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北京師範大學
BEIJING NORMAL UNIVERSITY

Understanding Climate Model Uncertainty Through an Earth System Model of Intermediate Complexity (EMIC)

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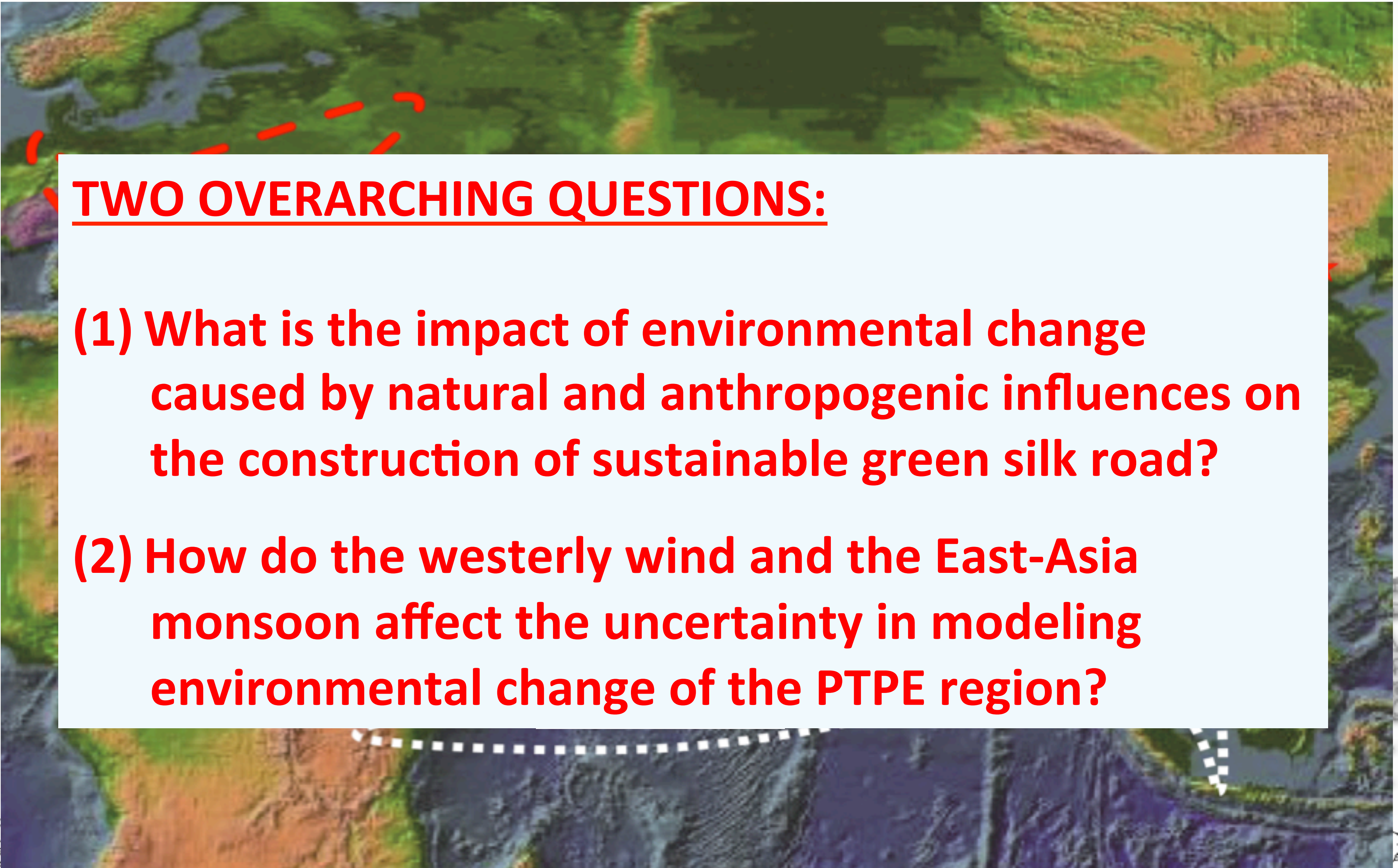
Pan Third Pole Environment (PTPE)

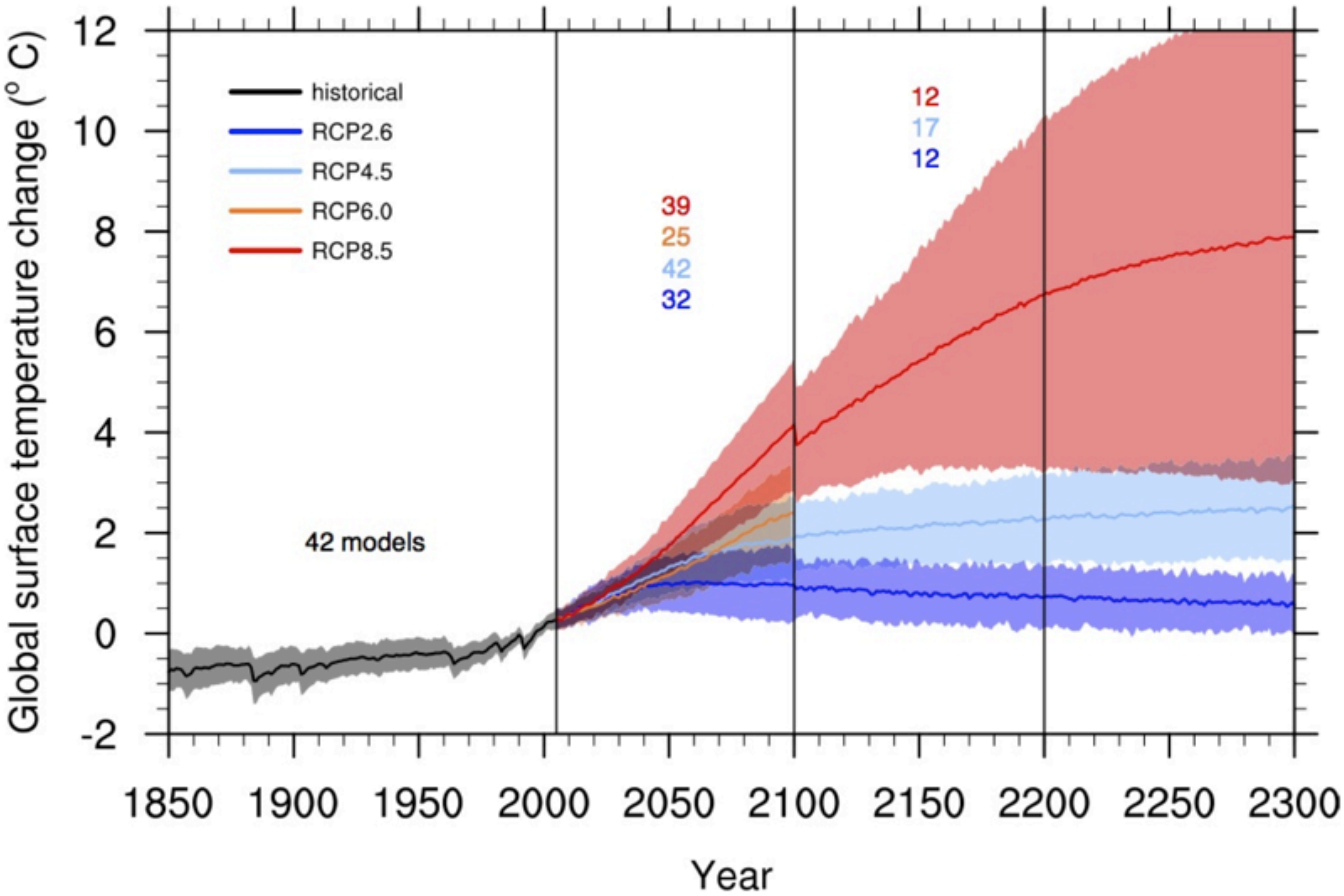


TWO OVERARCHING QUESTIONS:

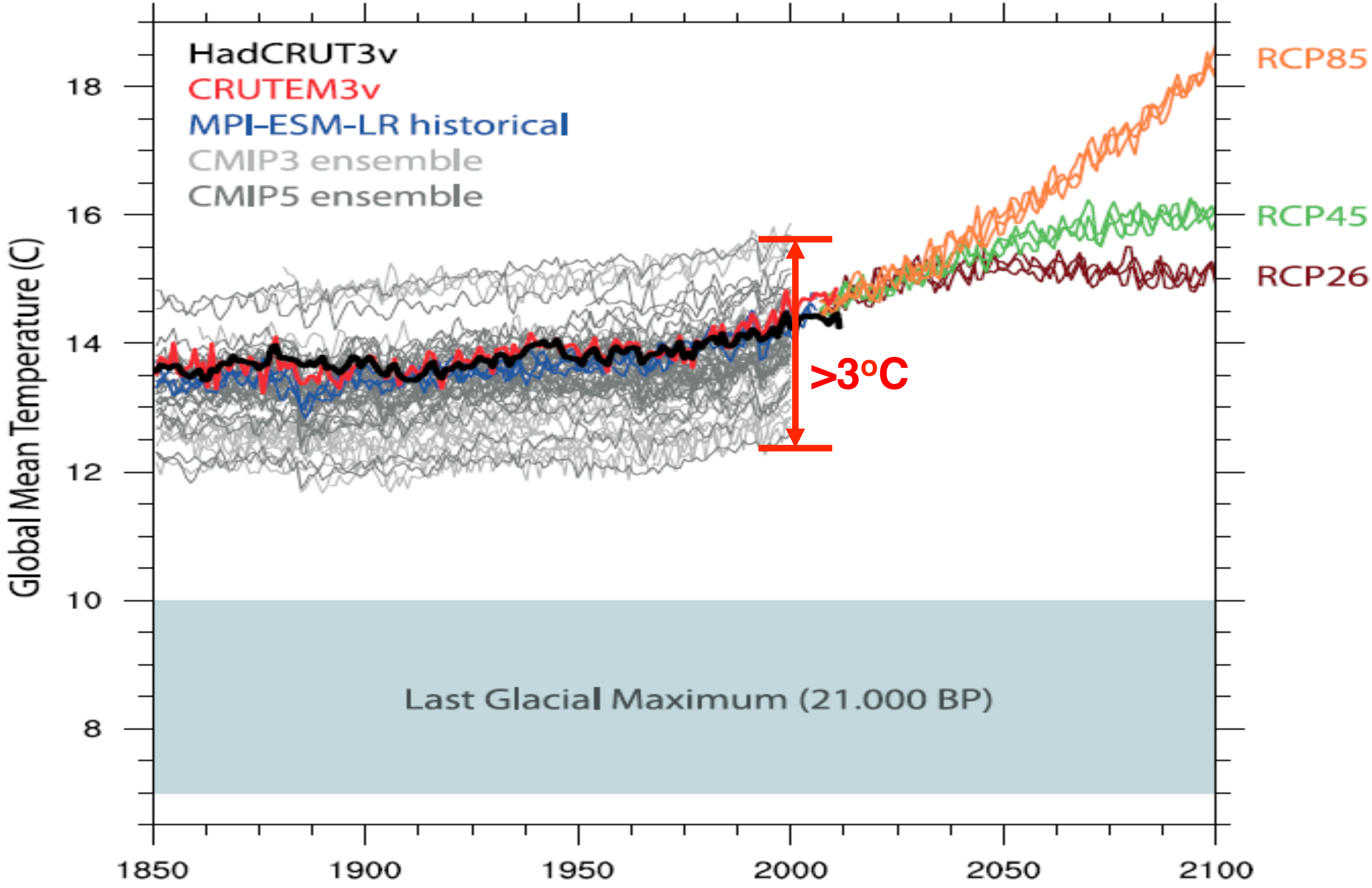
(1) What is the impact of environmental change caused by natural and anthropogenic influences on the construction of sustainable green silk road?

