A Seminar

NASA Goddard Institute for Space Studies,

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

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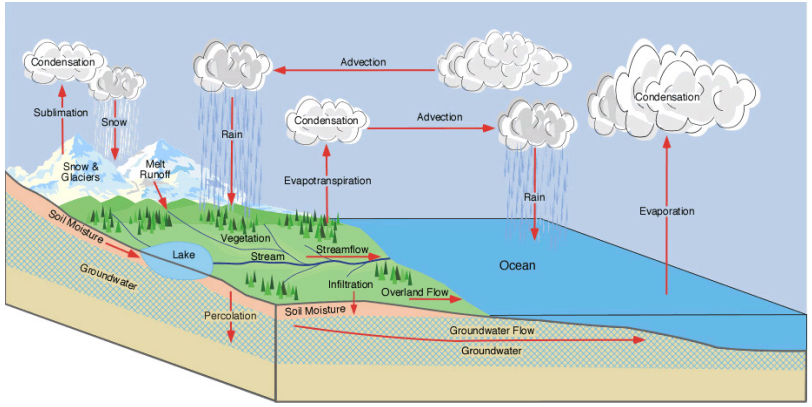

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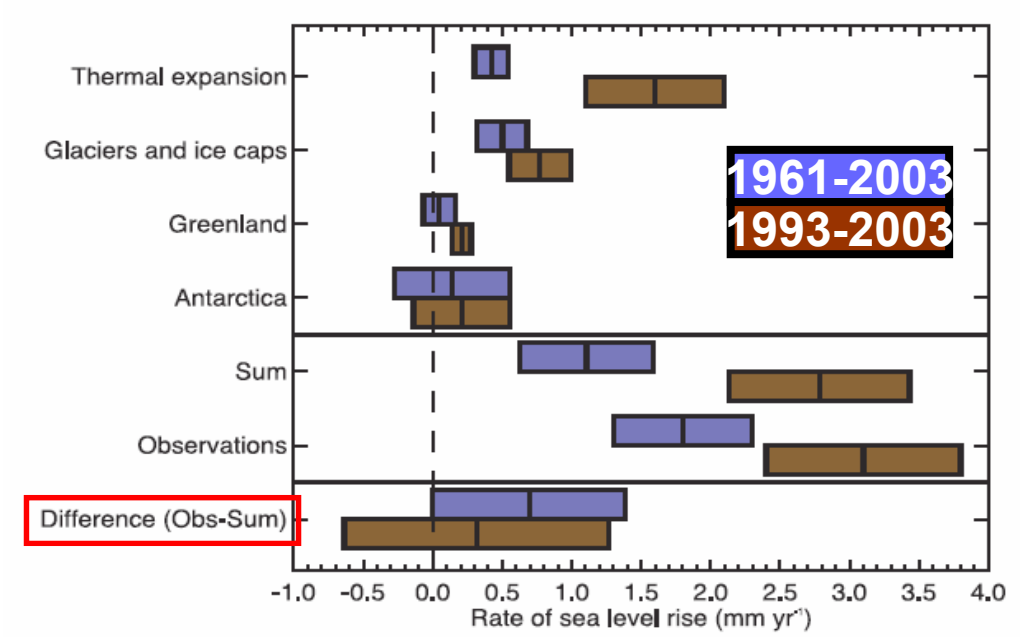
Land Water Contribution to Sea Level?



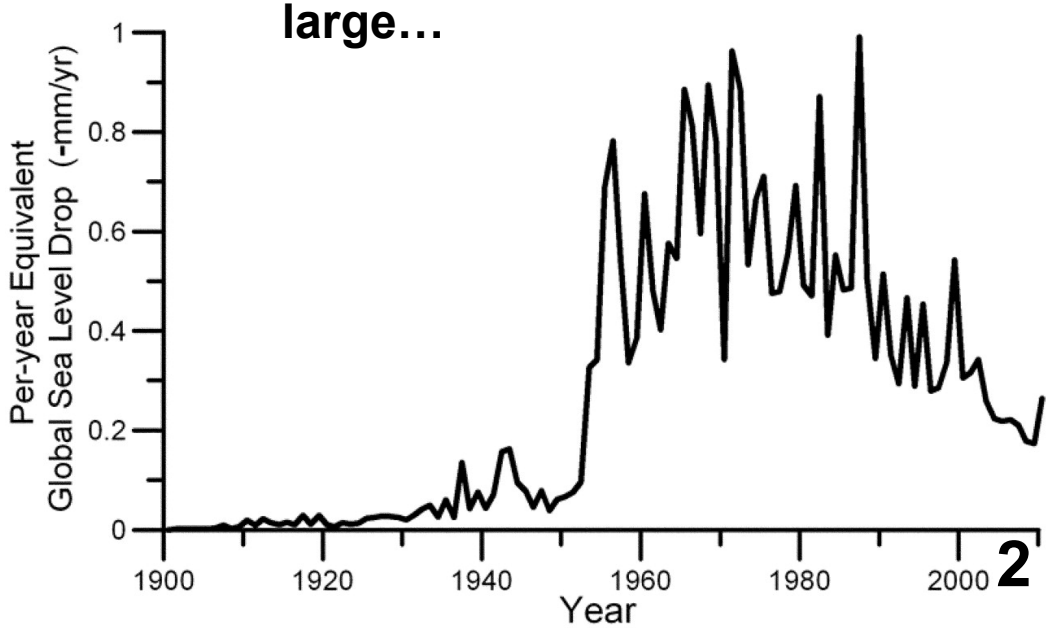
***IPCC AR3*:**
Terrestrial water storage change is a non-negligible component…

***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?

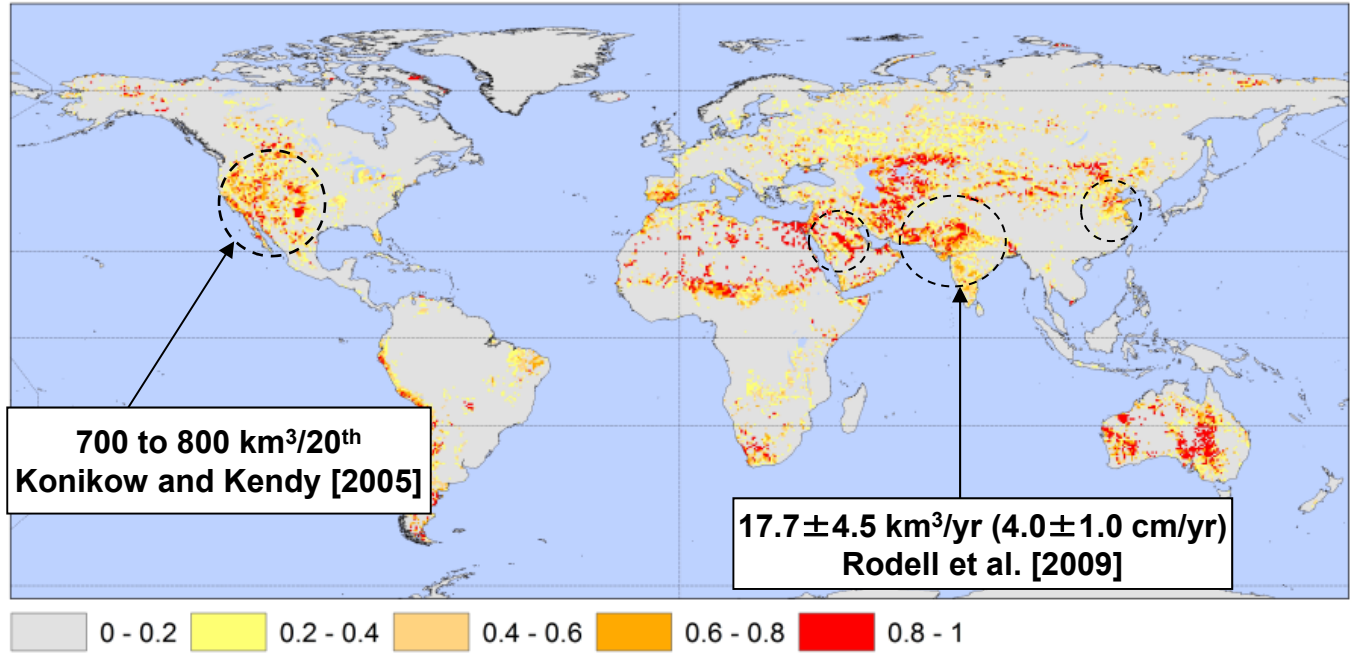


Groundwater extraction

- 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***

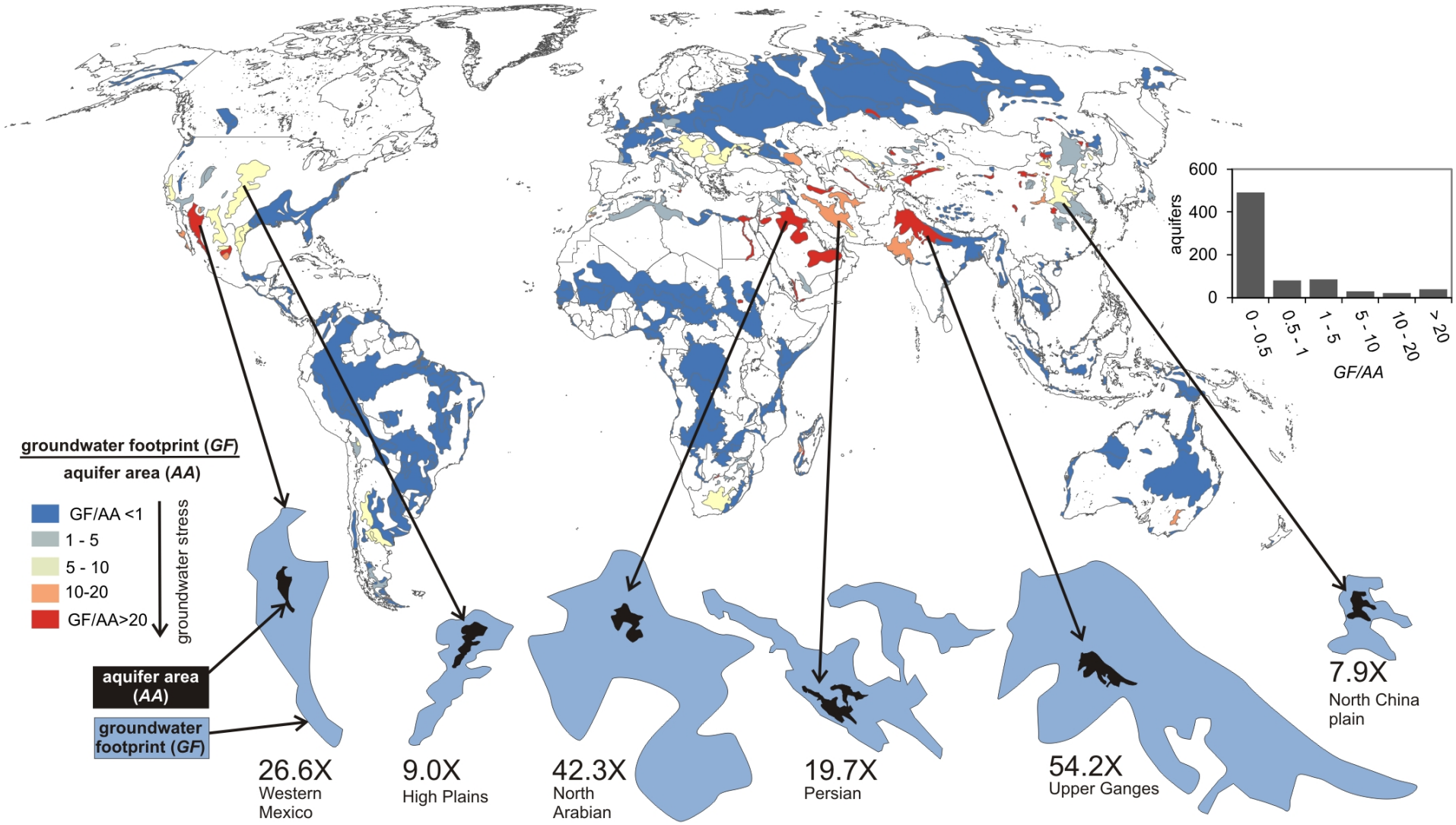
- Increasing reliance of human water use on nonrenewable groundwater resources worldwide



Global Water Stress

Wada et al. (2011; Water Resources Research)

