	Yes (2D diffusivity equation)	Yes (3D Richards equation)	

Table R1c: Advantages and limitations of the most used hydrological models

2) There is a lack of calibration, validation, and verification of the proposed model.
When a forecast is performed, one should use a part of the timeseries to calibratevalidate-verify their model, and then perform a forecast for the near future. I suggest
the authors see/discuss this procedure concerning their own model.

We didn’t employ a time-series based comparison for the climate model simulations because they are climate projections and not weather forecasts. VR-CESM is simulated under AMIP-protocols, meaning the atmosphere and land-surface components of the Earth system model are coupled and allowed to solve prognostic and diagnostic equations that describe the interactions between the atmosphere and land-surface while being prescribed new lower boundary conditions every month via observed sea-surface temperatures and sea-ice extents. Therefore, we do not expect VR-CESM to exactly recreate past historical water years and do not consider that these projections would exactly forecast the weather in a given future year. However, we do expect that our 30-year simulation can reasonably recreate the range of water year types over California and the Cosumnes, which is why we utilize the broader range of PRISM water years that are available to compare with our 30-year simulation.

To clarify, the VR-CESM simulations are not forecasts or predictions, but rather projections. There is a subtle but important difference in a prediction, which aims to exactly recreate an event or time period, versus a projection, which aims to encapsulate the envelope of plausible future scenarios given greenhouse gas emissions, sea-surface temperatures, sea ice extents, land-surface cover changes, etc. The end-century projections performed with VR-CESM allow the atmosphere and land-surface model to interact under assumptions of the high emissions scenario (RCP8.5), account for land-surface cover changes, and increases in sea-surface temperatures and decreases in sea-ice extent. Therefore, the 30-year period (2070-2100) encapsulated by these VR-CESM projections should be thought of as "what might happen to the middle and end member years (i.e., driest and wettest) if the world warms by +4 - 5°C?".

We have clarified it in the revised manuscript, please refer to lines 190-201 (see below the text in italic).

“The atmospheric model used for these simulations is the Community Atmosphere Model (CAM) version 5.4 with the spectral element dynamical core, with an atmospheric dynamics time step of 75 seconds, an atmospheric physics time step of 450 seconds, a prognostic treatment of rainfall and snowfall in the microphysics scheme (Gettelman and Morrison, 2015) and run under Atmosphere Model Intercomparison Project (AMIP) protocols (Gates, 1992). Under the AMIP protocols, the atmosphere and land-surface components of the Earth system model are coupled and periodically bounded by monthly observed sea-surface temperatures and sea-ice extents. Although this configuration does not exactly recreate historical water years and events, it is expected to reasonably simulate the distribution of water year types. Also, it should be noted that the model only projects future conditions, within the envelope of plausible future conditions of the RCP8.5 scenario and its assumptions of greenhouse gas emissions, sea-surface temperatures, and sea ice extents and would not be expected to exactly forecast individual water years.”

We calibrated and validated the hydrologic model using remotely sensed and ground measurements of streamflow, groundwater levels, snow water equivalent, soil moisture, and evapotranspiration. Below are the details of the comparisons which were published in Maina et al. (2020) and added to appendix C of the revised manuscript.
We have also added the following lines to the revised manuscript, please refer to lines 341-365 (see below the text in italic).

“We specifically compared simulated and measured river stages at three stations located in the Sierra Nevada headwater, foothill, and the Central Valley. The annual averages absolute differences between measurements and simulations were between 0.4 and 0.8 m. We selected four wells in the Cosumnes watershed based on their availability of data to compare measured and simulated groundwater levels. These wells are sparsely distributed in the Central Valley. The absolute differences observed and simulated groundwater levels vary between 0.47 to 3.73 m. The highest absolute differences were attributed to the lack of a best estimation of groundwater pumping rates in the region. Nonetheless, the reasonable agreement between observations and simulated variables has allowed us to conclude that the model can capture these extreme dynamics. We rely on remote sensing data to assess the ability of our model to simulate key land surface processes (evapotranspiration, soil moisture, and snow dynamics). We compared the simulated SWE to SNODAS (The National Weather Service’s Snow Data Assimilation, National Operational Hydrologic Remote Sensing Center, 2004) and a SWE reanalysis by Bair et al., (2016). Our comparisons indicated that the absolute differences between our SWE values and these data were equal to 3 mm on average. Moreover, the simulated key parameters controlling the snow dynamics such as peak snow and timing of snow ablation were also in agreement with remotely sensed data for both dry and wet years (Appendix C). Absolute differences between the simulated ET and the remotely sensed ET from METRIC (Mapping Evapotranspiration at High Resolution with Internalized Calibration, Allen et al., 2007) were equal to 0.036 mm/s while the differences between the simulated soil moisture and the SMAP (Soil Moisture Active Passive, SMAP, 2015) soil moisture were 0.2.”

