

Workshop IGEM

*“Impact of Groundwater in Earth System Models”*

October 3-5 2016 in Paris

# Fate of water pumped from underground and contributions to sea level rise

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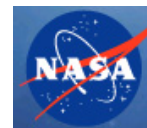
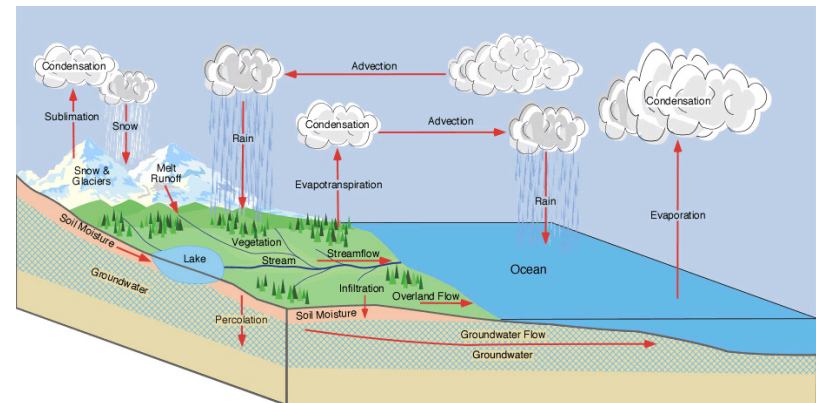
**James S. Famiglietti**

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NASA Goddard Institute for Space Studies  
International Institute for Applied Systems Analysis  
National Taiwan University  
National University of Singapore  
NASA Jet Propulsion Laboratory, California  
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University of California, Irvine  
National Center for Atmospheric Research

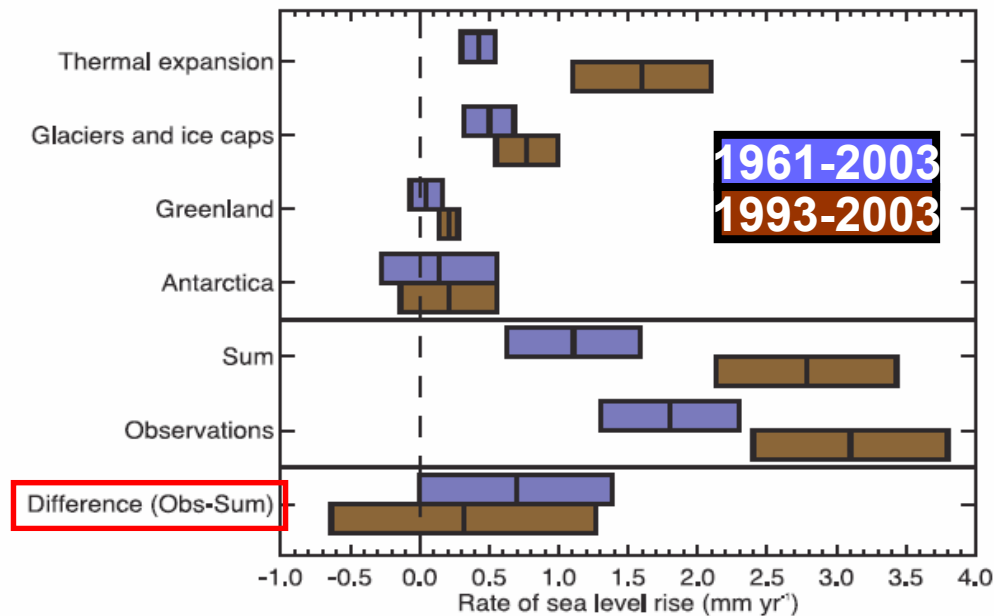
**Universiteit Utrecht**



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Goddard Institute for Space Studies



# Land Water Contribution to Sea Level?



**IPCC AR3:**

Terrestrial water storage change is a non-negligible component...

**IPCC AR4:**

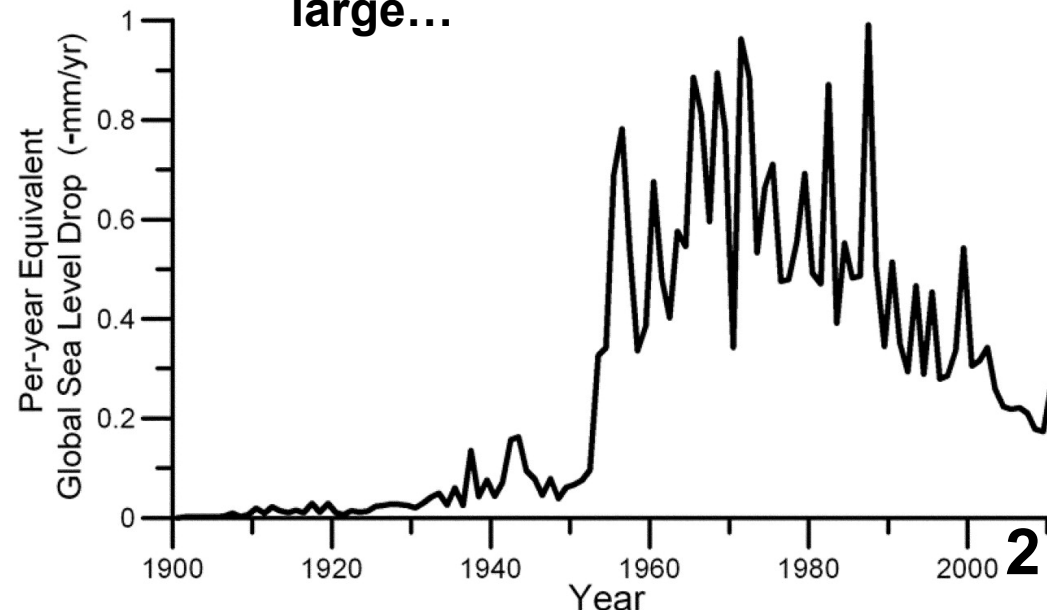
Terrestrial water storage contributions are poorly known and are omitted...

**IPCC AR5:**

Included but uncertainty remains large...

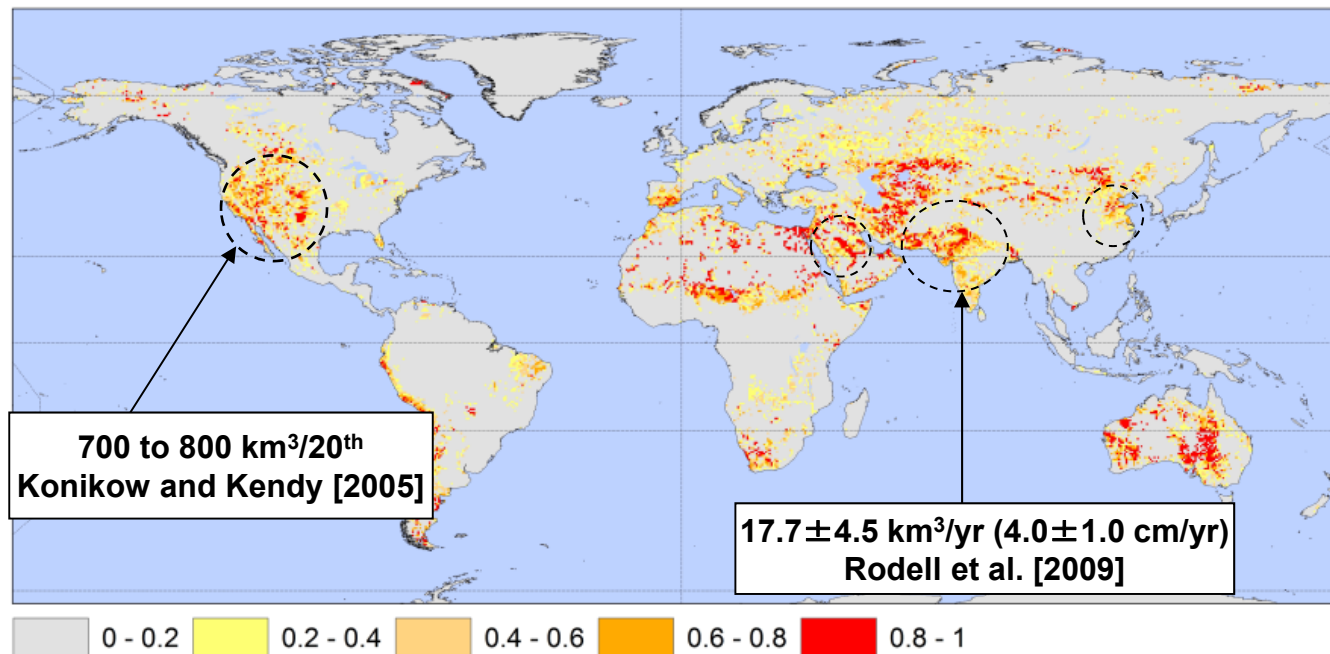
Chao et al. (2008; *Science*) estimated a negative contribution of -30 mm due to reservoir impoundment over the period 1900-2007

Any other missing?

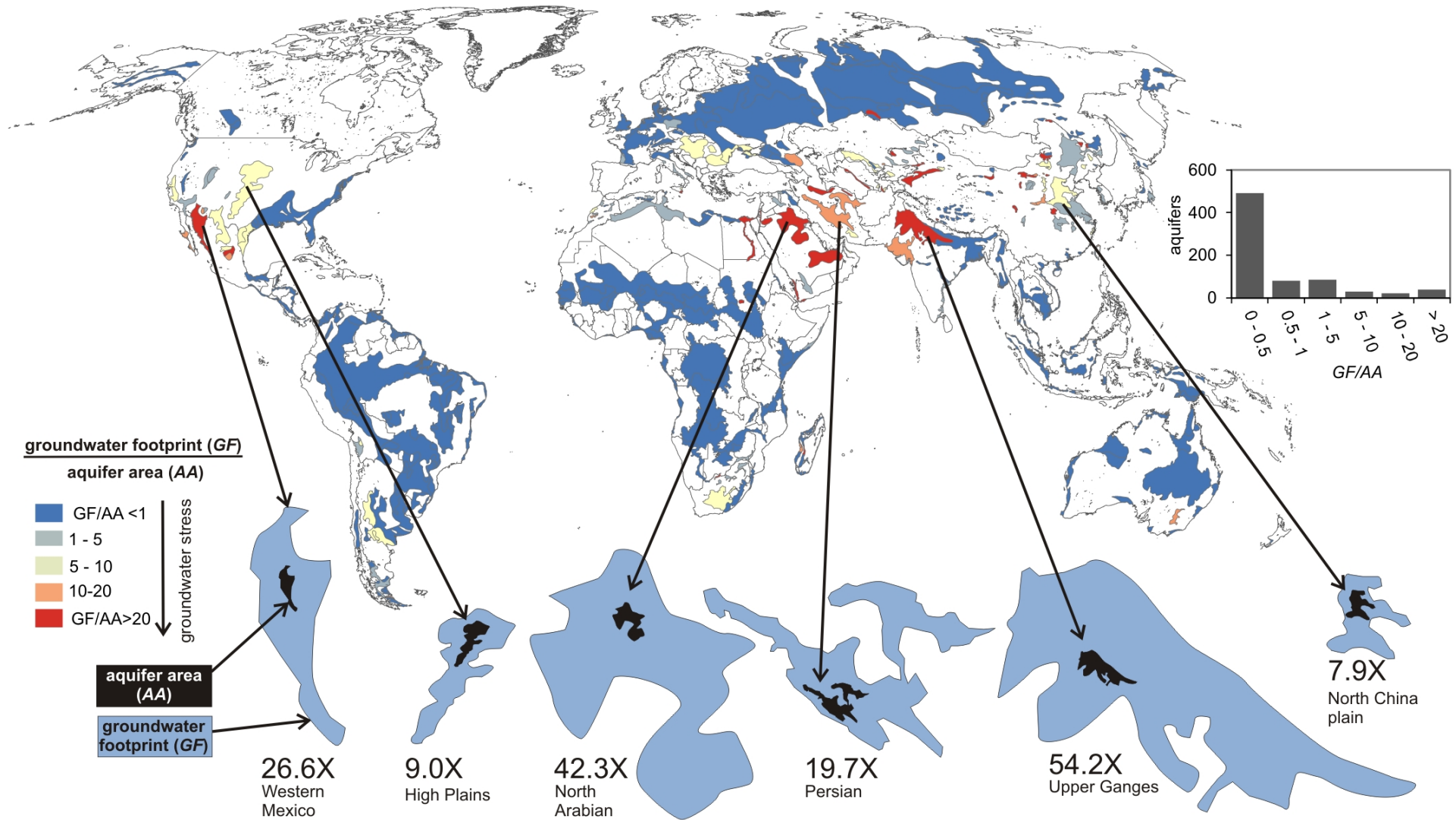


# Groundwater extraction

- Water demand is increasing due to population growth and food demand.
- Surface freshwater availability is often not enough to meet the demand (e.g., irrigation) in many (semi-)arid regions of the world.
- Additional water is mostly found by groundwater abstraction.
- Abstraction exceeds recharge over prolonged periods  
=> **Depletion**
- Increasing reliance of human water use on nonrenewable groundwater resources worldwide



