REPRESENTING INTERCELL LATERAL GROUNDWATER FLOW AND AQUIFER PUMPING IN THE COMMUNITY LAND MODEL

Farshid Felfelani, Yadu Pokhrel, and David Lawrence

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Water Resources Research

RESEARCH ARTICLE
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Key Points:

- A new prognostic groundwater model is implemented into the latest version of the Community Land Model (CLM5)
- The new model accounts for lateral groundwater flow and conjunctive use of groundwater and surface water for irrigation
- Significant improvements are achieved in simulating the spatiotemporal dynamics of water level over the heavily exploited US aquifers

Representing Intercell Lateral Groundwater Flow and Aquifer Pumping in the Community Land Model

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Abstract Representation of subsurface hydrology in global land surface models has been advanced but outstanding challenges and opportunities remain, especially in better simulating lateral groundwater flow and aquifer pumping for irrigation. This study improves the representation of groundwater in the latest version of the Community Land Model (version 5) by implementing a prognostic groundwater module that accounts for lateral groundwater flow, aquifer pumping, and conjunctive use of groundwater and surface water for irrigation. In particular, we introduce—for the first time—explicit representation

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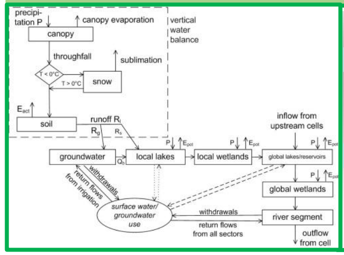
Challenges in Large-scale Groundwater (GW) Modeling

- GW dynamics in large-scale hydrological models is rather poorly parameterized
- Linear representation of GW (i.e., as a linear reservoir model)
- Not fully coupled SW-GW Systems
- Lack of pumping (not linking with irrigation)
- Lack of lateral GW flow

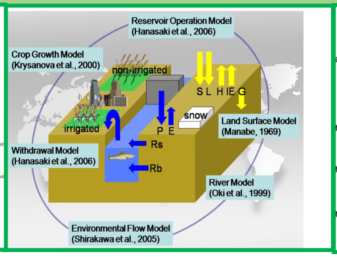
Filling the Gaps

- This study: to improve the representation of GW and irrigation interactions:
    - Lateral GW flow
    - GW pumping
    - More realistic irrigation scheme (Conjunctive water use for irrigation)
    - Water table dynamics

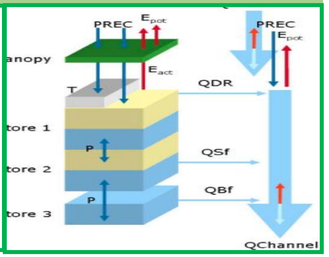
WaterGAP model (Alcamo et al., 2003; Doell et al., 2012)



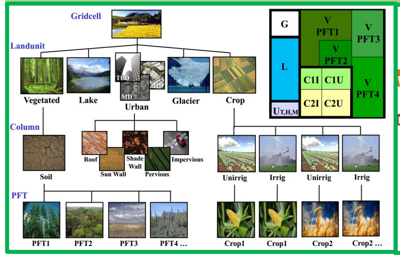
H08 model (Hanasaki et al., 2008a,b)



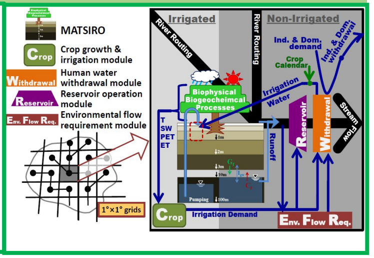
PCR-GLOWB (van Beek et al., 2011; Wada, 2011)

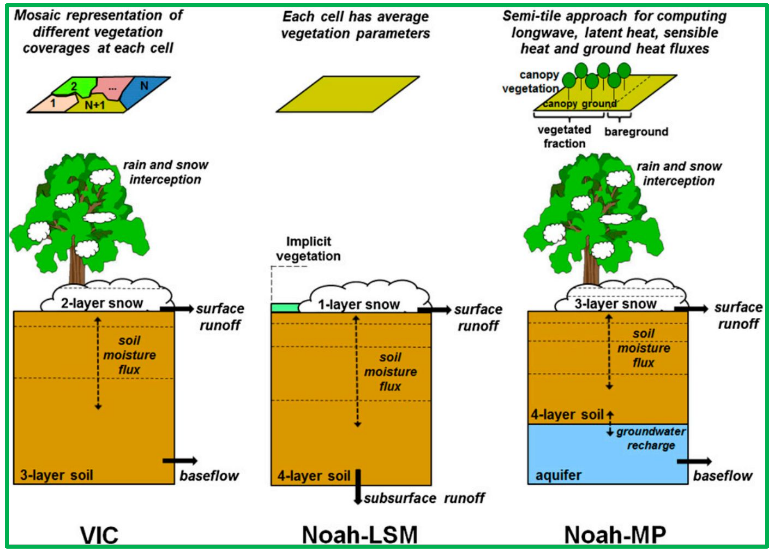


CLM model (Lawrence et al., 2019)



HiGW-MAT model (Pokhrel et al., 2015)





(Mendoza et al., 2015)

Lateral GW Flow from Darcy's Law and S.S. Well Eq.

- The GW mass balance for a grid cell (Fan et al., 2007)

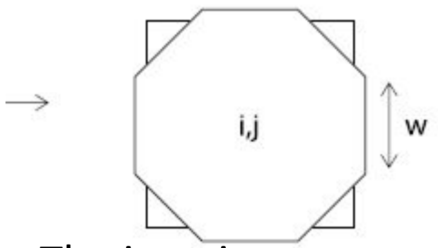
$$\frac{dS_g}{dt} = \Delta x \Delta y R + \sum_{1}^{8} Q_n - Q_r$$

- Steady state and for a hillslope cell

$$\Delta x \Delta y R = -\sum_{1}^{8} Q_n$$

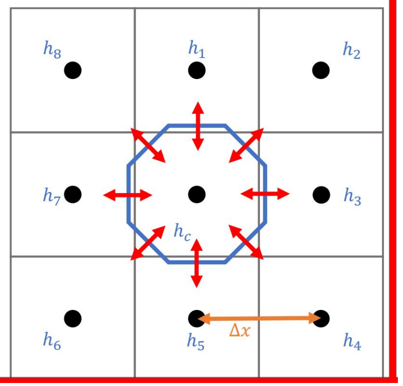
$$Q_n = wT\left(\frac{h_n - h}{l}\right) \quad , \quad w = \Delta x\sqrt{0.5\tan(\pi/8)}$$

(c) Width of Flow Cross-section



The imaginary octagon

(a) Without Pumping



- Well Equation

The radial form: $S_y \frac{\partial h}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} Tr \frac{\partial h}{\partial r} + \varepsilon$

B.C. $r = r_0,\ Q_p = K\frac{\partial h}{\partial r} \times 2\pi r_0 h$

$$\left(\frac{Q_p}{2\pi T} + \frac{\varepsilon r_0^2}{2T}\right) ln\frac{R}{r} - \frac{\varepsilon(R^2 - r^2)}{4T} = H - h$$

$$Q_{lat} = \frac{Q_p}{8} = \frac{\pi T\left(z_{wt@r_e} - z_{wt@a}\right)}{4ln\left(\frac{a}{r_e}\right)} + \frac{\varepsilon\pi(a^2 - r_e^2)}{16ln\left(\frac{a}{r_e}\right)} - \frac{\pi\varepsilon r_0^2}{8}$$