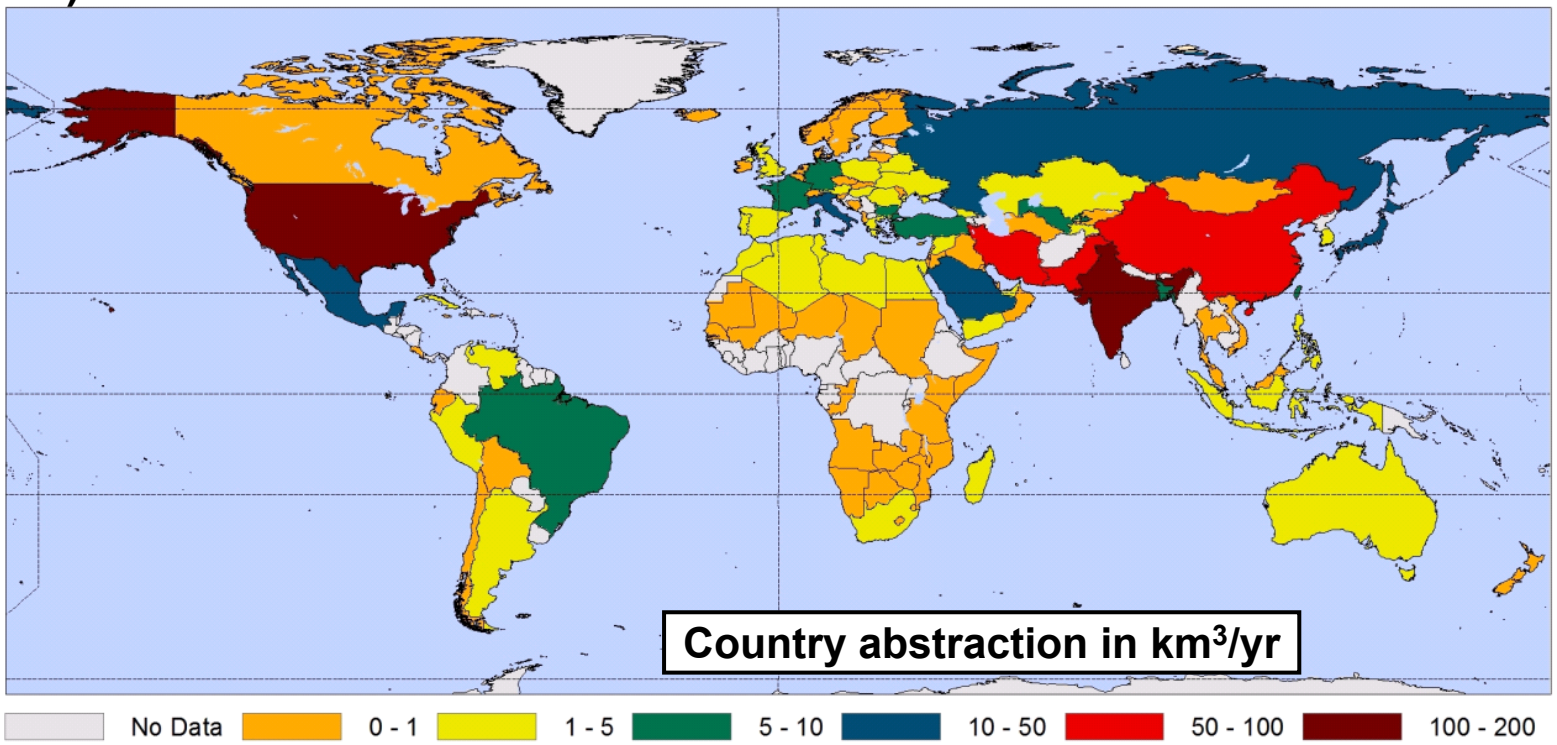
Groundwater Abstraction >> Recharge

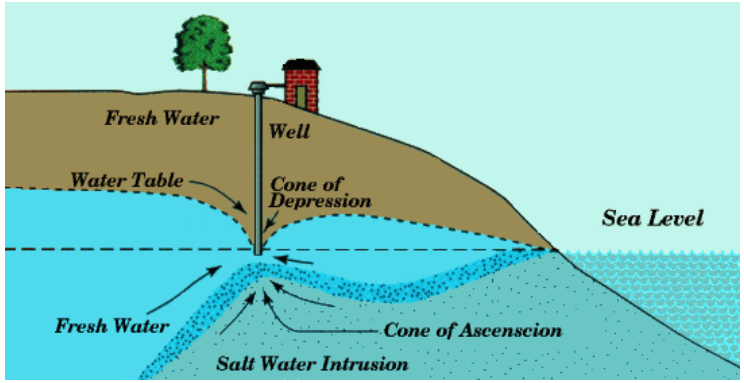


Gleeson, Wada et al. (2014; Nature)

Contribution of Groundwater Depletion to Sea Level?

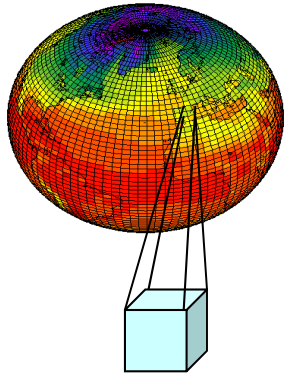
- Global groundwater abstraction amounts to 800 km^3 for 2000.
- Nearly 90% is used for irrigation.
- In many (semi-)arid regions, abstraction exceeds recharge over long periods, which results in groundwater depletion (GWD).
- Depleted groundwater ends up in ocean predominantly through evapotranspiration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





How to estimate?

Flux-based method:

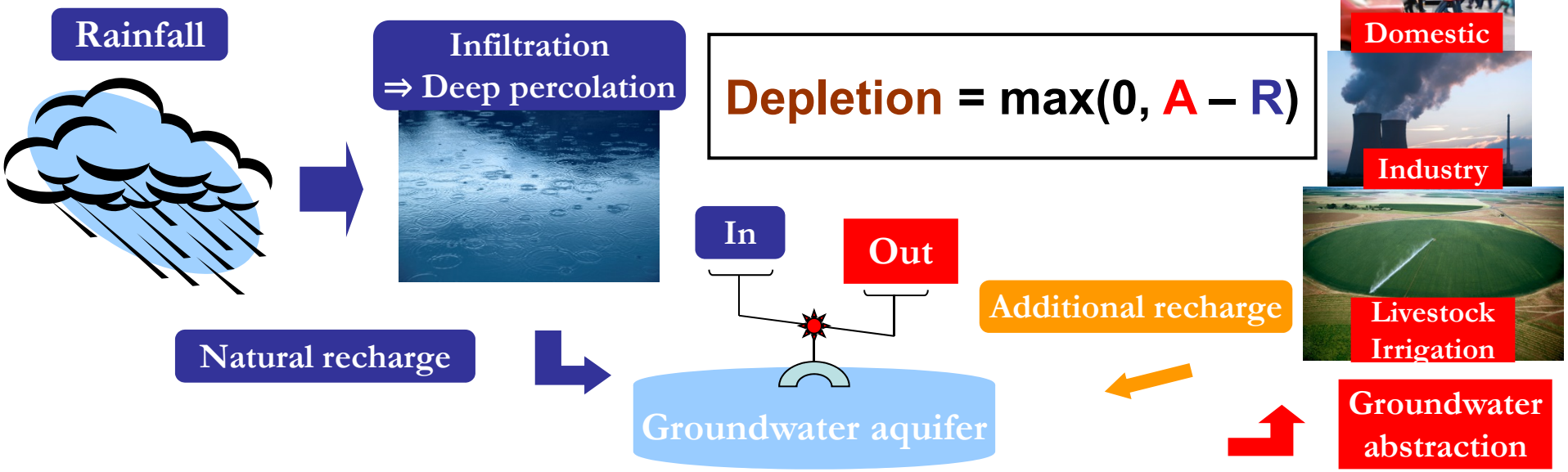


0.5° (50 km by 50 km)

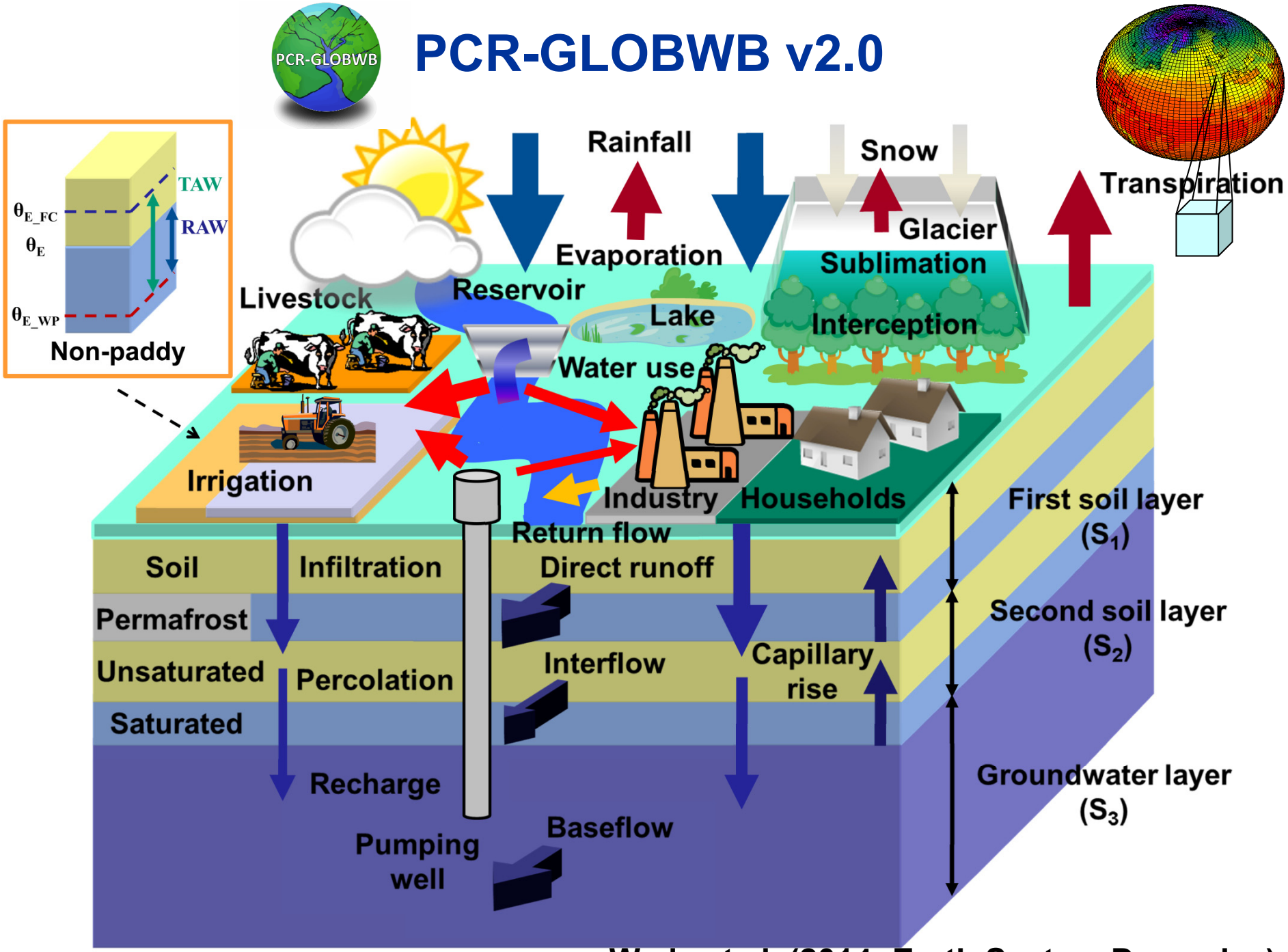
- Use a global hydrological model to simulate groundwater recharge

- Estimate groundwater abstraction

where Abstraction (A) >> Recharge (R)



