陆面过程模式

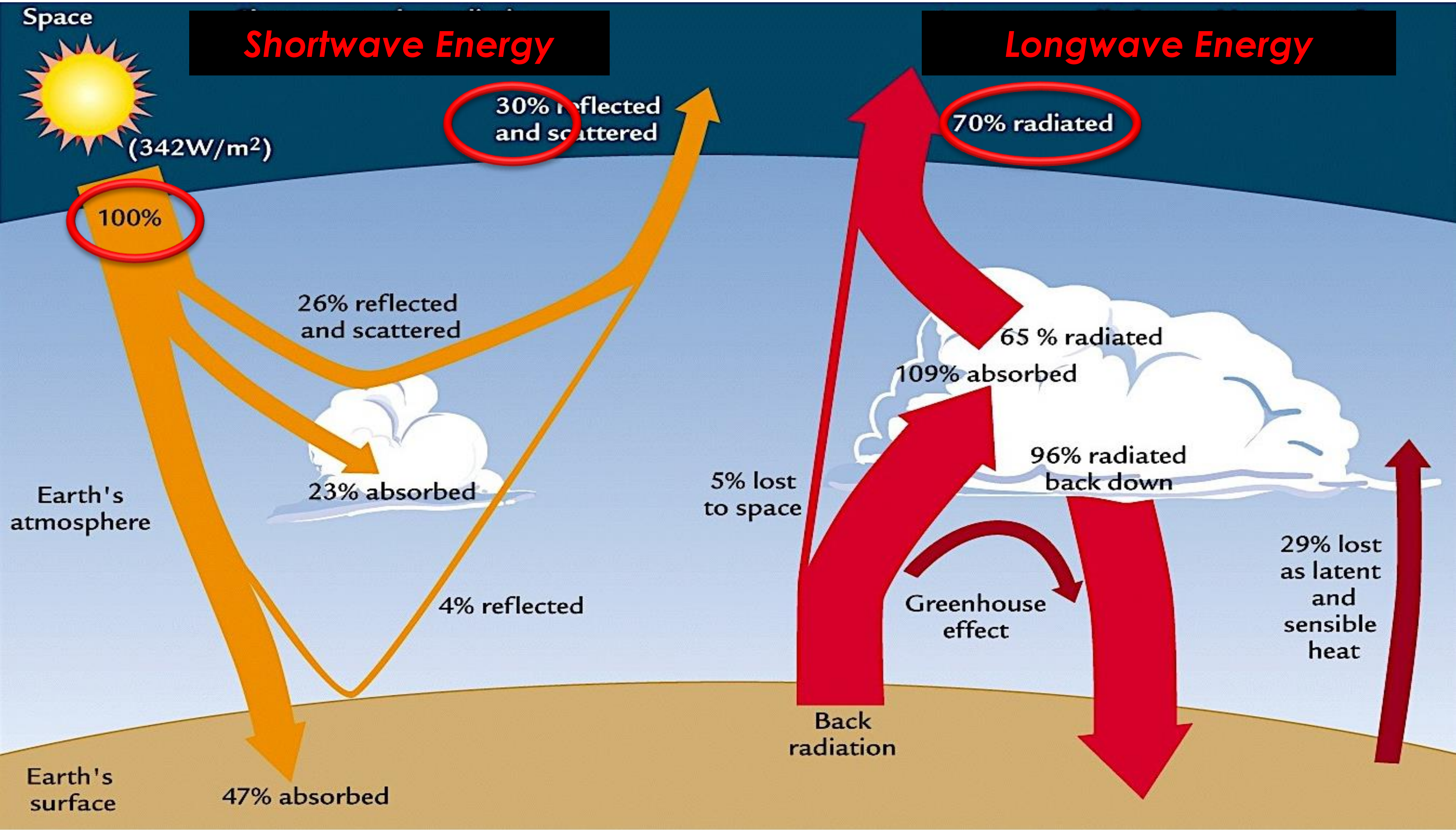
戴永久

中山大学 大气科学学院

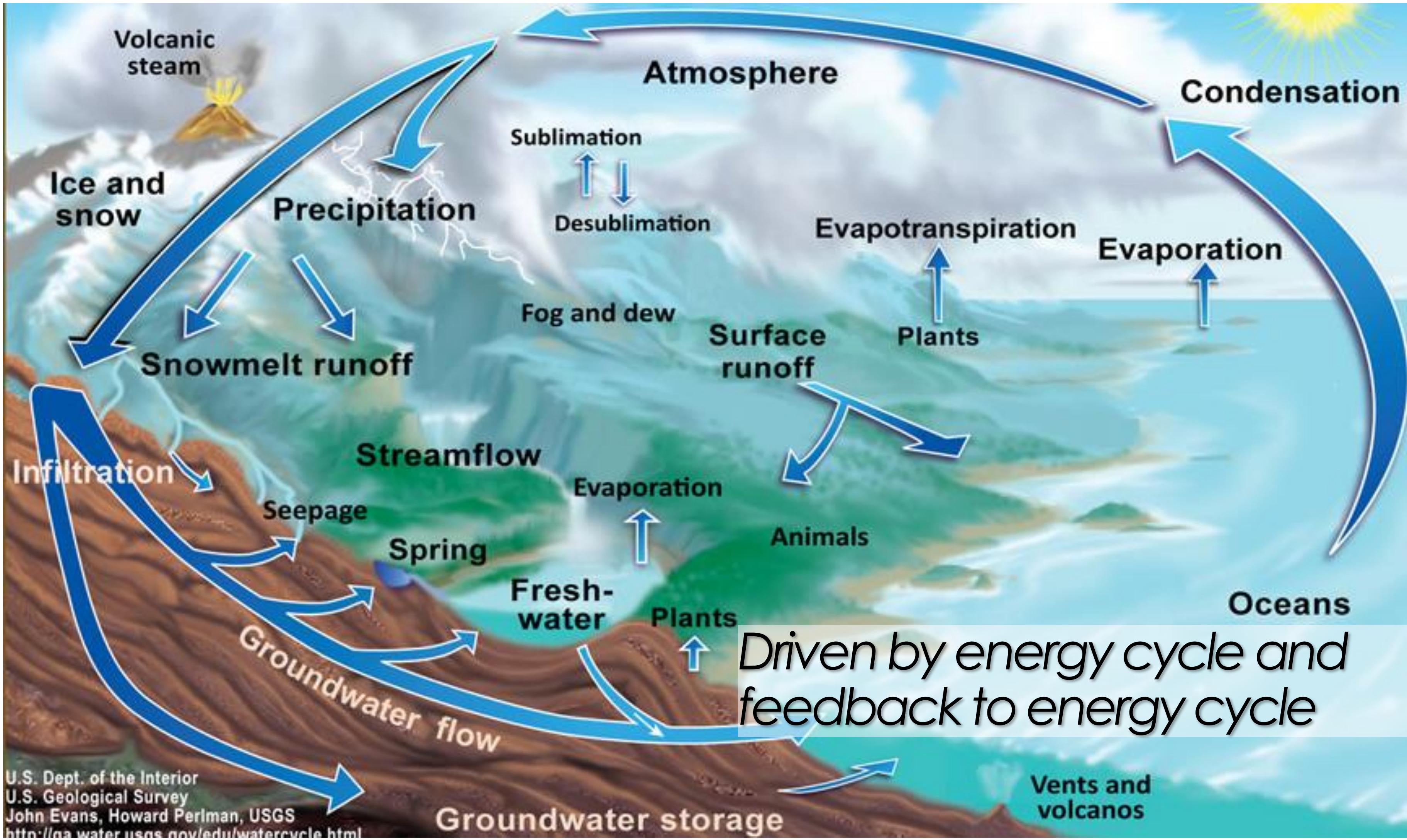
地球系统

Complex and Interactive: One thing changes everything

Earth's Energy Budget

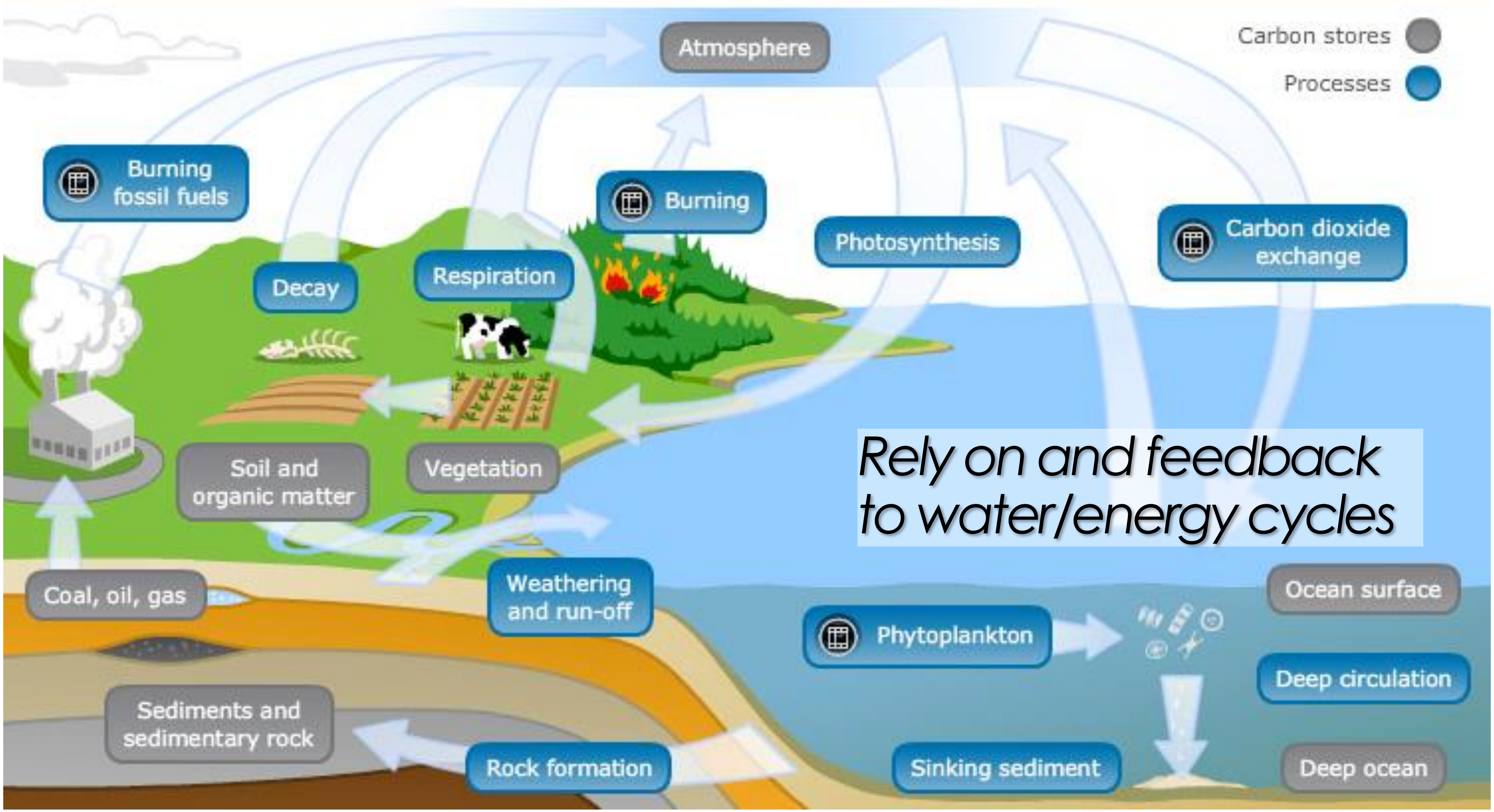


Global Water Cycle



Driven by energy cycle and feedback to energy cycle

Carbon Cycle



Rely on and feedback to water/energy cycles

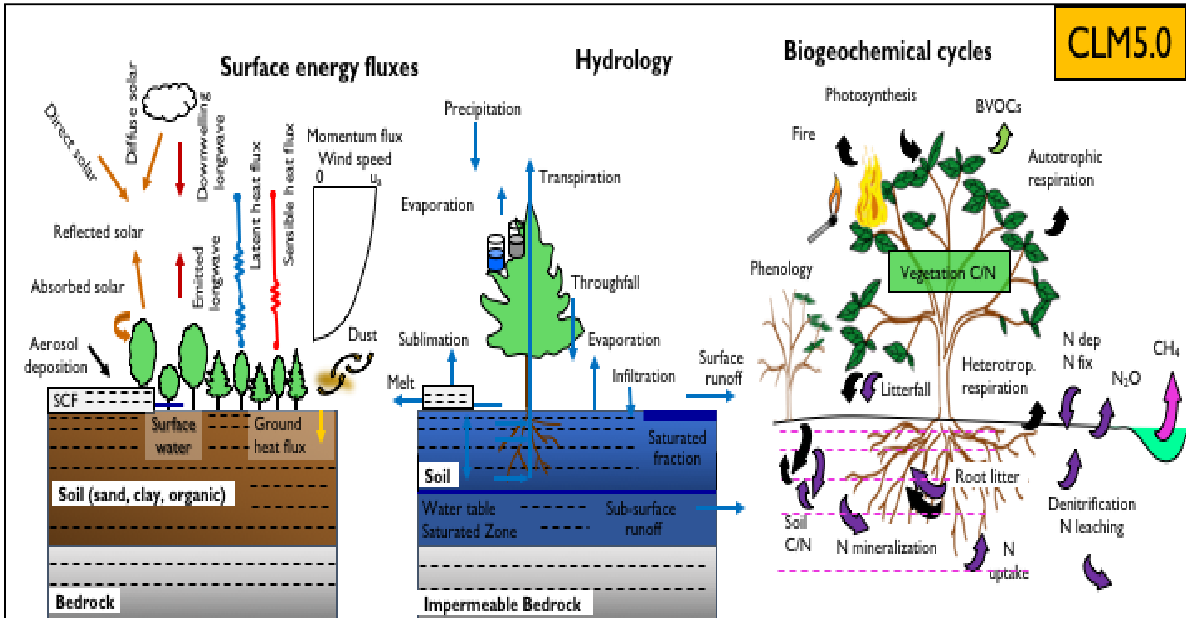
Land is a critical component of the Earth system

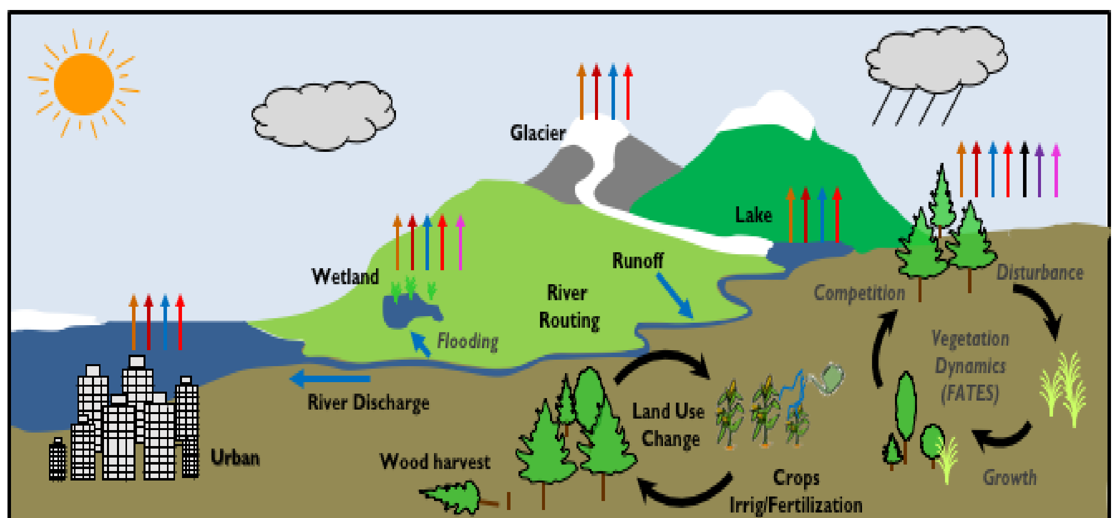
陆面过程与陆面模式

■ 陆面过程是指发生在陆地表层的**陆面与大气之间的相互作用**、**河流湖泊、冰川冻土、植物生理与生态、植被动力学、生物地球化学、人类活动等过程**。

■ 陆面模式是：

- **定量描述这些过程数学物理模式，**
- 天气/气候/地球系统模式的重要分量系统模式，
- **定量研究人类活动与环境相互作用的基本工具。**





陆面过程和陆-气相互作用：
天气/气候/环境系统的基本科学过程

大气模式

大气环流/大气对流/云/辐射/等

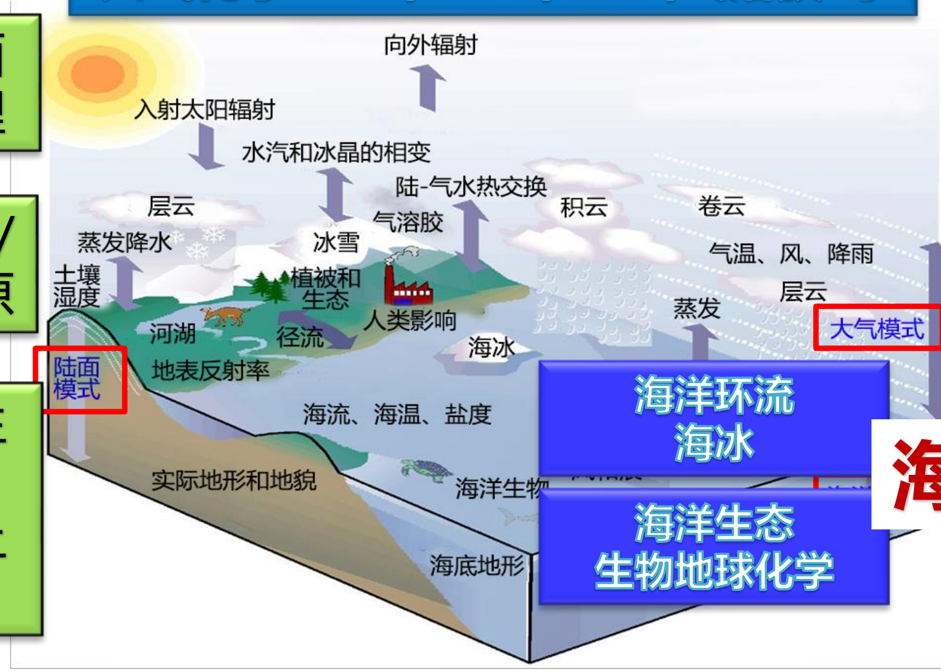
大气化学 CO_2, NO_x, SO_x,气溶胶 等

陆面过程模式

陆面物理/陆面水文/植物生理

植物生态/河流/湖泊/冰川/冰原

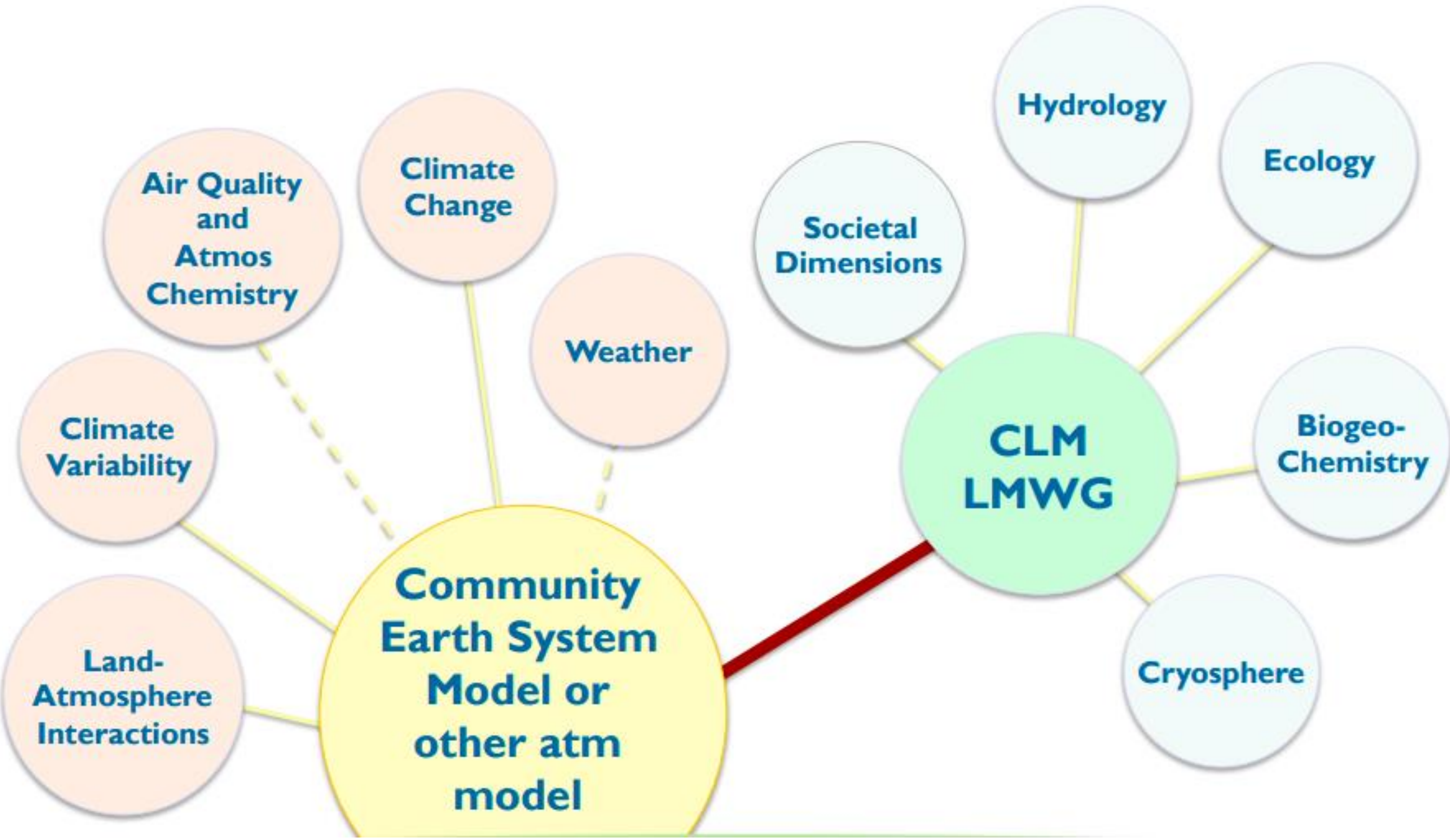
植被动力学/生物地球化学/冰原动力学/土地利用/ 等



海洋模式

陆面过程复杂，模式构建涉及：数学、物理学（流体力学和热力学）、生态学、地球系统科学、计算科学等

陆面过程模式是天气/气候/地球系统模式的重要组成部分，是陆面过程机理以及人类活动与全球变化关系研究的重要手段，也是全球气象/水文/生态的精细化预报的核心技术。


Air Quality and Atmos Chemistry
Climate Change
Weather
Climate Variability
Land-Atmosphere Interactions
Community Earth System Model or other atm model
Societal Dimensions
Hydrology
Ecology
CLM LMWG
Biogeo-Chemistry
Cryosphere

Land is a sink for ~30% of anthropogenic CO_2 emissions

CO_2 Sources

9.5 ± 0.5 PgC yr^{-1} 86%

1.5 ± 0.7 PgC yr^{-1} 14%

CO_2 Sinks

45%

4.9 ± 0.2 PgC yr^{-1}

29%

3.2 ± 0.8 PgC yr^{-1}

23%

2.5 ± 0.5 PgC yr^{-1}

Notes: Values are averaged from 2009-2018; Budget Imbalance: 0.4 Pg C/yr; Source: Friedlingstein et al. 2019

- **科学研究有两个最基本的目的：**一是寻求基本原理，二是解决实际问题。
- **科学研究有两种最基本的范式：**一是数据驱动的范式，二是基本原理驱动的范式。

- 物理学是基本原理的来源，也是培养直观理解、认清事物本质的学科。
- 数学是其他学科精确量化表达的基本语言和基本工具，比方说基本原理通常是由微分方程或变分原理来表述的。
- 无论是什么范式，最终解决问题都需要借助于计算机和算法。
- 所以物理学、数学（特别是应用数学）、计算机的基础知识是交叉科学人才培养的基石。

我们需要培养以下几方面能力：

- **物理能力的培养，**包括直观能力和基本原理方面的修养。
- **数据驱动的研究能力培养，**包括传统的统计分析方法、机器学习方法，以及其他一些数据分析方法，如图像处理、信号处理等。
- **算法能力的培养，**包括针对基本原理的算法、针对数据的算法、编程、高性能计算。