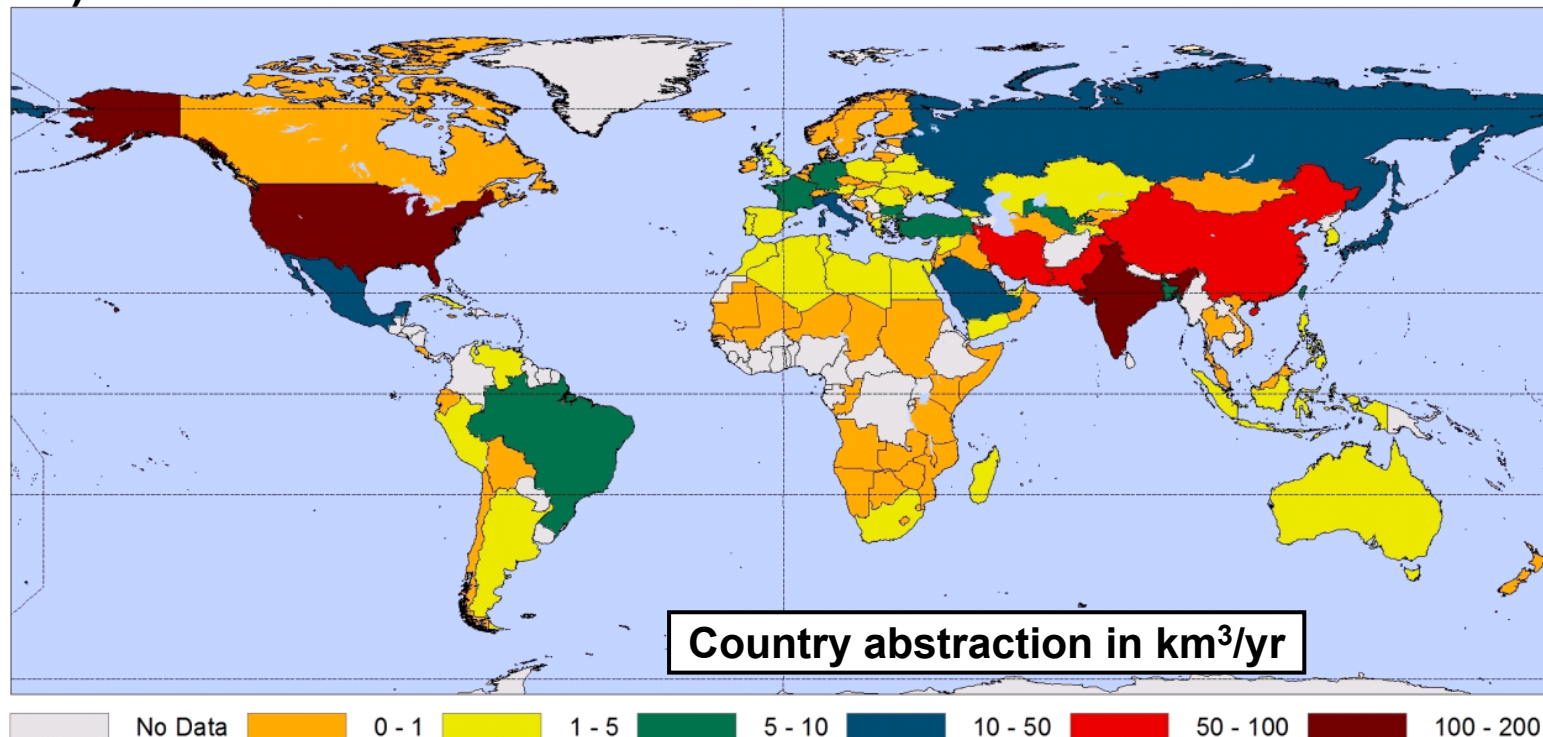
# Global groundwater footprint



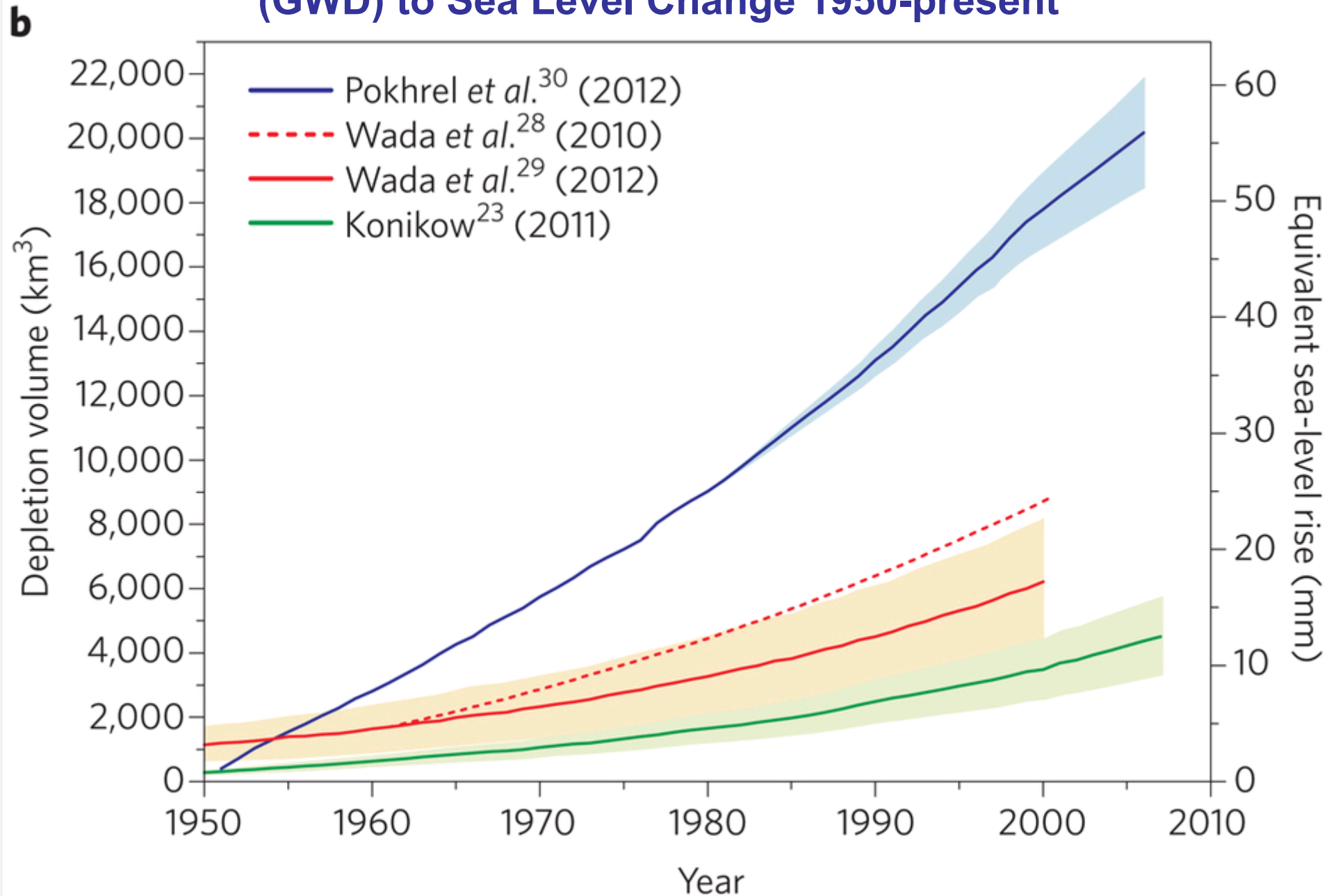


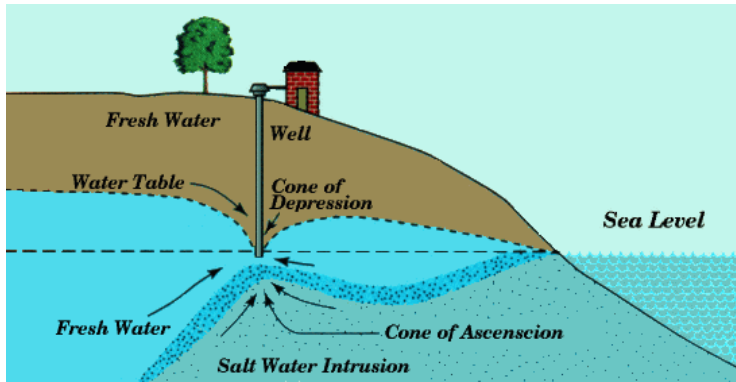
# Contribution of Groundwater Depletion to Sea Level?

- Global groundwater abstraction amounts to 800 km<sup>3</sup> for 2000.
- Nearly 90% is used for irrigation.
- In many (semi-)arid regions, abstraction exceeds recharge over long periods, which results in groundwater depletion (GWD).
- Depleted groundwater ends up in ocean predominantly through evapotranspiration and precipitation (net transfer of fossil water to ocean)??



## Other Estimates of Contribution of Groundwater Depletion (GWD) to Sea Level Change 1950-present

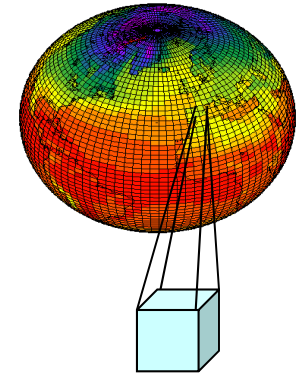




# How to estimate?

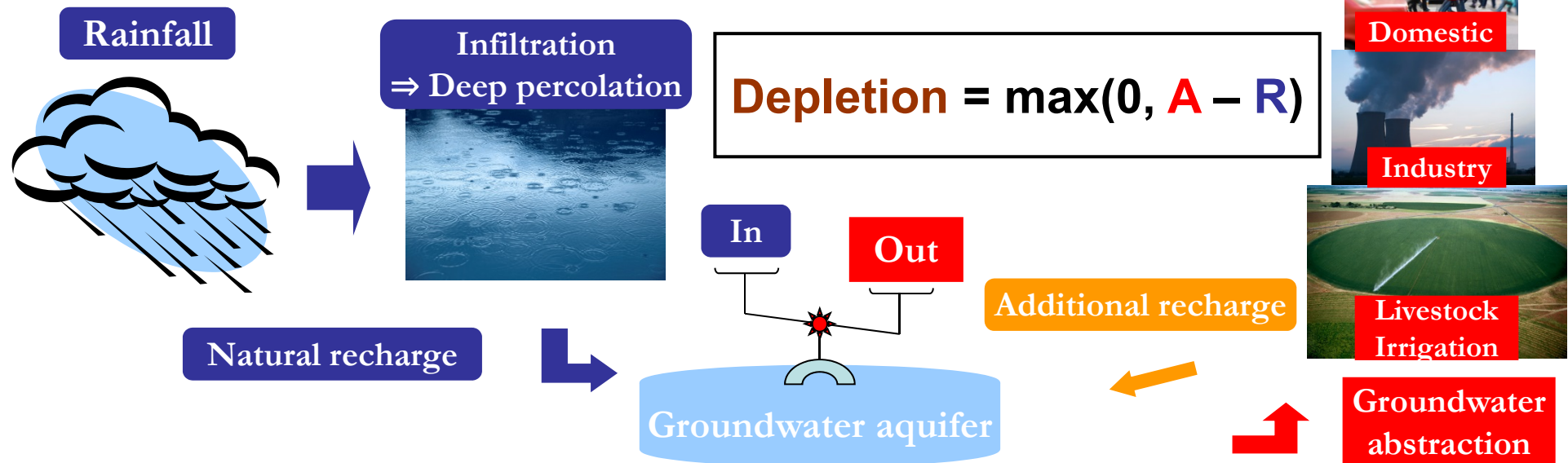
## Flux-based method:

- Use a global hydrological model to simulate groundwater recharge
- Estimate groundwater abstraction



0.5° (50 km by 50 km)