(2) How do the westerly wind and the East-Asia monsoon affect the uncertainty in modeling environmental change of the PTPE region?

Climate Change Projections from IPCC-AR5



Uncertainty in Global Mean Absolute Temperature Simulations in CMIP3 & CMIP5

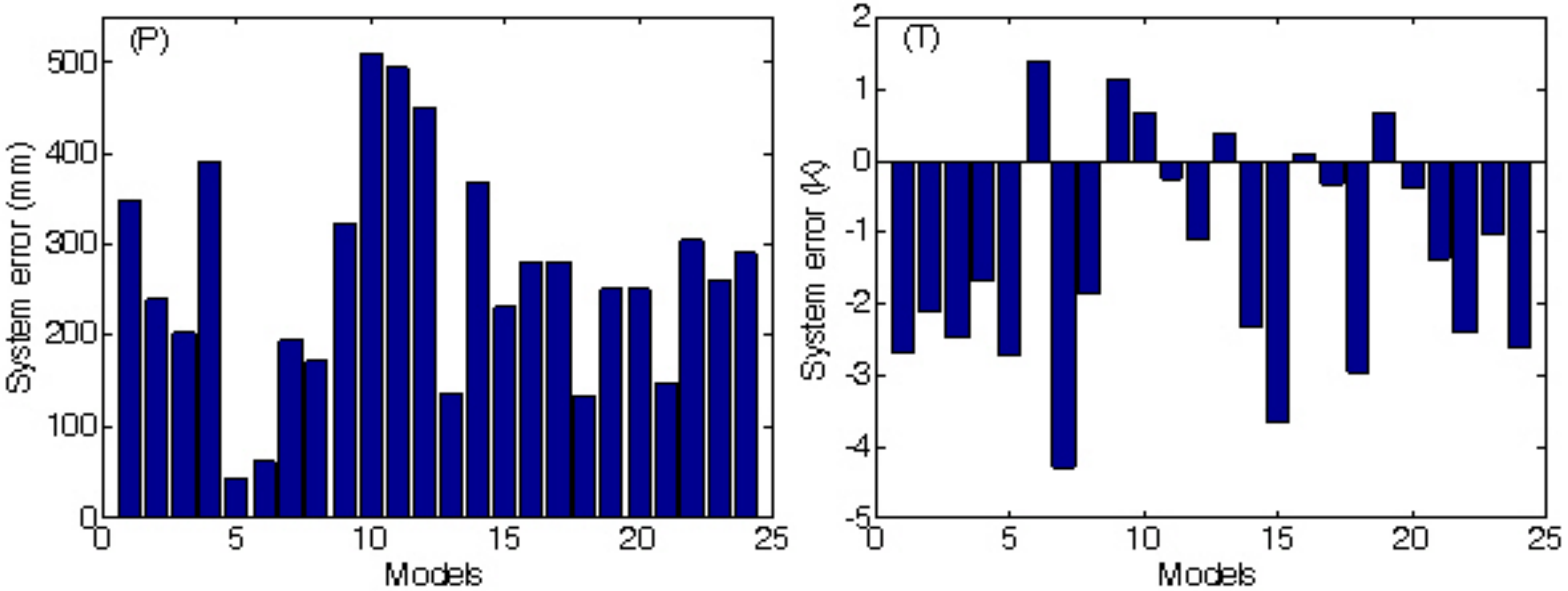


Mauritsen et al., JAMES, 2012

CMIP3 Global Land Temperature and Precipitation Simulations

Global Long-term Average Annual Precipitation and Temperature between 1960-2000

Precipitation **Temperature**



1 - BCC-CSM 1.1
2 - BCC-CSM1.1(m)
3 - BNU-ESM
4 - CanESM2
5 - CCSM4
6 - CNRM-CM5
7 - CSIRO-Mk3.6.0
8 - FGOALS-g2
9 - FIO-ESM
10 - GFDL-CM3
11 - GFDL-ESM2G
12 - GISS-E2-H
13 - GISS-E2-R
14 - HadGEM2-ES
15 - IPSL-CM5A-LR
16 - IPSL-CM5A-MR
17 - MIROC5
18 - MIROC-ESM
19 - MIROC-ESM-CHEM
20 - MPI-ESM-LR
21 - MPI-ESM-MR
22 - MRI-CGCM3
23 - NorESM1-M
24 - NorESM-ME

Note: Global mean annual land temperature: 8.09C°
Global mean annual precipitation: 697.88mm/yr

(Miao et al., Prog. Phys. Geog., 2013)

Why Should We Care About Uncertainty, Particularly in the Simulation of Global Mean Absolute Temperature?

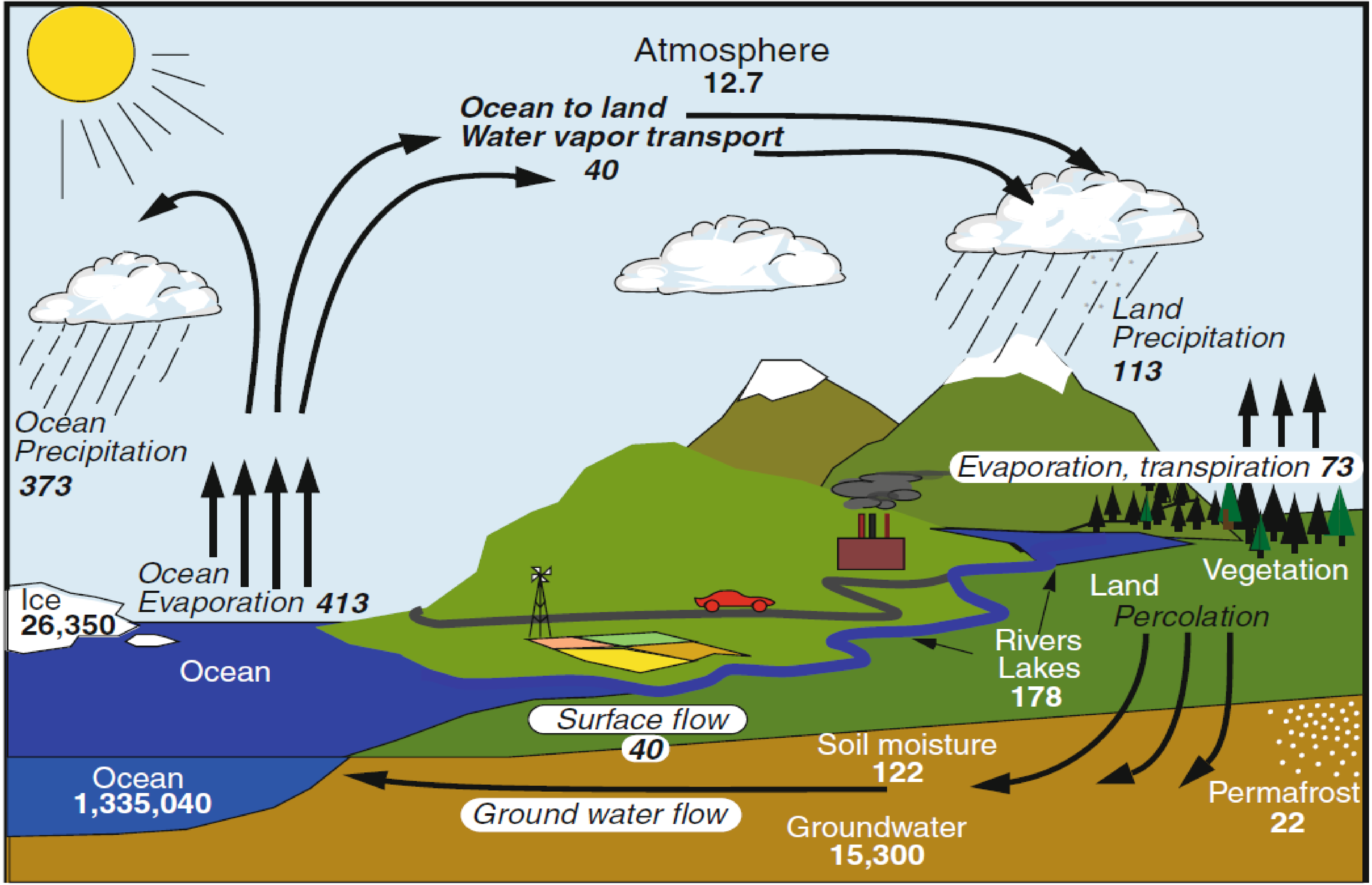
- All climate models are supposed to confirm to the first principle of thermodynamic law, (i.e., the freezing point of water is at **273.18°F**, and conservation of energy).
- When the global mean temperature simulations differ by 3°C or more, the following issues would arise:
  - The involved models would contain very different land states (i.e., water may be in liquid state more likely in one model, while in frozen state in another) and this would ultimately affect the land hydrological processes
  - The land-atmosphere interactions would be very different, leading to different global water and energy budgets

Hypotheses

- Proper tuning of climate model parameters can force simulated global mean absolute temperature of a climate model to be consistent with the observed global mean absolute temperature
- A more reasonable simulated global mean absolute temperature leads to more reasonable global water and energy budgets
- More reasonable global water and energy budgets lead to more reasonable climate simulations and projections

