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Simulations of soil frost and thaw front (FTF) dynamics using a land surface model

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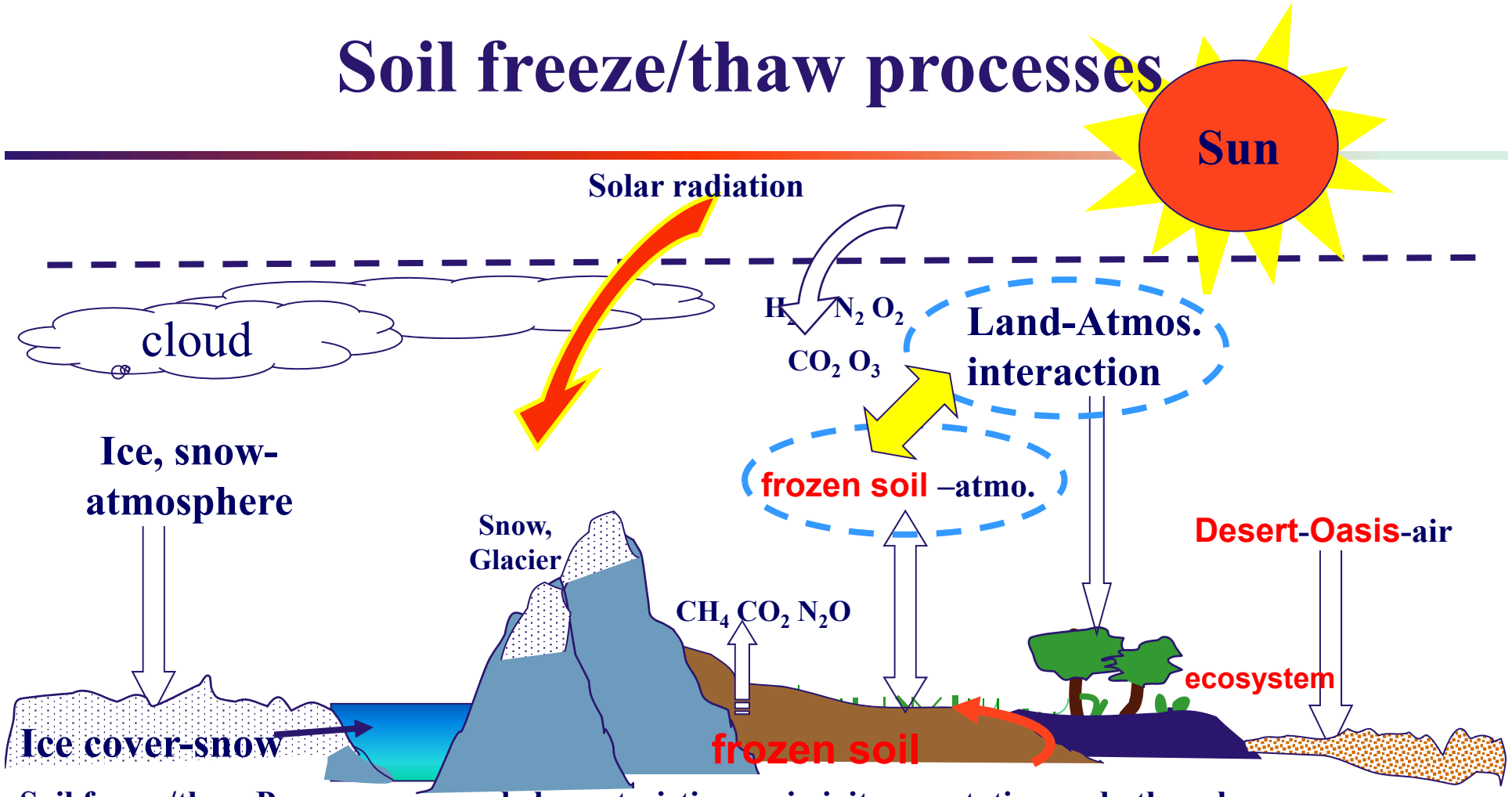
Outline

- Motivation
- A two-directional freeze and thaw algorithm
- A land model including changes in FTFs
- Model validation
- Results and conclusions

Soil freeze/thaw processes

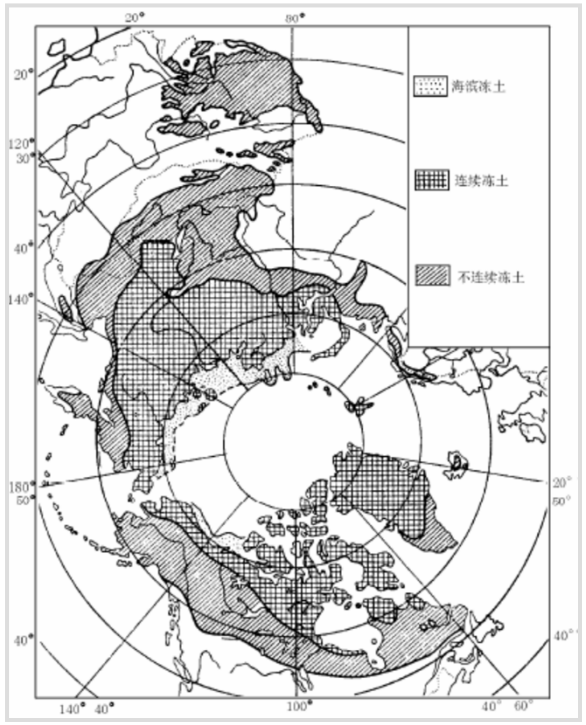


Soil freeze/thaw Processes, ground characteristics, emissivity, vegetation and other changes

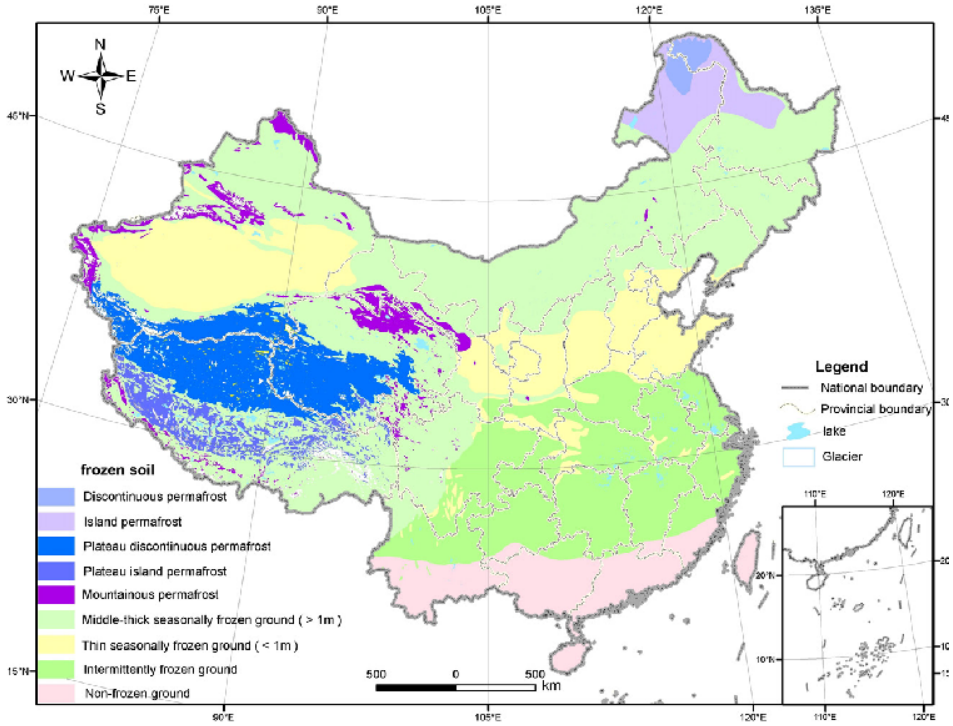
- Soil freeze/thaw processes including changes of frost/thaw depths significantly influence energy and water exchanges, vegetation growth and organic matter decomposition;
- Accurate representation of frost and thaw depths (FFTs) and their feedback is of significance for improving simulations of the hydrological and greenhouse gas exchange processes.

