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Effects of anthropogenic water regulation and groundwater lateral flow on land surface processes

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Workshop IGEM, Impact of Groundwater in Earth system Models
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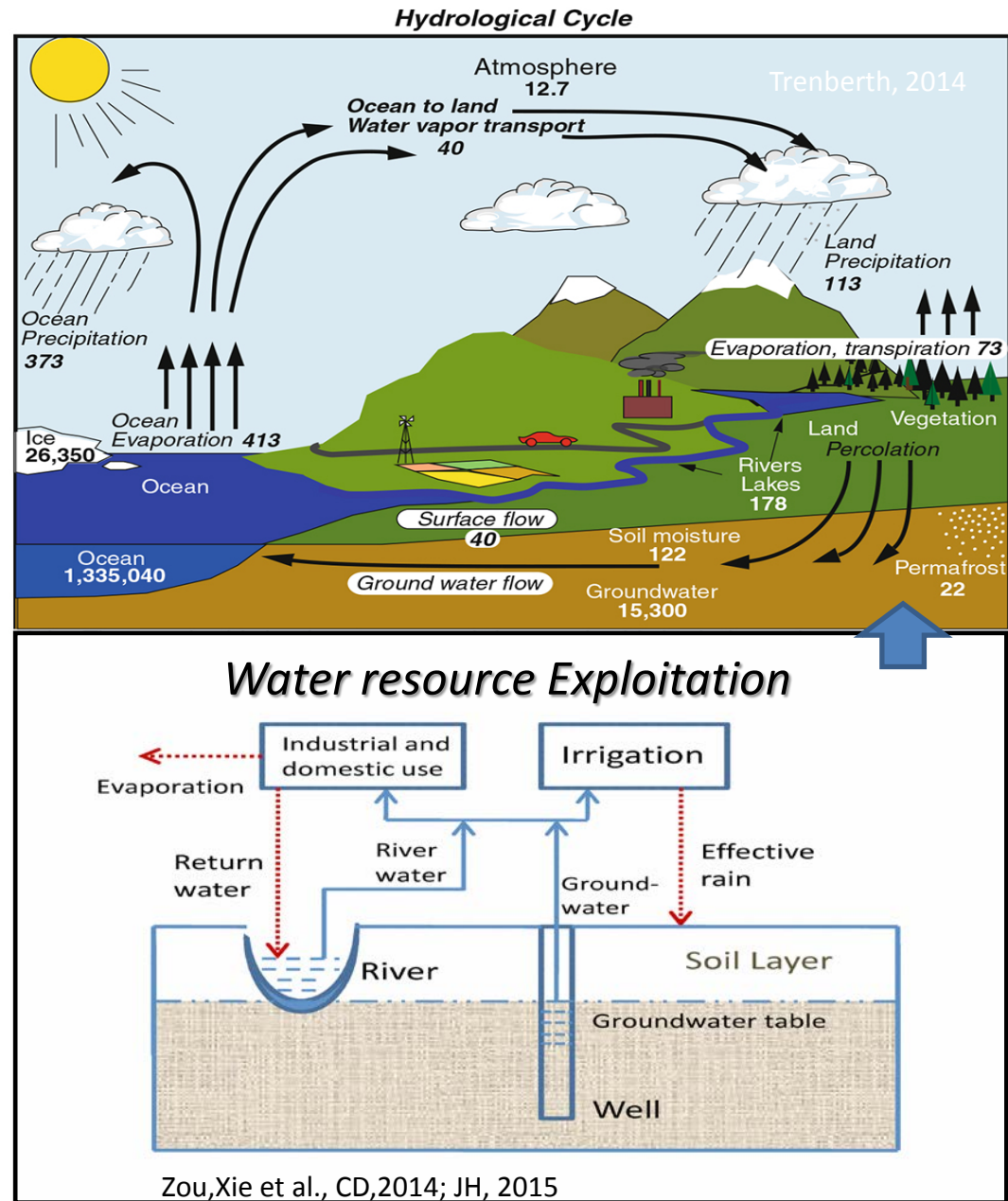
Outline

- **Model development and validation**
- **Effects of groundwater lateral flow and human water regulation**
- **Eco-hydrological effects of stream-aquifer water interaction**
- **Climatic responses to global anthropogenic groundwater extraction**
- **Summary and discussion**



Groundwater lateral flow and water resource exploitation

- It has interactions between surface water, groundwater, soil moisture, atmosphere
- To meet human demands for water resources, groundwater is exploited widely
- Continually pumping **groundwater** causes not only local declining of groundwater table through **lateral flow** but also altered regional water cycle and energy budget
- **Groundwater lateral flow; anthropogenic groundwater exploitation and use**



Motivation

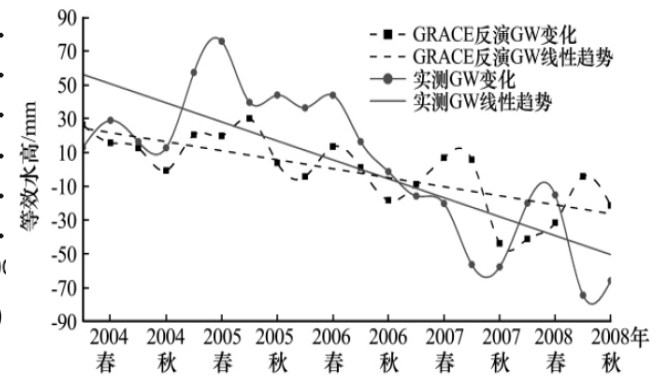
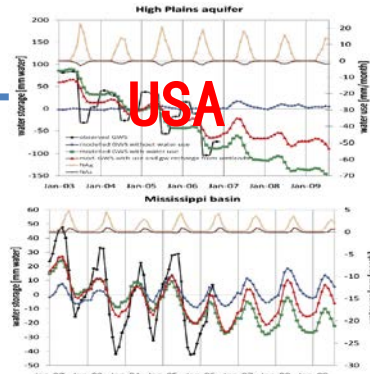
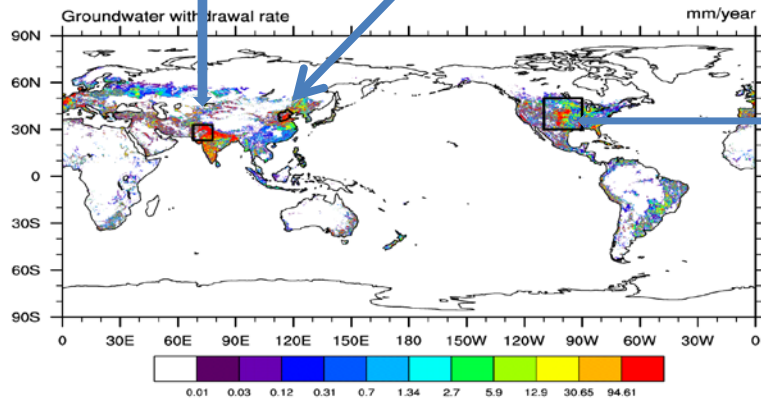
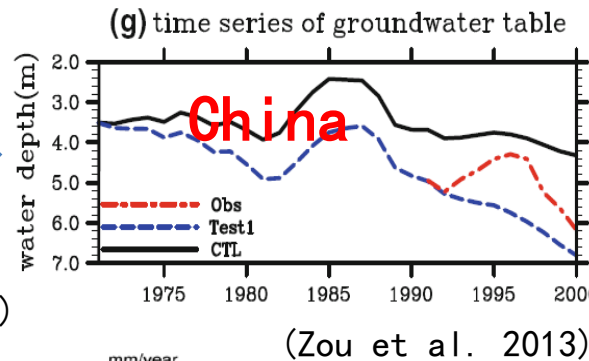
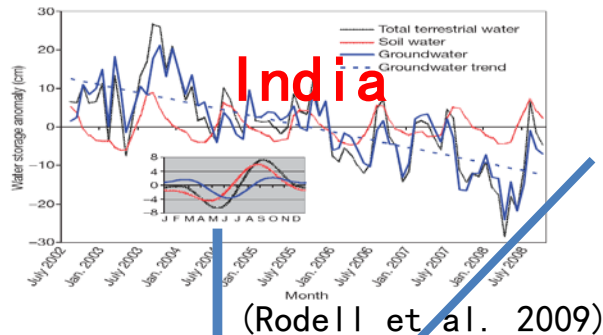


- Human water demand is becoming more intensive with population and economy growth.
- Large scale of water exploitation affects the environment:
 - (1) Reducing environmental base flow
 - (2) Reducing river and lake water storage
 - (3) Modifying water exchange between atmosphere and land surface.



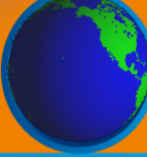


● Over-exploitation of groundwater depletes affects the sustainability of water use.



The decline trends of terrestrial water storage over Heihe River Basin, northern China shown by GRACE satellite (Y P Cao, et al. 2012)

Motivation

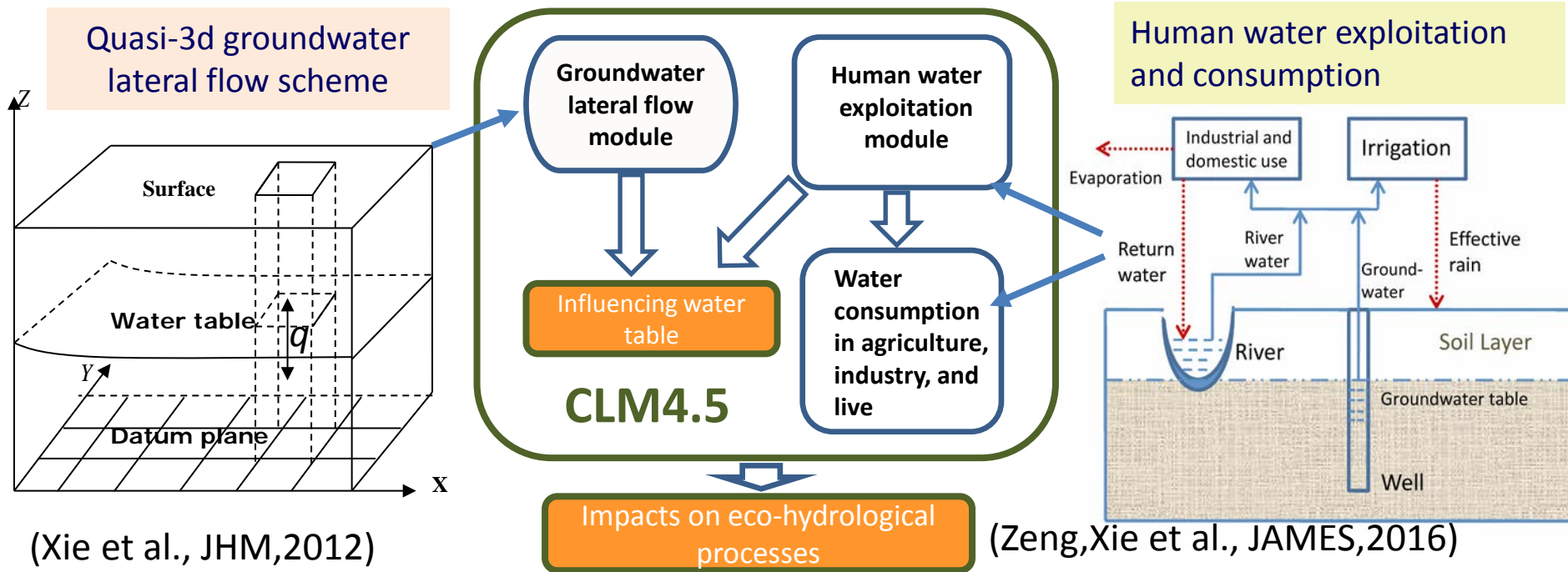


- The two processes including **groundwater later flow and withdrawal** play important roles in the interactions
 - How could land surface processes and climate response due to groundwater **lateral flow and anthropogenic groundwater exploitation and consumption** ?
-
- However, current land surface models for climate modeling lack representations of the two processes
 - In this work, a quasi-3D groundwater model and a scheme of groundwater exploitation and consumption are incorporated into CLM4.5
 - The effects of groundwater later flow and anthropogenic groundwater exploitation are then investigated.

The land model considering both groundwater lateral flow and human water regulation



- Schemes of groundwater lateral flow and human water regulation were incorporated into CLM4.5, and a land model which can model groundwater lateral flow, human surface water withdrawal and groundwater exploitation as well as its consumption is developed.



- Zou, J., Z. H. Xie, Y. Yu, C. S. Zhan, and Q. Sun, 2014: Climatic responses to anthropogenic groundwater exploitation: a case study of the Haihe River Basin, Northern China. *Climate Dynamics*, 42, 2125-2145.
- Zou, J., Z. H. Xie, C. S. Zhan, P. H. Qin, Q. Sun, B. H. Jia, and J. Xia, 2015: Effects of anthropogenic groundwater exploitation on land surface processes: A case study of the Haihe River Basin, northern China. *Journal of Hydrology*, 524, 625-641.
- Zeng, Y., Z. Xie, Y. Yu, S. Liu, L. Wang, J. Zou, P. Qin, and B. Jia (2016), Effects of anthropogenic water regulation and groundwater lateral flow on land processes, *J. Adv. Model. Earth Syst.*, 8, doi:10.1002/2016MS000646.

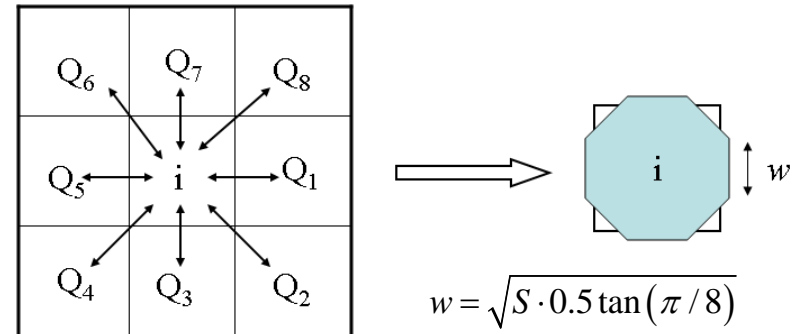
Model developed 1: Groundwater lateral flow scheme



Two-dimension shallow water equations

$$\begin{cases} n_e \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(Kf \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(Kf \frac{\partial h}{\partial y} \right) + R + L & (x, y) \in \Omega, t > 0 \\ h(x, y, 0) = h_0(x, y) & (x, y) \in \Omega, t = 0 \\ (-K_{\Gamma} f_{\Gamma} \cdot \nabla h_{\Gamma}) \cdot \mathbf{n}_{\Gamma}(t) + \beta h_{\Gamma} = Q_{\Gamma} & (x, y) \in \Gamma, t > 0 \end{cases}$$

Eight Flow Direction



Discretization

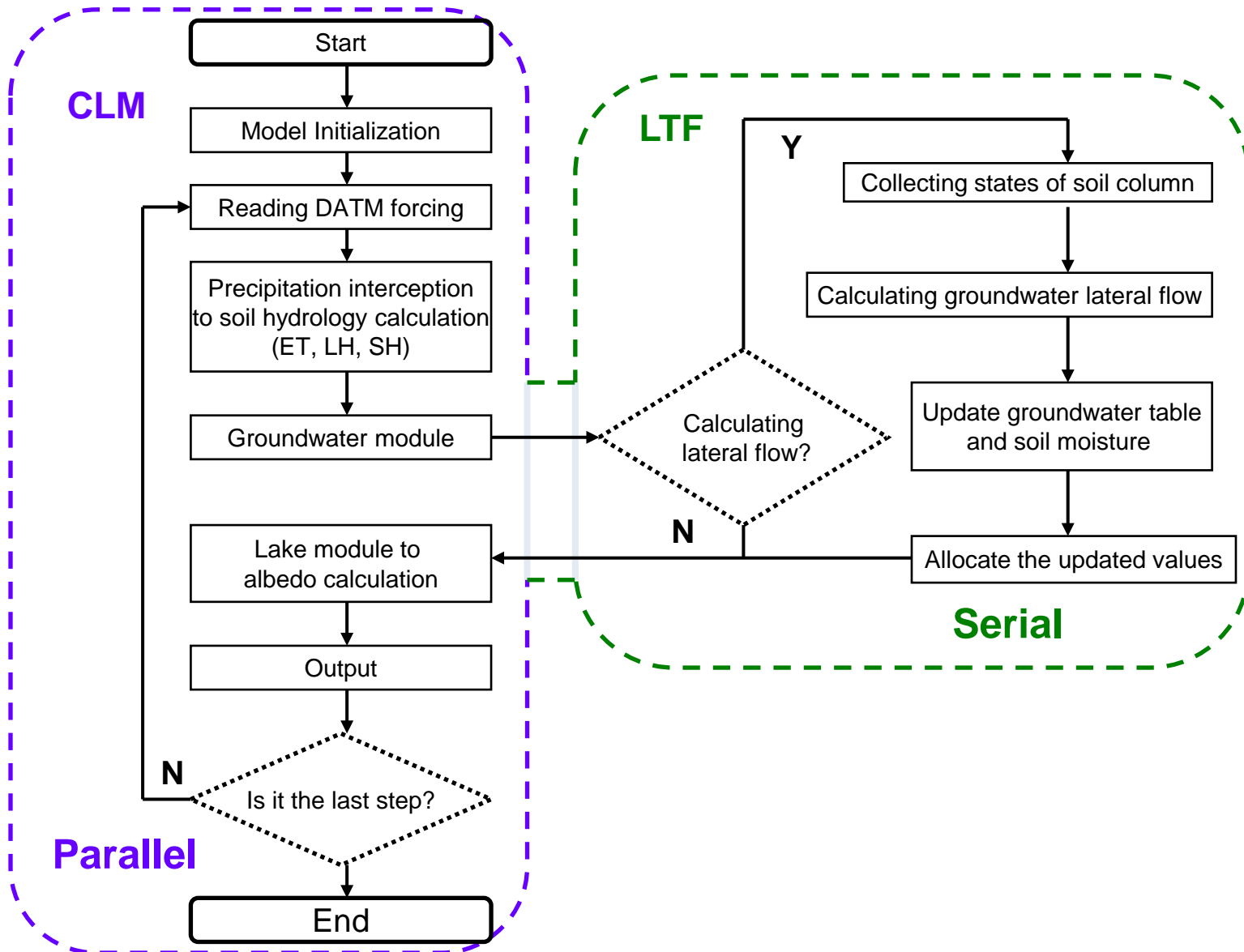
$$\begin{aligned} n_e \frac{\partial h}{\partial t} &= R + \sum_{n=1}^8 \frac{wT(h_n - h)}{l_n \cdot S} + L \\ \left(\frac{n_e}{\Delta t} + \sum_{n=1}^8 \frac{\tilde{w}_n \tilde{T}_n^{k+1}}{l_n \cdot S(i)} \right) h^{k+1}(i) - \sum_{n=1}^8 \frac{\tilde{w}_n \tilde{T}_n^{k+1}}{l_n \cdot S(i)} h^{k+1}(n) &= R(i) + \frac{n_e}{\Delta t} h^k(i) \quad i = 1, 2, \dots, N \end{aligned}$$