Model validation procedure (also added to the response to reviewer 1)

We compared temporal variations of streamflow at 3 stations, one each located in the Sierra (uplands), at the intersection between the Sierra and the Central Valley, and in the outskirts of Sacramento (see Figure R1). Four wells in the watershed (see Figure R1a) have reasonable, publicly-available records of groundwater levels and were used to check the ability of the model to reproduce water table depth variations.

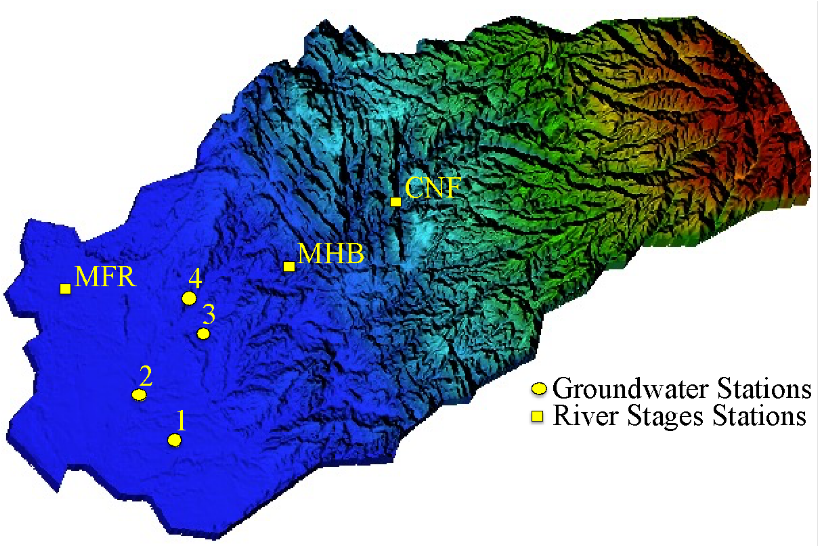

Figure R1a: The Cosumnes watershed geology and the locations of the 3 streamflow gauges (CNF, MHB, and MFR) and 4 groundwater wells (stars).

Figure R1b depicts the comparisons between simulated and measured river stages at the 3 stations indicated in figure R1a. Absolute errors (L1) in m and relative errors (L2) are shown in Table R1a. Differences between simulated and measured streamflow vary between 0.4 and 0.8 m (Table R1a) indicating that the model is able to reproduce the river dynamics.

(a)

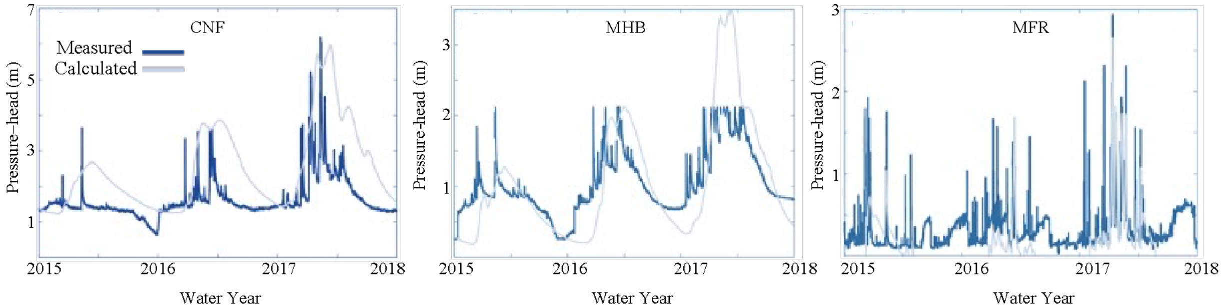

Figure R1b: Comparisons between measured and calculated river stages (i.e., pressure-heads simulated by ParFlow-CLM). Measurements locations are indicated in Figure R1a.