Permafrost and seasonally frozen ground

Distribution of permafrost and seasonally frozen ground in Northern Hemisphere



Distribution of permafrost and seasonally frozen ground in China (Li,et al.,2008)



- **Frozen soil：all kinds of ice-containing frozen soil at 0℃ or below 0℃。**
- **Permafrost and seasonally frozen soil account for 24% and 30% of the land area in the north Hemisphere, respectively；**
- **In China, the area of frozen soil is equivalent to 72% of land surface.**

Motivation

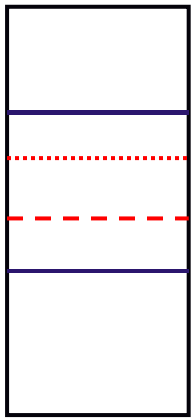
- **Current land-surface models such as SSIB, SIB2, SHAW, CoupModel, and CLM include description of permafrost hydrothermal processes. However, these models describe FTF depth as a diagnostic variable, and can not feedback due to its changes.**

- **In this study, a two-directional freeze and thaw algorithm for simulating FTFs was developed and incorporated into the community land surface model CLM4.5, and then investigate the dynamical changes of soil frost and thaw fronts (FTFs) using the developed model.**

Estimation method of FTF Depth

- **Direct method**

FTF depths can be interpolated from measured or simulated soil temperature (*Flerchinger et al.,1989; Frauenfeld et al., 2004; Kennedy et al., 1998*), using the 0 ℃ isotherm as the surrogate for the front.



Defects:

1. **Multiple FTFs cannot be simulated at the same time when they are in the same soil layer;**
2. **This isotherm usually exhibits large fluctuations during autumn freezing and spring snowmelt periods when soil temperature hovers around the freezing point. (*Yi et al., 2006*)**

A two-directional freeze and thaw algorithm

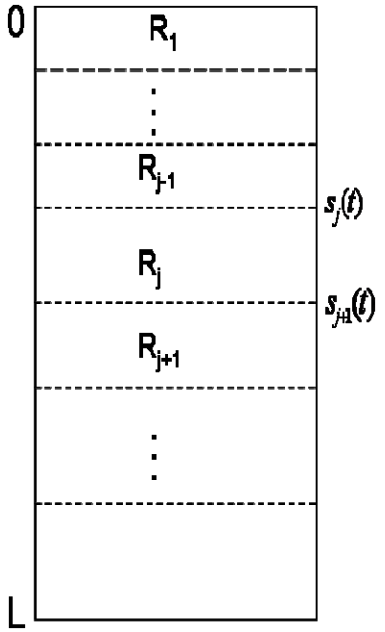
$$z_f = \sqrt{\frac{2\lambda \cdot D}{L \cdot \theta}}$$

$$z_f^{\,2} = \frac{2\lambda \cdot D}{L \cdot \theta}$$

$$2z_f \cdot \Delta z_f = \frac{2\lambda \cdot \Delta D}{L \cdot \theta}$$

$$\Delta D = (L \cdot \theta \cdot \Delta z_f) \cdot (\frac{z_f}{\lambda})$$

- The Stefan equation assume all the heat is used for the freezing or melting of ground ice.
- Soil profile is modelled as a homogeneous medium



$$N_1 = (L \cdot \theta_1 \cdot z_1)(\frac{R_1}{2})$$

$$N_2 = (L \cdot \theta_2 \cdot z_2)(R_1 + \frac{R_2}{2})$$

$$\cdots$$

$$N_i = (L \cdot \theta_i \cdot z_i)(\sum_{n=1}^{i-1} R_n + \frac{R_i}{2})$$

- Use the Stefan equation in a multi-layered system

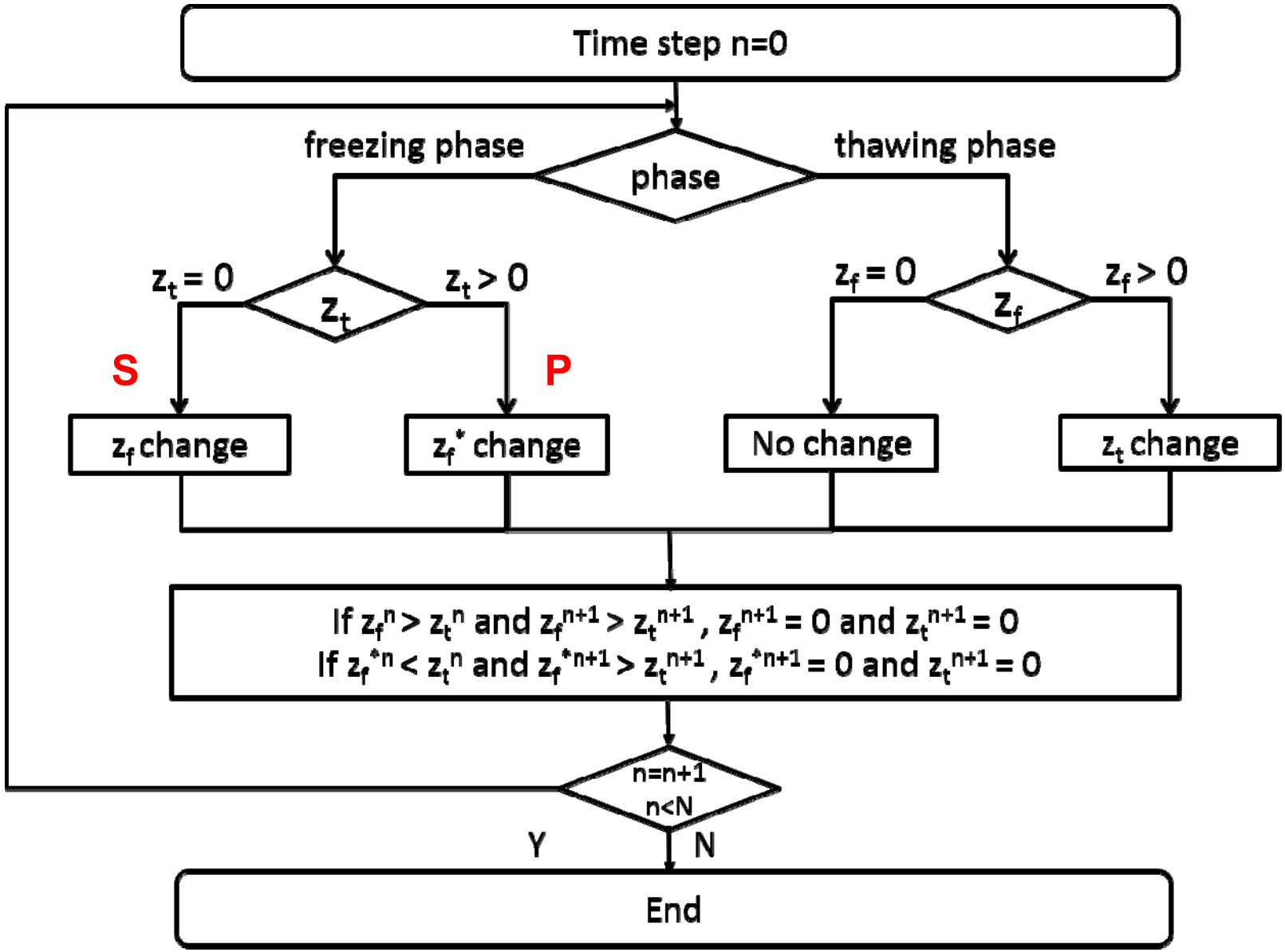
$$D - \sum_{n=1}^{i-1} N_n = (L \cdot \theta_i \cdot z_{f0})(\sum_{n=1}^{i-1} R_n + \frac{z_{f0}}{2\lambda_i})$$