Parameterization

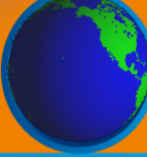
$$K = K_0 \exp\left(-\frac{z'}{f}\right), \quad f = \frac{a}{1+bs}, \quad f > f_{\min}$$

$$\begin{cases} T = T_1 + T_2, \quad T_1 = \sum K_m \Delta z_m, \quad T_2 = \int_0^{\infty} K dz' = \int_0^{\infty} K_0 \exp\left(-\frac{z'}{f}\right) dz' = K_0 f & zwt \leq d_0 \\ T = \int_{zwt-d_0}^{\infty} K dz' = \int_{zwt-d_0}^{\infty} K_0 \exp\left(-\frac{z'}{f}\right) dz' = K_0 f \exp\left(-\frac{h_s - h - d_0}{f}\right) & zwt > d_0 \end{cases}$$

Coupling scheme

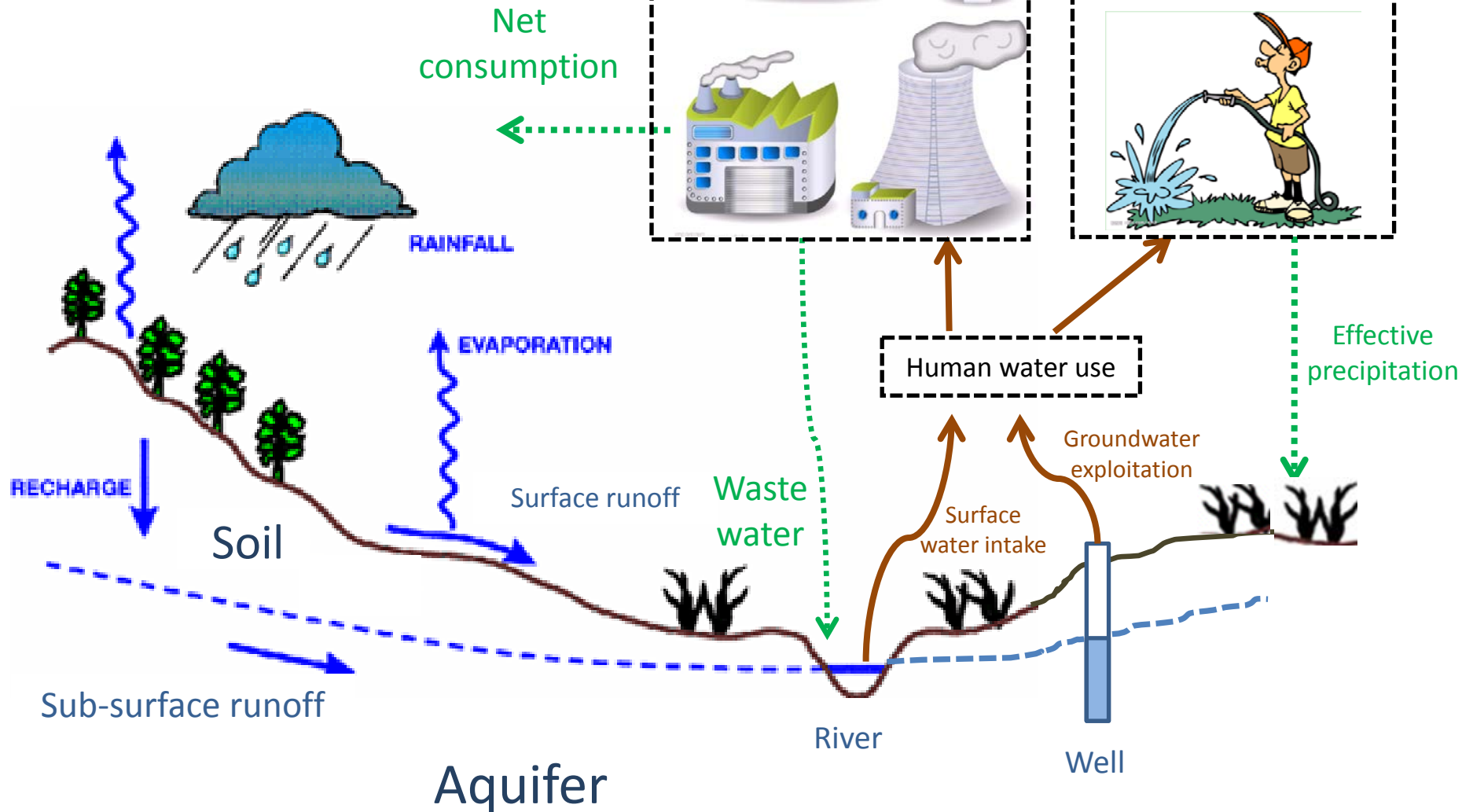


Description of human water regulation scheme

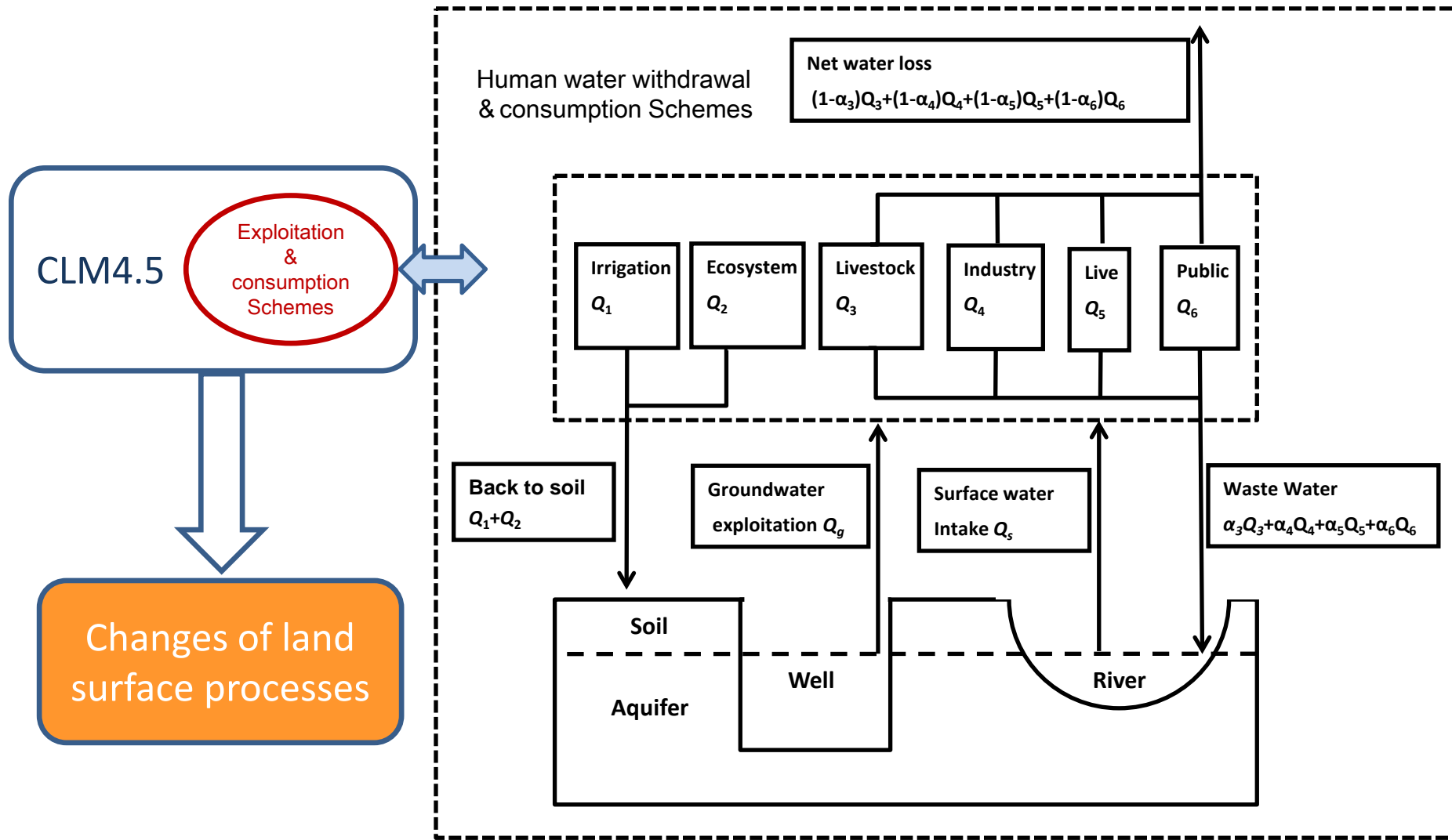


Zou,Xie et al., 2015,JH ;

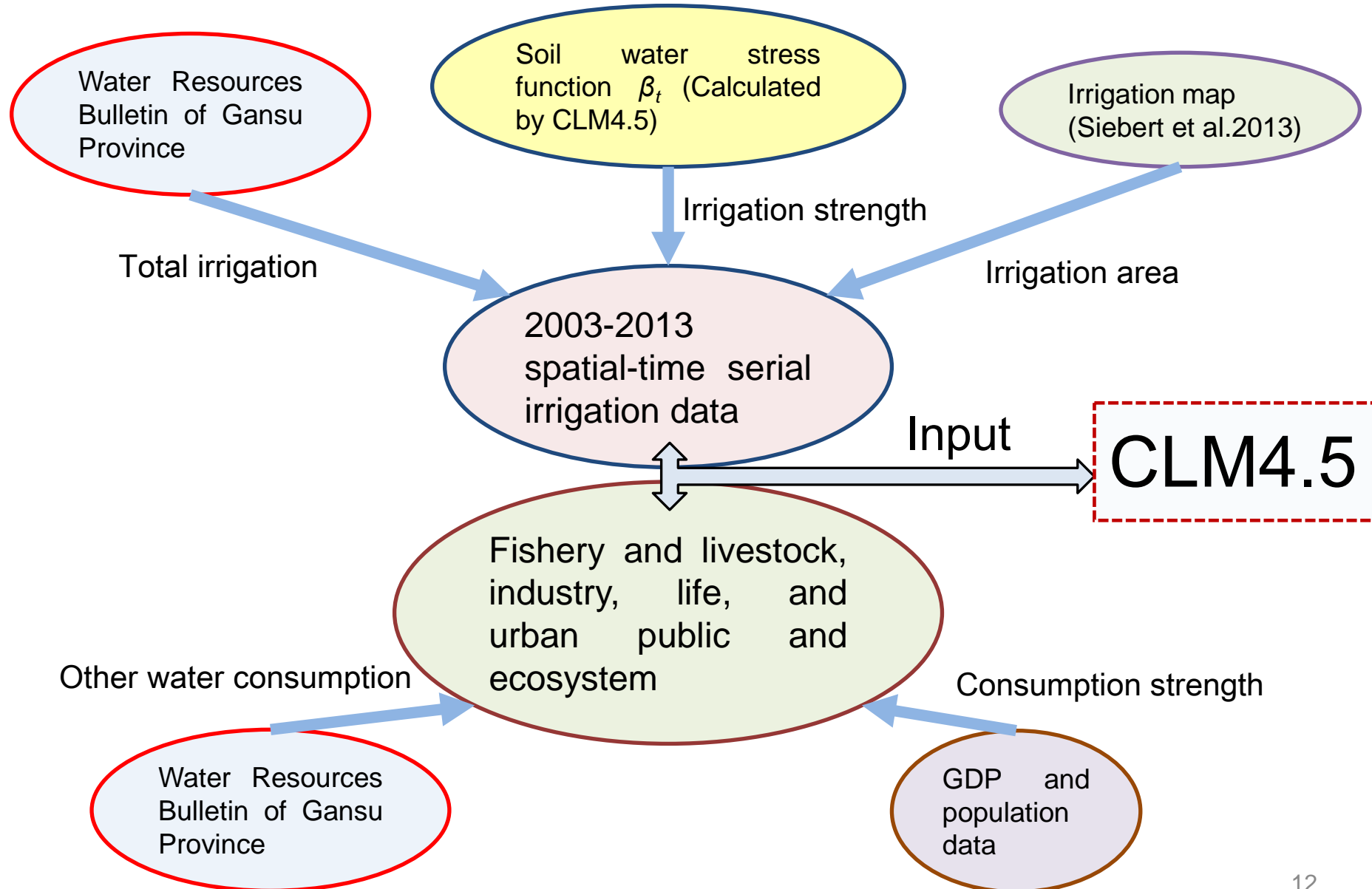
Zou,Xie et al., 2014,CD



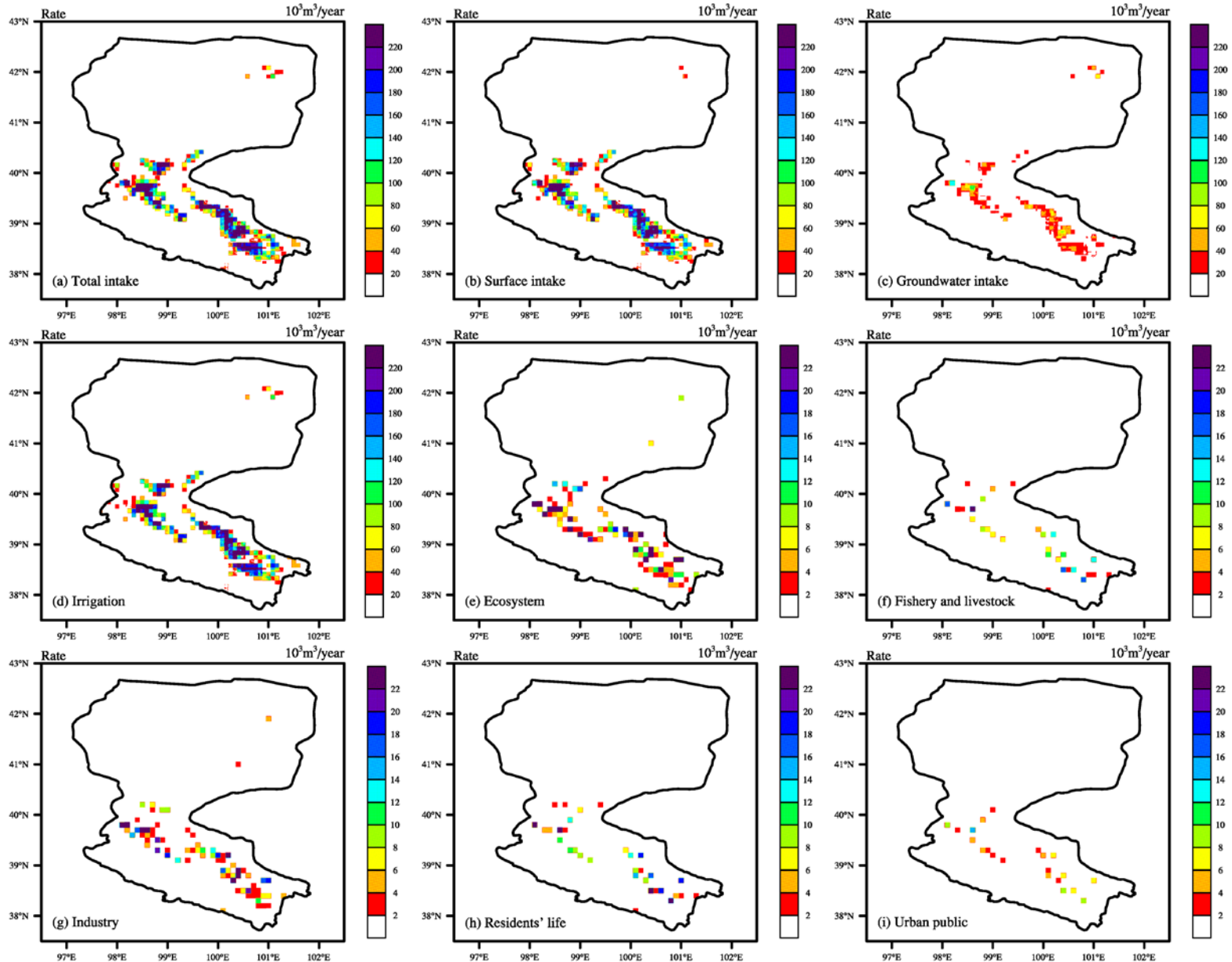
Model developed 2: Human water withdrawal and consumption scheme