Measurements	*L1 (m)*	*L2 (-)*
River Stages (CNF)	*0.8*	*0.5*
River Stages (MHB)	*0.4*	*0.36*

River Stages (MFR)	*0.57*	*1.06*
Groundwater Levels (Well 1)	*3.73*	*0.05*
Groundwater Levels (Well 2)	*1.63*	*0.02*
Groundwater Levels (Well 3)	*0.476*	*0.0077*
Groundwater Levels (Well 4)	*1.08*	*0.016*

Table R1a: Differences between measured and calculated surface and groundwater levels. L1 is the absolute error and R2 the relative error.

Comparisons between simulated and calculated groundwater levels (here referred to as the pressure-heads at the bottom of the domain) shown in figure R1c indicate that the model has reasonable agreements with measurements. As shown in table R1a, the error varies between 0.47 to 3.73 m depending on the station. Mismatches between simulated and observed groundwater levels at wells 1 and 2 are likely due to an inaccurate estimation of pumping in these areas. The temporal variations of the groundwater levels show an impact of withdrawals but because these withdrawals are hard to estimate the model does not correctly reproduce these trends.

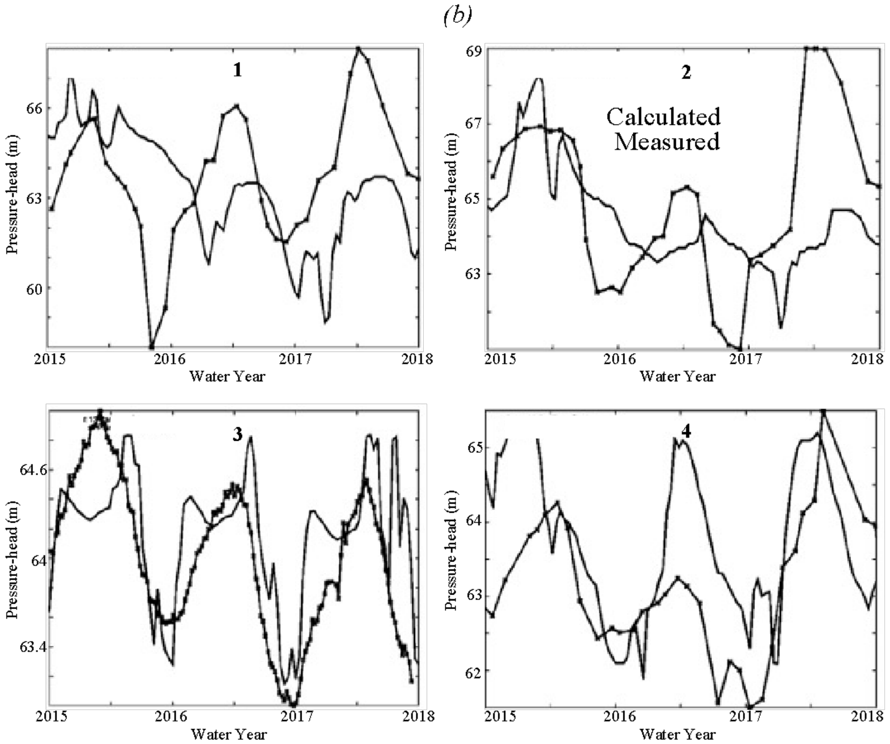

Figure R1c: Comparisons between measured and calculated pressure-heads at the bottom of the domain. Measurement locations are indicated in Fig. R1.

ParFlow-CLM also simulates the key land surface processes governing the transfer of water and energy at the land-atmosphere-soil interface: evapotranspiration, snow dynamics, and soil moisture. In Maina et al., (2020a), we conducted rigorous comparisons between the ParFlow-CLM simulated land surface processes and remotely sensed estimates of these variables. Table R1b shows the correlation coefficient between ParFlow-CLM results and the various datasets compared.