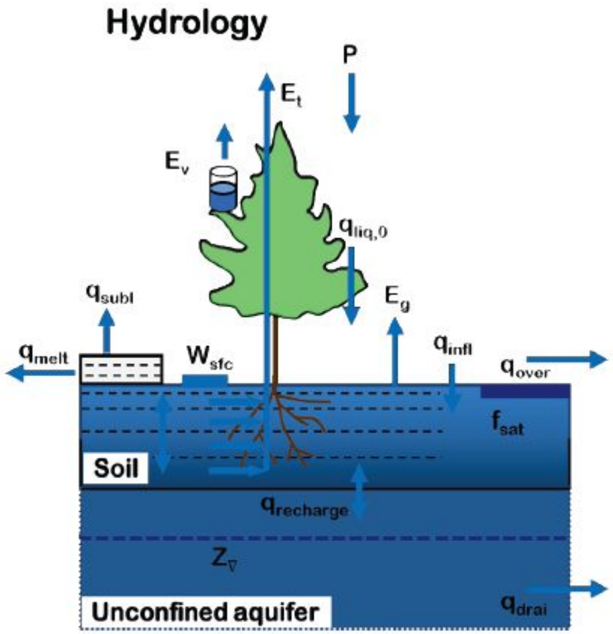
GW Pumping

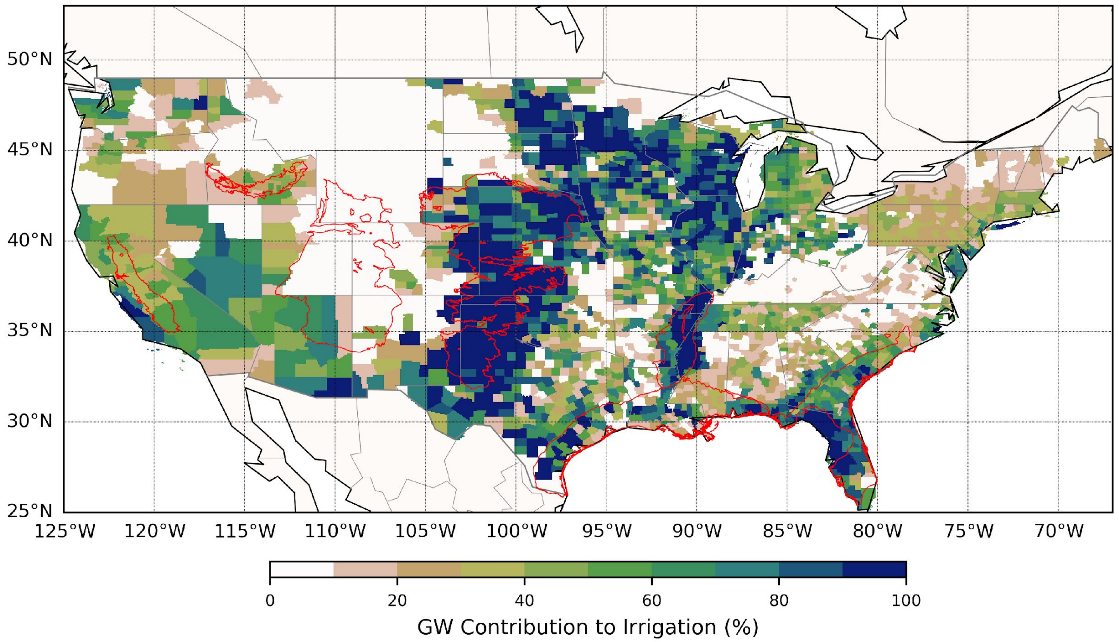
- Water Balance
  - A grid cell with pumping (Pokhrel et al., 2015)

$$\frac{dS_g}{dt} = \Delta x \Delta y R - GW_{pt} - Q_r$$

  - Water Table Depth

$$dd_{gw} = \frac{dS_g}{S_y}$$





USGS census data of irrigation water withdrawals (1985-2015)

Experimental Setting

•

Simulation	Lower BC	Aquifer Layer	Sub-surface Runoff	Pumping	Soil Configuration	Lateral Flow
NoLat_NoPump	Head-based	Active	Exponential	No	20 Layers, 8.5m	No
NoLat_wPump	Head-based	Active	Exponential	Yes	20 Layers, 8.5m	No
wLat_NoPump	Head-based	Active	Exponential	No	20 Layers, 8.5m	Darcy
wLat_wPump	Head-based	Active	Exponential	Yes	20 Layers, 8.5m	Darcy and Well Eq.

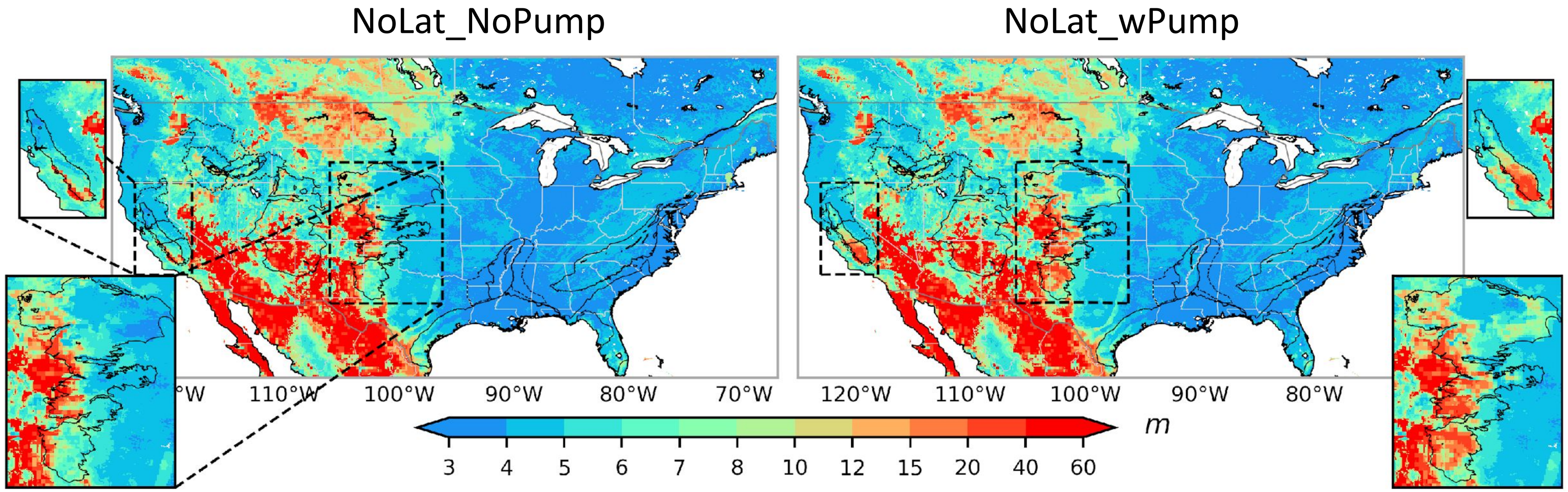
☑ Spatial resolution: 3 arc-minute (0.05°; 5 km)