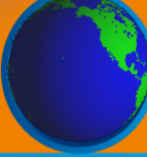
Estimation of spatial-time serial water consumption data for CLM4.5



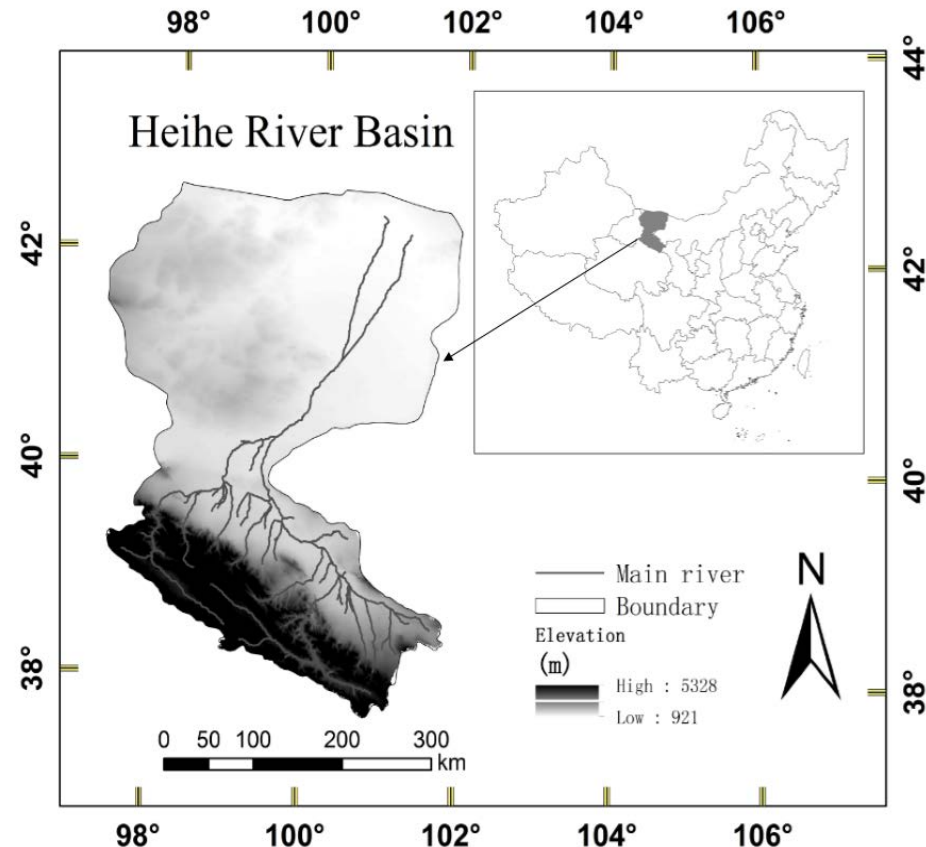
Spatial pattern of human water regulation data over Heihe River Basin



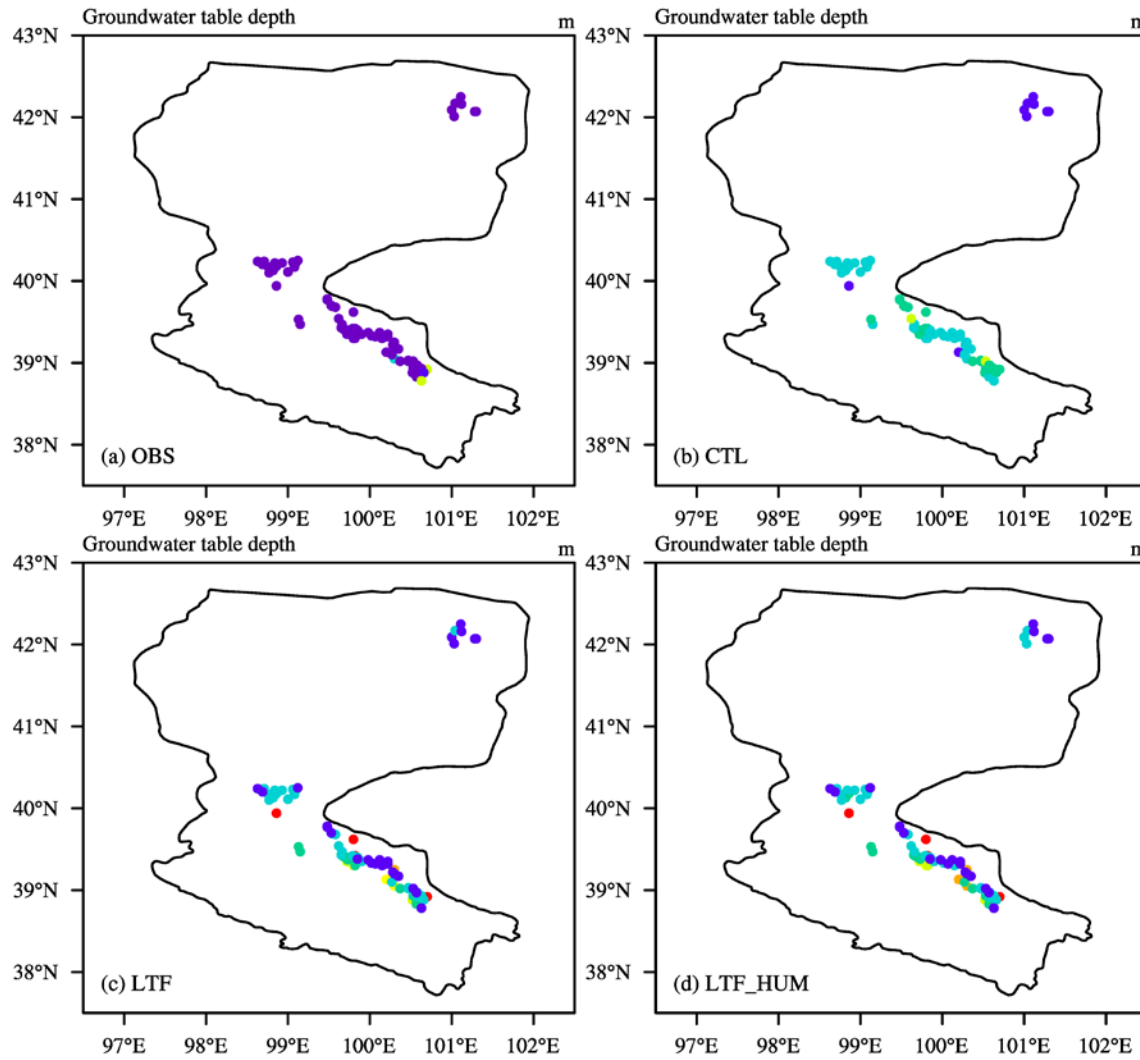
Experimental design (for validation)



- Study domain: Heihe River Basin
- Resolution: 1-km
- Simulation period: 2003-2013
- Atmospheric forcing : ITP (2003-2012, Dataset from Institute of Tibetan Research, Chinese Academy of Sciences) and CLDAS (2013, Dataset from China Meteorological Administration Land Data Assimilation System)
- Three runs:
 - CTL (Control run)
 - LTF (Only groundwater lateral flow (GLF) is included)
 - LTF_HUM (Both GLF and human activities are included)

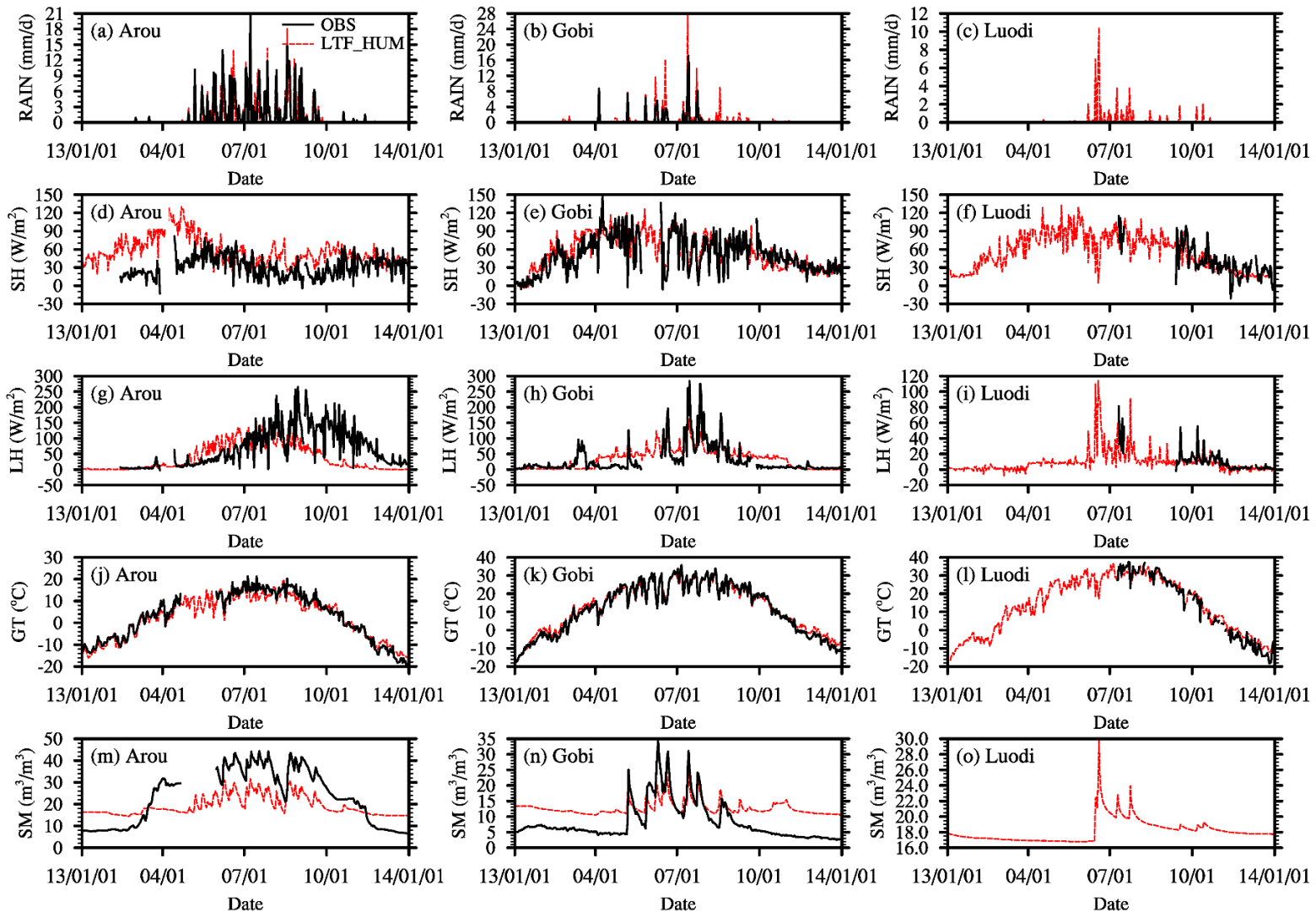
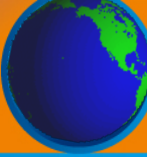


Model validation 1: VS groundwater observation from wells



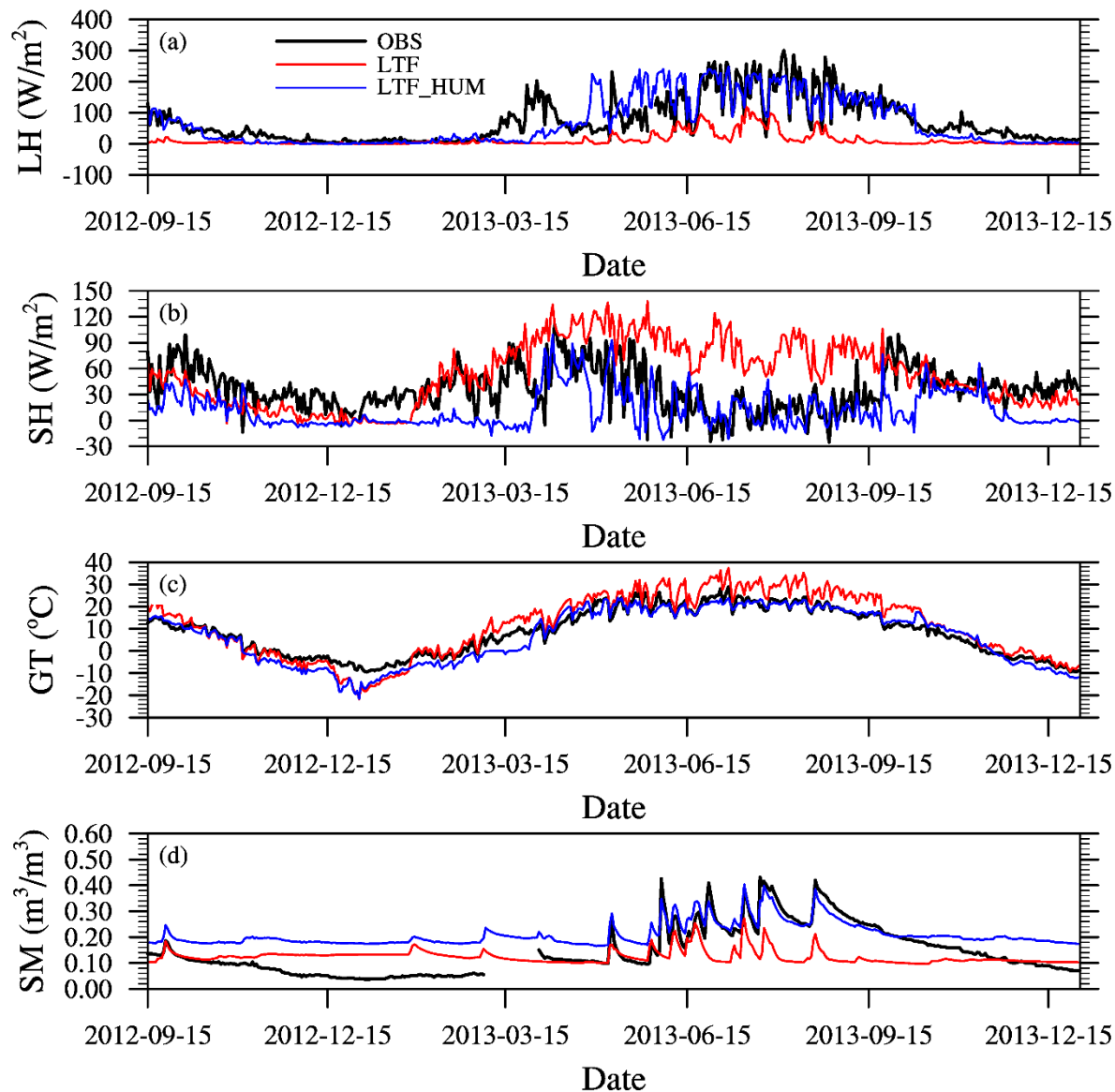
- Compared with CTL run, the simulated groundwater table is much closer to observation after the groundwater lateral flow is considered in LTF and LTF_HUM.

Model validation 2: VS observation from flux towers



- The simulated latent and sensitive heat flux, ground temperature are very close to observation while the seasonal variability of modeled soil moisture is smaller than observation.