$$z_{f0} = -\lambda_i \sum_{n=1}^{i-1} R_n + \left\{ \lambda_i^2 \left[\sum_{n=1}^{i-1} R_n \right]^2 + \left[2\lambda_i (D - \sum_{n=1}^{i-1} N_n) / (L \cdot \theta_i) \right] \right\}^{1/2}$$

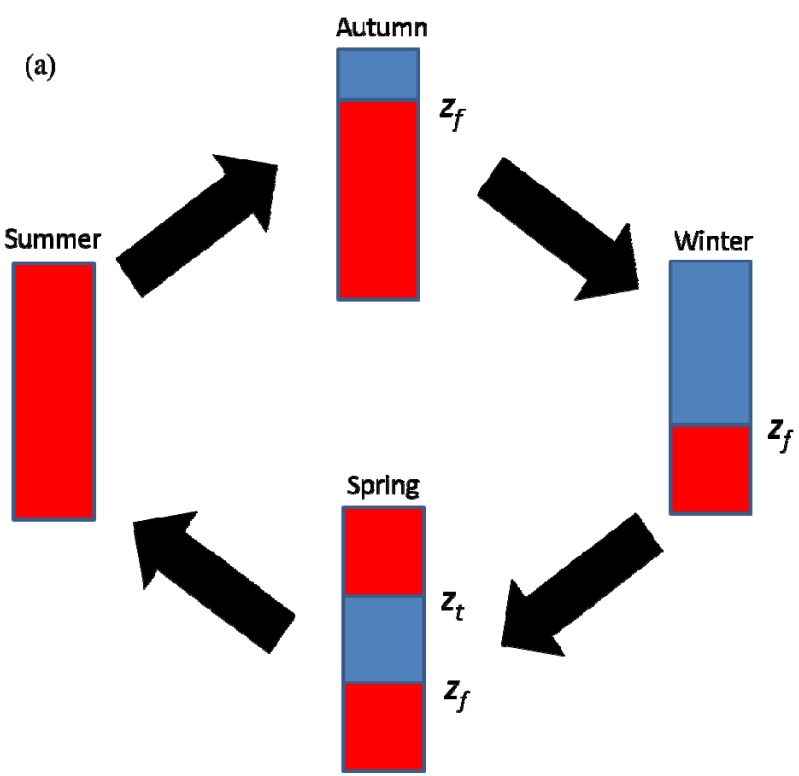
$$z_f = z_{i-1} + z_{f0}$$

(Woo et al., 2004 Gao et al., 2016)