☑ Spin-up for 120 years; simulations conducted for 1998-2016 period forced by NLDAS2

GW Table Depth

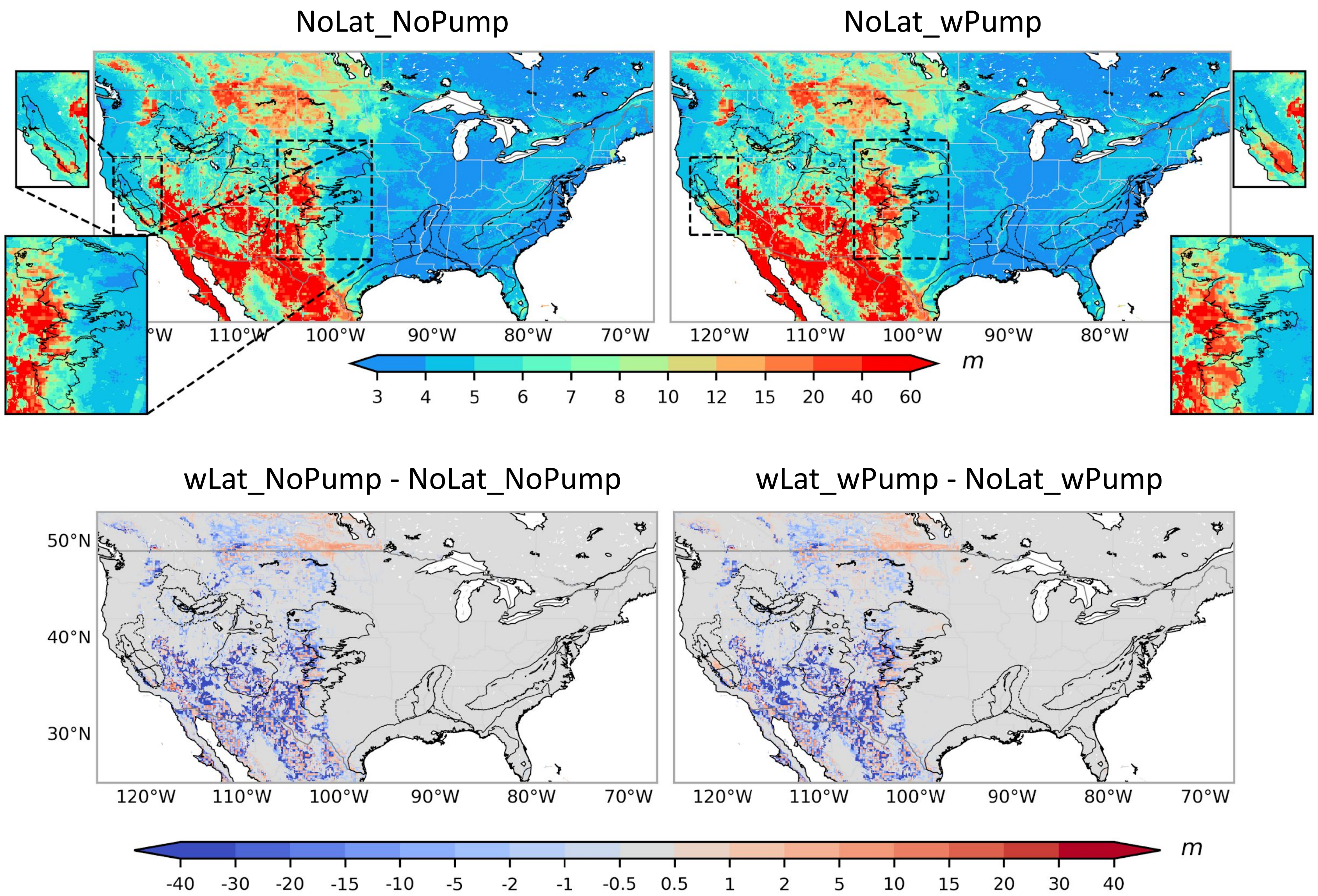
- GW table depth mostly reflects climate patterns in the absence of pumping

- Large water level drop caused by pumping. For example, in the HPA water level drops by ~2–27 m in the southern part



GW Table Depth

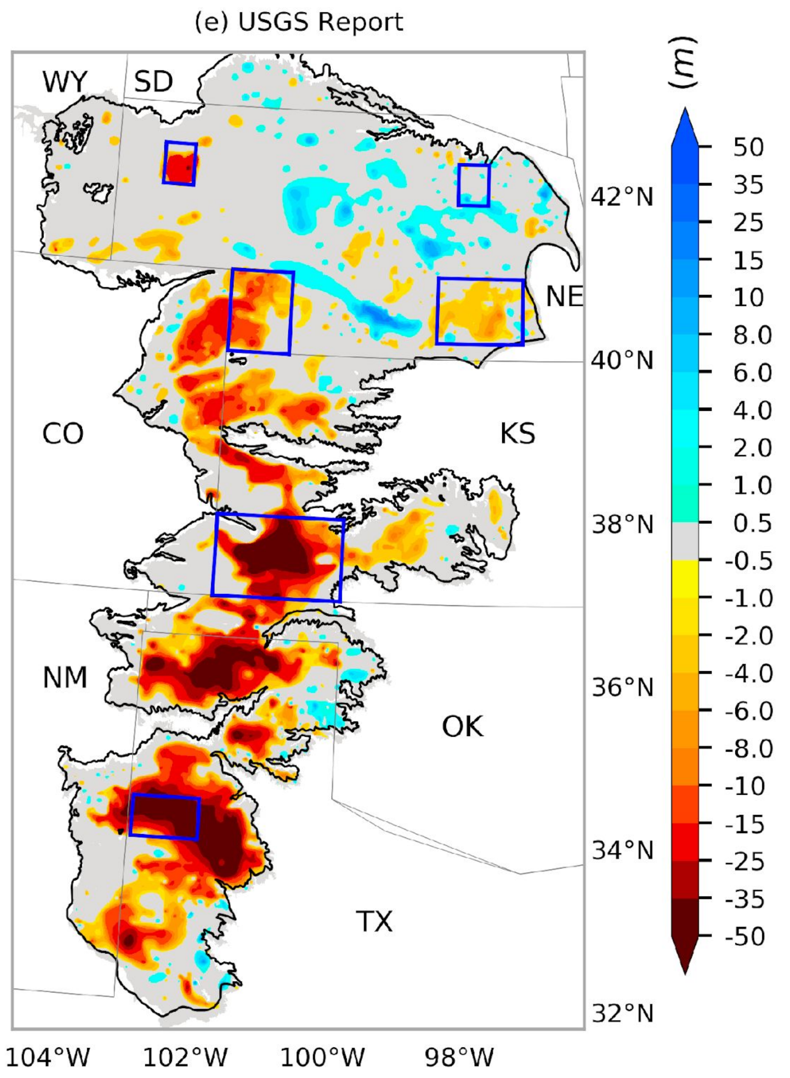
- GW table depth mostly reflects climate patterns in the absence of pumping
- Large water level drop caused by pumping. For example, in the HPA water level drops by ~2–27 m in the southern part
- Shallow water table: the recharge to be balanced by large baseflow causing relatively small lateral flow
- High water table gradients across the West and Southwest: large regional groundwater flows between intermountain hills and valleys