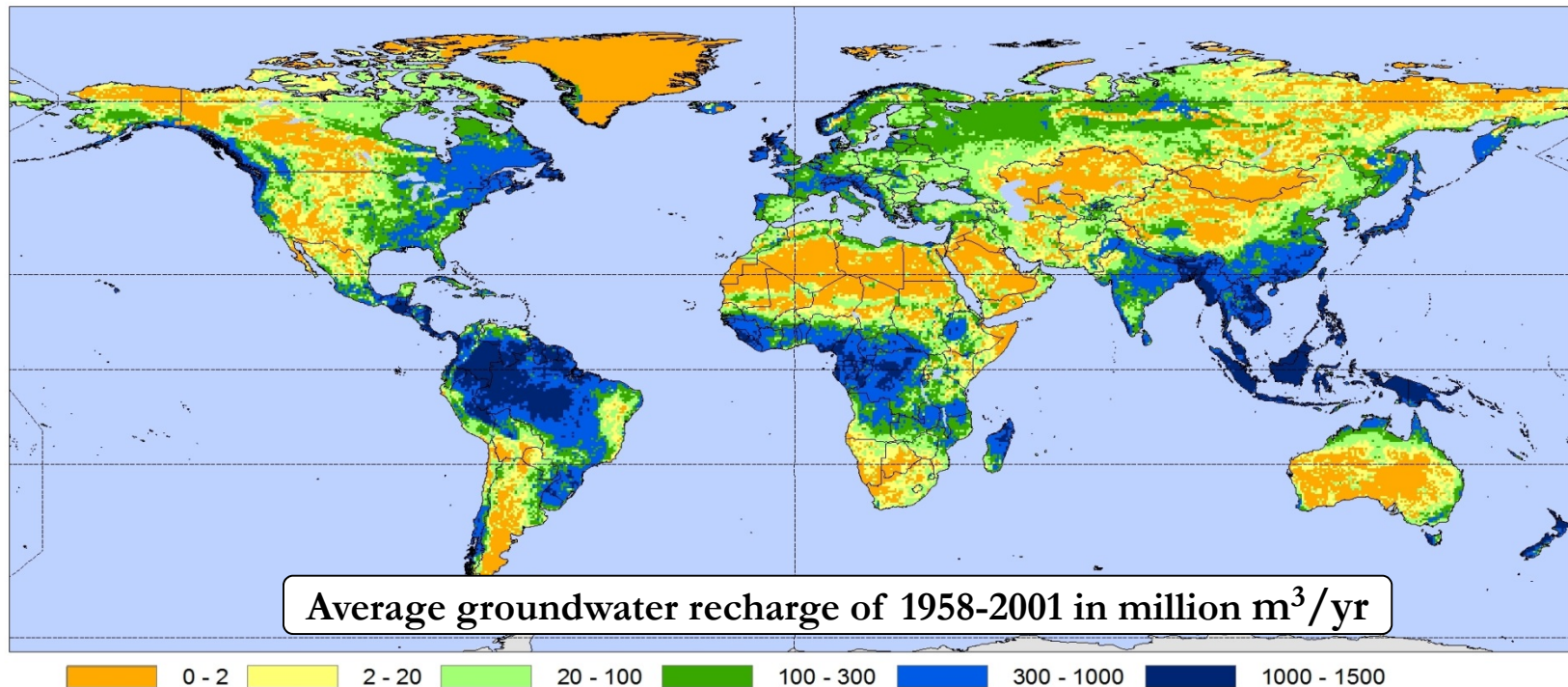
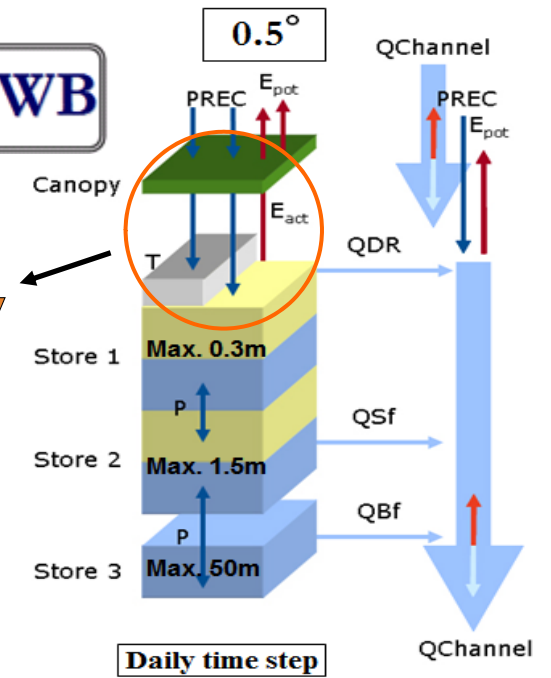
where **Abstraction (A)** >> **Recharge (R)**



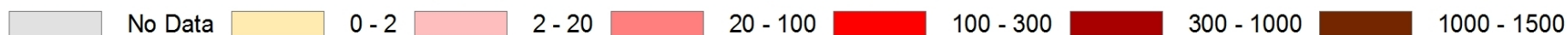
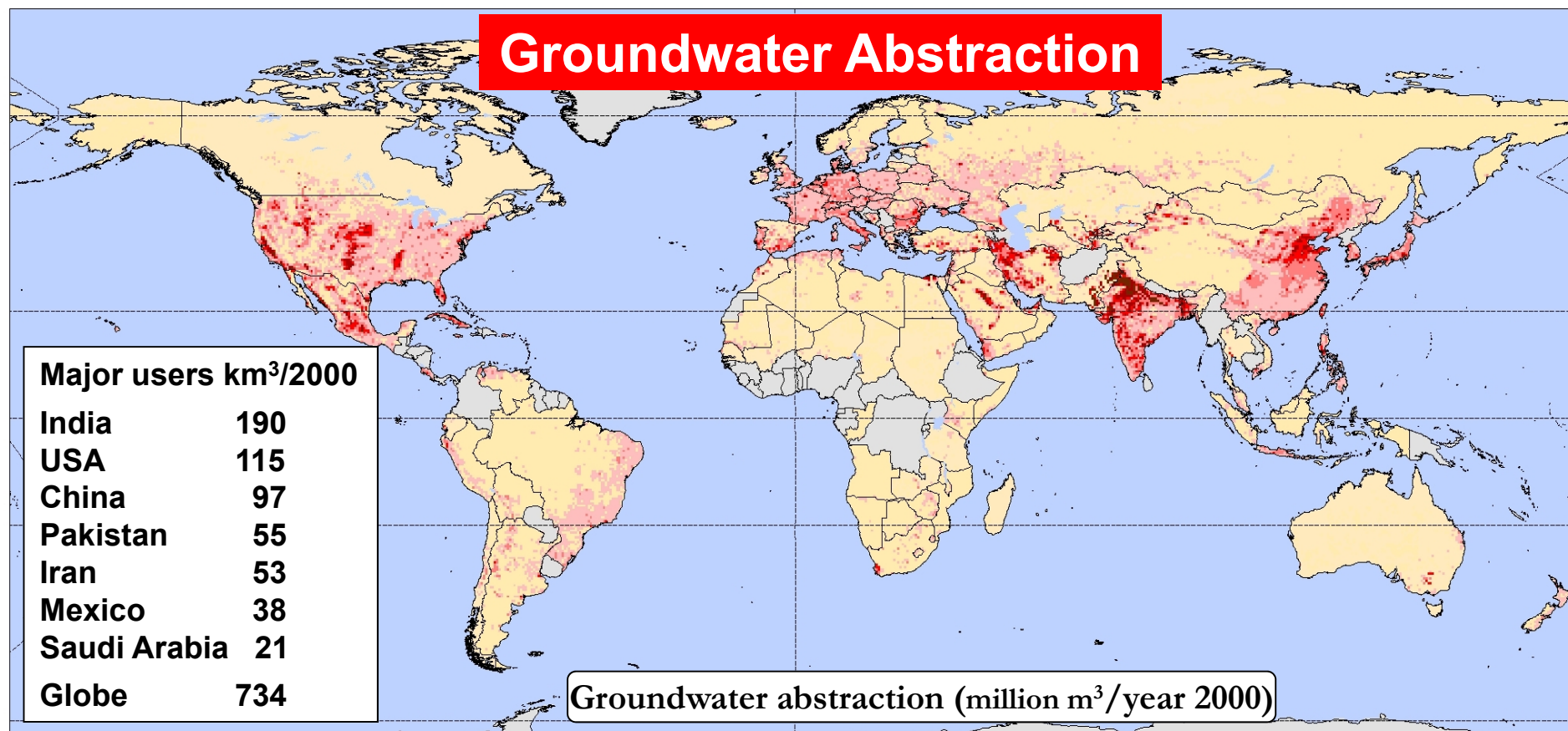
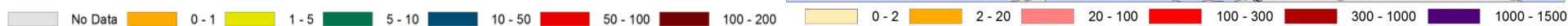
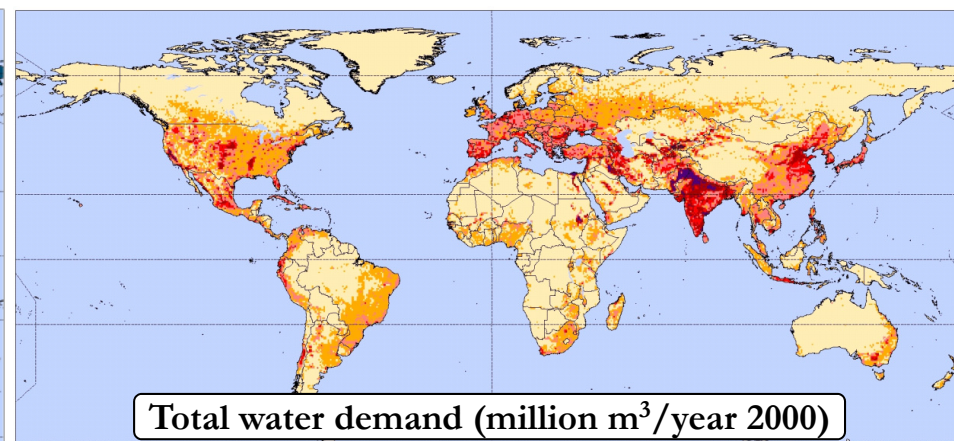
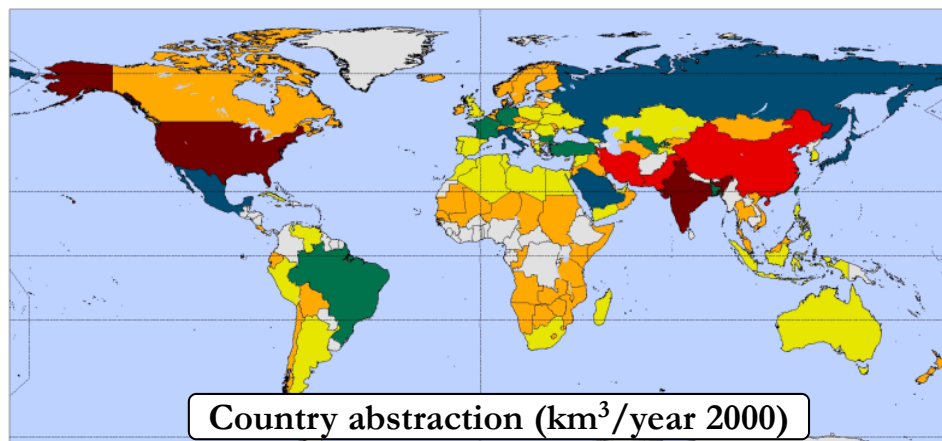
PCR-GLOBWB

**( Sub-grid variability )**

A vibrant, stylized illustration of a landscape. In the foreground, a bright blue river flows from the bottom right towards the center. To the left of the river is a small, light blue pond with green lily pads. The background features a range of yellow and brown mountains under a clear blue sky. Several large, green, rounded trees are scattered across the landscape, some on the left and some on the right. The entire scene is set against a light blue background with a subtle grid pattern.