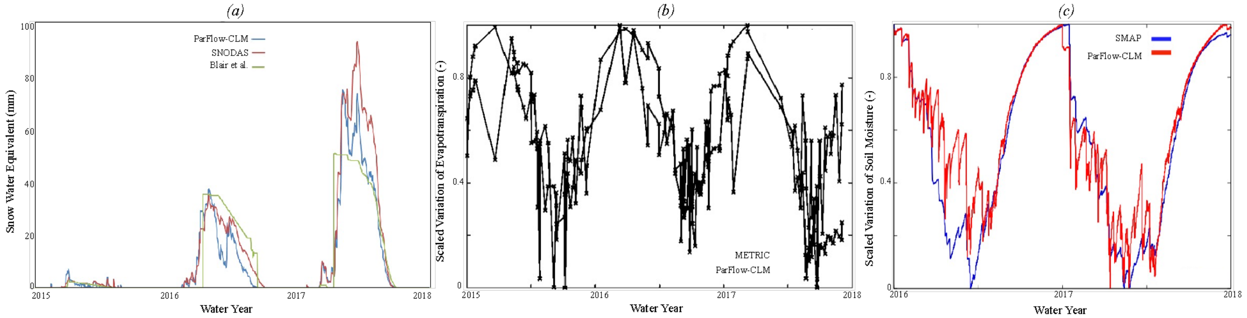

Figure R1d: (a) Comparisons between domain-averaged total snow water equivalent obtained with ParFlow-CLM, SNODAS and Bair et al., reconstruction, (b) Comparisons between actual evapotranspiration obtained with ParFlow-CLM and METRIC (c) Relative variation of soil moisture obtained with ParFlow-CLM and SMAP. Note that the time series of (c) is shorter because of the availability of SMAP data

Satellites based products	*L1 (m)*	*L2 (-)*	*Pearson Correlation Coefficient*
SWE SNODAS (mm)	*3.09*	*3.77*	*0.97*
SWE Bair et al., (mm)	*3.80*	*2.69*	*0.84*
Soil Moisture SMAP (-)	*0.217*	*3.07*	*0.94*
ET METRIC (mm/s)	*0.067*	*1.40*	*0.6*

Table R1b: differences between measured and remotely sensed evapotranspiration (METRIC), soil moisture (SMAP), and snow water equivalent (SNODAS and Bair et al., 2016)

Also, the End of Century (EoC) forecast for such a large area is very optimistic in my opinion. Since climate dynamics is highly complex, I imagine that a forecast of only a few steps ahead is possible. If one is studying, for example, runoff on an annual scale, then after a couple of years, the variability of the forecast would be very wide, thus, reducing the credibility of the result (e.g., see Han et al., 2021). Also, the credibility of the outcome should depend on the available length of records. Here, the authors perform a forecast of 80 years ahead, which is double the length of records the authors use to construct the climatic and hydrologic model. I suggest to test/discuss how the variability/probability of the forecasts change as we move away from the present/historic data.

The study mentioned by the reviewer (Han et al., 2021) uses a deep learning approach. The deep learning approach is different from the model we employed in this study, which solves physical equations both prognostically and diagnostically. Although physics-based models depend on the initial conditions, the impact of those initial conditions decreases with time (Maina et al, 2017). While the geology dictating the hydrodynamic parameters such as hydraulic conductivity, porosity, and specific storage could change with time, this change usually occurs on geological timescales (thousands or millions of years). As acknowledged in the manuscript, the land cover may change by the end of the century. However, this change is uncertain and difficult to predict hence we didn’t incorporate it in this study–in this sense our results are a sensitivity analysis focused on the shifts in meteorological forcing rather than a fully-integrated assessment of changes. We specifically used the physics-based integrated hydrologic models because these models do not strongly rely on the historical/initial conditions and rather are controlled by the representations of watershed processes and physical characteristics of the area. Likewise, because the climate model is also solving the fundamental physics of fluid flow, thermodynamics, etc. in the atmosphere, it doesn't rely on historical and past observations to bound the simulations. Moreover, the memory of physics-based climate models is shorter than that of the integrated hydrologic models. The uncertainties that could arise from the long forecast is the trajectory of CO_2 emissions that could potentially change by the end of the century. We also perform long-term, 30-year simulations because we are not trying to forecast the exact conditions at end-of-century rather looking to investigate the envelope of possibilities based on atmospheric dynamics and thermodynamics and their impacts on hydrologic processes.