GW Level Change in the High Plains Aquifer (HPA)

- ~450,000 km^2, development: ~1950
- Aquifer layer: mostly alluvial deposits and generally classified as unconfined
- ~30% of the total U.S. irrigated acreage
- ~10% of the total U.S. crop value
- ~95% of the total irrigation demand is GW supplied

1950-2015

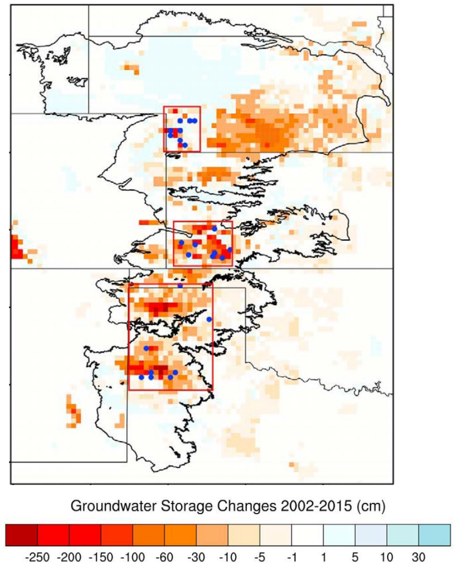


GW Level Change in HPA

1950-2015

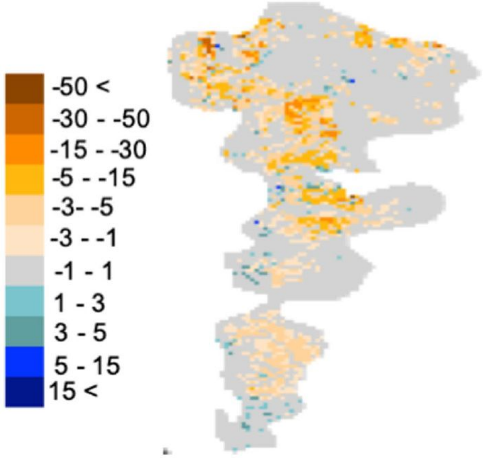
Nie (2018)

Noah-MP, 2002-2015



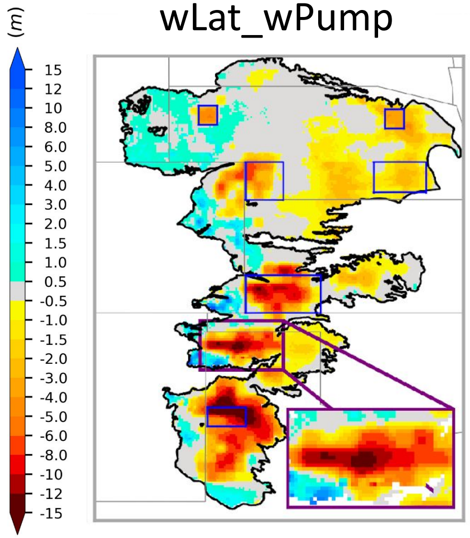
de Graaf (2019)