守恒（平衡）方程

（动量、能量、质量）

增量 ＝ 流入量 － 流出量

能量守恒方程

热储量变率　　对流传热　　传导传热　　辐射

其中：

ρ_k　　多孔介质成分固有密度,

θ_k　　多孔介质成分分体积,

h_k　　水(固、液、汽)和干土的**比焓**,

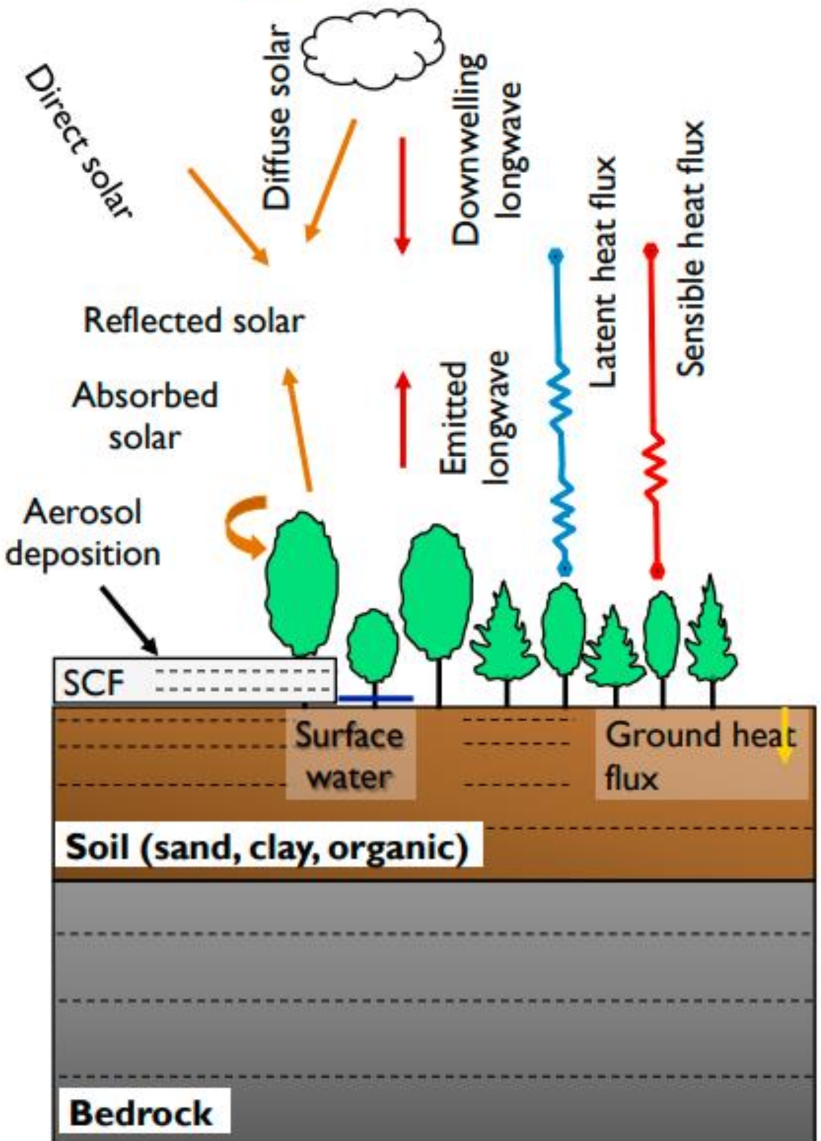
U_k　　物质流量,

λ　　热传导率,

R　　辐射

d, i, l, v (for dry soil, ice, liquid and vapor)

At each time step the land model solves Surface Energy Balance



$$S^{\uparrow} - S^{\downarrow} + L^{\uparrow} - L^{\downarrow} = \lambda E + H + G$$

$S^{\uparrow}$, $S^{\downarrow}$ are down(up)welling solar radiation,

$L^{\uparrow}$, $L^{\downarrow}$ are up(down)welling longwave rad,

λ is latent heat of vaporization,

E is evaporation,

H is sensible heat flux

G is ground heat flux

质量守恒方程

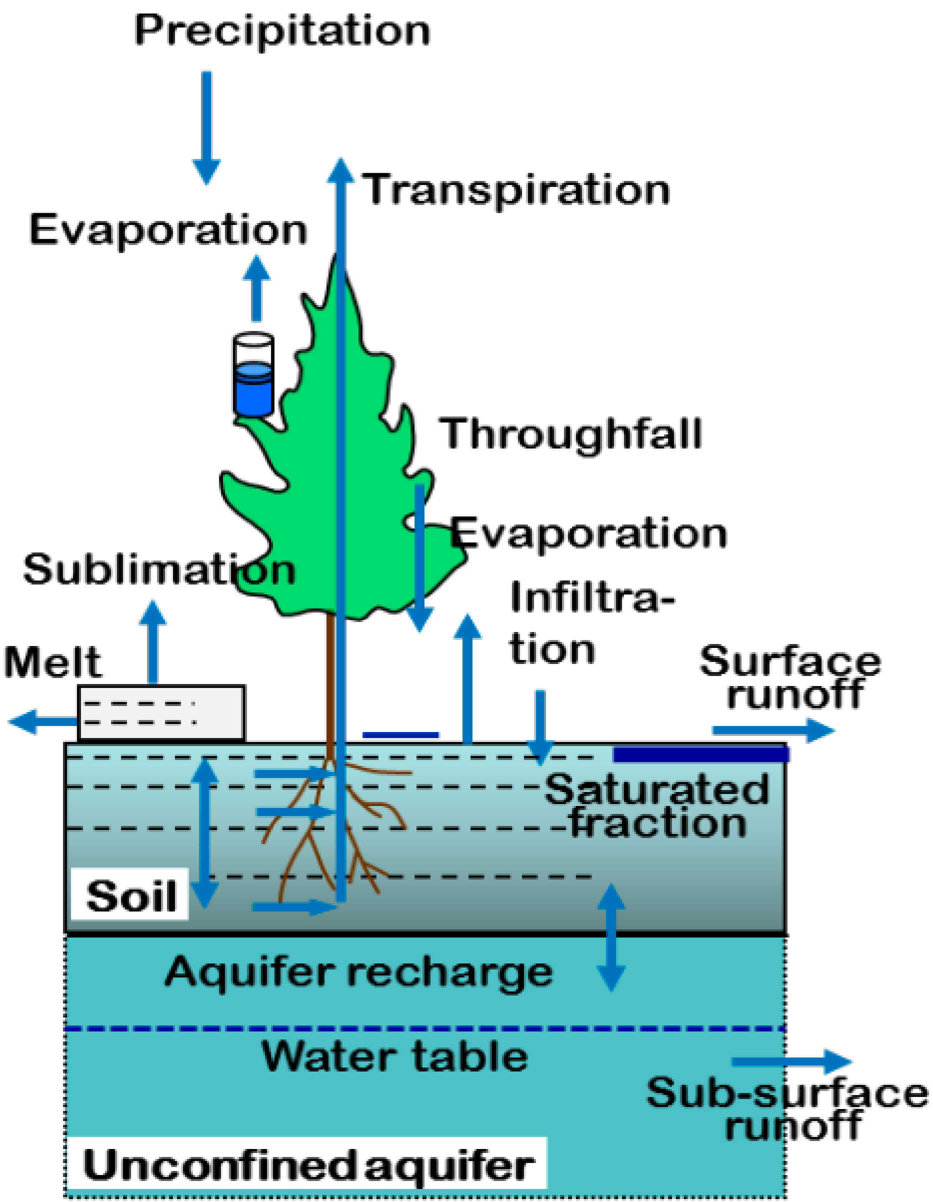
质量变率 质量流 相变 源或汇

其中：

ρ_k 多孔介质成分固有密度,
θ_k 多孔介质成分分体积,
U_k 物质流量,
$M_{k'k}$ 相变转换质量(k'相到 k相)
$\delta_{k'k}$ Kronecker delta函数
S_k 源或汇

d, i, l, v (for dry soil, ice, liquid and vapor)

… and the Surface Water Balance



$$P = E_S + E_T + E_C + R + (\Delta W_{soi} + \Delta W_{snw} + \Delta W_{sfcw} + \Delta W_{can}) / \Delta t$$

P is rainfall/snowfall,

E_S is soil evaporation,

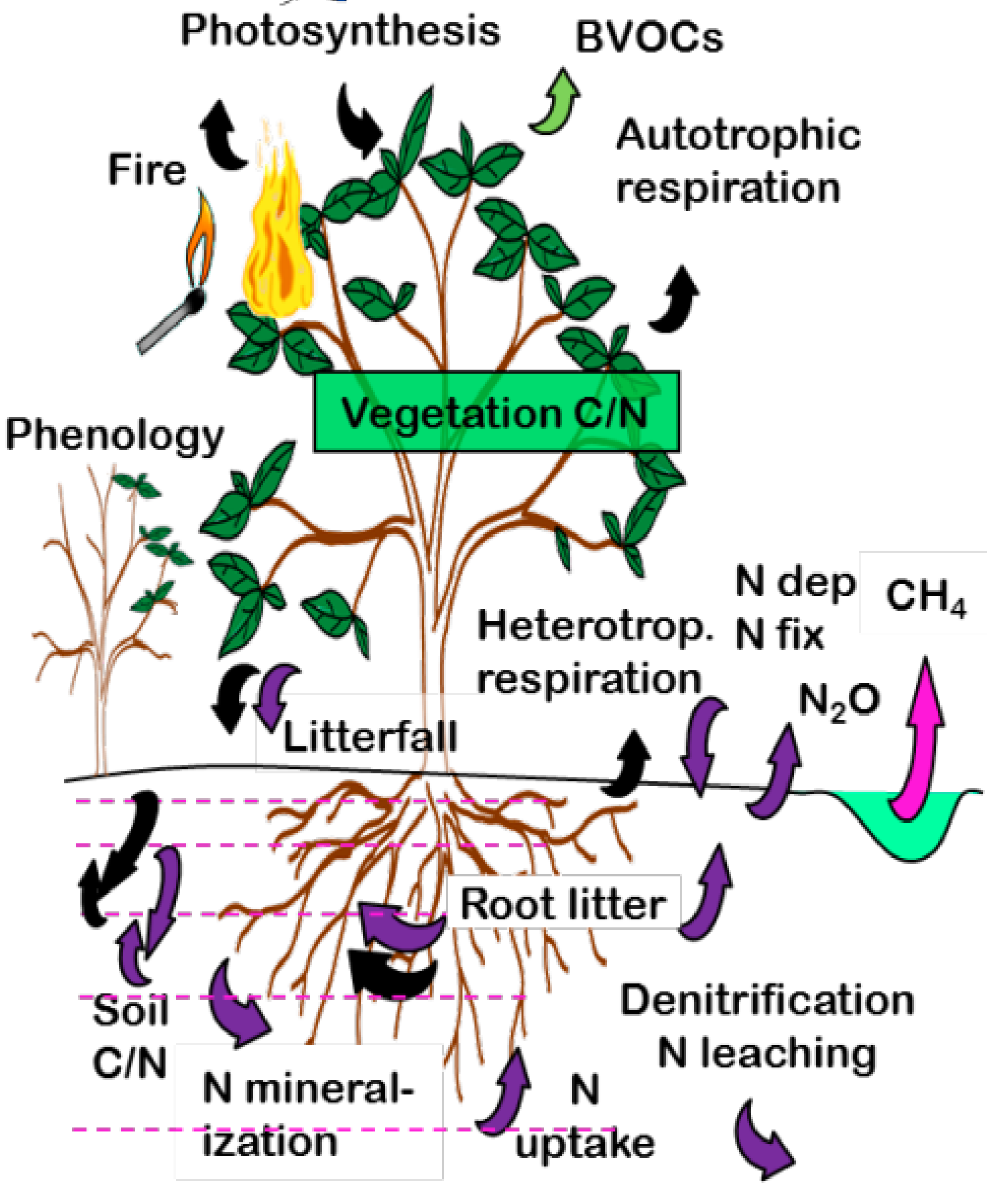
E_T is transpiration,

E_C is canopy evaporation,

R is runoff (surf + sub-surface),

$\Delta W_{soi} / \Delta t$, $\Delta W_{snw} / \Delta t$, $\Delta W_{sfcw} / \Delta t$, $\Delta W_{can} / \Delta t$, are the changes in soil moisture, surface water, snow, and canopy water over a timestep

… and Surface Carbon Exchange



NEE = GPP – HR – AR – Fire – LUC

NEE is net ecosystem exchange

GPP is gross primary productivity

HR is heterotrophic respiration

AR is autotrophic respiration

Fire is carbon flux due to fire

LUC is C flux due to land use change

陆面过程模式研制中挑战问题

陆面模式研制中的挑战性问题：

- 复杂(异质性、非线性、多尺度性等)陆地表层过程的数学物理表达？
- 不同尺度陆面过程(空间：分子尺度→全球尺度，时间：微秒→百年/千年)动力学统计表达？
- 影响天气/气候/地球系统的关键陆面过程？
- 数值适定性、计算稳定性、计算机可实现性？
- 用以验证模拟的观测资料在不同尺度上的正确性？

陆面模式的发展介绍

- **第一代陆面过程模式**(20世纪60年代末到70年代)的标志为“水桶模式”和简单能量平衡模式(Budyko, 1974; Manabe, 1969)。它假定土壤为容水量为15cm 的“水桶”，地面温度和陆-气水热通量计算非常简约，如地表反照率和粗糙度采用大尺度范围内均一化的参数。

- **第二代陆面过程模式**(20世纪80年代)中最具代表性的是 BATS (Dickinson et al., 1986)和SiB (Sellers et al., 1986)，IAP-LSM-1994 (Dai, Zeng, 1997)，NOAH (Chen et al., 2001)，它们细致地考虑了植被在陆地水、热过程中的作用，包括对辐射传输、动量交换、蒸腾、降水截流等过程的影响。

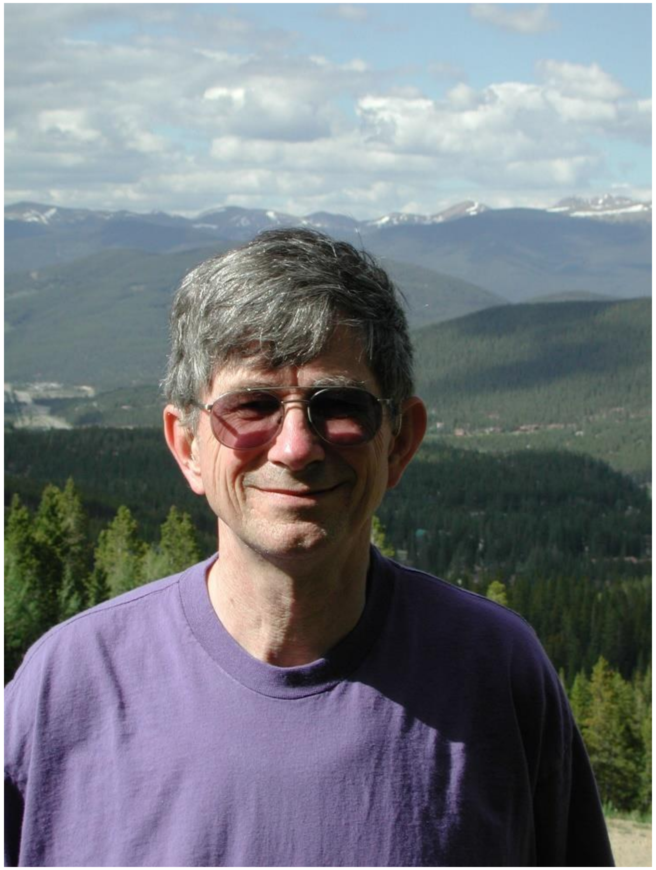
- **第三代陆面过程模式**(20世纪90年代)的标志模式有：BATS1e (Dickinson et al, 1993)，SiB2 (Sellers et al., 1996)，AVIM (Ji et al., 1989，1996)，其最显著的一个特点是耦合了光合作用、呼吸作用等关键植被生理与生态系统过程。

- **第四代陆面过程模式(20世纪90年代末-至今)中最具代表性的有：通用陆面模式(Dai et al., 2003)**，和后续的美国CLM (Oleson et al., 2010; Lawrence et al., 2019)，中国CoLM (Dai et al., 2004; 2014; 2021)，以及英国JULES (Wiltshire et al., 2019)，澳大利亚CABLE (Haverd et al., 2018)，美国NOAH-MP (Niu et al., 2011)。这些陆面过程模式对陆面物理、化学和生物等过程的描述更加精细化，加入大量新的子模式，包含的过程更加完备。

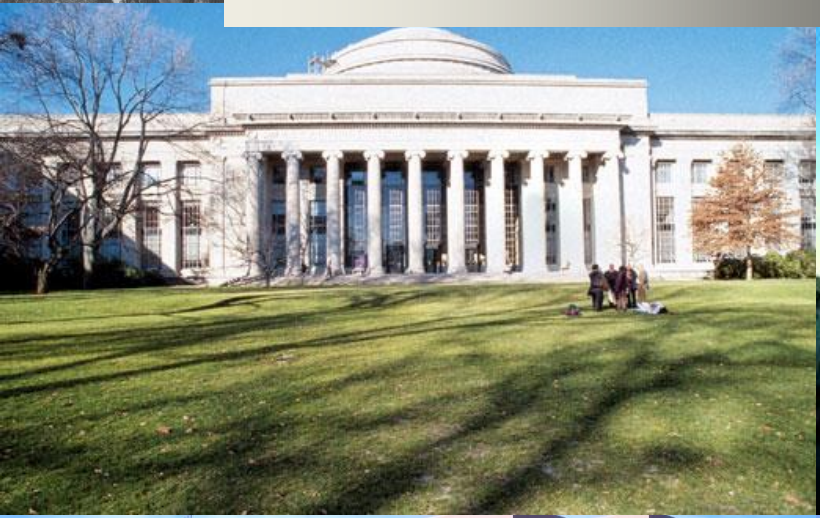
Robert E. Dickinson介绍

Robert E. Dickinson

- 美国 加州大学洛杉矶分校（UCLA）大气科学系 教授
- 美国科学院 院士
- 美国工程院 院士
- 美国地球物理联合会前主席
- 中国教育部、国家外国专家局“高等学校学科创新引智计划”全球变化科学项目首席科学家



哈佛大学→麻省理工学院→国家大气研究中心→亚利桑那大学 →佐治亚理工学院 →UT Austin →UCLA



主要学历：

1966 博士：气象学，麻省理工学院
1962 硕士：气象学，麻省理工学院
1961 学士：化学与物理学，哈佛大学

主要学术经历：

1966-1968 : **Research Associate**, MIT, Cambridge, MA

1968-1975 : **Scientist**, **美国国家大气研究中心**（NCAR)

1975-1981 : **Head**, **美国国家大气研究中心 气候部**

1981-1990 : **Deputy Director**, **美国国家大气研究中心**

1990-1999 : **Regents Professor**, **亚利桑那大学**

1999- present : **Georgia Power Chair Professor**, **佐治亚理工学院**

主要学术荣誉称号：

- 1988: Member, National Academy of Science （美国科学院 院士）
- 2002: Member, National Academy of Engineering （美国工程院 院士）
- 2002-2004: President - American Geophysical Union （美国地球物理联合会 主席）
- 2005: 中国科学院 爱因斯坦讲席教授
- 2004：中国科学院 大气物理研究所荣誉研究员
- 2004：北京师范大学 荣誉教授

2004: Honorary Membership in European Geosciences Union (EGU)

2003: ISI Web of Knowledge Highly Cited List, ISI HighlyCited.com

2002: Honorary Membership in the European Geophysical Society (EGS)

1987: Fellow, American Geophysical Union

1984: Fellow, American Association for the Advancement of Science

1973: Fellow, American Meteorological Society

主要科技奖励：

囊括了美国地球物理界所有最高级别奖项

1996: Roger Revelle Medal, American Geophysical Union
（美国地球物理联合会 最高奖）

1996: Rossby Award, American Meteorological Society
（美国气象学会 最高奖）

1996: G. Unger Vetlesen Award, Lamont-Doherty Earth Observatory of Columbia University
（地球科学界“诺贝尔”奖）

1992: Physics Distinguished Achievement Award for Outstanding Publication Contribution

1988: Jule G. Charney Award, American Meteorological Society**（美国气象学会）**

1973: Meisinger Award, American Meteorological Society
（美国气象学会）

http://www.ldeo.columbia.edu/vetlesen/recipients.html

About the Vetlesen Prize

Background Information

The Vetlesen Prize was established in 1959 by the G. Unger Vetlesen Foundation. The prize is awarded for scientific achievement resulting in a clearer understanding of the Earth, its history, or its relations to the universe and is administered by Columbia University's Lamont-Doherty Earth Observatory. **Designed to rank in its field in importance and dignity with the Nobel awards, the Vetlesen is acknowledged as the premier prize in this area.**

Eligibility

Competition for the Vetlesen Prize is open to any person anywhere in the world. Prizes may be awarded to more than one person at a time.

Frequency

The prize is awarded on average once every two years, if the jury selects at least one worthy candidate during this period.

The Prize

The prize consists of a cash award of $100,000, a medal.

1960年—2004年共授予25人次，每2至4年一次

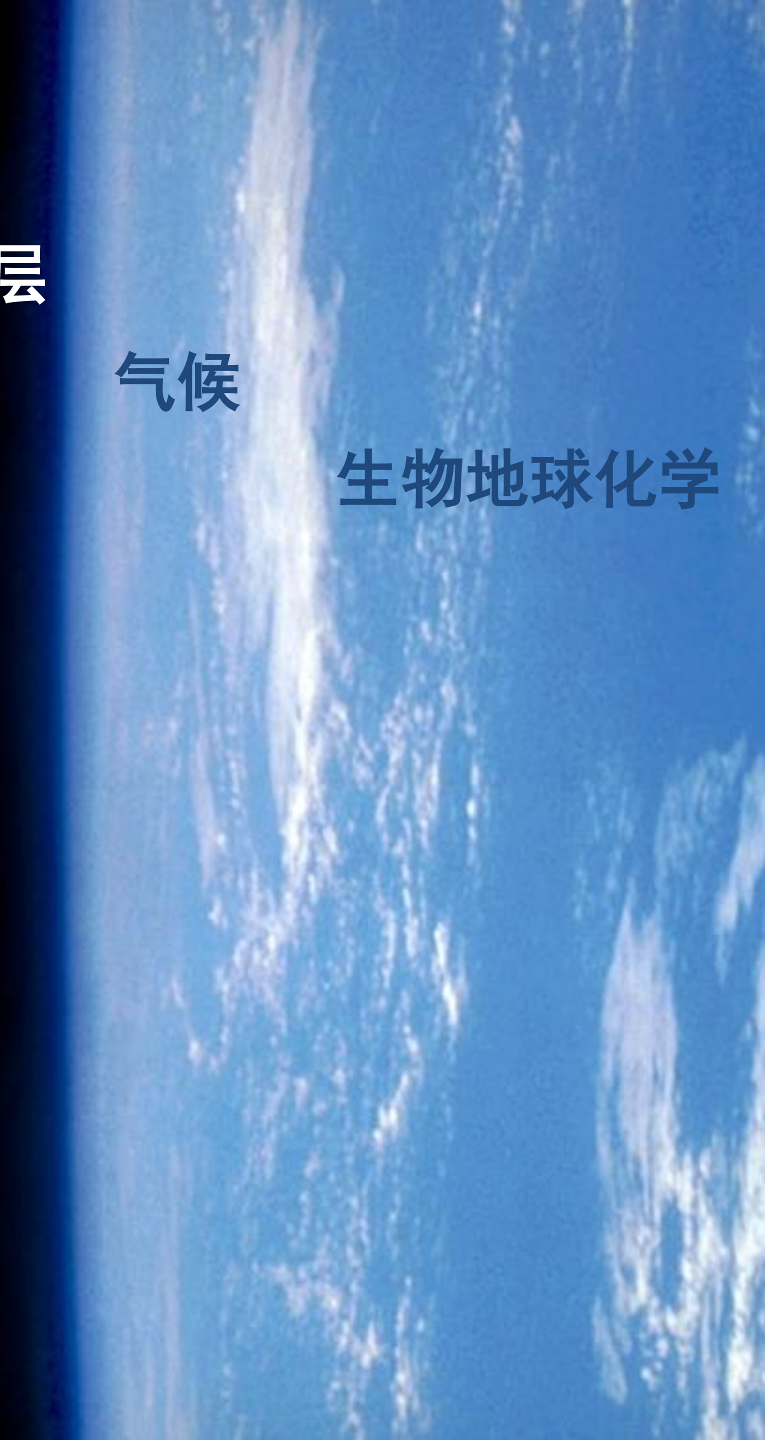
地球科学界的“诺贝尔奖”

Vetlesen 奖获得者及其研究领域

2004: Sir Nicholas Shackleton	气候变化,英国	[1]
W. Richard Peltier	气候变化,加拿大	[2]
2000: W. Jason Morgan	海底扩张、板块构造、地幔对流,美国	[3]
Walter C. Pitman III	板块构造理论、地貌和构造学理论,美国	[4]
Lynn R. Sykes	地震预测与预报、地下核试验地震测定,美国	[5]
1996: Robert E. Dickinson	大气科学、气候模拟、气候－生物圈相互作用	[6]
John Imbrie	沉积记录、地球轨道变化、气候变化,美国	[7]
1993: Walter Munk	地球物理学,美国	[8]
1987: Wallace S. Broecker	地球化学,美国	[9]
Harmon Craig	地球化学与海洋学,美国	[10]
1981: Marion King Hubbert	地球物理与地质学,美国	[11]
1978: J. Tuzo Wilson	地质学,加拿大	[12]
1974: Chaim Leib Pekeris	地心数学研究,以色列	[13]
1973: William A. Fowler	天体物理学,美国	[14]
1970: Allan V. Cox,	古磁学,美国	[15]
Richard R. Doell	古磁学,美国	[16]
S. Keith Runcorn	古磁学,英国	[17]
1968: Francis Birch	岩石物理性质,美国	[18]
Sir Edward Bullard	地心数学研究、磁学, 英国	[19]
1966: Jan Hendrik Oort	天体物理学,荷兰	[20]
1964: Pentti Eelis Eskola	岩石化学地质学,芬兰	[21]
Arthur Holmes	地质学,英国	[22]
1962: Sir Harold Jeffreys	地心,美国	[23]
Felix Andries Vening Meinesz	地心引力、地心,荷兰	[24]
1960: W. Maurice Ewing	地球物理学、地震学、海底研究,美国	[25]

大气热层

平流层



成就领域

行星大气 → 生物地球化学

成就领域

- 地球与行星大气大尺度动力学
- 中层大气辐射
- 气候变率
- 人类活动导致的气候变化
- 陆地表面过程
- 生物地球化学
- 卫星遥感反演方法及资料应用

- 共发表近300篇同行评审论文（peer reviewed publications）
- 出版30多章节书

成就领域：

- 六十年代：地球与行星大气大尺度动力学、中层大气辐射，发表21篇论文
- 七十年代：地球与行星大气大尺度动力学与全球气候模拟，发表55篇论文
- 八十年代：全球气候模拟与陆地表面过程，发表73篇论文
- 九十年代：全球变化与生物地球化学循环，发表113篇论文
- 2000’s：生物地球化学、卫星遥感资料应用、甚高分辨率全球气候模拟，发表 >37篇论文

Recognitions by Earth Science Community

- ***Dr. Dickinson formulated path-breaking computer models that simulated the basic workings of the Earth's atmosphere, from the troposphere to the thermosphere, and showed how atmospheric dynamics affect the Earth's climate.***
  - *Citation by the Vetlesen jury*
- ***His genius is reflected by a great breadth of accomplishment and by remarkable depth. His papers provide example after example of great attention to the details and complexities of a problem while pioneering whole new areas of investigation.***
- ***Bob's research spans the areas of assessment of future climate change, biometeorology and vegetation-climate interaction, remote sensing of the Earth's surface, upper atmosphere research, polar climates, aerosols and biomass burning, the general circulation of the atmosphere, the atmosphere of Venus, and the climate of the early Earth.***
  - *Citation by AGU in recognition of sustained and continued superior contributions to the science of climate dynamics and to predictions of expected climate changes*

Biosphere - Atmosphere Interaction in climate

- Developed the first biosphere-atmosphere transfer scheme for global general circulation and meso-scale weather models (Dickinson 1984), and current NCAR Community Land model (Dai et al. 2003).
- Pioneered modeling of land use impacts on climate (Dickinson and Henderson-Sellers 1988) and draw internation attensions to tropical deforestation (Dickinson 1987).
- Led Remote sensing of land surface/vegetation of NASA Earth Observing System

- A world leader who has created and led the field of vegetation-atmosphere interaction in climate research for the past two decades. Today, this is one of the most active and for-front areas of climate research.

