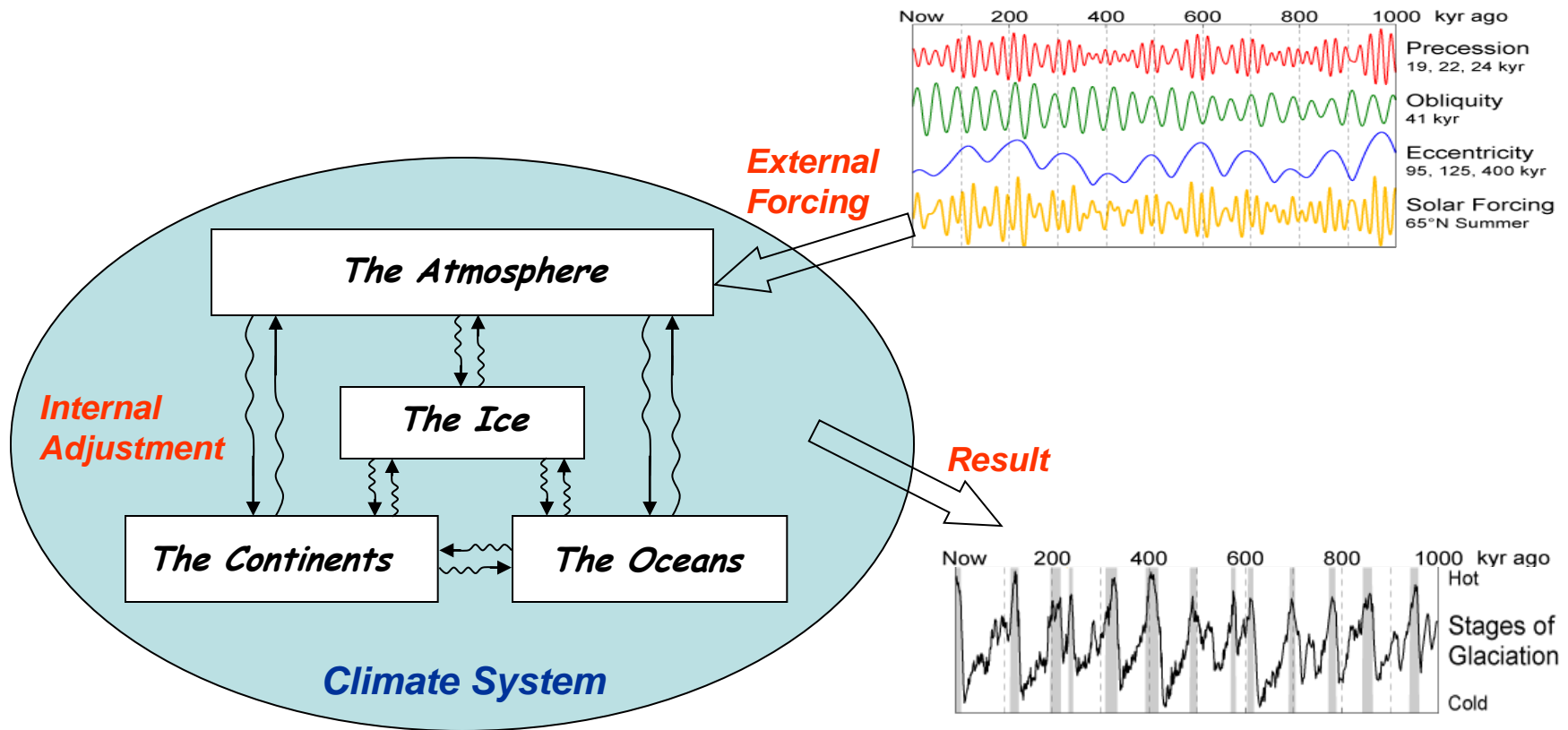
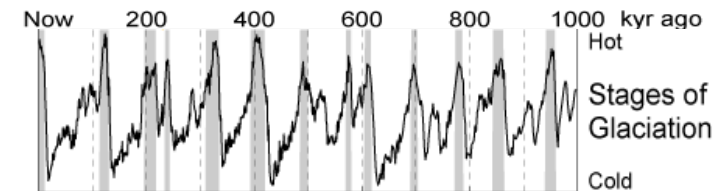
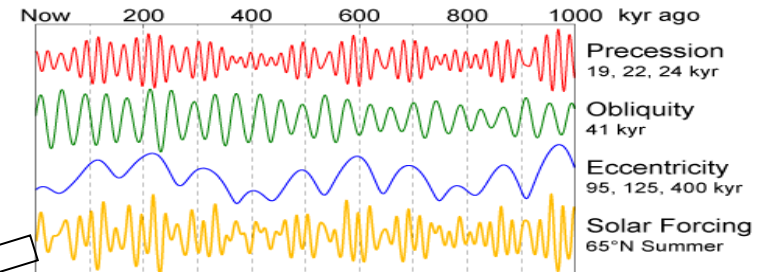
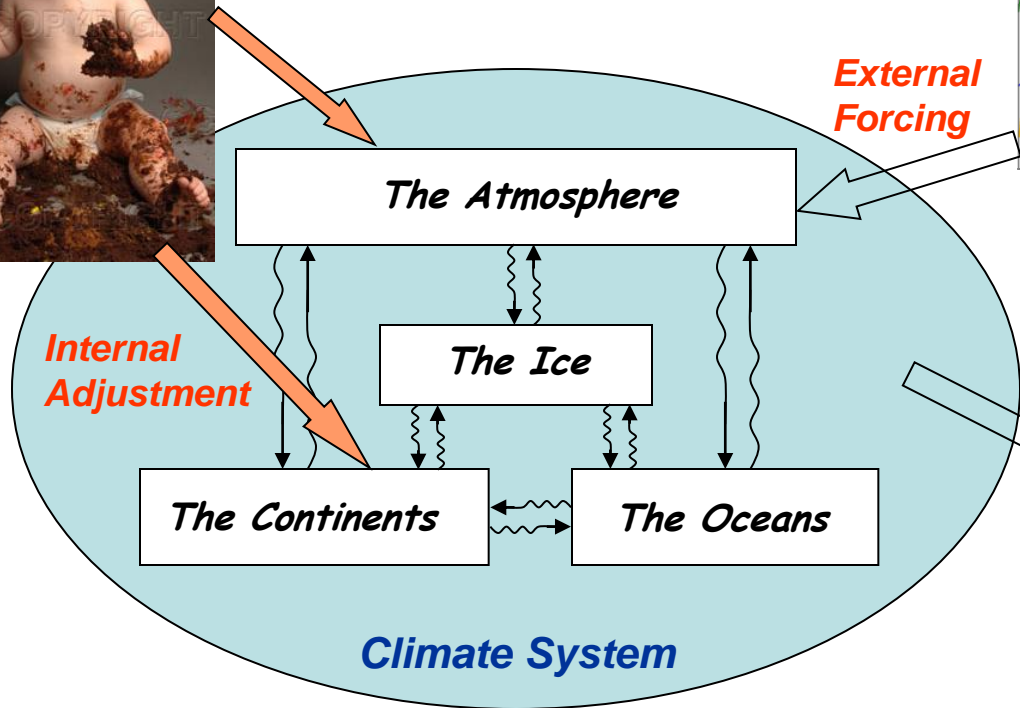


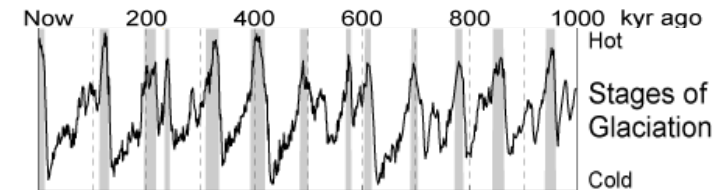
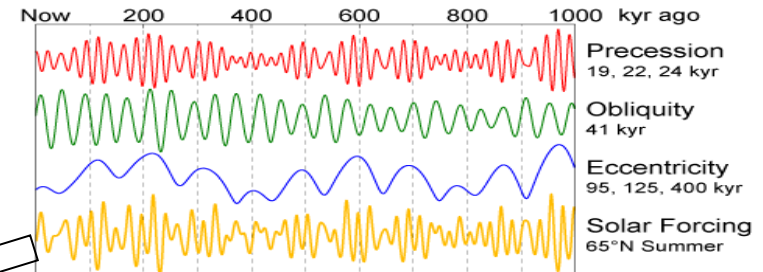
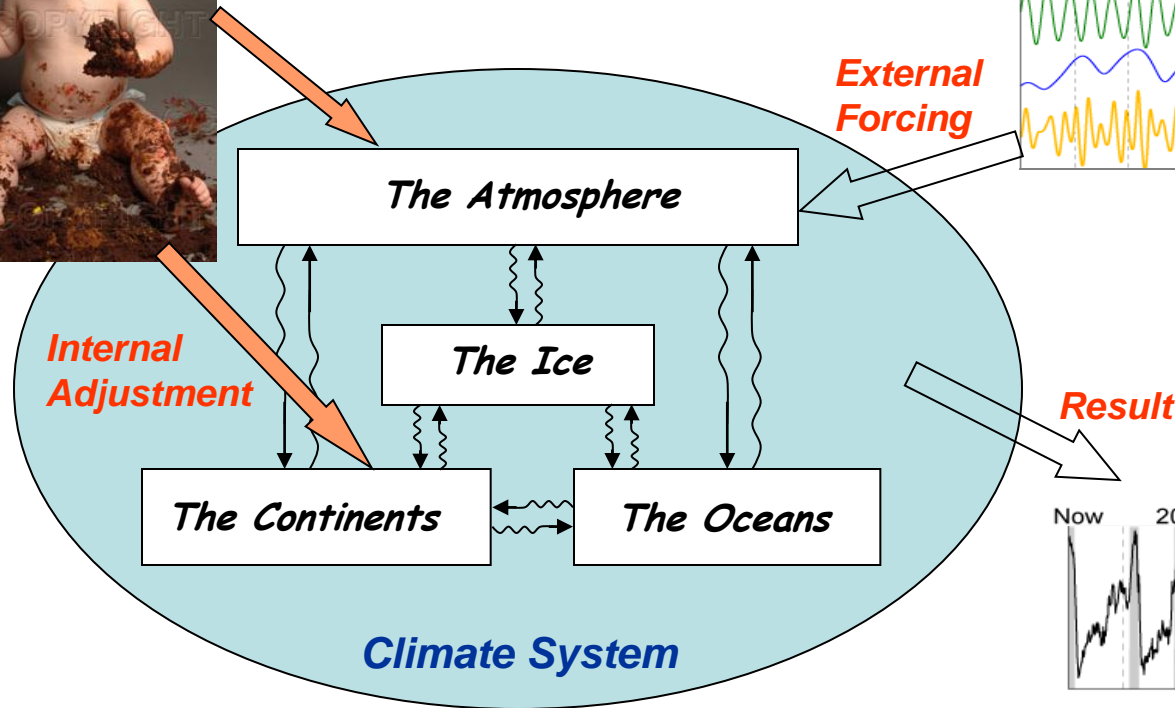
# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks



# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks

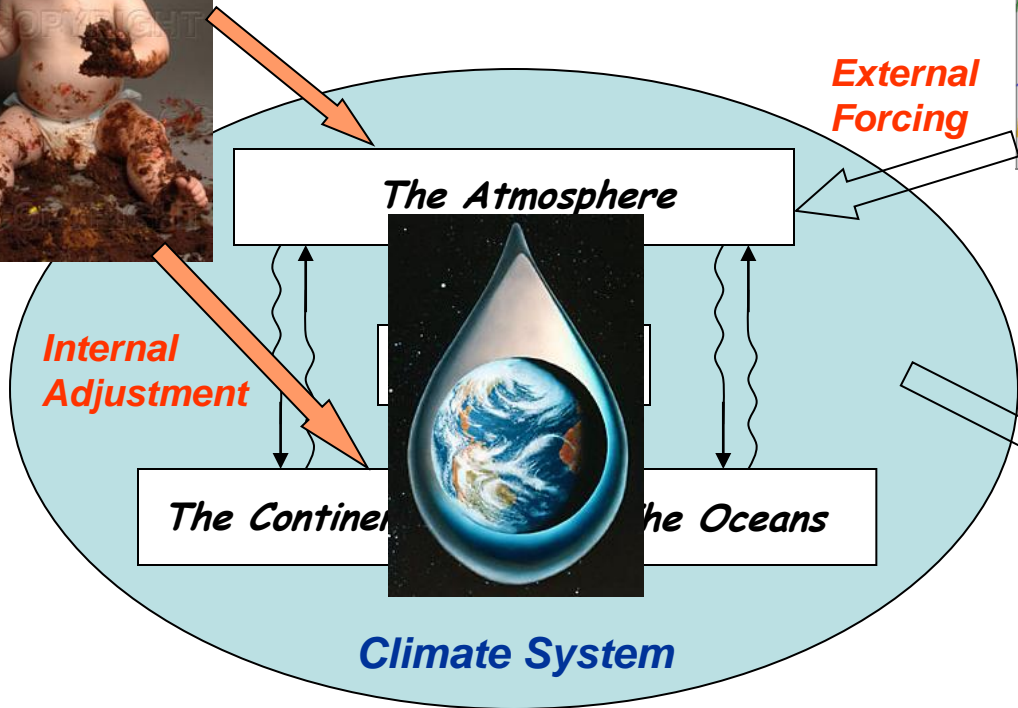


# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks

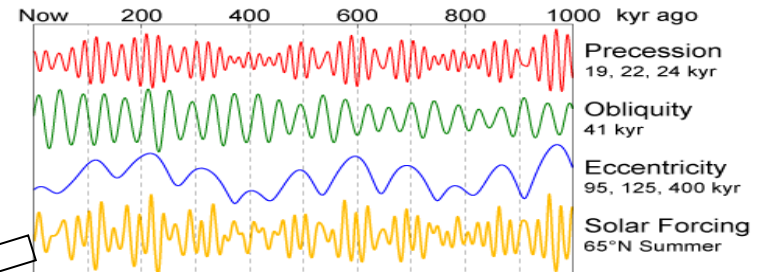


**Questions:** How did the internal adjustment work in the past?  
How will it work in the future?

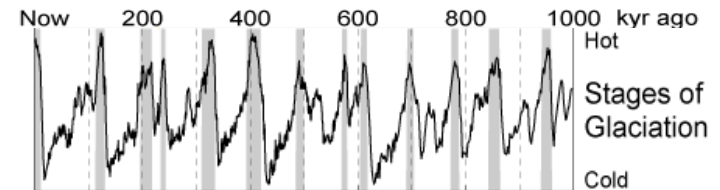
# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks