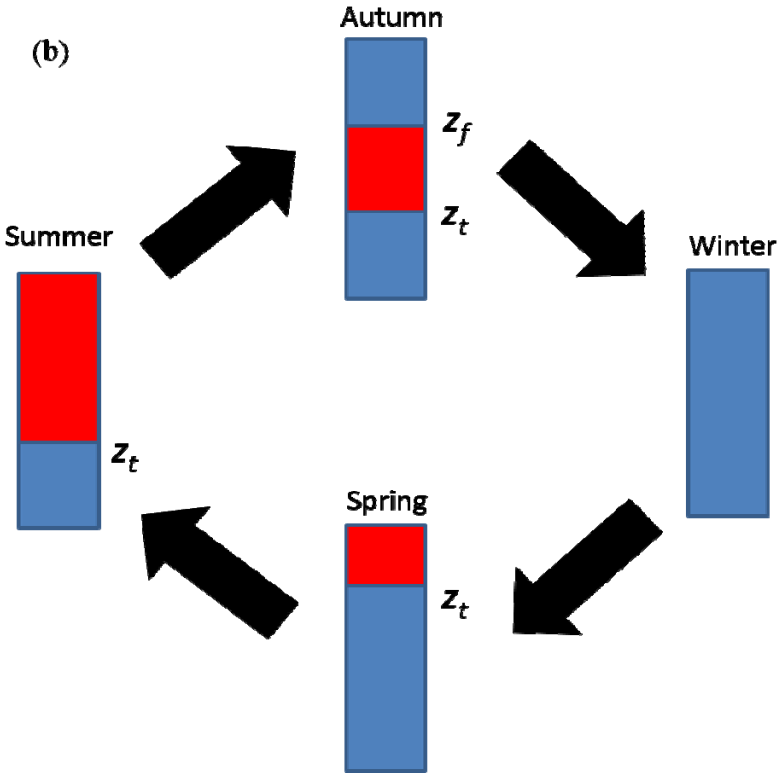
Schematic diagram of FTFs



Permafrost and seasonally frozen ground



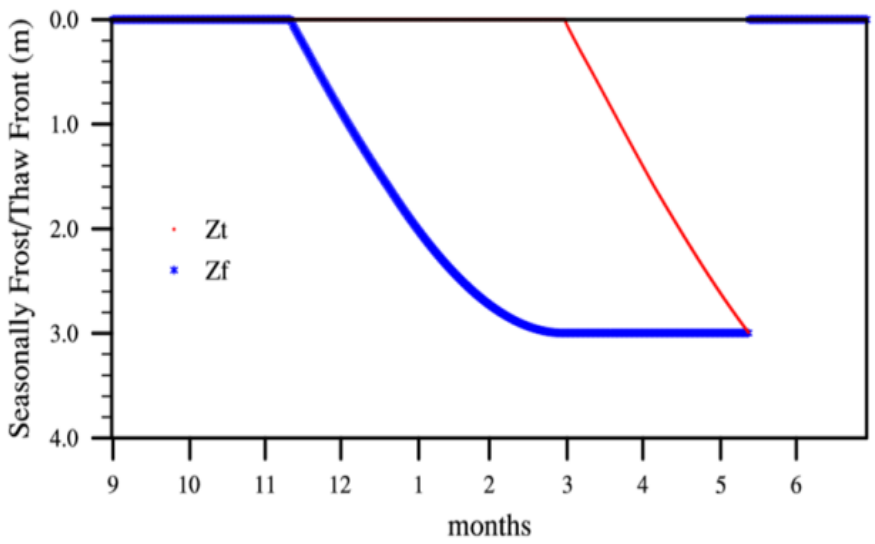
Seasonally frozen ground

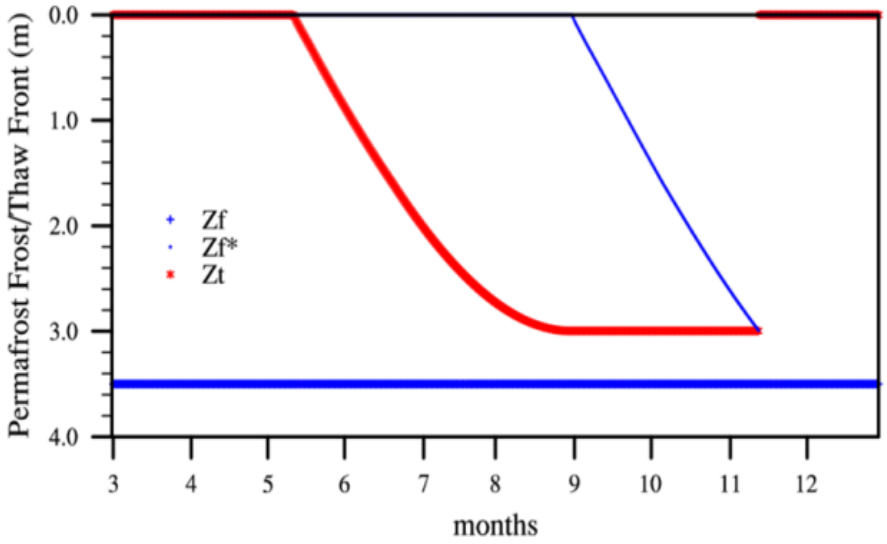


Permafrost

Red part: Soil temperature > 0℃
Blue part: Soil temperature < 0℃

Permafrost and seasonally frozen ground



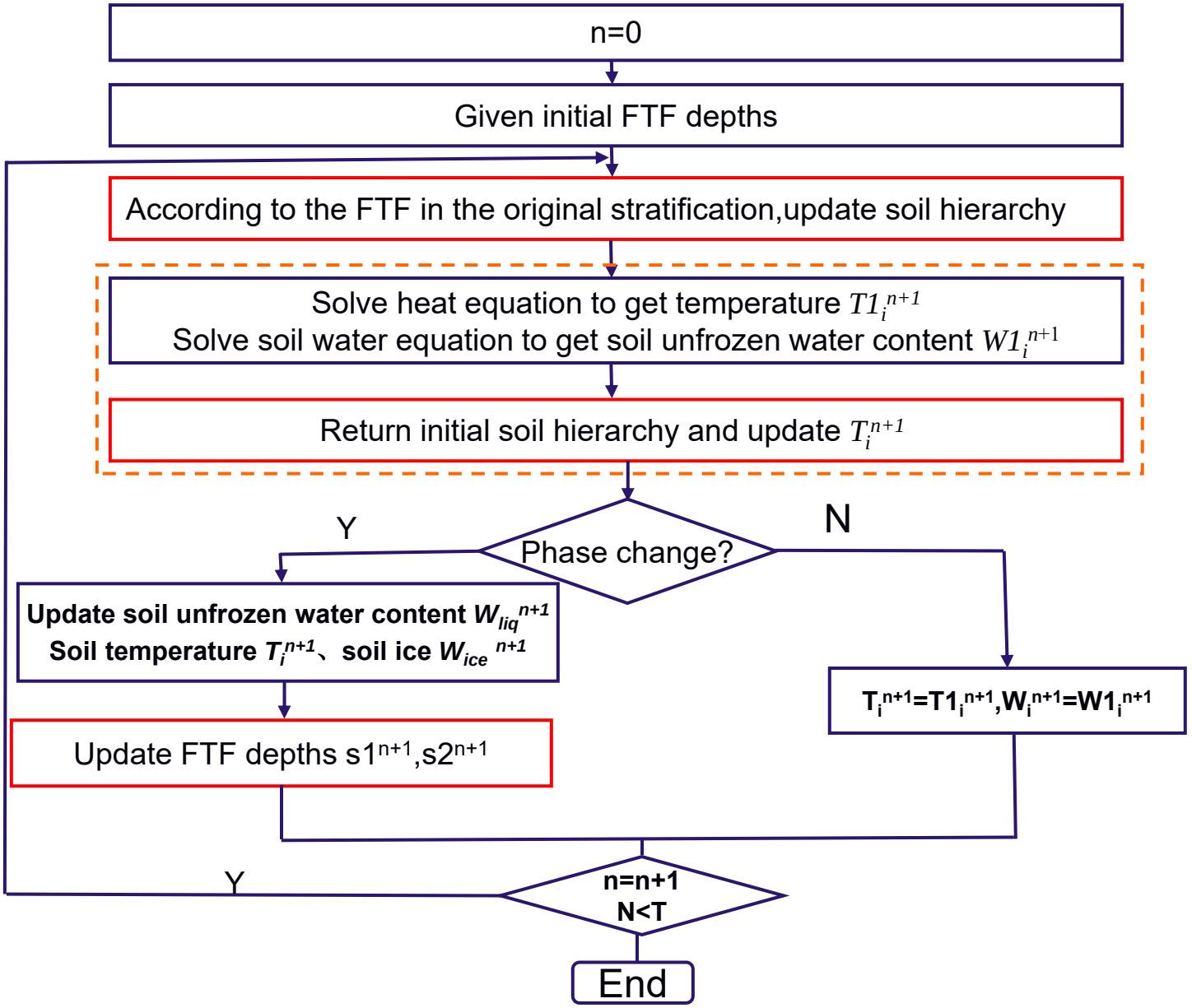


Seasonally frozen ground **Permafrost**

Red line: Thaw front
Blue line: Frost front

Simulation corresponds reasonably with frozen ground condition.

Model coupling (CLM4.5_FTF)



Model Validation

Forcing data: ITP(1979-2012).

temporal resolution:3hours, spatial resolution:0.1°x0.1°。

1. Regional simulation

Simulation period:1979~2012.

Simulation region: China.

Initial FTF depths: 0m.