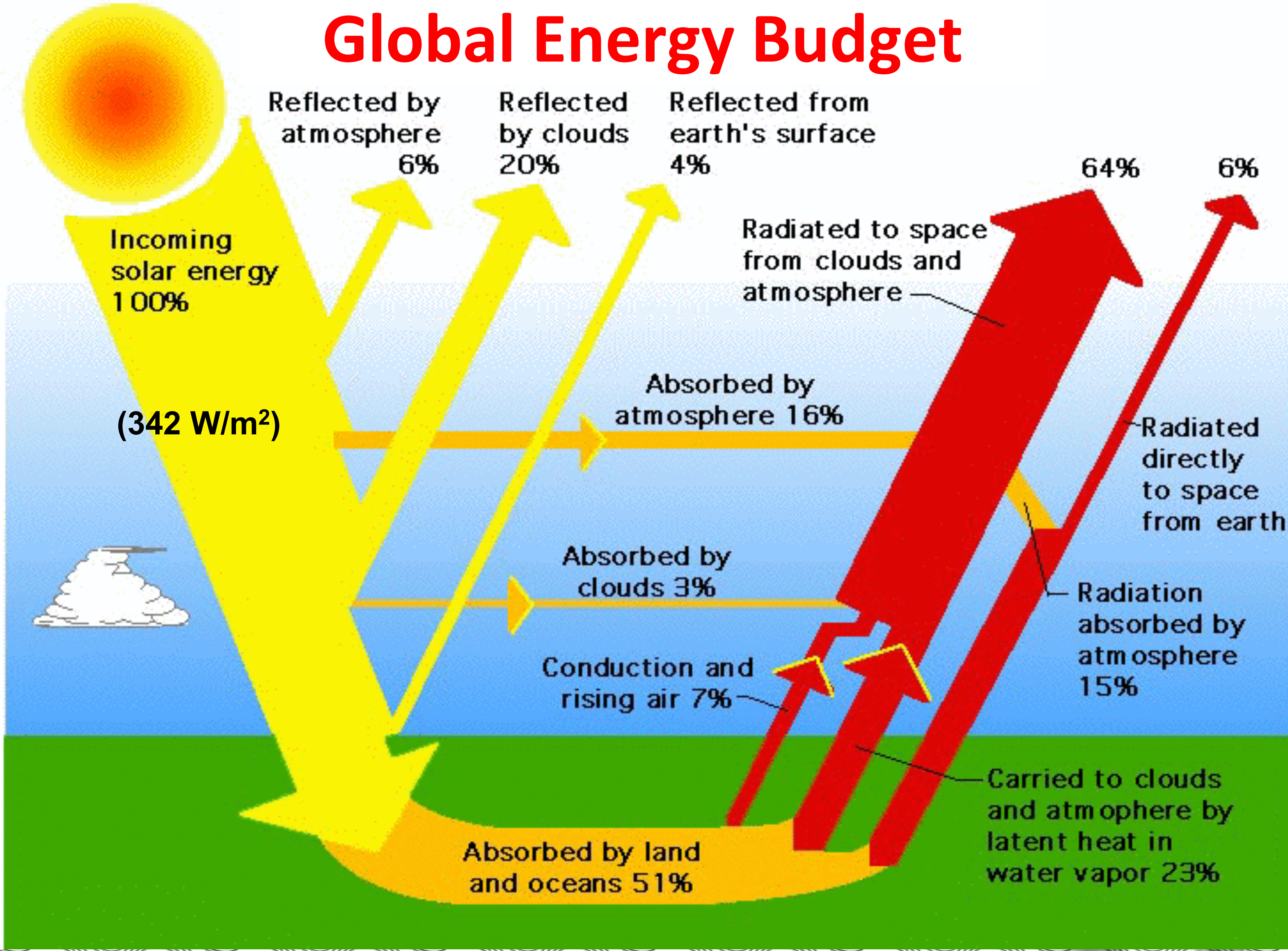
Global Water Budget

(Trenberth & Asrar, 2014)



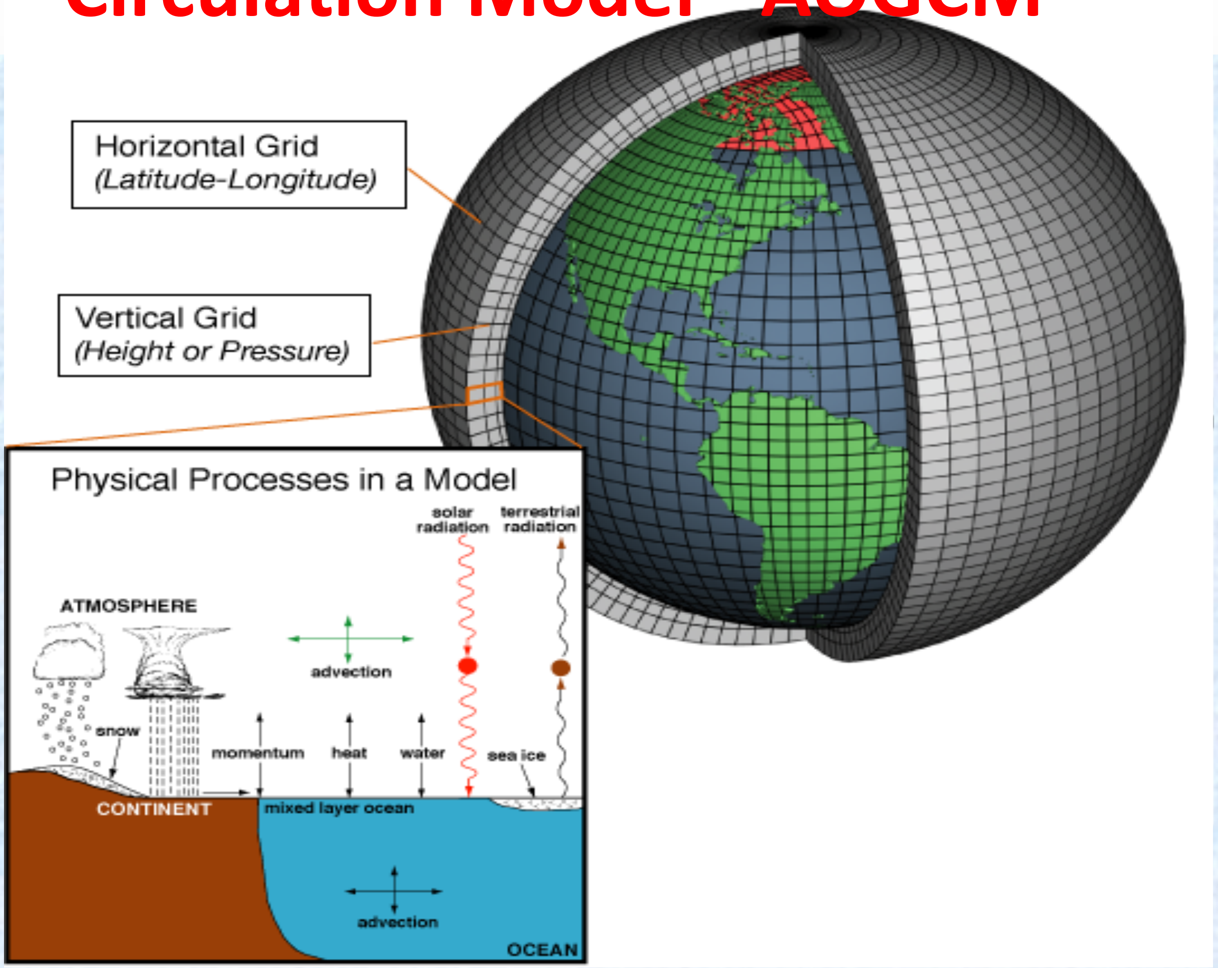
Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

Global Energy Budget

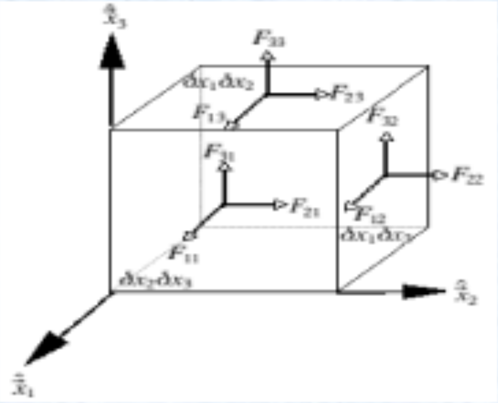


(342 W/m^2)

Atmosphere Ocean General Circulation Model - AOGCM



Grid cell



Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0.$$

Thermodynamic

$$\rho c_v \frac{DT}{Dt} = -p \nabla \cdot \vec{v} - \nabla \cdot \vec{F} + k \nabla^2 T + \rho \dot{q},$$

Fluid motion on rotating sphere

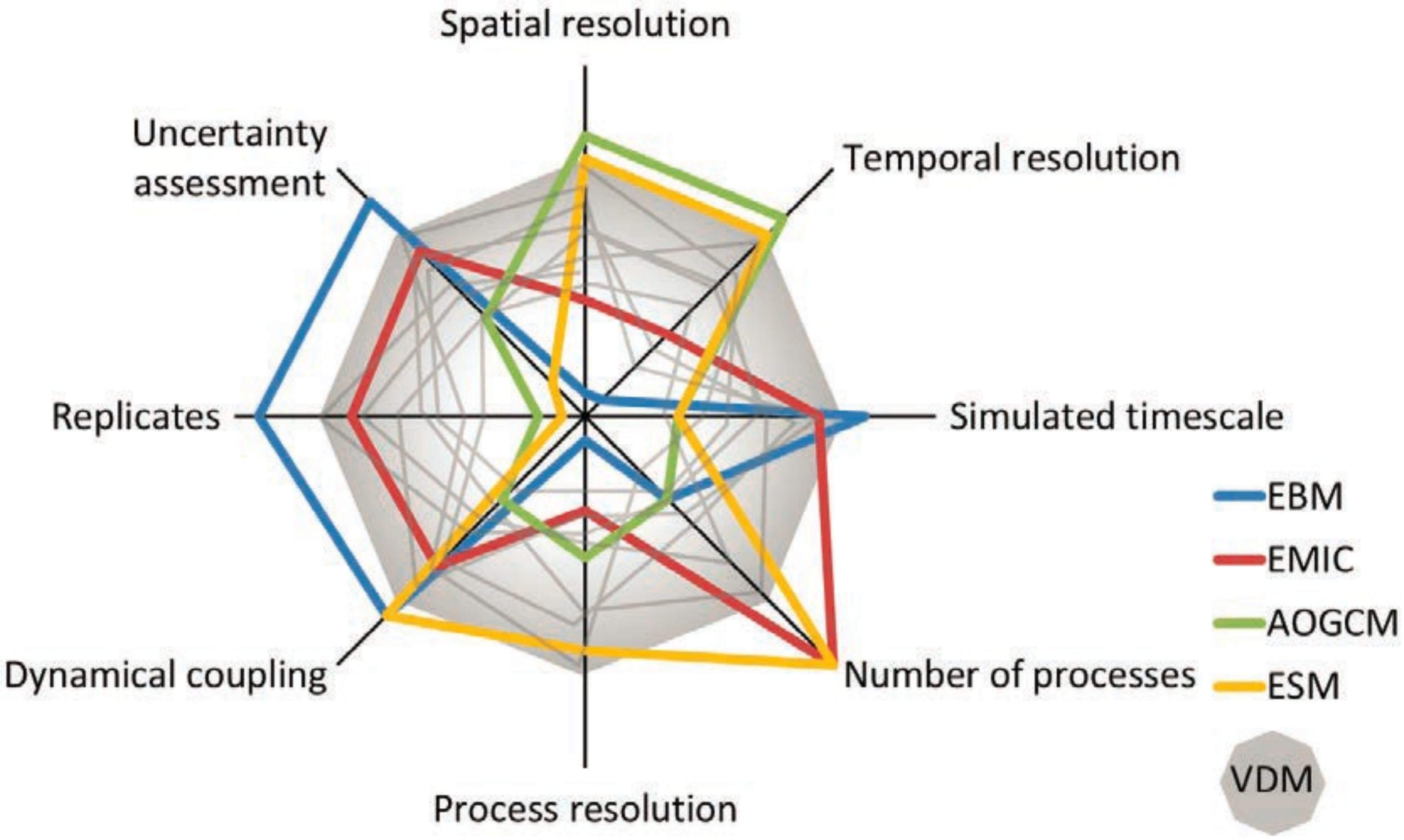
$$\vec{F}_{Cor} = 2\rho\Omega\delta V \begin{pmatrix} v \sin\phi \\ -u \sin\phi \\ 0 \end{pmatrix} = 2\rho\Omega\delta V \sin\phi \begin{pmatrix} v \\ -u \\ 0 \end{pmatrix} = \delta V \rho f \begin{pmatrix} v \\ -u \\ 0 \end{pmatrix},$$