**External  
Forcing**

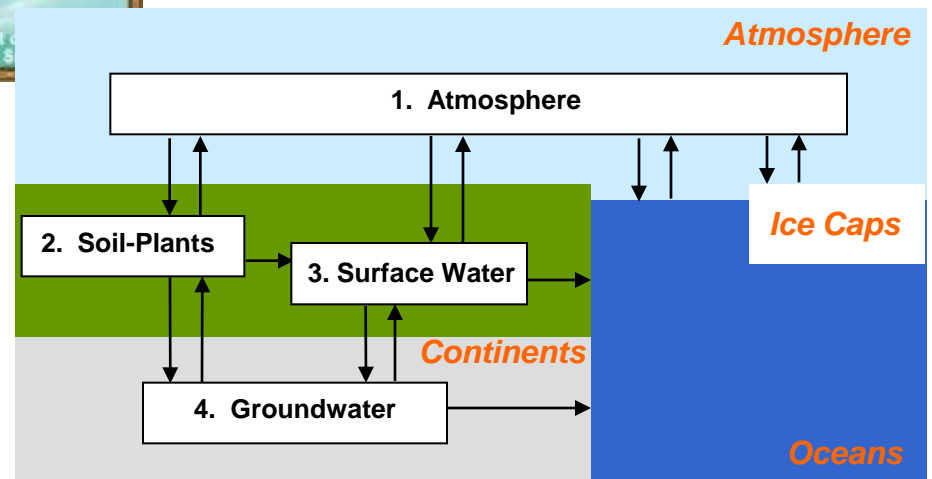
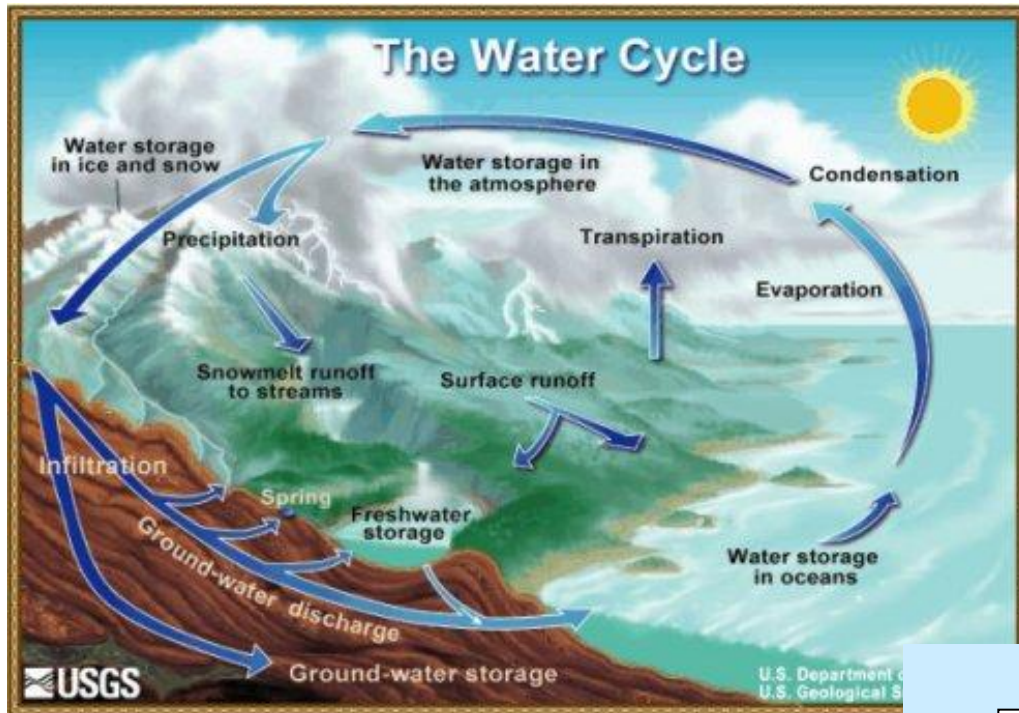


**Result**



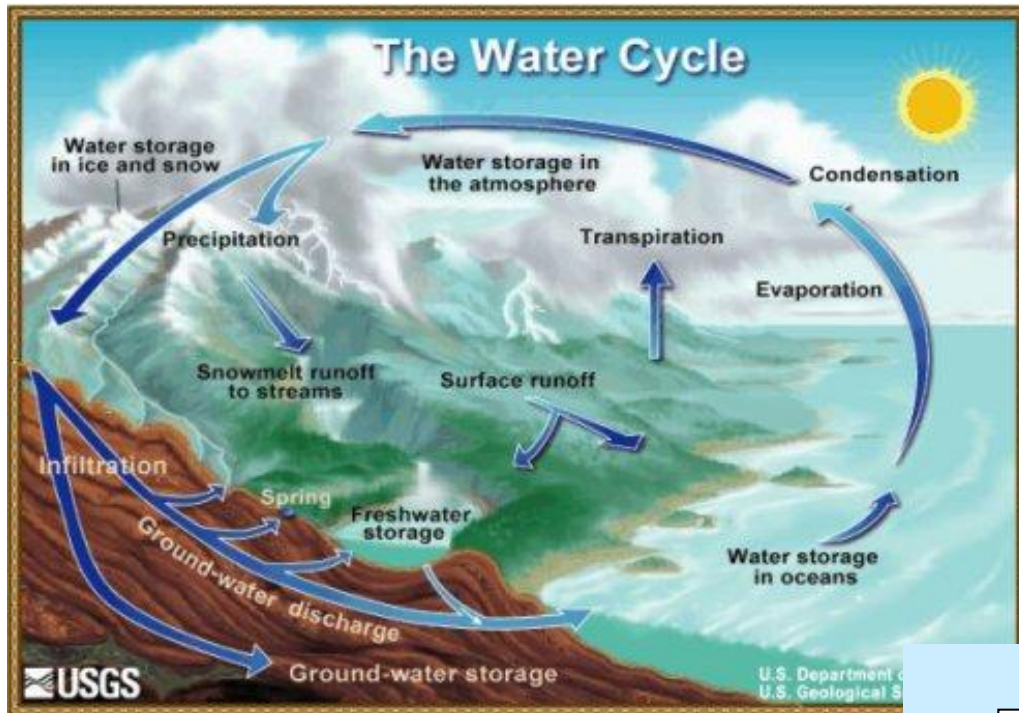
**Questions:** How did the internal adjustment work in the past?  
How will it work in the future?  
**What is the role of the water cycle?**

# The Water Cycle



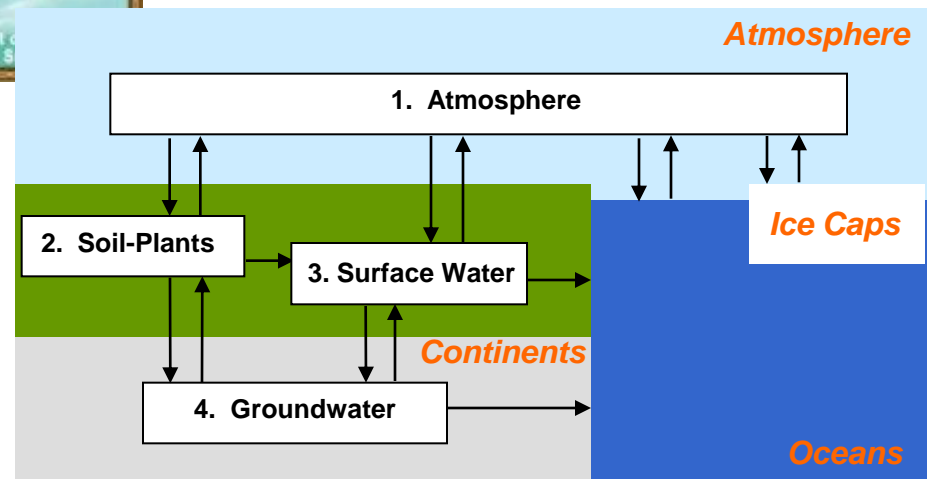


# The Water Cycle

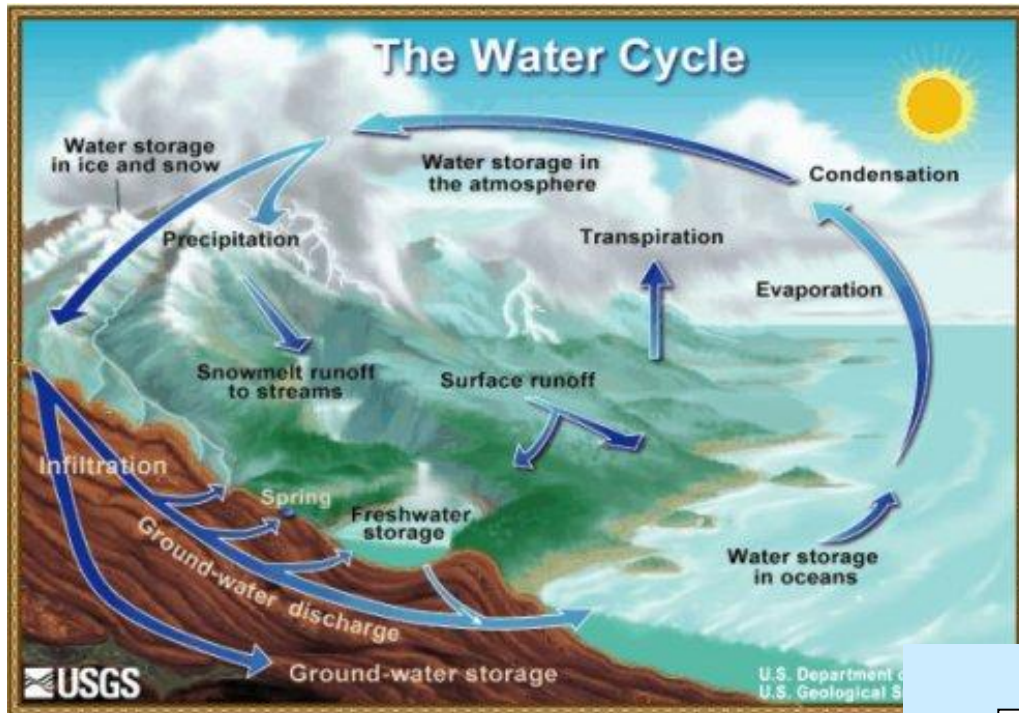


## Question:

- What components are important, what are not?

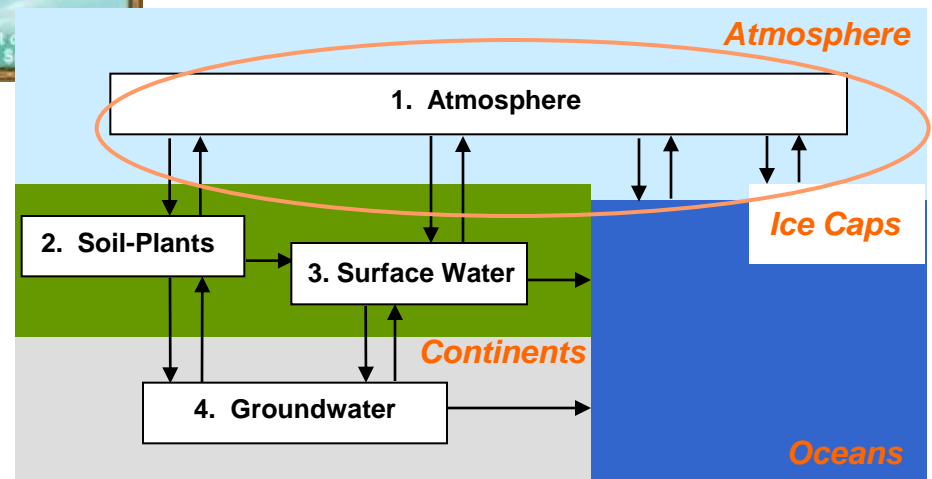


# The Water Cycle

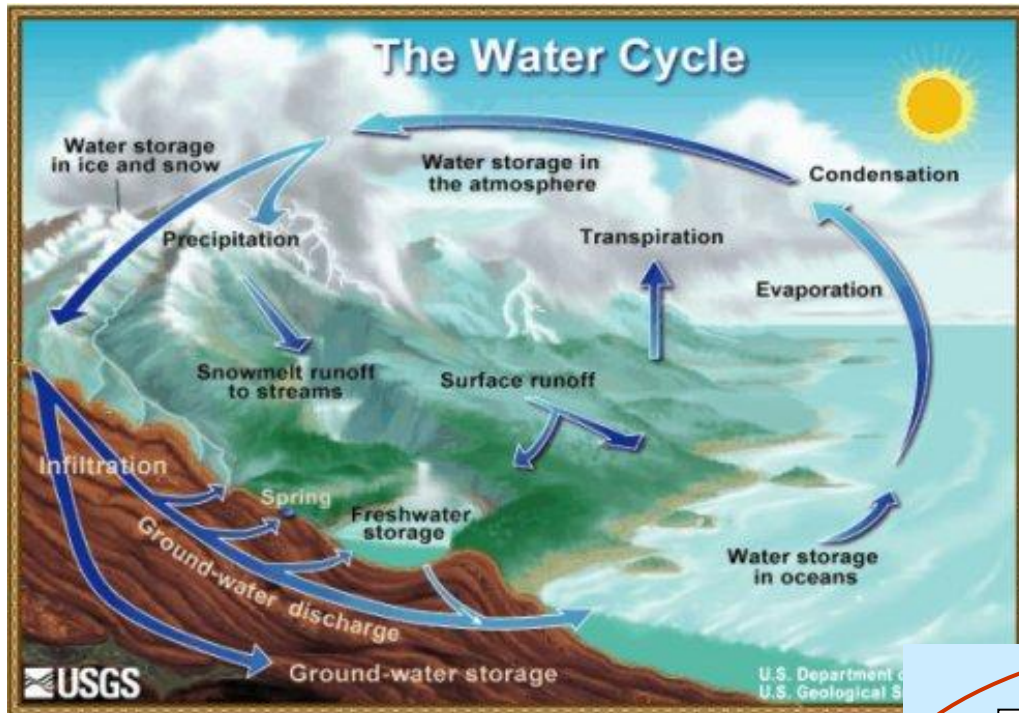


## Question:

- What components are important, what are not?