PCR-GLOBWB v2.0

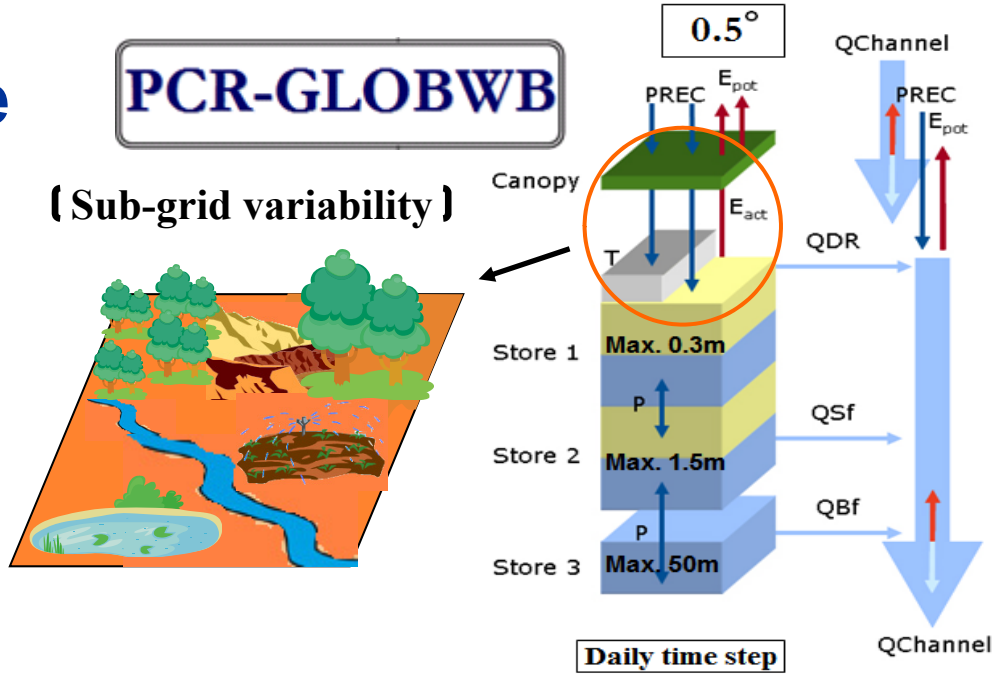


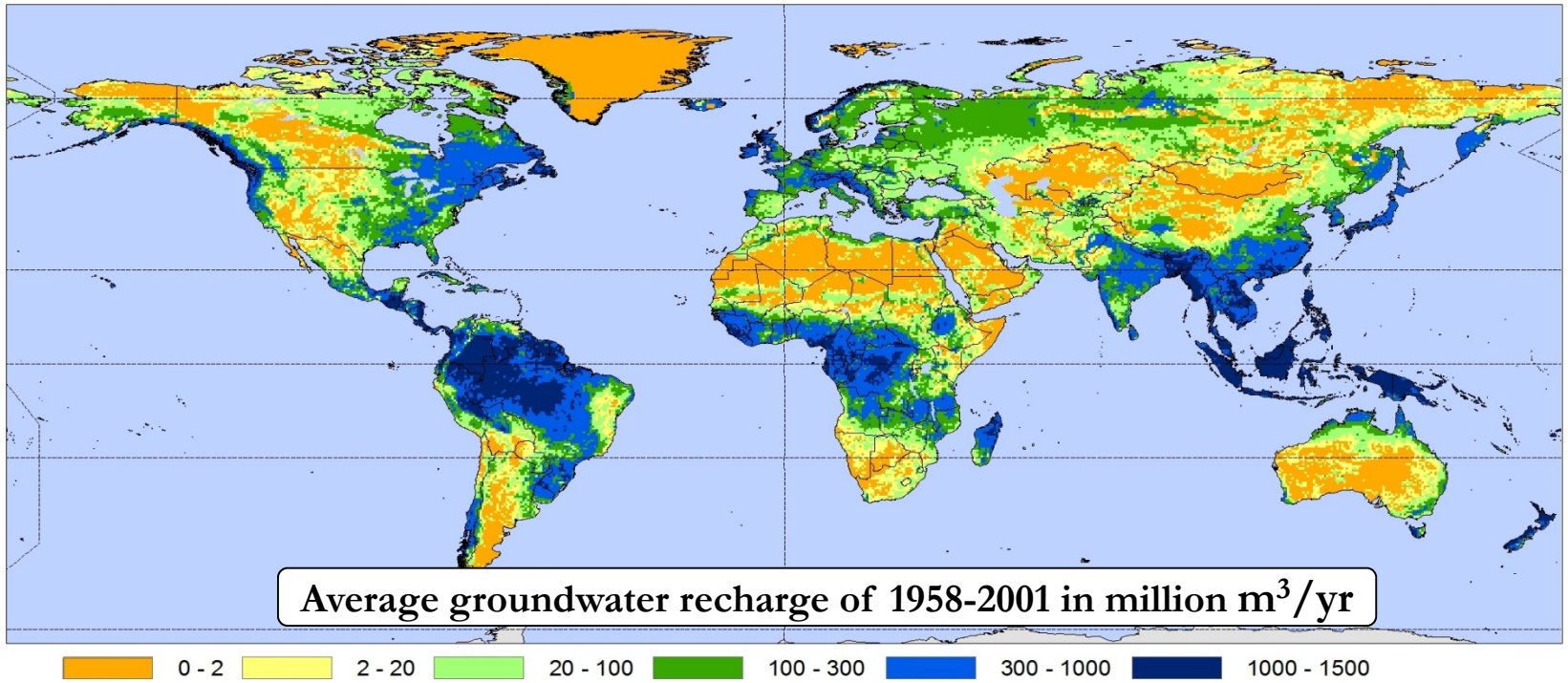
Wada et al. (2014; Earth System Dynamics)

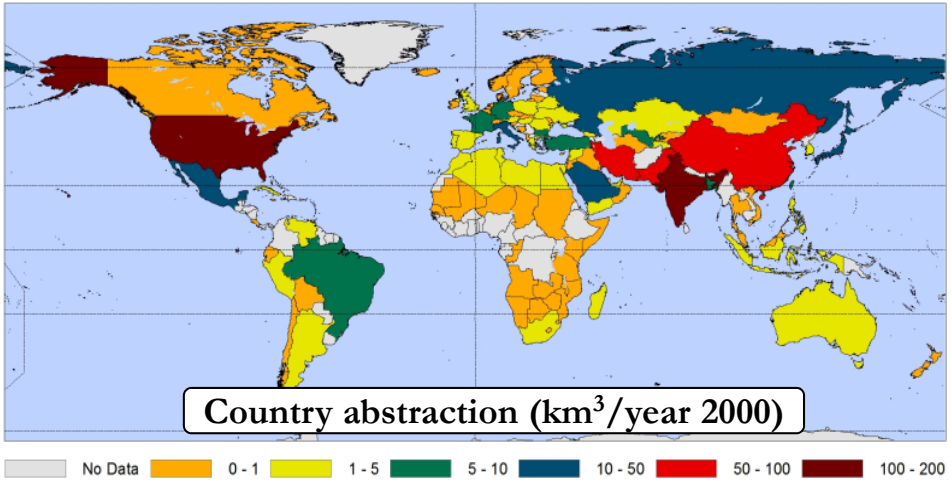
Groundwater Recharge

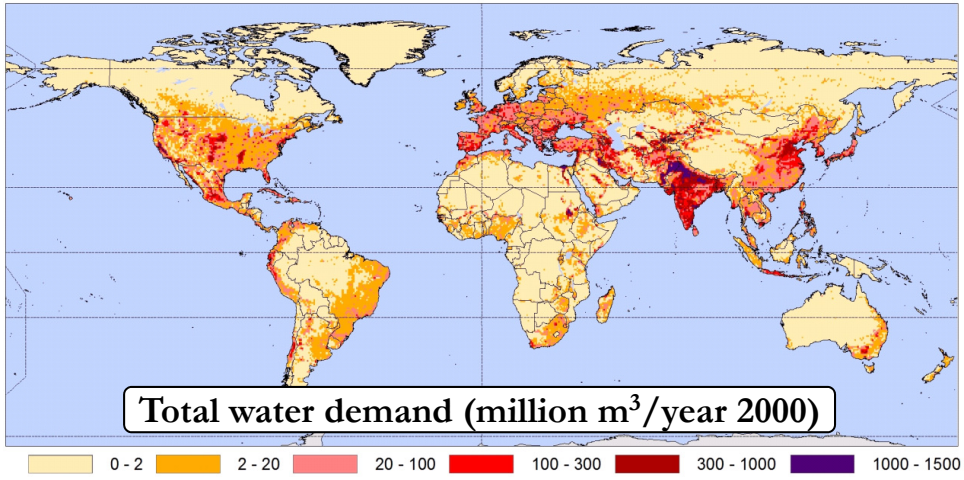
Average natural groundwater recharge: 15225 km³/year

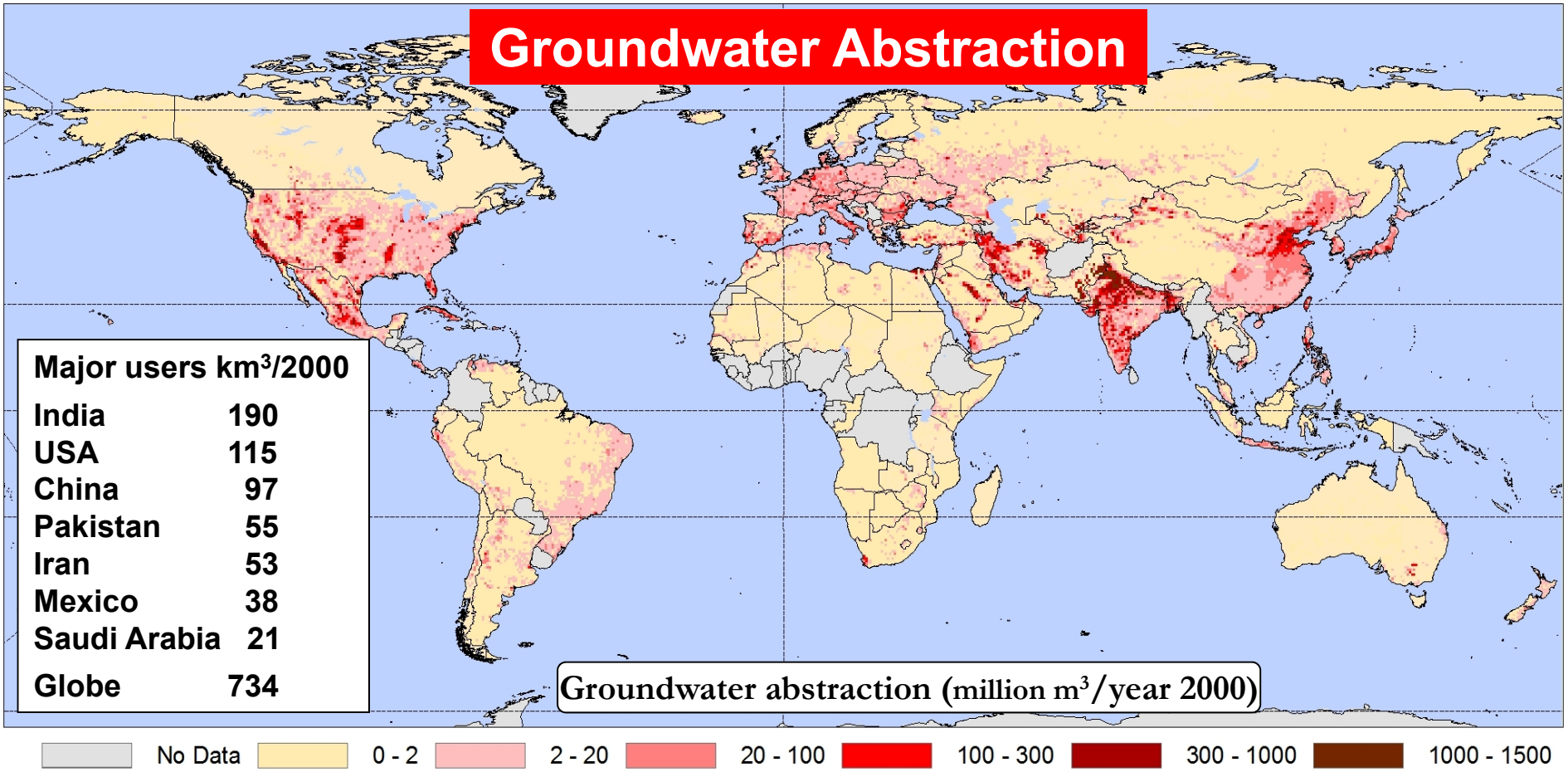
Additional recharge from irrigation: 420 km³/year 2000






Country abstraction (km³/year 2000)
No Data
0 - 1
1 - 5
5 - 10
10 - 50
50 - 100
100 - 200

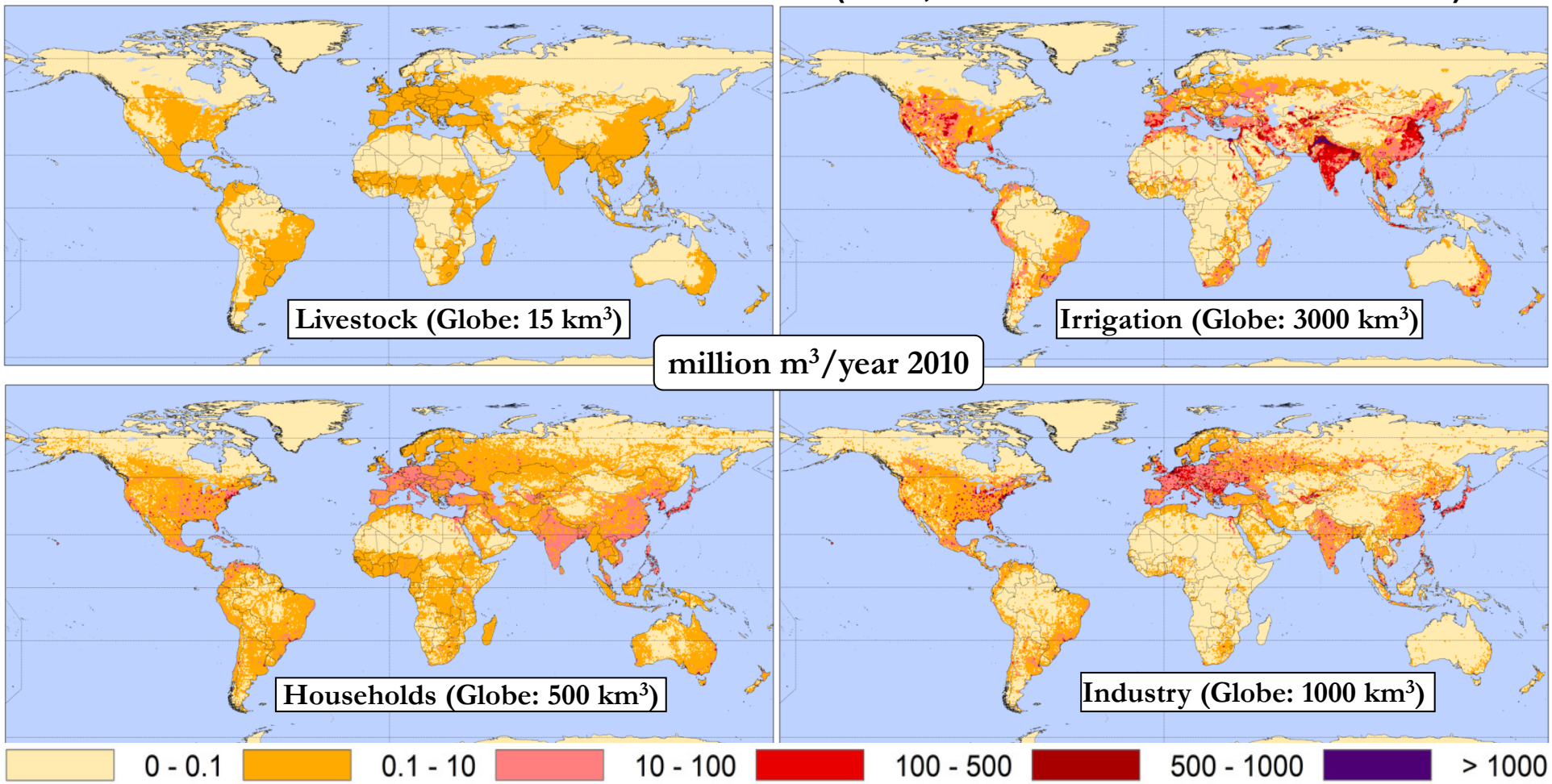

Total water demand (million m³/year 2000)
0 - 2
2 - 20
20 - 100
100 - 300
300 - 1000
1000 - 1500