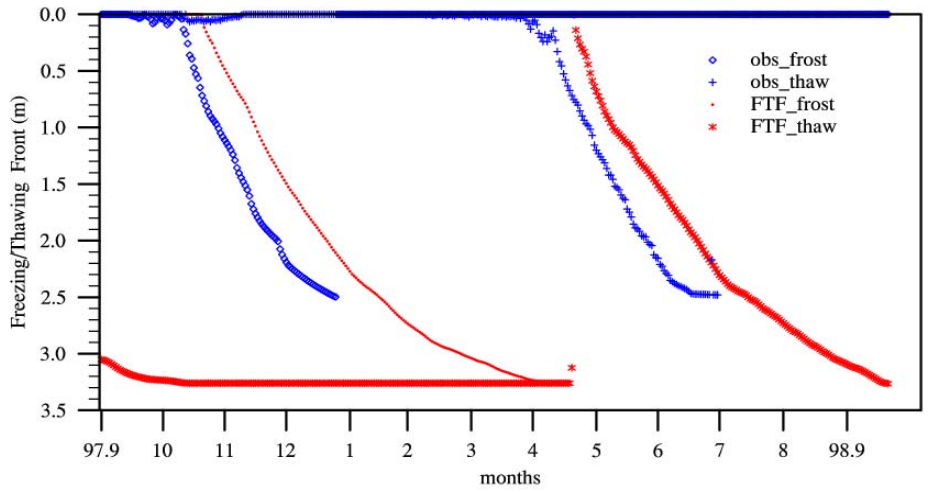
2. Single Point simulation

Simulation period:1979~2012.

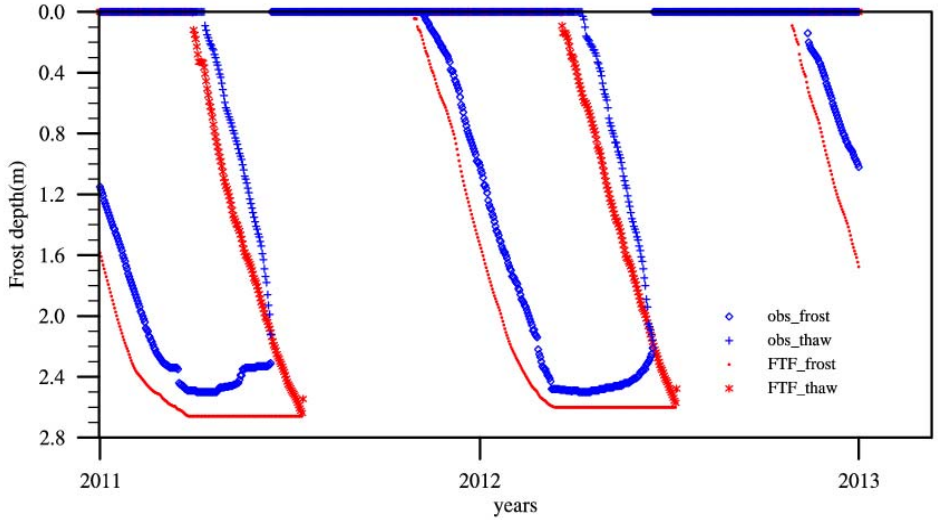
Station : D66 Station in Tibetan Plateau permafrost

Hulugou Station in Heihe basin seasonally frozen soil

Single Point Model Validation



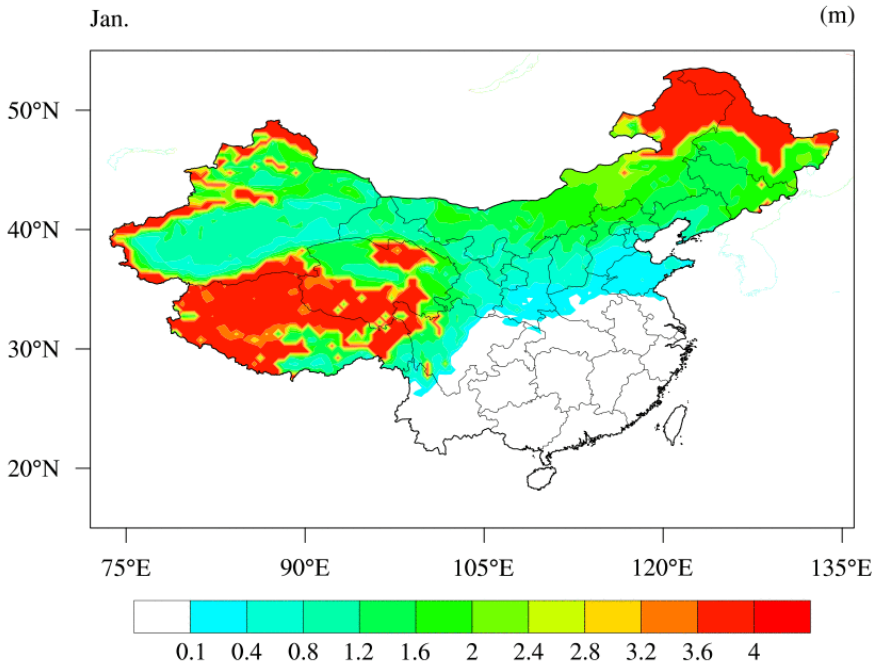
- **D66 station FTFs simulation (permafrost)**



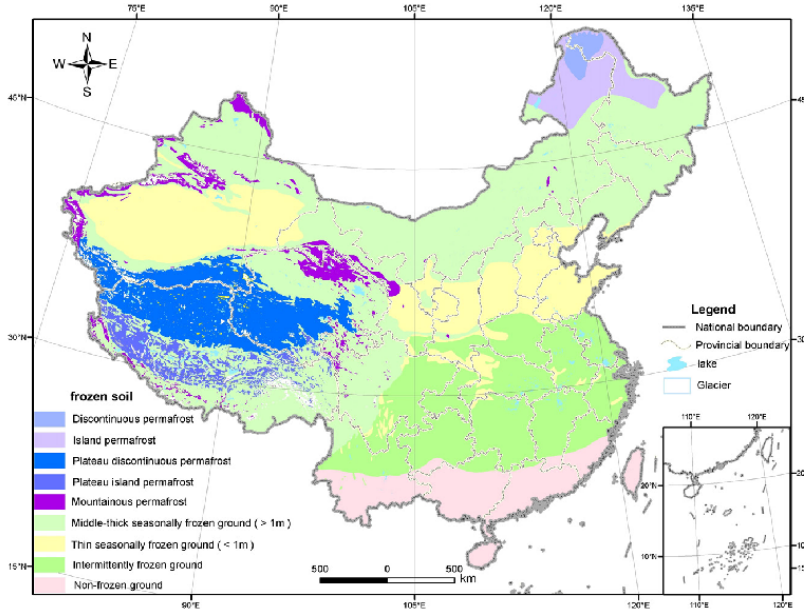
- **Hulugou station FTFs simulation (seasonally frozen soil)**