3) It is shown that due to long-range dependence effect to key hydrological-cycle processes (e.g., Dimitriadis et al., 2021) such as the ones the authors use, the variability of each climatic process would be even higher than, for example, under the assumption of zero auto- and cross- correlation (i.e., white noise). Please show/discuss whether the proposed model assumes a correlation function for the input variables. I also suggest the authors see/discuss whether their model forecasts also capture (and verify) the stochastic characteristics of the historical timeseries including the effects from climate change (such as marginal distribution function, autocorrelation function, etc.).

As mentioned in the previous answer, we used a physics-based model not a machine learning model that is based on the previous observations to perform prediction and is strongly dependent on the previous conditions and the period used to do the training and make the predictions.
Also, because these models are based on physics there is no need to account for a longer historical period that captures the statistical distribution of the event. Nonetheless, we validate our model by testing its ability to simulate dry and wet years in California. The comparisons (please refer to the previous answer) have shown that the developed model captures such extremes.

4) There are many equations in the text. Please consider creating a Table with all the inputs variables, output variables, boundary conditions, model assumptions, model limitations, simulation times, discretization method, etc., in order to help the readers identify the complexity/strength of the proposed model.

We have added the following paragraphs to Appendix B of the revised manuscript.

1. **Input Variables**

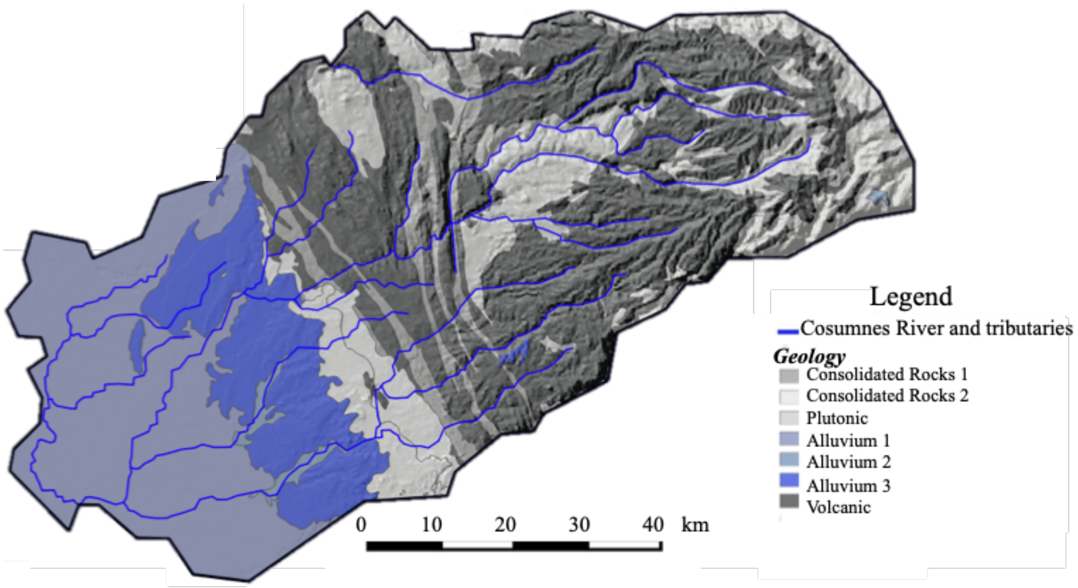

Figure R2a: Geological map of the Cosumnes watershed (source: USGS, Jennings et al., 1977)

Hydrodynamic properties based on the geology

Geological Formation	Porosity (-)	Specific Storage (m-1)	Van Genuchten α (m-1)	Van Genuchten n (-)
Bedrock (Consolidated, Plutonic and Volcanic Rocks)	0.02	10-6	3.0	3.0
Alluvial aquifers	0.2	10-4	3.0	3.0

Table R2b: Assigned values of hydrodynamic parameters (porosity, specific storage and Van Genuchten parameters). Values are based on literature review (Faunt et al., 2010; Faunt and Geological Survey (U.S.), 2009; Flint et al., 2013; Gilbert and Maxwell, 2017; Welch and Allen, 2014).