Groundwater Abstraction
Major users km³/2000
India 190
USA 115
China 97
Pakistan 55
Iran 53
Mexico 38
Saudi Arabia 21
Globe 734
Groundwater abstraction (million m³/year 2000)
No Data
0 - 2
2 - 20
20 - 100
100 - 300
300 - 1000
1000 - 1500

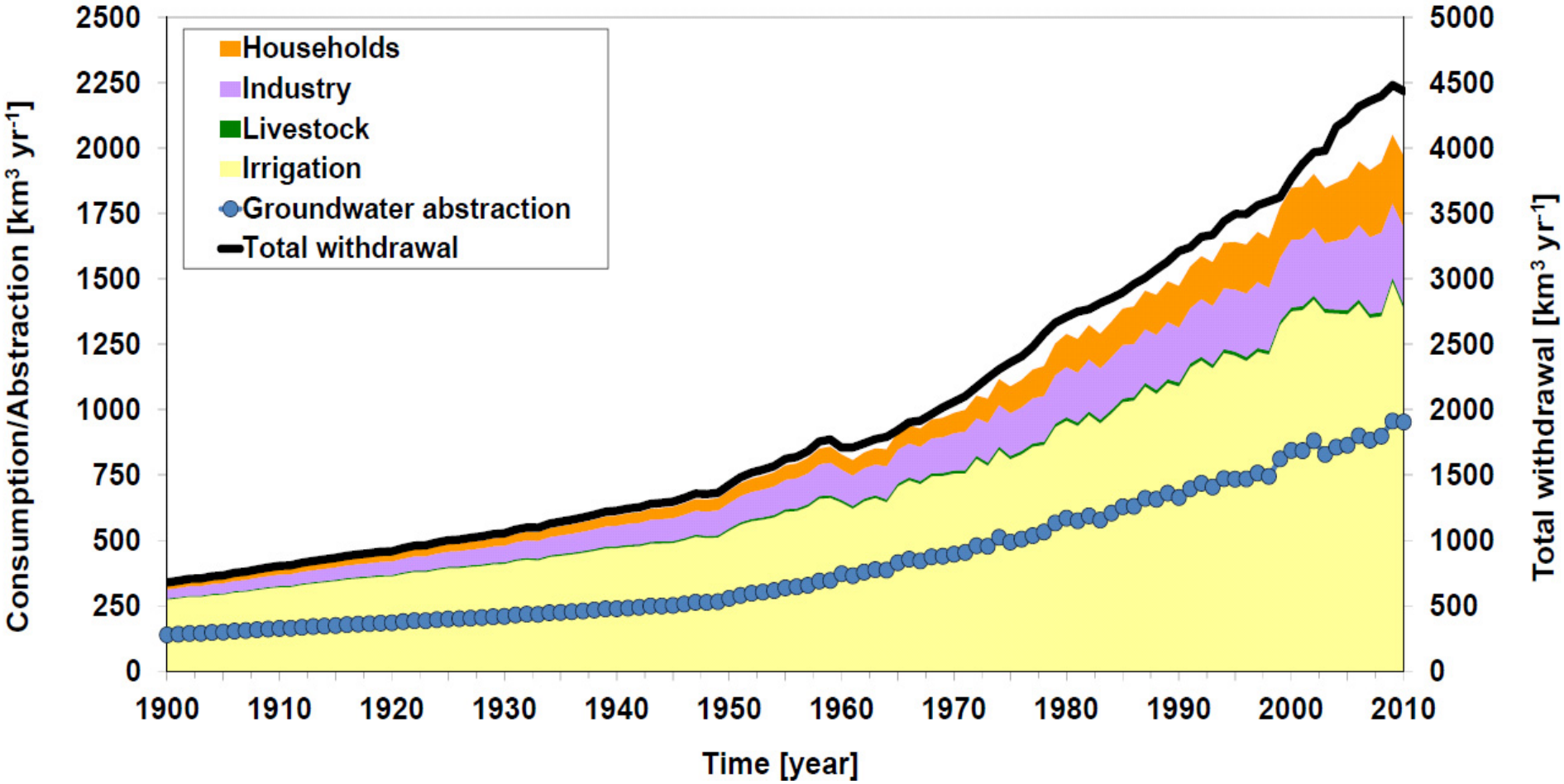
Water demand

- **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)

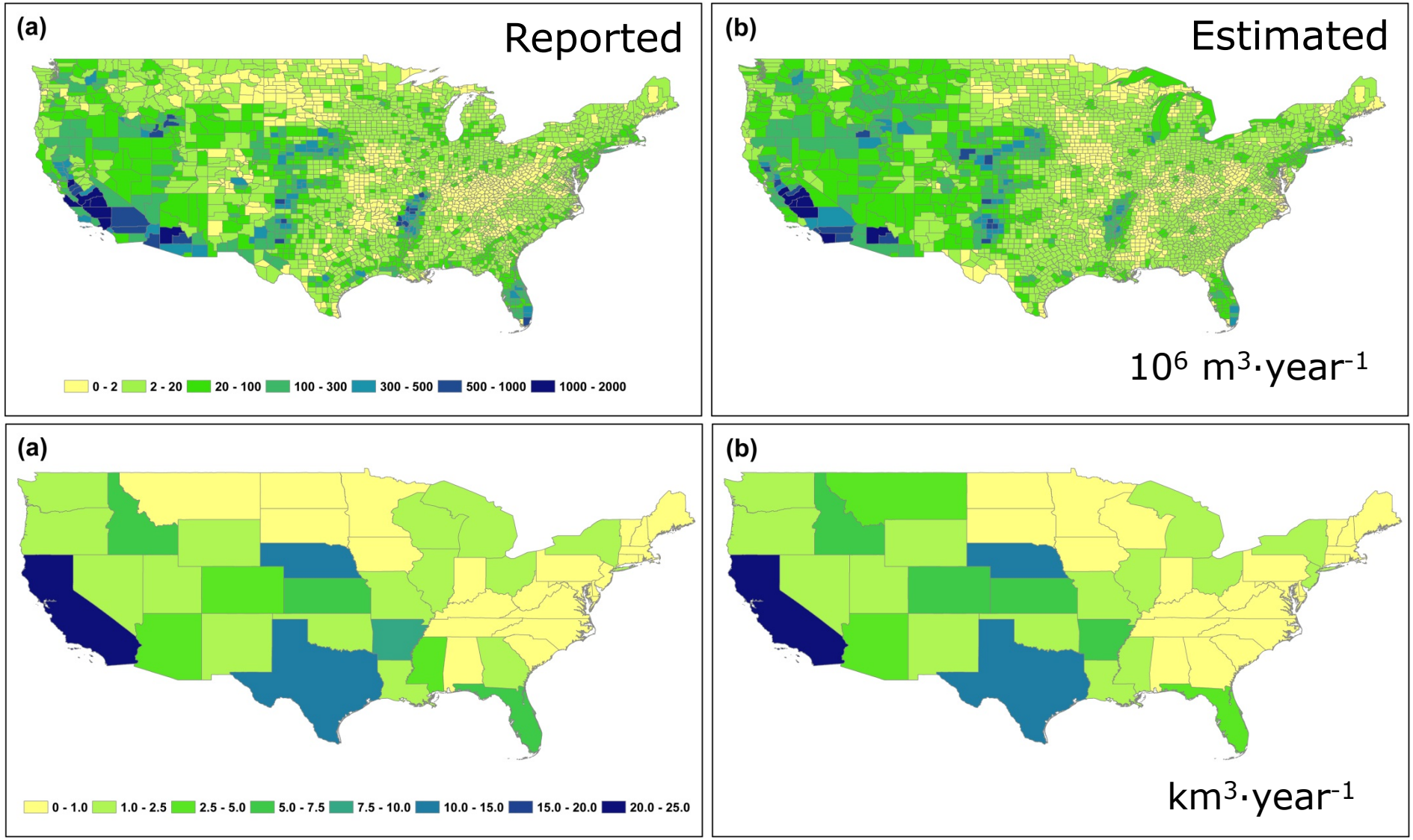


20th and Early 21st Century Groundwater Use

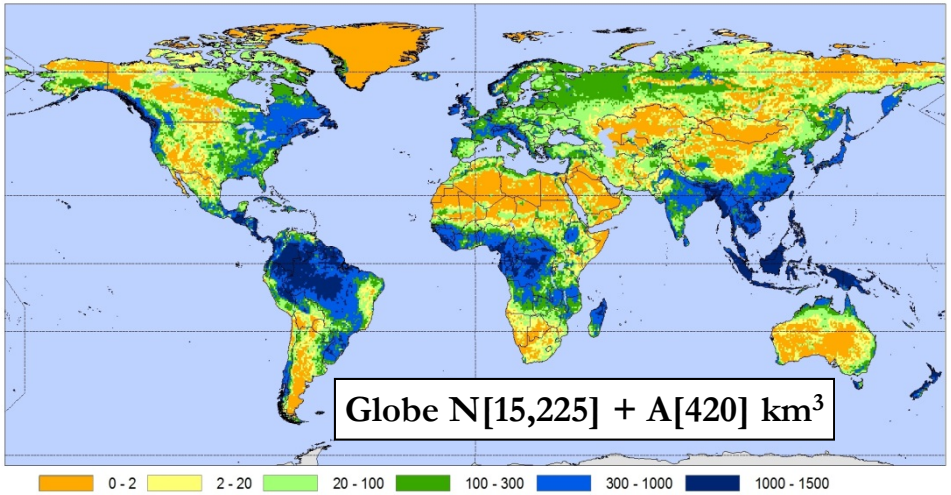


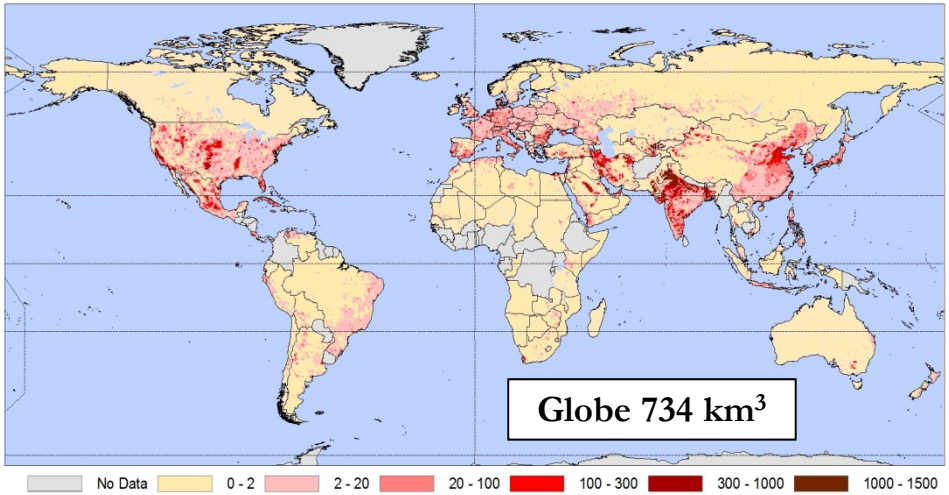
Wada et al. (2012; GRL)