VS observation from a flux tower in irrigation district

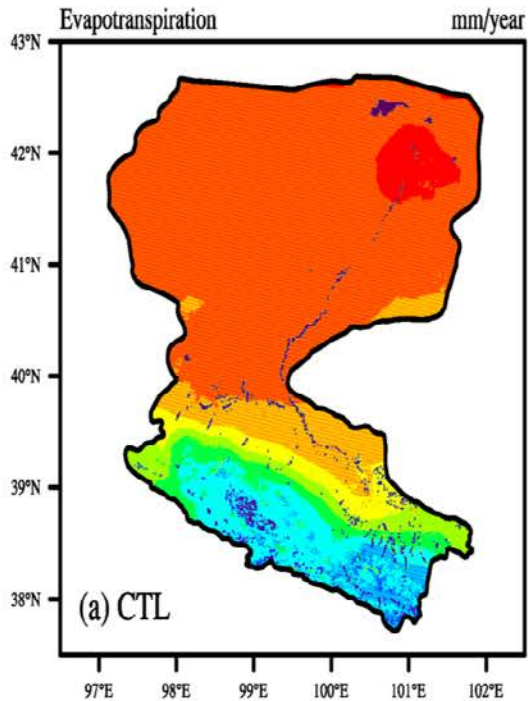


- The modeled latent heat flux, sensible heat flux, groundwater temperature and soil moisture were much closer to observations when human water regulation was included.

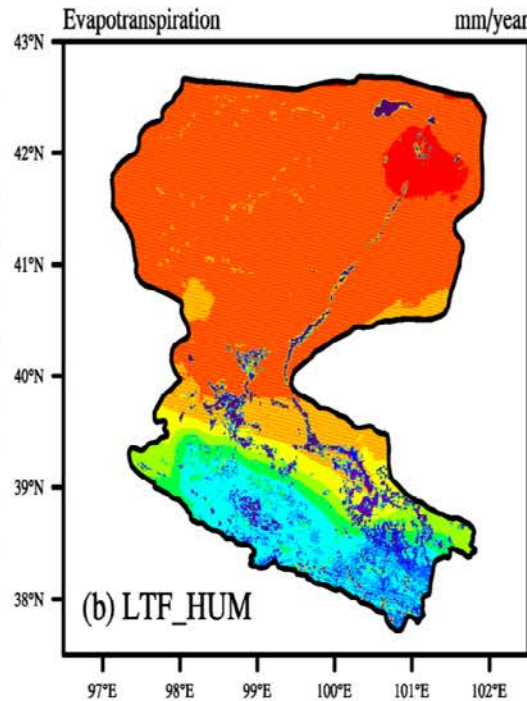
Model validation 3: VS remote sensing data of ET



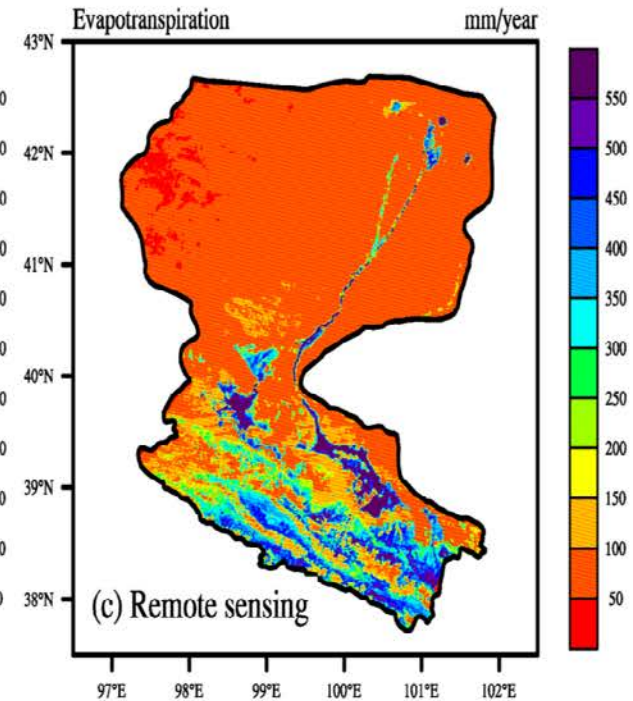
CTL



LTF_HUM



Remote sensing



- After human water regulation was included, the simulated ET pattern was significantly improved.



Outline

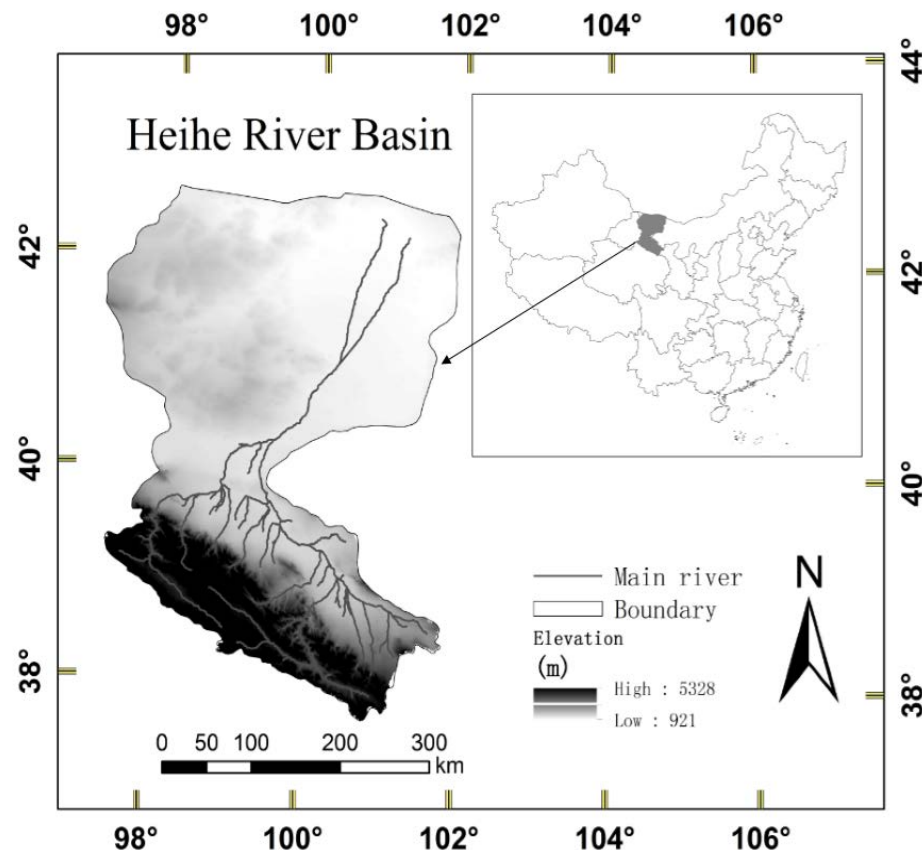
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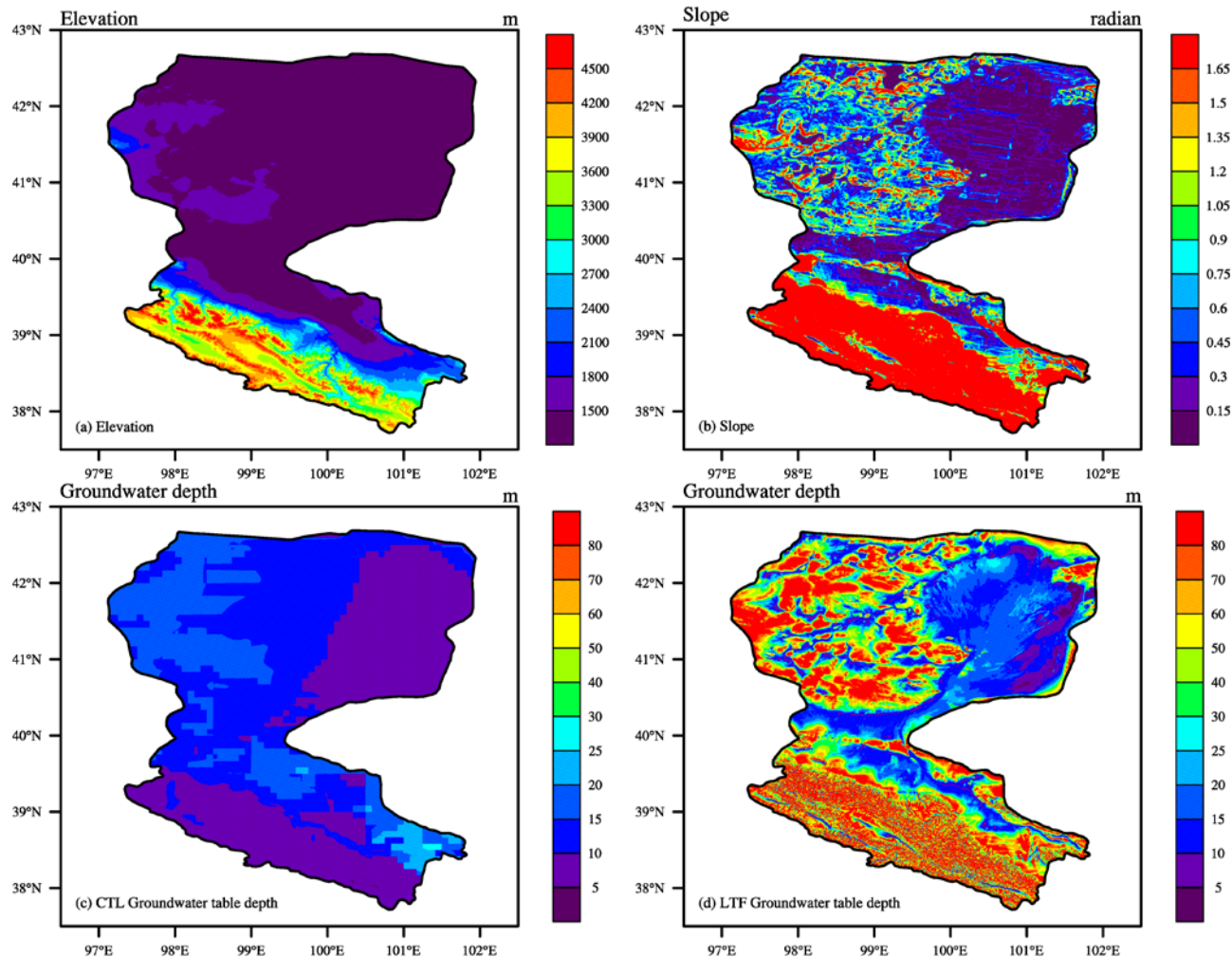
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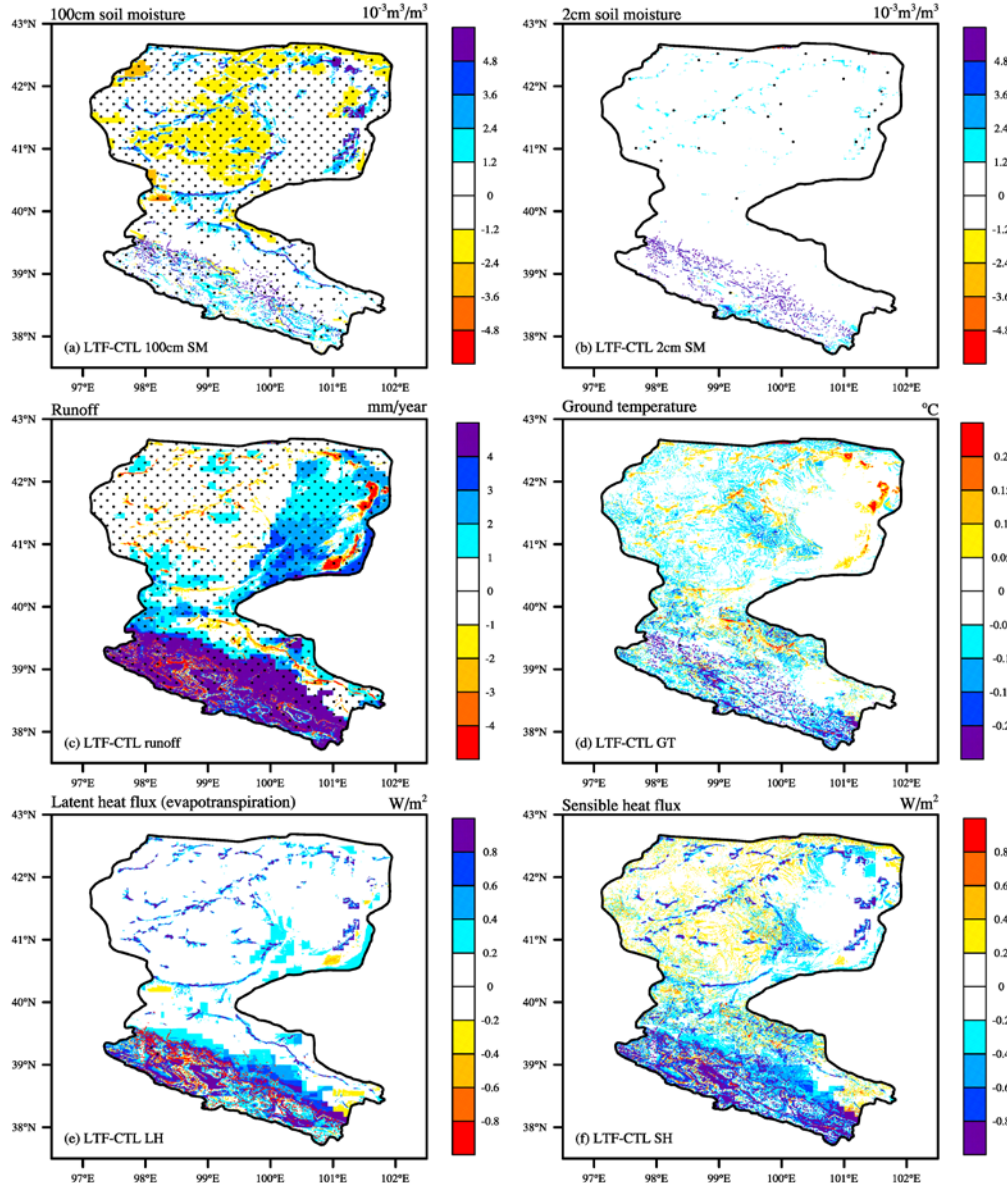


Groundwater table pattern is much changed by lateral flow



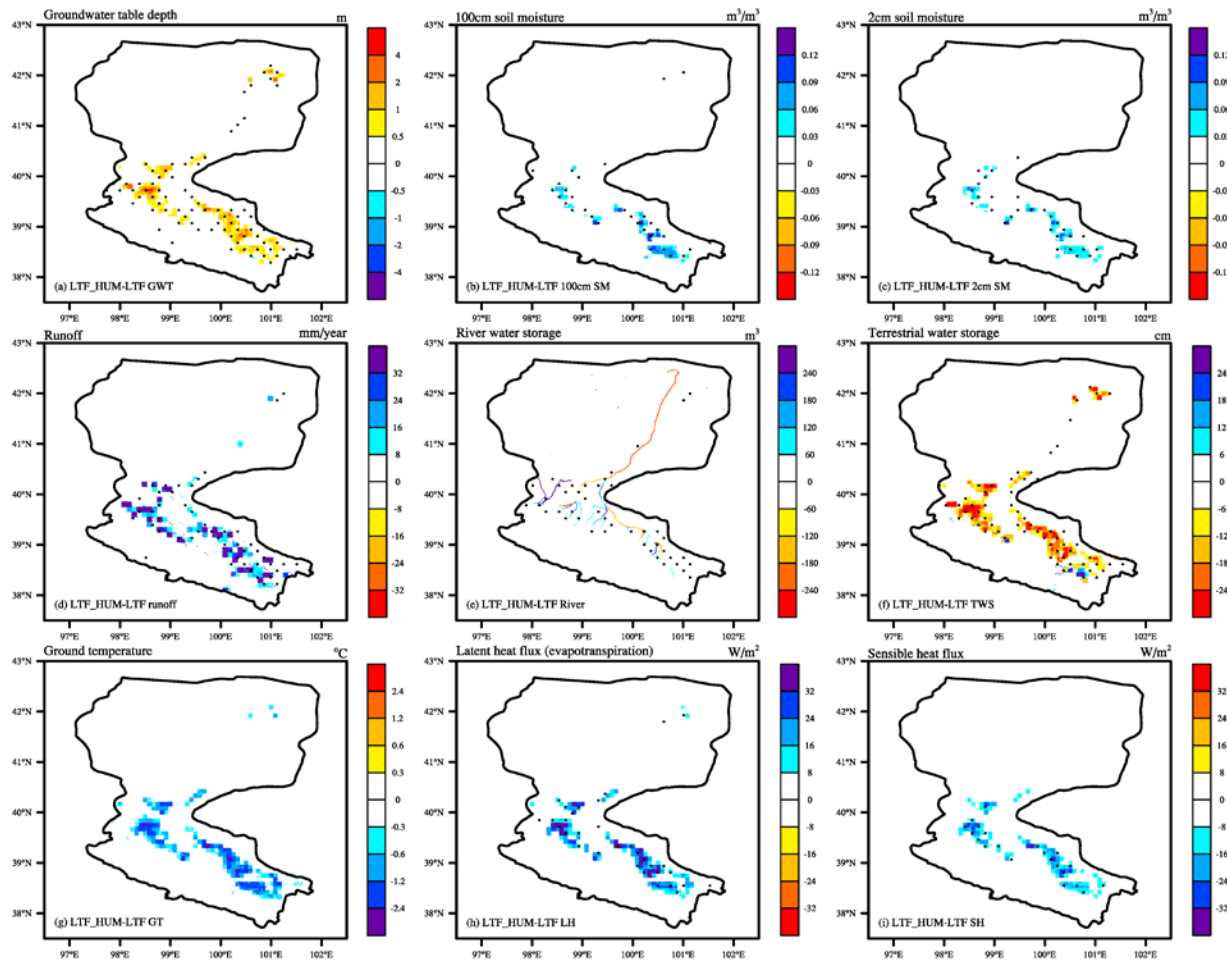
- Following the topographic distribution, the groundwater table is deep in high and precipitous region, and shallow in low and flat region after lateral flow is included.