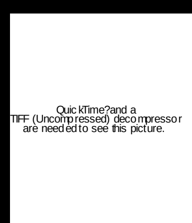
Laid Foundation for major advancements of Stratospheric Dynamics and Transport:

Charney & Drazin 1961

Elaissen & Palm 1961

Wave-Mean Flow Interaction at critical lines, role of wave damping (Dickison 1969a, b)

Importance of 2D wave propagation & refraction (Dickinson 1968a, b)



Dickinson's
4 papers in 1968-69

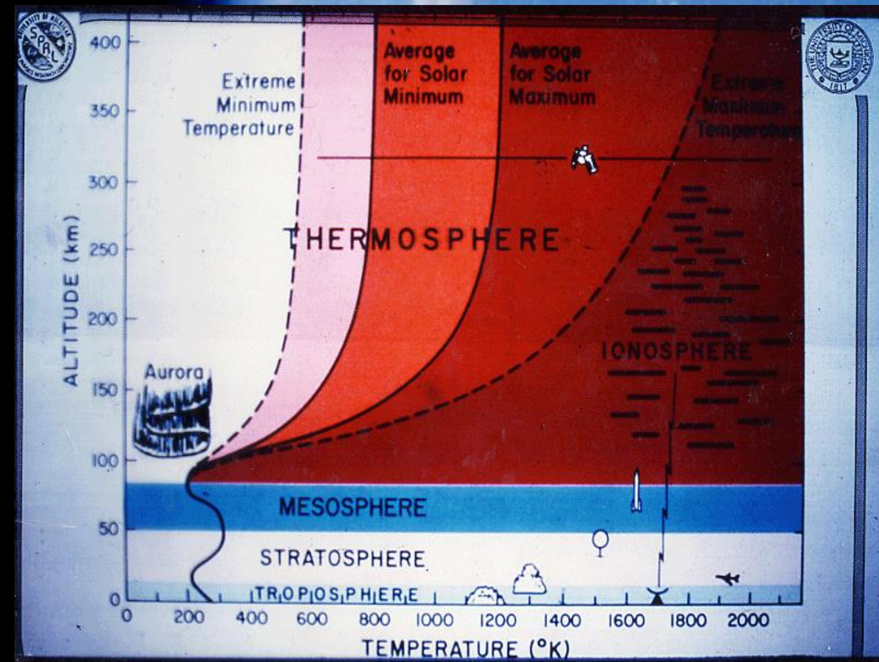
Sudden warming theory [Matsuno, 1971, …]

Generalized wave mean flow interaction [Andrews & McIntyre, 1976; Boyd 1976]

Refractive index [Matsuno, 1970, Palmer, 1982]

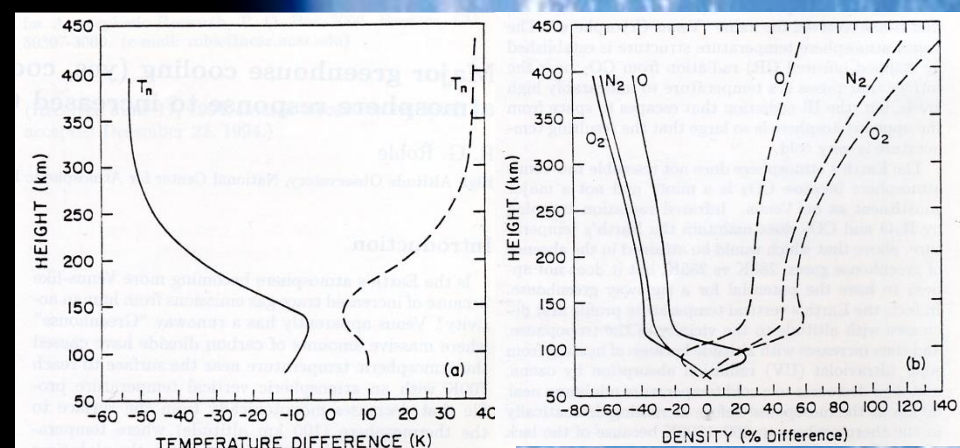
EP flux diagnostics [Edmon et al. 1980]

Global Change in the Thermosphere and Mesosphere



Pioneered

- ***Model of thermosphere/mesosphere***
- ***Predictions of thermosphere/mesosphere cooling from increased CO_2, CH_4***

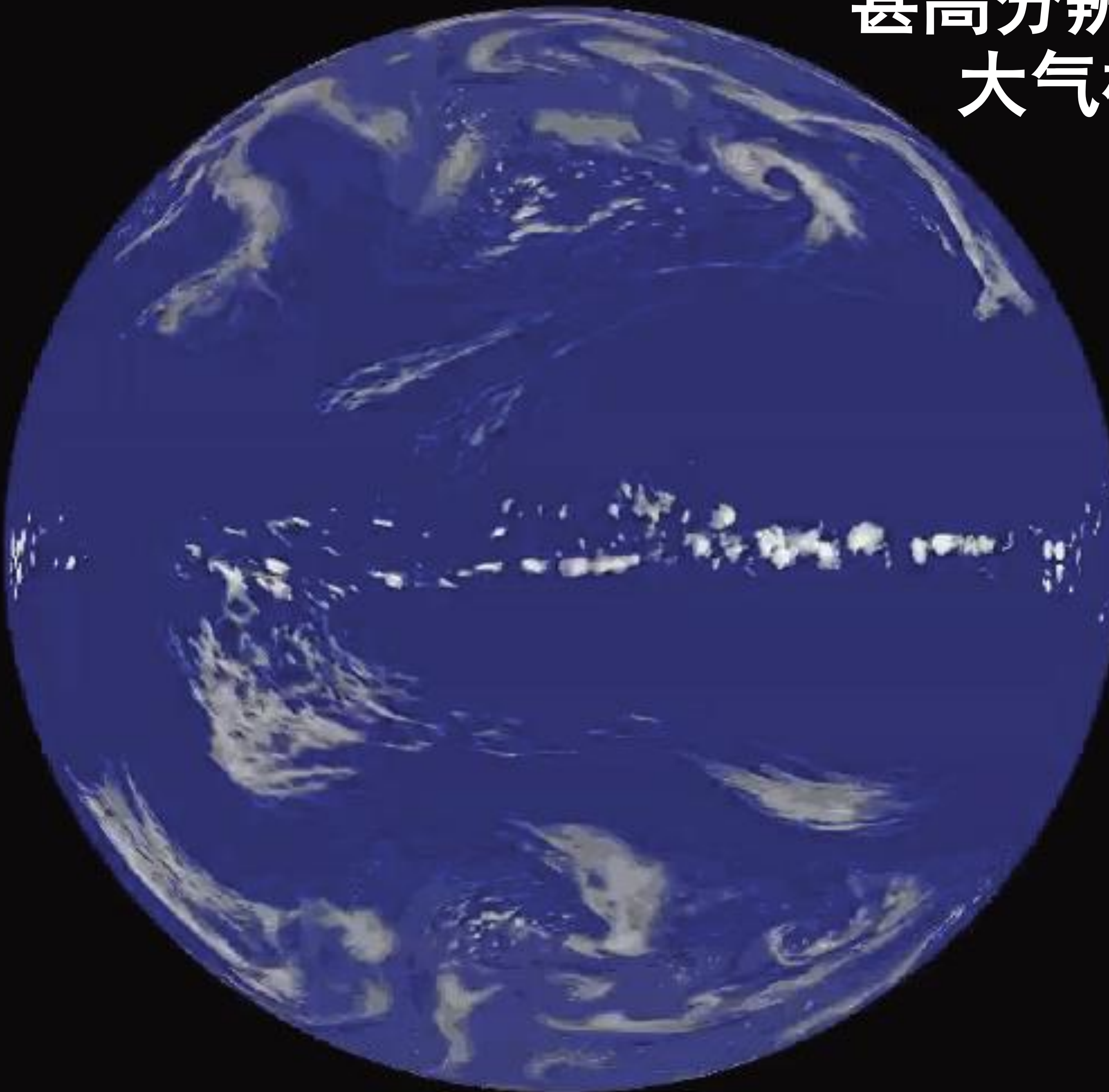


ble and Dickinson (1989)

Climate Research

- Important contributions to the framework of climate sensitivities to human influences
  – Dickinson 1982: Modeling climate changes due to carbon dioxide increase (Oxford University Press)
  – Dickinson 1986a: How will climate change The climate system and modeling of future climate (Wiley)
  – Dicknson 1986b: Impact of human activities on climate - A framework (Cambridge University Press).

甚高分辨率全球
大气模拟



对中国科学技术事业的重要贡献

从1981年Dickinson第一次访问中国起，与中国同行开展了非常全面合作。平均每年访问中国1－2次。


全国重点文物保护单位
汉长城


奉献能源创造和谐
工农携手共写和
民族团结
进入沙漠公路
注意消防安全


虎门鸦片焚烧池


IAMAS 2005
BEIJING
MAS 2005
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Symposium (S1)
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YONGJIU
DAI
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QINGYUN
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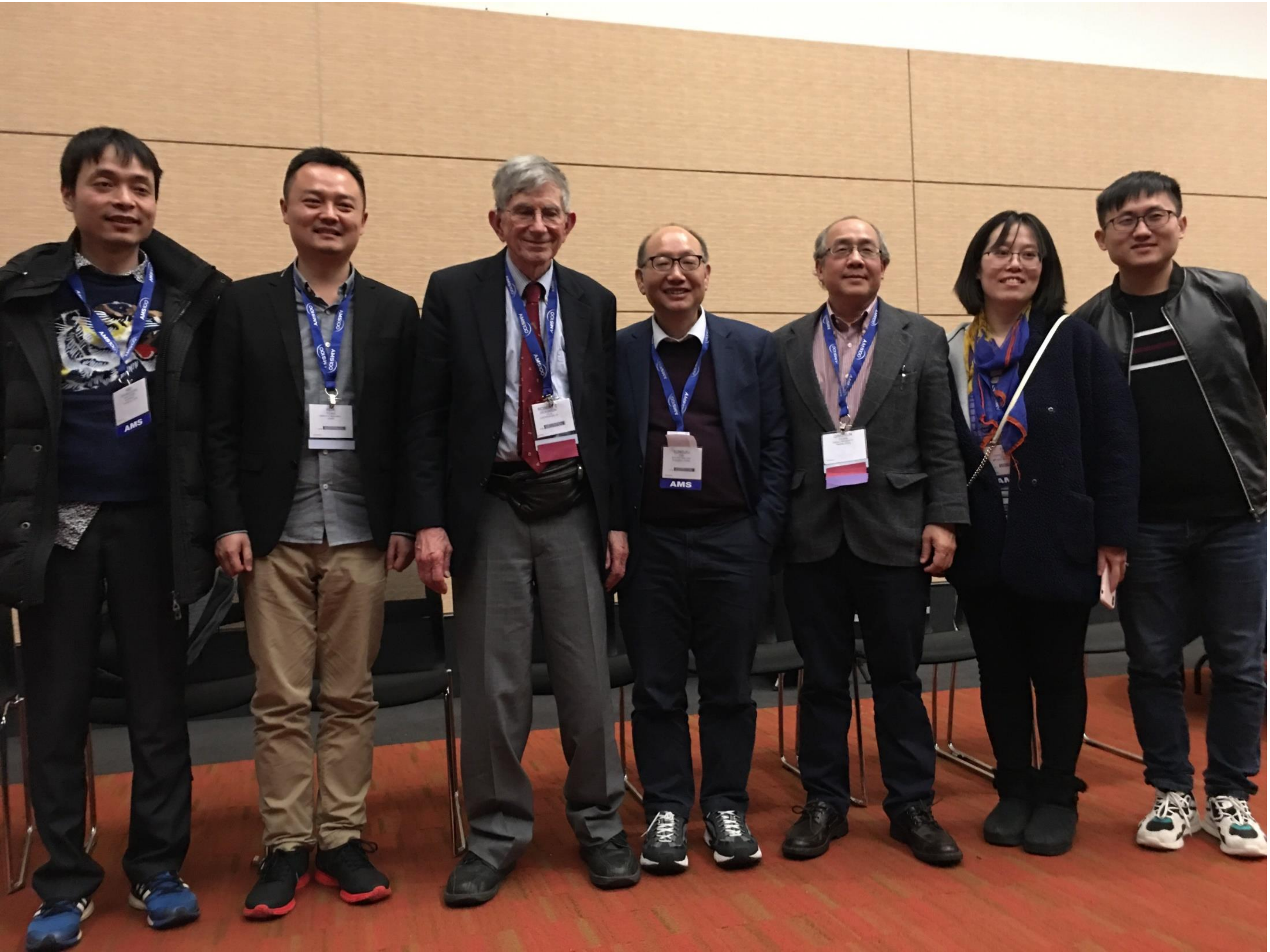

AMS

Piers Sellers (1955-2016)

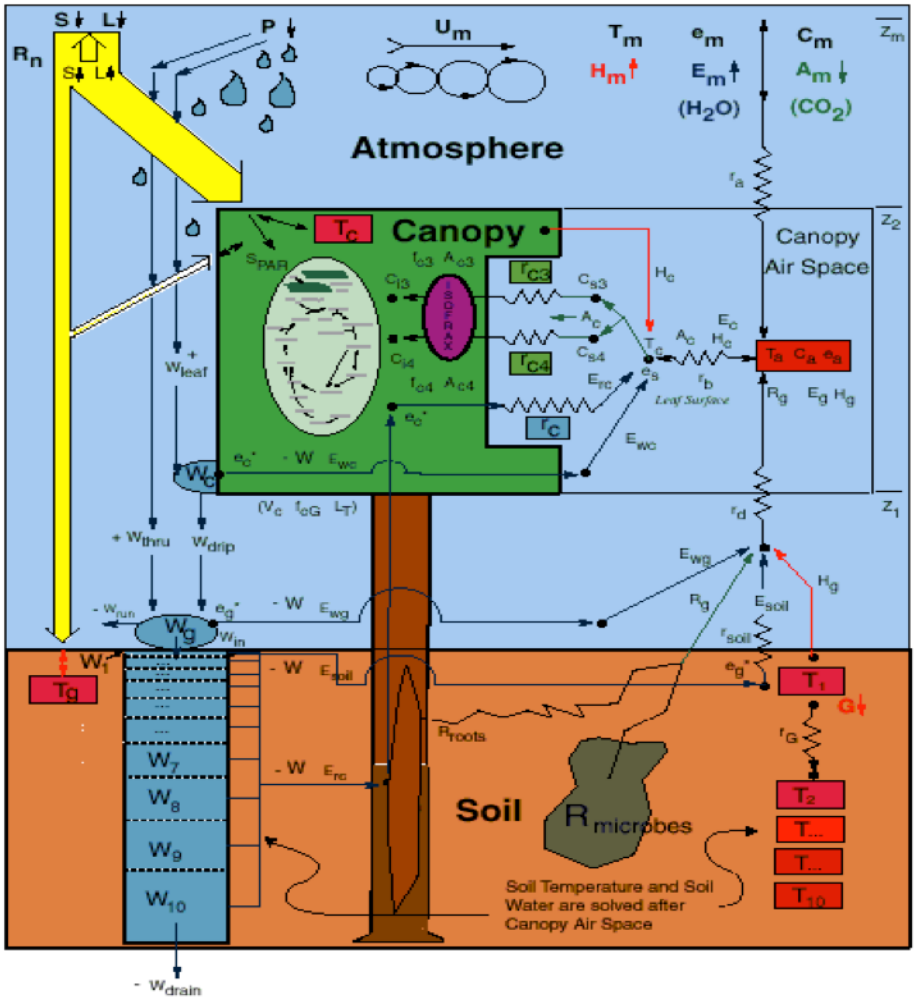
NASA Astronaut / Former Director of Earth Sciences at Goddard Space Flight Center

- Dr. Piers Sellers earned his B.Sc. from the University of Edinburgh and his Ph.D. from Leeds University.
- In 1982, he moved from the U.K. to the U.S. in 1982 to carry out climate research at NASA/GSFC, where, from 1982 to 1996, he worked on global climate problems, particularly those involving interactions between the biosphere and the atmosphere, and was involved in constructing **computer models** of the global climate system, **satellite data interpretation** and conducting **large-scale field experiments in the U.S., Canada, Africa, and Brazil.**
- In 1998, he was the project scientist for the **first large Earth Observing System platform, Terra**.
- In 1996, he joined the NASA astronaut corps and has flown on **three space missions to the International Space Station (ISS) in 2002, 2006, and 2010**, carrying out **six spacewalks** and working on ISS assembly tasks.

Piers Sellers in the International Space Station during the STS-132 space shuttle Atlantis mission in May 2010.

Piers Sellers stands on the International Space Station's Canadarm2 to work on the station at the end of the STS-112 mission's second spacewalk on Oct. 12, 2002.

Simple Biosphere Model (SiB)

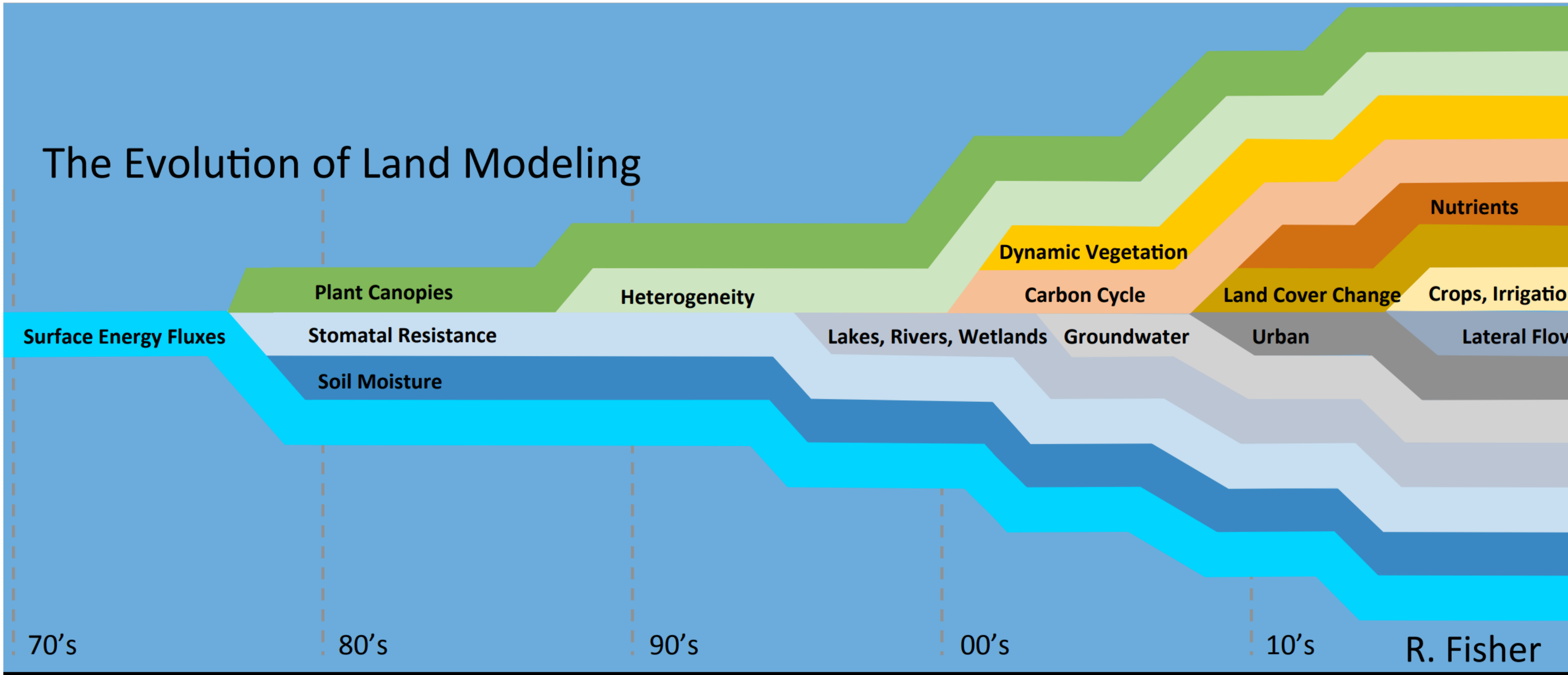


- The Simple Biosphere (SiB) Model was originally developed by Piers Sellers in the mid-1980’s as an internally-consistent module to surface-atmosphere exchanges of radiation, heat, moisture, and momentum over land.
- It was extended in the mid-1990’s by a team of interdisciplinary scientists to include mechanistic linkages to photosynthesis, stomatal physiology, and satellite remote sensing.
- Since that time it has been extended to include improved treatment of carbon cycling, soils, snow, hydrology, stable isotopes, phenology, and crops.

- Sellers, P. J., Y. Mintz, Y. C. Sud, and A. Dalcher, A simple biosphere model (SiB) for use within general circulation models, *J. Atmos. Sci.*, **43**, 505-531, 1986.
- Sellers, P.J., D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, G. D. Collelo, L. Bounoua, A revised land surface parameterization (SiB2) for atmospheric GCMs, Part 1: Model formulation. *Jour. Clim.*, **9**, 676-705, 1996a.