Frozen ground distribution validation

Simulation of frozen ground in China



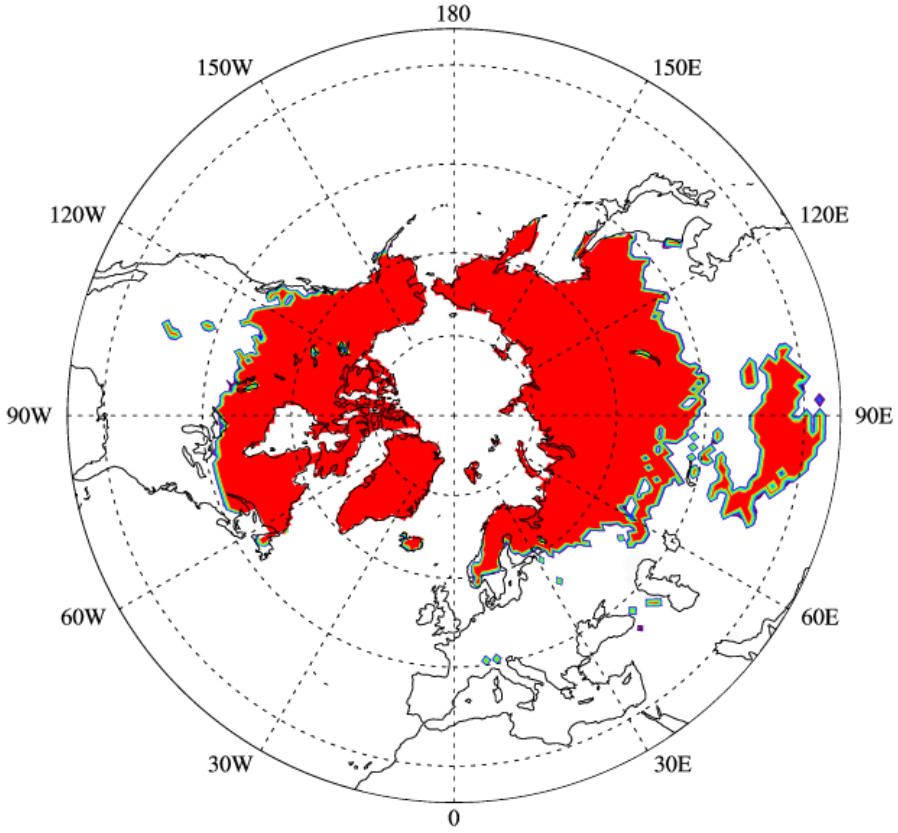
Distribution of frozen ground in China (Xin Li, et al.,2008)



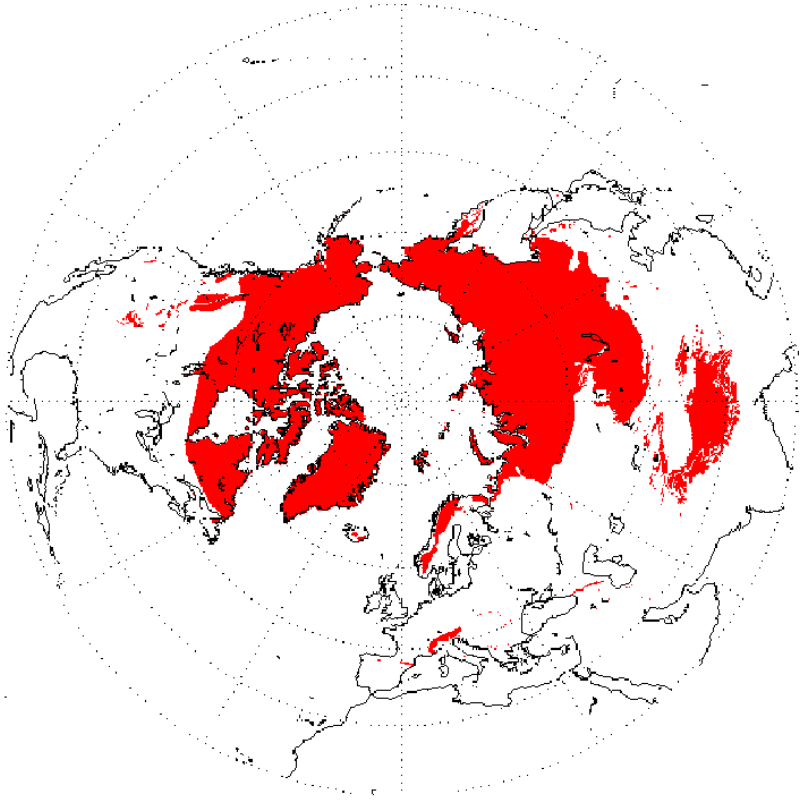
- **North of China is underlain by seasonal frozen soil.**
- **Tibetan Plateau, Tianshan Mountain, Qilian Mountain and northeast of China are underlain by permafrost.**