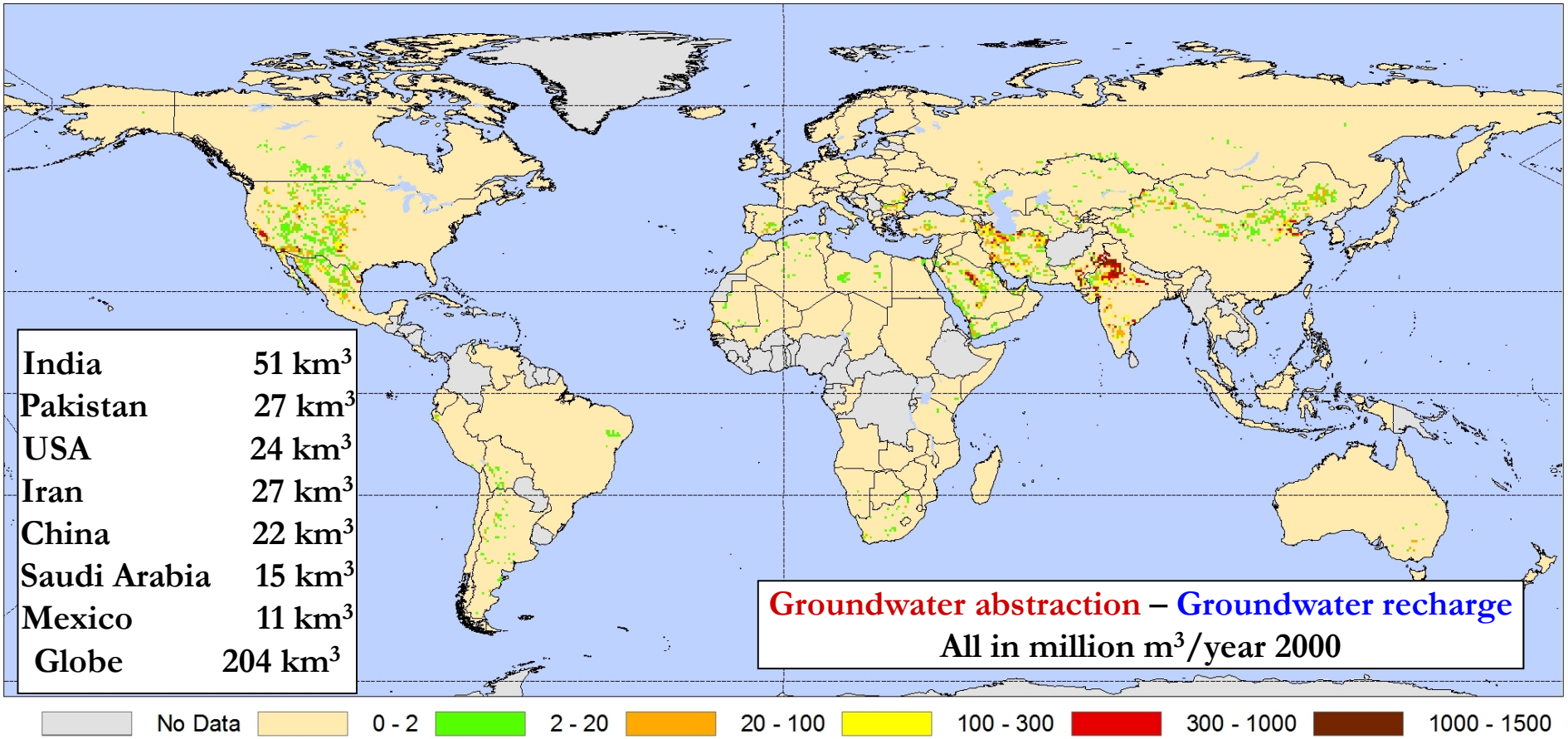
Validation: Groundwater abstraction

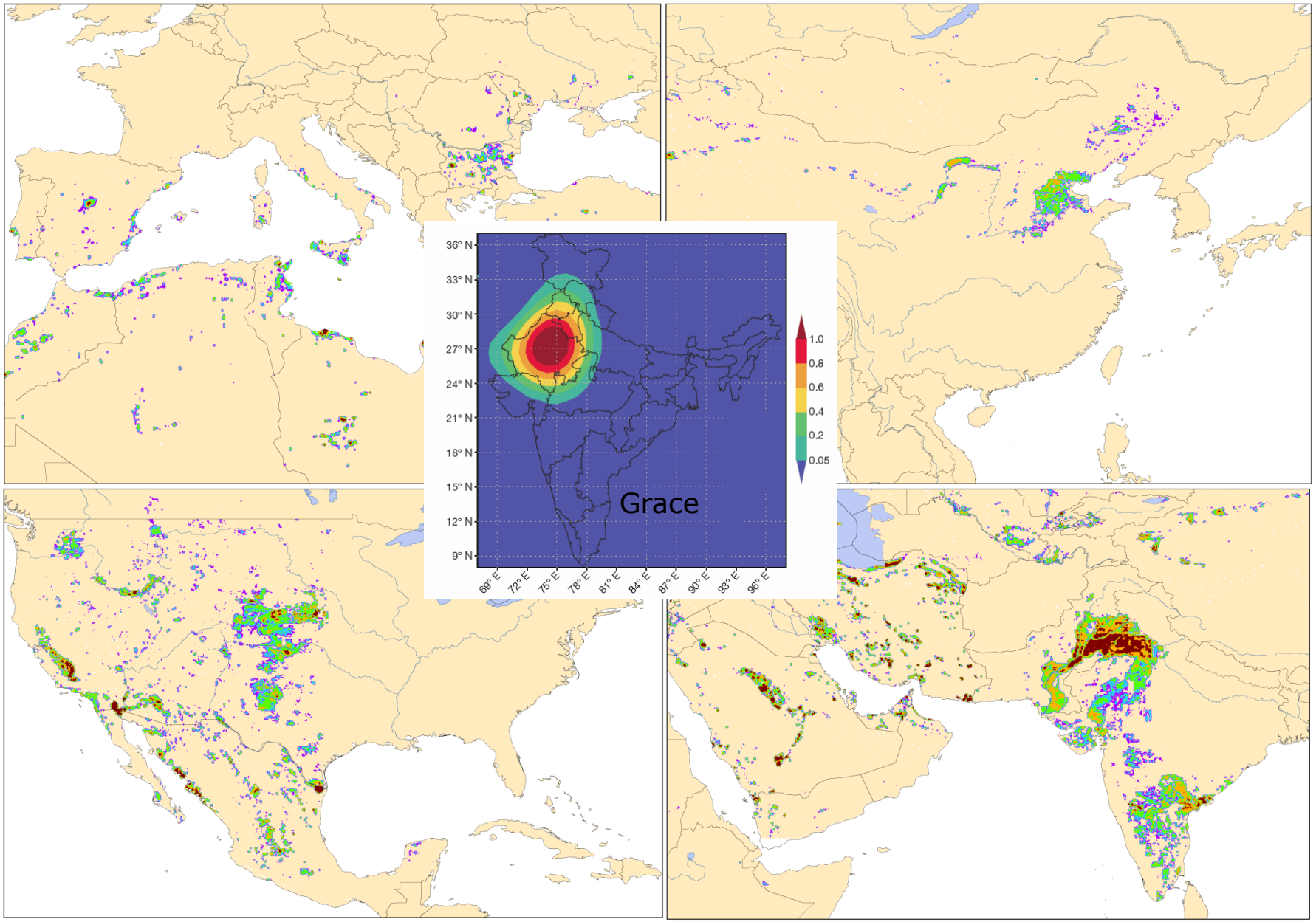


Comparison of reported and estimated groundwater abstraction for 2000: USA county and state level (USGS).


Globe N[15,225] + A[420] km³
0 - 2
2 - 20
20 - 100
100 - 300
300 - 1000
1000 - 1500

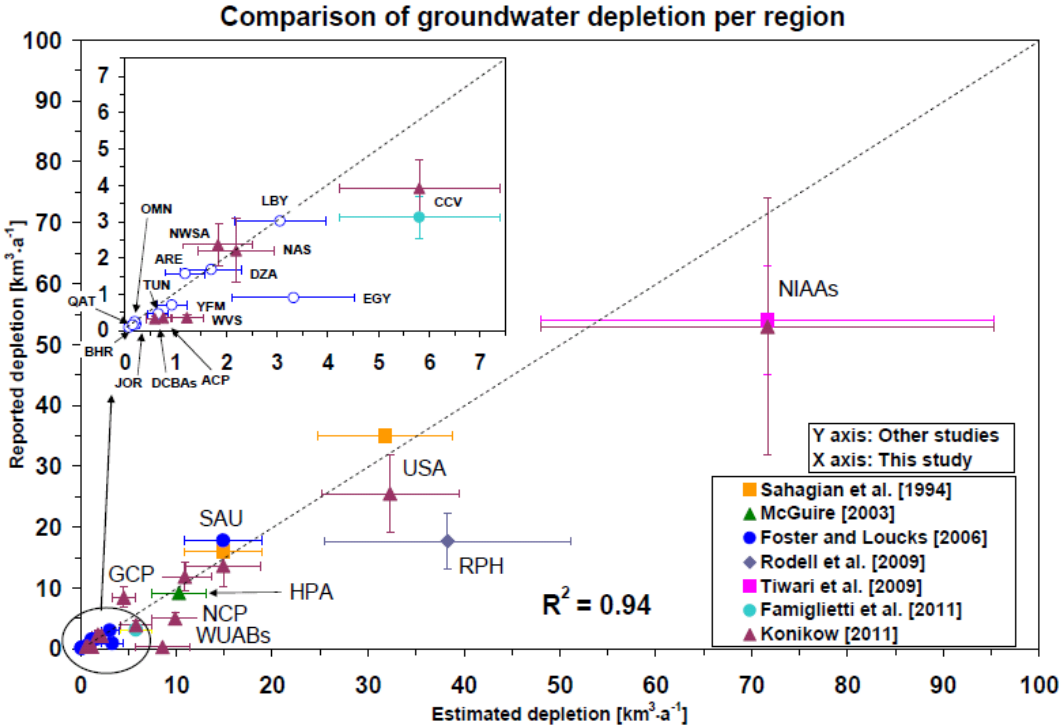

Globe 734 km³
No Data
0 - 2
2 - 20
20 - 100
100 - 300
300 - 1000
1000 - 1500


India 51 km³
Pakistan 27 km³
USA 24 km³
Iran 27 km³
China 22 km³
Saudi Arabia 15 km³
Mexico 11 km³
Globe 204 km³
Groundwater abstraction – Groundwater recharge
All in million m³/year 2000
No Data
0 - 2
2 - 20
20 - 100
100 - 300
300 - 1000
1000 - 1500



Groundwater depletion [million cubic meter per year]

0 - 0.5 | 0.5 - 1 | 1 - 2 | 2 - 5 | 5 - 10 | > 10



Validation

Compare to independent, mostly volume-based, estimates

Correction

Our estimates tend to overestimate depletion in non-arid regions

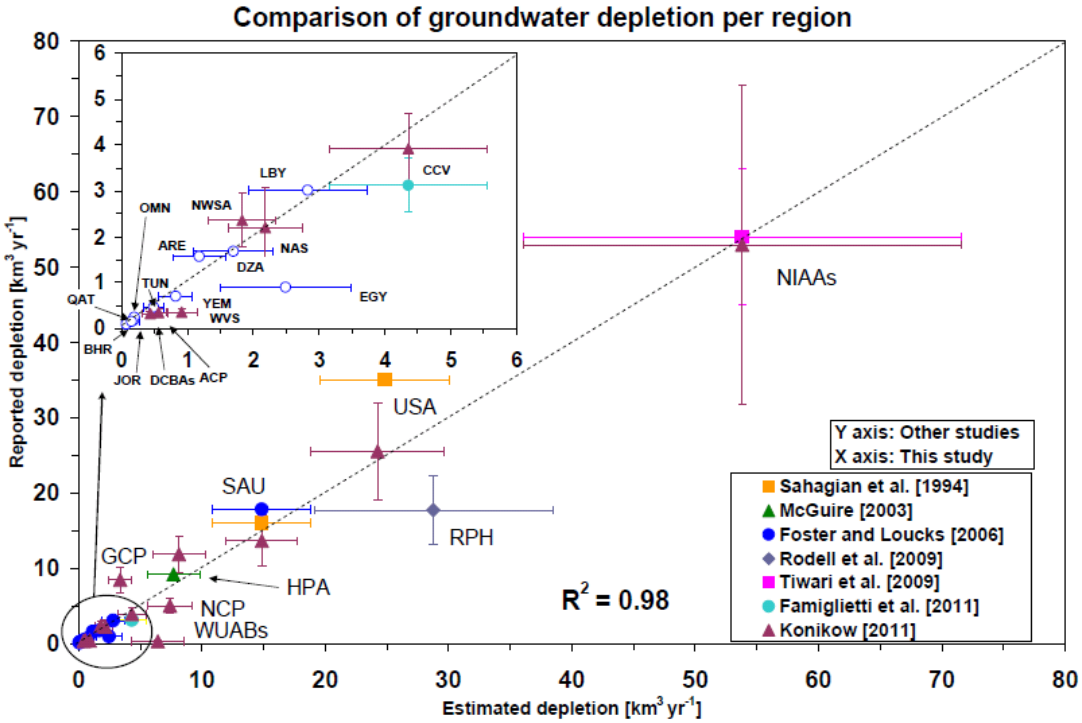
Global total (year 2000)