Land complexity: Submodels of CLM

- Biogeophysics
  - Photosynthesis and stomatal resistance
  - Hydrology
  - Snow
  - Soil thermodynamics
  - Surface albedo and radiative fluxes
- Biogeochemistry
  - Carbon / nitrogen pools, allocation, respiration
  - Vegetation phenology
  - Decomposition
  - Plant Mortality
  - External nitrogen cycle
  - Methane production and emission
- Vegetation dynamics
- Urban
- Crop and irrigation
- Lakes
- Glaciers and ice sheets
- Fire and fire emissions
- Dust emissions
- River flow
- Biogenic Volatile Organic Compound emissions



Land models are increasing in complexity

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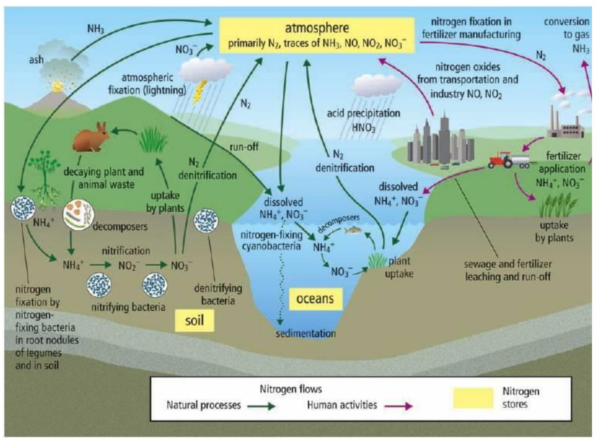
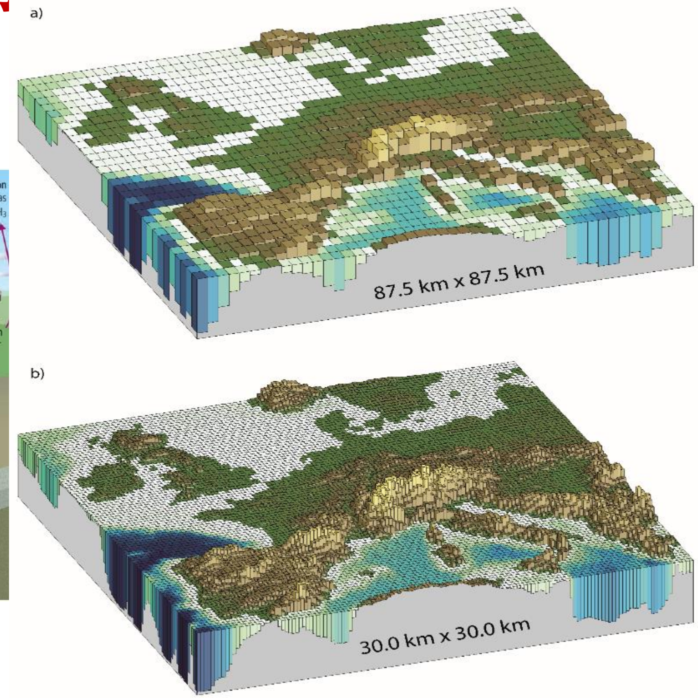
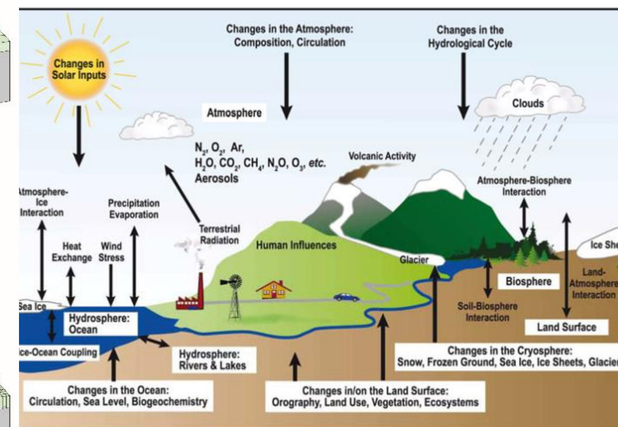
我国完全自主知识产权的、具备国际先进地位的

新一代陆面过程模式







耦合人类活动的
陆面过程精细化建模

全球高分辨率

适用于天气/气候/地
球系统模式耦合应用

"Essentially, all models are wrong, but some are useful.“

(George E. P. Box, Robustness in the strategy of scientific model building, 1979)

高分辨率全球天气预报和气候预测

Local effects such as thunderstorms, crucial for predicting global warming, could be simulated by fine-scale global climate models.

Build high-resolution global climate models

International supercomputing centres dedicated to climate prediction

建造高分辨率全球气候模式
Build high-resolution global climate models.
Tim Palmer, Nature, Nov. 2014.

The quiet revolution of numerical weather prediction

Peter Bauer[1], Alan Thorpe[1] & Gilbert Brunet[2]

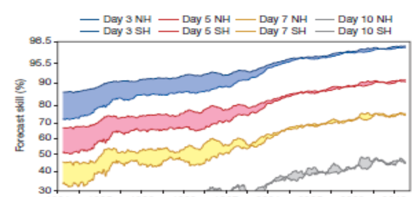
Advances in numerical weather prediction represent a quiet revolution because they have resulted from a steady

未来天气、气候预报的空间分辨率：

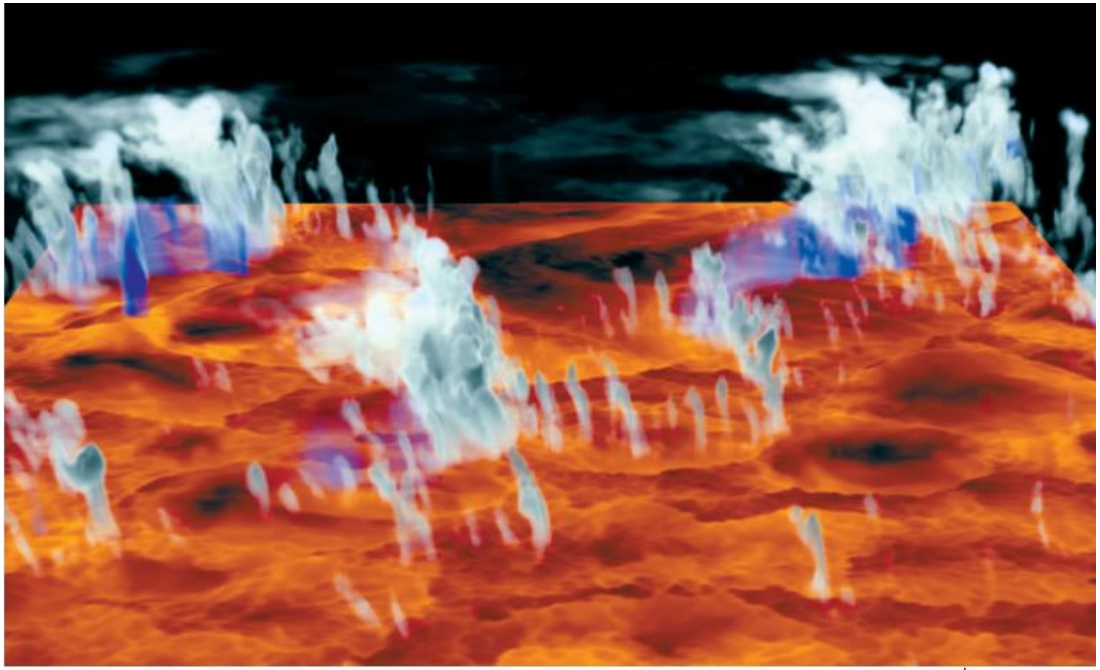
- **Global convection-permitting simulation～O(1km)**
- **Finer-scale local forecast for detailed weather ～O(100m)**

A touchstone of scientific knowledge and understanding is the ability to predict accurately the outcome of an experiment. In meteorology, this translates into the accuracy of the weather forecast. In addition, today's numerical weather predictions also enable the forecaster to assess quantitatively the degree of confidence users should have in any particular forecast. This is a story of profound and fundamental scientific success built upon the application of the classical laws of physics. Clearly the success has required technological acumen as well as scientific advances and vision.

Accurate forecasts save lives, support emergency management and mitigation of impacts and prevent economic losses from high-impact weather, and they create substantial financial revenue—for example, in energy, agriculture, transport and recreational sectors. Their substantial benefits far outweigh the costs of investing in the essential scientific

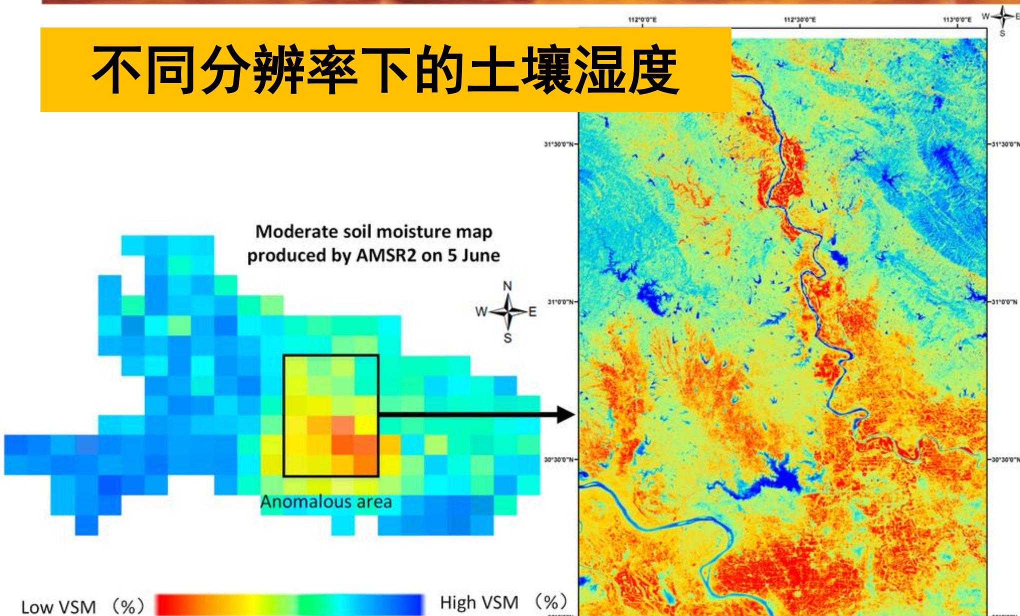


WMO白皮书
地球系统无缝隙预报：分钟→月

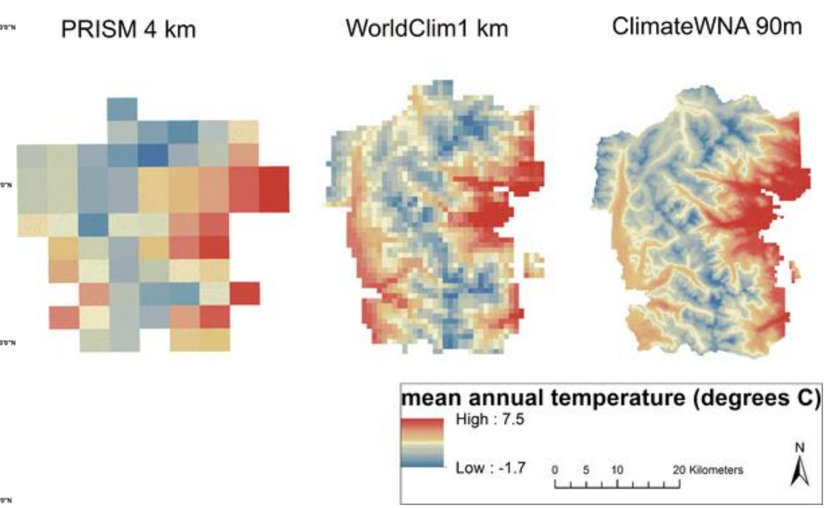


高分辨率气候模式模拟的对流云系统
Build high-resolution global climate models.
Tim Palmer, Nature, Nov. 2014.

不同分辨率下的土壤湿度



不同分辨率下的地表空气温度



高分辨率的大气模拟需要高分辨率的土壤湿度、温度等信息。

现阶段陆面模式的迫切需要改进之处

1. 耦合完备的人类活动精细化过程建模

上述诸代模式，对人类活动陆面过程扰动影响的描述相对缺乏或过于简单，缺乏相应的定量化描述能力。人类活动通过陆面各系统之间的相互作用，深刻地影响着全球/区域生态系统碳汇的强度和空间分布。因而，发展耦合人类活动的陆面过程模式和区域地球系统模式是实现陆面环境的精细模拟、准确预估区域碳排放空间以及有效评估碳中和行动环境效益的迫切需求。

2. 实现真正意义上高分辨率模拟

高分辨率模拟是众多模式共同发展的目标之一。但“高分辨率”模拟不仅仅是简单意义上的网格划分变细，而是需要与尺度相匹配的物理过程描述和数据集支撑。人类活动虽然空间尺度较小，但深刻改变了地表面貌和区域的水循环过程，给区域地球系统模式的精确模拟和预测带来了极大的挑战。因此，提高模式的分辨率以满足对人类活动高精度模拟需求是当前亟需解决的科学问题。

3. 建立综合性、一体化的陆面模拟系统

综模式和观测的进步大大地提高了我们对陆面系统的认识水平。然而，如何把模式、观测集成为一个系统来解决区域乃至全球尺度的社会需求问题已经成为地球系统科学领域内的一种挑战，也是国际上竞相研究的前沿学科之一。一个有效的陆面模拟系统能够为我们识别和量化气候变化与人类活动对环境变化的影响、探索水文气象灾害成因并且进行预报与预警、优化水资源配置、水土保持、粮食安全和生态环境保护，以及“碳达峰、碳中和”的国家与地方行动的评估与预估等提供科学支撑。

项目目标：

- 研究耦合人类活动的天气气候、水文水资源、生态环境变化等科学问题，揭示人类活动与地球系统的互馈机理。
- 建立耦合人类活动的陆面过程模式及陆面模拟系统，实现对广东省全境的30 x 30米分辨率的气象、水文、土壤、生态环境的精细化模拟预测。
- 为陆面环境的精细化模拟预测，以及国家“碳达峰、碳中和”行动的评估与预估提供基础理论与应用平台，为政府决策和公众服务提供科学支撑。

- **创建涉及更广泛科学群体的开发和分析范式，更直接地让非科学用户参与模式开发，促进知识协同生产。**
- **加速广东省向更高的数字化程度转型，使决策者快速知情成为可能，增强广东省陆面环境预报以及抵御风险的能力。**

项目研究内容

1、耦合人类活动的陆面物理过程建模

1) 水体(湖泊、水库、江河等)能量过程；
2) 地表水与地下水运动过程；
3) 河川径流和洪泛过程；
4) 三维植被冠层辐射传输和冠层能量平衡过程；
5) 山地辐射过程(复杂地形条件下的地面辐射通量计算)；
6) 城市冠层模式(人为热源-能源使用)；
7) 水利工程对河川水文过程的扰动过程模式；
8) 人类活动(人口与经济发展-土地利用) 对陆面物理过程的扰动过程模式。

2、耦合人类活动的陆面生态系统过程建模

1) 植被生理过程与生态过程；
2) 碳、氮、磷为主的营养元素的循环过程；
3) 作物模式(包含人类活动因素)；
4) 植被-环境相互作用过程(包括温室气体排放对陆面过程的扰动过程)；
5) 植被生态与全球植被动力学过程；
6) 大气污染对生态系统过程的影响；
7) 河口-陆架海-大气多界面碳氮循环的动力学过程。

3、高分辨率全球陆面过程模式集成及基础数据集建设

1) 陆面过程分量模式集成；
2) 陆面过程基础数据(全球分辨率为1千米并与陆面模式相匹配)集成；
3) 陆面模式/基础数据的尺度转换方法研究；
4) 全球模式验证资料；
5) 模式整体性能评估平台建设及其应用。

4、高分辨率全球陆面过程模式的多尺度应用示范

1) 陆地表层格局变化综合模拟与预估平台建设及应用；
2) CoLM 与天气模式GRAPES的耦合应用；
3) CoLM 与气候系统模式BCC_CSM的耦合应用；
4) CoLM 与地球系统模式CAS_ESM 的耦合应用。

层结土壤变饱和流数值计算方案

Yongjiu Dai, **Shupeng Zhang**, Hua Yuan, Nan Wei,
Modeling variably saturated flow in stratified soils with explicit tracking of wetting front and water table locations.
Water Resources Research, 55 (2019), 7939-7963.

NOVEMBER, 1931 PHYSICS VOLUME 1

CAPILLARY CONDUCTION OF LIQUIDS THROUGH POROUS MEDIUMS

By L. A. Richards
Cornell University

(Received April 16, 1931)

Abstract

The flow of liquids in unsaturated porous mediums follows the ordinary laws of hydrodynamics, the motion being produced by gravity and the pressure gradient force acting in the liquid. By making use of Darcey's law, that flow is proportional to the forces producing flow, the equation $K\nabla^2\psi+\nabla K\cdot\nabla\psi+g\partial K/\partial z=-\rho_s A\partial\psi/\partial t$ may be derived for the capillary conduction of liquids in porous mediums. It is possible experimentally to determine the capillary potential $\psi=\int dp/\rho$, the capillary conductivity K, which isdefined by the flow equation $q=K(g-\nabla\psi)$, and the capillary capacity A, which is the rate of change of the liquid content of the medium with respect to ψ. These variables are analogous, respectively, to the temperature, thermal conductivity, and thermal capacity in the case of heat flow. Data are presented and application of the equations is made for the capillary conduction of water through soil and clay but the mathematical formulations and the experimental methods developed may be used to express capillary flow for other liquids and mediums. The possible existance of a hysteresis effect between the capillary potential and moisture content of a porous medium is considered.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h(\theta)}{\partial z}-1\right)\right]-S(\theta)$$

自1931年 Richards提出方程，每年有相当数量关于Richards方程的工作发表。

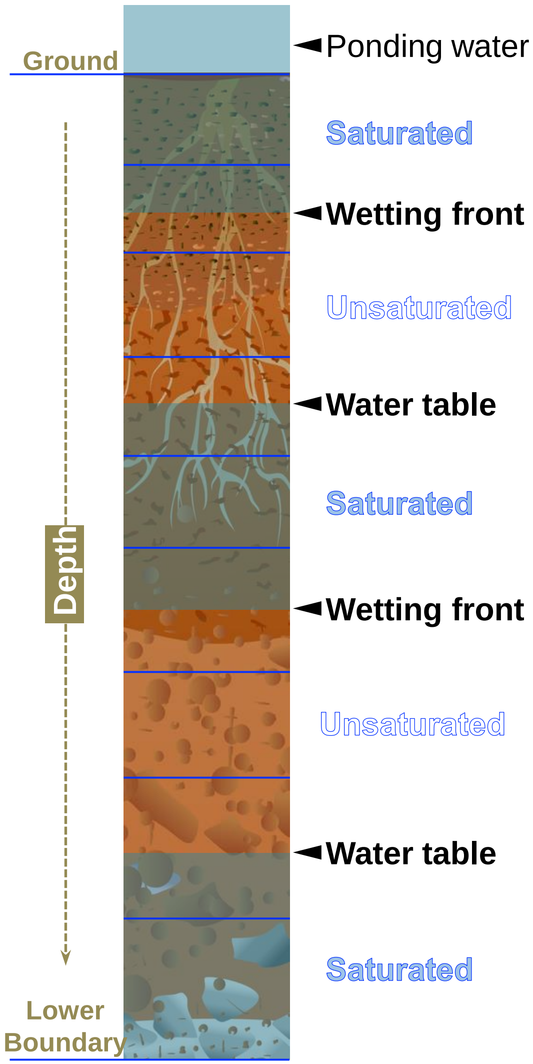
物理和数学上的困难

- 饱和-非饱和区共存，移动边界（湿润锋面和地下水位）
  - 物理上，两个区域内土壤水的运动具有不同的驱动力；
  - 数学上，方程为椭圆-抛物混合型，不能统一求解.
- 很薄的干湿过渡区（湿润锋面和地下水位附近）
  - 由方程本身的非线性造成；
  - 湿润锋面和地下水位可以位于计算分层内的任何位置，用固定分层难以精确追踪.
- 土壤分层
  - 数学上会导致光滑性很差的.

至今尚未有一个完整的、合理的、满足物理守恒性的数值解方案可应用于自然界的复杂土壤条件、极端初值和边值条件的数值计算方案。

Modeling variably saturated flow in stratified soils

Spatial discretization & Prognostic variables



Governing equations

Ponding water

$$\frac{\partial h_{\text{pond}}}{\partial t} = q_{\text{surf}} - q_{\text{infl}}$$

Saturated

$$q(z) = -K_s\left(\frac{\partial h(\theta)}{\partial z} - 1\right)$$

Unsaturated

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\frac{\partial h(\theta)}{\partial z} - 1\right)\right]$$

Wetting front

$$\frac{\partial w_f}{\partial t} = \frac{q_{sat} - q_{wf}}{q_s - q_u}$$

Water table

$$\frac{\partial w_t}{\partial t} = \frac{q_{wt} - q_{sat}}{q_s - q_u}$$

NEW **Explicit tracking of wetting front and water table**

Numerical scheme

Spatial discretization:
Cell-centered approach
➛ Suitable for stratified soil

NEW

Equivalent hydraulic conductivity formula:
Weighted geometric mean
➛ Lead to oscillation free solution

NEW

Time integration:
Mixed implicit-explicit scheme
➛ Stable and mass conserved

Nonlinear least square problem solver:
Gauss-Newton algorithm
➛ Approach quadratic convergence rate

Dai et al., 2019, Water Resource Resear

新方案的数学物理创新

- 基于移动网格的思想，在固定计算分层内增加新的预报变量
  - 追踪**湿润锋面**和**地下水位**
  - 解析很薄的干湿过渡区
- 新的等效导水率计算公式
  - 适应非线性
  - 可导出理论上**无条件稳定**的数值解
- 半隐式时间积分格式
  - 提高**数值稳定性、可靠性、高效性**。
- 采用与自然土壤层结相容的计算分层，在自然土壤层结边界上建立衔接条件
  - 处理**土壤层结边界面的间断性**。

- “一个满足物理守恒的可**显式表达可变饱和流**的土壤水运动方程数值计算方案”
- “可显式追踪**湿润锋面、地下水位**，为高分辨率地球系统模式提供一**完全协调的地表水和地下水**数值计算方案”

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Water Resources Research

RESEARCH ARTICLE
10.1029/2019WR025368

Key Points:
- Locations of water table and wetting front are tracked explicitly in solving Richards' equation
- An equivalent hydraulic conductivity formula, which can yield oscillation-free solution of Richards' equation, is proposed
- A mixed implicit-explicit temporal discretization is adopted to improve the stability and guarantee mass conservation of water

Modeling Variably Saturated Flow in Stratified Soils With Explicit Tracking of Wetting Front and Water Table Locations

Yongjiu Dai[1], Shupeng Zhang[1], Hua Yuan[1], and Nan Wei[1]

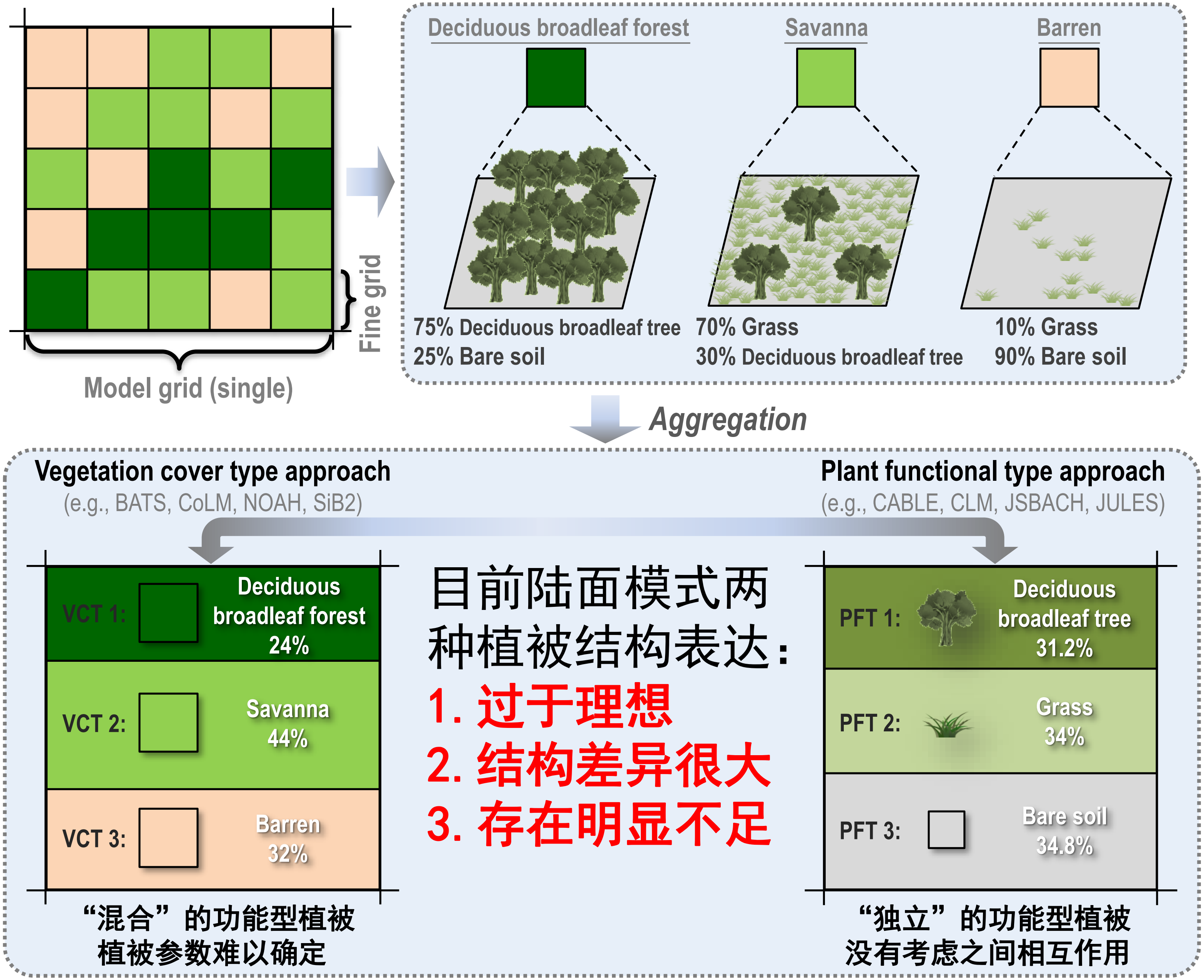
[1]Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, and School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou, China