Effects of groundwater lateral flow on land processes



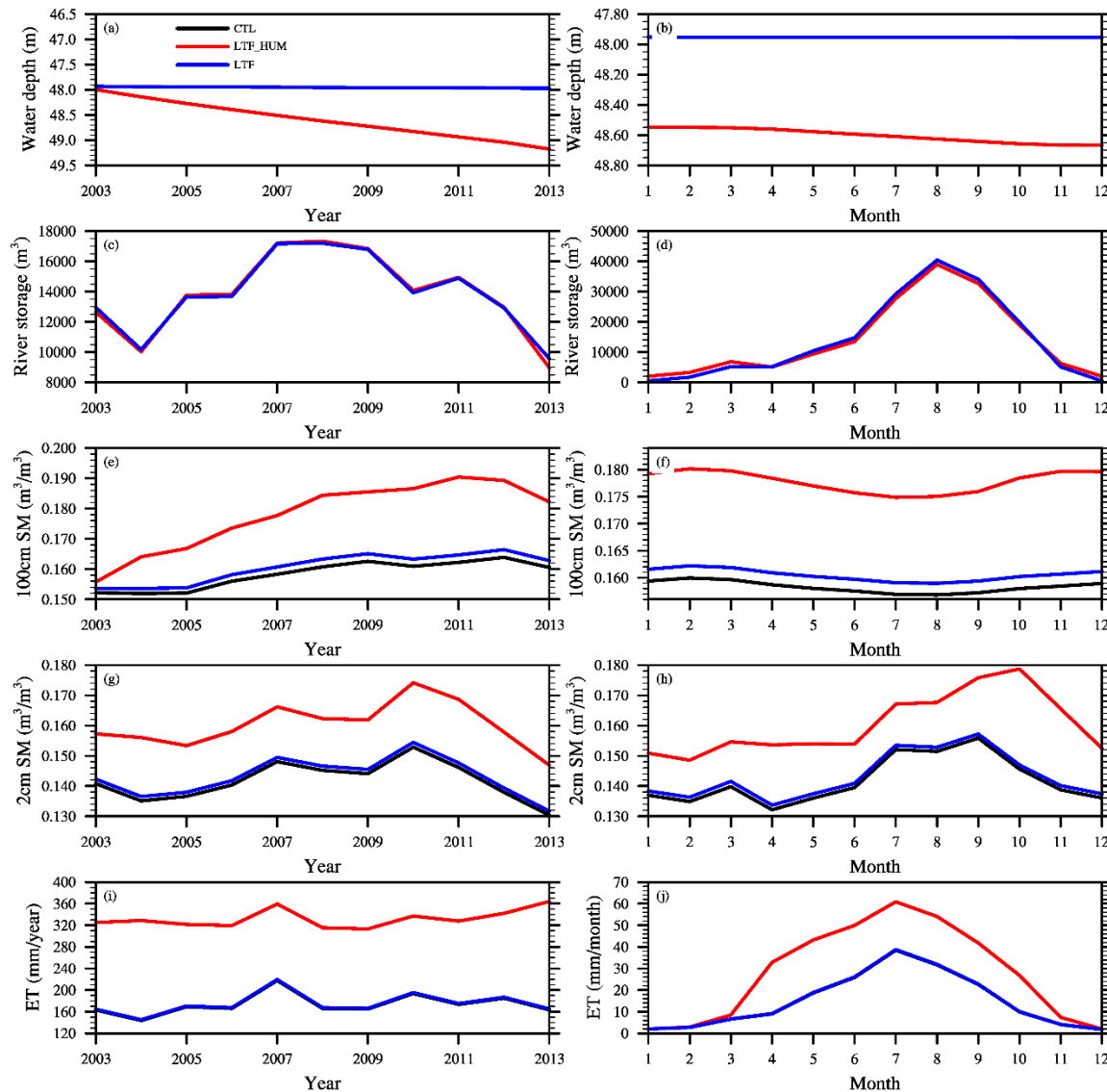
- Other land elements, such as soil moisture, runoff, ground temperature, evapotranspiration and land-atmosphere fluxes are also modified following change of groundwater table.

Human effects on land processes



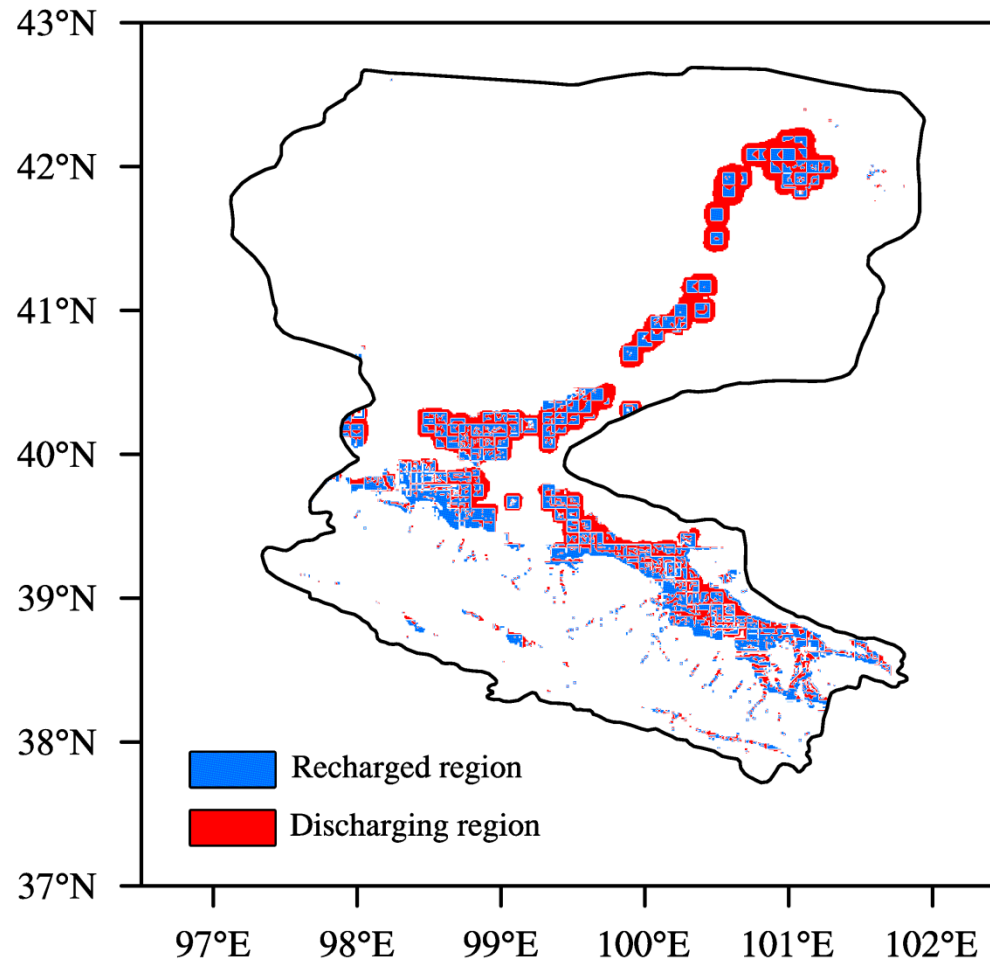
- Groundwater exploitation significantly deepens the water table in middle reaches of Heihe River and Ejinaqi in the lower reaches.
- The river water storage in middle and lower reaches of the main stream is reduced by surface water withdrawal.
- Irrigation wets soil moisture and lifts latent heat flux when cooling the surface temperature.²³

The intra-annual and inter-annual effects of human water regulation



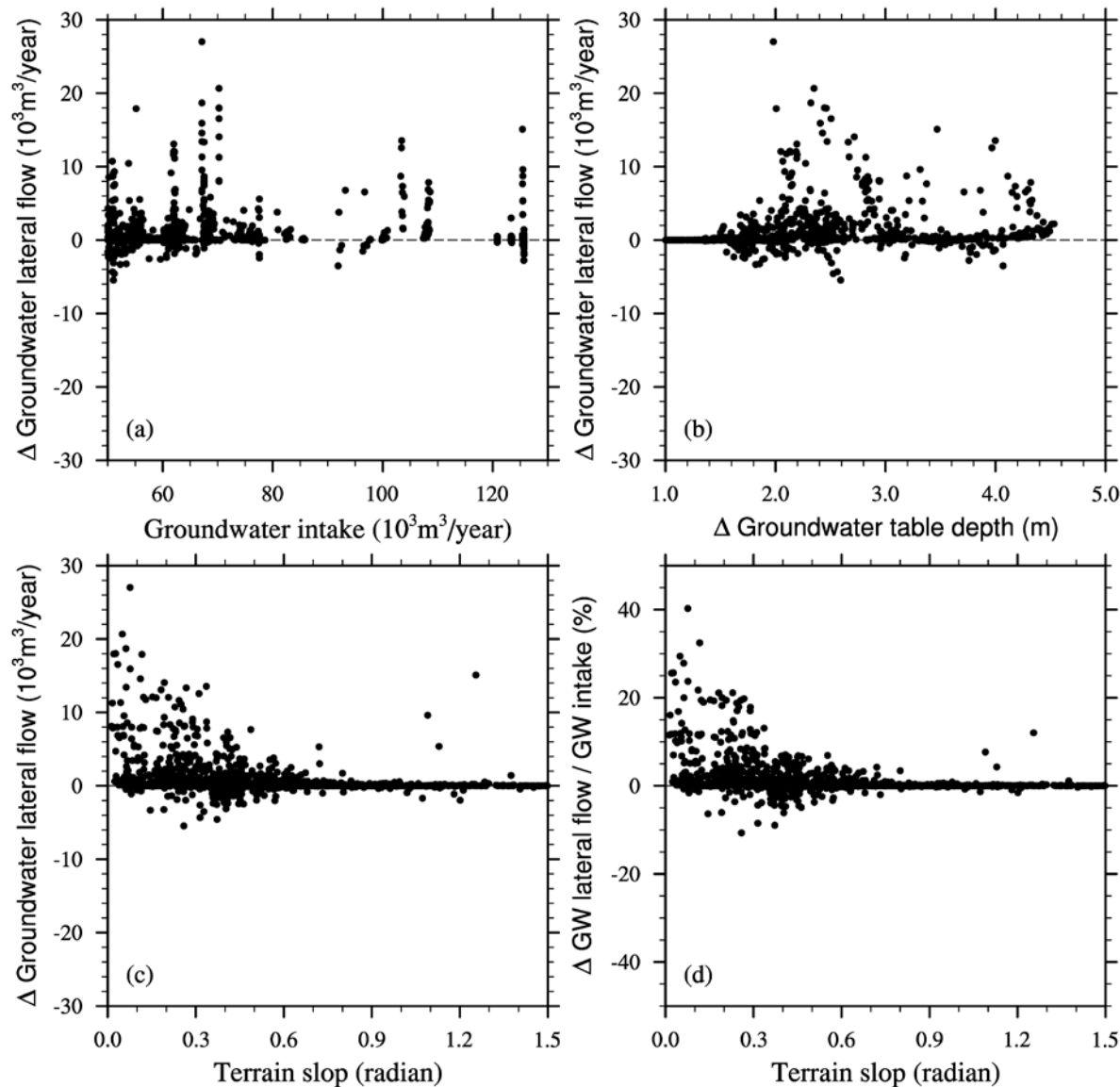
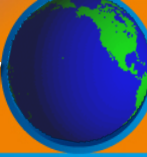
- Groundwater table is linearly declined in last decade of Heihe River Basin.
- The deep soil moisture will be increased by irrigation all year round while the surface soil moisture is only increased in growing season.

The relationship between groundwater exploitation and lateral flow



- Groundwater lateral flow can recharge the groundwater funnels caused by over-exploitation.
- In the middle reaches, the discharging region is mainly located over northeast of the exploited region.
- In the lower reaches, the discharging region is surrounding the exploited region.

Relationship between groundwater exploitation and lateral flow



- The groundwater funnel in flat region keeps a higher ability to get recharging water from neighboring area.
- The groundwater funnel in precipitous region can be hardly offset by groundwater lateral flow.



Outline

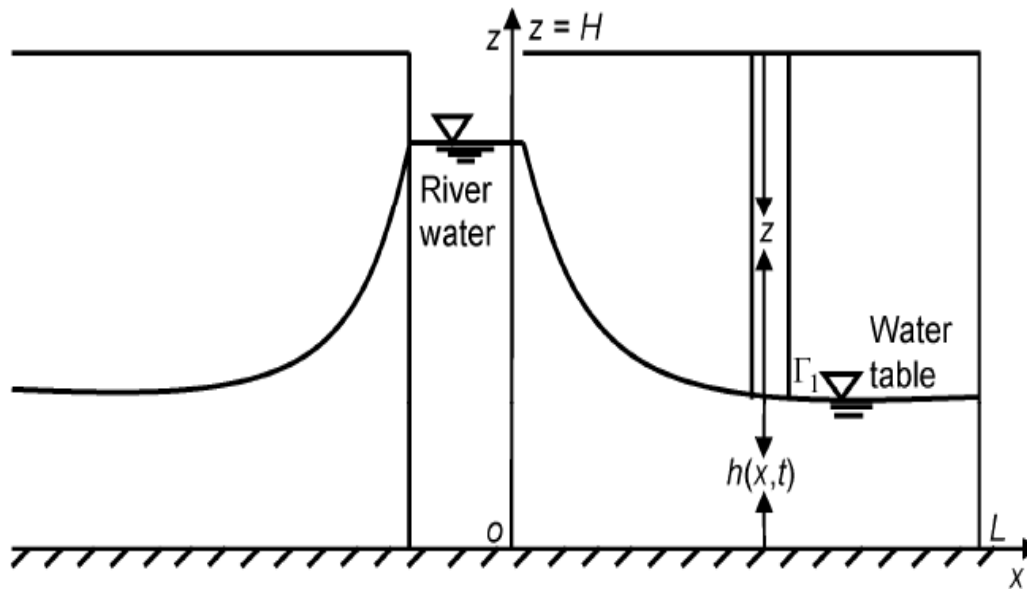
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Stream-aquifer Water Interaction Model



- A quasi-two-dimensional model with vertical soil water flow, soil water-groundwater interaction and horizontal groundwater flow (Di and Xie 2011).



Unsaturated region: vertical soil water movement

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[D(\theta) \frac{\partial \theta}{\partial z} \right] + \frac{\partial K(\theta)}{\partial z} + f(x, z, t),$$

$$h(x, t) < z < H,$$

$$\theta(x, z, 0) = \theta_0(x, z), \quad h_0(x) < z \leq H,$$

$$q_{z=H}(x, t) = P - E - R, \quad z = H, \quad t > 0,$$

$$\theta = \theta_s, \quad z = h(x, t), \quad t > 0,$$

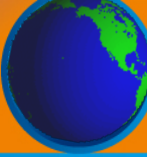
horizontal groundwater flow:

$$n_e \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(K_s h \frac{\partial h}{\partial x} \right) - q_{z=h(x,t)}(x, t),$$

$$0 < x < L, \quad 0 < z \leq h(x, t).$$

- ◆ Xie, Z. H., and X. Yuan, 2010: Prediction of water table under stream-aquifer interactions over an arid region. *Hydrological Process*, 24, 160-169.
- ◆ Di, Z. H., Z. H. Xie, X. Yuan, X. J. Tian, Z. D. Luo, and Y. N. Chen, 2011: Prediction of water table depths under soil water-groundwater interaction and stream water conveyance. *Science in China (D)*, 54, 420-430.
- ◆ Xie, Z. H., Z. H. Di, Z. D. Luo, and Q. Ma, 2012: A Quasi-Three-Dimensional Variably Saturated Groundwater Flow Model for Climate Modeling. *Journal of Hydrometeorology*, 13, 27-46.
- ◆ Zeng, Y., Xie, Z., Yu, Y., Liu, S., Wang, L., Jia, B., Qin, P., and Chen, Y.: Ecohydrological effects of stream-aquifer water interaction: a case study of the Heihe River basin, northwestern China, *Hydrol. Earth Syst. Sci.*, 20, 2333-2352, doi:10.5194/hess-20-2333-2016, 2016.