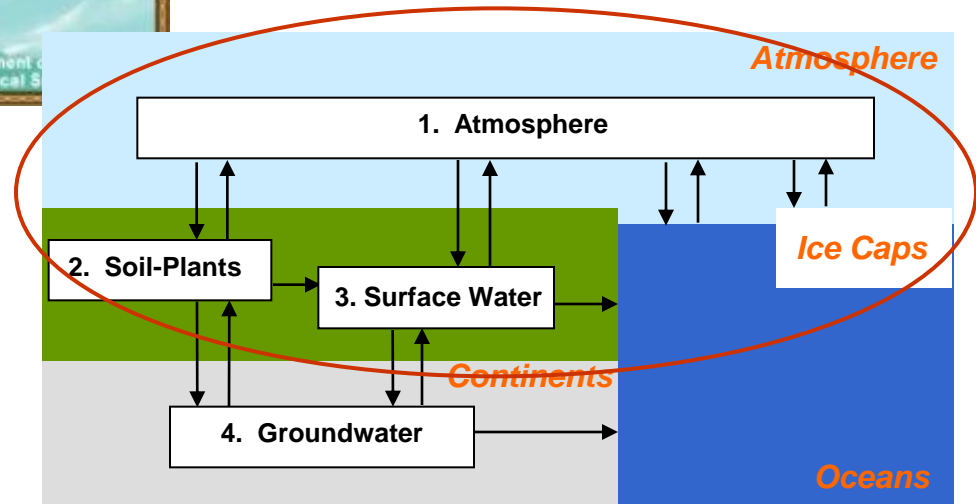


# The Water Cycle



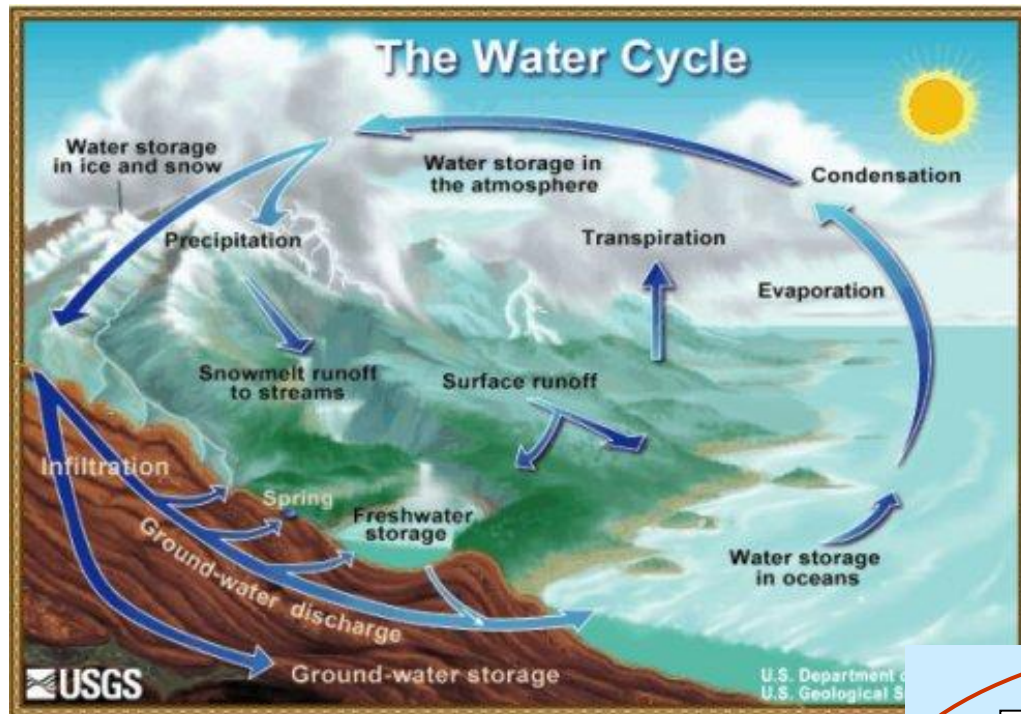
## Question:

- What components are important, what are not?



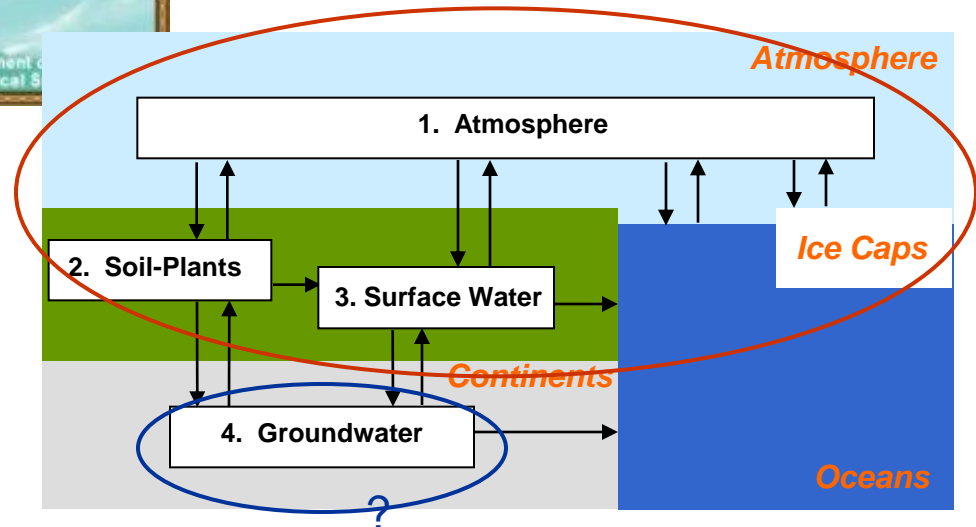


# The Water Cycle



## Question:

- What components are important, what are not?
- Is the groundwater important?

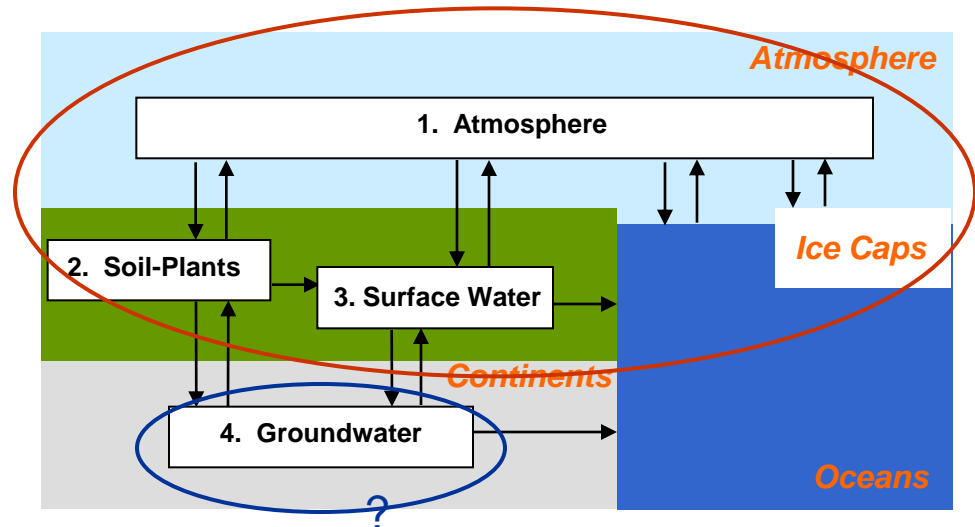


# Is the Groundwater Reservoir Important?

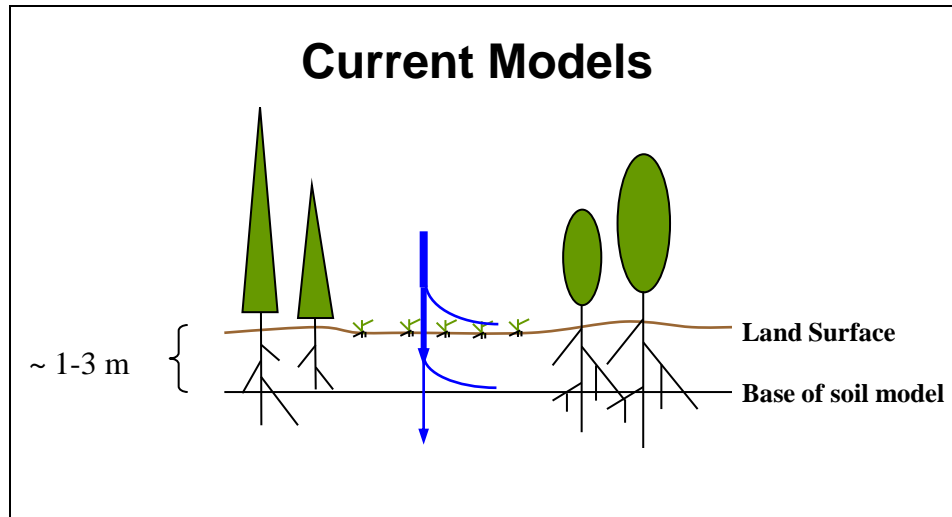
## What does groundwater do?

- Temporarily holds wet-period surplus, and later supplies dry-period deficit
- Sustains stream flow in humid and sub-humid climate, receives losing streams in arid climate
- It is the slow component of the system: regulating dynamics ?

Reservoirs	Volume (1000 km <sup>3</sup> )	Residence Time
Oceans	1,338	~ 4,000 years
Atmosphere	0.01	hours - days
Ice	24.1	10 - 10,000 years
Soil Water	0.02	hours - months
Surface Water	0.14	days - years
Groundwater	23.4	days - 10,000 years

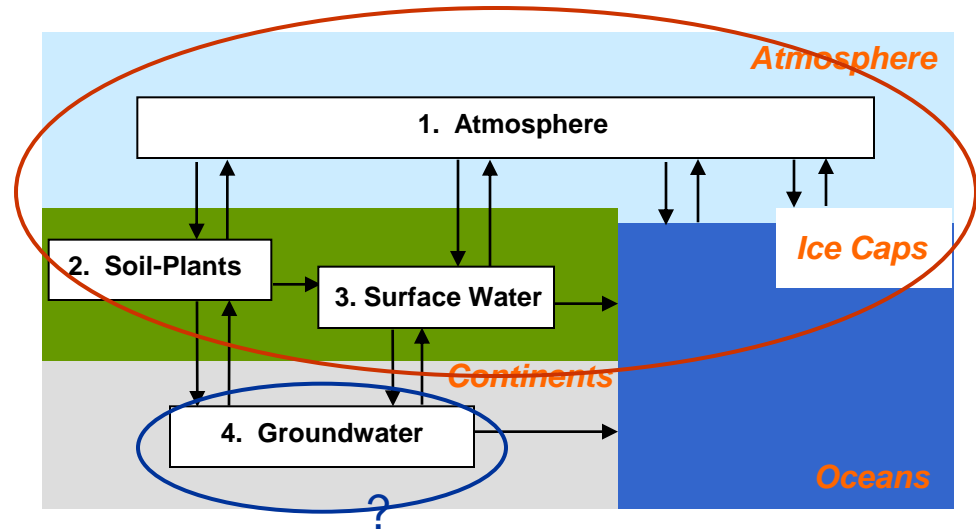


# Is the Groundwater Reservoir Important?



## Without Groundwater:

- Model climate drifts away (little memory)
- Cannot close the water budget
- Model impact on water resources unrealistic and inconsistent
- Feedback cut off
- Uncertainty in future predictions