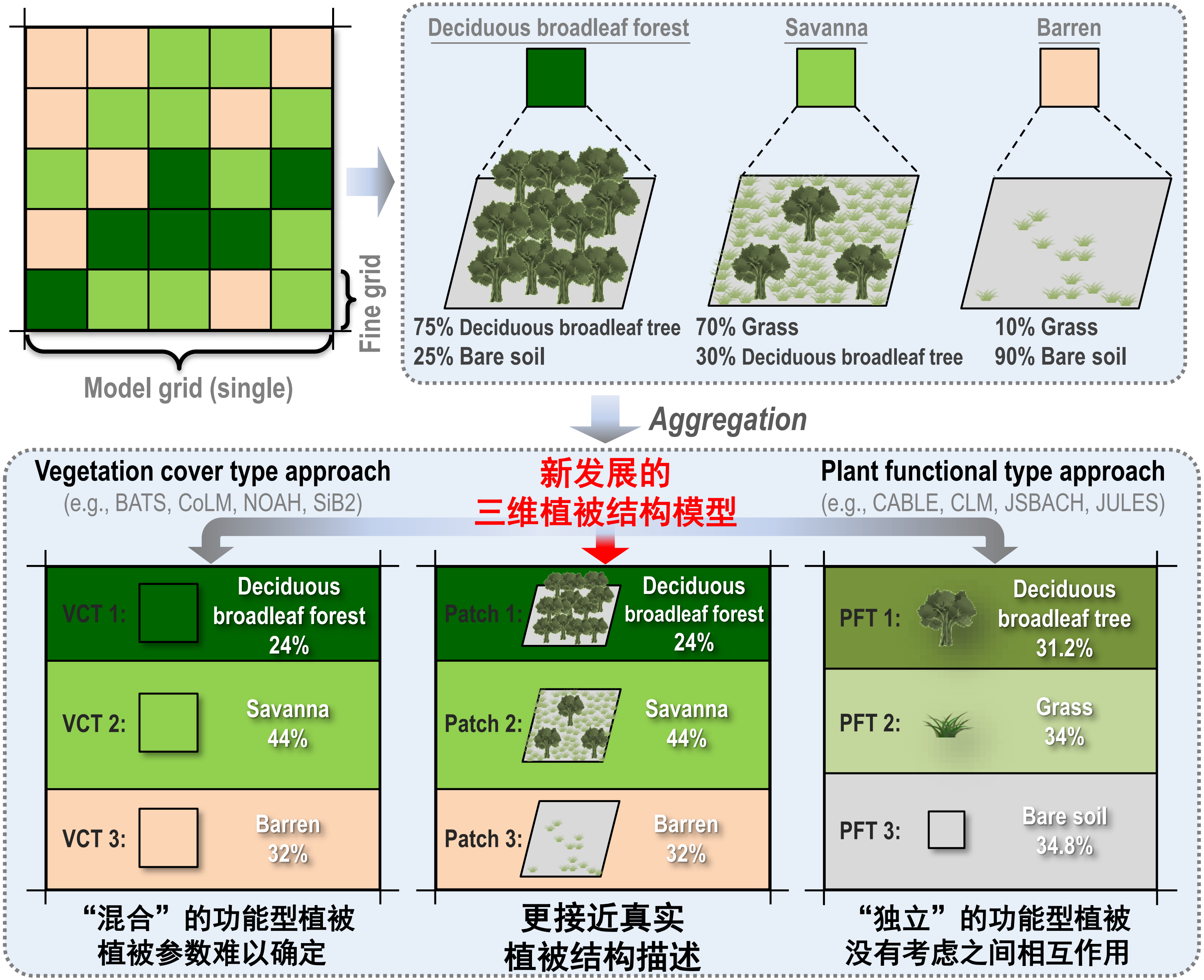
Abstract The locations of wetting front and water table are key variables in an integrated surface-groundwater modeling. In current land surface models, they are either diagnosed from pressure head

三维植被冠层辐射传输和冠层能量平衡过程模式

Yongjiu Dai, **Hua Yuan**, Qinchuan Xin, Dagang Wang, Wei Shangguan, Shupeng Zhang, Shaofeng Liu, Nan Wei, Different representations of canopy structure—a large source of uncertainty in global land surface modeling. ***Agricultural and Forest Meteorology***, 269-270 (2019), 119-135.

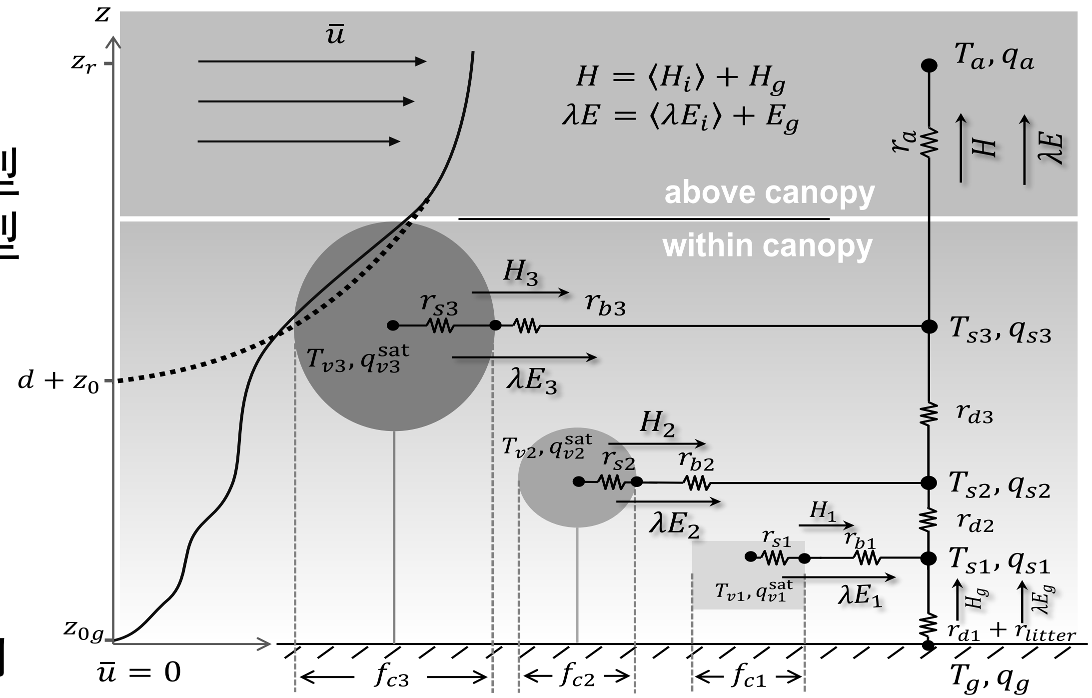
Dai et al., 2-19, AFM

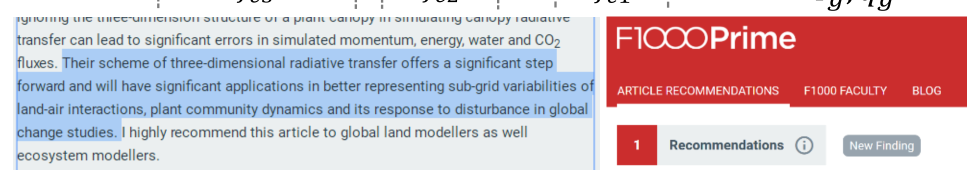



Deciduous broadleaf forest
Savanna
Barren
Fine grid
Model grid (single)
75% Deciduous broadleaf tree
25% Bare soil
70% Grass
30% Deciduous broadleaf tree
10% Grass
90% Bare soil
Aggregation
Vegetation cover type approach
(e.g., BATS, CoLM, NOAH, SiB2)
新发展的
三维植被结构模型
Plant functional type approach
(e.g., CABLE, CLM, JSBACH, JULES)
VCT 1:
Deciduous broadleaf forest 24%
VCT 2:
Savanna 44%
VCT 3:
Barren 32%
Patch 1:
Deciduous broadleaf forest 24%
Patch 2:
Savanna 44%
Patch 3:
Barren 32%
PFT 1:
Deciduous broadleaf tree 31.2%
PFT 2:
Grass 34%
PFT 3:
Bare soil 34.8%
“混合”的功能型植被
植被参数难以确定
更接近真实
植被结构描述
“独立”的功能型植被
没有考虑之间相互作用

三维植被模型

- 植被辐射传输模型 (Yuan et al.,2014; Dai et al, 2019)
  - 三维植被(短波)辐射传输模型
  - 三维植被(长波)辐射传输模型
- 三维植被湍流交换模型 (Dai et al., 2019)
  - 阻抗网络结构
  - 零平面位移高度 (d) 计算
  - 地表粗糙度 (z_{0m}) 计算
  - 风速/湍流交换系数在冠层内的衰减系数 (a) 计算
  - 地表风速廓线($\bar{u}(z)$)计算
  - 地表湍流交换系数廓线($\bar{K}(z)$)计算

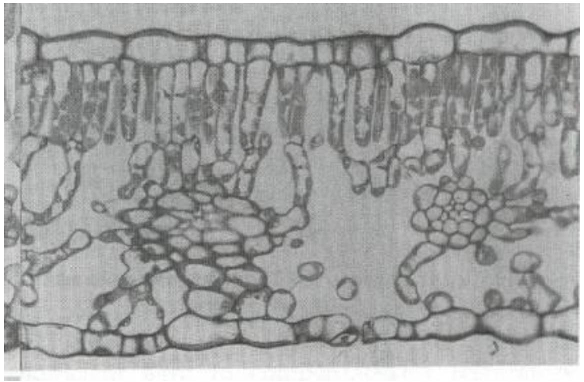




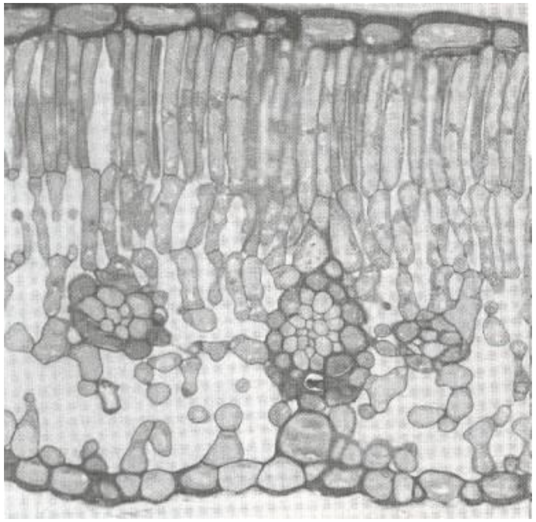
戴永久等建立的植被3D结构表达是显著性的进步，实现了次网格尺度植被过程的3D建模，为陆面模式从基于简约化的功能型为单元的植被动力学模式向基于集合种群为单元的植被种群生态学模式发展奠定了基础。

The F1000Prime Faculty comprises peer-nominated, internationally-renowned researchers from across the world, who pick out and recommend articles they consider to be highly important to others working both in their field and beyond.

植被冠层叶面温度、光合作用、气孔导度



Typical shaded leaf



Typical sunlit leaf

The micrographs of typical shaded and sunlit leaf on the same tree. Sunlit leaf has dense palisade mesophyll, and its spongy mesophyll is in the lower half of the leaf. Shaded leaf has less dense palisade mesophyll and the spongy mesophyll is more extensive.

CO_2 Concentration within Canopy

The CO_2 flux budget within canopy can be described by a CO_2 concentration conservation equation:

$$C_{co2}\frac{\partial c_a}{\partial t} = 0 = -F_c - [A_n]_{j=1} - [A_n]_{j=2} + R_p + R_{soil}$$

R_{soil} = CO_2 flux from soil surface to canopy air;

R_p = non-leaf plant respiration

$[A_n]_j$ = net CO_2 assimilation of canopy by sunlit and shaded leaves:

$$[A_n]_j = \{[g_b]_j \div 1.37\}\{c_a - [c_s]_j\}$$

F_c is the CO_2 flux from canopy to atmosphere

$$F_c = \{g_a \div 1.37\}[c_a - c_m]$$

Photosynthesis capacity of sunlit and shaded leaf fractions

The leaf assimilation rates as the minimum of three limiting rates:

$$A = \min(w_c, w_e, w_s)$$

w_c: Leaf enzyme limitation rate,

$$w_c = \begin{cases} V_m \left[\dfrac{c_i - \Gamma^*}{c_i + K_c(1 + O_2 \div K_o)} \right], \text{ for } c_3 \\ V_m, \text{ for } c_4 \end{cases}$$

w_e: Light-limitation rate,

$$w_e = \begin{cases} j \dfrac{c_i - \Gamma^*}{(c_i + 2\Gamma^*)}, \text{ for } c_3 \text{ plant} \\ j, \text{ for } c_4 \text{ plant} \end{cases}$$

w_s: Capacity for export or utilization of the products of photosynthesis for C_3 plant and CO_2-limited capacity for C4 plants

$$w_s = \begin{cases} 0.5 V_m, \text{ for } c_3 \\ 2 \times 10^4 V_m c_i \div p, \text{ for } c_4 \end{cases}$$

Maximum catalytic capacity of Rubisco V_m:

$$V_{\mathrm{m}} = V_{\max} f_T(T_l) f_w(\theta)$$

$$V_{\max} = V_{\mathrm{cmax}} \exp(-k_n x)$$

V_{cmax} is correlated with leaf nitrogen concentration

Electron transport rate:

$$J = \min\left(\varepsilon I_s,\ J_m \div 4\right)$$

$$J_{\max} = J_{\mathrm{cmax}} \exp(-k_{d,1}^{*} x)$$

J_{cmax} is correlated with leaf nitrogen concentration

The effect of soil water stress on assimilation

$$f_w(\theta) = \sum_{1}^{n} f_{root,j} \left[\frac{\psi_{\max} - \psi_j}{\psi_{\max} - \psi_{fc}} \right]$$

Scaling up from leaf to canopy

Maximum catalytic capacity of Rubisco :

$$V_{cmax}(L) = V_{cmax}(0)\exp(-\, k_N L / L_{AI})$$

$$\begin{cases} V_{cSun} = \int_0^{L_{AI}} V_{cmax}(\xi) f_{Sun}(\xi) d\xi \\ V_{cSha} = \int_0^{L_{AI}} V_{cmax}(\xi) f_{Sha}(\xi) d\xi \end{cases}$$

Maximum electron transport rate :

$$j_{max} = j_{max}(0)\exp(-k_{d,1}^{*}\xi)$$

$$\begin{cases} J_{cSha} = j_{max}(0) \int_0^{L_{AI}} e^{-k_{d,1}^{*}\xi} f_{Sha}(\xi) d\xi \\ J_{cSun} = j_{max}(0) \int_0 e^{-k_{d,1}^{*}\xi} f_{sun}(\xi) d\xi \end{cases}$$

Equations for photosynthesis-stomatal conductance

$$[g_s]_j = m \frac{[A_n]_j}{[c_s]_j} \frac{[e_s]_j}{[e_i]_j} p_s + [b^*]_j$$

$$[A_n]_j = [A]_j - [R_d]_j$$

The complete equation set can be solved to yield mutually consistent values of leaf photosynthesis and transpiration.

Exchange with environmental variables

$$[E_{tr}]_j = [g_b]_j([e_s]_j - e_a)\frac{\rho c_p}{\lambda\gamma} = [g_s]_j([e_i]_j - [e_s]_j)\frac{\rho c_p}{\lambda\gamma}$$

$$[A_n]_j = \frac{c_a - [c_s]_j}{p}\frac{[g_b]_j}{1.4} = \frac{[c_s]_j - [c_i]_j}{p}\frac{[g_s]_j}{1.6}$$

E_a	$= [E_{tr} + E_{wet}]_{sun+sha}$	$+ E_g$		e_a
$F_{co2\ a}$	$= - [A_n]_{sun+sha}$	$+ F_{co2\ soil}$		c_a

陆面基础数据库

Surface Field	Resolution
地形高度(DEM)	30 arc-seconds
√ 全球土壤属性数据集 Global Soil Characteristics	30 arc-seconds
全球土地覆盖/土地利用数据集Global Land Cover Characteristics	30 arc-seconds
√ 全球植被叶面积指数 Global Leaf Area Index	30 arc-seconds
森林高度Global Forest Height	30 arc-seconds
根深度及分布Global Plant Rooting Depth	30 arc-seconds
冰川和冰原Global Glacier Characteristics	30 arc-seconds
湖泊和湿地Global Lakes and Wetlands Characteristics	30 arc-seconds
湖面积和湖深Global Lake Coverage and Lake Depth	30 arc-seconds
耕作Global Cultural Characteristics	30 arc-seconds
灌溉Global Map of Irrigation Areas	30 arc-seconds
城市Global Urban Characteristics	30 arc-seconds
√ 河流Global River Characteristics (flow direction, …)	
……	

- 陆面模式 ＝ 陆面属性数据库 ＋ 陆面模式数学物理 ＋ [陆面状态变量初始值(前处理、数据同化) ＋ 模拟评估(后处理)]。
- 陆面属性数据库建设与物理建模同等重要，属性数据在很大程度上决定于模式模拟性能。
- 陆面属性数据建设是公认的难事和大事，是一项非常费人、费钱、不讨好的工作，通常得不到重视。

地球科学是一门由观测驱动的科学

The global soil data set for earth system modeling

Shangguan et al., **2014**: A Global Soil Data Set for Earth System Modeling. **Journal of Advances in Modeling Earth Systems**, 6: 249-263.

The soil general information (Products 1) :

No.	Description	Units	Binary file	NetCDF file
1	additional property		ADD_PROP	ADD_PROP
2	available water capacity		AWC_CLASS	AWC_CLASS
3	drainage class		DRAINAGE	DRAINAGE
4	impermeable layer		IL	IL
5	nonsoil class		NONSOIL	NONSOIL
6	phase1		PHASE1	PHASE1
7	phase2		PHASE2	PHASE2
8	reference soil depth	cm	REF_DEPTH	REF_DEPTH
9	obstacle to roots		ROOTS	ROOTS
10	soil water regime		SWR	SWR
11	topsoil texture		T_TEXTURE	T_TEXTURE

Soil properties (34) of CoLM/CLM soil horizons (Products 2):

No	Attrubute	units	Scale factor	Binary file	NetCDF file
1	Total carbon	% of weight	0.01	TC	TC1,TC2
2	Organic carbon	% of weight	0.01	OC	OC1,OC2
3	Total N	% of weight	0.01	TN	TN1,TN2
4	Total S	% of weight	0.01	TS	TS1,TS2
5	CaCO3	% of weight	0.01	CACO3	CACO31,CACO32
6	Gypsum	% of weight	0.01	GYP	GYP1,GYP2
7	pH(H2O)		0.1	PHH2O	PHH2O1,PHH2O2
8	pH(KCl)		0.1	PHK	PHK1,PHK2
9	pH(CaCl2)		0.1	PHCA	PHCA1,PHCA2
10	Electrical conductivity	ds/m	0.01	ECE	ECE1,ECE2
11	Exchangeable calcium	cmol/kg	0.01	EXCA	EXCA1,EXCA2
12	Exchangeable magnesium	cmol/kg	0.01	EXMG	EXMG1,EXMG2
13	Exchangeable sodium	cmol/kg	0.01	EXNA	EXNA1,EXNA2
14	Exchangeable potassium	cmol/kg	0.01	EXK	EXK1,EXK2
15	Exchangeable aluminum	cmol/kg	0.01	EXAL	EXAL1,EXAL2
16	Exchangeable acidity	cmol/kg	0.01	EXH	EXH1,EXH2

No.	Attrubute	units	Scale factor	Binary file	NetCDF file
17	Cation exchange capacity	cmol/kg	0.01	CEC	CEC1,CEC2
18	Base saturation	%		BS	BS1,BS2
19	Sand content	% of weight		SAND	SAND1,SAND2
20	Silt content	% of weight		SILT	SILT1,SILT2
21	Clay content	% of weight		CLAY	CLAY1,CLAY2
22	Gravel content	% of volume		GRAV	GRAV1,GRAV2
23	Bulk density	g/cm3	0.01	BD	BD1,BD2
24	Volumetric water content at -10 kPa	% of volume		VMC1	VMC11,VMC12
25	Volumetric water content at -33 kPa	% of volume		VMC2	VMC21,VMC22
26	Volumetric water content at -1500 kPa	% of volume		VMC3	VMC31,VMC32
27	Amount of phosphorous using the Bray1 method	ppm of weight	0.01	PBR	PBR1,PBR2
28	Amount of phosphorous by Olsen method	ppm of weight	0.01	POL	POL1,POL2
29	Phosphorous retention by New Zealand method	% of weight	0.01	PNZ	PNZ1,PNZ2
30	Amount of water soluble phosphorous	ppm of weight	0.0001	PHO	PHO1,PHO2
31	Amount of phosphorous by Mehlich method	ppm of weight	0.01	PMEH	PMEH1,PMEH2
32	Exchangeable sodium percentage	% of weight	0.01	ESP	ESP1,ESP2
33	Total phosphorus	% of weight	0.0001	TP	TP1,TP2
34	Total potassium	% of weight	0.01	TK	TK1,TK2

The global depth to bedrock dataset for Earth System Modeling

Shangguan et al., 2017. Mapping the global depth to bedrock for land surface modeling. **Journal of Advances in Modeling Earth Systems,** 9, doi:10.1002/2016MS000686.

The global high-resolution dataset of soil hydraulic and thermal properties for land surface modeling

Dai et al., 2019: A global high-resolution dataset of soil hydraulic and thermal properties for land surface modeling, Journal of Advances in Modeling Earth Systems.

Dai et al., 2019: Evaluation of soil thermal conductivity schemes for use in land surface modelling. Journal of Advances in Modeling Earth Systems.