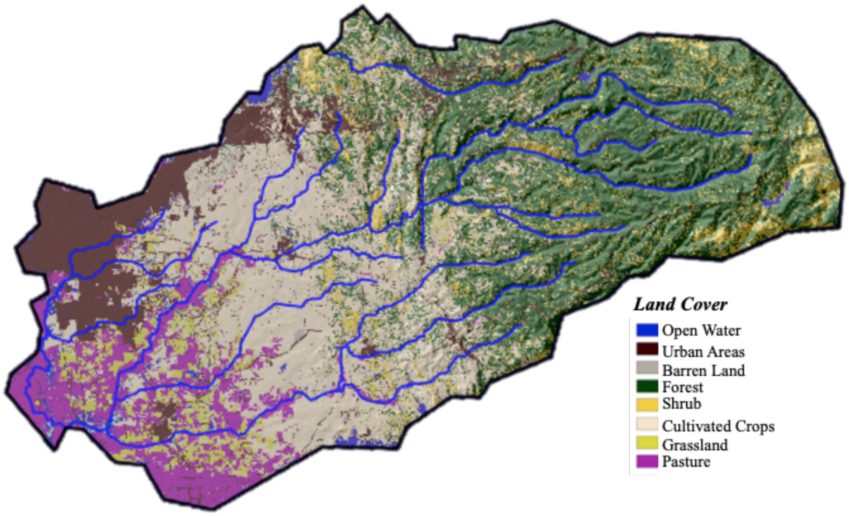

Figure R2b: Cosumnes watershed characteristics: land use and land cover (source: Homer et al., 2015), and model boundaries.

Surface roughness based on land use	
Land Use	**Manning Coefficient (h.m-1/3)**
Forest	5x10-2
Shrub land and agricultural area	5x10-3
Urban areas	5x10-5

Crop properties			
Crop Type and Reference	**Height (m)**	**Maximum Leaf Area Index (-)**	**Minimum Leaf Area Index (-)**
Alfalfa (Evett et al., 2000; Orloff, 1995; Robison et al., 1969)	0.6	6.0	2.0
Pasture (Buermann et al., 2002; King et al., 1986; Rahman and Lamb, 2017)	0.12	6.0	1.0
Vineyards (Johnson and Pierce, 2004; Vanino et al., 2015)	0.9	3.0	0.6

Table R2b: Manning coefficients and crop properties

Boundary conditions	**Value**
Mokelumne and American river	Weekly-varying Dirchlet boundary conditions. These values are based on the measured river stages.
Sierra Nevada limit	No flow Neumann boundary condition
Bottom of the model	No flow Neumann boundary condition

Table R2c: boundary conditions

2. Numerical model set-up

<table>
<tr><td>Domain size</td><td>~7000 km2</td></tr>
<tr><td>Spatial discretization</td><td>200 m horizontal from 0.1 m to 30 m in the vertical direction
<table>
<tr><td colspan="9">Vertical Resolution</td></tr>
<tr><td>Layer</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td>Δz (m)</td><td>0.1</td><td>0.3</td><td>0.6</td><td>1.0</td><td>8.0</td><td>15.0</td><td>25.0</td><td>30.0</td></tr>
</table></td></tr>
<tr><td>Simulation time</td><td>Model validation (from water year 2012 to water year 2017), then future water years.</td></tr>
<tr><td>Temporal discretization</td><td>hourly</td></tr>
</table>

Table R2d: Numerical model discretization

3. Output variables

Selected output variables	**Temporal scale**	**Spatial scale**
Snow Water Equivalent	Yearly, monthly, and hourly	Domain-average and point scale
Evapotranspiration	Yearly, monthly, and hourly	Domain-average and point scale
Soil Moisture	Yearly, monthly, and hourly	Domain-average and point scale
River Stages (also surface water storages)	Yearly, monthly, and hourly	Domain-average and point scale
Groundwater levels variations (also subsurface storages)	Yearly, monthly, and hourly	Domain-average and point scale

Table R2e: Selected output variables

5) Please include more details on the water-energy balance equation and show whether is preserved in historical and forecasts. Also, have the authors included in the mass-energy balance analysis groundwater depletion in California (e.g., Badiuzzaman et al., 2017) and effects from sea level rise and ocean dynamics (e.g., Katsman et al., 2008)?