# NCEP-NCAR and ECMWF 40-yr Reanalysis Surface Water Budget for Mississippi River Basin (Roads and Betts, 2000)

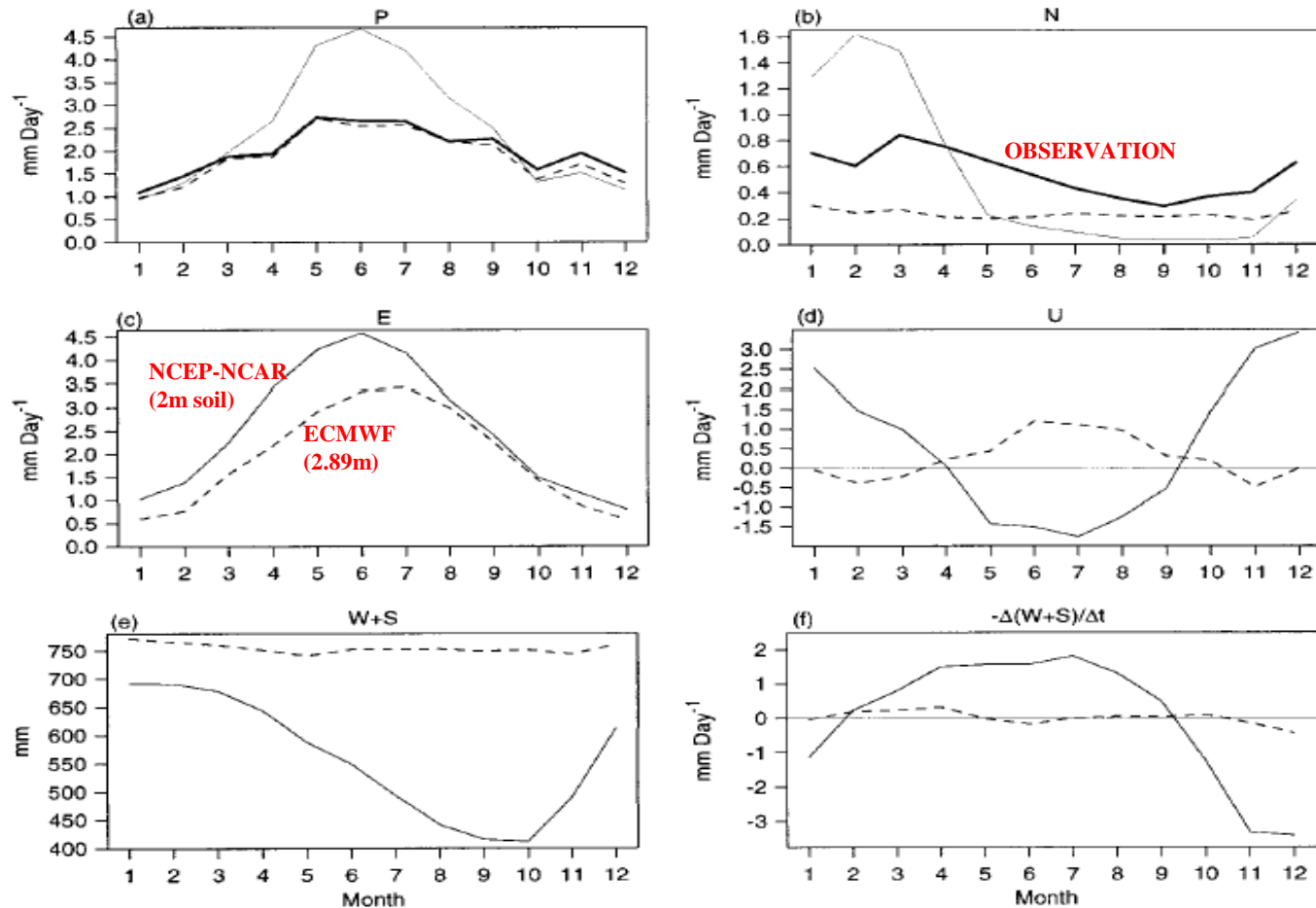
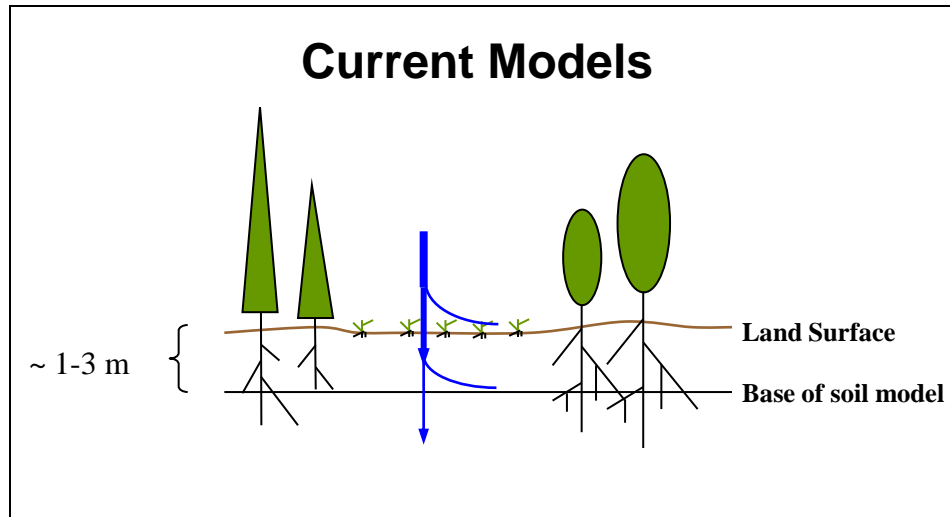


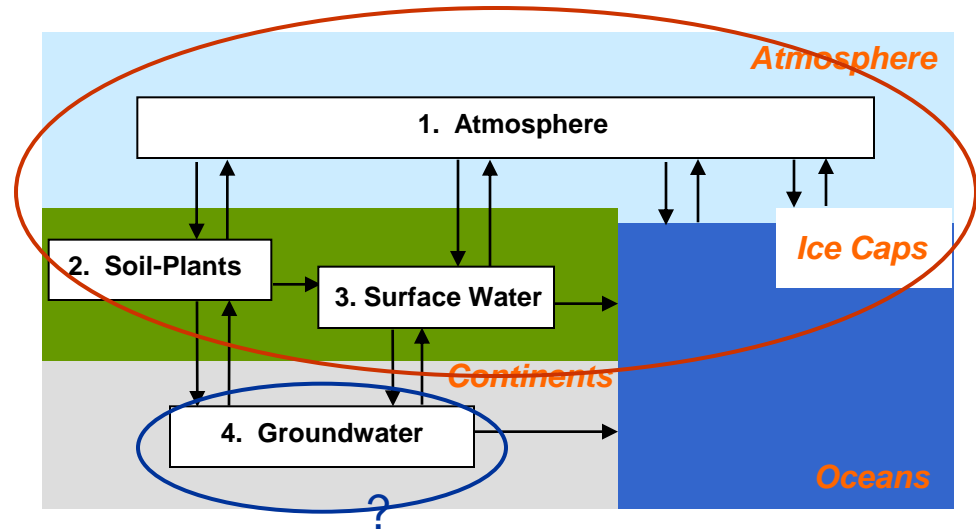
FIG. 1. Seasonal surface water NCEP-NCAR (light solid) and ECMWF (dashed) reanalysis budgets for the Mississippi basin: (a) precipitation ( $P$ ); (b) runoff ( $N$ ); (c) evaporation ( $E$ ); (d) artificial surface water forcing ( $U$ ); (e) total soil water plus snow ( $W$ ); and (f) surface water tendency  $\Delta W/\Delta t$ . In (a) and (b) precipitation and stream flow observations are shown as heavy solid lines.

# Is the Groundwater Reservoir Important?



## Without Groundwater:

- Model climate drifts away (little memory)
- Cannot close the water budget
- Model impact on water resources unrealistic, and inconsistent
- Feedback cut off
- Uncertainty in future predictions





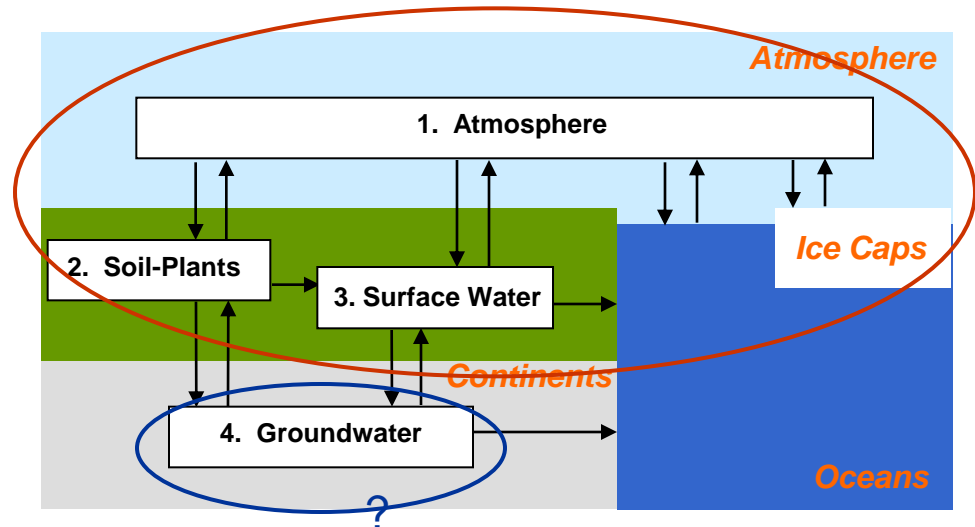
# Is the Groundwater Reservoir Important?

## Hypothesis:

- The groundwater reservoir directly influences the soil moisture (spatial structure, temporal memory) and boundary layer processes.
- It regulates the duration of floods and droughts through land-atmosphere feedbacks.
- It is essential to closing the continental water budget.

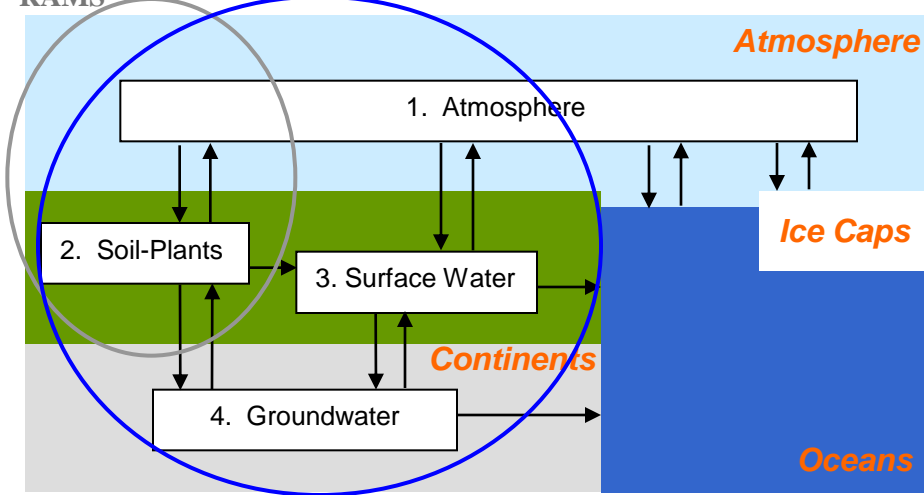
## Approach:

- Mechanistic process model
  - first principles
  - observations
- Model experiments: links?

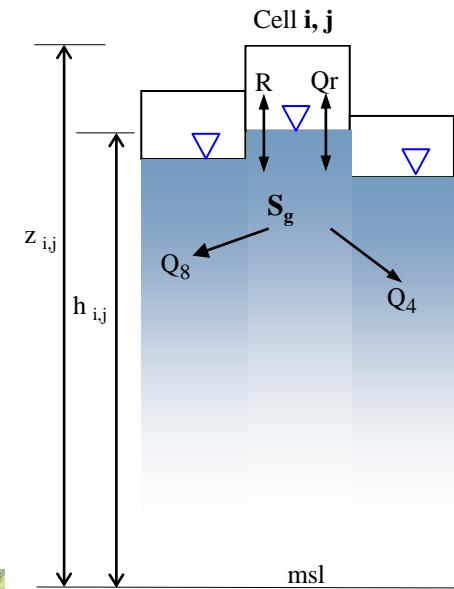


Standard  
RAMS

RAMS-Hydro



(a) Cross-section View



## Equations:

Mass balance in groundwater storage:

$$\frac{dS_g}{dt} = \Delta x \Delta y R + \sum_1^8 Q_n - Q_r$$

Darcy's Law for lateral groundwater flow:

$$Q_n = \left( \frac{K_n + K}{2} \right) \left[ w \frac{h - (z - b) + h_n - (z_n - b)}{2} \right] \left( \frac{h_n - h}{s} \right)$$

Darcy's Law for groundwater – river exchange:

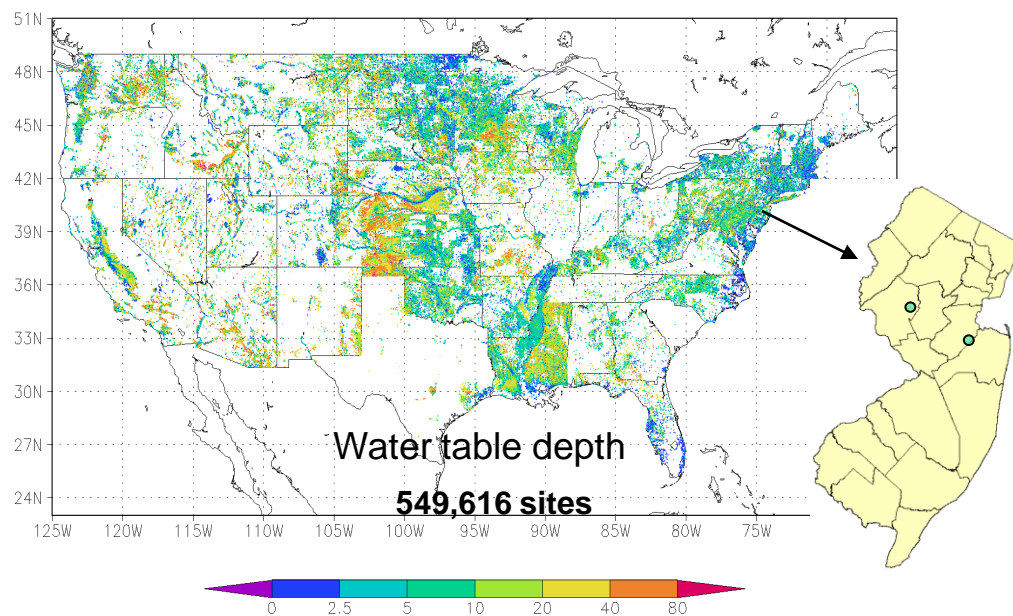
$$Q_r = (h - \bar{z}_{rb}) \left( \frac{\bar{K}_{rb}}{\bar{b}_{rb}} \right) (\bar{w}_r \sum L_r)$$

Mass balance in surface water storage:

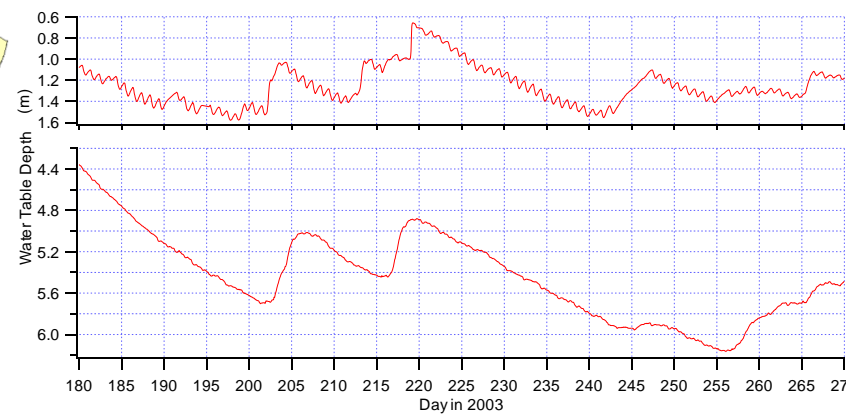
$$\frac{dS_s}{dt} = Q_h + Q_r + \sum_1^7 I_n - Q_s$$