Status of soil hydraulic parameters and soil data in land surface models

- The soil water contents are calculated numerically using the Richards equation,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h(\theta)}{\partial z} - 1\right)\right] - S(\theta)$$

- Clapp and Hornberger (1978) functions have been widely used in land surface schemes for climate/weather models:

$$\psi = \psi_s(\theta / \theta_s)^{-1/\lambda}$$

$$K(\theta) = K_s(\theta / \theta_s)^{(3+2/\lambda)}$$

- Four parameters are required:

K_s = saturated hydraulic conductivity (cm/d)

θ_s = saturated water content (cm3/cm3)

ψ_s = saturated capillary potential (cm)

λ = pore-size distribution index

Status of soil thermal parameters and soil data in land surface models

- The soil temperatures are calculated numerically using the equation,

$$c\frac{\partial T}{\partial t} = -\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + S_h$$

- The volumetric soil heat capacity and thermal conductivity have been widely used in land surface :

$$c = c_s + v_{air}c_{air} + v_{water}c_{water} + v_{ice}c_{ice}$$

$$k = \left(k_{sat} - k_{dry}\right)K_e + k_{dry}$$

- Three parameters are required:

c_s the volumetric eat capacity of soil solids in a unit soil volum

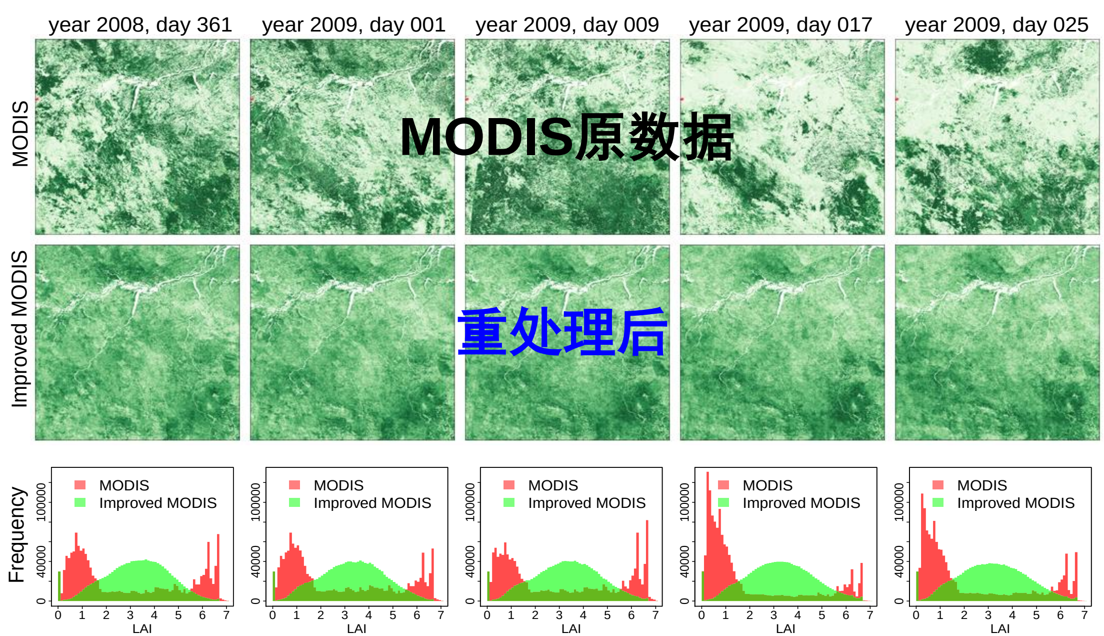
k_{sat} the saturated thermal conductivities

k_{dry} the dry thermal conductivities

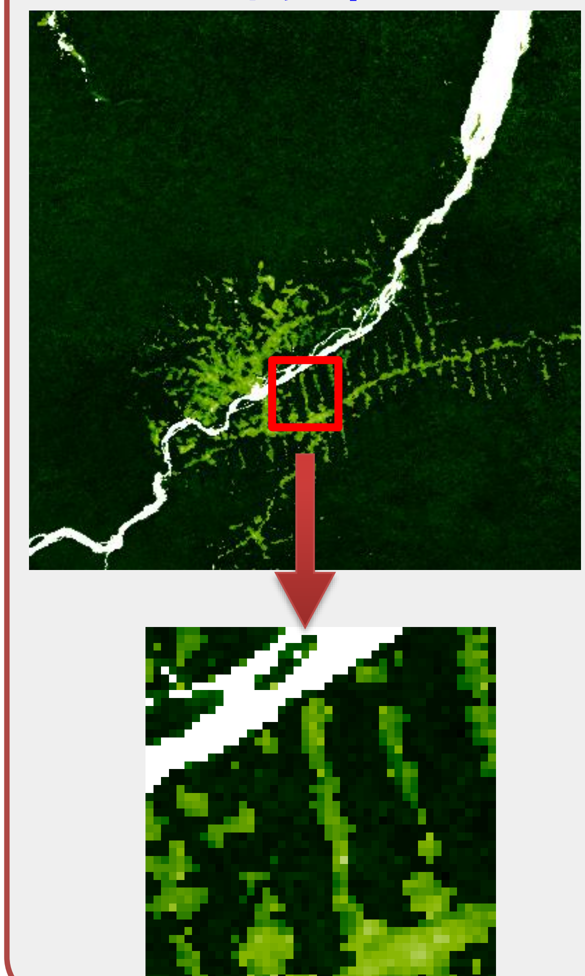
全球高分辨率叶面积指数数据集

构建了相互协调的滤波算法和订正方法，解决了MODIS原数据由于云、季节性雪盖、反演算法的不确定性等所导致的时空不连续和不一致性问题，建立了可直接为全球模式所用的、高分辨率的全球 LAI（2000-2018年）数据集。

处理结果：时空比较



时空更连续
细节更丰富



The data could be freely downloaded from http://globalchange.bnu.edu.cn

1. The Global Dataset of Soil Hydraulic and Thermal Parameters for Earth System Modeling

2. The Global Depth to Bedrock Dataset for Earth System Modeling

3. The Global Soil Dataset for Earth System Modeling

4. The Soil Database of China for Land Surface Modeling

5. The China Dataset of Soil Hydraulic Parameters Using Pedotransfer Functions for Land Surface Modeling

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A global soil data set for earth system modeling

Wei Shangguan, Yongjiu Dai, Qingyun Duan, Baoyuan Liu, Hua Yuan

Journal of Advances in Modeling Earth Systems | Pages: 249-263 |
First Published: 14 February 2014

- A global soil data set was developed for earth system modeling
- Various data sources were harmonized using consistent processes
- Examples of the data set were given show the vertical and horizontal variations

Abstract | Full text | PDF | References | Request permissions

Open Access

Mapping the global depth to bedrock for land surface modeling

Wei Shangguan, Tomislav Hengl, Jorge Mendes de Jesus, Hua Yuan, Yongjiu Dai

Journal of Advances in Modeling Earth Systems | Pages: 65-88 |
First Published: 20 December 2016

- Observations from soil and geological surveys are combined for developing global spatial prediction models of depth to bedrock
- Machine learning explains 59% of variation in spatial distribution of depth to bedrock for interpolation but much less for extrapolation

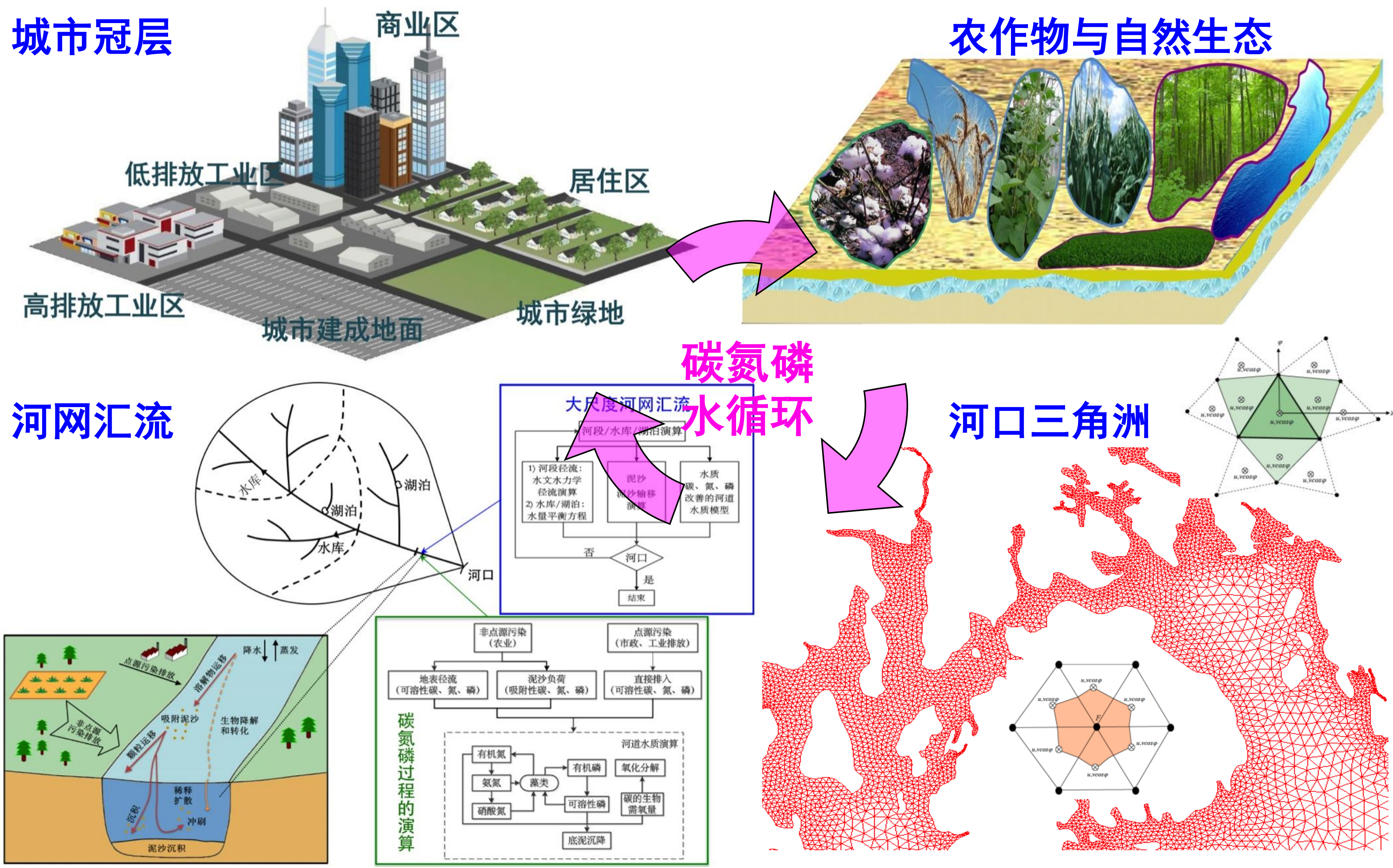
国内主要机构采用

- 中国科学院地球系统模式 (CAS-ESM)。
- 中国气象局 中短期全球天气数值模拟系统 (GRAPES)。
- 北京师范大学地球系统模式 (BNU-ESM)。
- 中国气象局 国家气候中心 气候系统模式 **(部分采用)**。
- 中国气象科学研究院气候系统模式。
- 中山大学地球系统模式。
- 。。。。。。

创建中国特色精细化区域地球系统模式

扩展耦合器CPL7，攻克多尺度、多界面、多圈层耦合技术

刻画人类-自然相互作用



模式的“中国特色精细化”主要体现

气象高质量发展纲要（2022—2035年）

（二）**发展目标：**到2025年，气象关键核心技术实现自主可控。到2035年，气象关键科技领域实现重大突破，气象监测、预报和服务水平全球领先。

（六）**建设精密气象监测系统。**

（七）**构建精准气象预报系统。**加强地球系统数值预报中心能力建设，发展自主可控的地球系统数值预报模式，逐步形成“五个1”的精准预报能力，实现**提前1小时预警局地强天气、提前1天预报逐小时天气、提前1周预报灾害性天气、提前1月预报重大天气过程、提前1年预测全球气候异常**。

（八）**发展精细气象服务系统。**

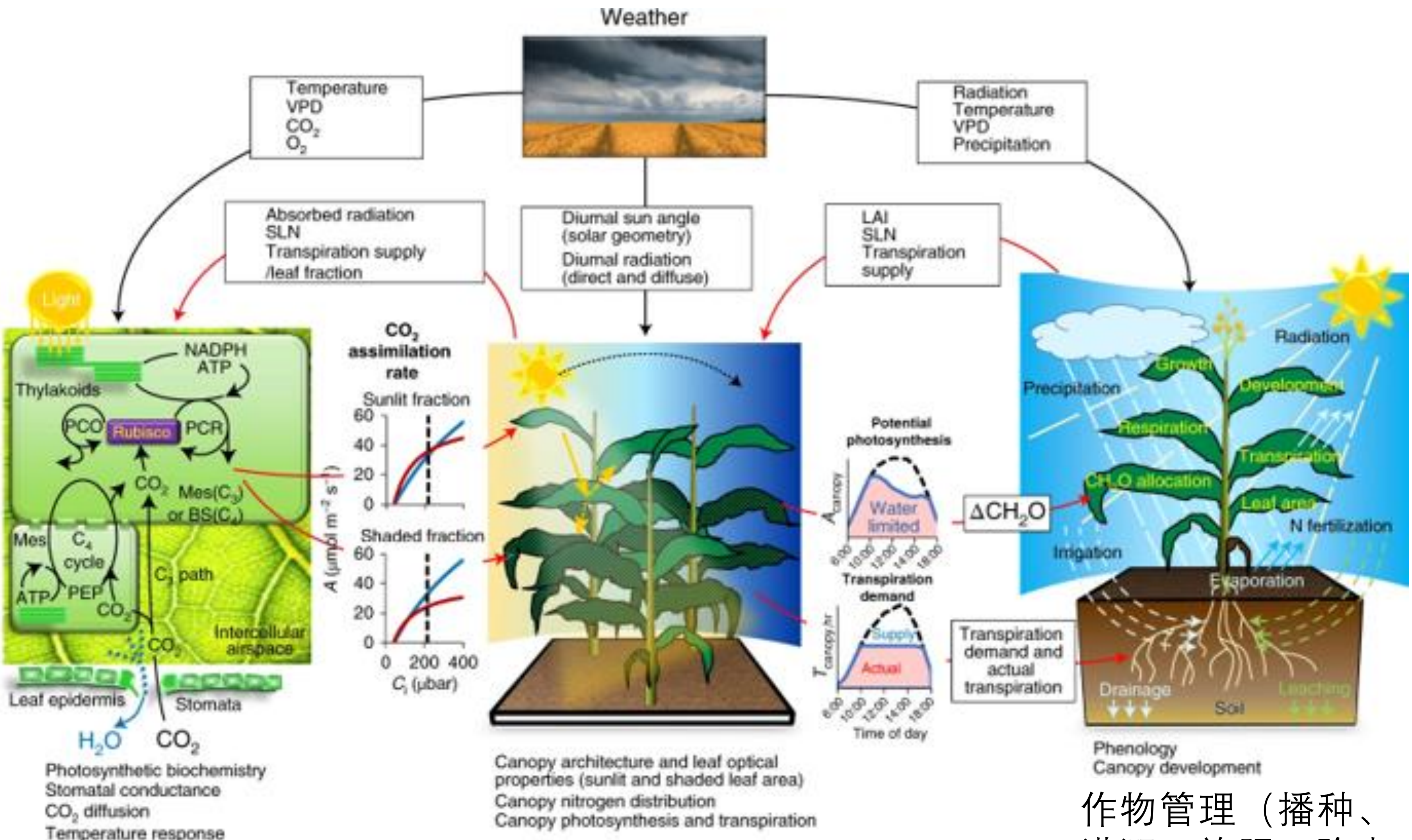
（十四）**实施气象为农服务提质增效行动。**

（二十四）**强化生态系统保护和修复气象保障。**

（十四）实施气象为农服务提质增效行动。提升粮食生产全过程气象灾害精细化预报能力和粮食产量预报能力。建立全球粮食安全气象风险监测预警系统。实现面向新型农业经营主体的直通式气象服务全覆盖。充分利用气候条件指导农业生产和农业结构调整。

（二十四）强化生态系统保护和修复气象保障。实施生态气象保障工程，加强重要生态系统保护和修复重大工程建设、生态保护红线管控、生态文明建设目标评价考核等气象服务。

挑战性工作（一）：作物模式



作物管理（播种、灌溉、施肥、除虫、除草、收割等农业生产活动）

叶子光合、呼吸等植物生理过程

植株光合、呼吸等植物生理过程

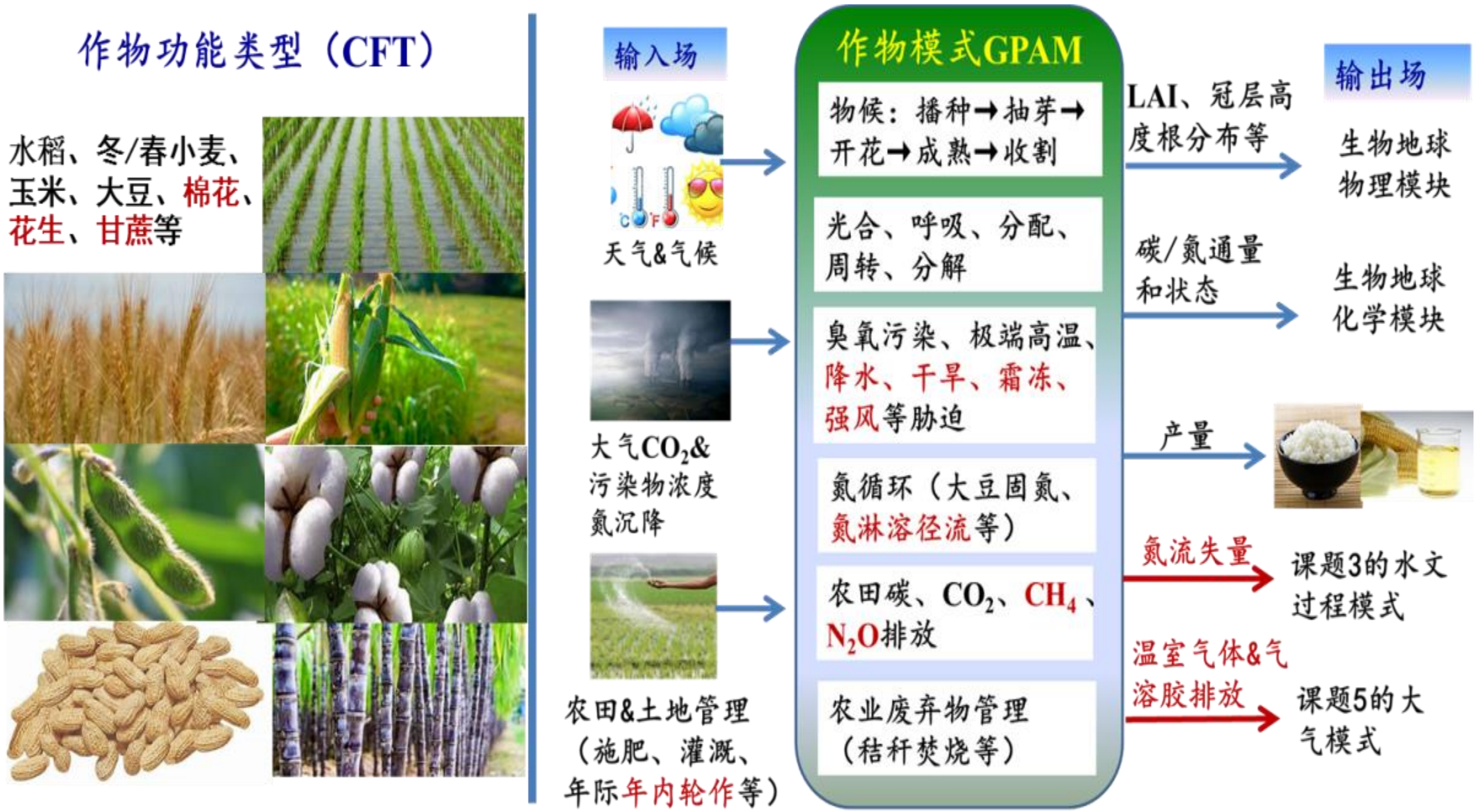

作物功能类型（CFT）
水稻、冬/春小麦、玉米、大豆、棉花、花生、甘蔗等
输入场
天气&气候
大气CO_2&污染物浓度氮沉降
农田&土地管理（施肥、灌溉、年际年内轮作等）
作物模式GPAM
物候：播种→抽芽→开花→成熟→收割
光合、呼吸、分配、周转、分解
臭氧污染、极端高温、降水、干旱、霜冻、强风等胁迫
氮循环（大豆固氮、氮淋溶径流等）
农田碳、CO_2、CH_4、N_2O排放
农业废弃物管理（秸秆焚烧等）
LAI、冠层高度根分布等
碳/氮通量和状态
产量
氮流失量
温室气体&气溶胶排放
输出场
生物地球物理模块
生物地球化学模块
课题3的水文过程模式
课题5的大气模式

ILLUSTRATION BY PAWEL JOŃCA

HEALTHY DIETS FOR PEOPLE AND THE PLANET

Fruit & Vegetable Supply Chains

Climate Adaptation & Mitigation Opportunities

Enhancing the productivity, resilience, and sustainability of domestic fruit and vegetable systems

Objectives

- Identify and test climate adaptation and mitigation intervention strategies that can be applied to enhance sustainability and resilience of fruit and vegetable supply chains in the United States.
- Provide actionable strategies that contribute to a nutritious, reliable, affordable, and environmentally sound food supply.

Desired Impact

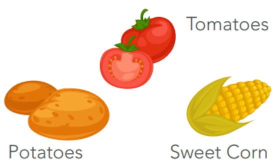
- Supply decision makers, growers, and other stakeholders in fruit and vegetable supply chains with science-based evidence to adapt to climate change impacts and mitigate greenhouse gas emissions.
- Sustainably deliver the nutritional value associated with greater consumption of fruits and vegetables, which is central to improving diets and combatting obesity in the United States.

Approach

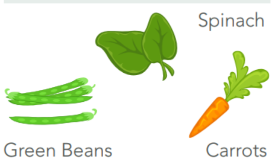
- Use crop, economic, and environmental modeling to determine current and future climate and water availability impacts on selected fruit and vegetable crops.
- Investigate mitigation strategies and land use change that may result from future relocation of crops from water-stressed areas to new regions.

Crop Prioritization

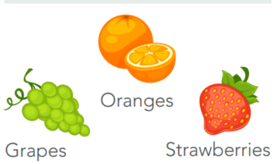
Year 1



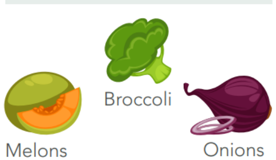
Year 2



Year 3

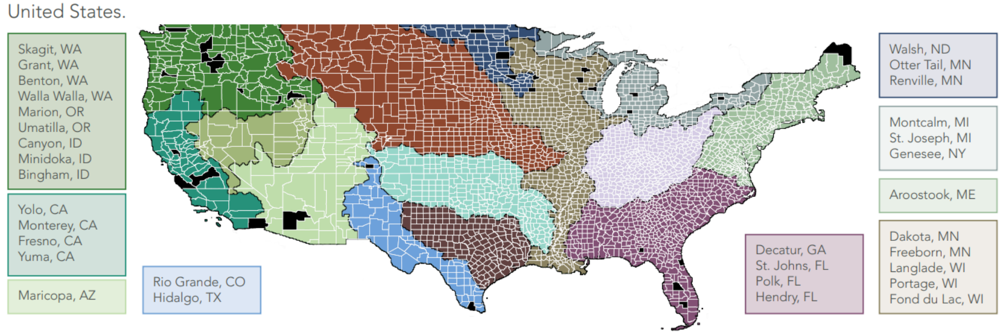


Year 4



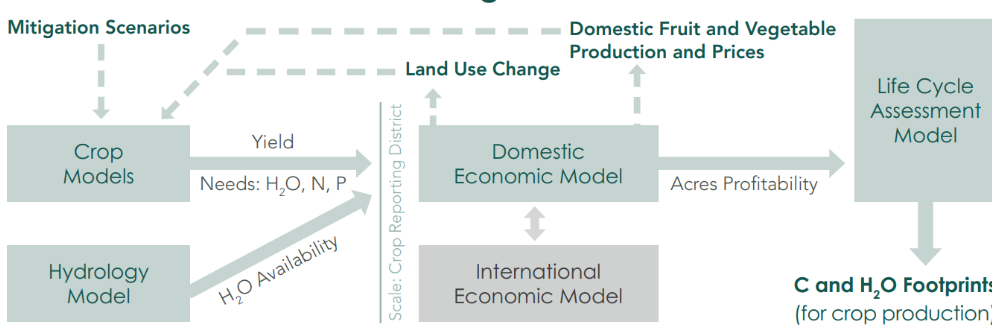
Crop Modeling Counties

The 32 crop modeling counties chosen for the project are located in 9 of the 14 major watersheds of the contiguous United States.



These are the highest target crop acreage counties in the 31 crop reporting districts that collectively include 80% of the area in the United States where the target crops are planted (St. Johns, FL added to better represent potatoes).