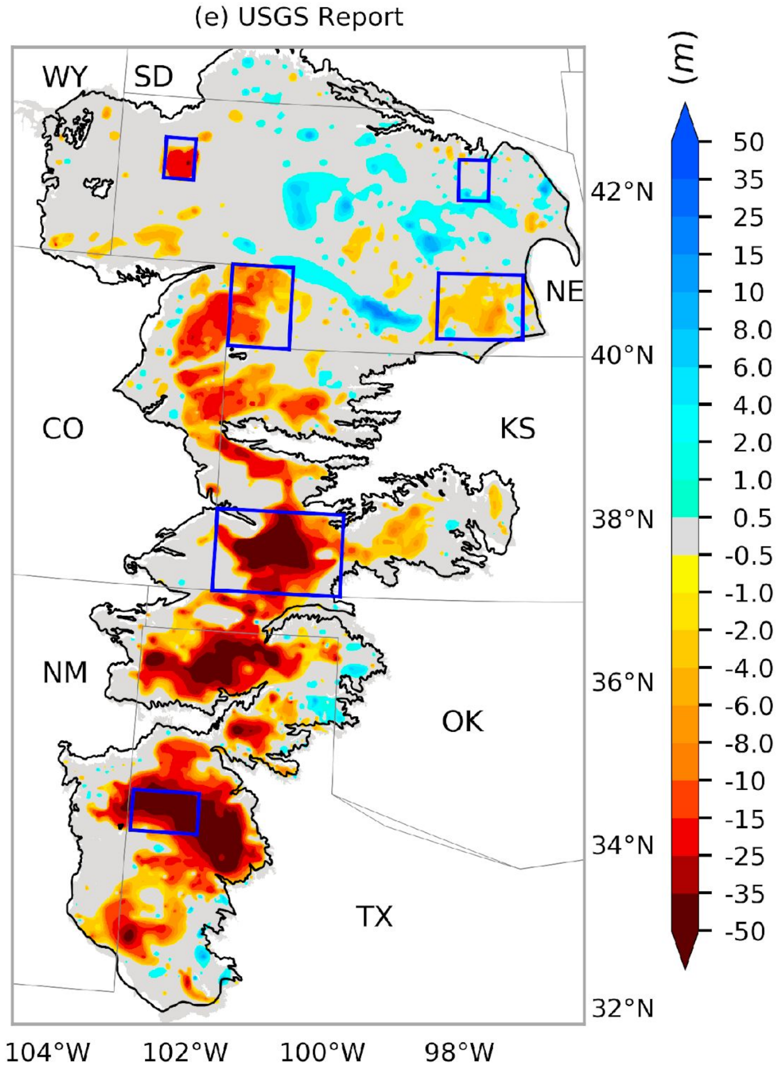
PCR-GLOBWB, 1960-2007



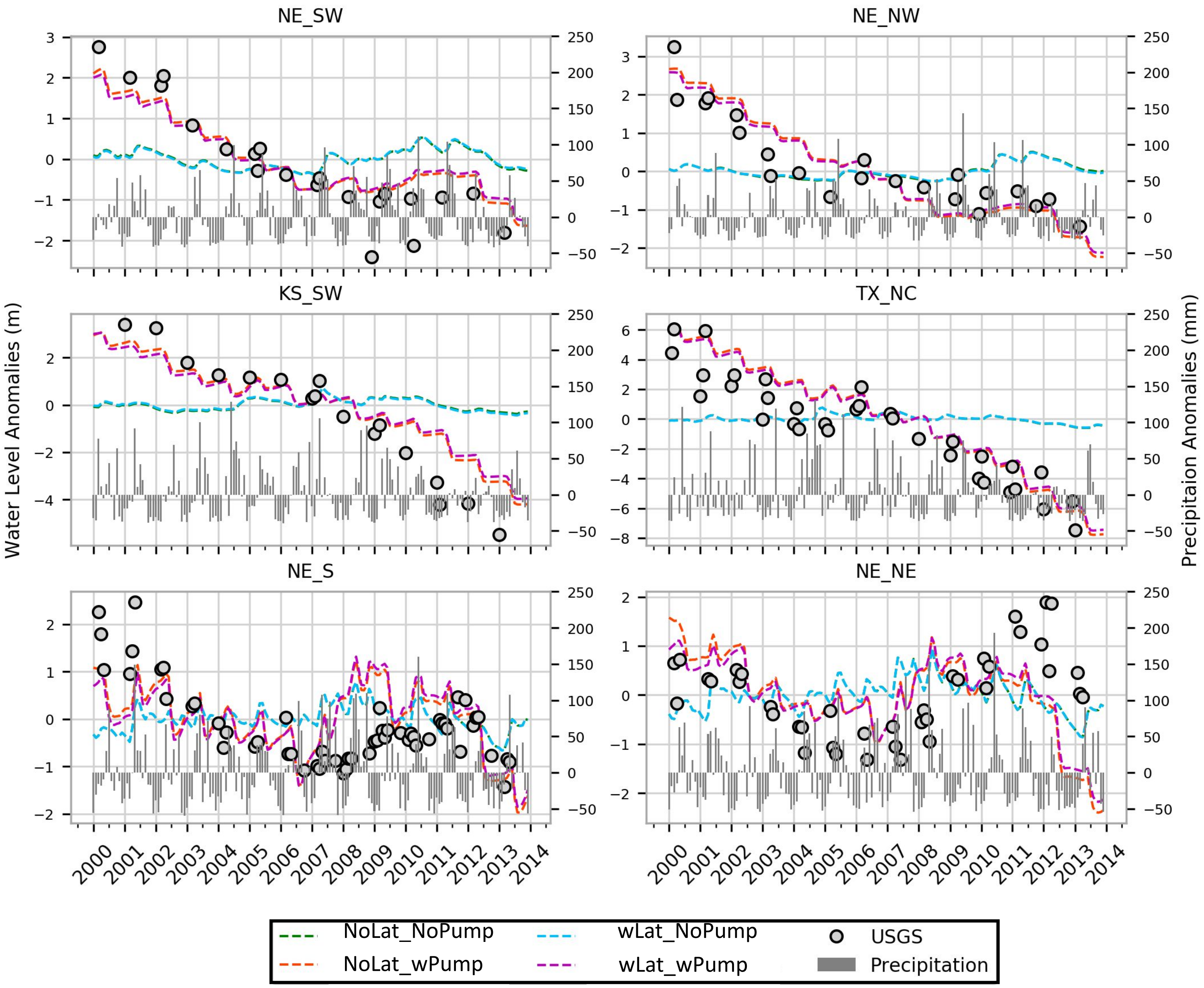
2000-2015

wLat_wPump

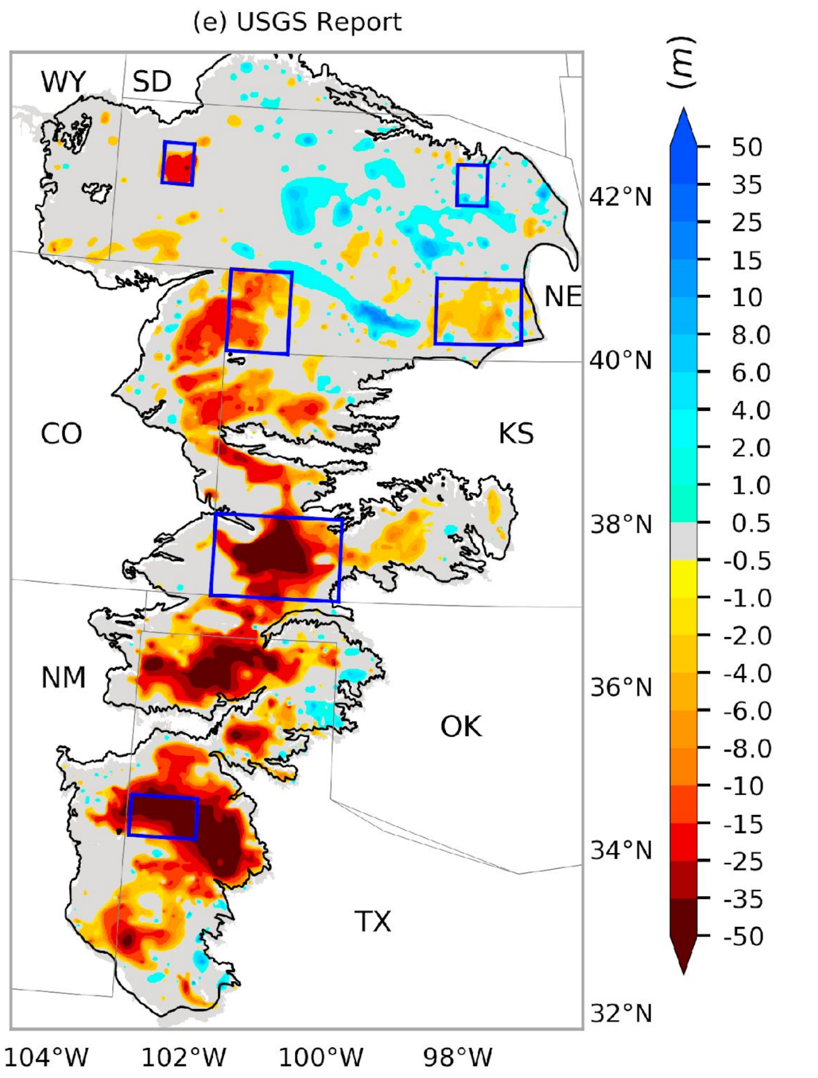




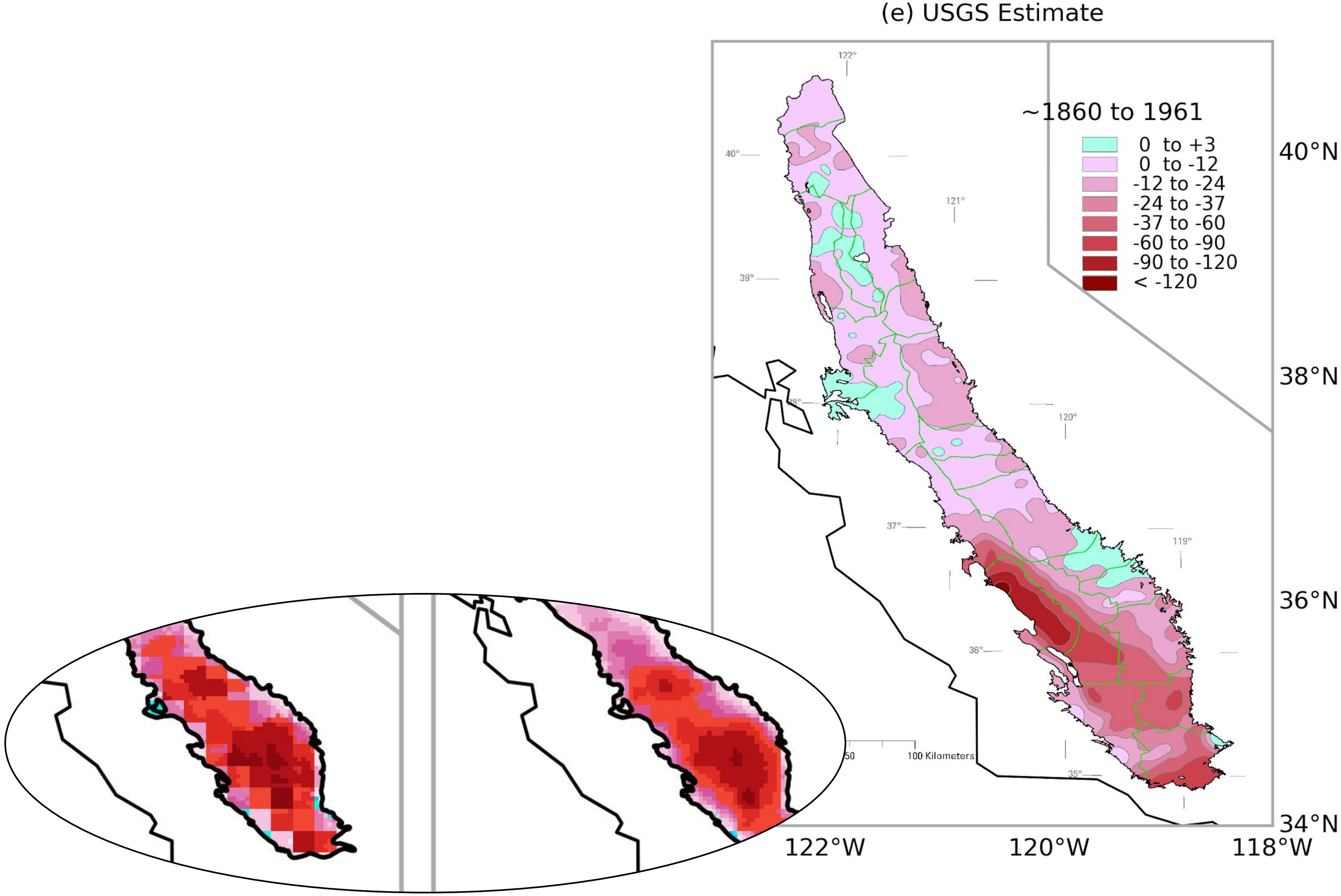
GW Level Change in HPA



1950-2015

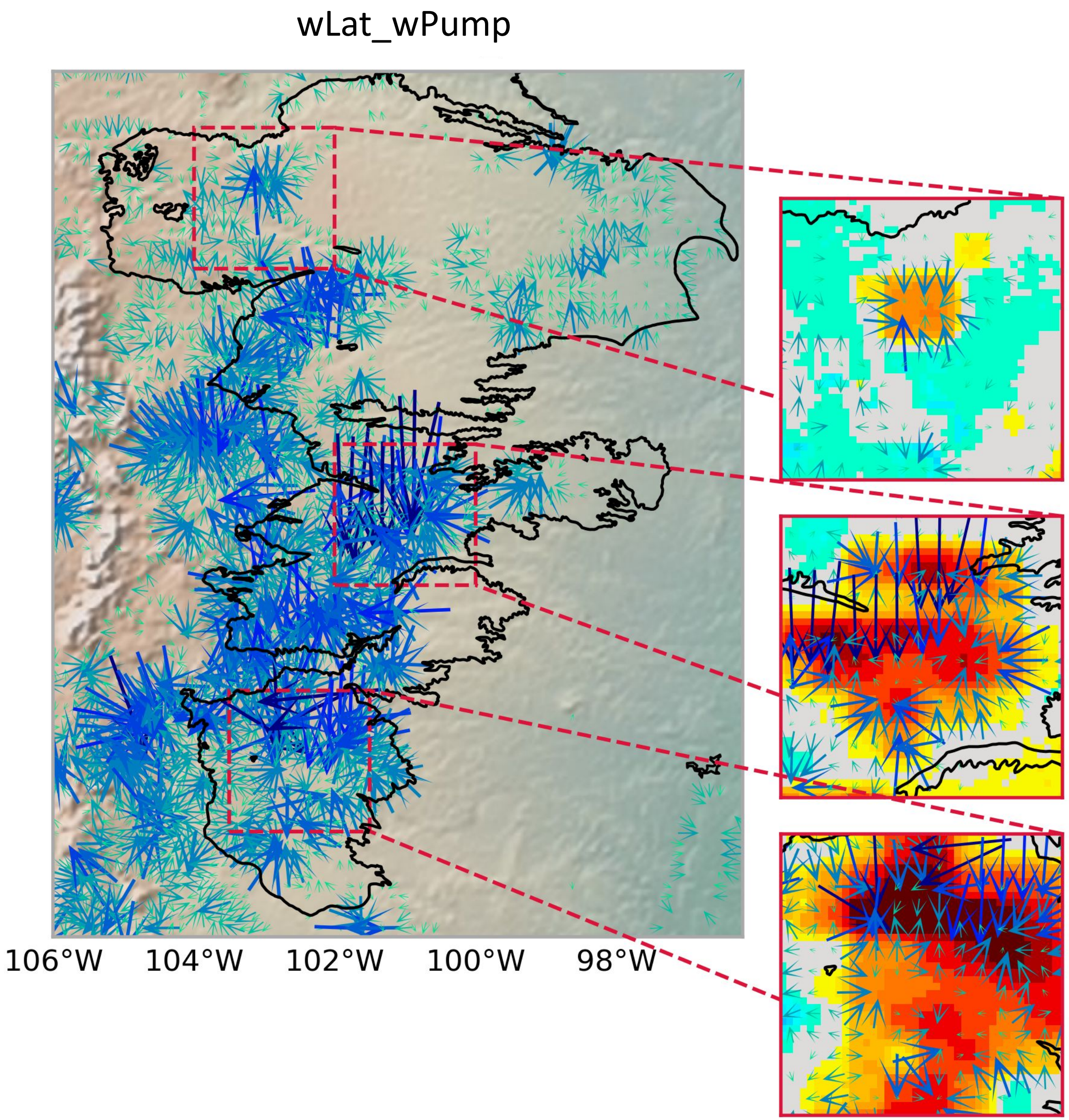


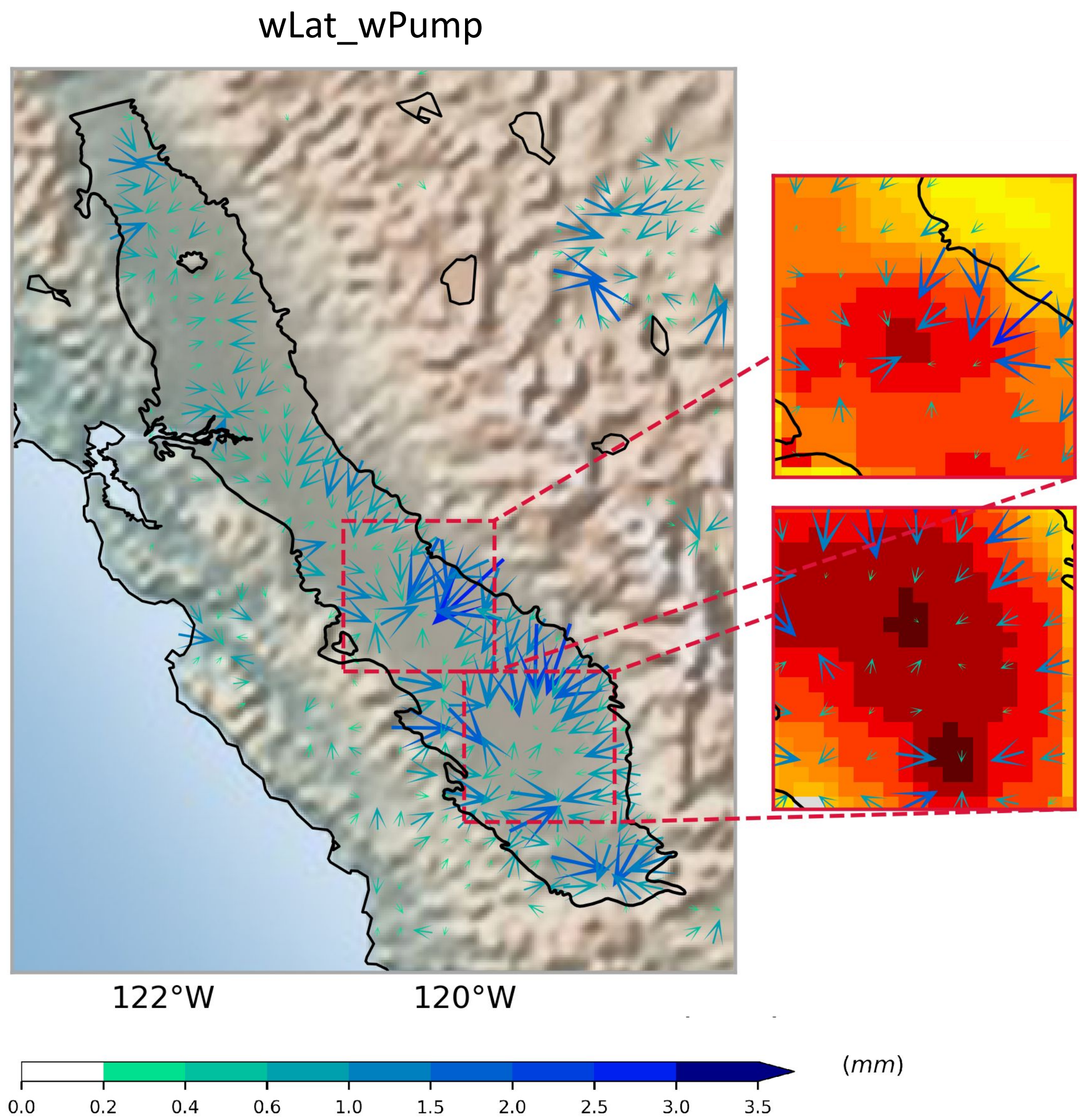
GW Level Change in California's Central Valley Aquifer (CVA)