where $f \equiv 2\Omega \sin\phi$

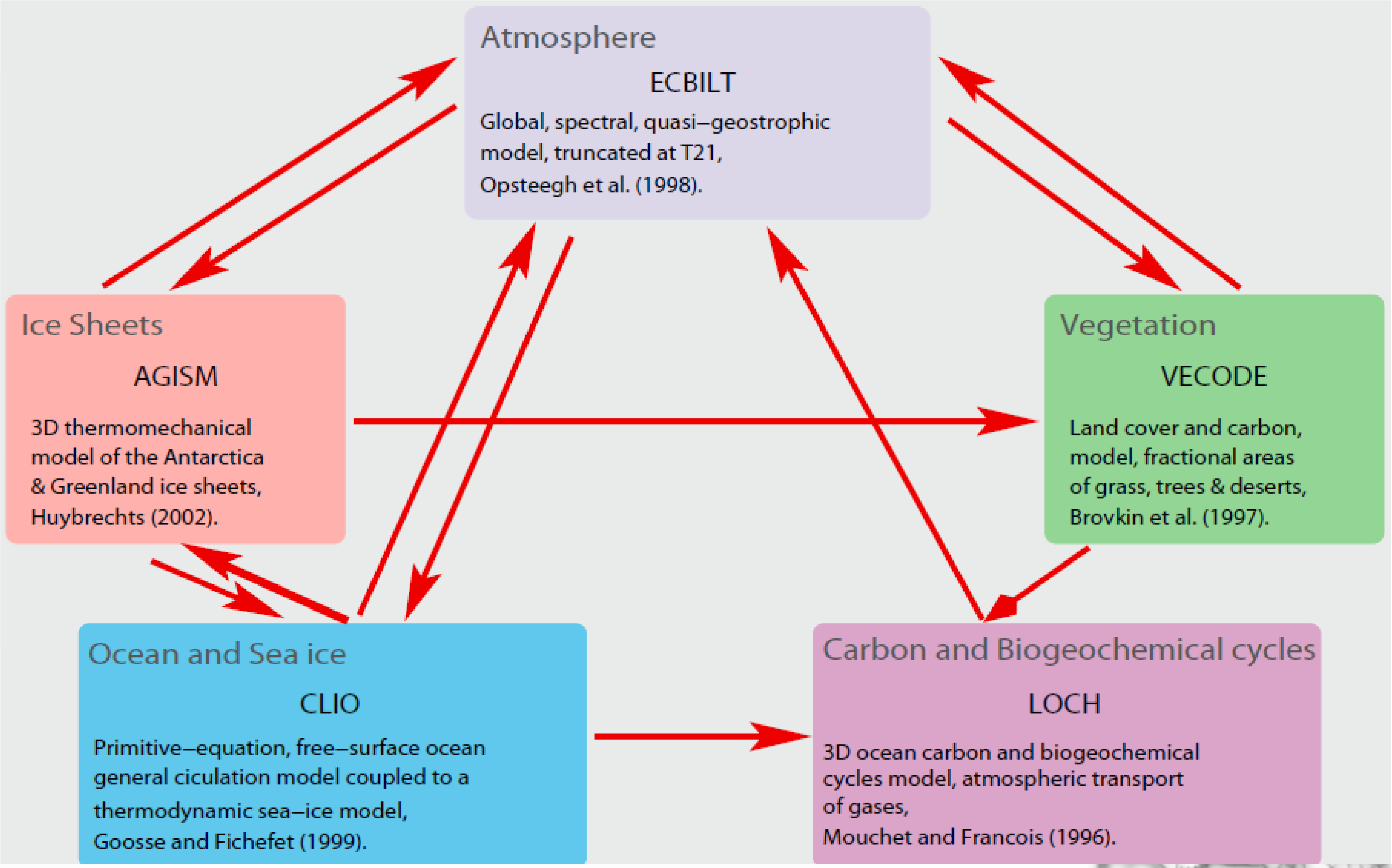
Earth System Model of Intermediate Complexity (EMIC)

- Low resolution, global ‘earth system models’ intended to be used for very long (thousand year) simulations
- Combines elements of GCMs with those of complex box model EBMs
- Limited applicability for short-term climate change
- Used extensively for millenial-scale paleoclimate simulations (can provide perspective for future change)
- Good test bed for exploring different model components and couplings

AOGCM vs EMIC



LOVECLIM – An EMIC Model



Atmosphere

ECBILT

Global, spectral, quasi–geostrophic model, truncated at T21, Opsteegh et al. (1998).

Ice Sheets

AGISM

3D thermomechanical model of the Antarctica & Greenland ice sheets, Huybrechts (2002).

Vegetation

VECODE

Land cover and carbon, model, fractional areas of grass, trees & deserts, Brovkin et al. (1997).

Ocean and Sea ice

CLIO

Primitive–equation, free–surface ocean general ciculation model coupled to a thermodynamic sea–ice model, Goosse and Fichefet (1999).

Carbon and Biogeochemical cycles

LOCH

3D ocean carbon and biogeochemical cycles model, atmospheric transport of gases, Mouchet and Francois (1996).

About LOVECLIM

- **LOVECLIM** is a three-dimensional Earth system model of intermediate complexity, i.e. its spatial resolution is coarser than that of state-of-the-art climate General Circulation Models(GCMs) and its representation of physical processes is simpler.

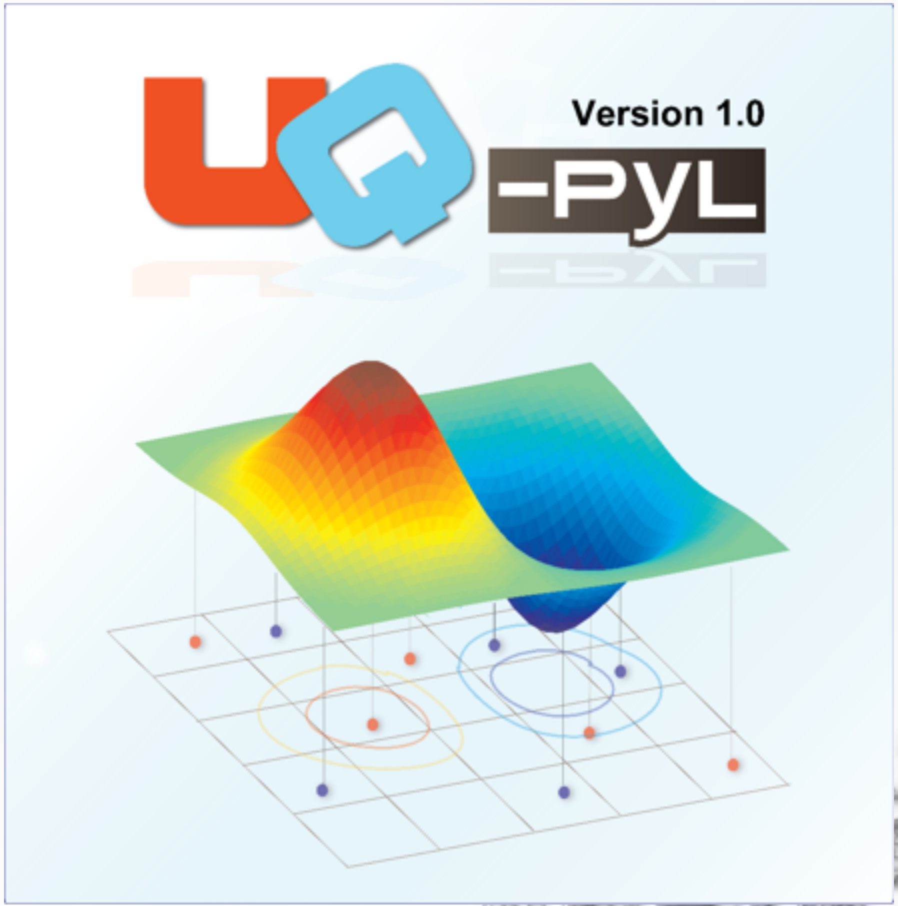
- **LOVECLIM** is an acronym made from the names of the five different models that have been coupled to built the Earth system model: LOch–Vecode-Ecbilt-CLio-agIsm Model (LOVECLIM).