Modeling Workflow

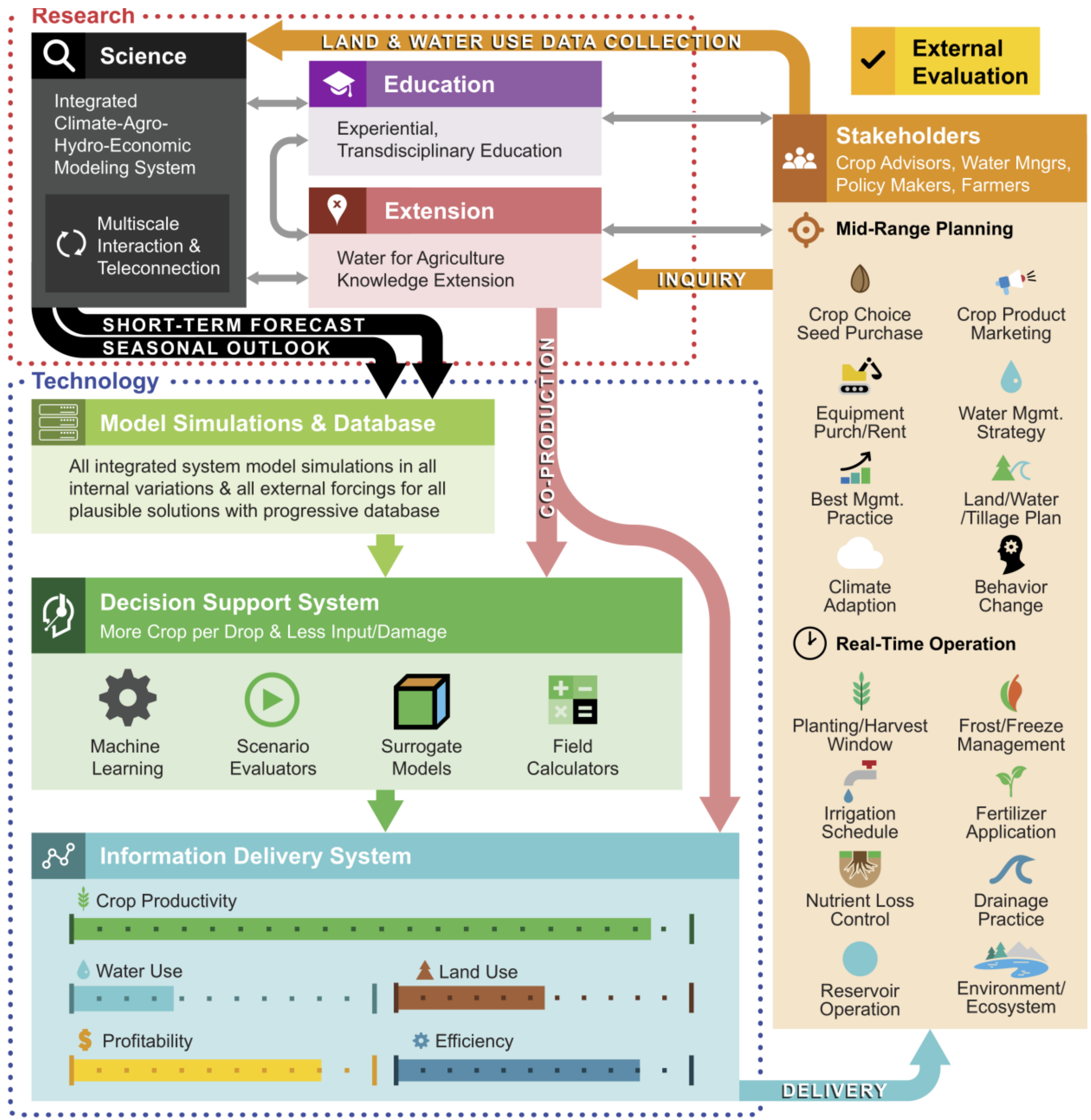


USDA/NIFA Award No. 2017-68002-26789

www.foodsystems.org/fv

气候-农业-水文-经济综合模拟系统

创建一个综合模拟与应用平台。结合先进的科学和创新技术，为农业生产者和水资源管理者提供可信、有用的信息，以改善多个系统和规模的土地、水和肥料使用协同效应。



挑战性工作（二）：城市及道路模式

目前城市模型发展存在的不足

城市模型经过半个多世纪以来的发展，已取得了相当的进步。但其发展还有很大的空间，存在以下不足：

① 目前的城市过程模型几乎都是基于街谷假设，不能很好地描述城市结构特征；

② 植被在城市模型中的生物物理过程表达还不完整；

③ 高分辨率城市相关遥感数据并没有得到充分的利用。

精细化的城市及道路模式

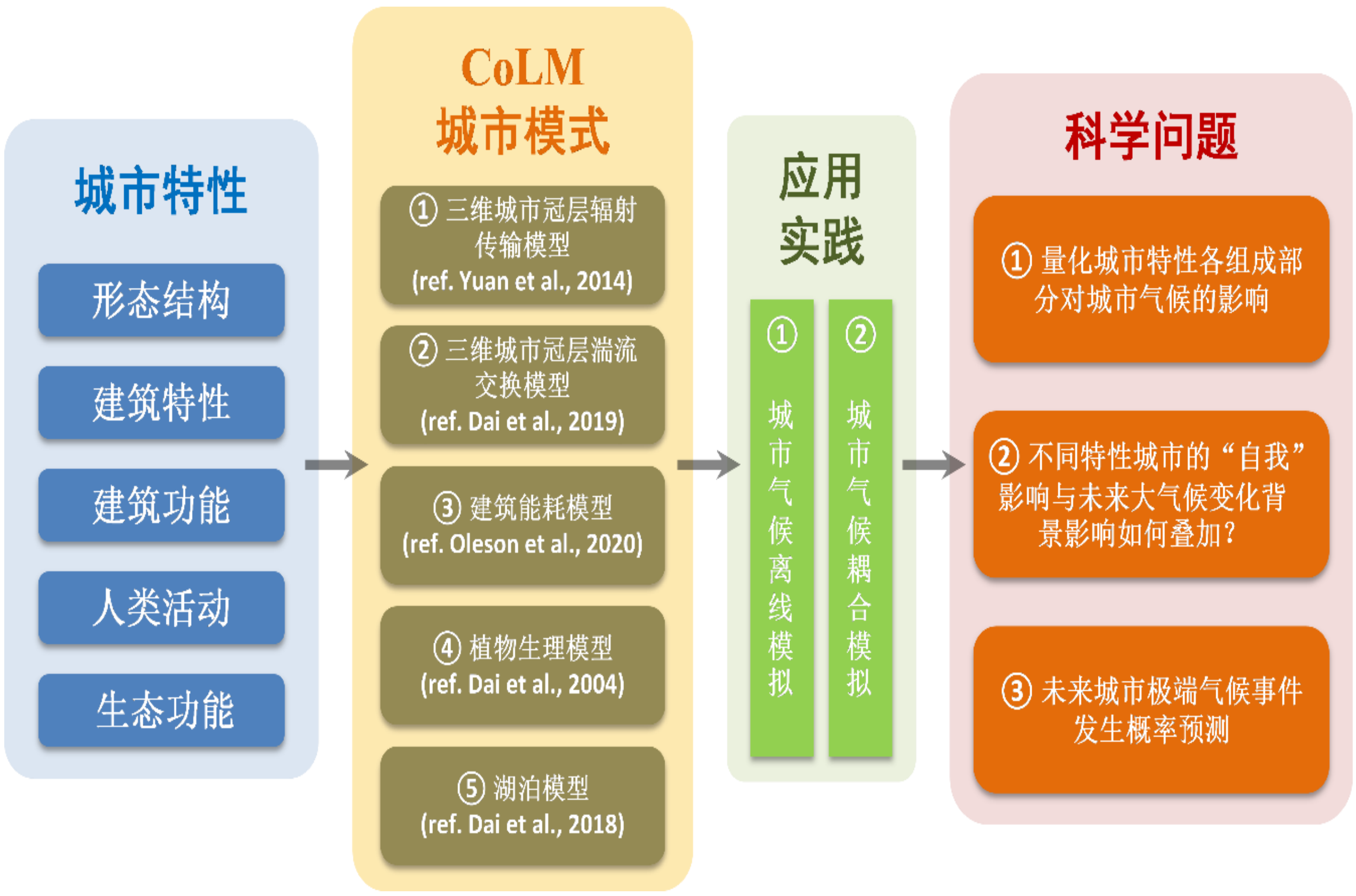
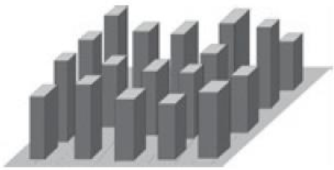
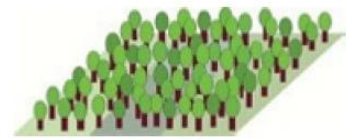
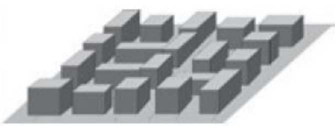
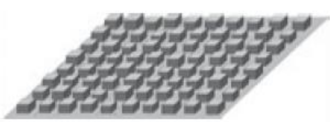
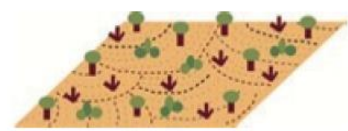


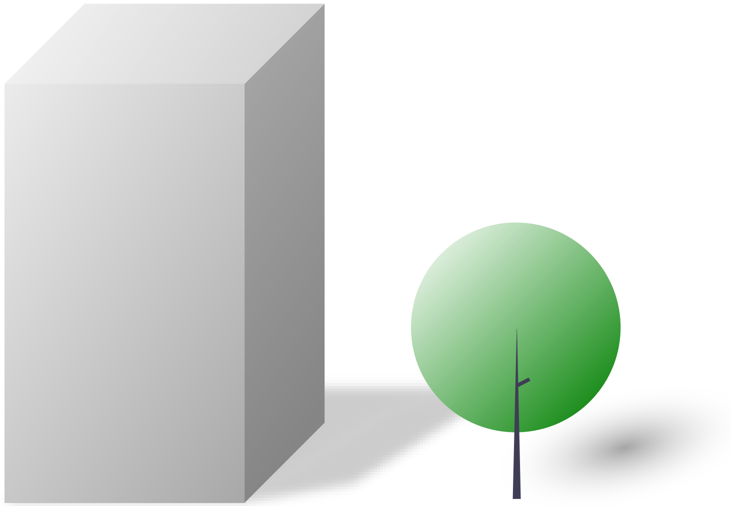
Table 2. Abridged definitions for local climate zones (see electronic supplement for photographs, surface property values, and full definitions). LCZs 1–9 correspond to Oke's (2004) urban climate zones.

Built types	Definition	Land cover types	Definition
1. Compact high-rise 	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees 	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise 	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees 	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise 	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub 	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise 	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants 	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise 	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved 	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.

辐射传输方案简介

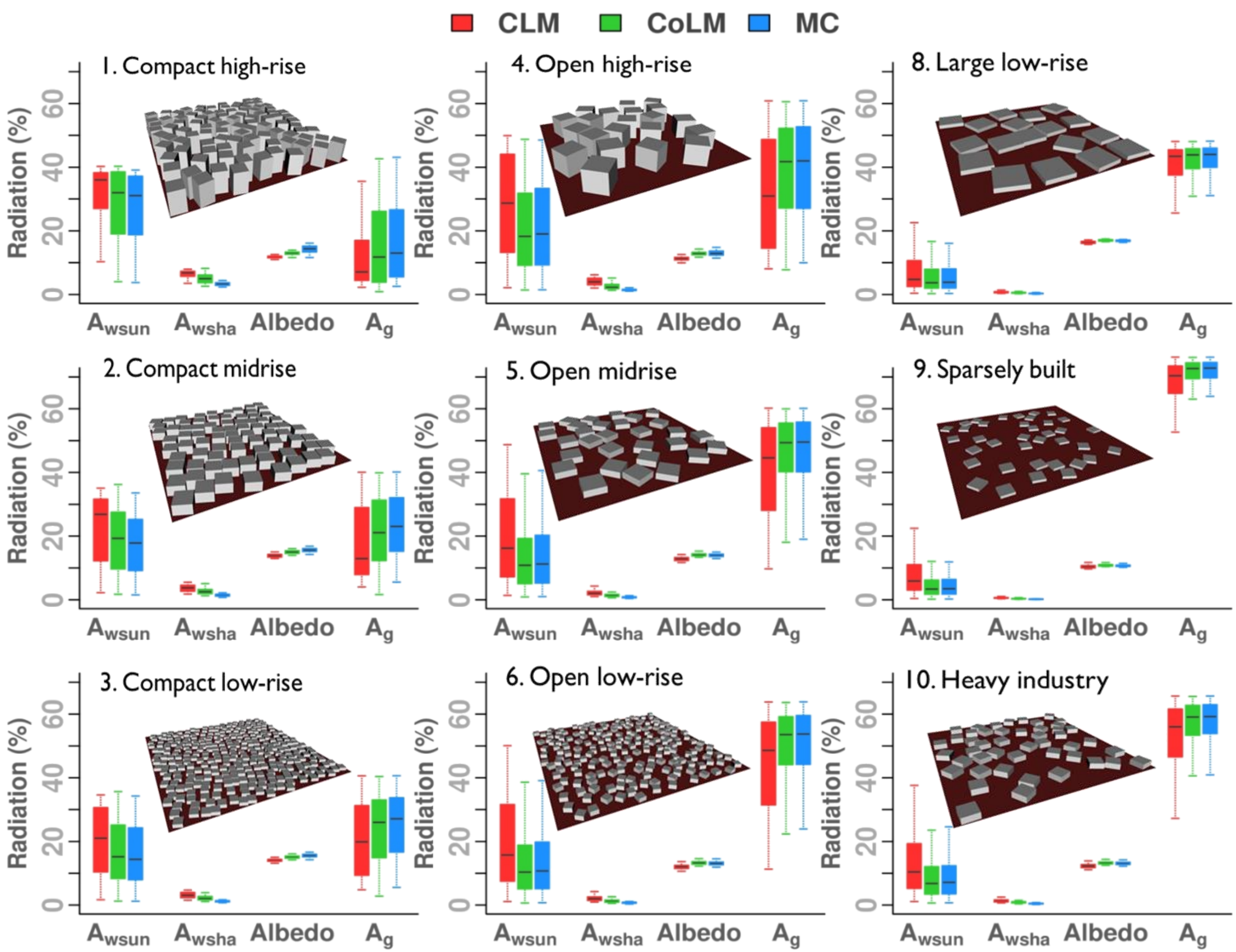
基于Yuan et al., 2014三维植被辐射传输模型：

- 参数设计：
  - 建筑物覆盖度f_b
  - 地面(透水、不透水面)覆盖度f_g
  - 建筑物高度H
  - 建筑物高度:平均地面宽度 H/W
  - 植被冠层中心高度h，叶面积指数LAI



- 计算过程：
  - 计算单个建筑物阴影面积
  - 考虑多个建筑物(覆盖率$\boldsymbol{f_b}$)互相遮挡时阴影面积
  - 考虑建筑物与植被冠层($\boldsymbol{f_t}$)的相互遮挡
  - 计算天空、建筑物墙面、植被、地面之间可视因子
  - 建立辐射传输矩阵，求解辐射平衡方程

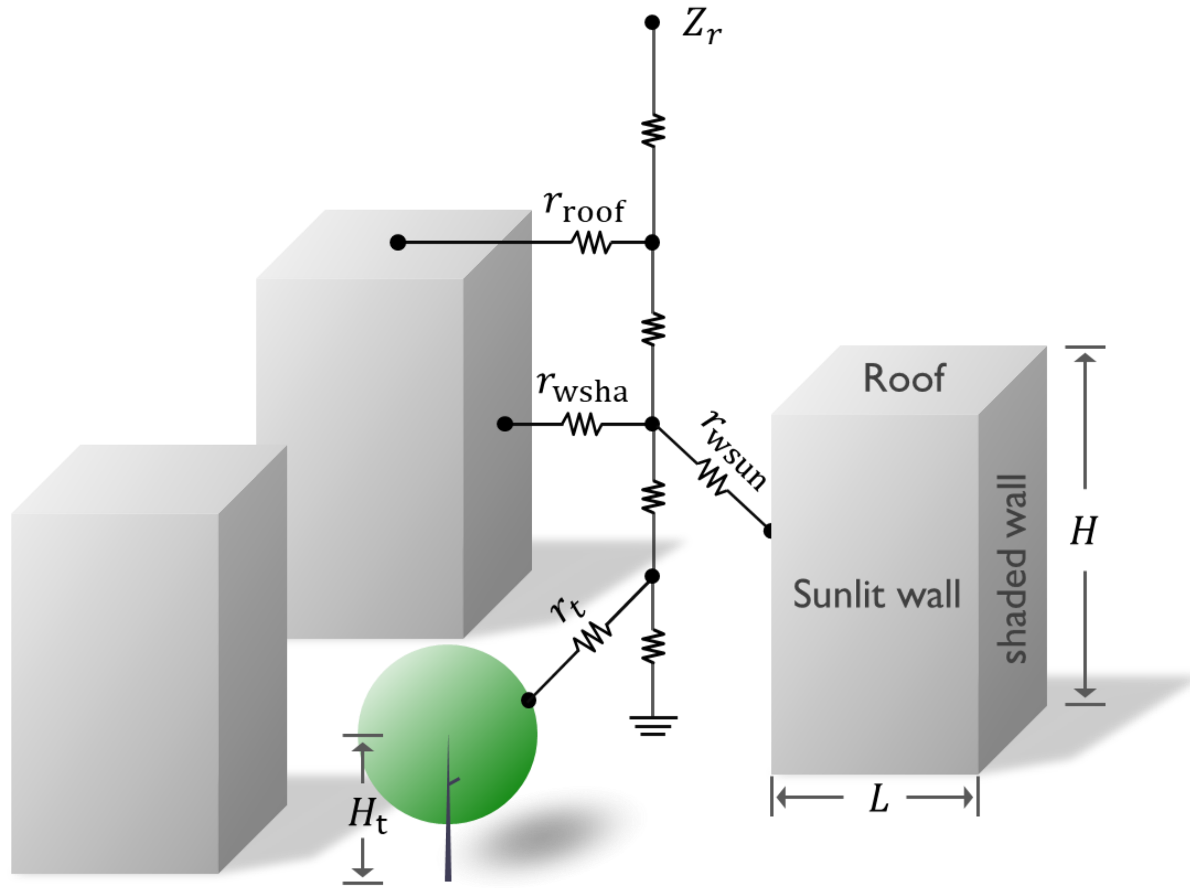
直射光入射时比较验证



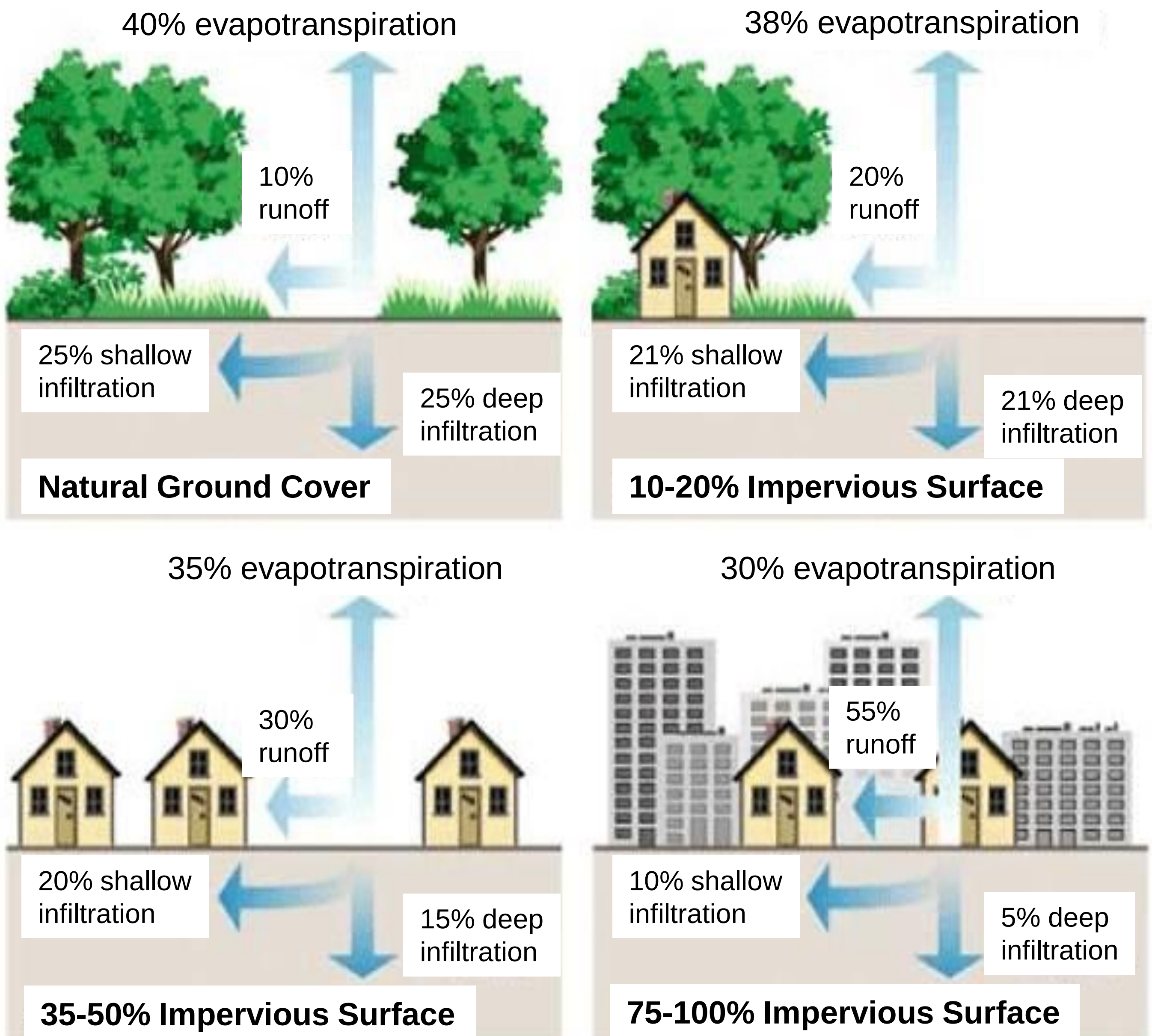
A_{wsun}: 阳面墙吸收 A_{wsha}: 阴面墙吸收 Albedo: 城市反照率 A_g: 地面吸收

湍流交换方案简介

基于CoLM植被湍流交换方案、Dai et al., 2019三维植被湍流交换方案，建立植被、建筑物墙面、建筑物屋顶三层等效交换阻抗网络。



城市水文过程



40% evapotranspiration
10% runoff
25% shallow infiltration
25% deep infiltration
Natural Ground Cover
38% evapotranspiration
20% runoff
21% shallow infiltration
21% deep infiltration
10-20% Impervious Surface
35% evapotranspiration
30% runoff
20% shallow infiltration
15% deep infiltration
35-50% Impervious Surface
30% evapotranspiration
55% runoff
10% shallow infiltration
5% deep infiltration
75-100% Impervious Surface

挑战性工作（三）：
耦合人类活动(包括水库、调水、农田灌溉、工业用水和生活用水等)的水文过程模式

■ To solve the 1-D St. Venant equation for momentum conservation for flow in natural rivers:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\partial}{\partial x}(h+z) + \frac{gn^2|Q|Q}{R^{4/3}A} = 0$$

local acceleration | advection | pressure and bed gradients | friction slope

- Q is the river discharge, A is the flow crosssection area, h is the flow depth, z is the bed elevation, R is the hydraulic radius, g is acceleration due to gravity, and n is the Manning’s friction coefficient. The parameters x and t are the flow distance and time.
- The friction slope is given by the Manning’s coefficient in equation.

参数: 1) 每一网格的下游网格, 2) 流域单元面积, 3) 河床高程, 4) 河道长度, 5) 河道深度, 6) 河道宽度, 7) 下游距离 , 8) 洪泛平原高程。

输出变量：1）河流流量，2）河流蓄水量，3）河水深度，4）河水流速，5）河水漫滩流量，6）漫滩水量，7）洪泛水深，8）洪泛面积，9）洪泛比例, 10）水面高程，11）总流量，12）总蓄水量。

河道径流模式

高精度的地形数据 → 河道建模

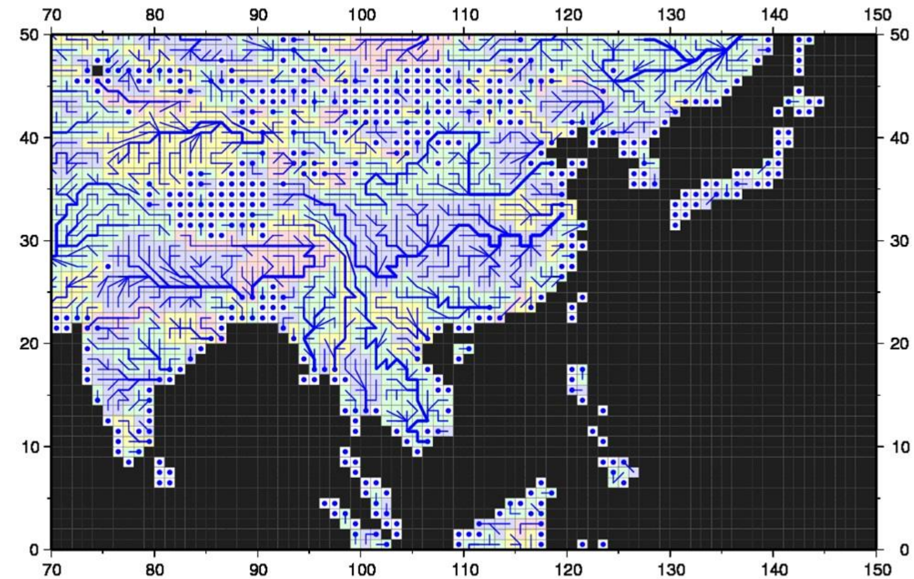
- 河道长度
- 河道宽度
- 河床高度
- 河岸高度
- ……

→ 求解 **扩散波方程**

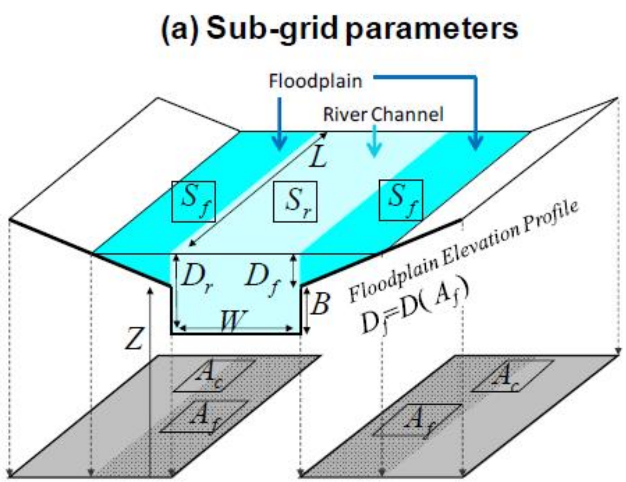
$$\frac{\partial h}{\partial t} = -\frac{1}{w}\frac{\partial}{\partial l}(vwh) + R$$