Permafrost distribution validation

Simulation



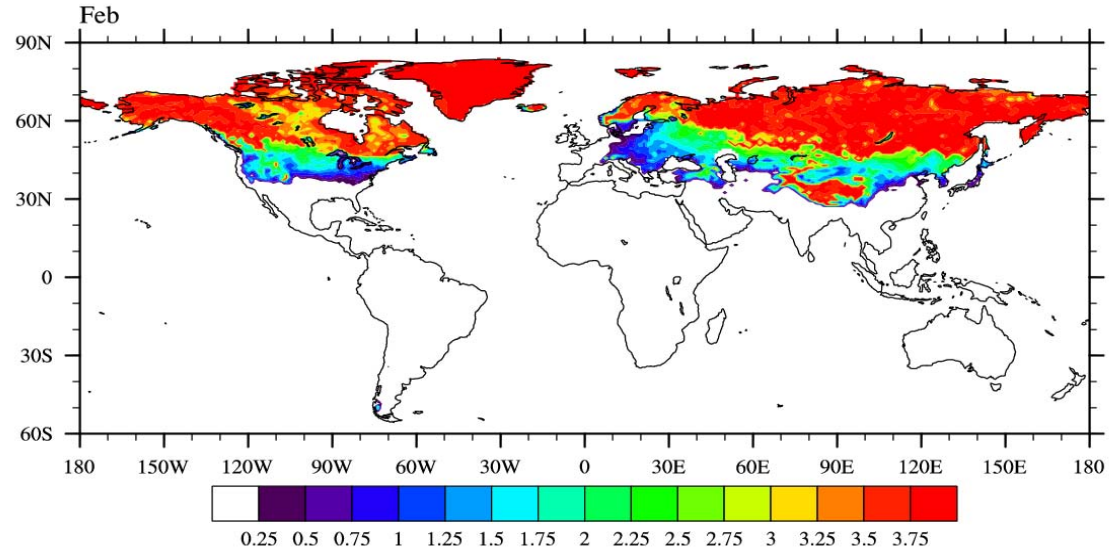
IPA observation



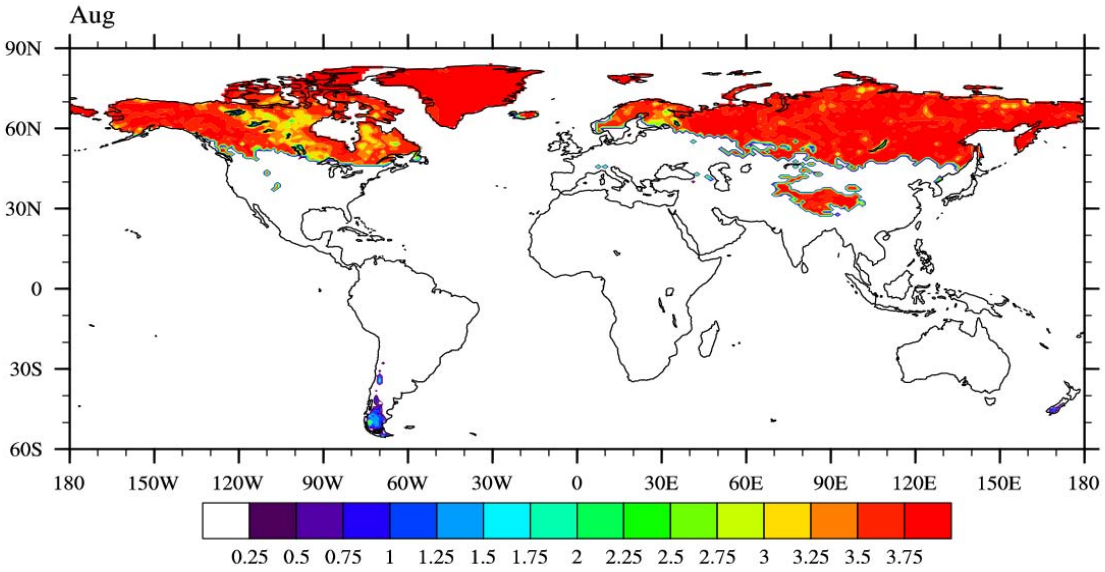
Experimental Design

- **Study domain: Global simulation**
- **Resolution： 0.9°× 1.25°**
- **Simulation period： 1970-2000**
- **Atmospheric forcing： CRUNCEP (The standard forcing provided with the model, 110-year dataset (1901-2010))**