Mass balance is preserved when solving the mixed form of the Richards equation shown in equation (1) (Celia, et al., 1990). ParFlow-CLM numerically solves this equation by using the New-Krylow linearization scheme, this scheme iteratively solves the equation at each time step until the mass balance criteria set (equal to 10^{-3}) is satisfied. Any large errors in the mass balance will automatically stop the resolution of the equation.
We have added the mass conservative properties of the mixed of the Richards equation in the revised manuscript, please refer to lines 265-266, see below the text in italic.

"ParFlow solves the mixed form of the Richards equation which has the advantage of conserving the mass (Celia et al., 1990)."

The Richards equation as shown in (1) accounts for groundwater depletion which is included in the term qs. While groundwater depletion plays an important role in the hydrodynamics of California we didn't account for this effect in this study (stated in lines 377-382 of the revised manuscript) because the current pumping rates are difficult to estimate and their prediction by the end of the century is highly uncertain as it depends on many factors including policy and management. We, however, tested the impacts of this assumption of excluding pumping in our simulation (please see below the discussion: Discussion on the potential impacts of groundwater depletion on hydrologic projection in California). We found that the simulations without pumping do not significantly change the observed dynamics of the system, but they could overestimate the depletion of aquifer by evapotranspiration by 5 to 10%.

The watershed is not located near the coastal region; therefore, the effects of sea level rise are negligible.

Discussion on the potential impacts of groundwater depletion on hydrologic projection in California

Because pumping rates may substantially change in the future due to new demands, policies/ regulations, and changes in land cover and land use, a model which includes a projection (or an envelope of these projections) is a work in itself. Therefore, we did not include them in this work, although the ParFlow-CLM model of this basin was developed to account for an approximation of the pumping and irrigation practices (to date) in the Central Valley. In the simulations originally shown here, we chose to simulate the natural system, given the constraints and uncertainty around the aforementioned projections in water and land management practices. However, we have taken the reviewer's comment seriously and have performed additional simulations comparing the EoC simulations with pumping and irrigation as a type of "numerical experiment". Specifically, we performed two additional simulations for both historical and EoC median water years with pumping and irrigation. The two simulations are as follow:

- *Baseline without any pumping and irrigation*
- *Pumping and irrigation, around 700 pumping wells operating from April to November have been placed in the Central Valley aquifers. The number of wells, timing, and rates of pumping were determined by discussion with stakeholders in the areas and an estimation technique, which accounts for the water required by each crop for its optimal growth. More details about the estimation technique can be found in Maina et al., (2020a).*

Figure R6 illustrates the temporal variations of surface water and groundwater storages obtained with the four simulations. As expected, the pumping scenarios have lower storages than the baselines. We notice that both pumping and baseline EoC scenarios are characterized by an earlier and higher increase in groundwater and surface water storage compared to the historical conditions (similar to the main conclusions of our study). These storages decrease by the end of the water year to become nearly equal to the historical baseflow conditions. In the baseline scenarios, the EoC groundwater storage is lower than the historical groundwater storage into August, though the historical baseline storage dips below the EoC baseline in September. In contrast, in the historical pumping scenario the groundwater storage remains lower throughout *the summer, showing distinct behavior in the pumping scenarios. We attribute this difference to reduced evapotranspiration in the pumping scenarios because of the deep water tables.*