Experimental design

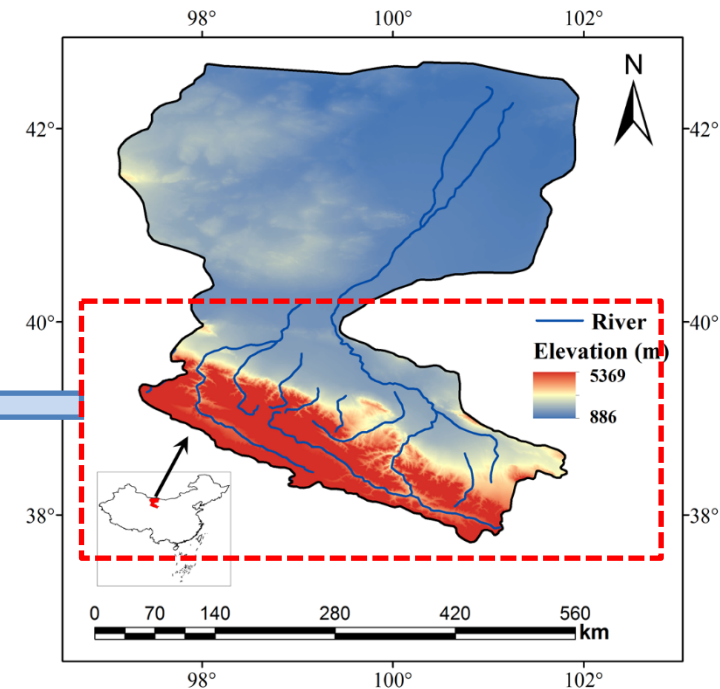
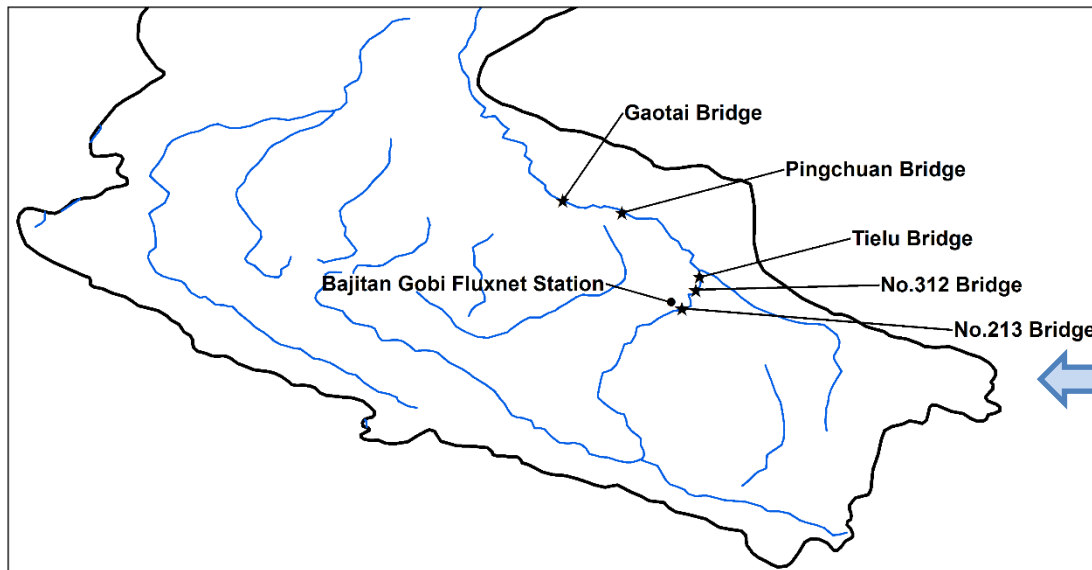


- **Study Region:** Five typical cross-sections over middle reaches of Heihe River Basin, northwest China
- **Resolution:** 60 m
- **Simulation period:** 2012.07.01 - 2013.06.30
- **Atmospheric forcing:** CLDAS
- **Two runs:** TEST and CTL (do and do not accounting stream-aquifer water exchange)

Study domain



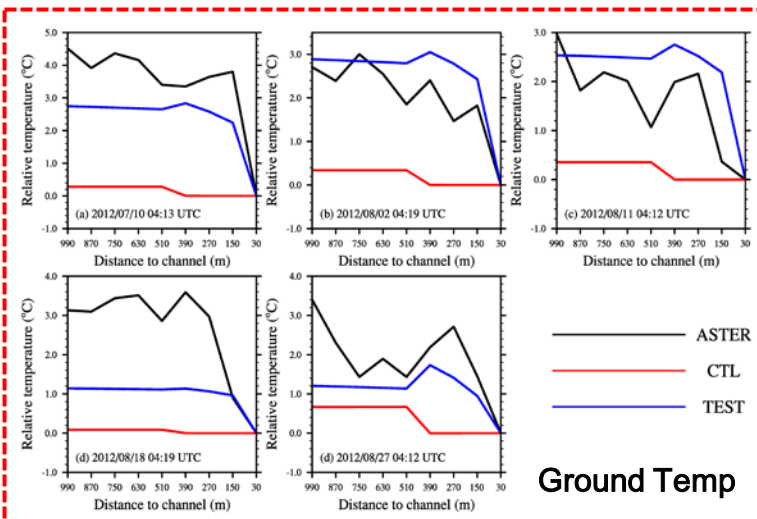
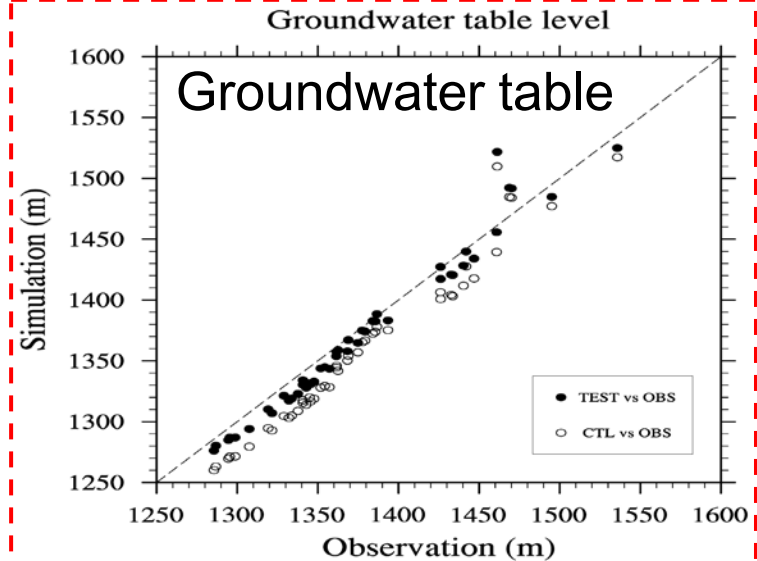
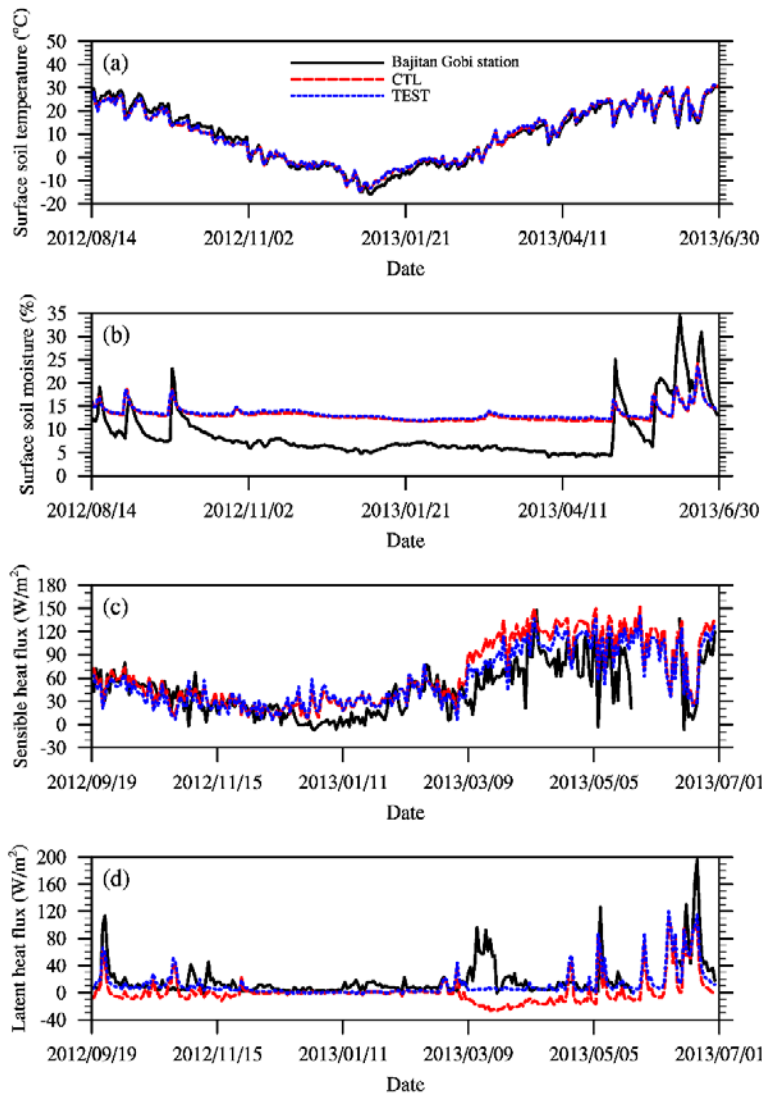
- Five typical cross-sections on the middle reaches of Heihe River Basin, northwestern China



VS observations



Soil Temp
Soil Water
Sensible Heat
Latent Heat

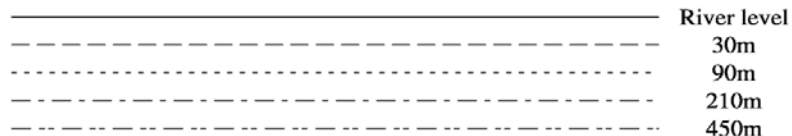
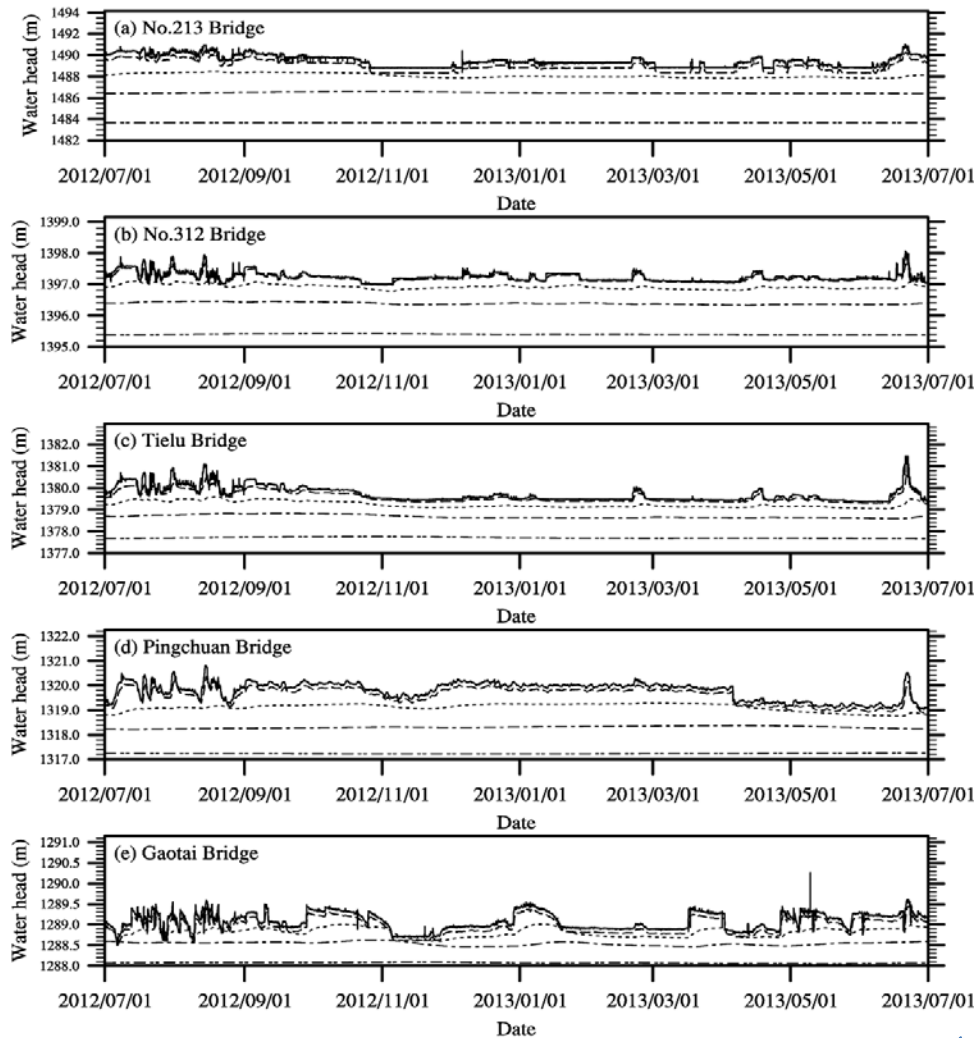
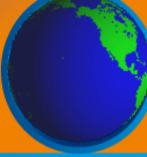


Groundwater Table OBS

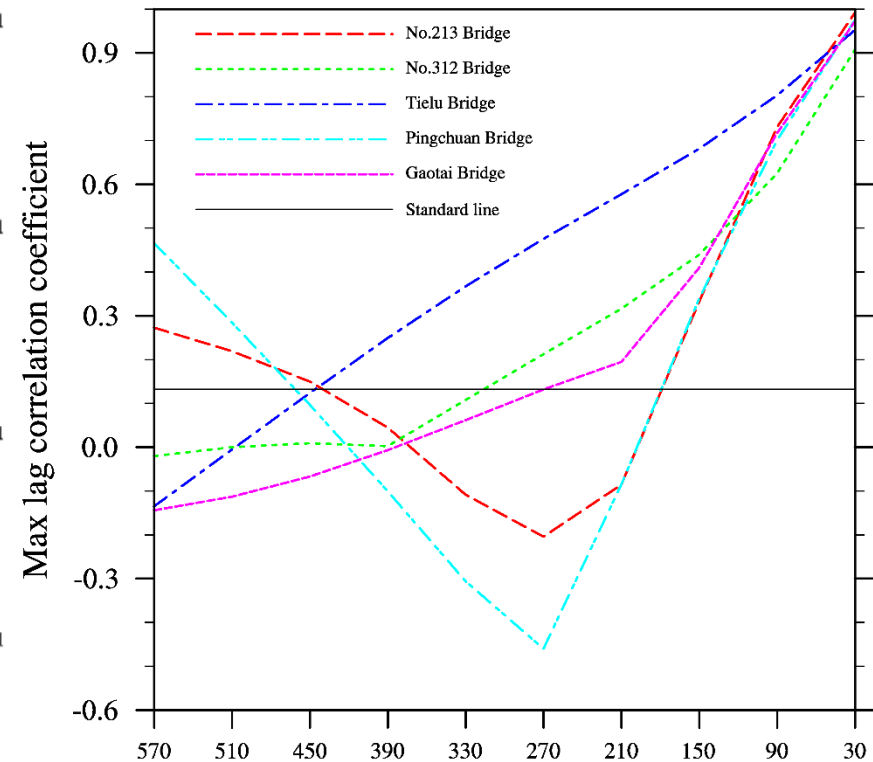
ASTER Ground Temp

Fluxnet measurements (Bajitan station)