Global Simulation by CLM4.5_FTF

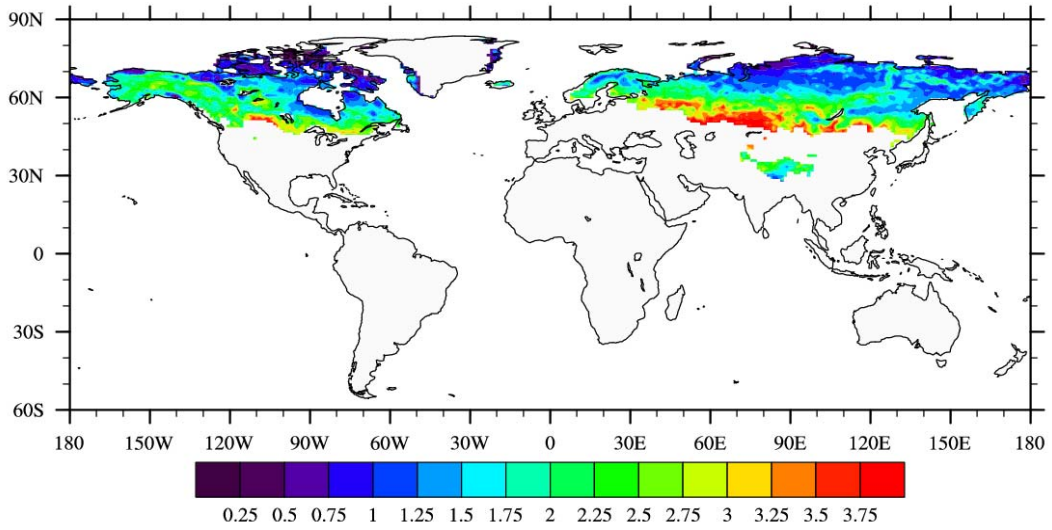


- **Frost front depth in Feb (m).**

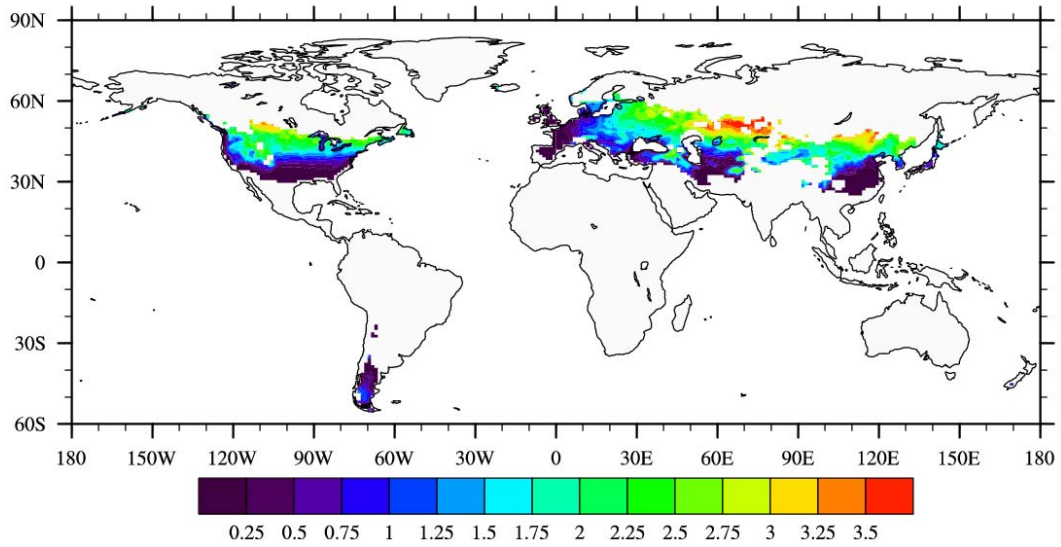


- **Frost front depth in Aug (m).**

Global Simulation by CLM4.5_FTF



- **Active layer depth in permafrost (m).**



- **Max frost front depth in seasonally frozen soil (m).**

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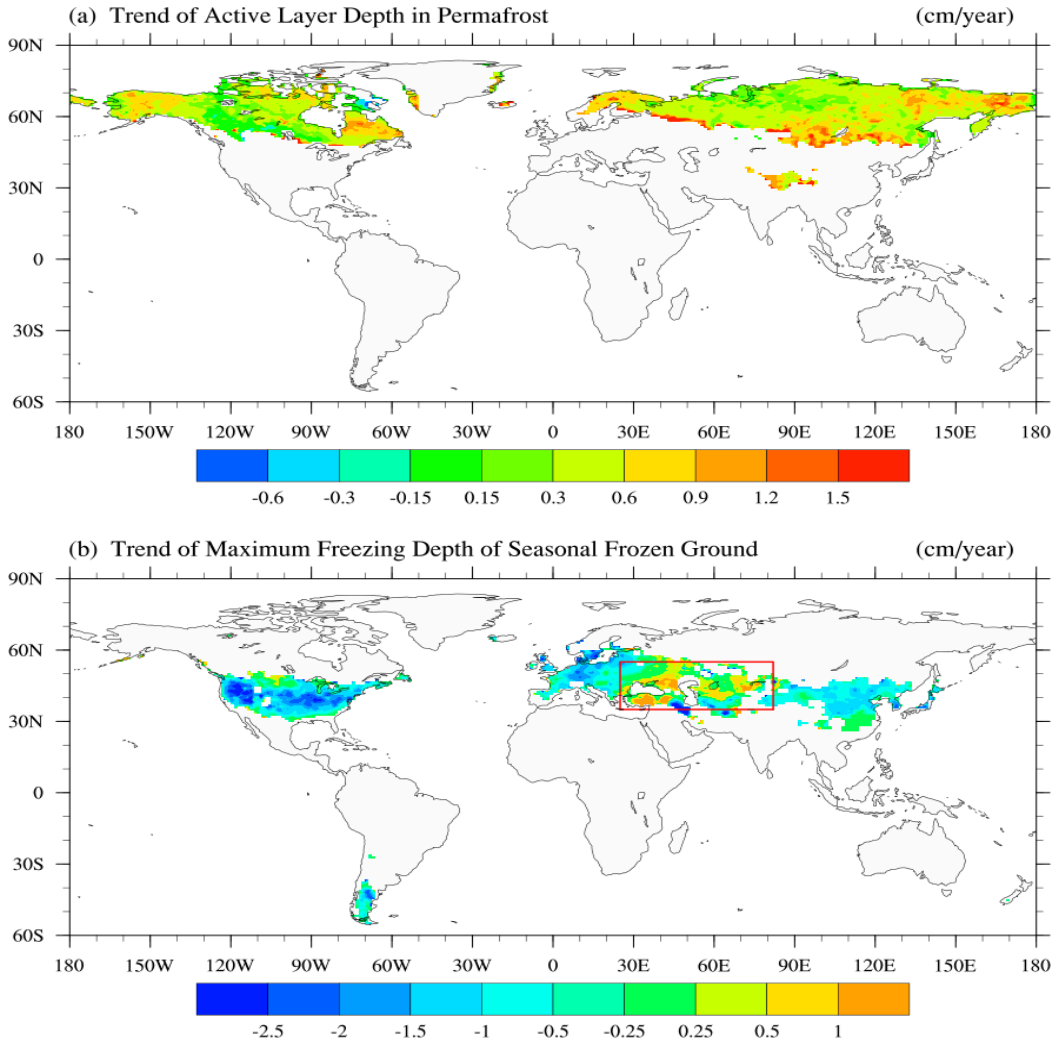
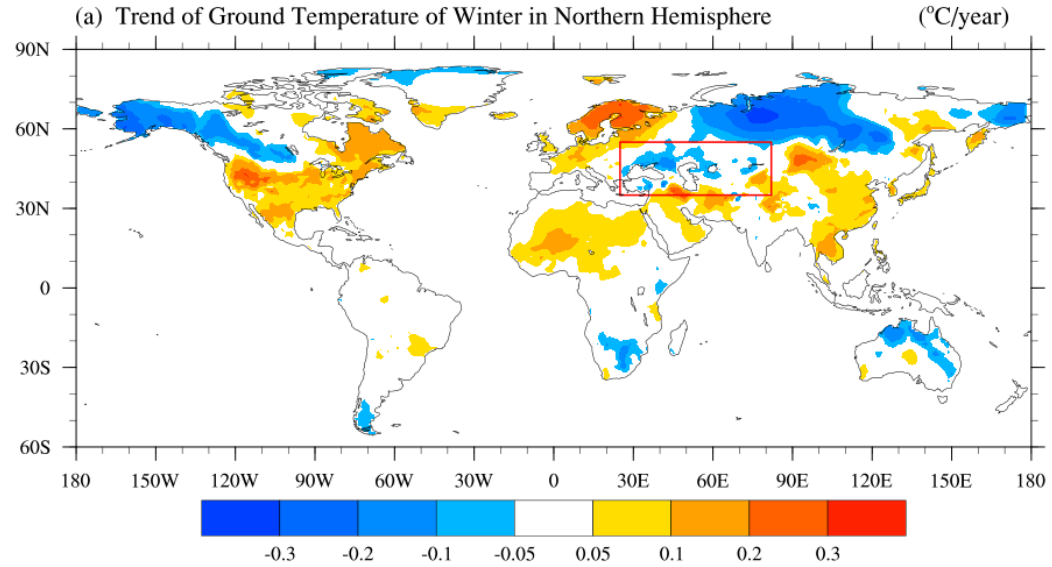
Global Simulation by CLM4.5_FTF

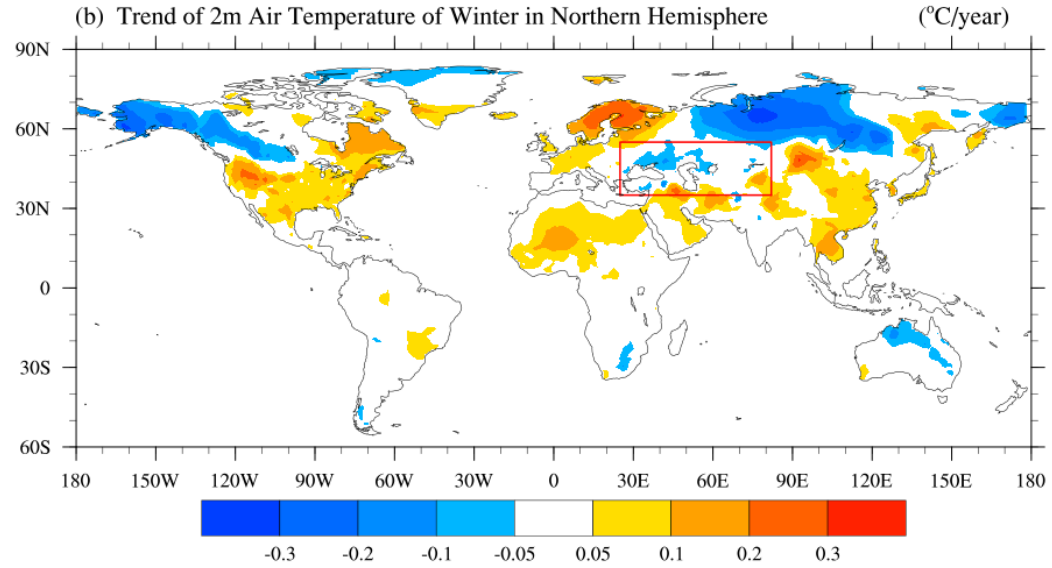


- **Trend of active layer depth in permafrost (cm/year).**
- **Trend of max frost front depth in seasonally frozen ground (cm/year).**
- **Trend of active layer depth in permafrost is positive and trend of maximum freezing depth in seasonally frozen soil region is negative, except the west of Black Sea.**

Global Simulation by CLM4.5_FTF



- **Trend of ground temperature in the winter (°C/year).**



- **Trend of 2m air temperature in the winter (°C/year).**

Conclusion and Discussions

- **In this study, we developed a two-directional freeze and thaw algorithm and incorporated it into a land surface model to simulate the FTFs.**

- **The new model performed well in site validation and frozen ground distribution in China and in northern hemisphere.**

- **With the global warming, trend of active layer depth in permafrost is positive and trend of maximum freezing depth in seasonally frozen soil region except the region around the Black Sea and the Caspian Sea.**

Thanks for your Attentions!

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