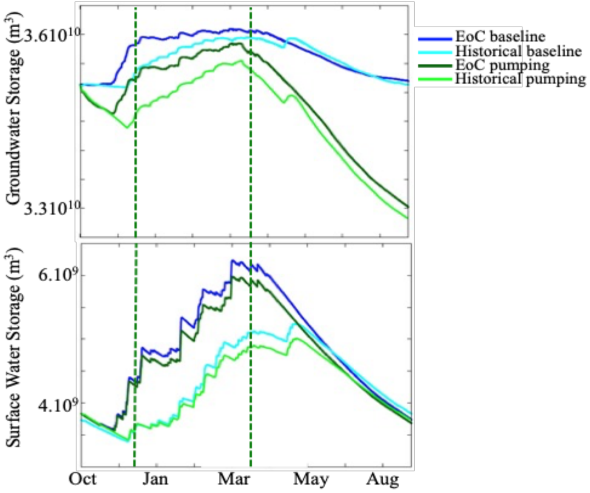

Figure R2c: Temporal variation of groundwater and surface water storages associated with EoC and historical baseline and pumping scenarios. The dashed green lines indicate the beginning and end of the pumping.

An analysis of the spatial differences between the baseline and the pumping differences (not shown here) has shown that these differences are mostly located in areas close to the pumping wells. Figure R7 depicts the temporal variation of water table depth and recharge associated with EoC and historical baseline and pumping scenarios at a selected point (located close to the pumping wells) in the Central Valley.

In the pumping scenarios, the water table decreases in the first two months whereas the water table is constant during this period in the baseline simulations. As the water table becomes deeper, the recharge also decreases. In the EoC, there is an early rise of the water table and an increase in recharge in both pumping and baseline scenarios due to the meteorological conditions (high and early precipitation). The water table rises earlier in the baseline compared to the pumping scenario. This rise is much earlier in the EoC than the historical conditions because the high precipitation of the EoC quickly compensates for the depressions created by pumping and increases the water table and therefore increases the recharge as explained in the schematic figure R8.

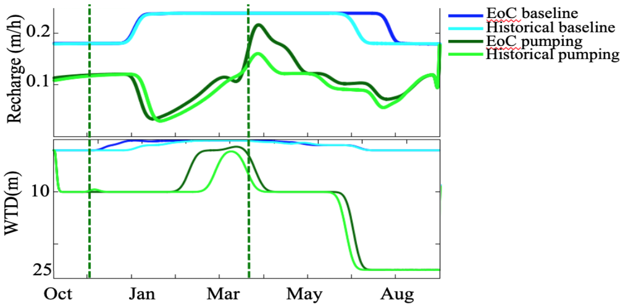

Figure R2d: Temporal variation of water table depth (WTD) and recharge associated with EoC and historical baseline and pumping at a selected point in the Central Valley. The dashed green lines indicate the beginning and end of the pumping.

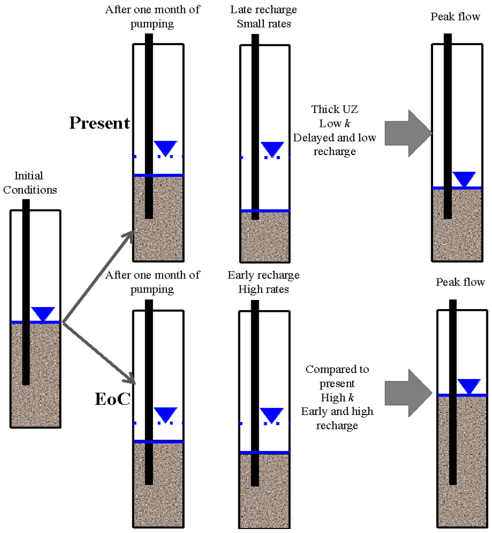

Figure R2e: Schematic representation of the influence (on recharge) of pumping in historical and EoC conditions. At a local point, early and high precipitation of the EoC leads the water table to rise earlier and the recharge to increase because the unsaturated zone (UZ) becomes less thick, and the effective permeability k becomes higher.

While the pumping simulations have lower storages than the baselines, the mechanisms (early and high increases in storages and depletion in spring and summer) in both EoC and historical conditions remain the same. This is because we applied the same rate of pumping in both EoC and historical conditions and the timing of the pumping is assumed to be the same in both simulations. However, we note that the simulations without pumping could overestimate the depletion of aquifer by evapotranspiration by 5 to 10%.

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