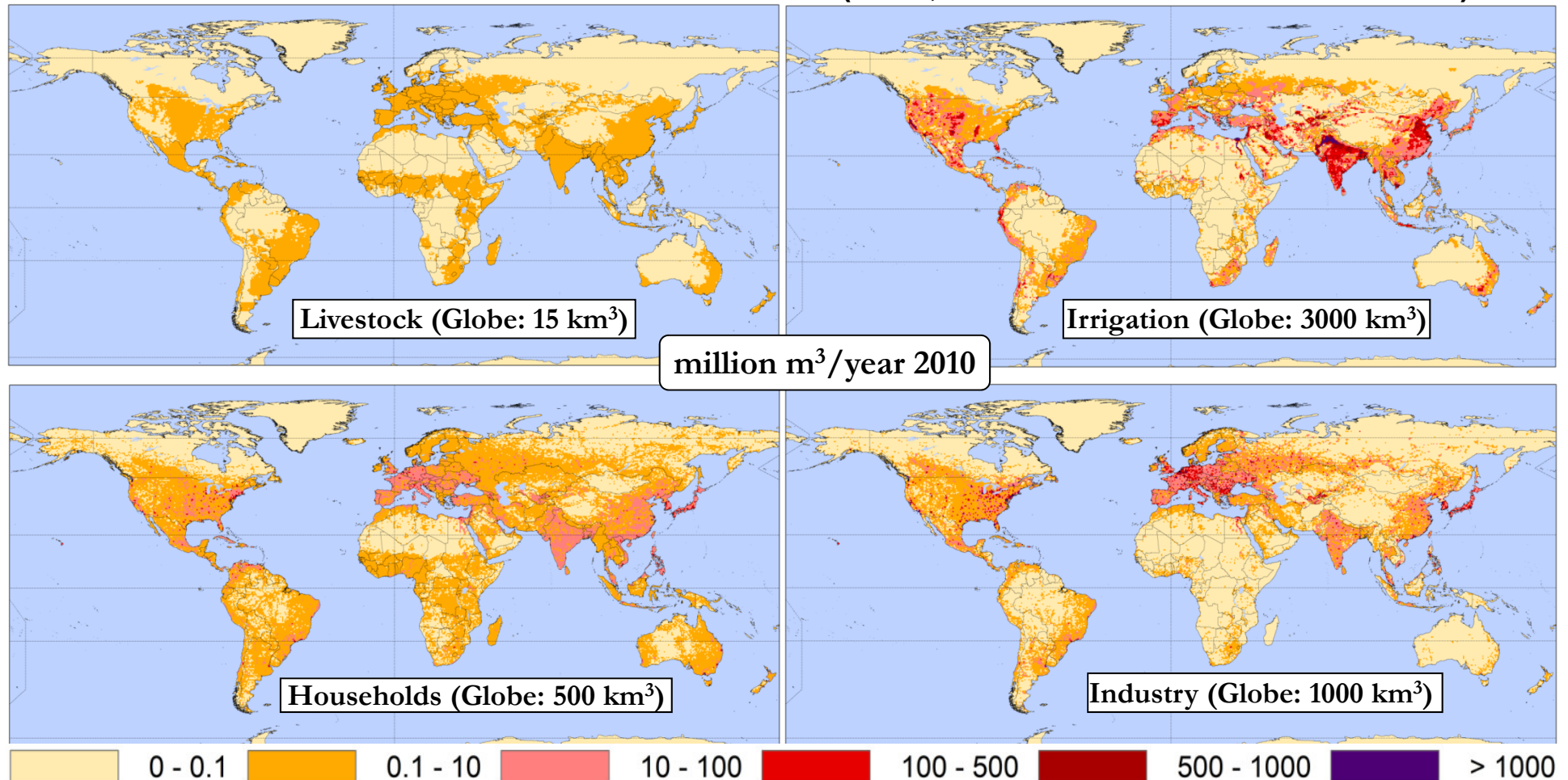




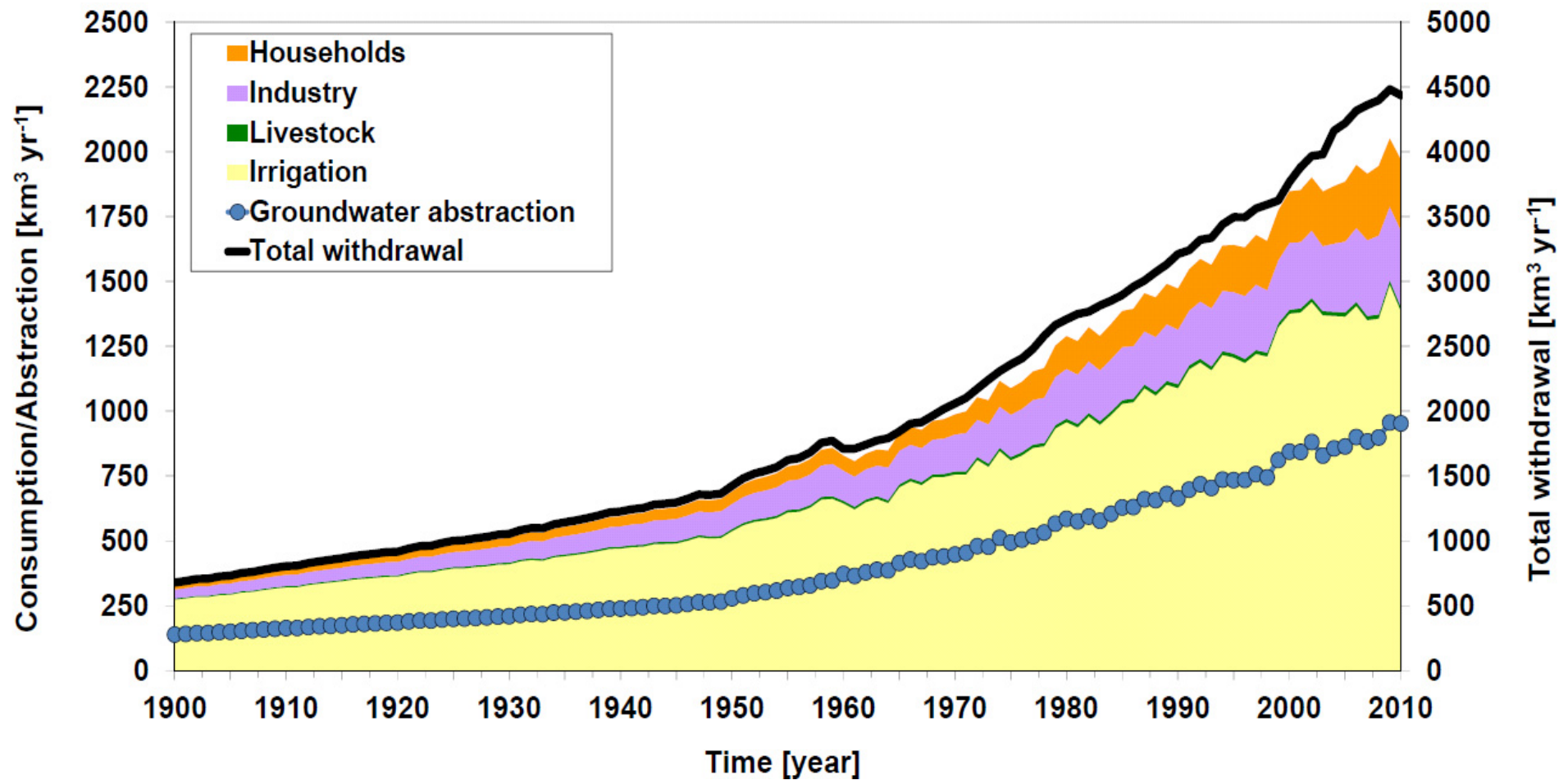
# Water demand

- **Livestock:** Cattle, buffalo, sheep, goats, pigs and poultry
- **Irrigation:** Daily surface and soil water balance with irrigation losses
- **Industry:** GDP, Electricity production, and energy consumption with water recycling
- **Households:** Per capita water use and population with people access to water

Wada et al. (2013; Environmental Research Letter)