- ~52,000 km^2, development: ~1860
- Includes: Sacramento Valley, San Joaquin Valley, and the Tulare Basin
- Surface Water accounts for a large fraction (~50%)
- Over 90% of croplands and pasturelands are irrigated
- Unconfined in the shallow parts and semiconfined or confined in the deep parts to the south

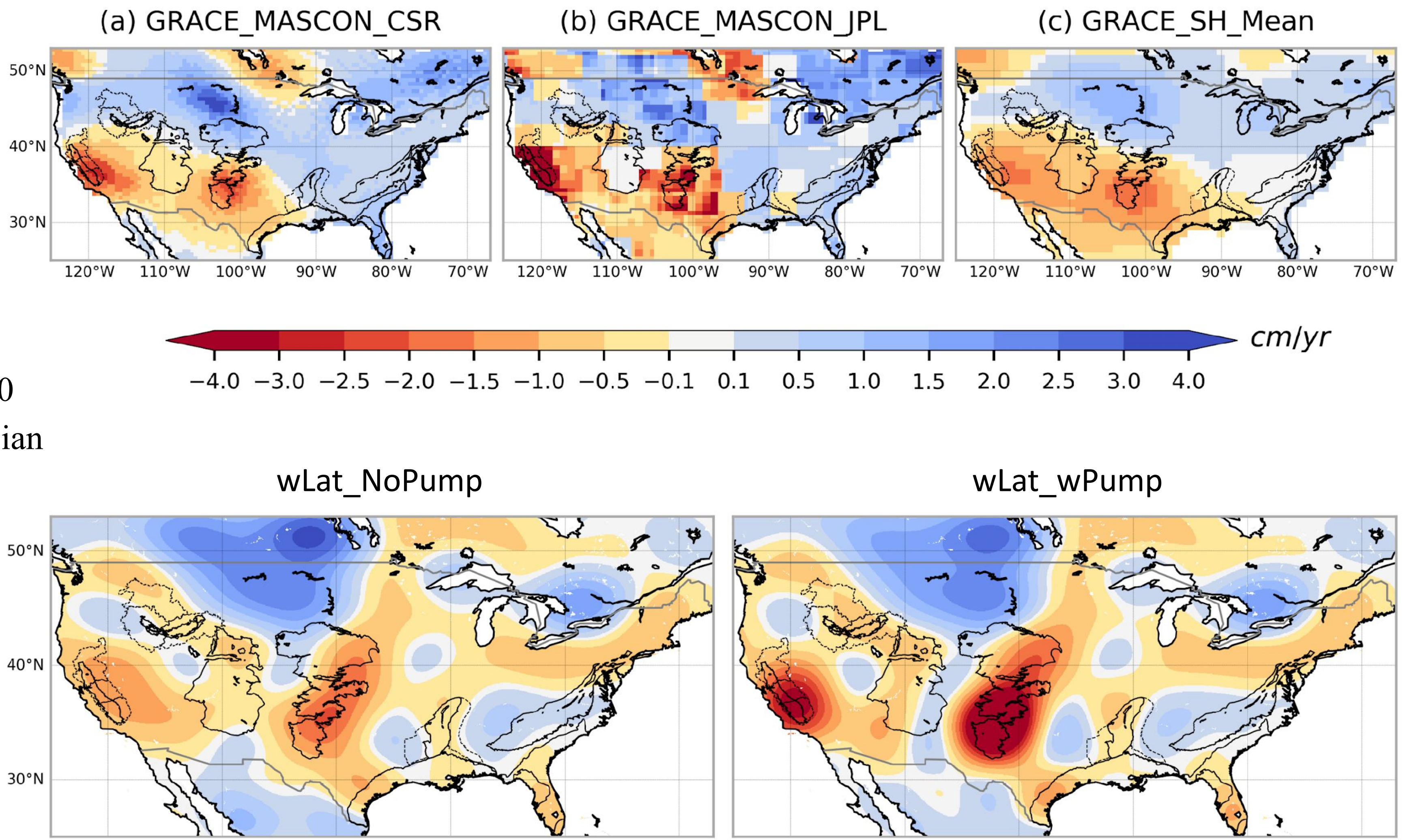
Mean Lateral Flow Fields





Terrestrial Water Storage Trend

- GRACE
  - 2005-2015 trend
  - Resolution 0.5° × 0.5° (MASCON); 1° × 1° (SH)
- Uncertainties in GRACE
- CLM
  - Transformed to SH domain
  - Truncated at degree and order 60
  - Smoothed by the 300-km Gaussian filter
- Lateral flow relatively insignificant at the GRACE spatial scale
- Overestimating the pumping-induced TWS depletion rate (e.g., over the HPA)
- Discrepancies across eastern U.S