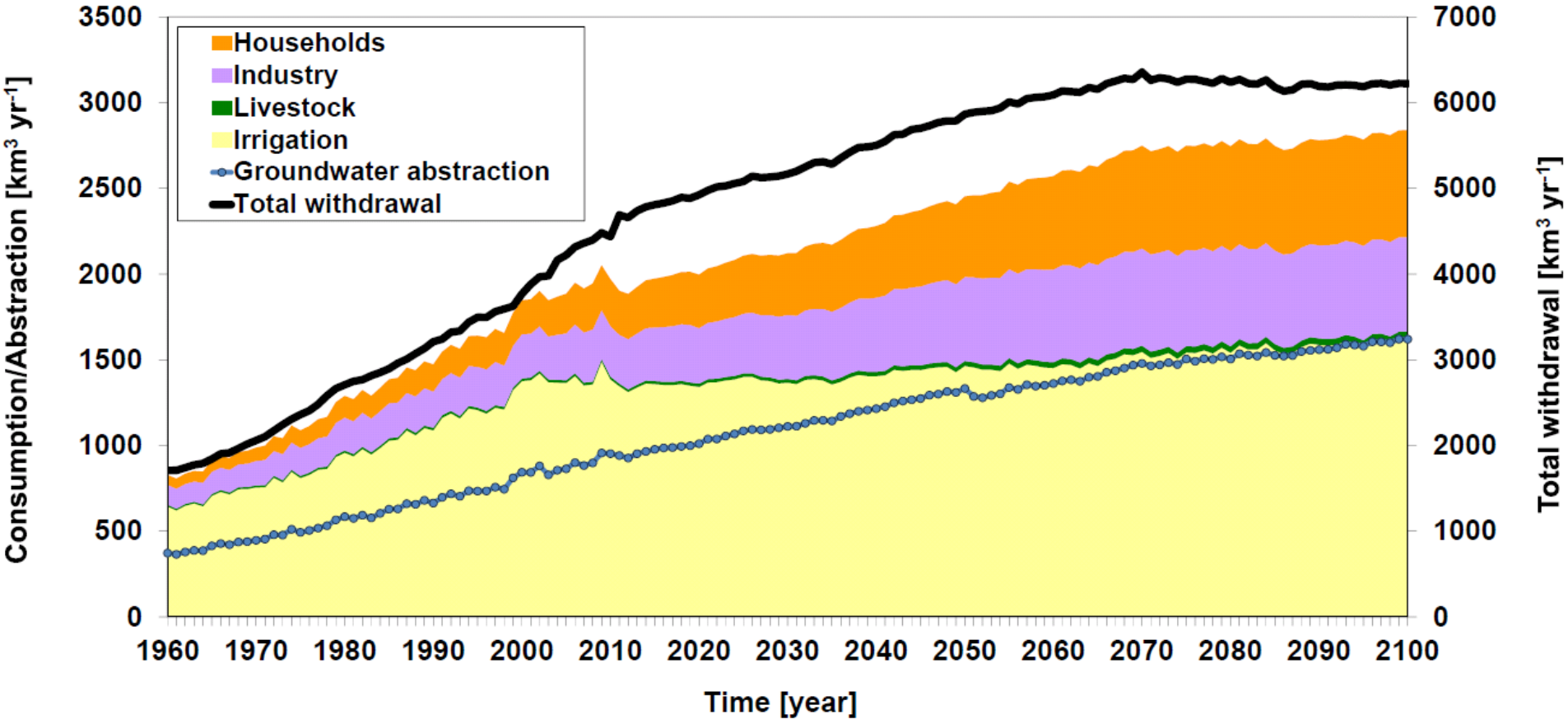
This study: 204 km³/year

= 0.57 mm/year

Konikow (2011): 145 km³/year

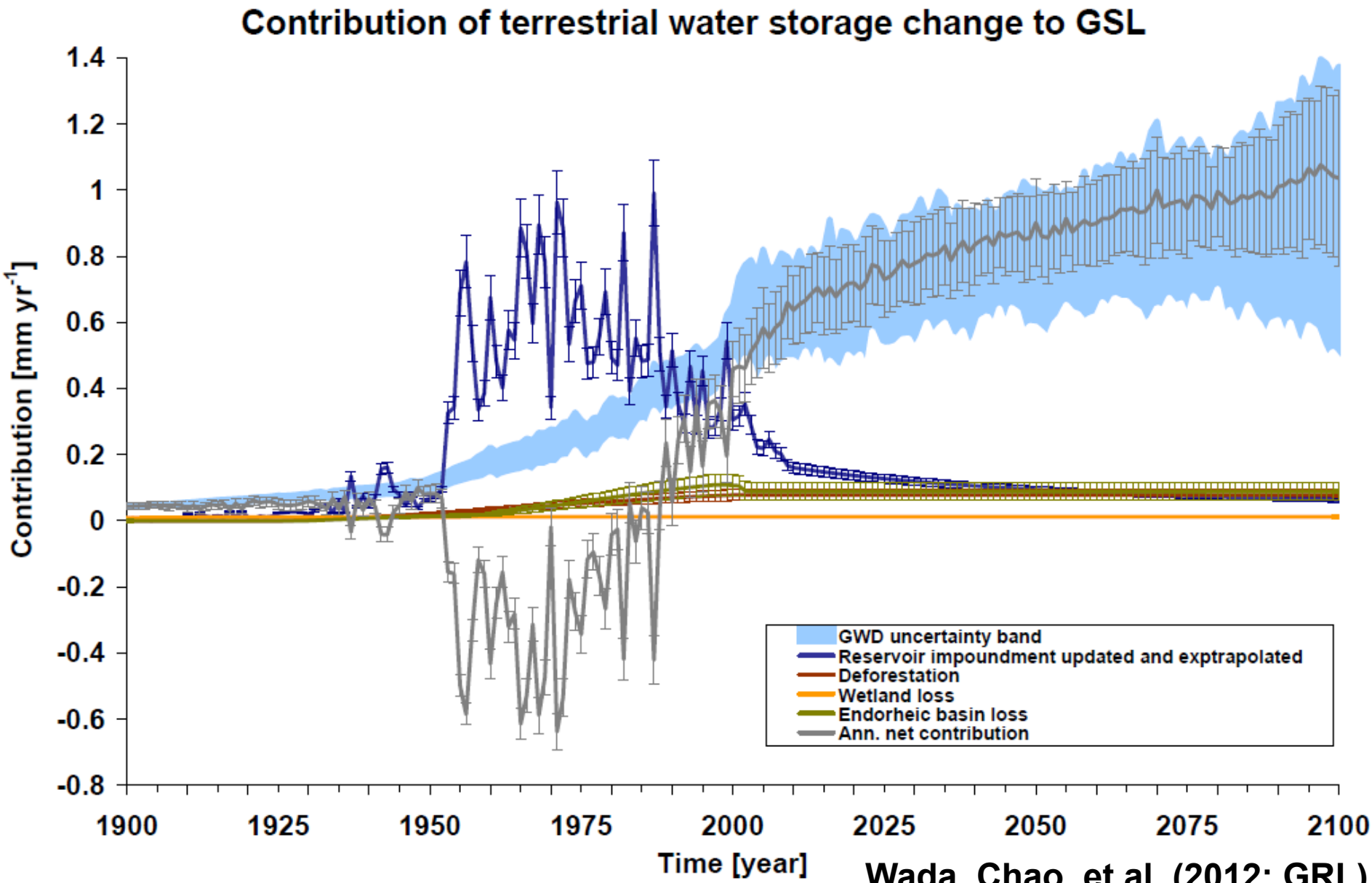
= 0.40 mm/year





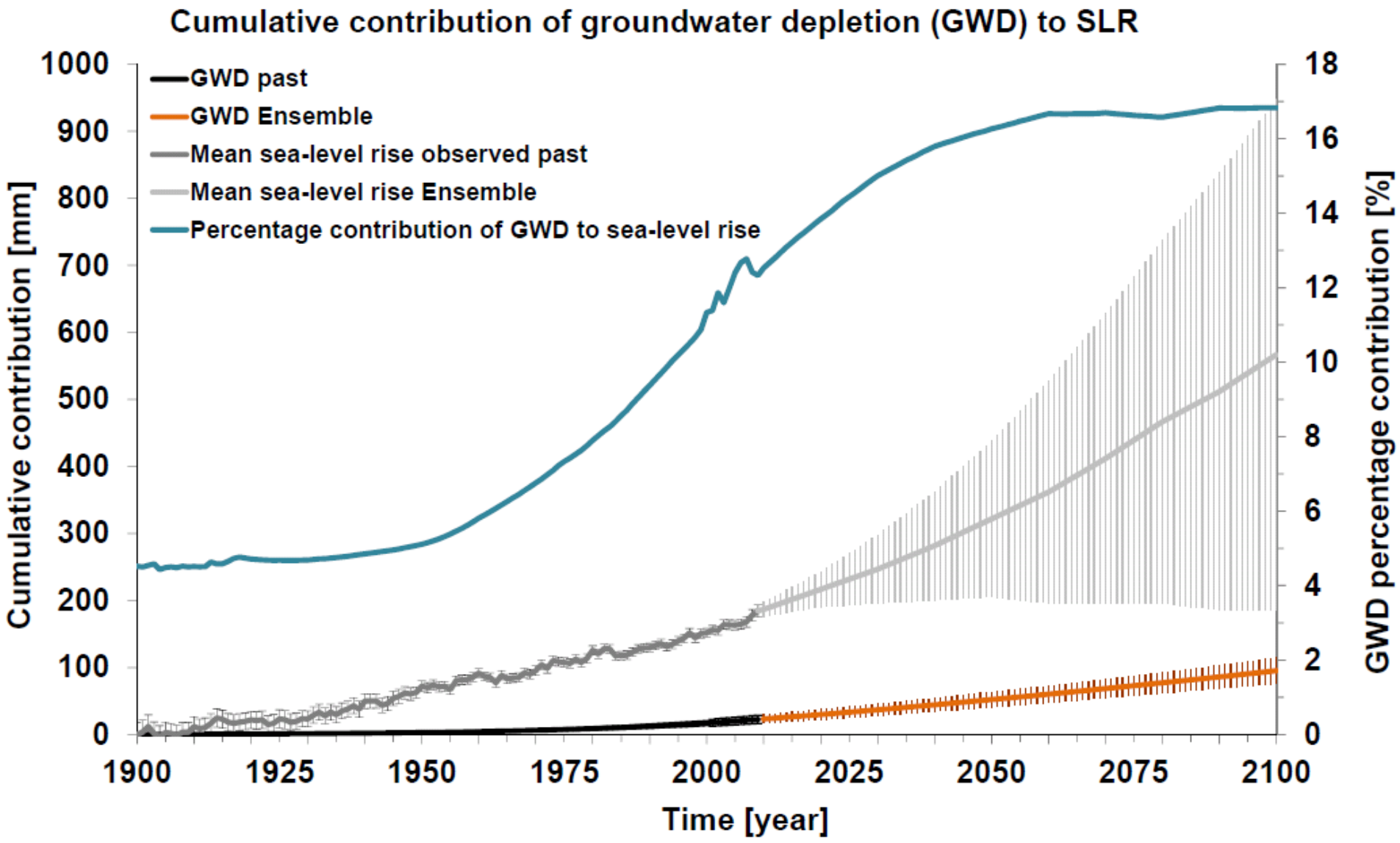
Past trends and future projections of groundwater use (by the end of this centry)

Net Contribution from TWS Change to Sea Level 1900-2100

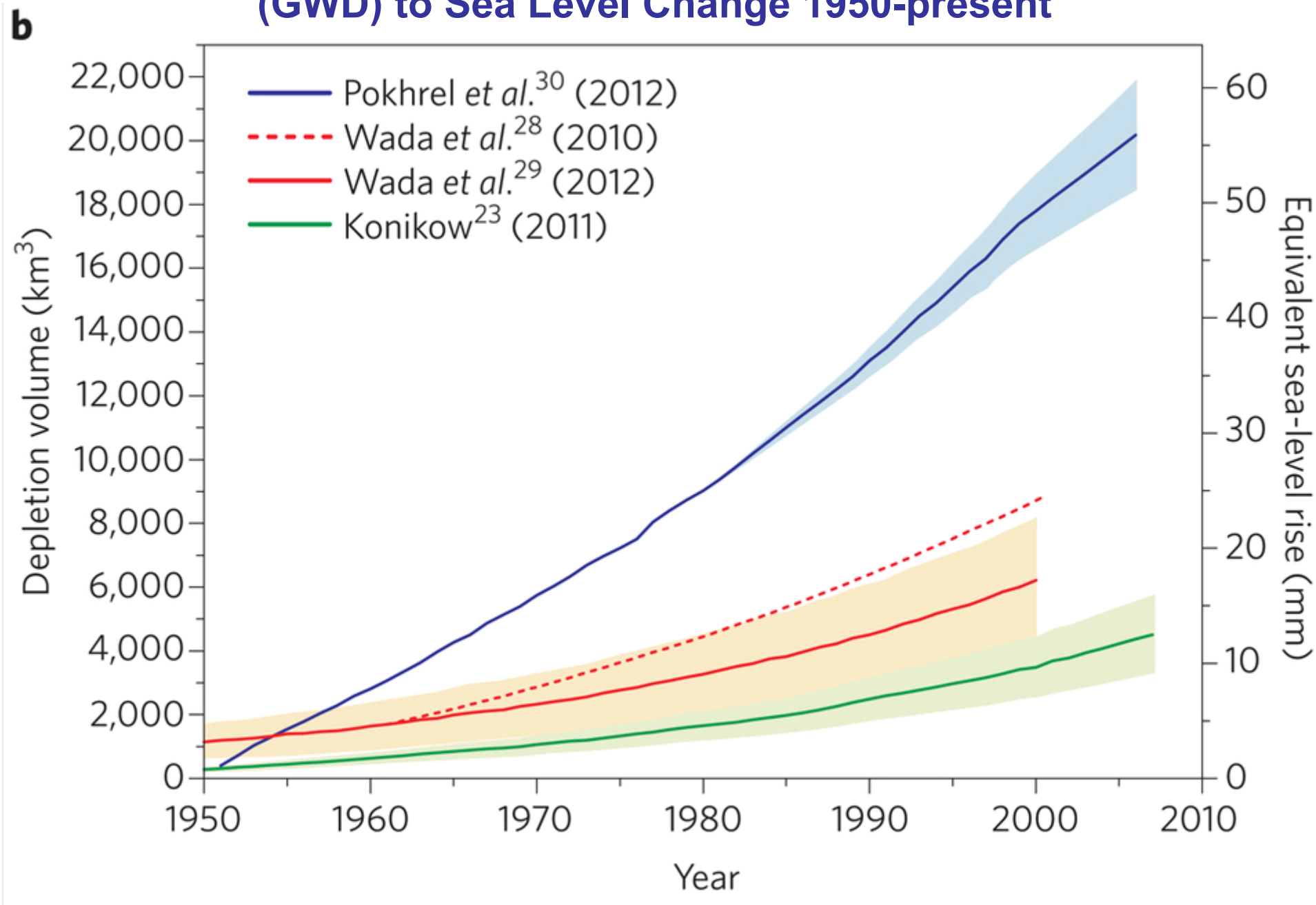


Wada, Chao, et al. (2012; GRL)