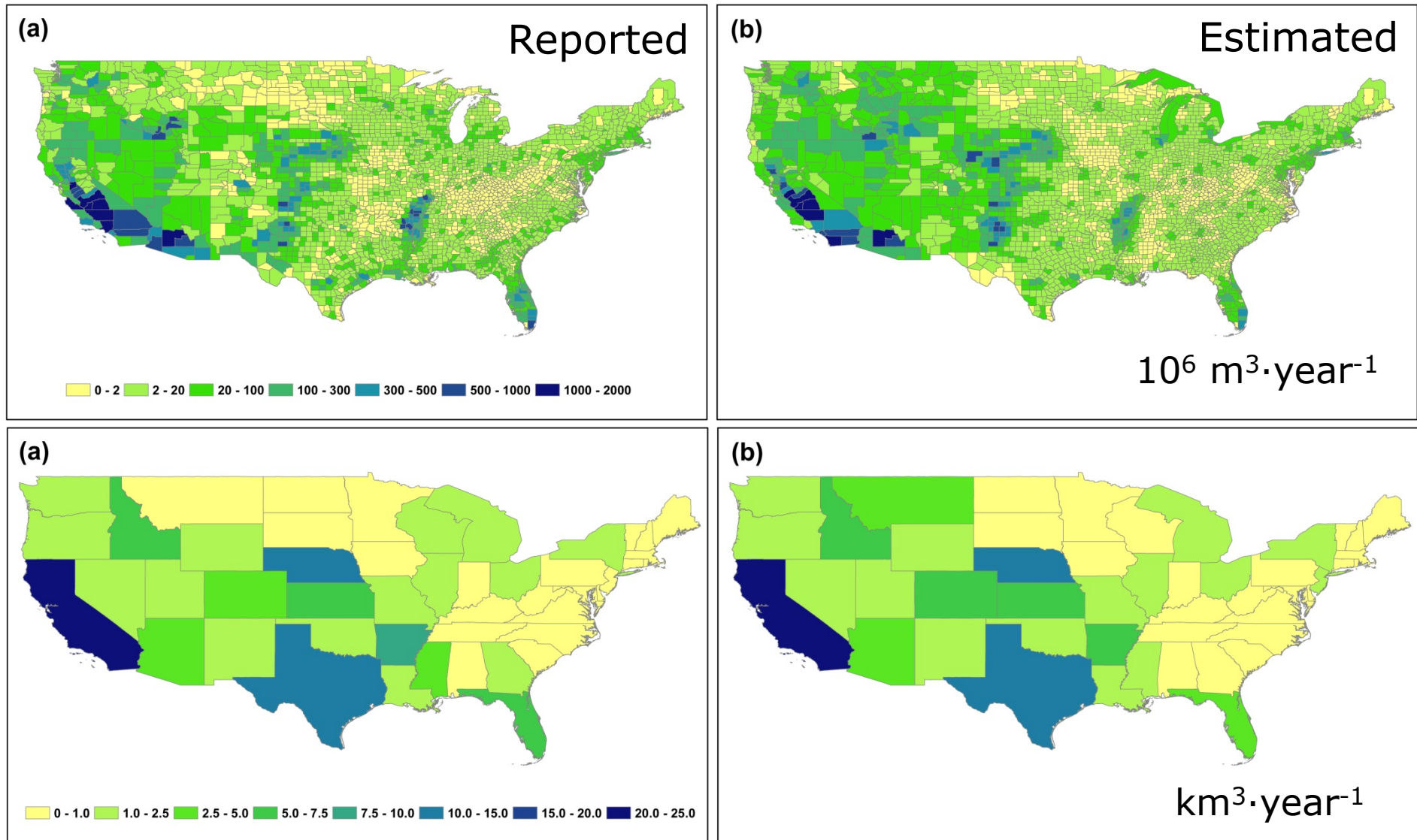


# 20th and Early 21st Century Groundwater and Surface Water Use



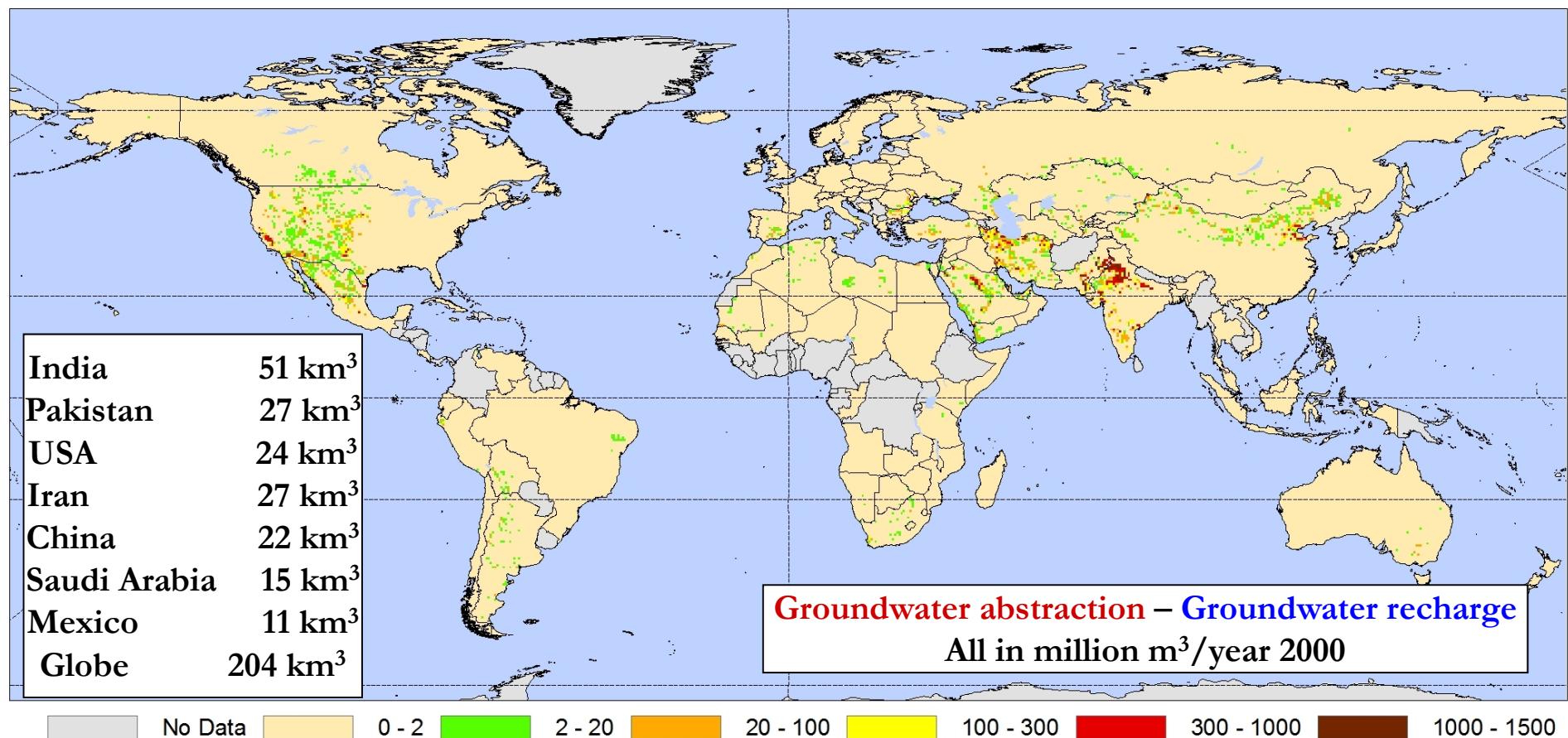
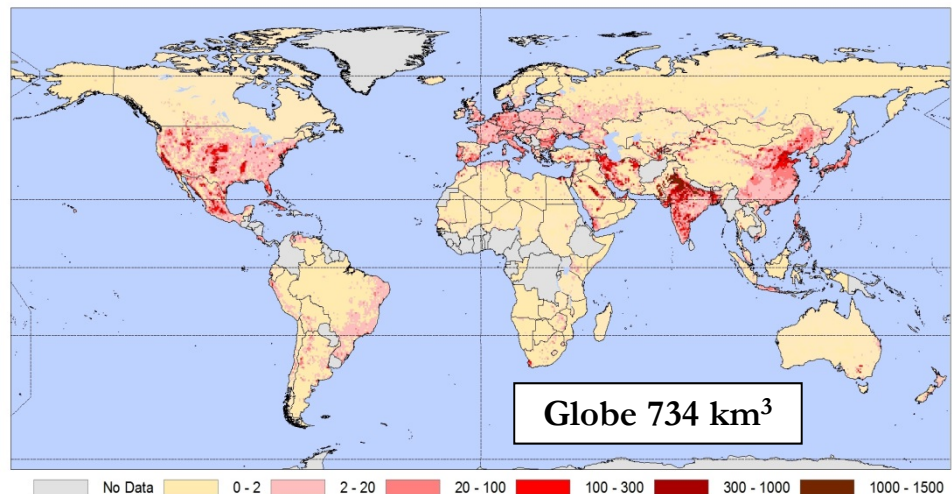
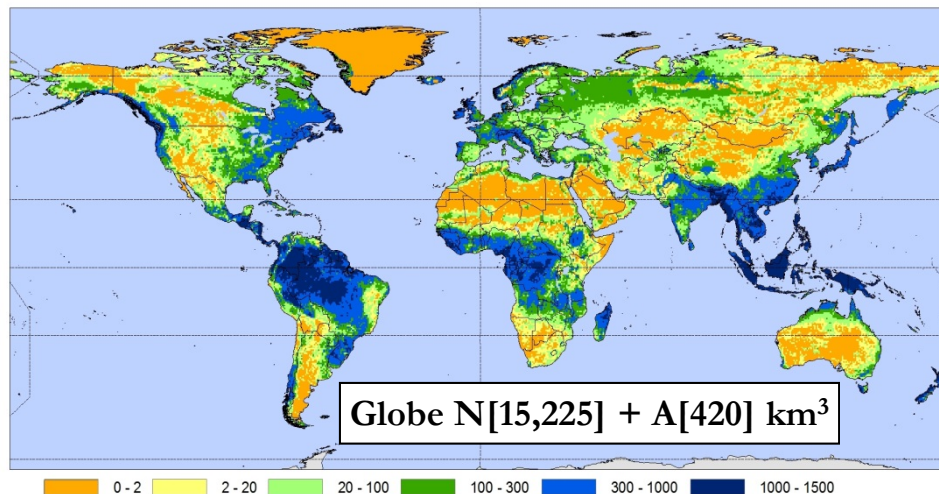


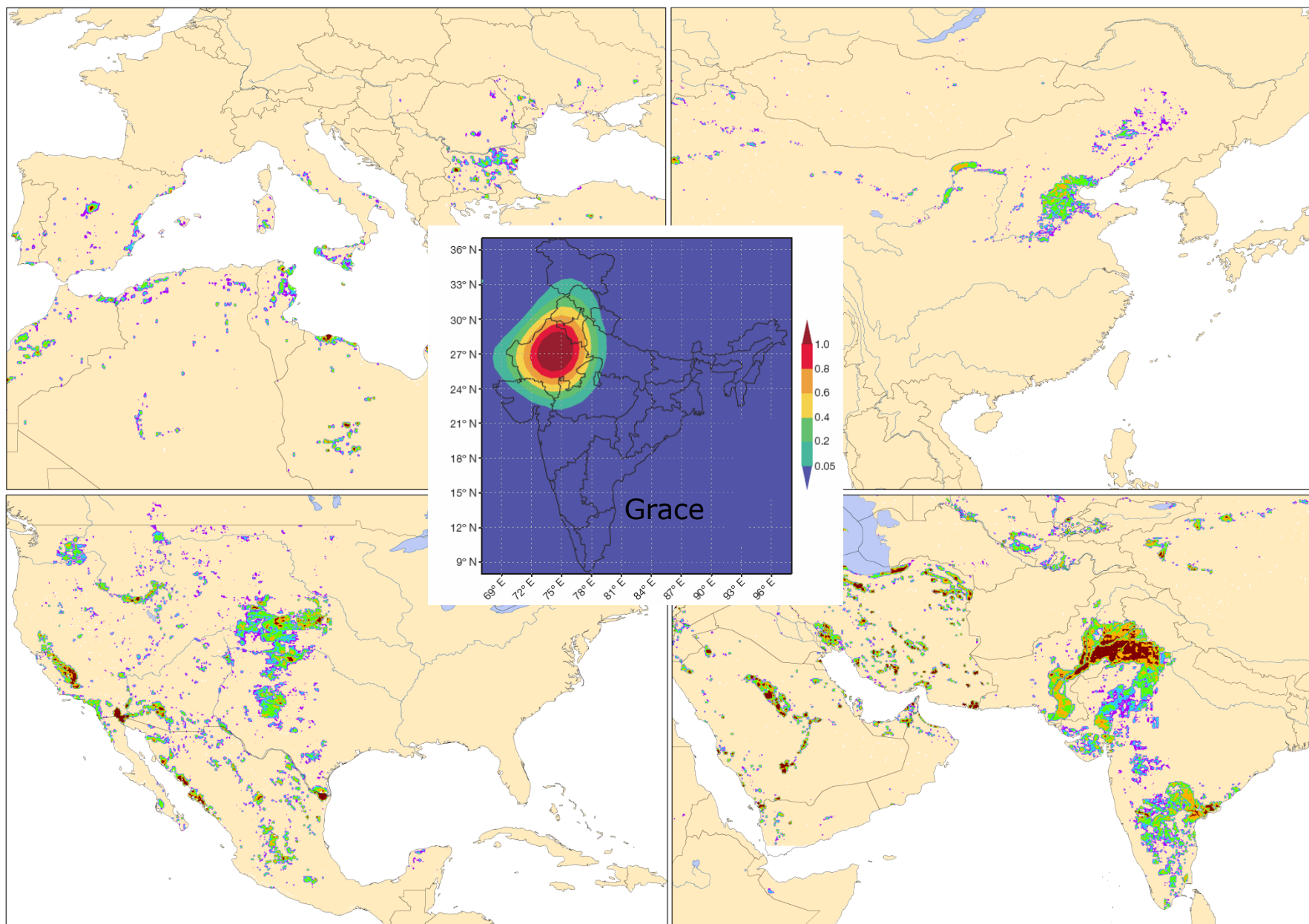
# Validation: Groundwater abstraction



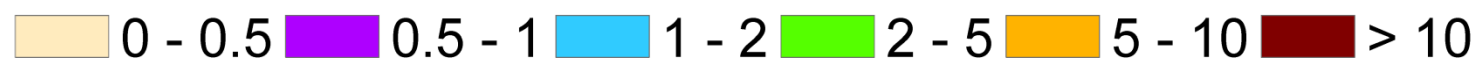
Comparison of reported and estimated groundwater abstraction for 2000: USA county and state level (USGS).