Groundwater response to river level

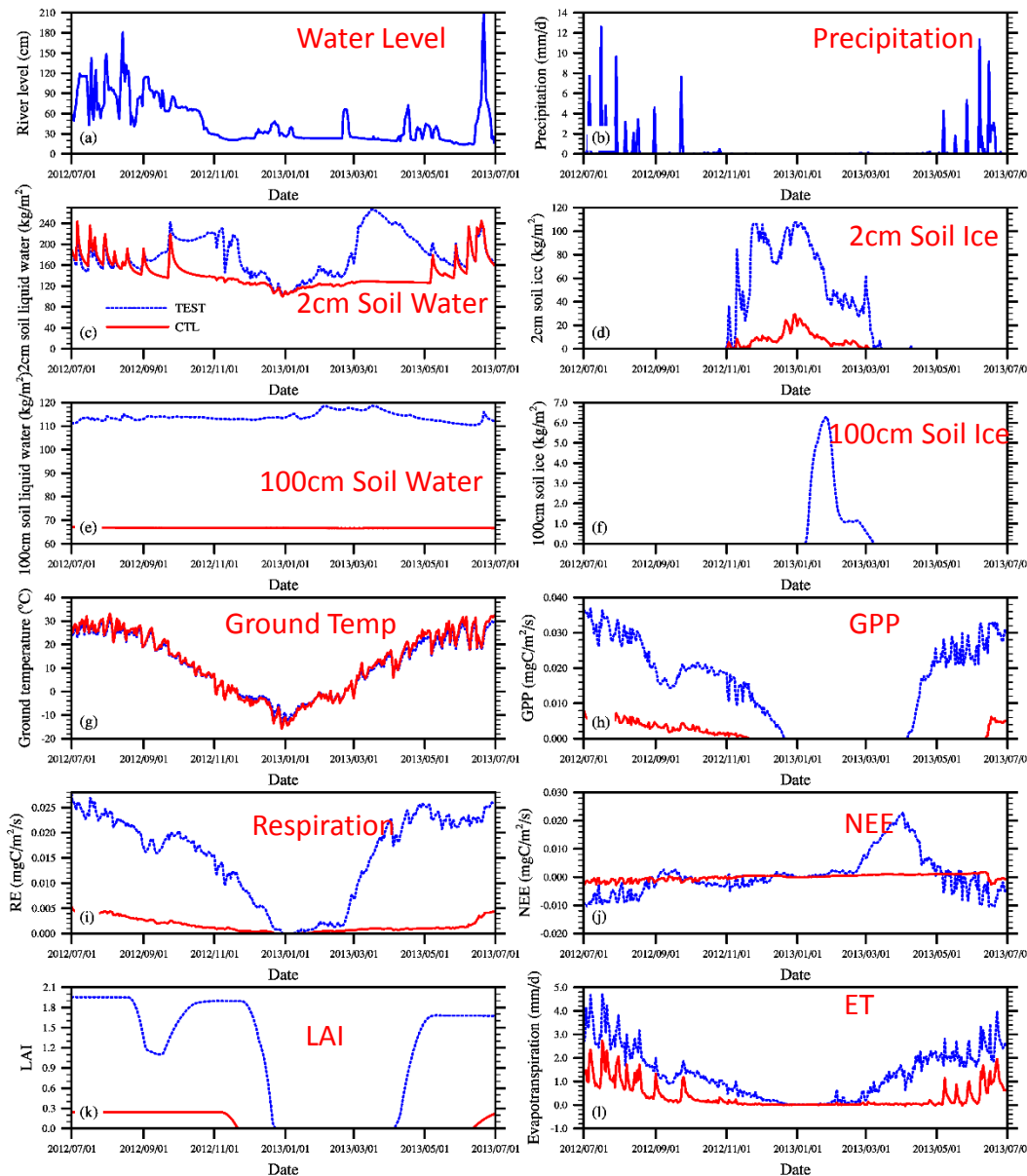


Correlation between groundwater and river level



Groundwater table and river levels

Eco-hydrological response to river level (Tielu Bridge)

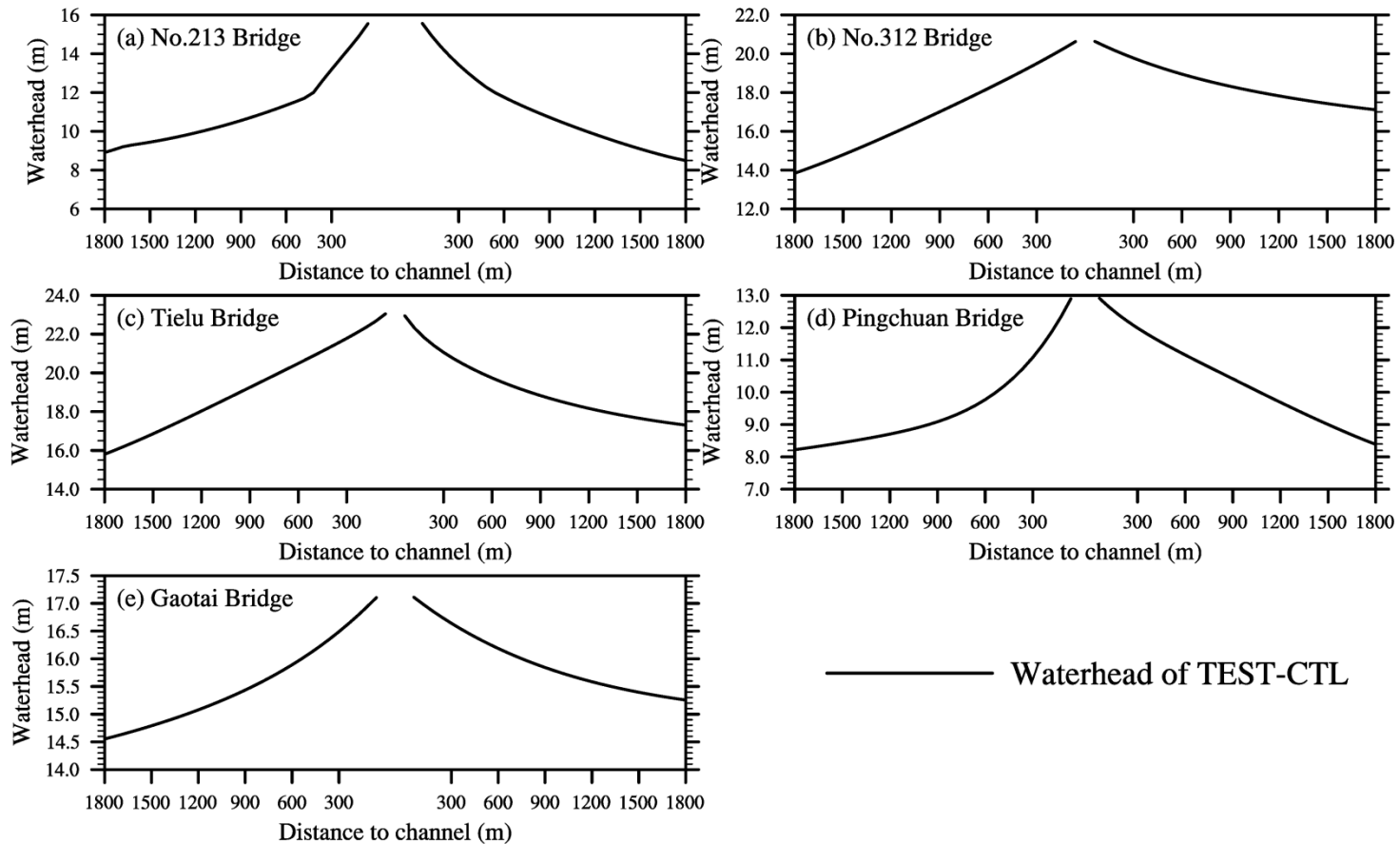


- The riparian hydrology cycle was affected by the stream water convey:
 - Groundwater table was elevated;
 - Soil moisture and ET were increased;
- The ecological system was improved:
 - GPP, respiration, NEE, LAI were increased;
 - Transpiration was increased.

Groundwater table spatial patterns



Groundwater Table



- Annual groundwater table over both sides of the river were significantly lifted.



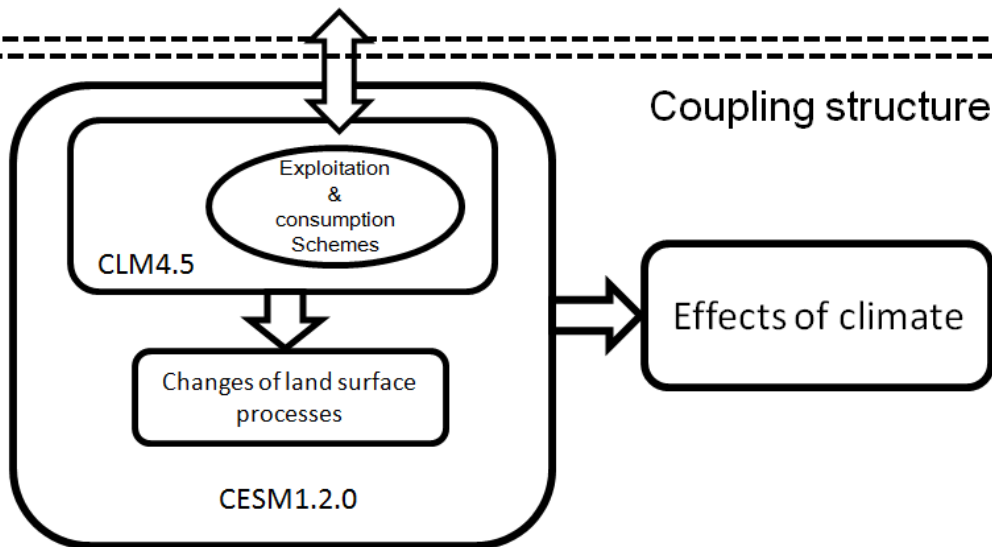
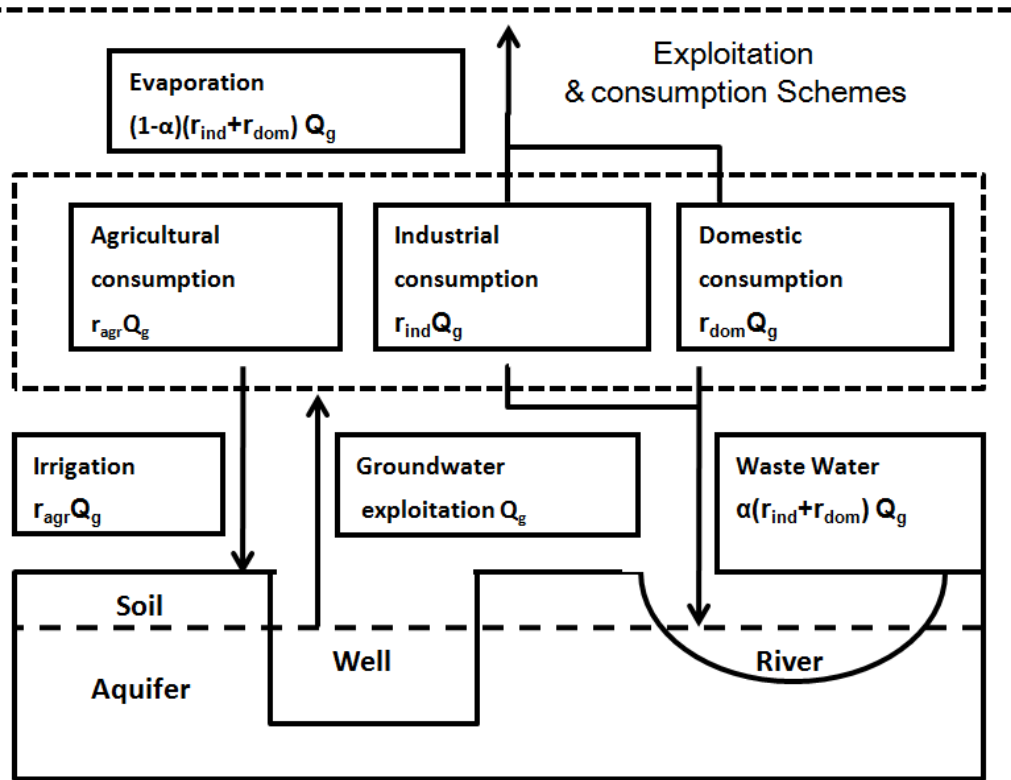
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Model Development

- A scheme of groundwater exploitation and consumption was incorporated into CLM4.5, the land surface module of earth system model CESM1.2.0;
- Climatic responses to anthropogenic groundwater exploitation were investigated.



Zeng, Y., Z.H. Xie & J. Zou (2016). Hydrologic and climatic responses to global anthropogenic groundwater extraction. ***Journal of Climate***, (In press). doi:10.1175/JCLI-D-16-0209.1.

Groundwater withdrawal and consumption 1965 to 2005



The Global Map of Irrigation Areas v5
(Siebert et al, 2013) $A_{irr}(i, j), f_{gw}(i, j)$

Monthly soil moisture and saturated soil
moisture (by CLM4.5 offline run) $W_{def}(i, j)$

$$Q_{agr_gw}(i, j) = Q_{agr_glob} \times \frac{A_{irr}(i, j)W_{def}(i, j)}{\sum_{i, j} A_{irr}(i, j)W_{def}(i, j)} \times f_{gw}(i, j)$$

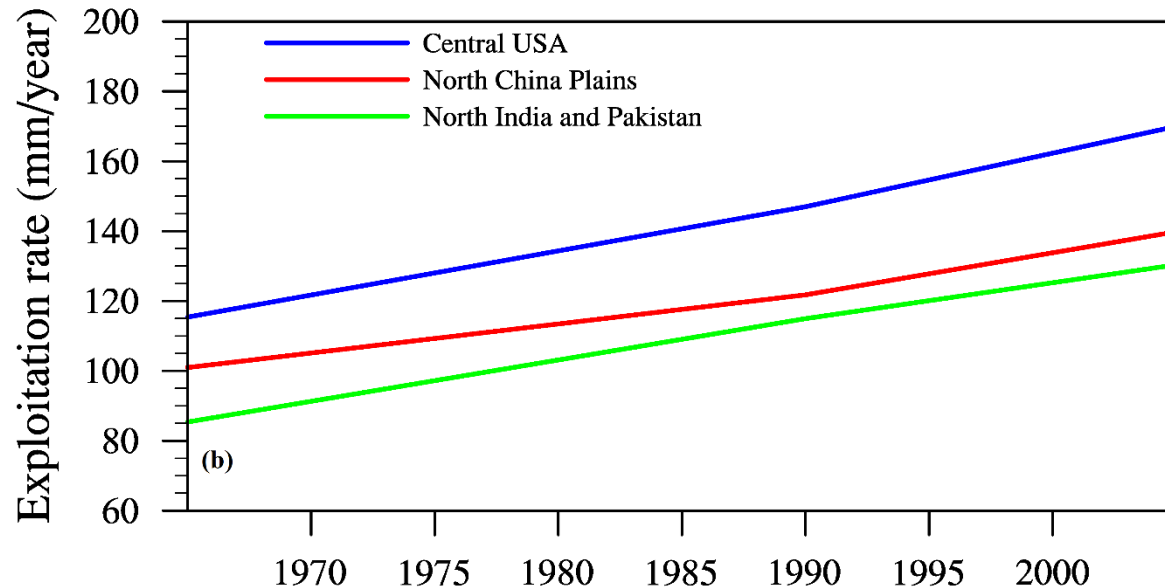
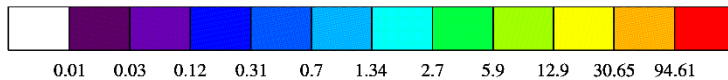
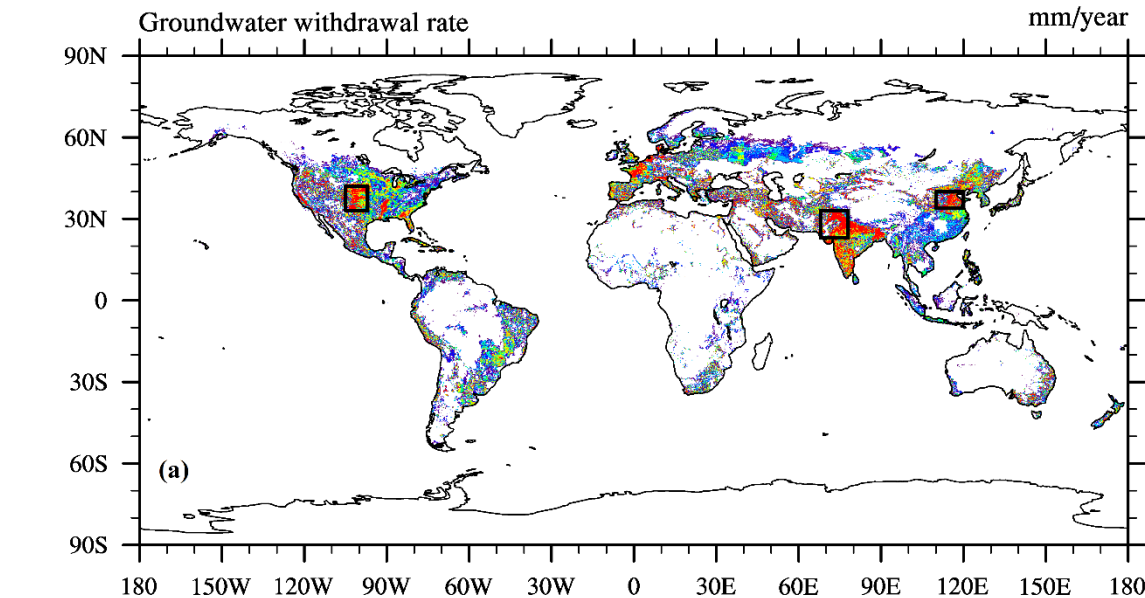
The municipal, industrial and agricultural water use data (FAO) $f_{agr}(i, j), f_{ind}(i, j), f_{live}(i, j)$

$$Q_{tot_gw}(i, j) = Q_{agr_gw}(i, j) / f_{agr}(i, j)$$

$$Q_{ind_gw}(i, j) = Q_{tot_gw}(i, j) \times f_{ind}(i, j)$$

$$Q_{live_gw}(i, j) = Q_{tot_gw}(i, j) \times f_{live}(i, j)$$

Groundwater withdrawal amount and its consumption in agricultural,
industrial and domestic of each grid from 1965 to 2005, estimated