River flow routing from cell to cell to the ocean:  
(linear reservoir model)

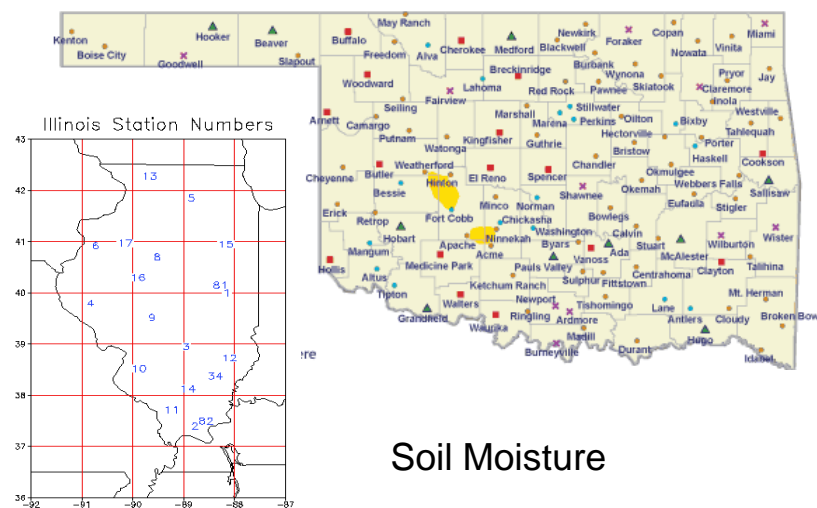
$$Q_s = S_s / k_s$$



## Observations

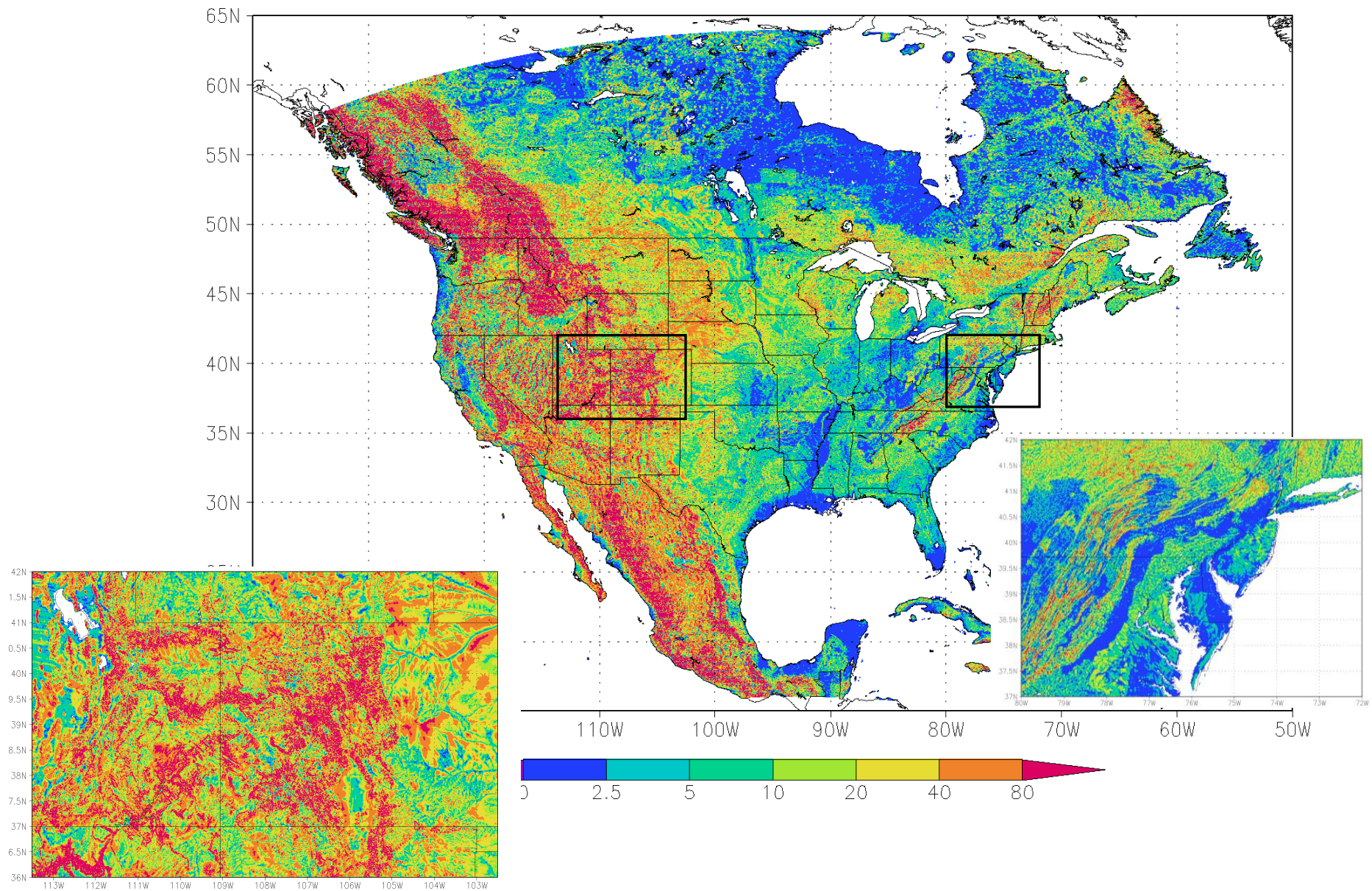


## River flow



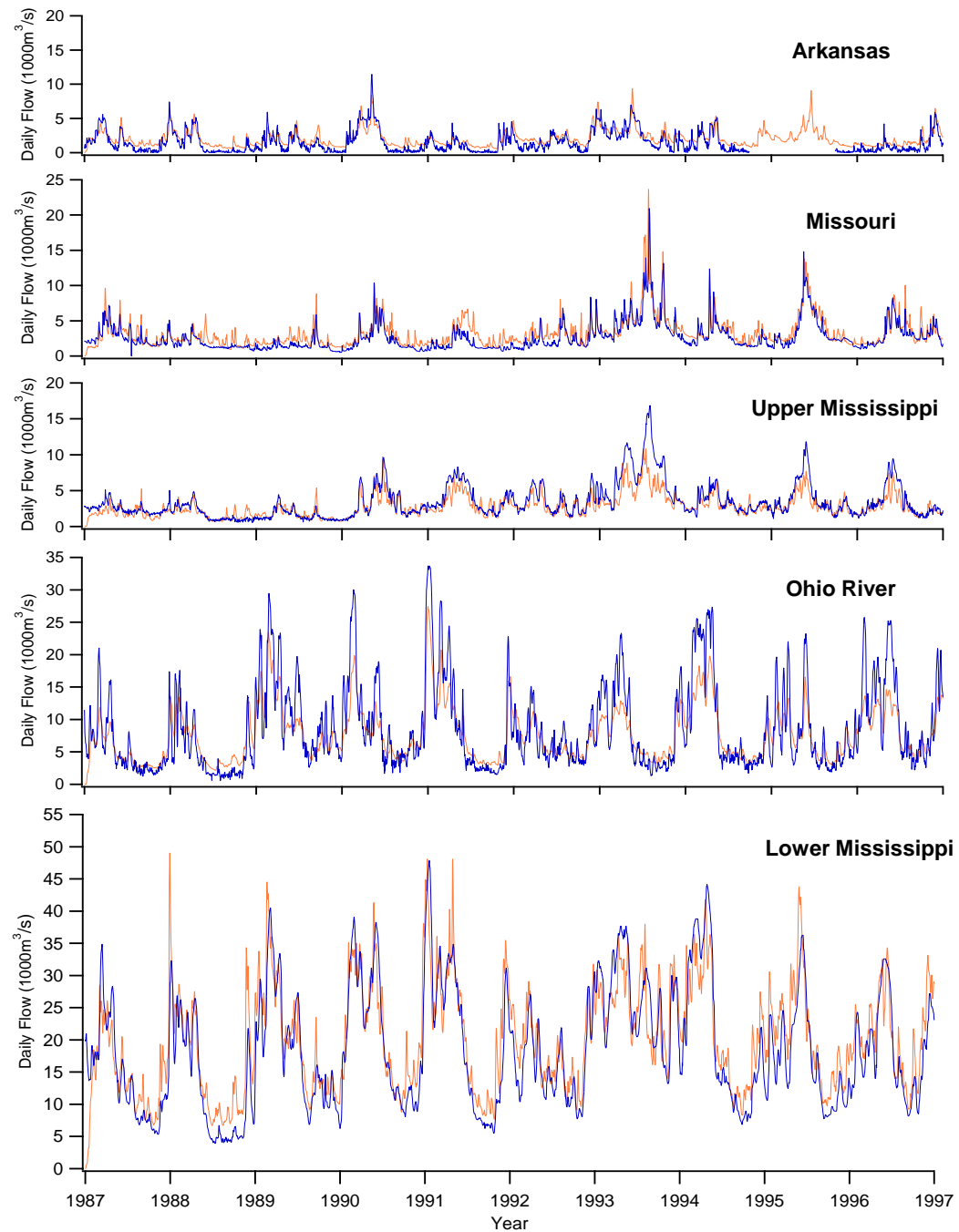
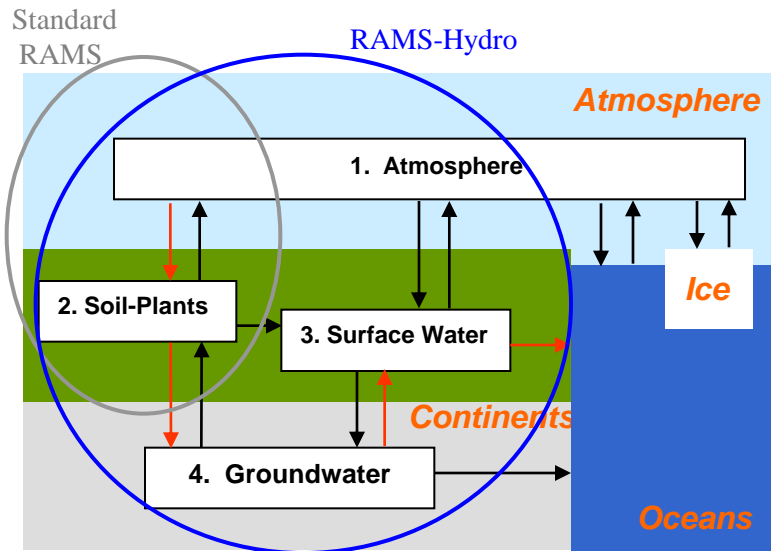
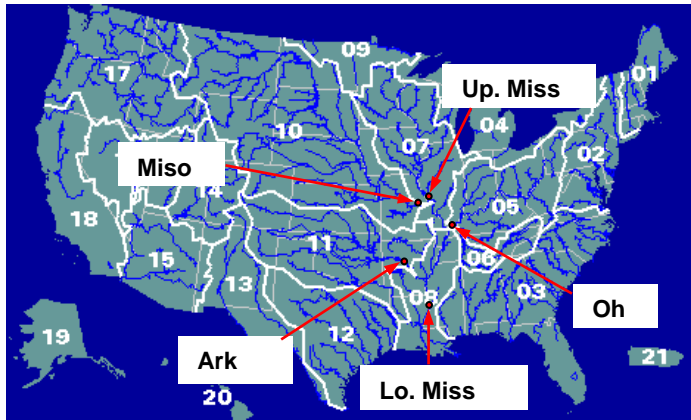


Result-1: Equilibrium water table



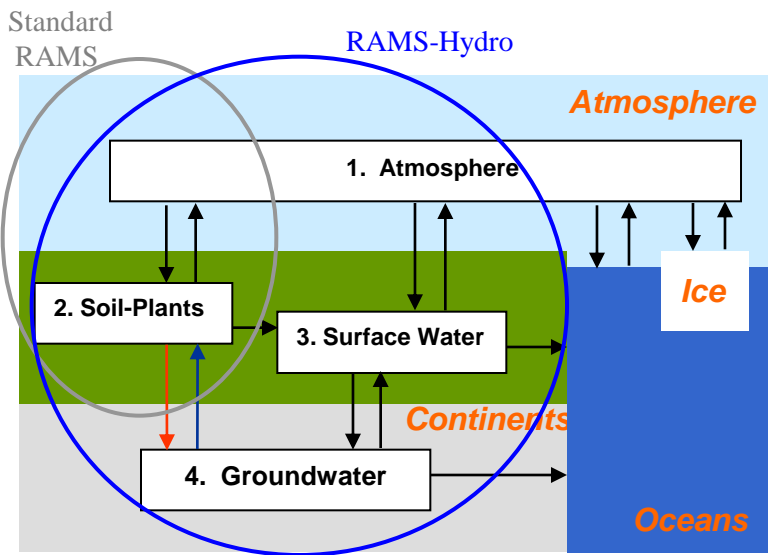


## Result-2: Groundwater - River link

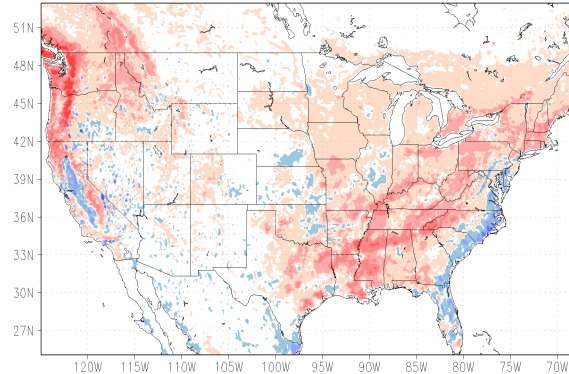


## Result-3:

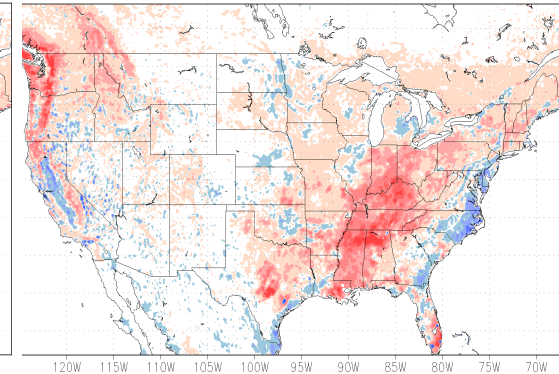
Flux across the water  
table: Soil/Plant –  
Groundwater link