Study Experimental Design

- Select an intermediate complexity model, LOVECLIM, to test the aforementioned hypotheses
- Select a set of adjustable parameters in LOVECLIM and specify their uncertain ranges and distributions
- Sample the parameter space use a design of experiment (DoE) approach
- Select a number of model performance metrics
- Compute a number of global sensitivity indices
- Screen sensitive parameters from insensitive ones according to the sensitivity indices
- Construct surrogate models for various performance targets
- Optimize the sensitive parameters using a multi-objective approach
- Compare simulations using default and optimized parameters

Uncertainty
Quantification
Python Laboratory
(UQ-PyL)

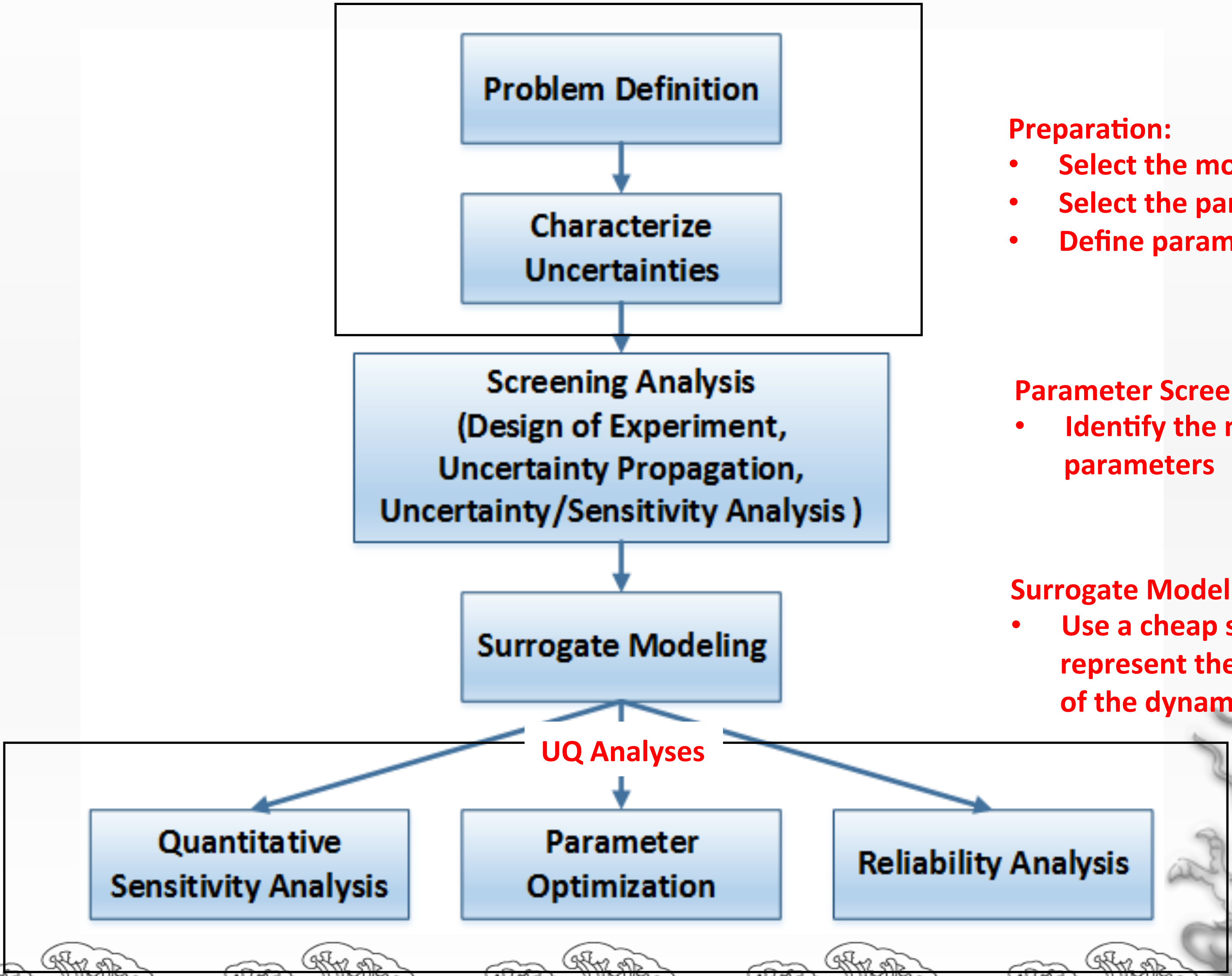
http://uq-pyl.com



What is UQ-PyL?

- A new, general-purpose, cross-platform UQ framework with a GUI for large complex system models
- Made of several components that perform various functions, including
    - *Design of Experiments*
    - *Statistical Analysis*
    - *Sensitivity Analysis*
    - *Surrogate Modeling*
    - *Parameter Optimization;*
- Suitable for parametric uncertainty analysis of any computer simulation models

The UQ Process for Large Complex System Models


Problem Definition

Characterize Uncertainties

Screening Analysis (Design of Experiment, Uncertainty Propagation, Uncertainty/Sensitivity Analysis)

Surrogate Modeling

UQ Analyses

Quantitative Sensitivity Analysis

Parameter Optimization

Reliability Analysis

Preparation:

- Select the model
- Select the parameters
- Define parameter ranges

Parameter Screening:

- Identify the most sensitive parameters

Surrogate Modeling:

- Use a cheap surrogate to represent the response surface of the dynamic model

Table 1: Adjustable parameters of LOVECLIM

No.	Module	Name	Definition	Default value	Lower bound	Upper bound
1	ECBilt-atm	ampwir	Scaling coefficient in the longwave radiative scheme (amplw) General value except equator area.	1	0.5	1.5
2	ECBilt-atm	ampeqir	Scaling coefficient in the longwave radiative scheme (amplw) For equator area between 15S and 15N.	1.8	1.0	2.5
3	ECBilt-atm	expir	Exponent in the longwave radiative scheme	0.4	0.2	0.6
4	ECBilt-atm	relhmax	Precipitation also occurs if the total precipitable water below 500hPa is above this relevant threshold.	0.83	0.50	0.99
5	ECBilt-atm	cwdrag	Drag coefficient to compute wind stress	2.1E-3	1.0E-3	4.0E-3
6	ECBilt-atm	cdrag	Drag coefficient to compute sensible and latent heat fluxes	1.4E-3	1.0E-3	2.0E-3
7	ECBilt-atm	uv10rfx	Reduction of the wind speed between 800 hPa and 10m	0.8	0.7	0.9
8	ECBilt-atm	dragan	Rotation of the wind vector in the boundary layer (Unit: degree)	15	10	20
9	ECBilt-land	alphd	Albedo of snow	0.72	0.60	0.90
10	ECBilt-land	alphdi	Albedo of bare ice	0.62	0.50	0.80
11	ECBilt-land	alphs	Albedo of melting snow	0.53	0.30	0.60
12	ECBilt-land	albice	Albedo of melting ice (general)	0.44	0.30	0.60
13	ECBilt-land	albin	Albedo of melting ice (arctic)	0.44	0.30	0.60
14	ECBilt-land	albis	Albedo of melting ice (antactic)	0.44	0.30	0.60
15	ECBilt-land	cgren	Increase in snow/ice albedo for cloudy conditions	0.04	0.01	0.10
16	ECBilt-atm	corAN	Reduction of precipitation in the Atlantic (North)	-0.085	-0.10	-0.05
17	ECBilt-atm	corAS	Reduction of precipitation in the Atlantic (South)	-0.085	-0.10	-0.05
18	ECBilt-atm	corAC	Reduction of precipitation in the Arctic	-0.25	-0.30	-0.20
19	ECBilt-land	evfac	Maximum evaporation factor over land	1	0.5	1
20	ECBilt-land	bmoismfix	Maximum bucket depth (Unit: m)	0.15	0.01	0.50
21	CLIO-ocean	bering	Scaling factor in the computation of the Bering Strait throughflow	0.3	0.2	0.5
22	CLIO-ocean	ai	Coefficient of isopycnal diffusion (Unit: m^2s^{-1})	300	200	400

Model Performance Metrics

What metrics of the state and variability are specifically used in the model tuning process, and how are they weighted in cases where compromises needs to be made?

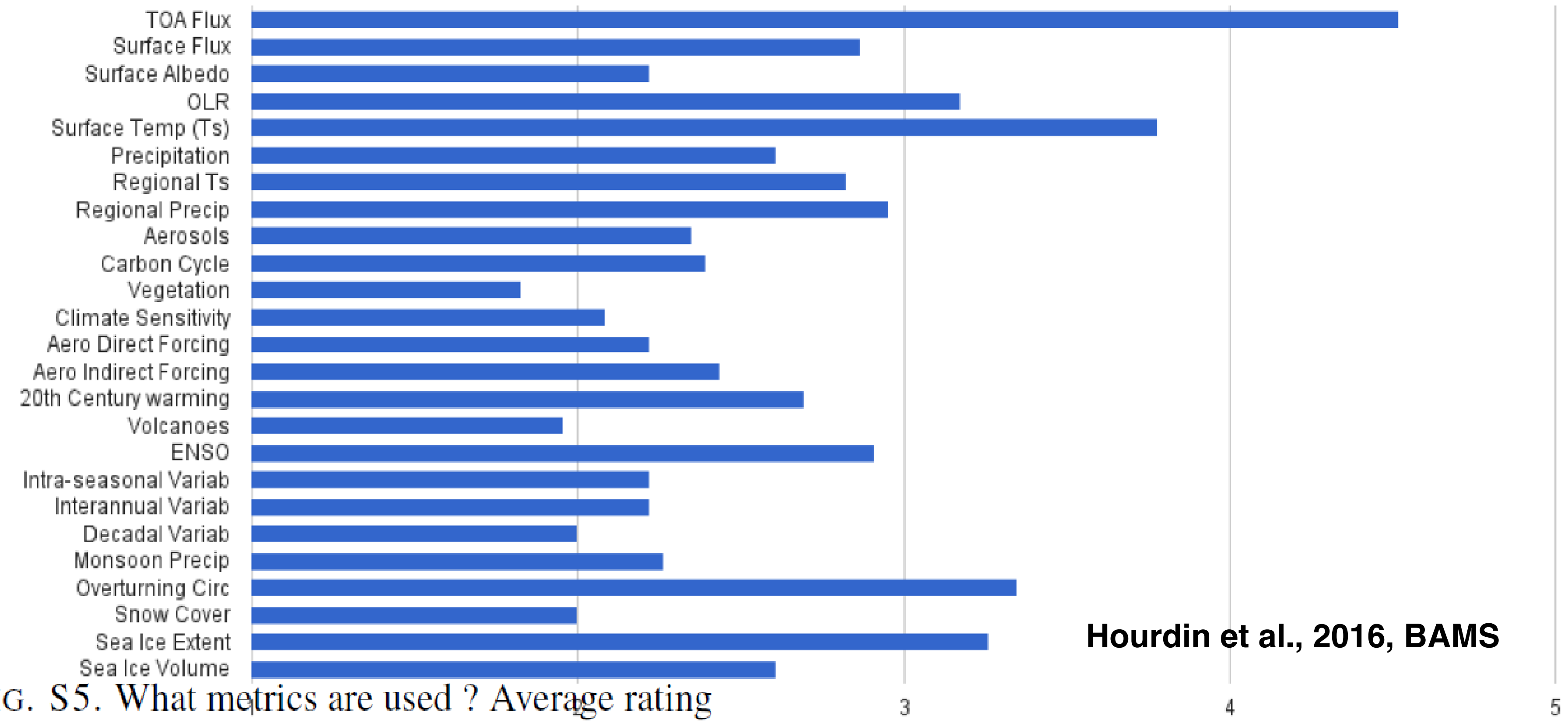
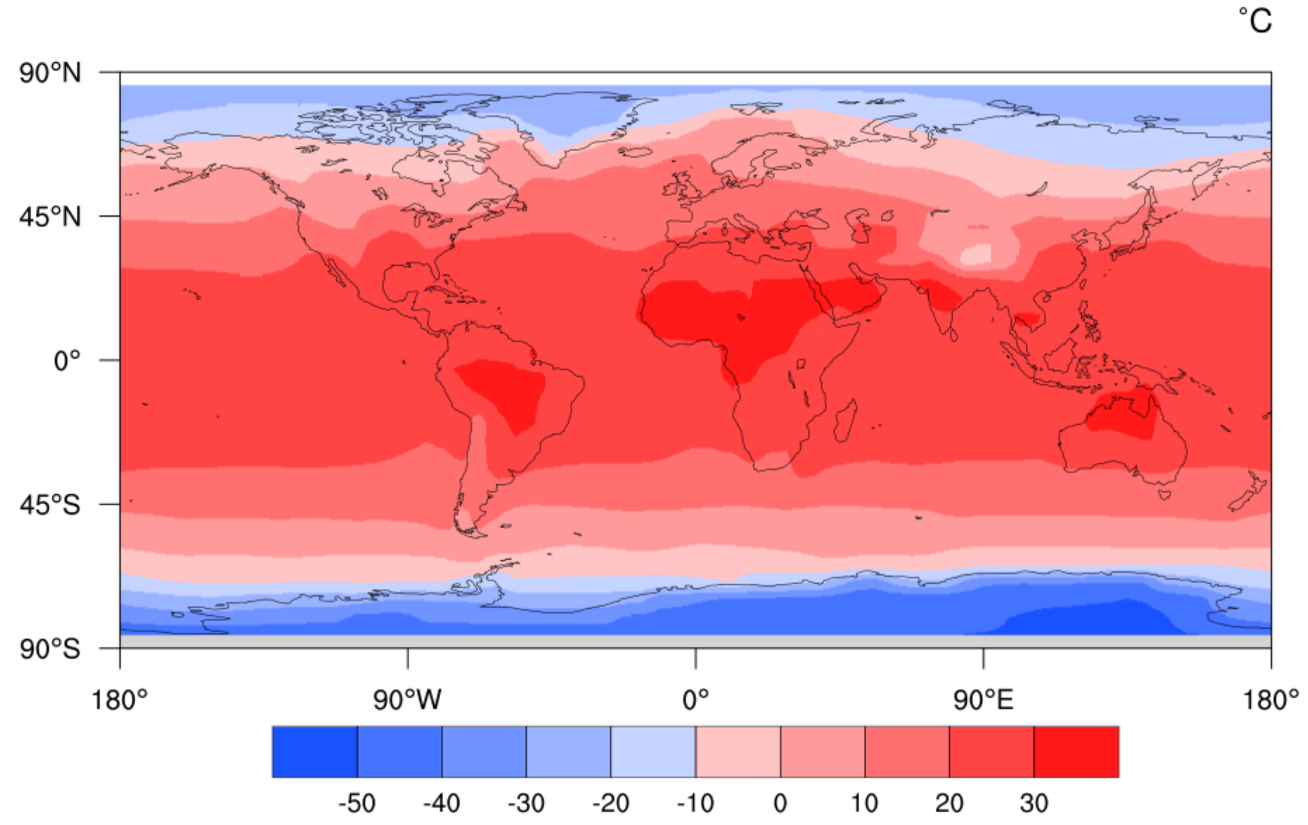