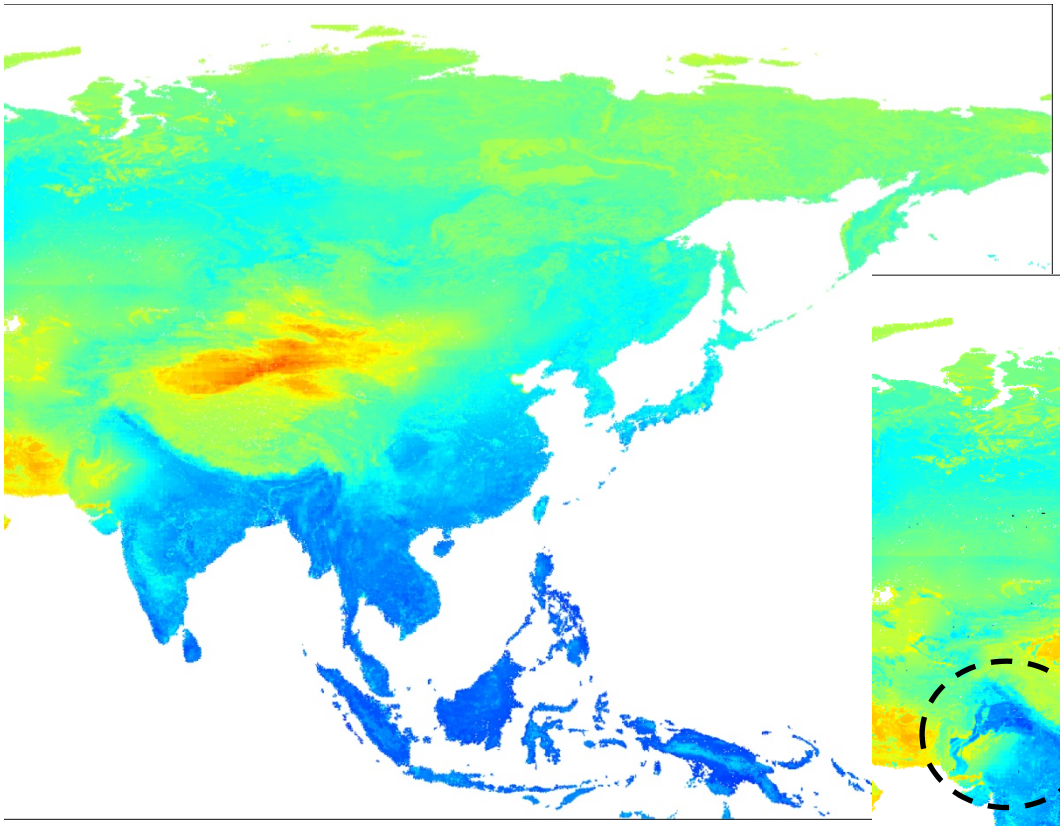
Percentage Contribution of Groundwater Depletion (GWD) to Sea Level Change 1900-2100



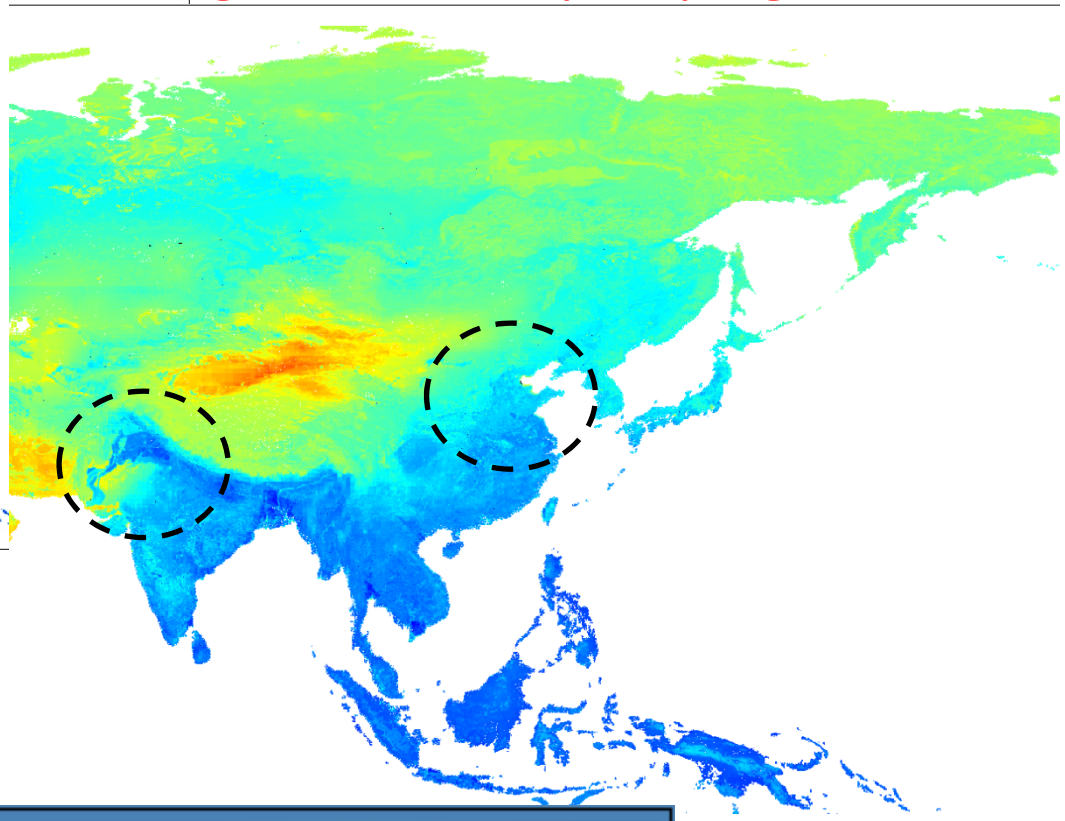
Other Estimates of Contribution of Groundwater Depletion (GWD) to Sea Level Change 1950-present



Big “But”..what about land-atmospheric interaction??

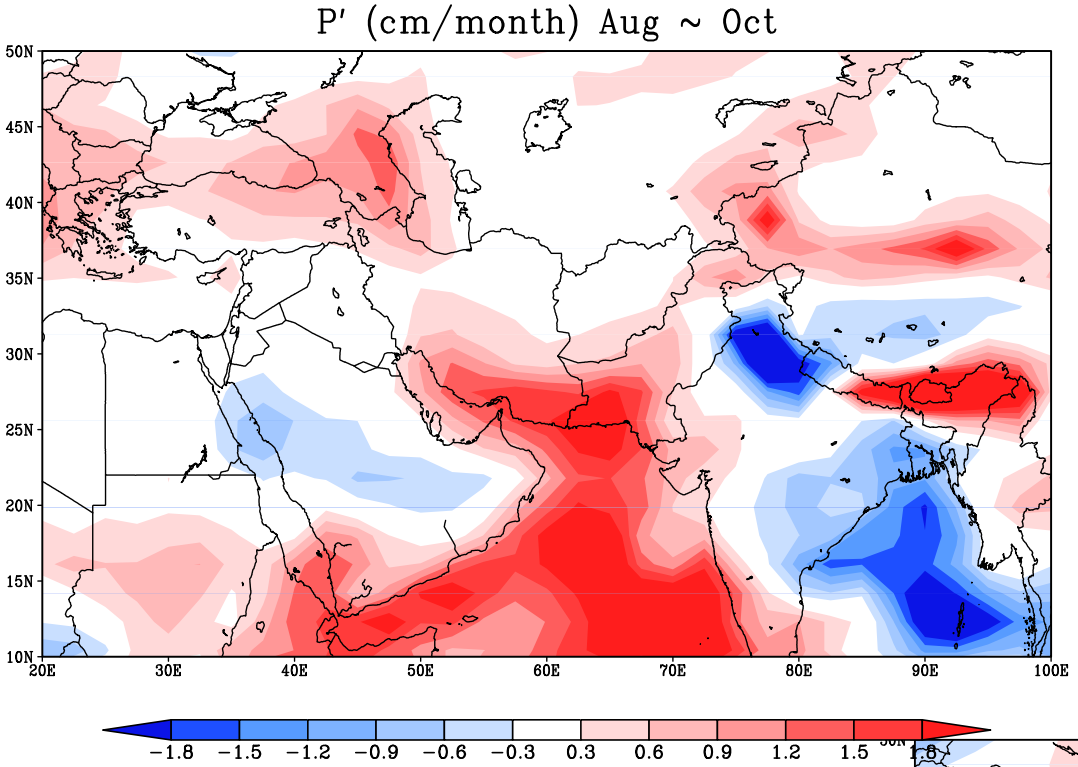


Enhanced evapotranspiration from irrigation and groundwater pumping!!



Pristine vs. Humans

[m/day]

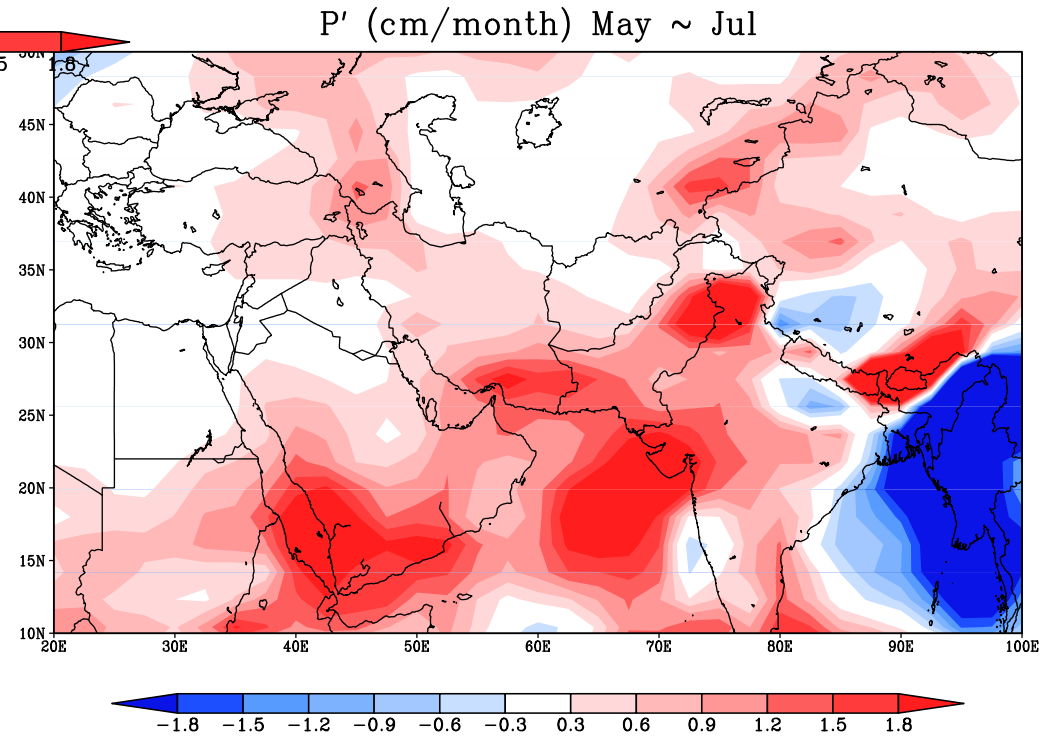


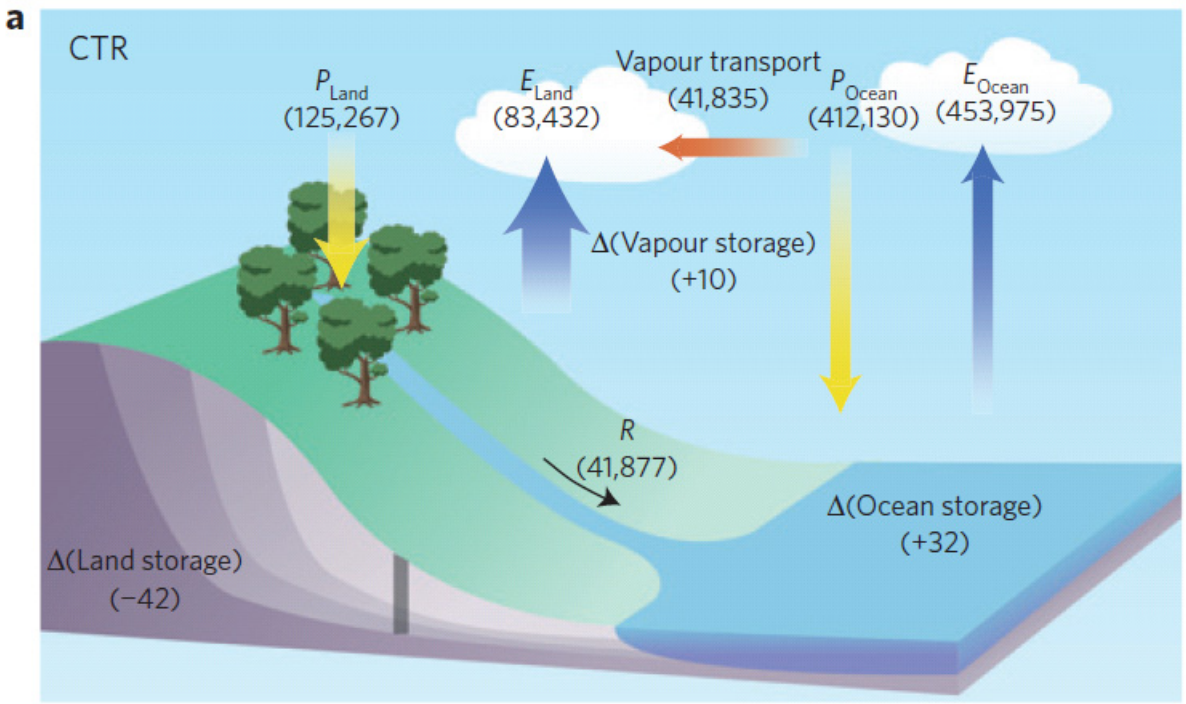
Transient runs (using the irrigation water from 1960~2010, and compare to that without irrigation water applied), in this case, the ocean mode is activated so there will be ocean feedbacks.