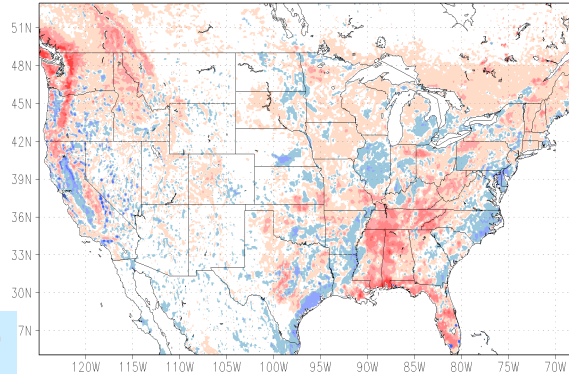
Total net recharge (mm) May



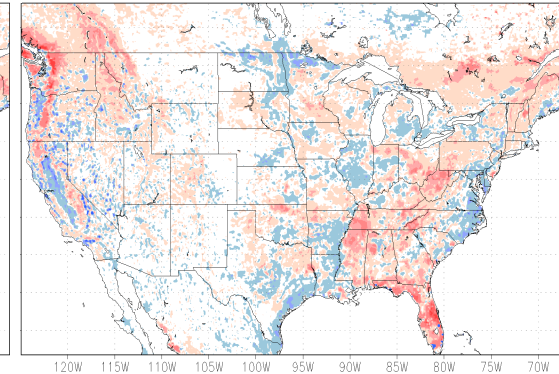
Total net recharge (mm) June



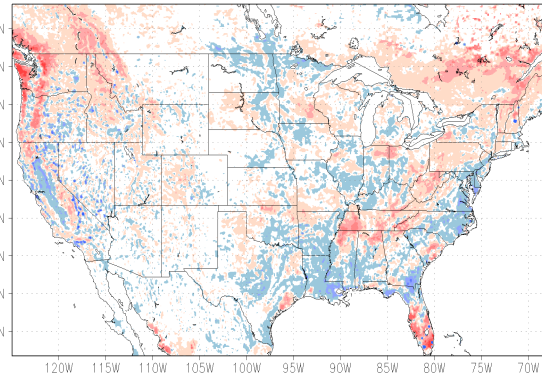
Total net recharge (mm) July



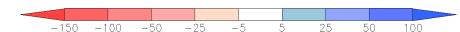
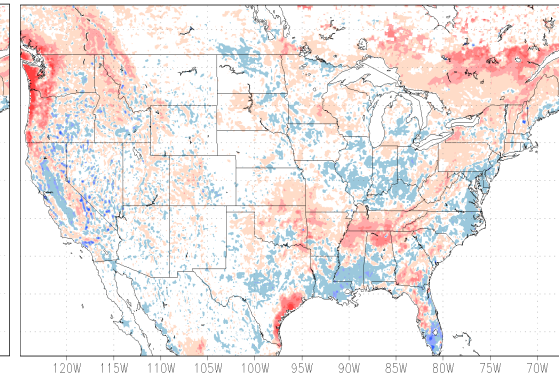
Total net recharge (mm) August



Total net recharge (mm) September



Total net recharge (mm) October

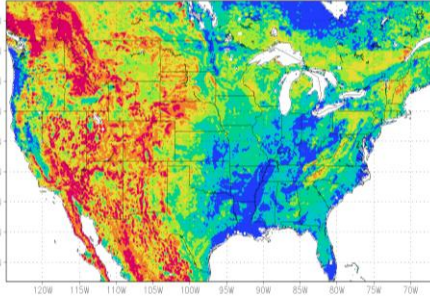




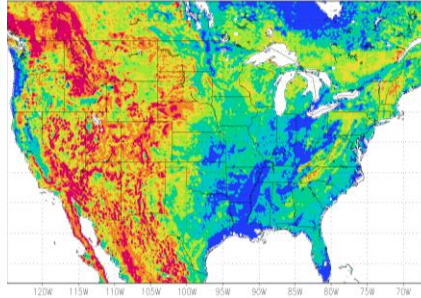
## Result-3: Groundwater – Soil/Plant link

### Water table depth

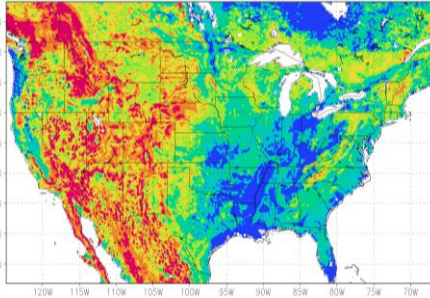
Water table depth (m) 1 May



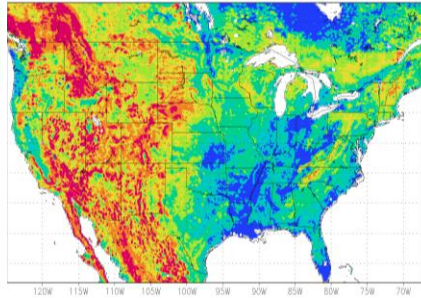
Water table depth (m) 1 June



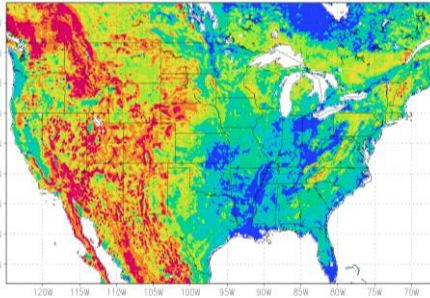
Water table depth (m) 1 July



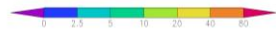
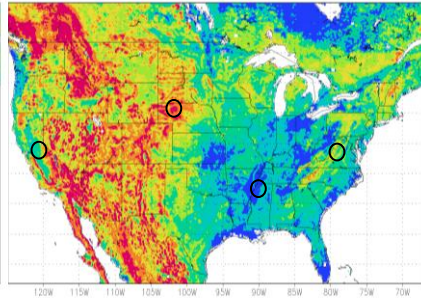
Water table depth (m) 1 August



Water table depth (m) 1 September

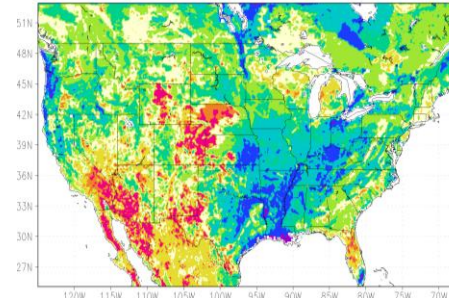


Water table depth (m) 1 October

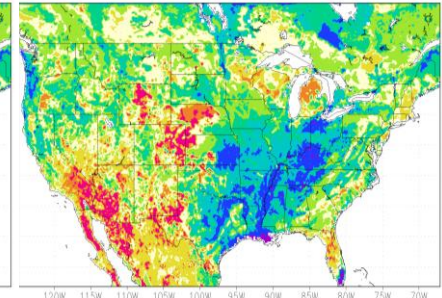


### Root zone soil water

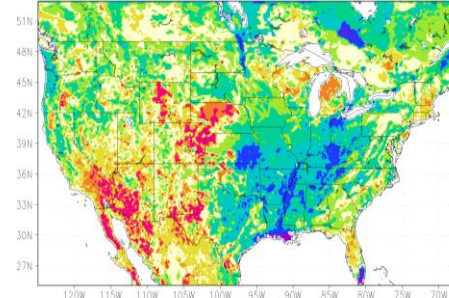
top 2m vol. soil moisture May, WT-run



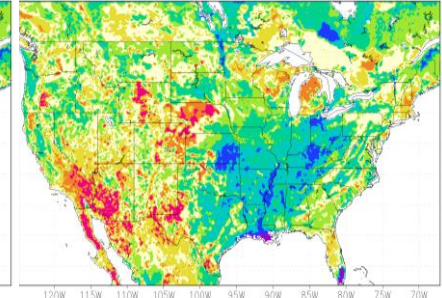
top 2m vol. soil moisture June, WT-run



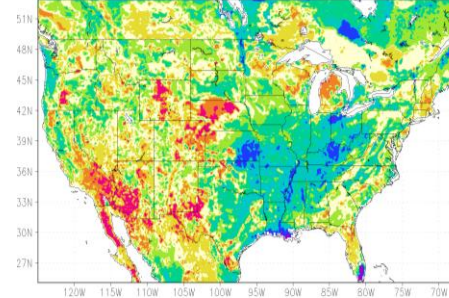
top 2m vol. soil moisture July, WT-run



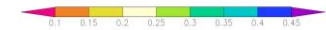
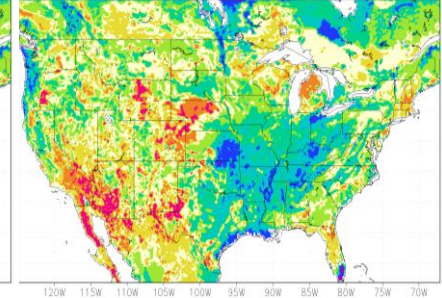
top 2m vol. soil moisture August, WT-run



top 2m vol. soil moisture September, WT-run



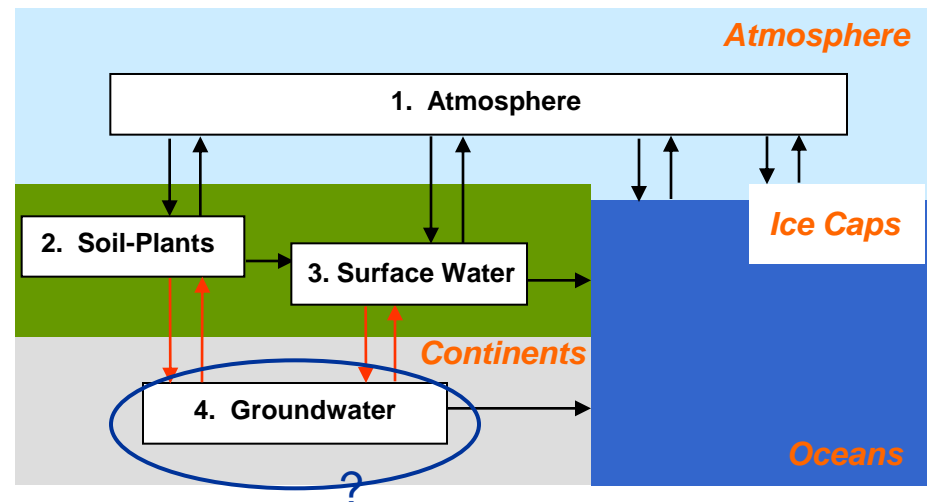
top 2m vol. soil moisture October, WT-run



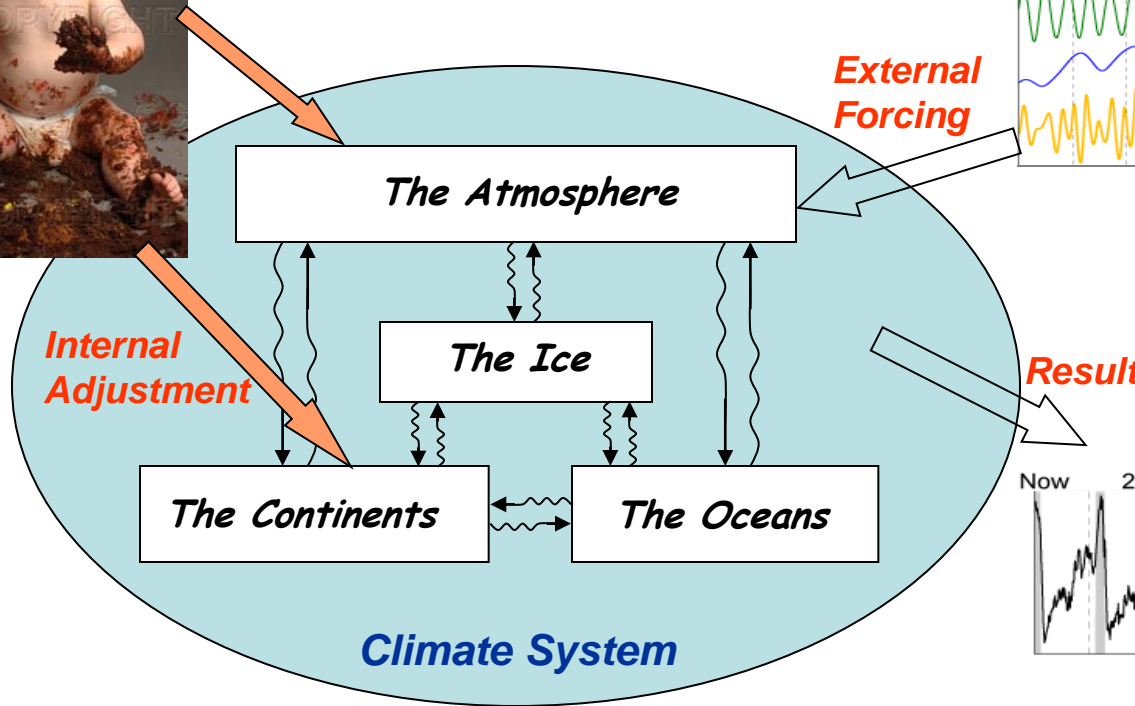
# Is the Groundwater Reservoir Important?