FIG. S5. What metrics are used ? Average rating

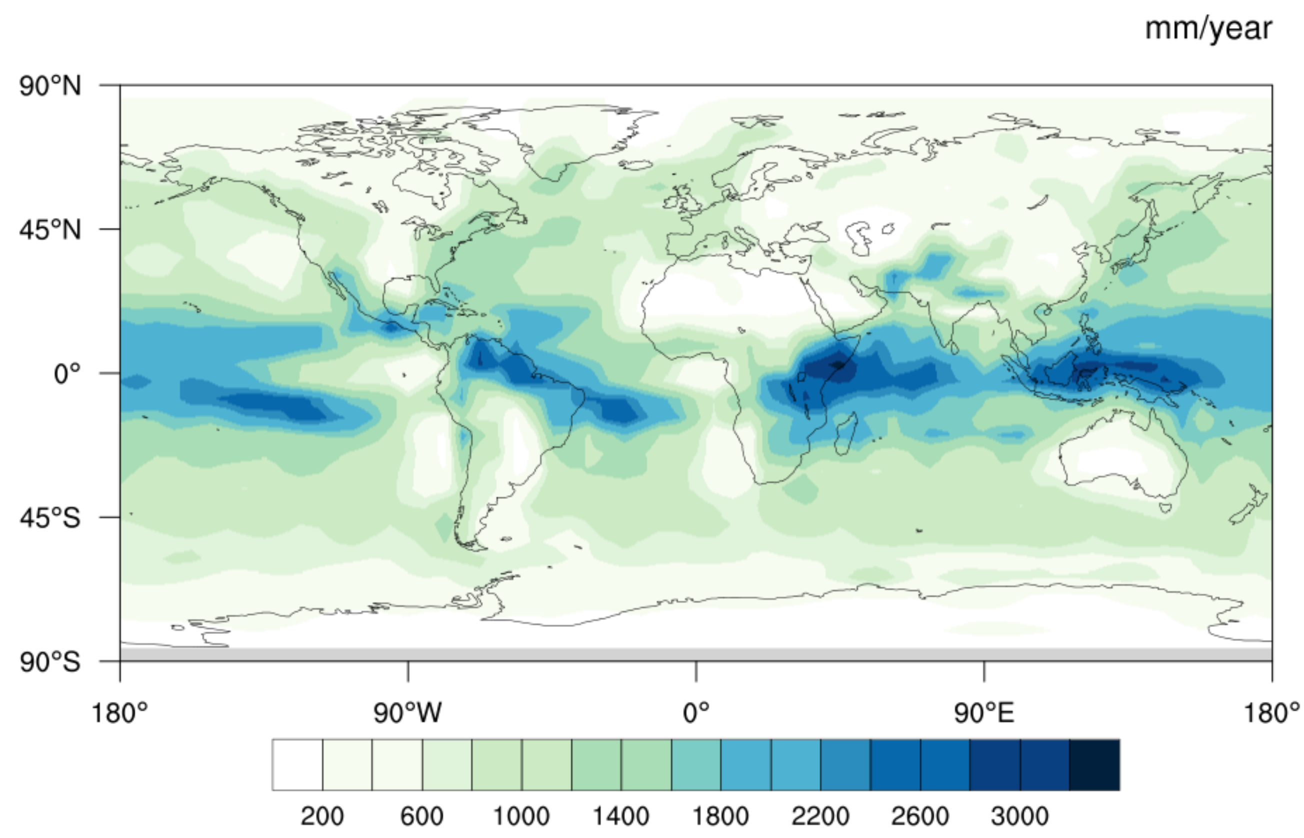
Hourdin et al., 2016, BAMS

In this study, we use global mean absolute temperature, and global water and energy budgets as tuning targets

Simulated Global Mean Temperature from 1981-2010

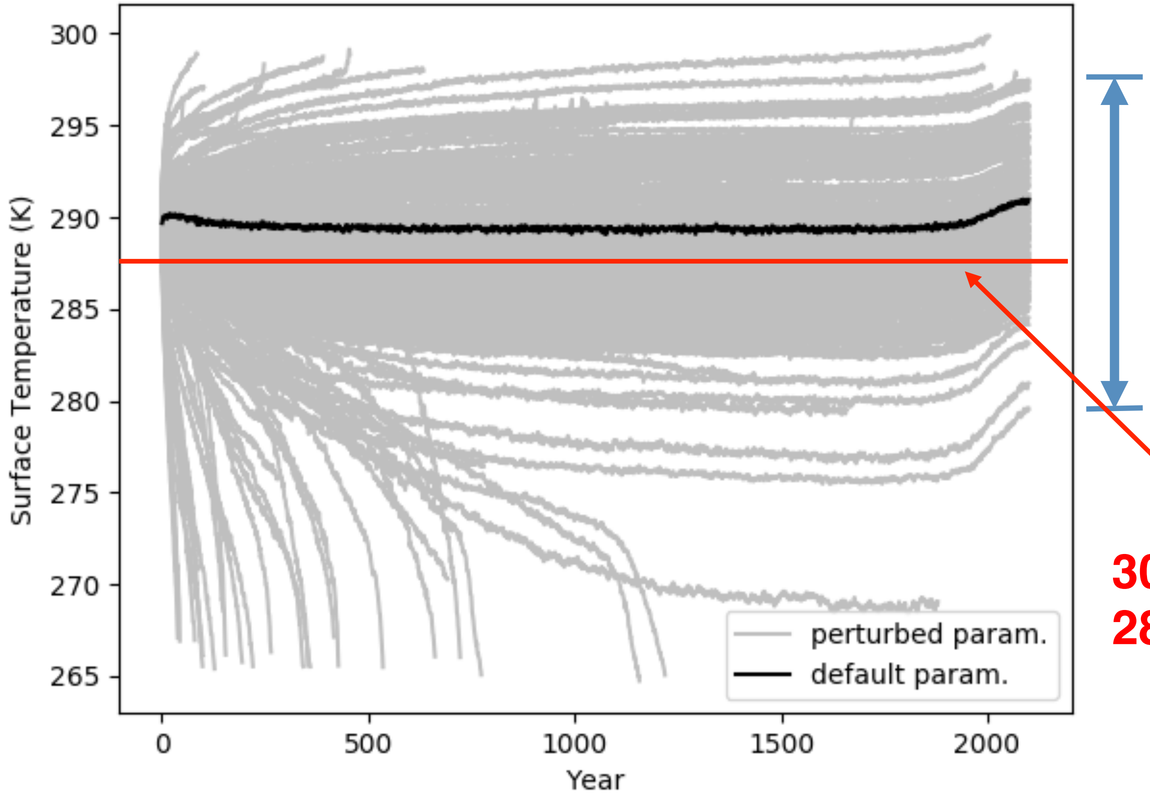


Simulated Global Mean Annual Precipitation from 1981-2010



Global Surface Temperature Simulated by LOVECLIM

Simulated surface temperature with default parameters and perturbed parameters
Total Number of perturbed parameter runs: 250
Valid perturbed runs (can simulate 2100 years without crash): 147