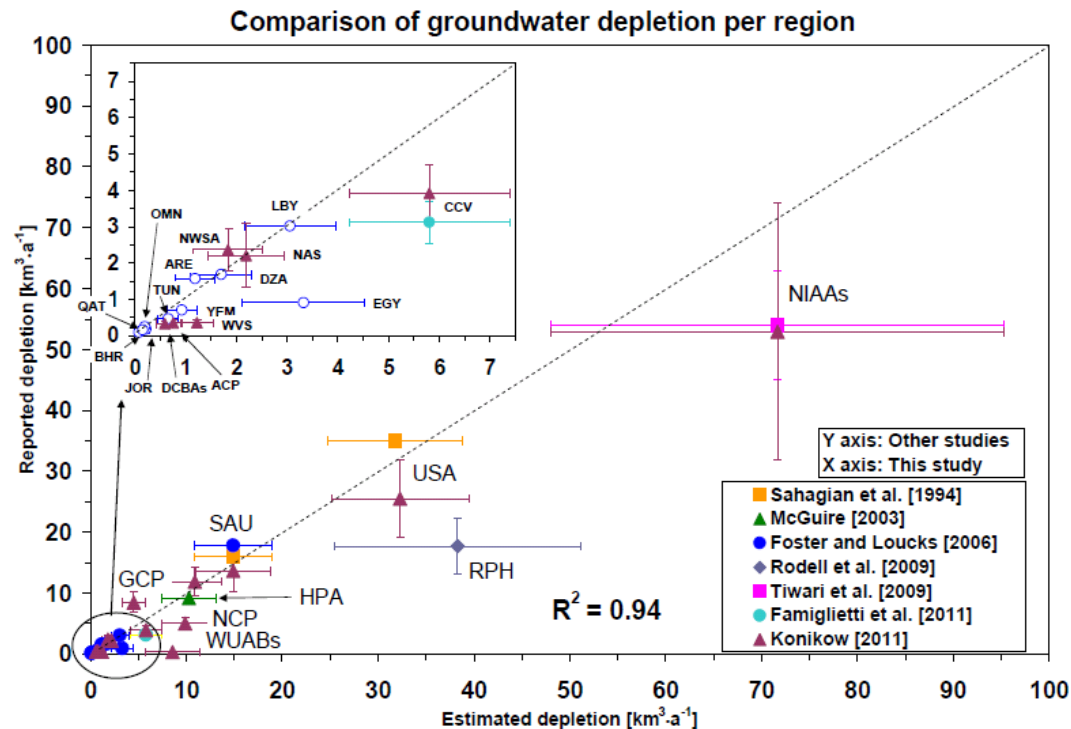






**Groundwater depletion [million cubic meter per year]**





## Validation

Compare to independent, mostly volume-based, estimates

## Correction

Our estimates tend to overestimate depletion in non-arid regions

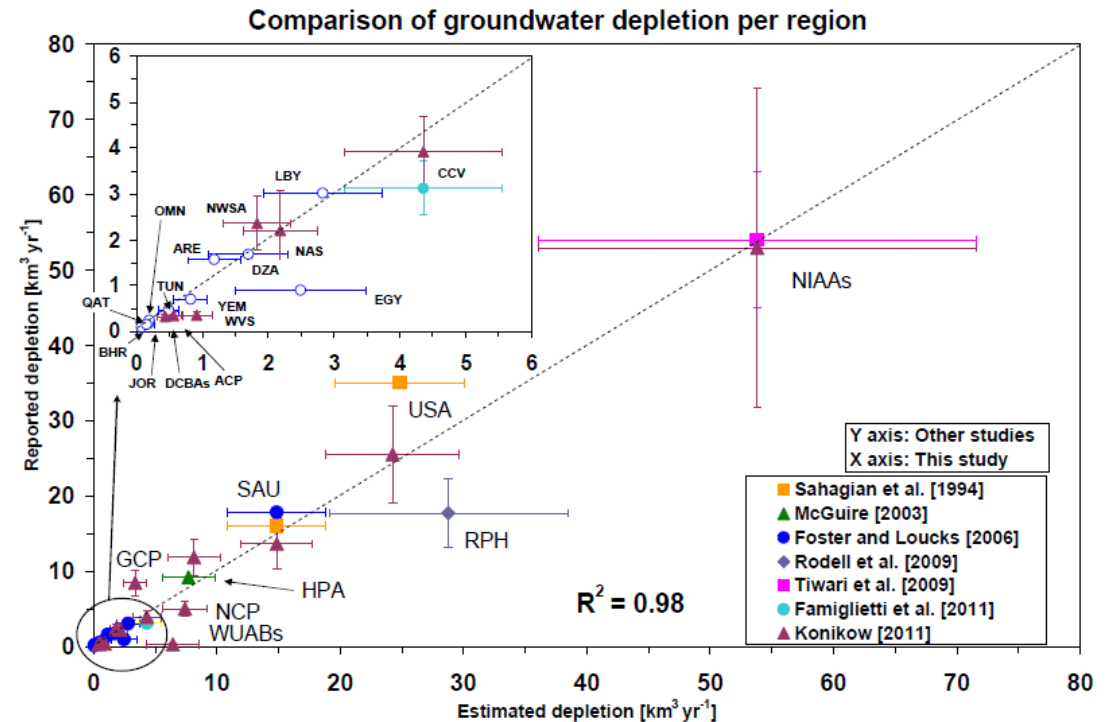
**Global total (year 2000)**

**This study:  $204 \text{ km}^3/\text{year}$**

**$= 0.57 \text{ mm/year}$**

**Konikow (2011):  $145 \text{ km}^3/\text{year}$**

**$= 0.40 \text{ mm/year}$**

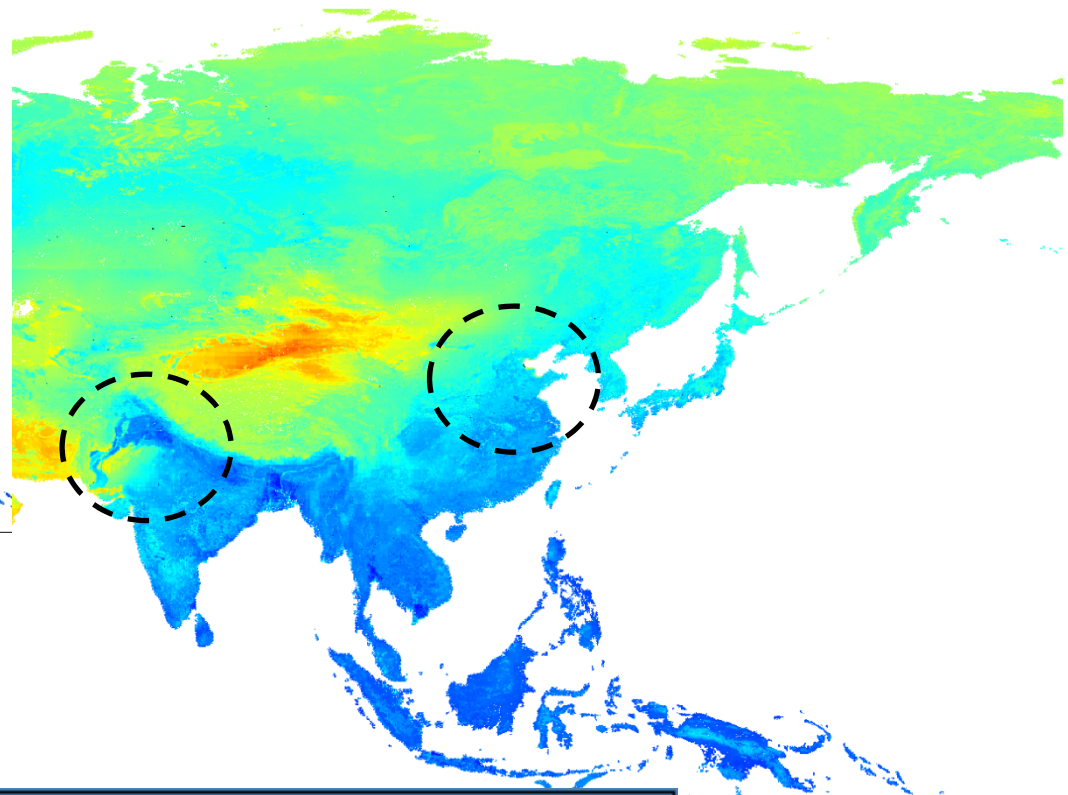
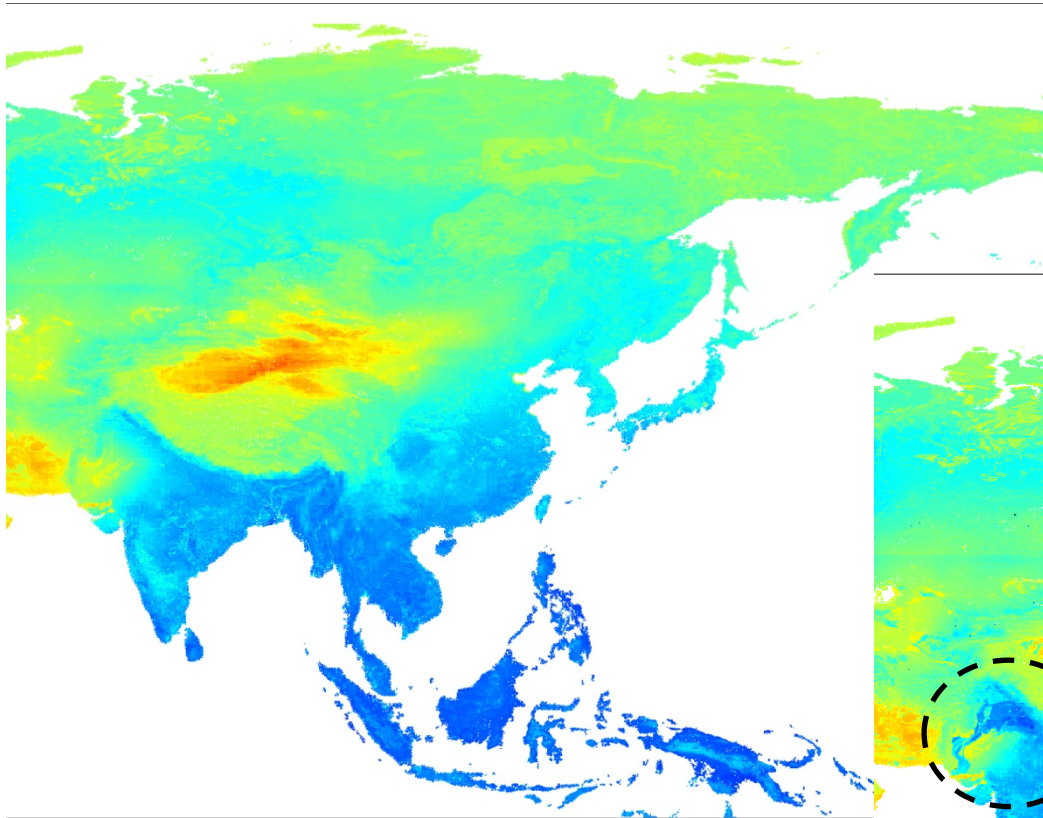




# Anthropogenic effects on the global water cycle

Enhanced evapotranspiration

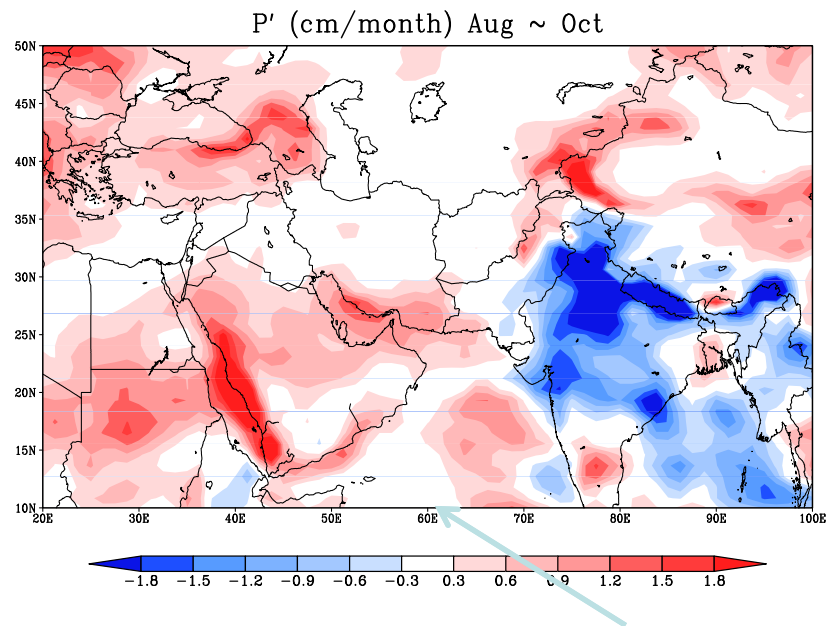
Change in regional precipitation?  
with NASA-GISS and NCAR



Pristine vs. Humans

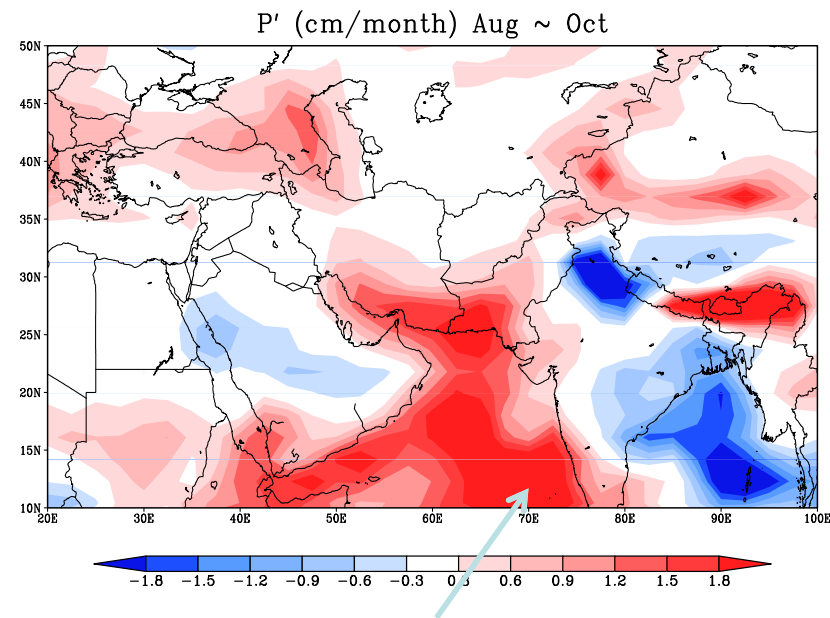




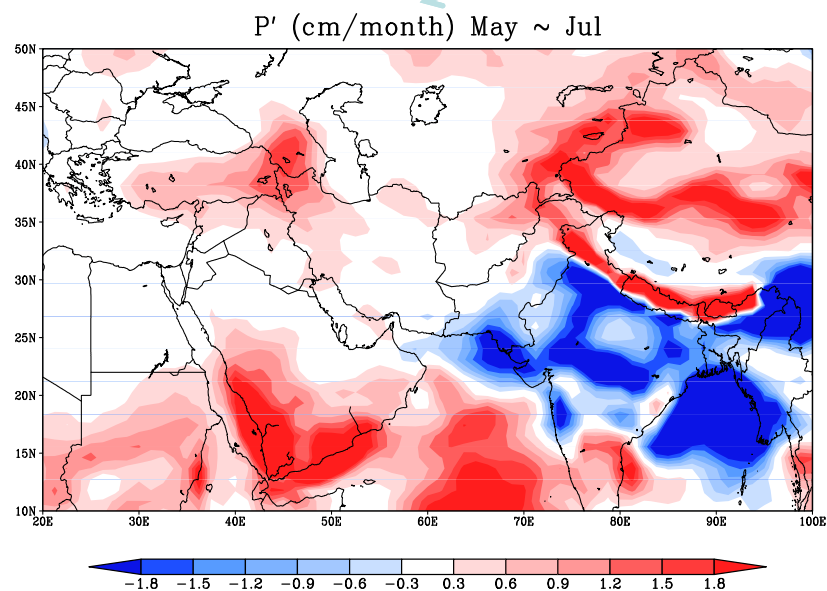


Aug, Sep, and Oct

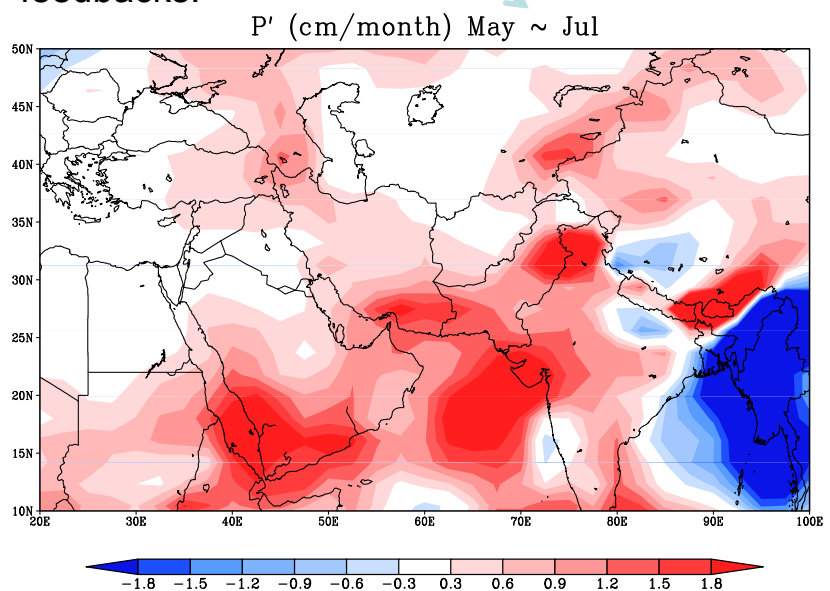
(a) the steady state runs (using the irrigation water from the last 10 years) and compare to that without irrigation water applied. Sea surface temperature is prescribed at climatology.