Concluding Remarks

- New GW model
  - Equipped with pumping, lateral GW flow, and conjunctive use

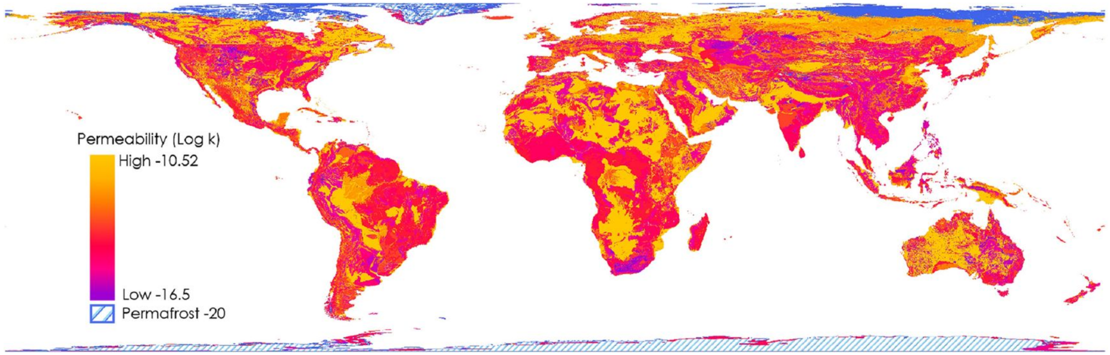
- Groundwater pumping
  - Improving the simulation of GW level change (spatial and temporal)
  - Capturing most of the hotspots of GW depletion
  - Capturing the GRACE-detected downward trend in areas such as the CVA
  - Overestimation of declining TWS trend where groundwater supplies the majority of irrigation water use (such as HPA)

- Lateral GW flow
  - Improved subsurface response to pumping
  - Smoothening the pixelated groundwater-level change to form a cone of depression
  - The impact is not substantial at the basin scale or coarse grids

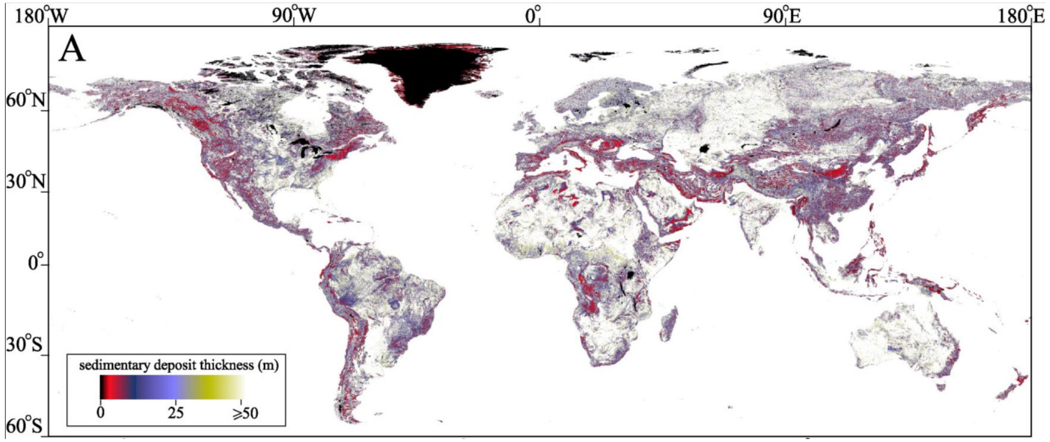
Path Forward …

- Leverage newly available datasets: global aquifer properties, permeability, DTB

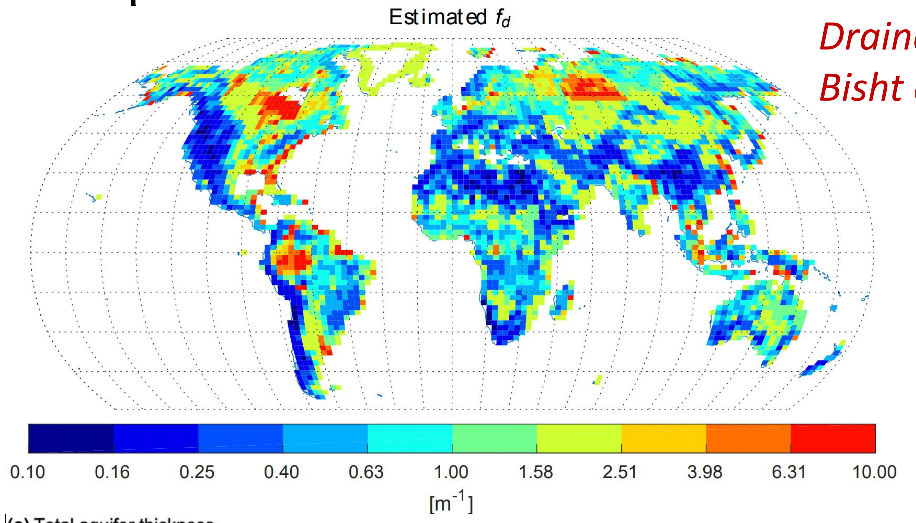
Permeability,
Huscroft et al. (2018); Gleeson et al. (2014)



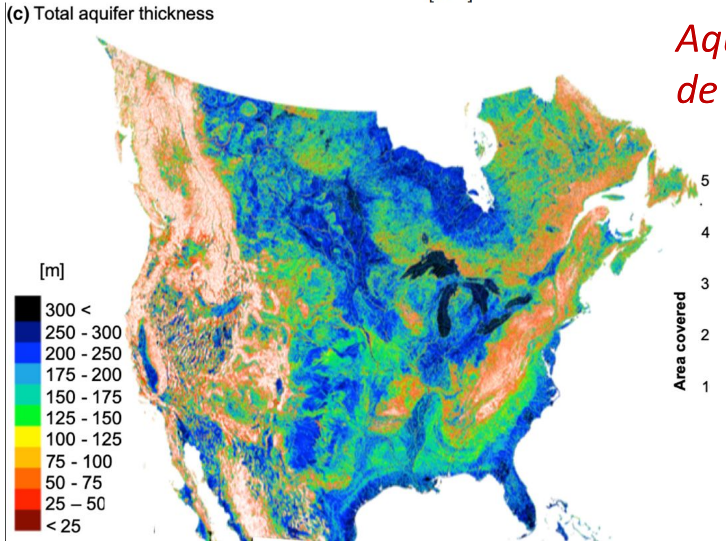
Depth to bedrock (DTB),
Pelletier et al. (2016)



- Pumping impacts on river discharge
  - Spatial calibration of the subsurface runoff parameters



Drainage Parameter,
Bisht et al. (2018)



Aquifer Thickness, Conductivity
de Graaf et al. (2020)