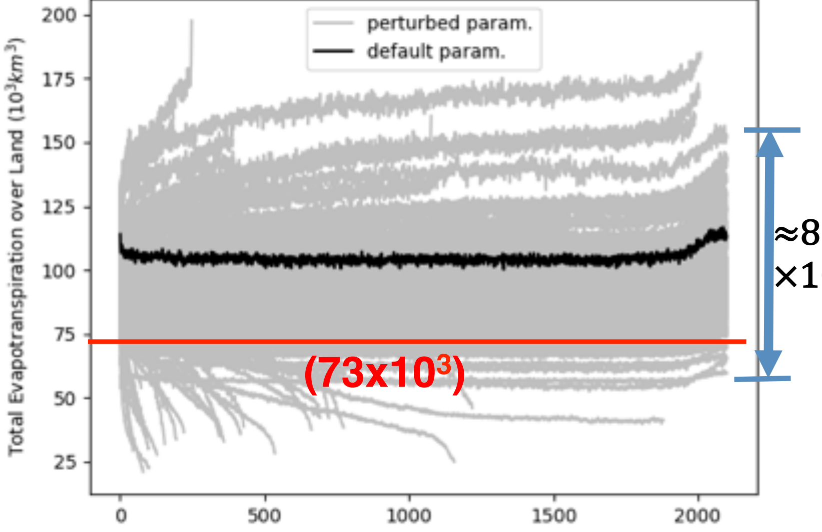


Temperature range:
$\approx 17.7K$

30-yr climatological value: 287.5K

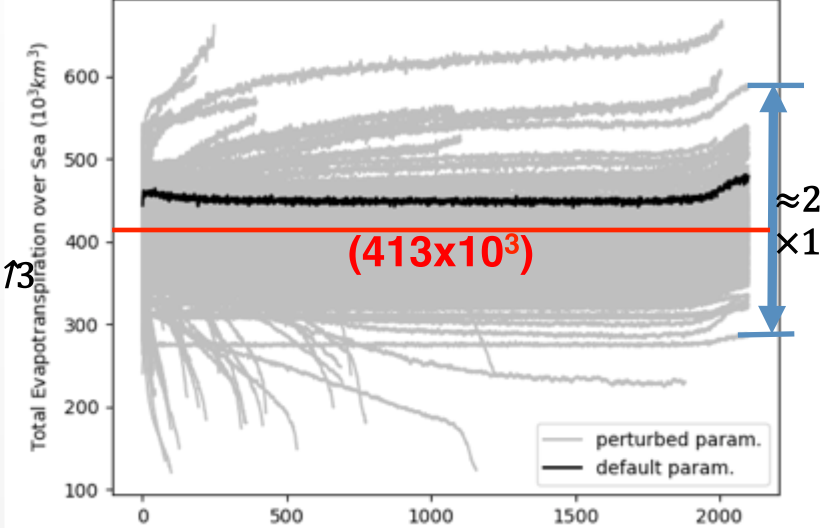
Simulated Evapotranspiration and Precipitation

Evapotranspiration on land



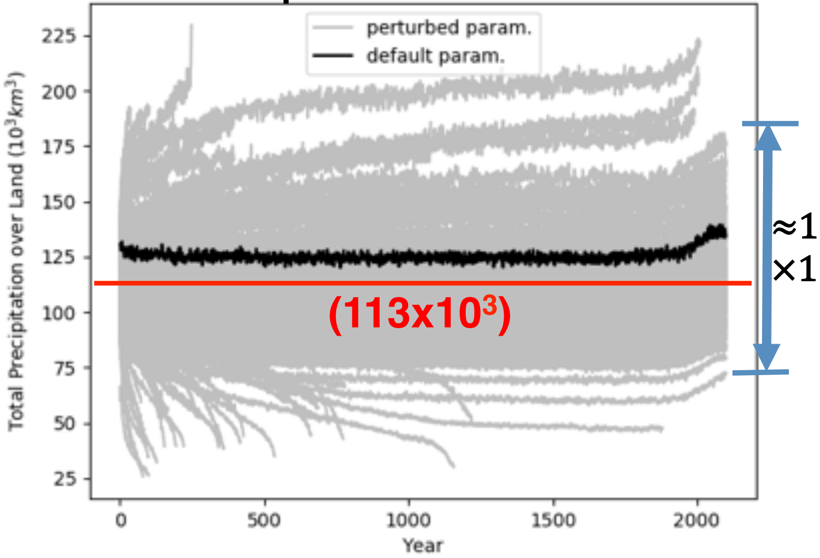
≈87.84
×10↑3 km↑3

Evaporation on sea surface



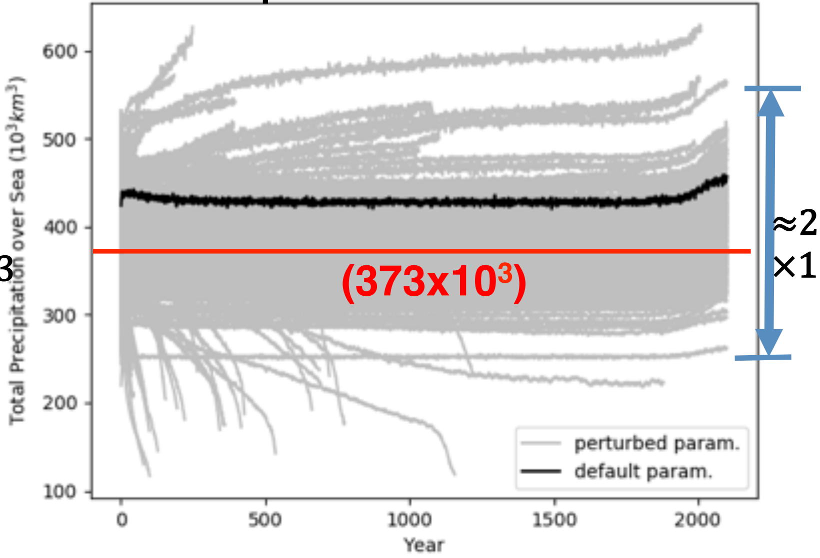
≈281.58
×10↑3 km↑

Precipitation on land



≈103.76
×10↑3 km↑3

Precipitation on sea surface



≈283.75
×10↑3 km

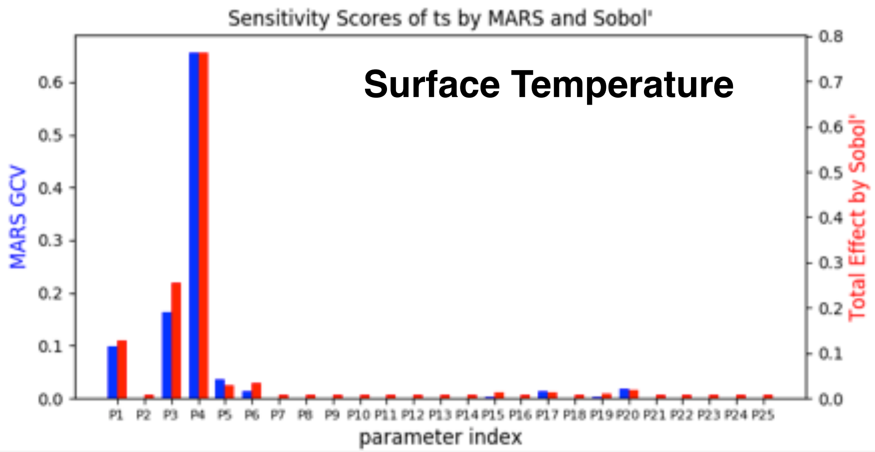
Global Water Budget by LOVECLIM

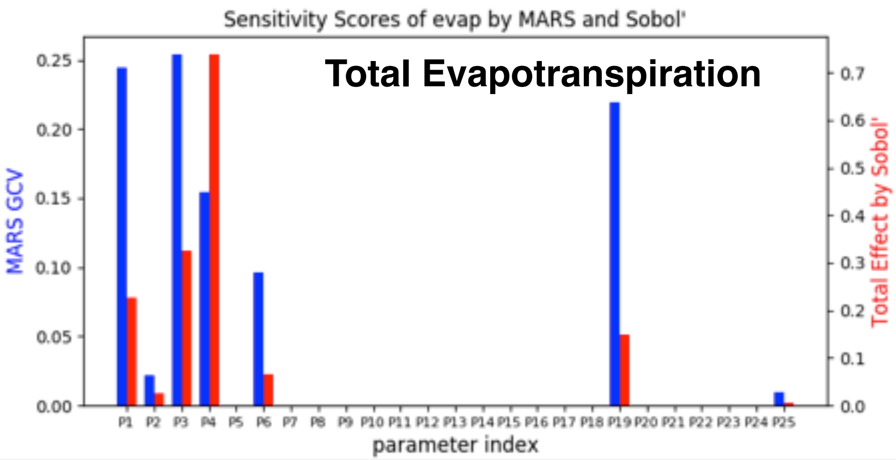
Water volume per year (10↑3 *km*↑3)	**ERA-Interim reanalysis (1989-2006)**	**LOVECLIM (default parameters, 1980-2006)**	**Difference**
Total Precipitation	537.49	571.64	34.15
Total Evapotranspiration	536.38	571.71	35.33
Precipitation on sea surface	412.70	440.22	27.52
Evaporation on sea surface	449.04	461.88	12.84
Precipitation on land	124.78	131.42	6.64
Evaporation on land	87.35	109.83	22.48
Global runoff	37.44	21.59	-15.85
[Global 2m air temp (°C)]	14.38	15.32	0.94

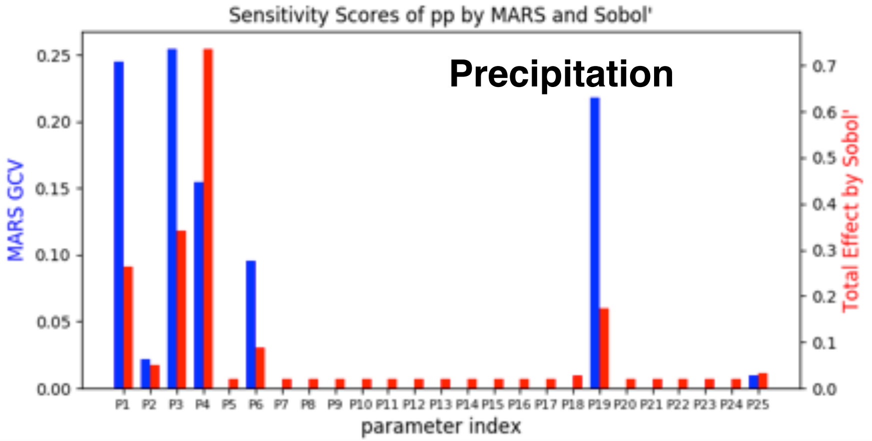
The error of global 2m air temperature is only about 1℃.
But the error of global runoff is as large as 15.85×10↑3 km↑3 (42.3% of global runoff).

The global hydrological cycle in LOVECLIM is significantly biased.