## Hypothesis:

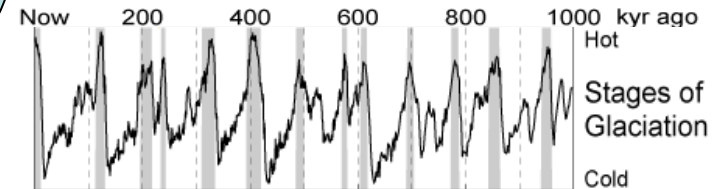
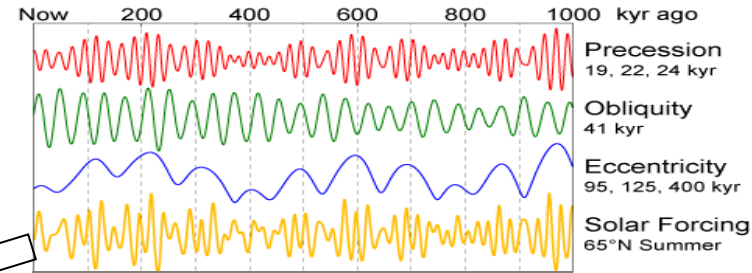
- The groundwater reservoir directly influences root zone soil water (spatial structure, temporal memory) and boundary layer processes ([Richard Anyah](#)).
- It regulates the duration of floods and droughts through its long term memory and land-atmosphere feedbacks ([Richard Anyah](#), [Deniz Kustu](#)) – NSF Water Cycle
- It is essential to closing the continental water budget ([Gonzalo Miguez-Macho](#)).



# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks



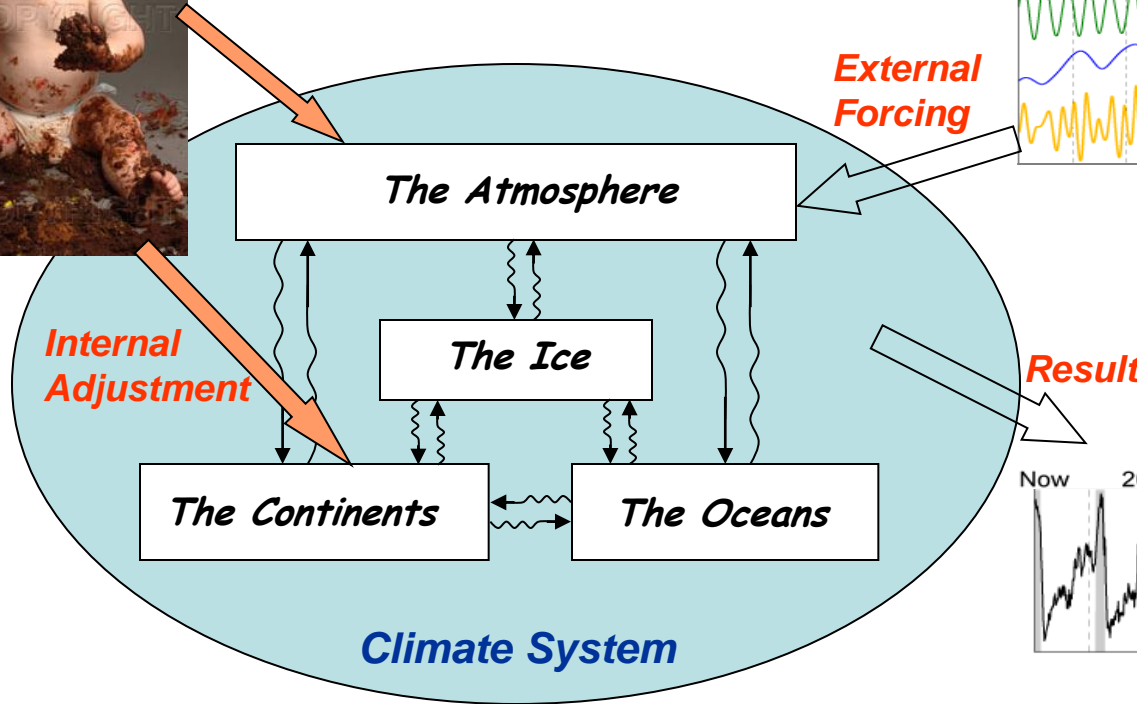
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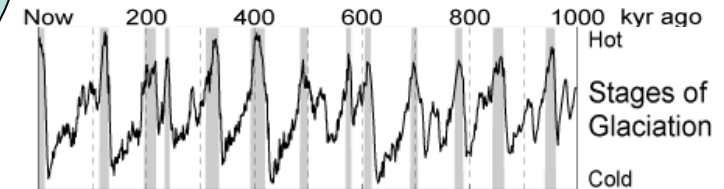
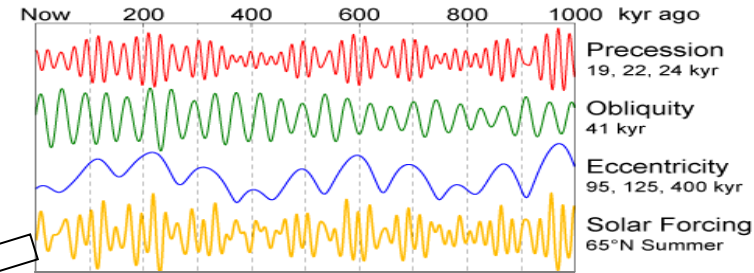
**Q1:** How does climate change modify the terrestrial water cycle?



# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks



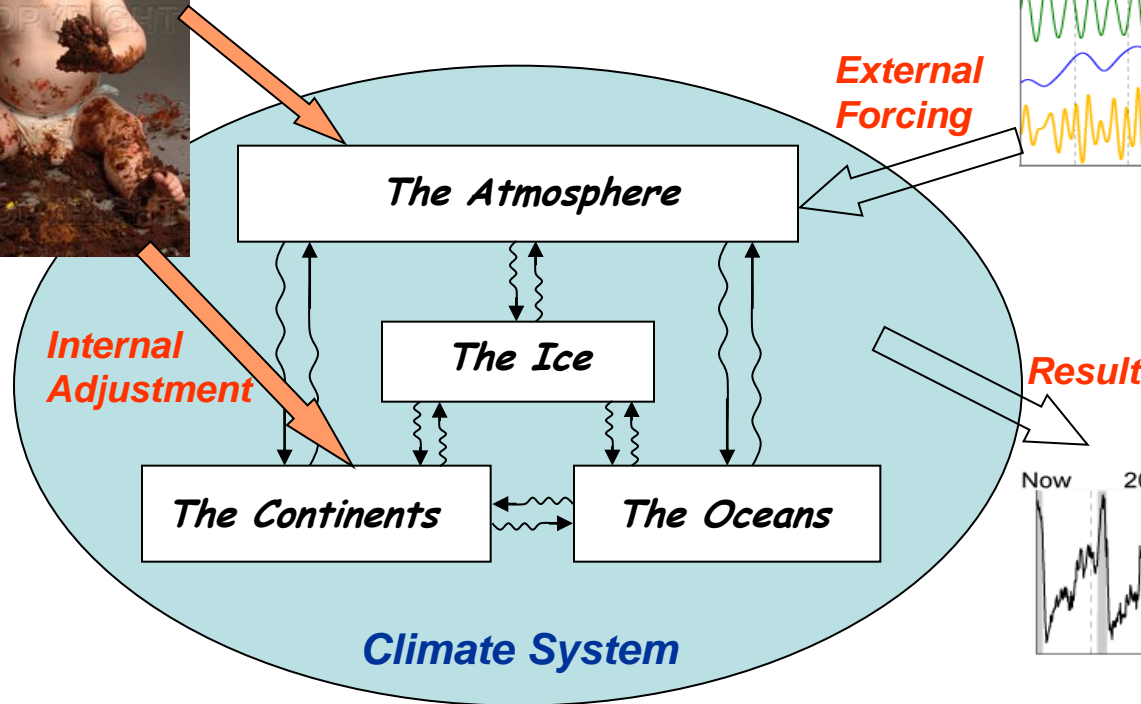
**External  
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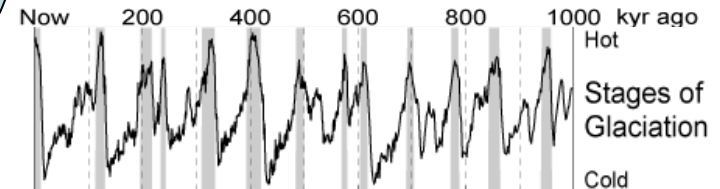
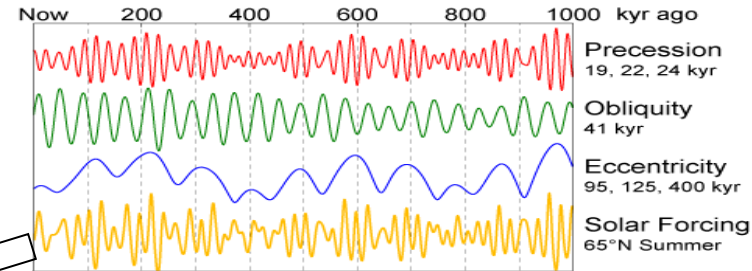
**Q1:** How does climate change modify the terrestrial water cycle?

**Q2:** How does the change in water cycle modify the climate?

# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks

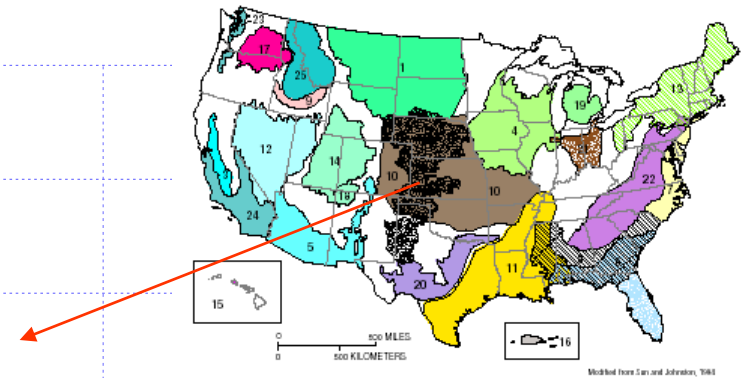
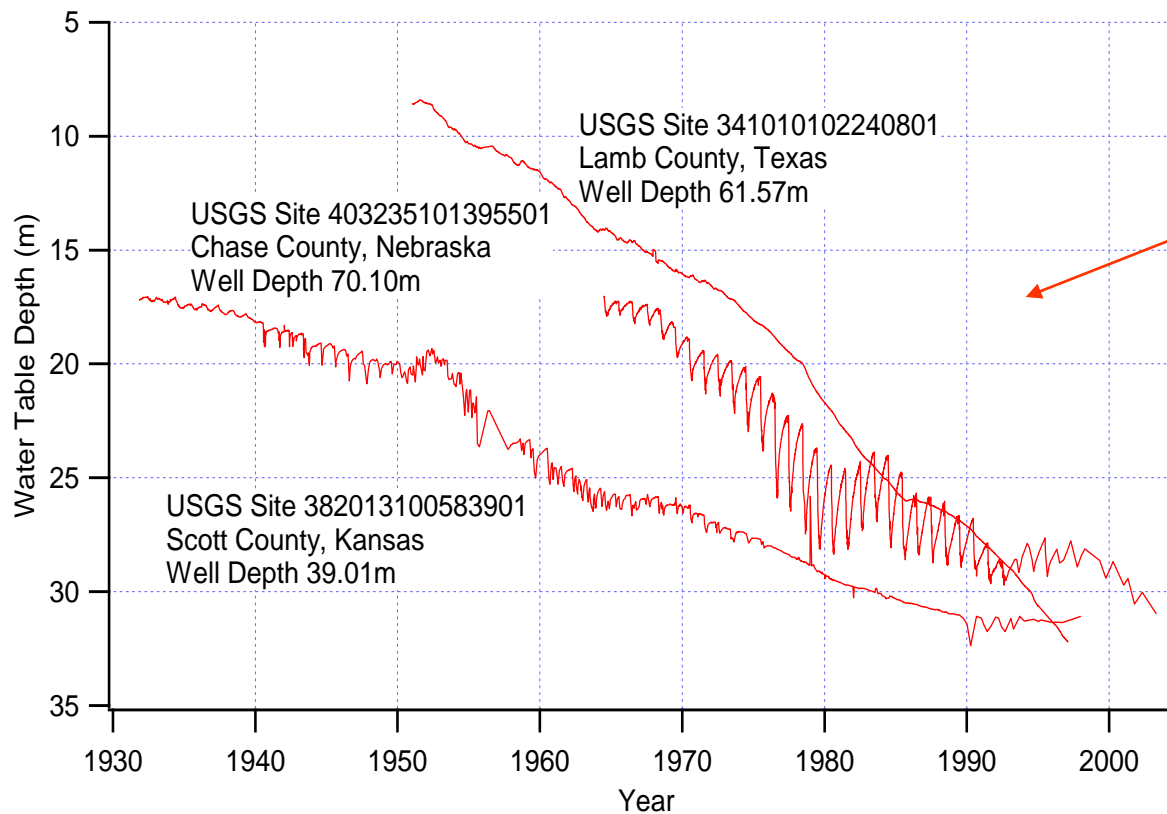