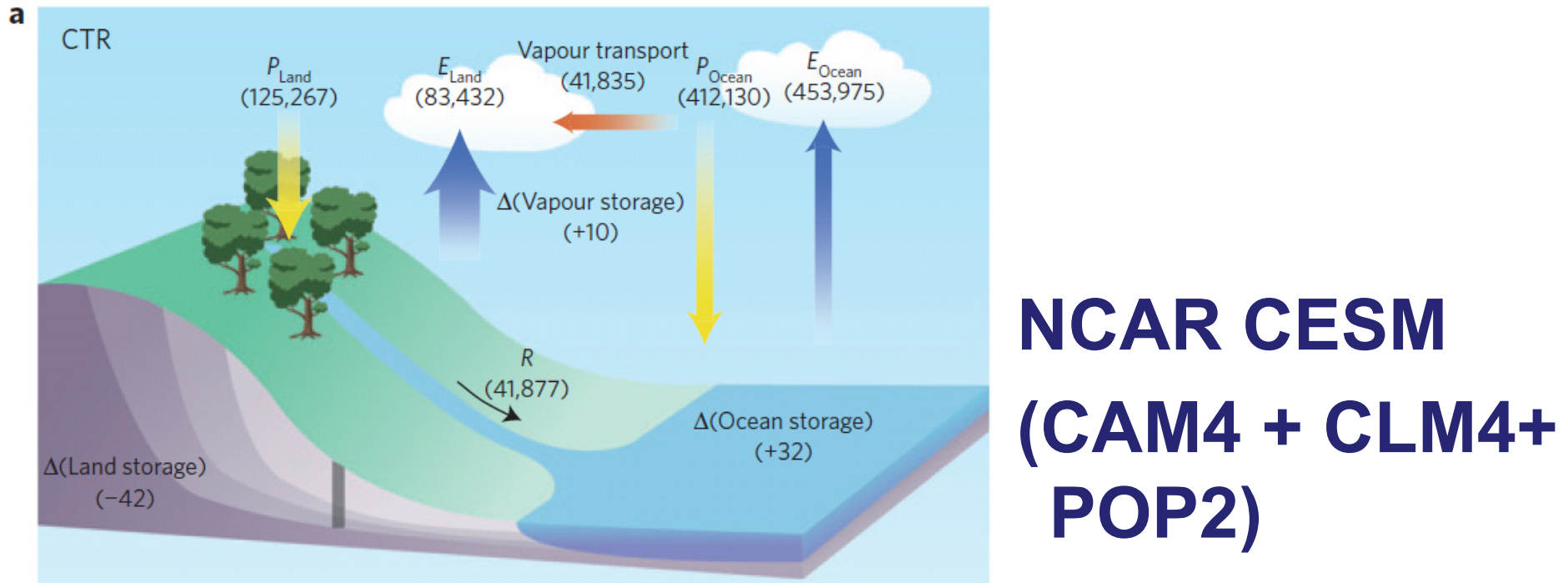


(b) transient runs (using the irrigation water from 1960~2010, and compare to that without irrigation water applied), in this case, the ocean mode is activated so there will be ocean feedbacks.

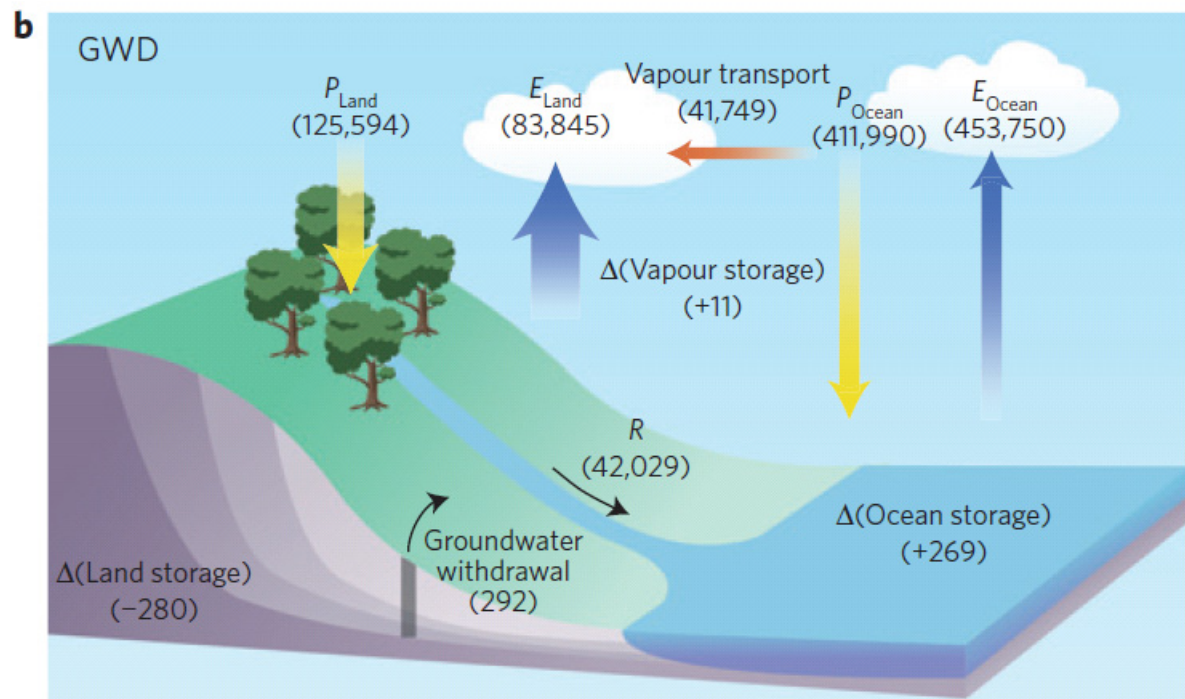


May, Jun, and Jul





**Coupled  
land  
-atmospheric  
simulation**



## Global mean annual water budget over the land and ocean (km<sup>3</sup>/yr)

	Precipitation ( $P$ )	Runoff ( $R$ )	Evaporation ( $E$ )	Total storage change ( $\Delta S$ )	Precipitation minus evaporation	Atmospheric water vapour change
Land				$P - R - E$	$P - E$	
(1) GWD	125,594	42,029	83,845	-280	41,749	-
(2) CTR	125,267	41,877	83,432	-42	41,835	-
(3) GWD-CTR	+327	+152	+413	-238	-86	-
Ocean				$P + R - E$	$P - E$	-
(1) GWD	411,990	42,029	453,750	+269	-41,760	-
(2) CTR	412,130	41,877	453,975	+32	-41,845	-
(3) GWD-CTR	-140	+152	-225	+237	+85	-
Global						
(1) GWD	-	-	-	-	-	+11
(2) CTR	-	-	-	-	-	+10

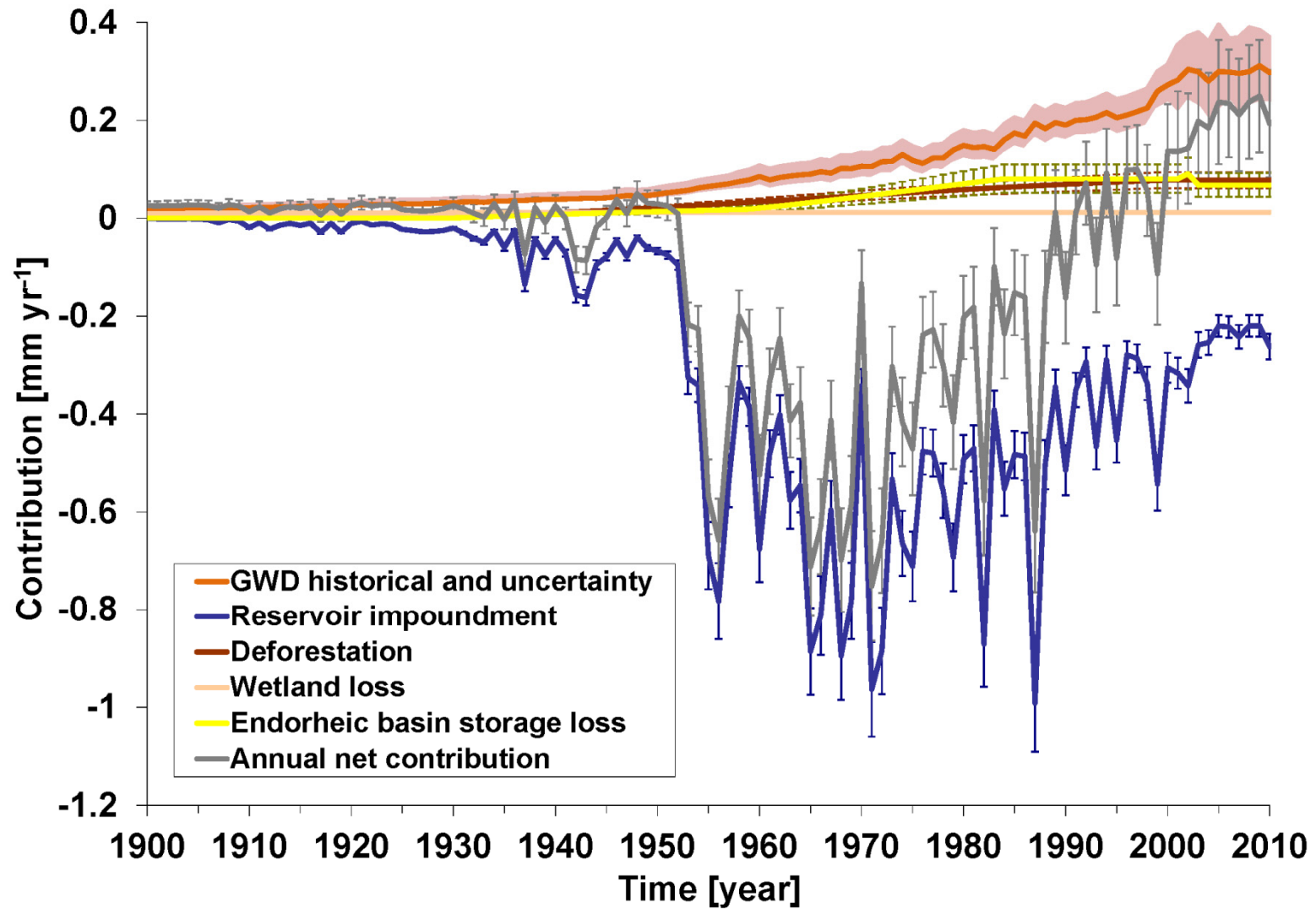
## Global sea-level budget compared to IPCC AR5

Component	Comparison	1971-2010 (mm yr <sup>-1</sup> )	1993-2010 (mm yr <sup>-1</sup> )
Observed SLR		2.0 (±0.3)	3.2 (±0.4)
Observed			
Thermal expansion		0.8 (±0.3)	1.1 (±0.3)
Glaciers except in Greenland and Antarctica		0.62 (±0.37)	0.76 (±0.37)
Glaciers in Greenland		0.06 (±0.03)	0.10 (±0.03)
Greenland ice sheet			0.33 (±0.08)
Antarctica ice sheet			0.27 (±0.12)
Modelled			
Thermal expansion		0.96 (±0.45)	1.49 (±0.53)
Glaciers except in Greenland and Antarctica		0.62 (±0.22)	0.78 (±0.35)
Glaciers in Greenland		0.10 (±0.05)	0.14 (±0.09)
Land water storage	IPCC AR5	0.12 (±0.09)	0.38 (±0.12)
	This study	−0.10 (±0.03)	0.12 (±0.04)
Total including land water storage	IPCC AR5	1.8 (±0.5)	2.8 (±0.7)
	This study	1.58 (±0.4)	2.53 (±0.6)
Residual	IPCC AR5	0.2 (±0.6)	0.4 (±0.8)
	This study	0.42 (±0.6)	0.67 (±0.8)



# Net Contribution from TWS Change to Sea Level 1900-2010

Wada et al. (2016; Nature Climate Change)



**2010**

(a)

# Human water consumption

Wada and Bierkens

(2014; ERL)