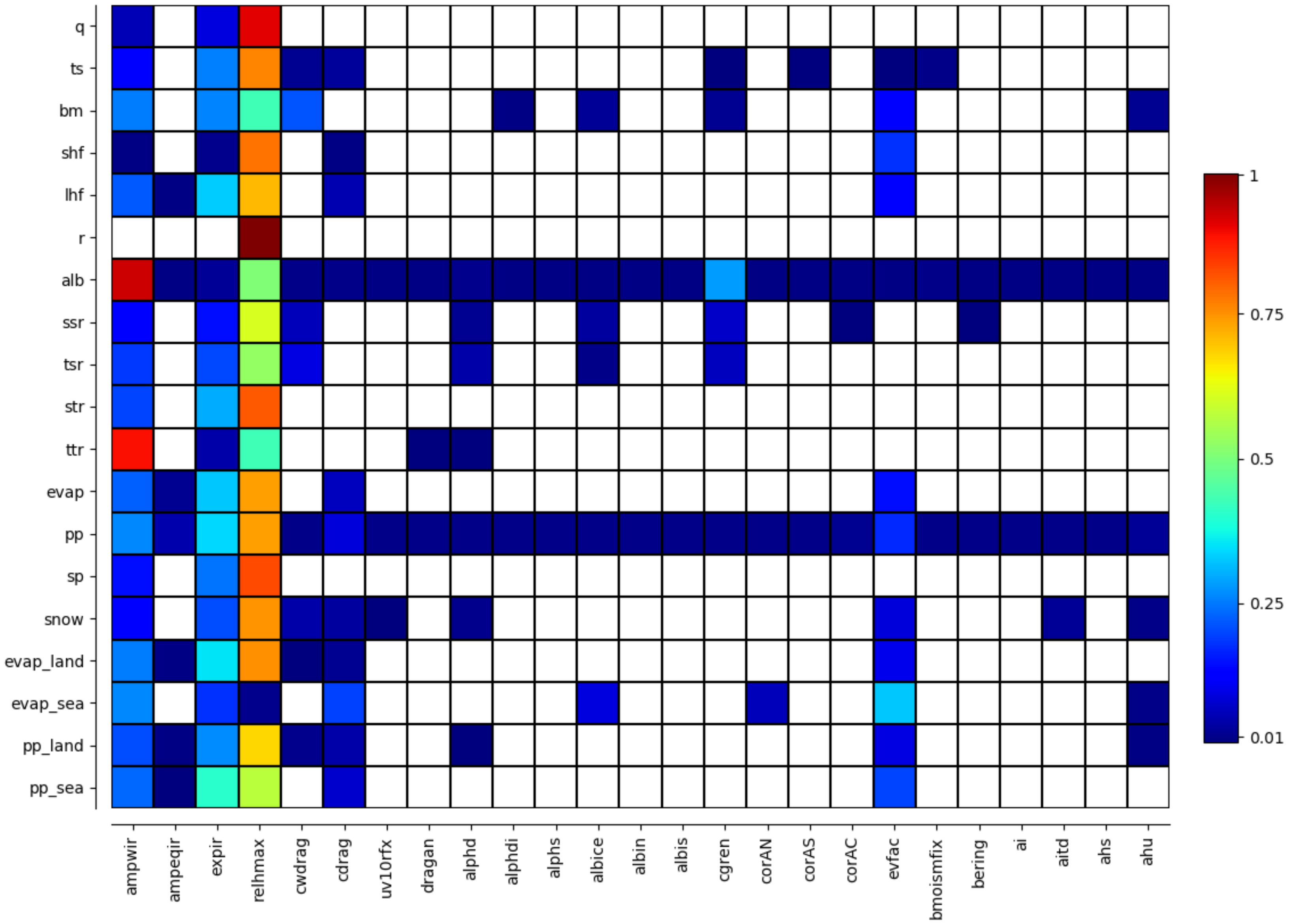
Sensitivity Analysis Results by Two Methods (MARS & Sobol’)







Sensitivity Analysis Results of Different Variables

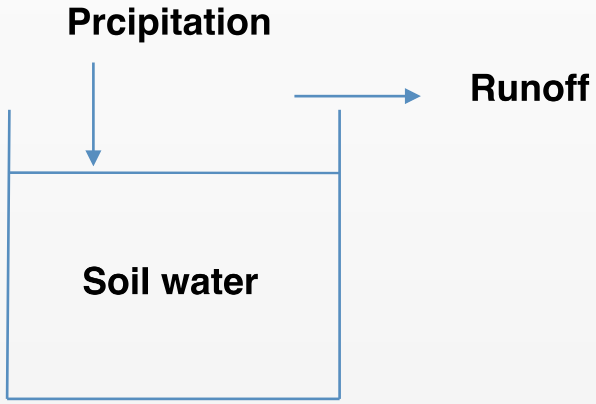

Total Effects by Sobol' Sensitivity Analysis

Next Step

- Identify important model parameters
- Investigate model structural improvement
- Perform multi-objective optimization of important parameters
- Analysis of optimized results vs default results

Improving the Physical Representation of LOVECLIM

Hydrological process in LOVECLIM



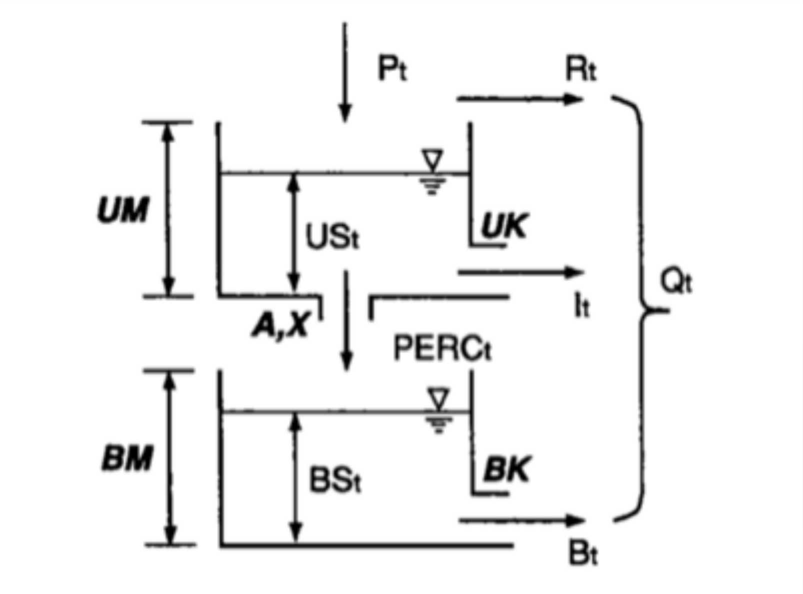
Prcipitation

Runoff

Soil water

Hydro module in LOVECLIM only has one tank.
Runoff only generates from surface.
Surface flow only!

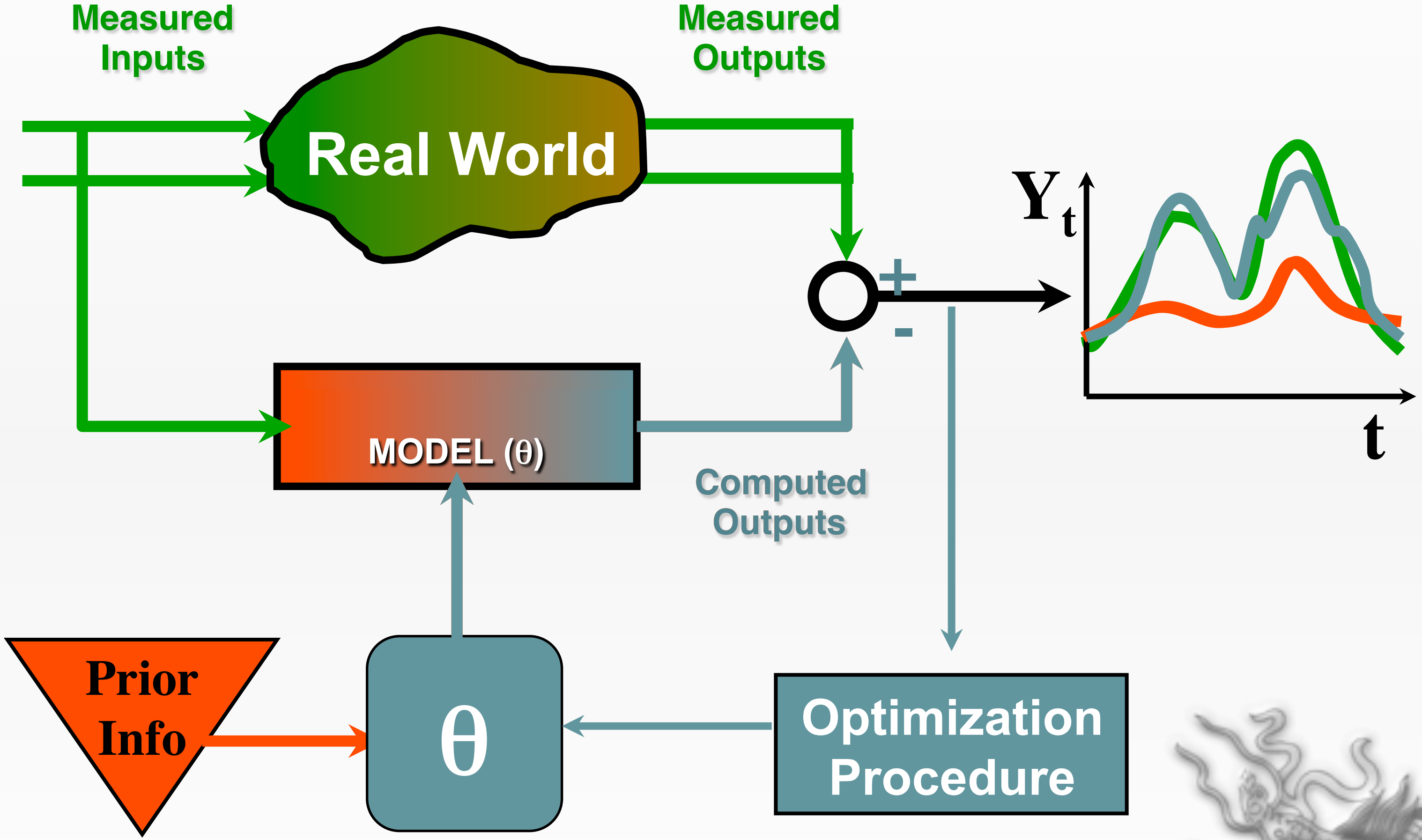
Hydrological process in SIXPAR mode



SIXPAR model has two tanks.
Runoff generates from surface, bottom of upper tank and lower tank.
Surface flow and base flow!

Parameter perturbation and optimization cannot fit model structure deficit.

Parameter Optimization



QUESTIONS?