Enhanced evapotranspiration

=>

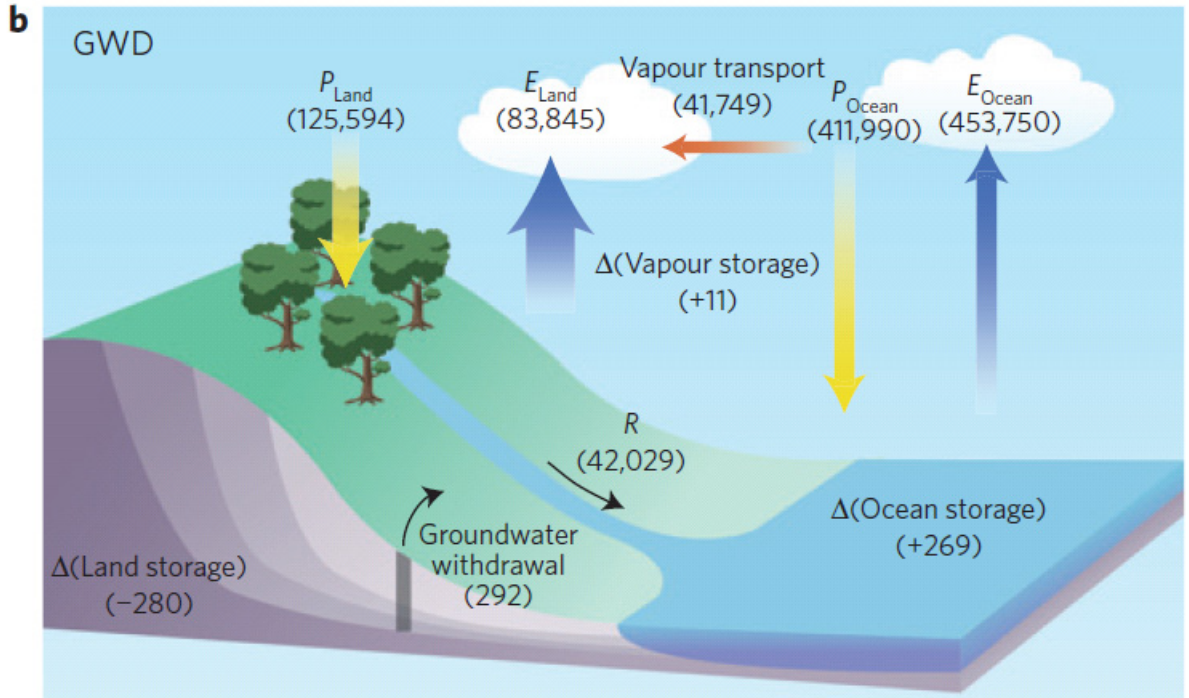
Change in regional precipitation?





NCAR CESM (CAM4 + CLM4+ POP2)

Coupled land -atmospheric simulation



Global mean annual water budget over the land and ocean (km^3/yr)

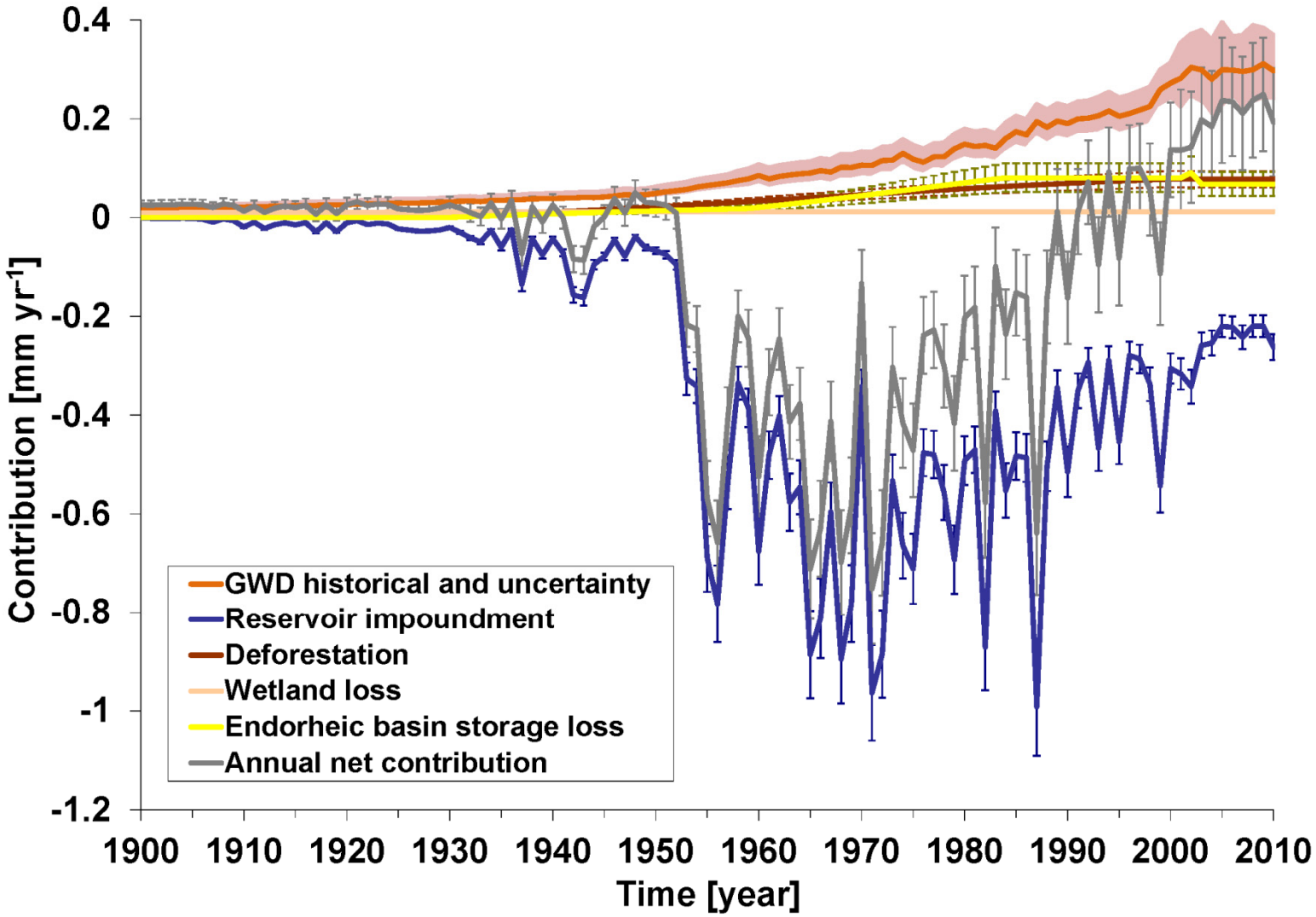
	Precipitation (P)	Runoff (R)	Evaporation (E)	Total storage change (ΔS)	Precipitation minus evaporation	Atmospheric water vapour change
Land				$P-R-E$	$P-E$	
(1) GWD	125,594	42,029	83,845	−280	41,749	-
(2) CTR	125,267	41,877	83,432	−42	41,835	-
(3) GWD-CTR	+327	+152	+413	−238	−86	-
Ocean				$P+R-E$	$P-E$	-
(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^{-1})	1993-2010 (mm yr^{-1})
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)

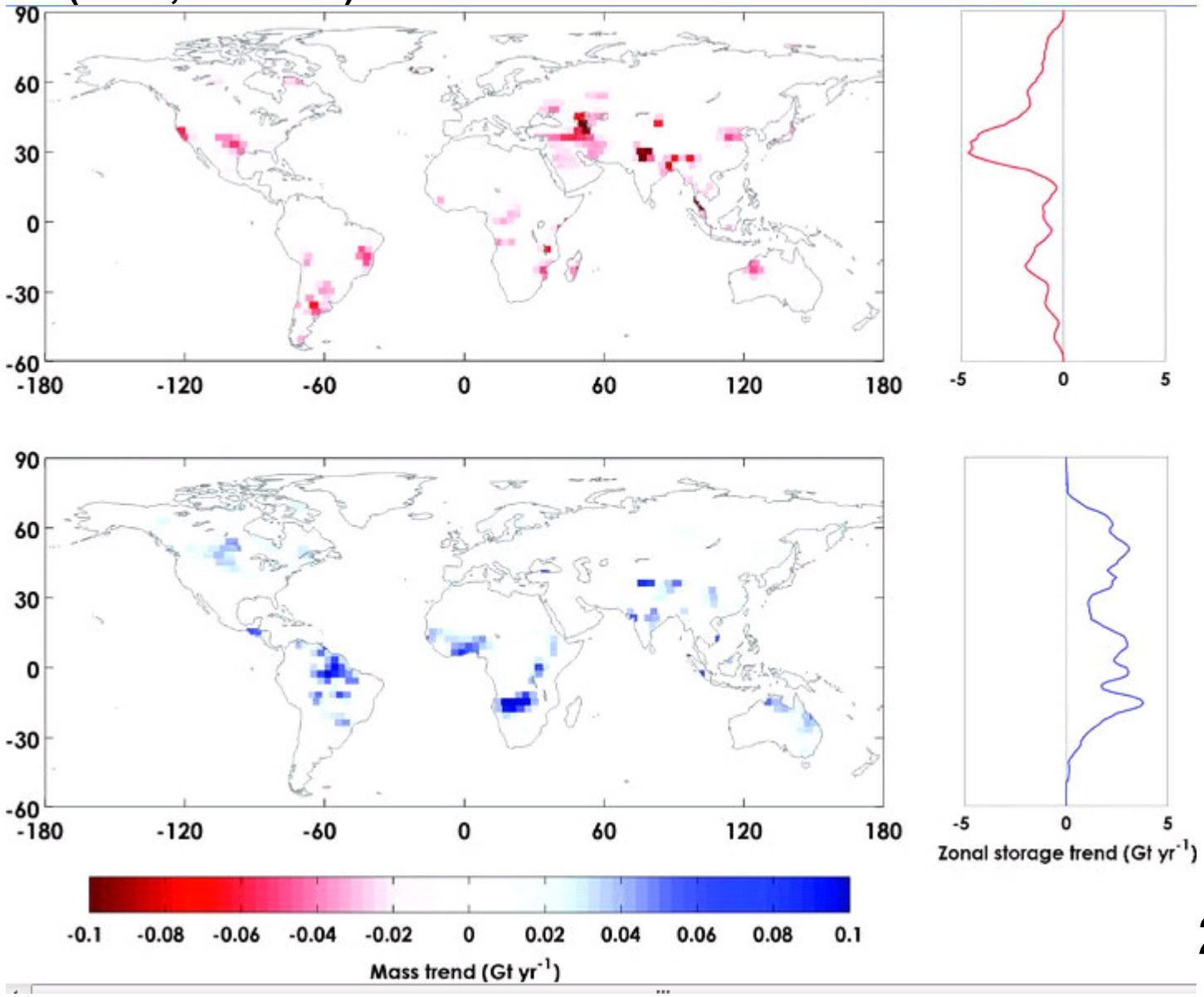
Net Contribution from TWS Change to Sea Level 1900-2010

Wada et al. (2016; Nature Climate Change)



Still Big "But"…what about climate-driven water storage change??

Reager et al. (2015; Science)



Finally….overview of land water budget and contribution to sea-level rise

Wada, Reager, Chao, Lo, et al. (2017; Surveys in Geophysics)

		2002–2014 (mm year^{-1})
Observed SLR	Church et al. (2013) (1993–2010)	3.2 (±0.4)
	Cazenave et al. (2014) (2003–2011)	2.4
Estimated Land water storage		
Groundwater	Wada et al. (2016)	0.30 (±0.1)
Reservoir impoundment	This study	−0.24 (±0.02)
Deforestation (after 2010)	This study	0.035
Wetland loss (after 1990)	This study	0.075
Endorheic basin storage loss		
Caspian	This study	0.109 (±0.004)
Aral Sea	This study	0.036(±0.0003)
Climate-driven land water storage	Reager et al. (2016)	−0.71 (±0.2)
Net land water storage	This study	−0.40 (±0.2)
	IPCC AR5 (1993–2010)	0.38 (±0.12)

Conclusions and Outlook

- **Groundwater pumping (800 km^3) has more than doubled in size since 1960, and is projected to double by the end of this century.**
- **Groundwater contribution (positive) to SLR is exceeding the reservoir contribution (negative) over the last decade**
- **In land-atmospheric coupled simulation, only 80% of groundwater depletion going to oceans.**
- **Contribution of groundwater depletion to sea-level increased from 0.002 ($\pm$0.004) mm yr^{-1} in 1900 to 0.27 ($\pm$0.04) mm yr^{-1} in 2000.**
- **Although uncertain, groundwater depletion is the dominant land water contribution to sea-level rise.**
- **Climate-driven contribution (negative over the last decade) can be substantial over a decade period, but how about a century scale??**
- **Due to climate-driven and reservoir contribution, groundwater contribution is cancelled out, and the overall contribution is negative.**