In cooperation with

IIASA for WFaS project

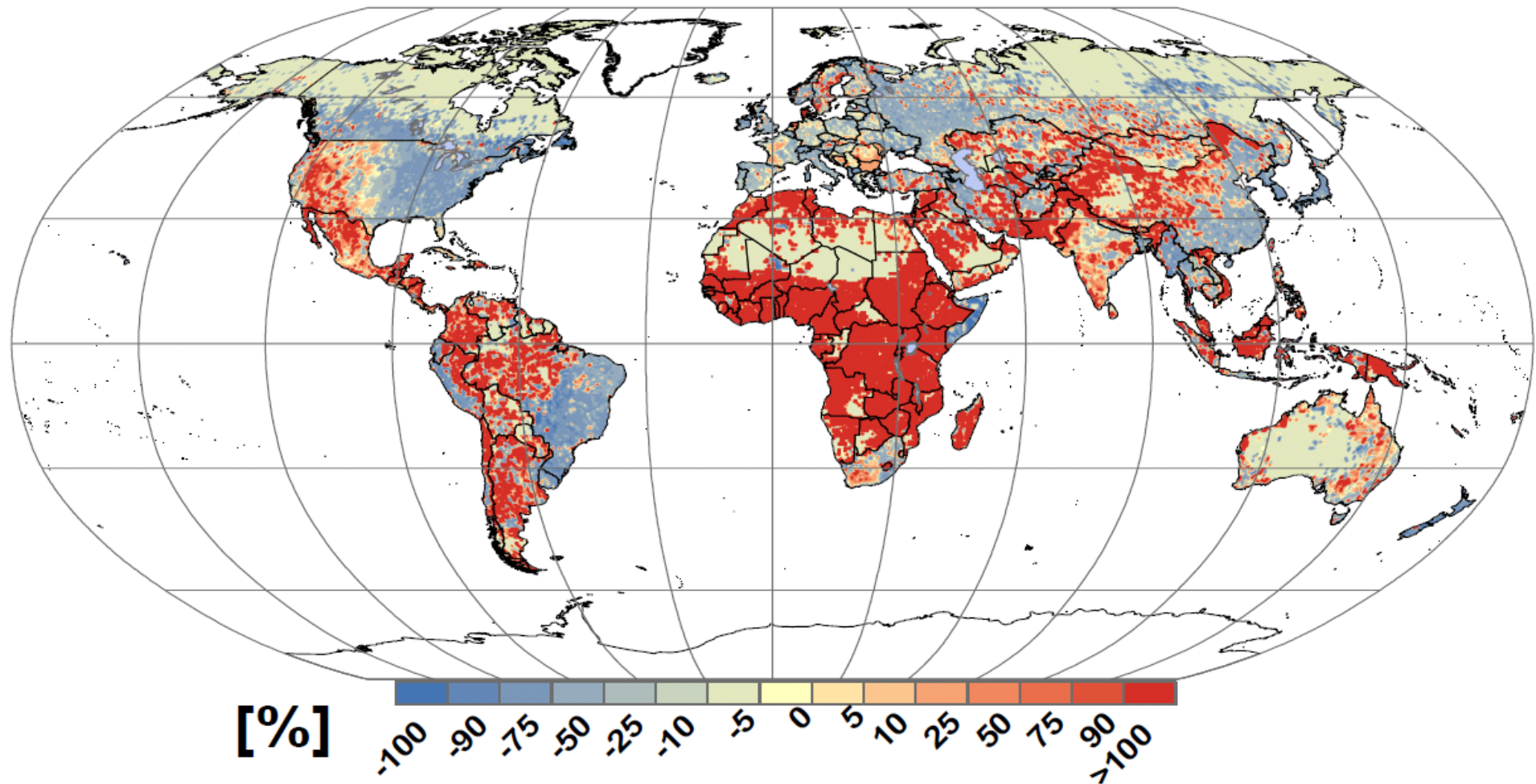
**2100**

(b)

Total blue water consumption [million cubic meter per year]

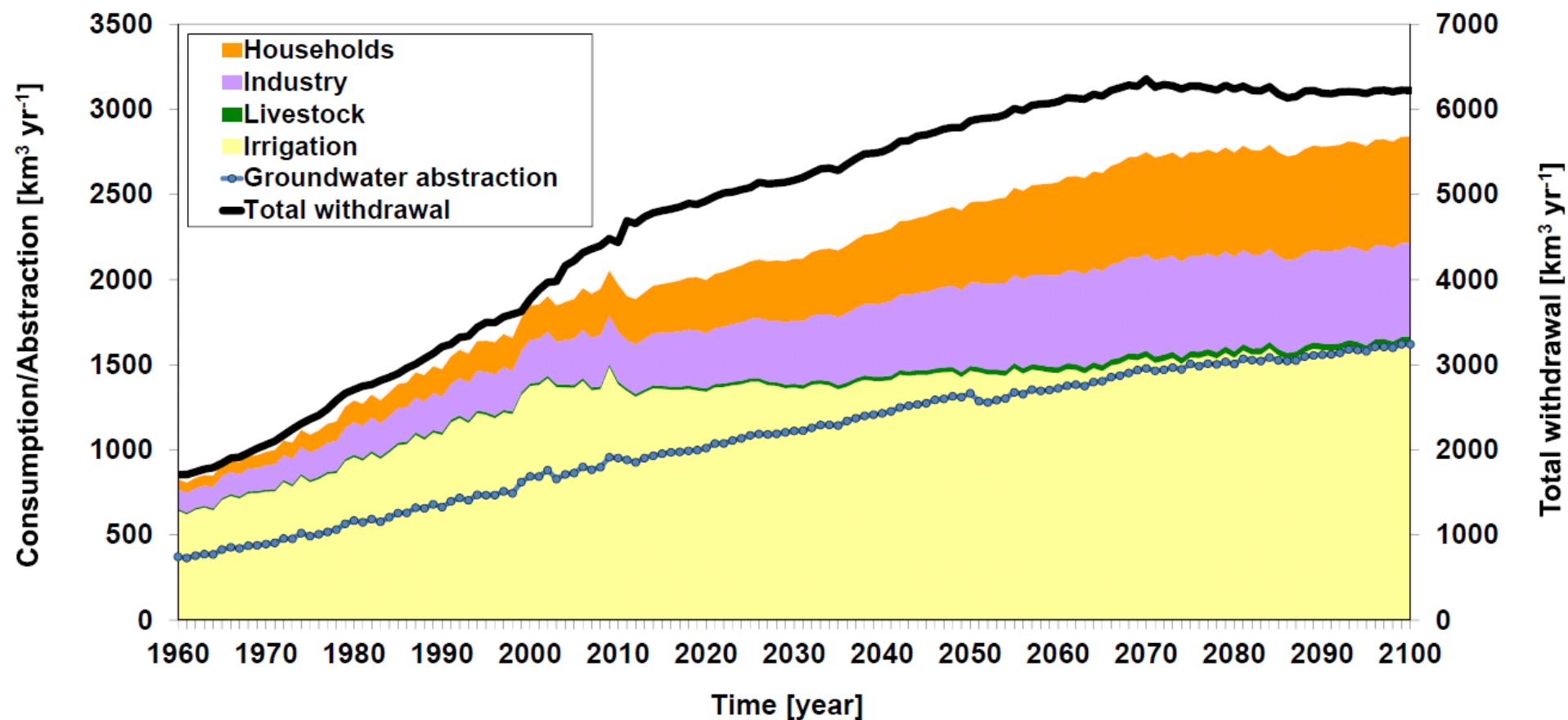
0 - 2   2 - 20   20 - 100   100 - 300   300 - 1000   > 1000

# Relative change in human water consumption

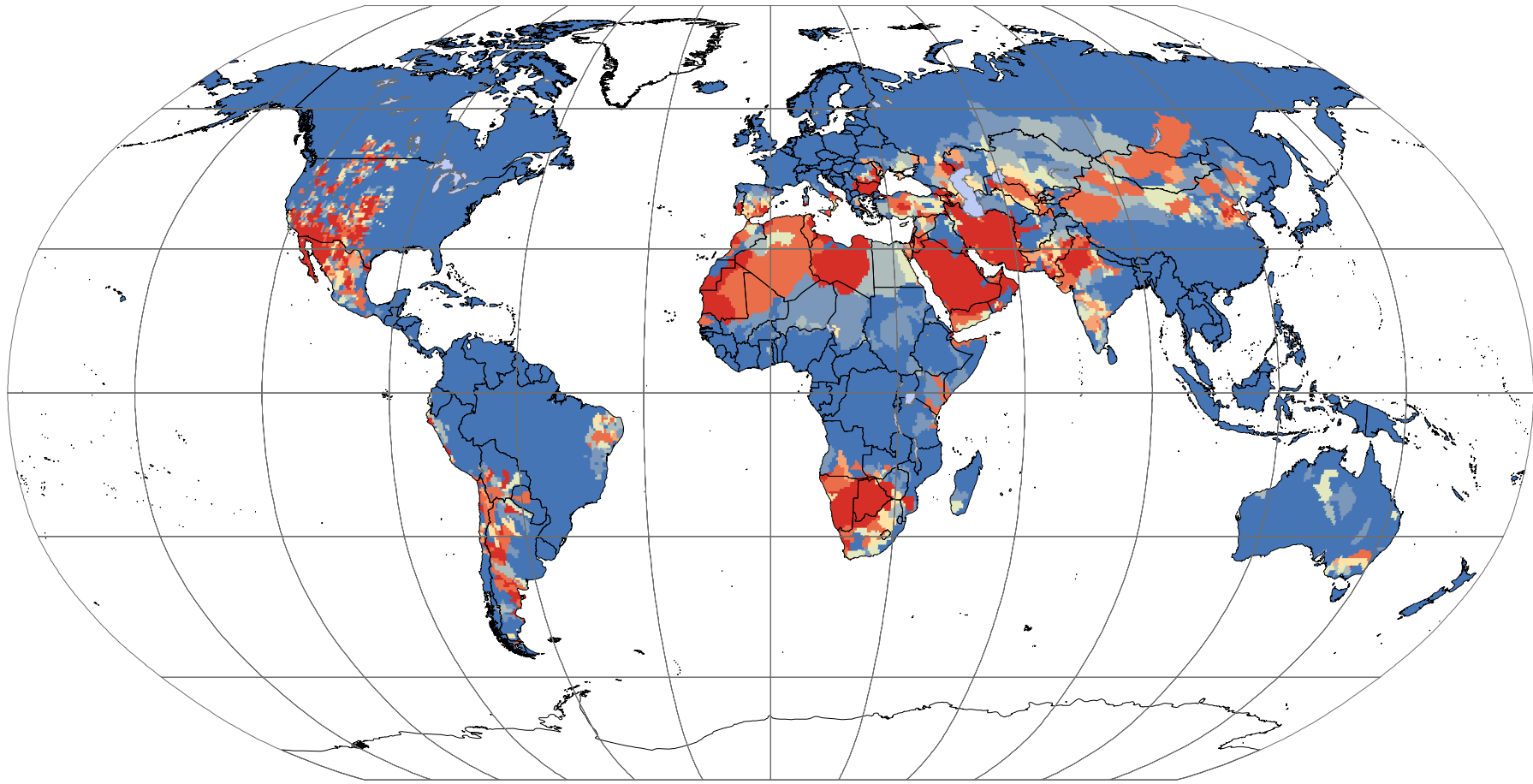


**2100 – 2010**

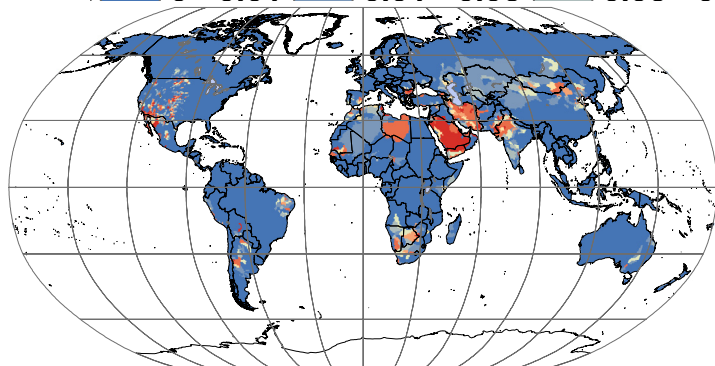




**Past trends and future projections of  
human water use  
(1960-2100)**



**BIWSI - Groundwater [-]**



**BIWSI - Groundwater [-]**

0 - 0.01	0.01 - 0.05	0.05 - 0.1	0.1 - 0.15	0.15 - 0.2	0.2 - 0.25	0.25 - 0.5	> 0.5
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**Average nonrenewable  
groundwater abstraction over  
the total (2069-2099)**

**25**

**Wada and Bierkens (2014; ERL)**

# Conclusions and Outlook

- **Groundwater pumping ( $800 \text{ km}^3$ ) has more than doubled in size since 1960, and is projected to double by the end of this century.**
- **Nonrenewable groundwater is a major source for irrigation: India, Pakistan, Iran, the Middle East (20-50%).**
- **Irrigation has redistributed water storage thorough groundwater and surface water extraction, and 80% of groundwater depletion going to oceans.**
- **Contribution of groundwater depletion to sea-level increased from  $0.002 (\pm 0.004) \text{ mm yr}^{-1}$  in 1900 to  $0.27 (\pm 0.04) \text{ mm yr}^{-1}$  in 2000.**
- **Although uncertain, groundwater depletion is the dominant land water contribution to sea-level rise.**
- **GWD is projected to increase in African continent.**
- **Improve land water storage estimates with data assimilation framework using GRACE satellite.**