**External  
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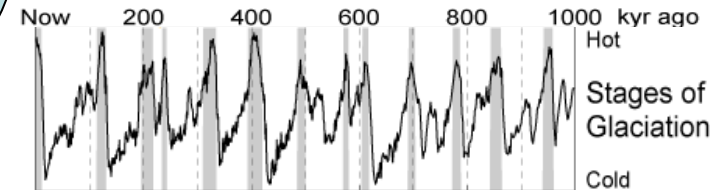
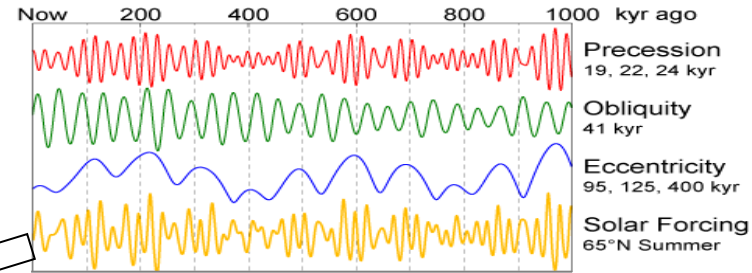
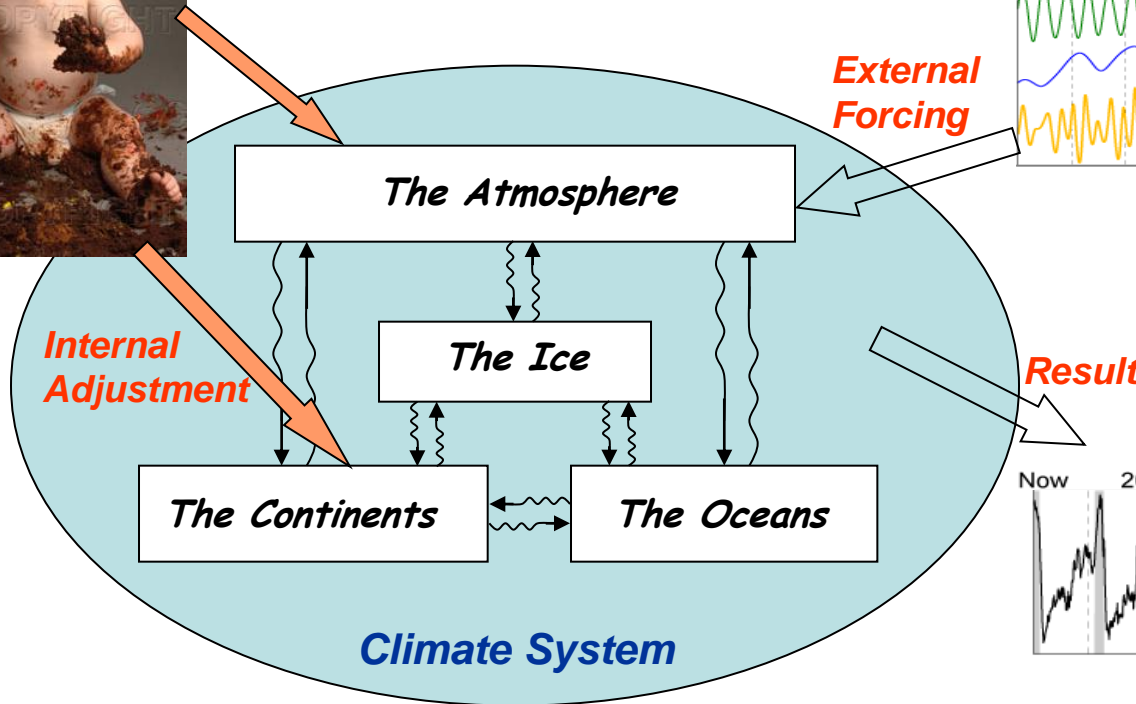


- Q1:** How does climate change modify the terrestrial water cycle?
- Q2:** How does the change in water cycle modify the climate?
- Q3:** What will the humans add to this 2-way traffic?

# Large-Scale, Decades-long Groundwater Pumping

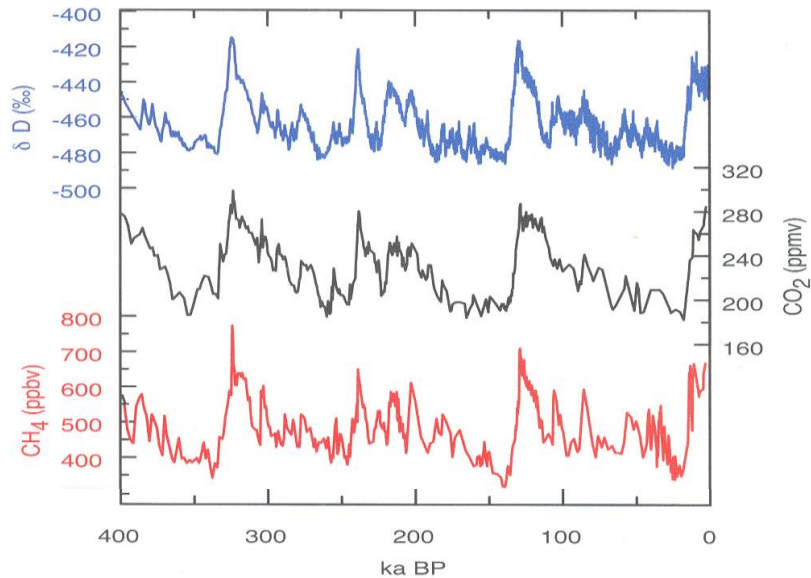


# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks



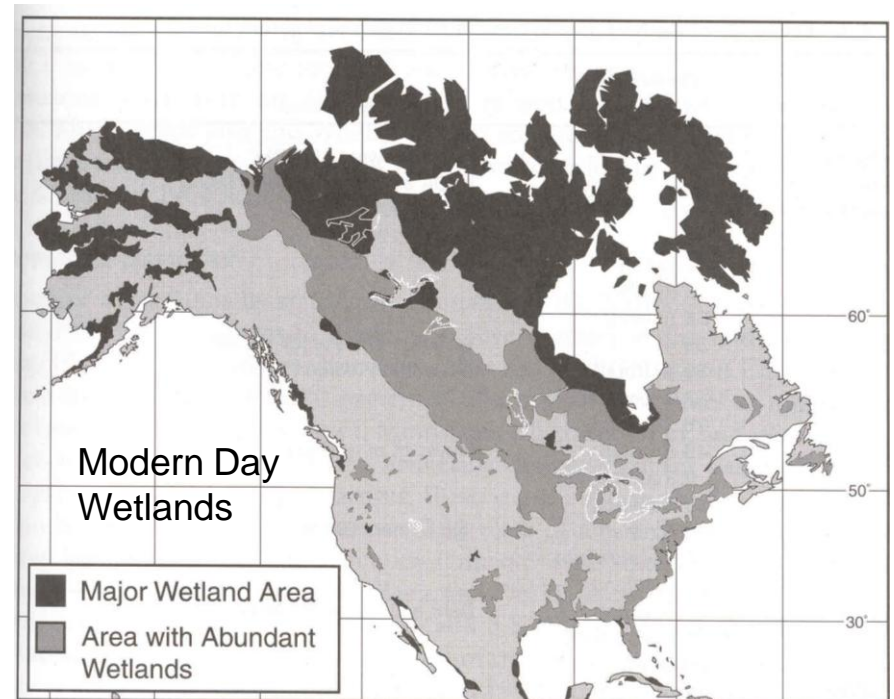
- Q1:** How does climate change modify the terrestrial water cycle?
- Q2:** How does the change in water cycle modify the climate?
- Q3:** What will the humans add to this 2-way traffic?
- Q3:** What role did the water cycle play in the past (G-IG)?

## Ice Core Records:



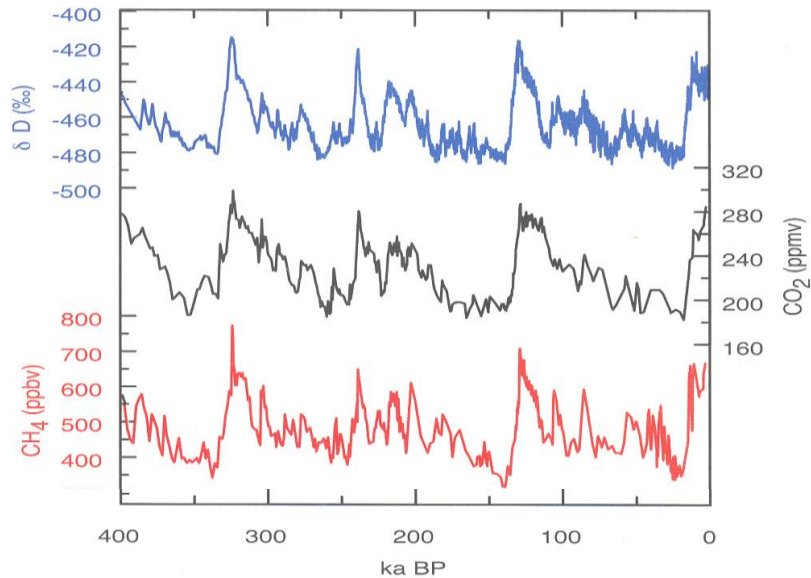
$CH_4$  Source ~ Wetlands

Questions: what was the extent of the wetlands?





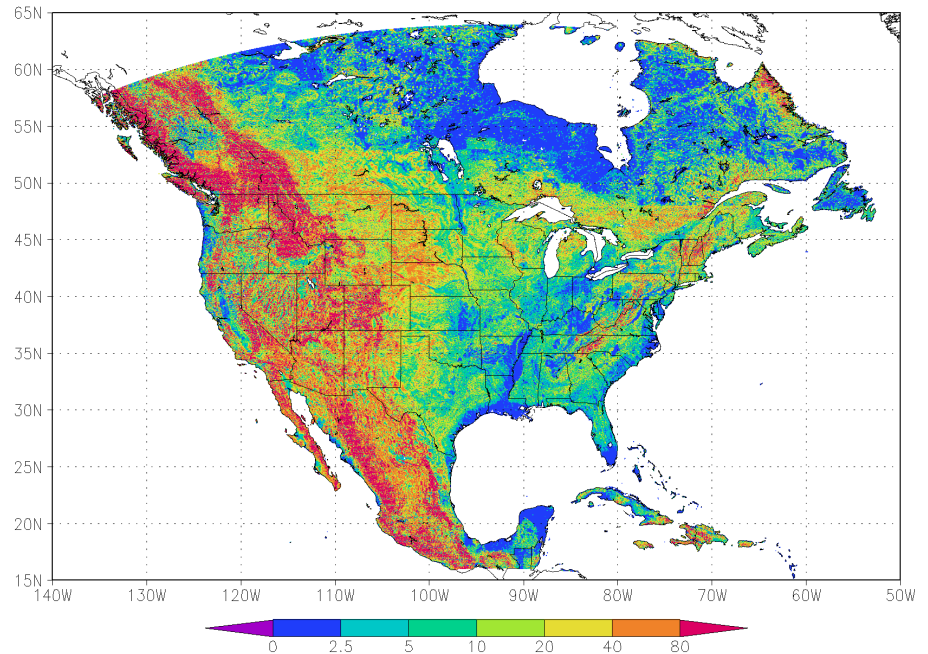
## Ice Core Records:



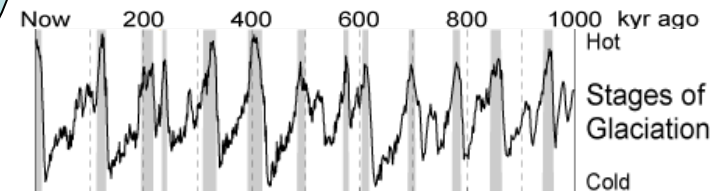
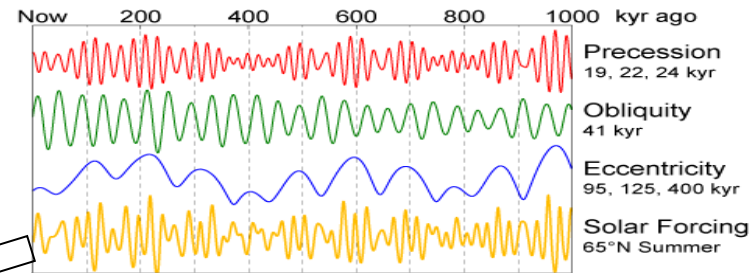
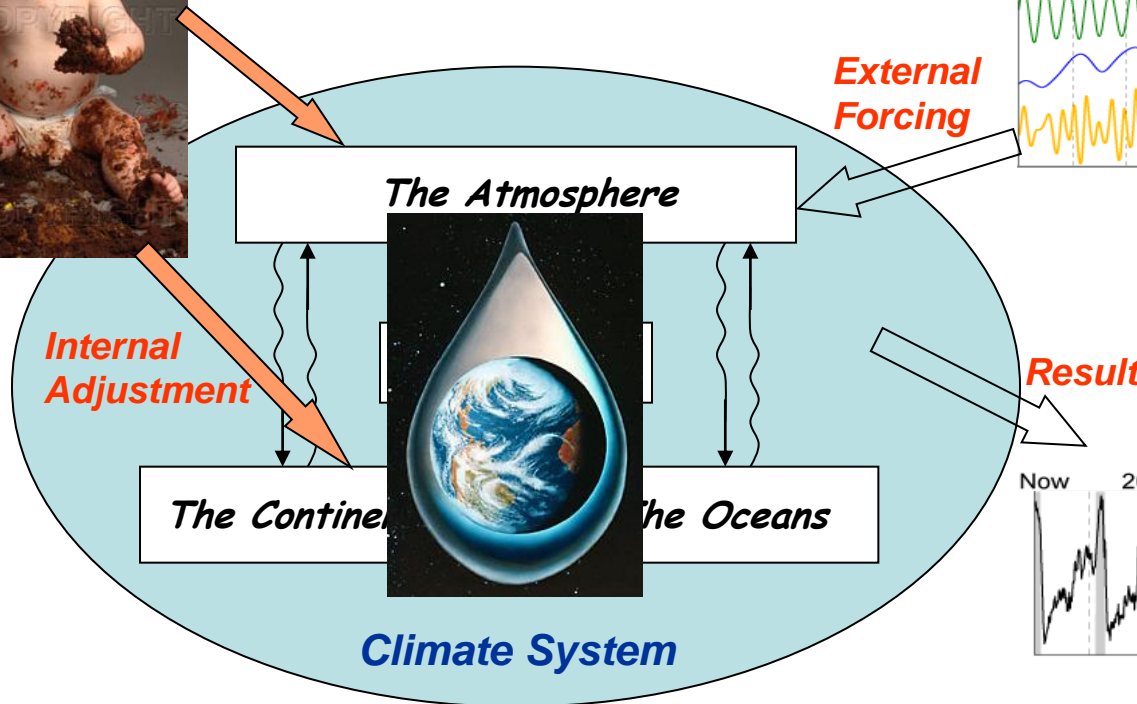
$CH_4$  Source ~ Wetlands

Can we reconstruct the paleo-hydrology?

## Modern Day Equilibrium Groundwater



# Terrestrial Water Cycle and Climate Change: Linkages and Feedbacks



- Q1:** How does climate change modify the terrestrial water cycle?
- Q2:** How does the change in water cycle modify the climate?
- Q3:** What will the humans add to this 2-way traffic?
- Q3:** What role did the water cycle play in the past (G-IG)?