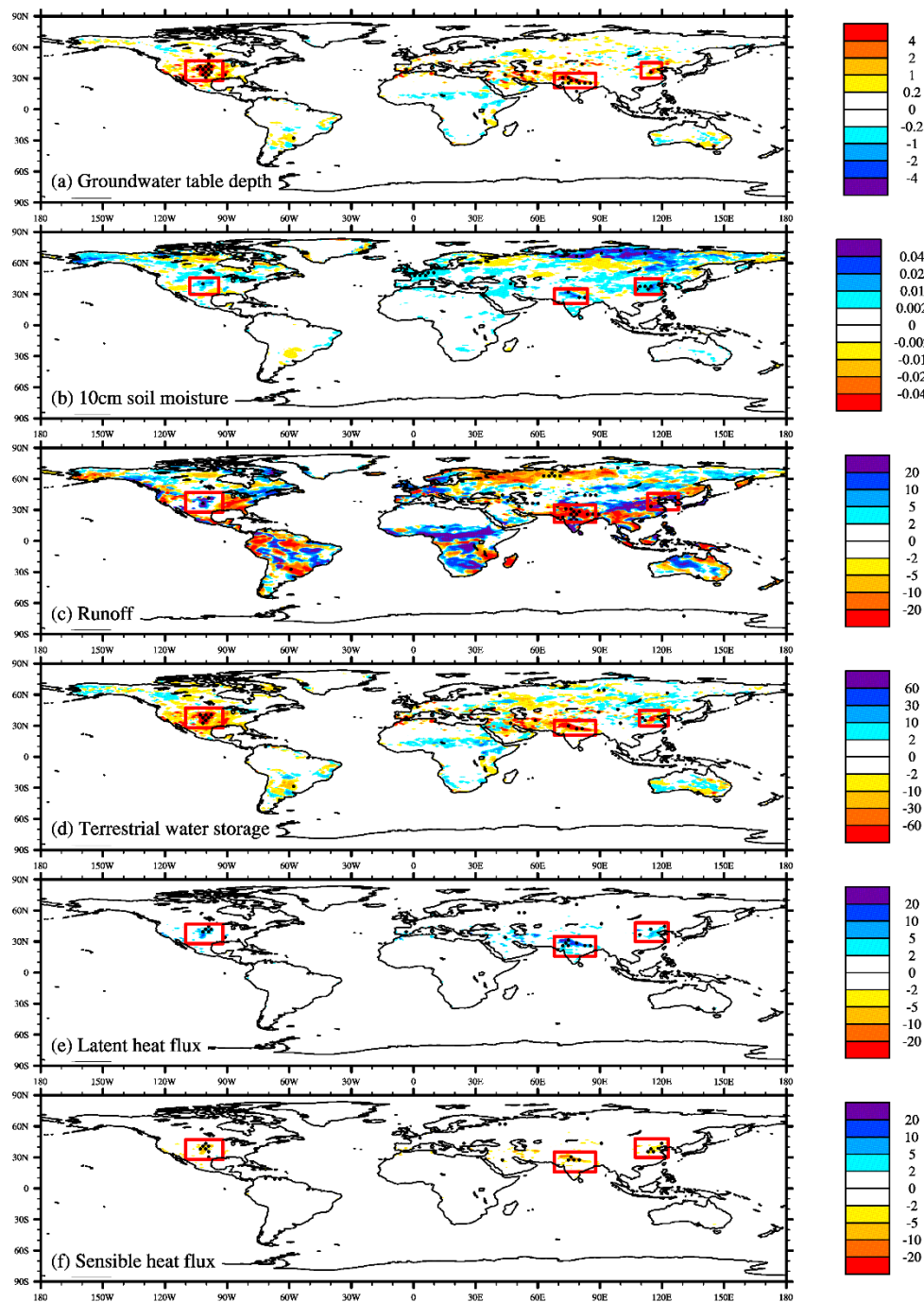


- The three largest contiguous areas with high groundwater exploitation rate are located in **central USA**, in **north China Plains** and in **north India and Pakistan**.

Experimental design

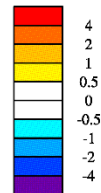
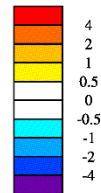
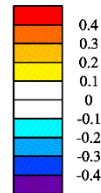
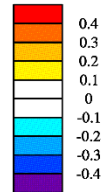
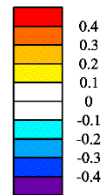
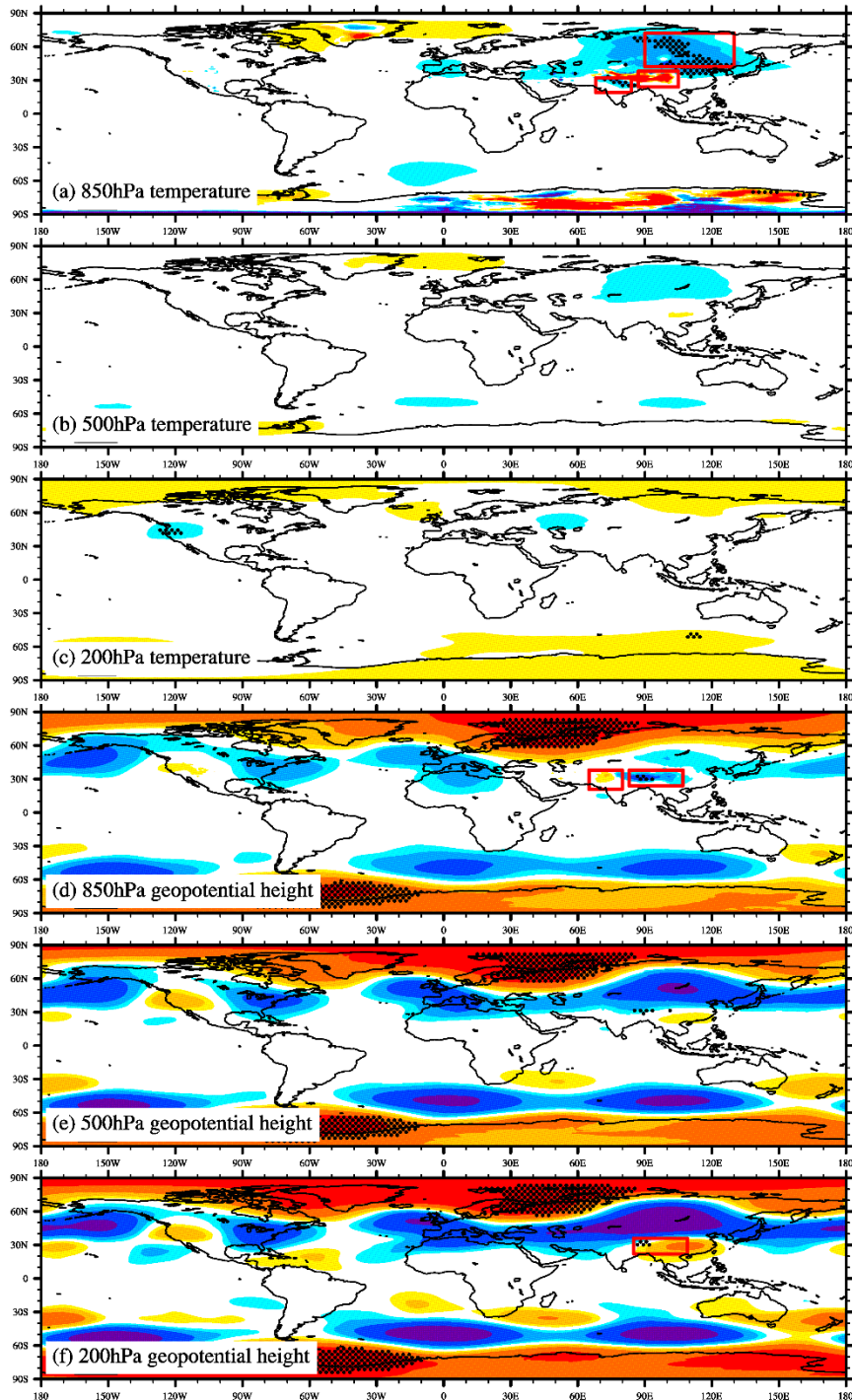


- **Study Region: Global scale**
- **Resolution: $0.9^{\circ} \times 1.25^{\circ}$**
- **Component sets: CAM4+CLM4.5 (Land-atmosphere interactively coupled). SSTs are prescribed by monthly observation from Hadley Centre.**
- **Simulation period: 1965-2005 (1965-1969 for spin-up)**
- **There are two ensemble simulations with and without groundwater exploitations respectively (EXP and CTL), and each ensemble contains six runs with different initial conditions).**



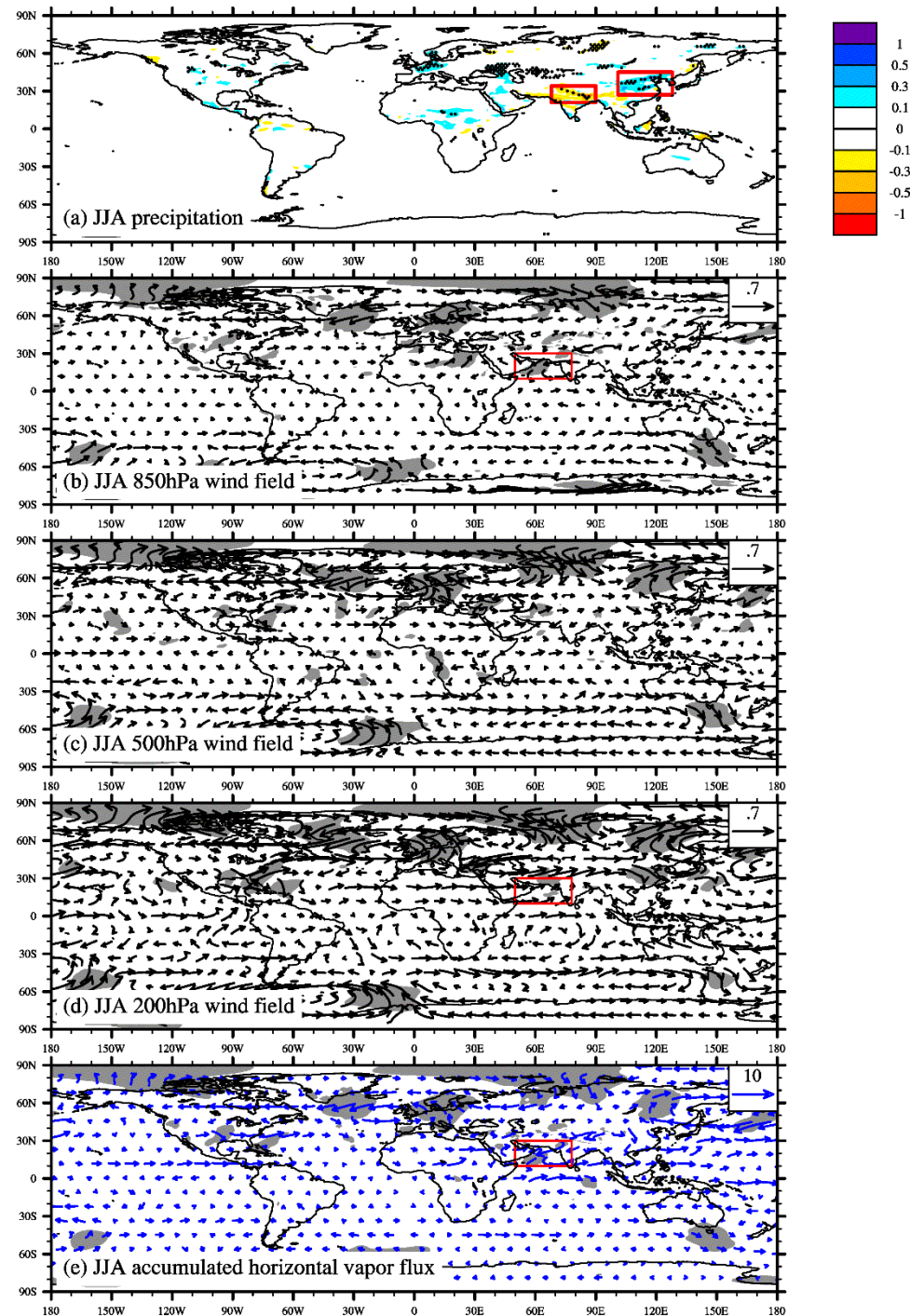
Differences in spatial distribution of hydrologic variables

- Decreasing effects on runoff and terrestrial water storage, along with a rapidly declining groundwater table occurred in areas with serious groundwater exploitation.



Differences in spatial distribution of temperature and geopotential height at 850hPa, 500hPa and 200hPa

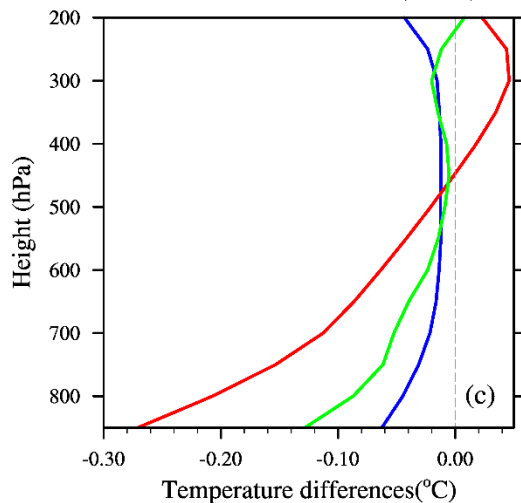
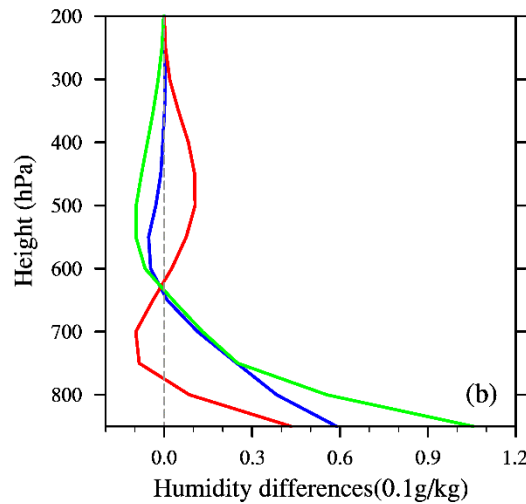
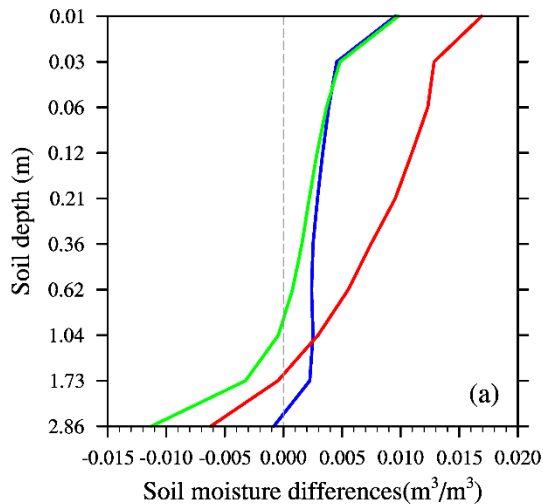
- Two contiguous areas experiencing a significant cooling effect of $\sim 0.3^{\circ}\text{C}$ were obvious. One of these areas was located in north India and Pakistan; the other area was the north China plus a large area of central Russia.
- The Tibet Plateau in China experienced lower geopotential height at 850 hPa level



Differences in spatial distribution of JJA precipitation, wind field at 850hPa, 500hPa and 200hPa levels and horizontal vapor flux

- Significantly cooling effects are occurred in Northern China, India and Pakistan.
- Precipitation is increased in North China Plain but decreased in Northern India. Decreased precipitation occurred in north India because the Indian monsoon and its transport of water vapor were weaker as a result of cooling induced by GW use.

Effects of groundwater exploitation on vertical profiles



— Central USA
— North China Plains
— North India and Pakistan

- Climatology results of EXP-CTL, ensemble averaged on vertical profiles of soil moisture, air humidity and temperature;
- In all the three regions, groundwater exploitation makes the deeper soil dryer, upper soil wetter, and the lower troposphere cooler and wetter.



Outline

- **Model development and validation**
- **Effects of groundwater lateral flow and human water regulation**
- **Eco-hydrological effects of stream-aquifer water interaction**
- **Climatic responses to global anthropogenic groundwater extraction**
- **Summary and discussion**



Summary and discussion



- A land model which can model groundwater lateral flow, human surface water withdrawal and groundwater exploitation as well as its consumption is developed.
- Effects of groundwater lateral flow and human water regulation were then investigated for a river basin.
- Eco-hydrological effects of stream-aquifer water interaction were investigated (Riparian groundwater table responds to river water level, GPP, respiration, NEE, LAI and ET of riparian vegetation significantly respond to the river level variation).
- Climatic responses to global anthropogenic groundwater extraction were investigated (without considering groundwater laterflow, Cooling and wetting effects appear on lower troposphere, Increased precipitation occurs in Haihe River Basin while decreased precipitation occurs in Northern India).
- Global groundwater laterflow representation in a climate model is developing, the key point is to extend the case for a river basin to global area, two aspects should be considered: in the river basin boundaries and land-ocean boundary conditions.

Thank you !

<http://web.lasg.ac.cn/staff/xie/xie.htm>



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