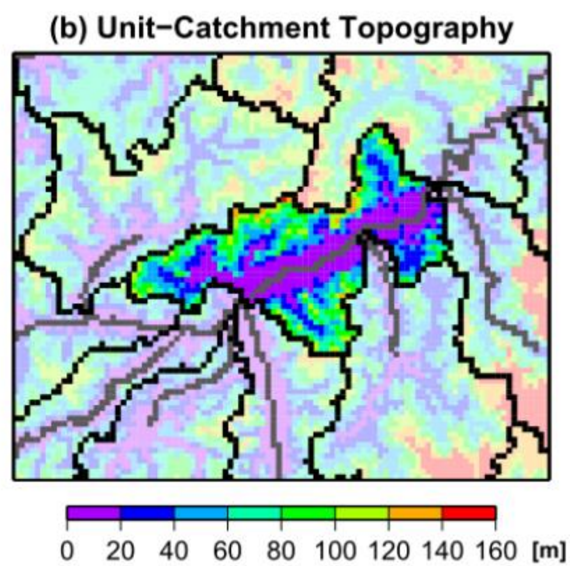
$$\frac{\partial h}{\partial l} = S_0 - S_f$$

$$v = -\frac{1}{n} h^{2/3}\sqrt{S_f}$$

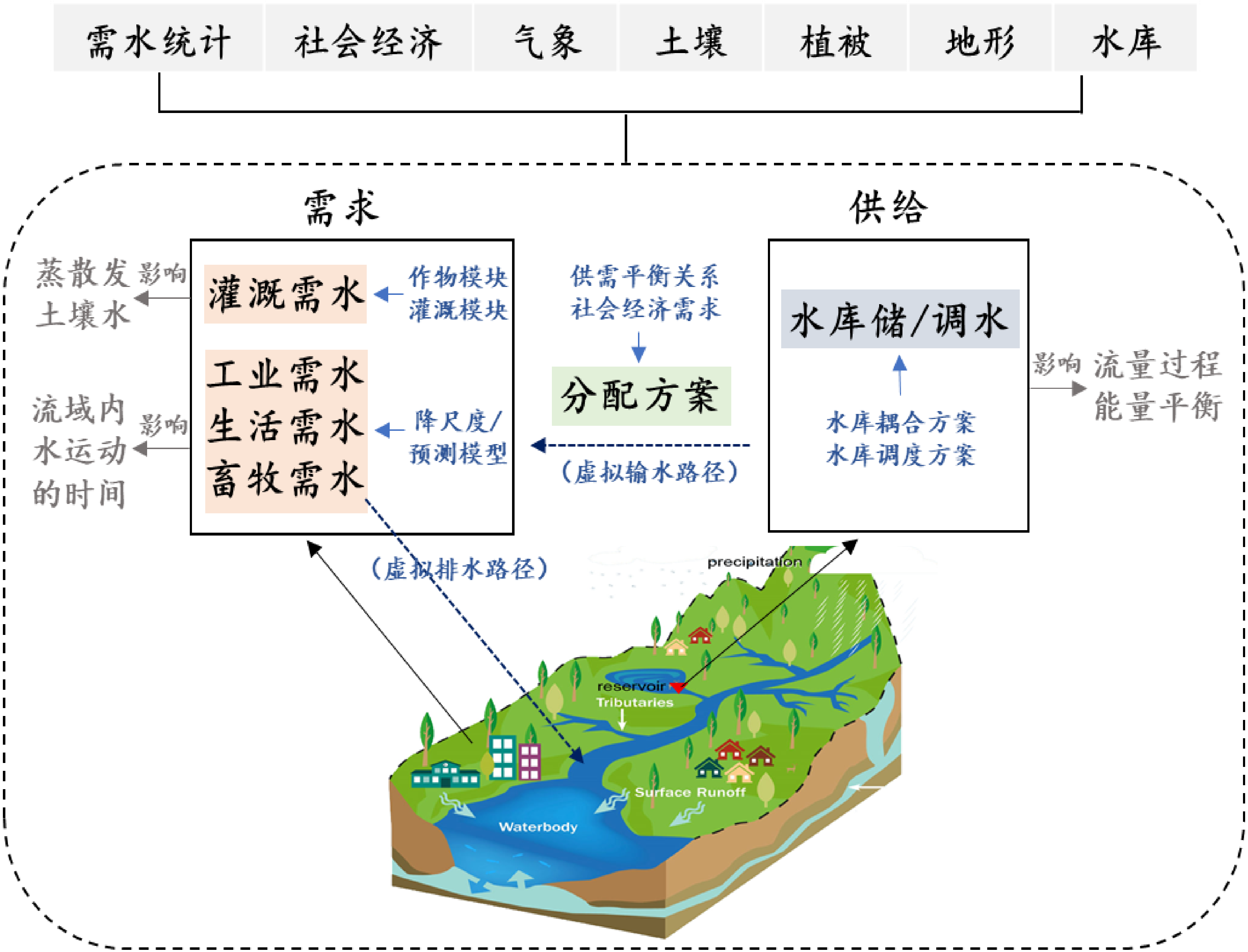


CaMa-Flood的河道网络

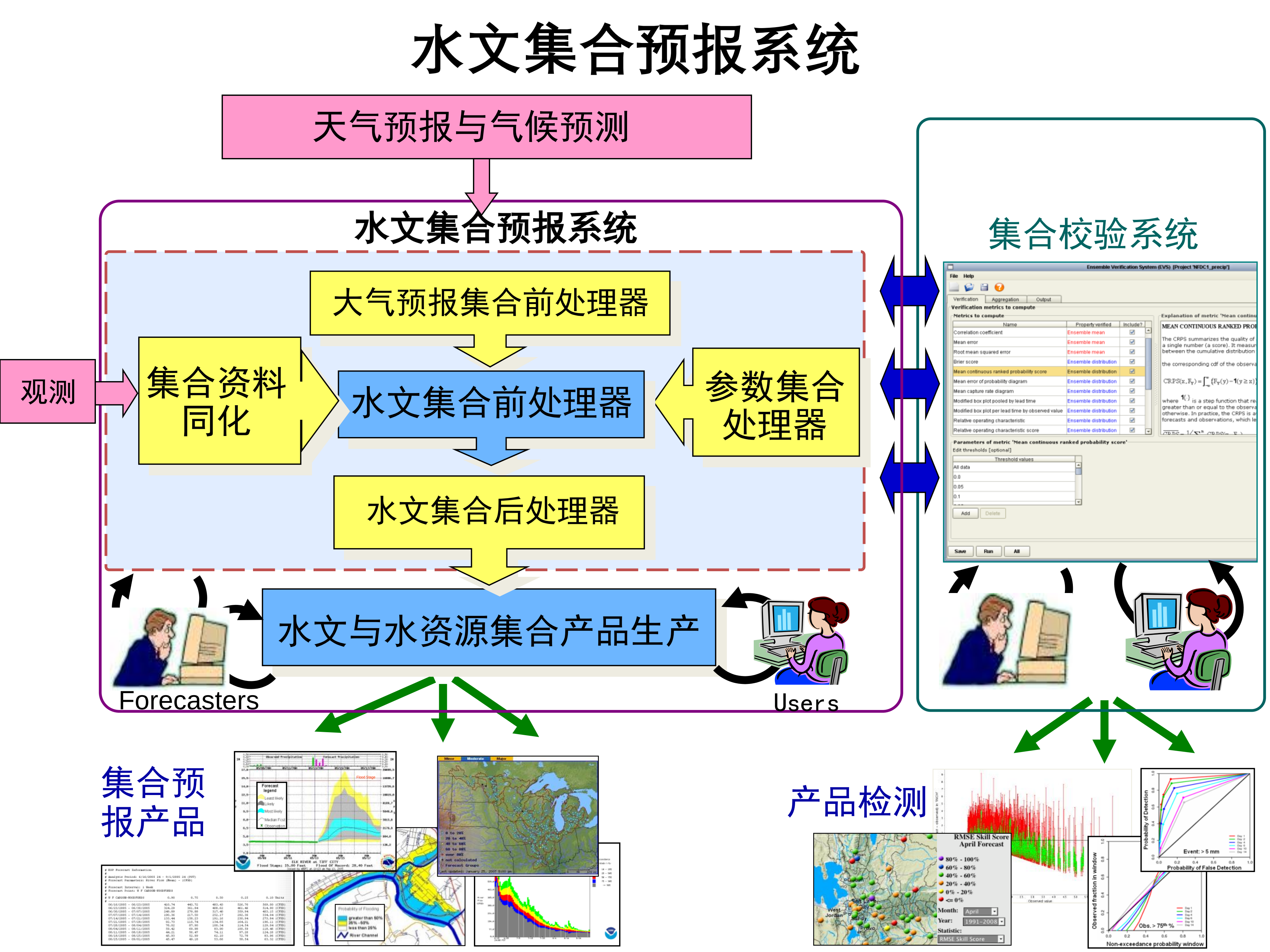




实现CoLM与CaMa-Flood河道模式的耦合，实现河道与地表径流、河道与地下水的双向耦合。

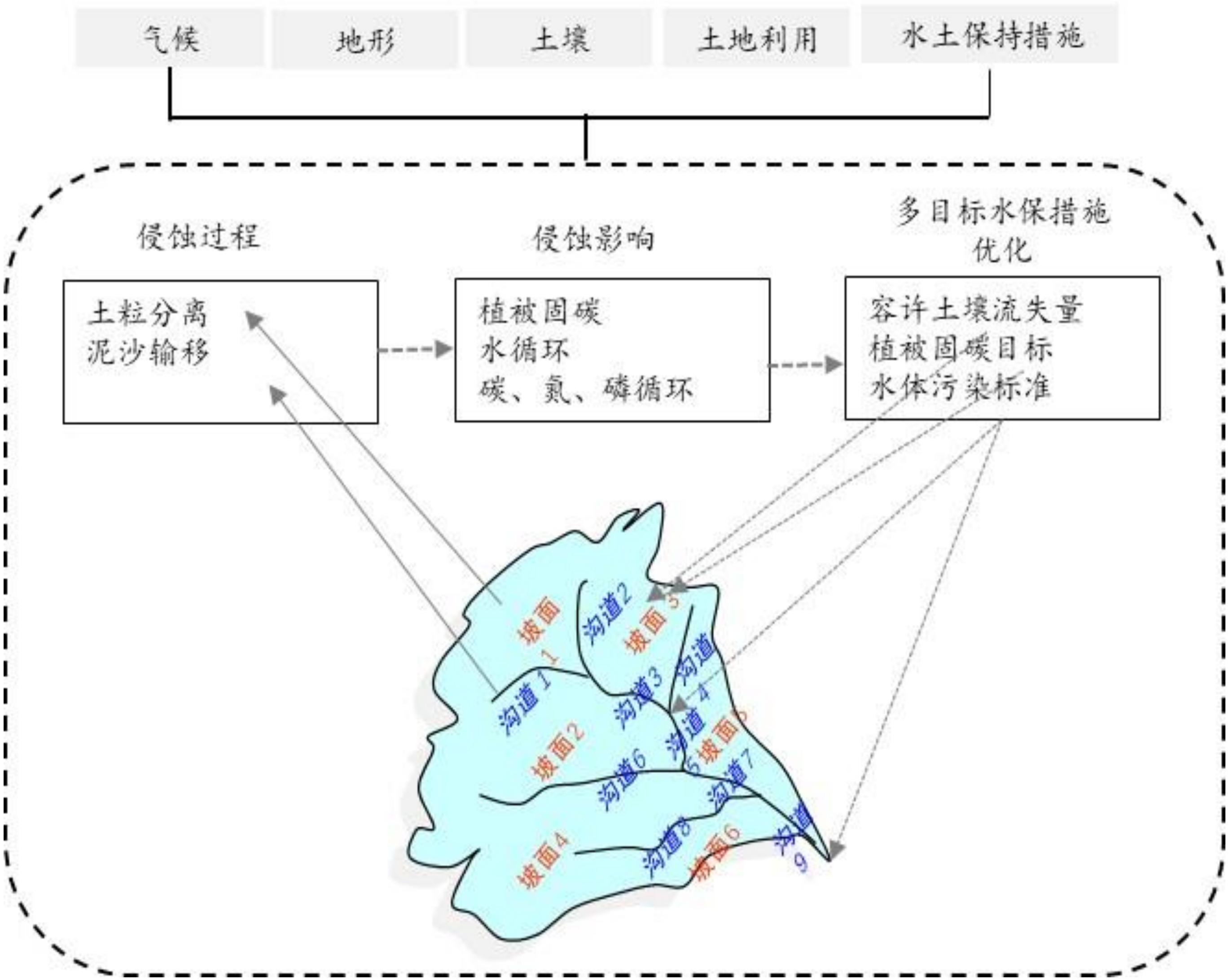


需水统计
社会经济
气象
土壤
植被
地形
水库
需求
供给
蒸散发
土壤水
影响
灌溉需水
作物模块
灌溉模块
供需平衡关系
社会经济需求
水库储/调水
工业需水
生活需水
畜牧需水
降尺度/
预测模型
分配方案
影响
流量过程
能量平衡
流域内
水运动
的时间
影响
(虚拟输水路径)
水库耦合方案
水库调度方案
(虚拟排水路径)
precipitation
reservoir
Tributaries
Surface Runoff
Waterbody

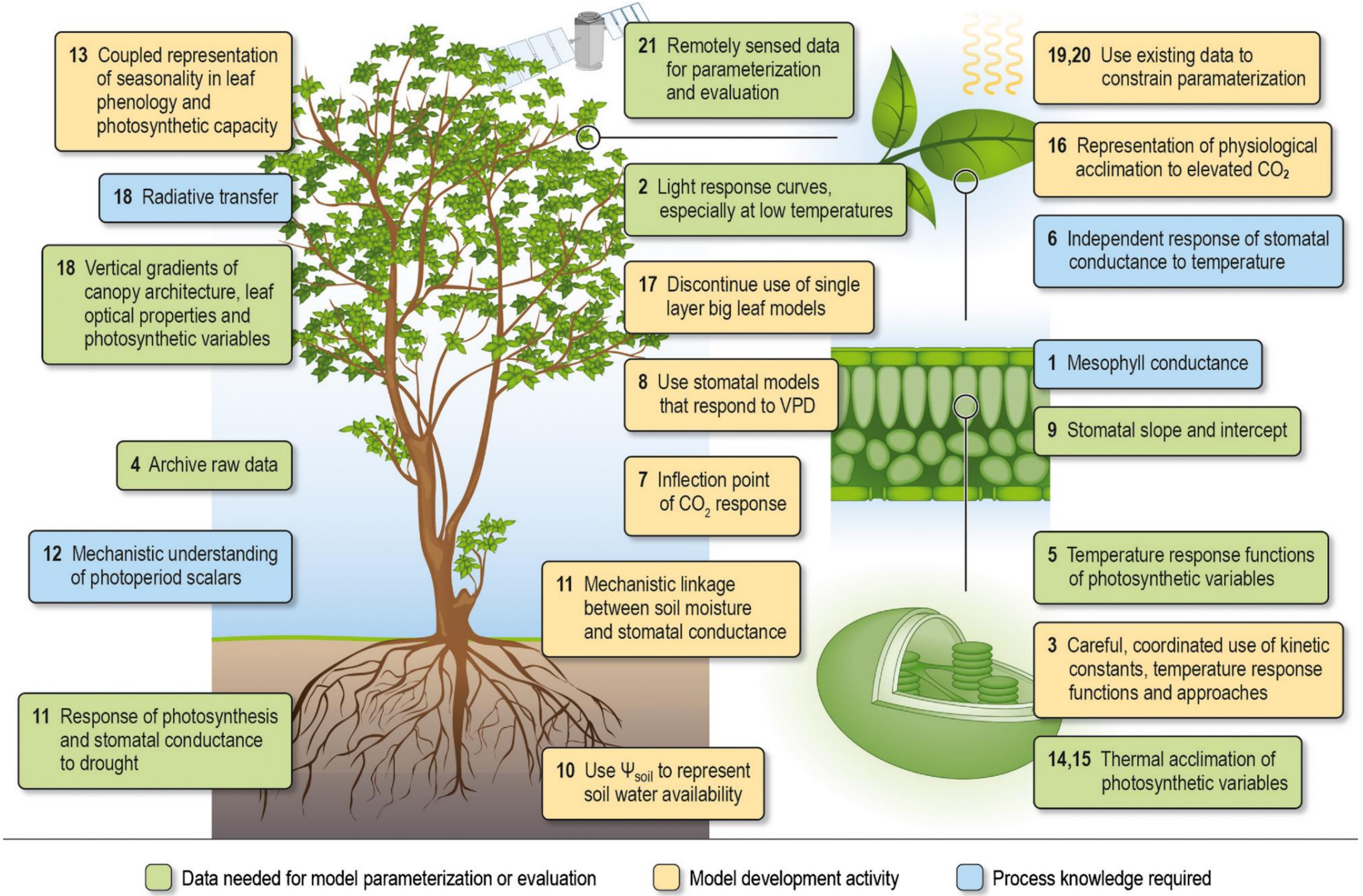


水文集合预报系统
天气预报与气候预测
水文集合预报系统
大气预报集合前处理器
观测
集合资料同化
水文集合前处理器
参数集合处理器
水文集合后处理器
水文与水资源集合产品生产
Forecasters
Users
集合校验系统
Ensemble Verification System (EVS)
集合预报产品
产品检测
RMSE Skill Score
April Forecast
Probability of Detection
Probability of False Detection
Non-exceedance probability window

挑战性工作（四）：土壤侵蚀模式



A roadmap for improving the representation of photosynthesis in Earth system models

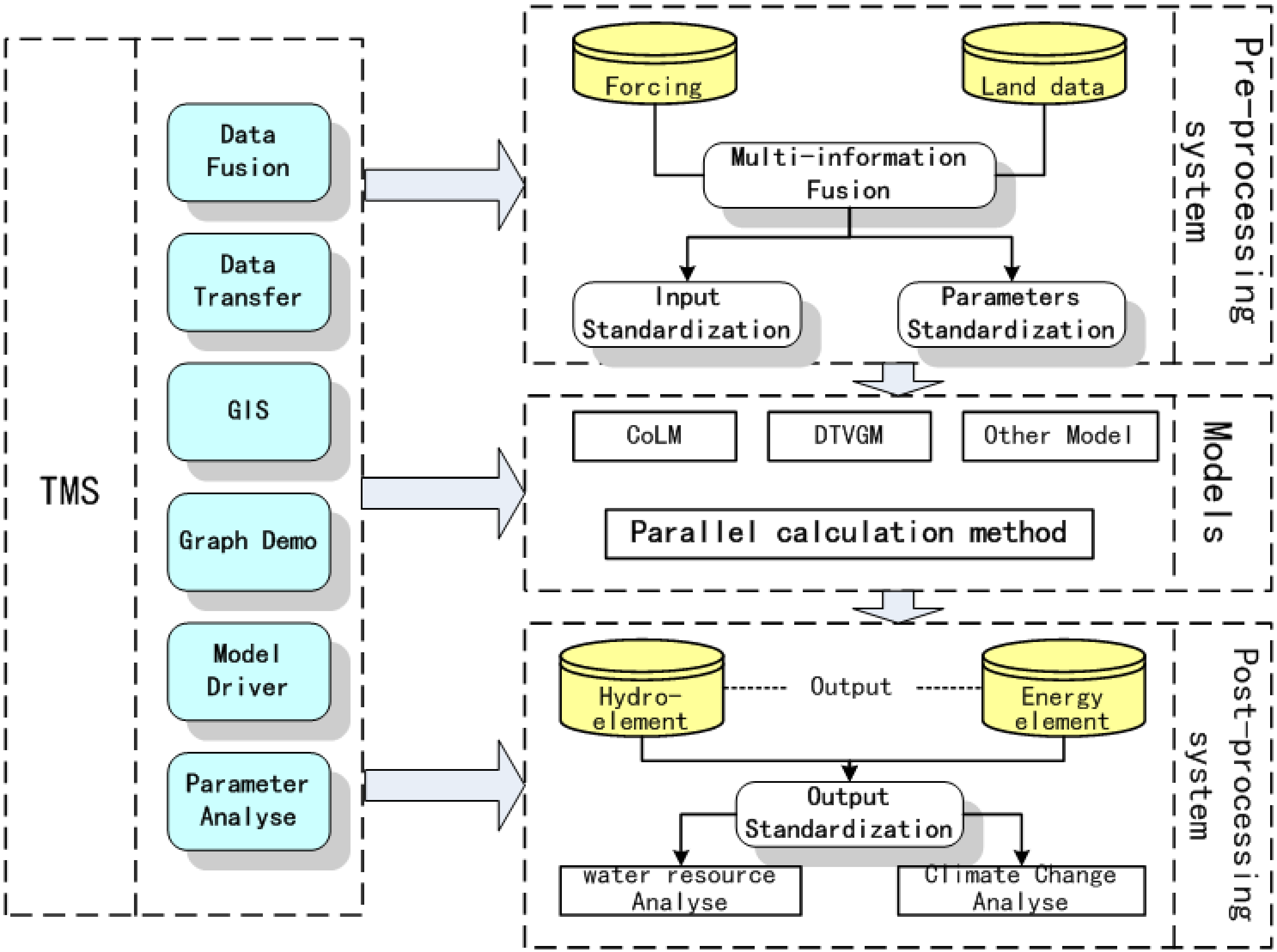


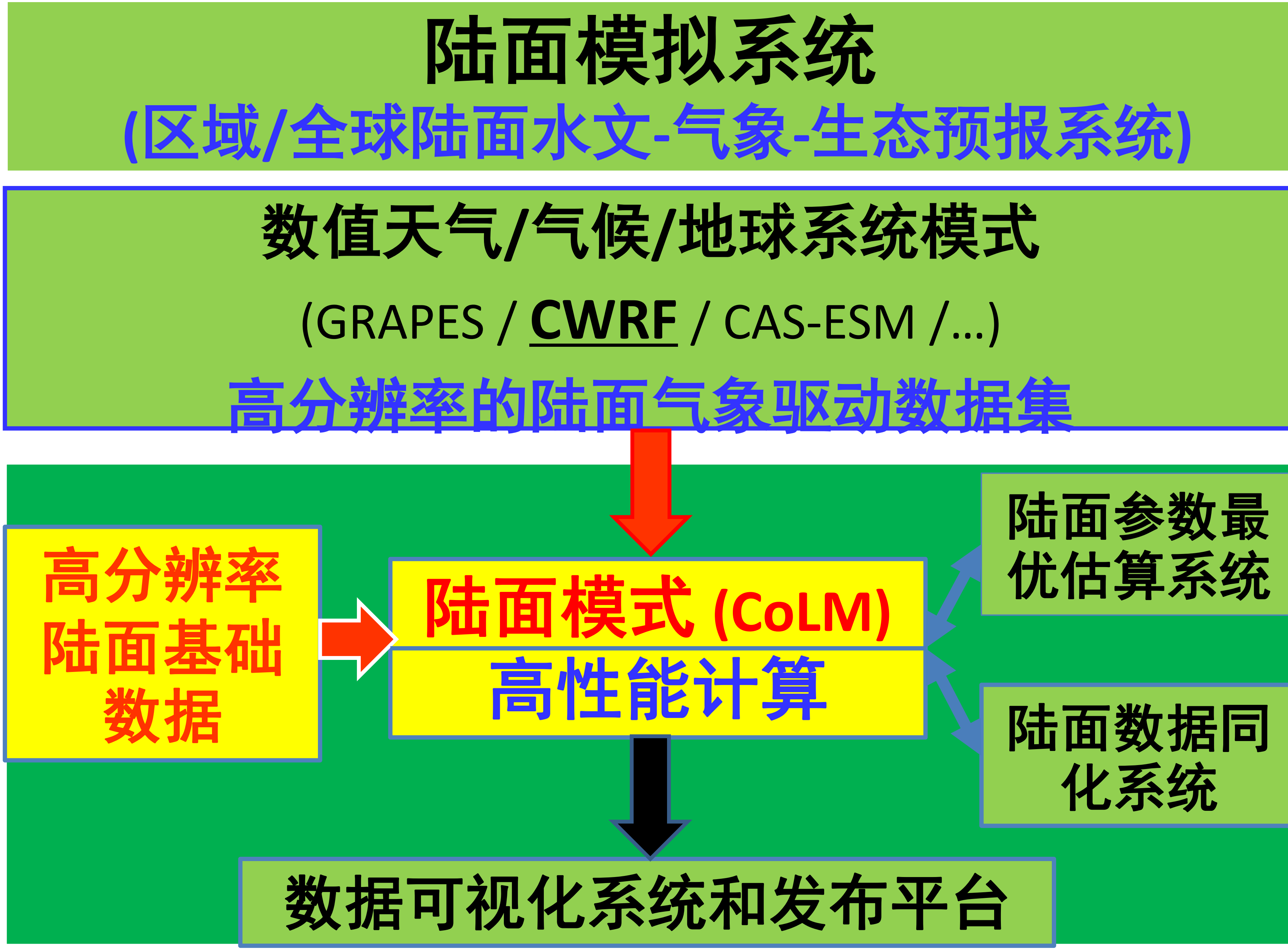
A roadmap for improving the representation of photosynthesis in Earth system models, Vol.: 213（1）, 22-42, 28 Nov. 2016

Opportunities for Future Land Surface Model Development

Model Development Opportunities	Expected Impact
Explicitly represent variably saturated flow using the mixed form of Richards' equation	Improve simulations of shallow groundwater dynamics and soil moisture
Explicitly represent vapor flow through soil	Improve simulations of evapotranspiration
Explicitly represent macropore and fracture flow	Improve simulations of soil moisture, evapotranspiration, groundwater dynamics, and runoff
Explicitly represent reinfiltration of surface runoff as water moves across the landscape	Improve simulations of soil moisture and partitioning of precipitation into evapotranspiration and runoff
Explicitly represent hydraulic gradients throughout the soil-plant-atmosphere continuum	Improve simulations of root water uptake and evapotranspiration
Explicitly represent "among-grid" groundwater flow, using 2-D or 3-D models	Improve simulations of groundwater dynamics and evapotranspiration
Explicitly (or implicitly) represent "within-grid" groundwater flow, using representative hillslopes	Improve simulations of groundwater dynamics and evapotranspiration
Explicitly represent stream-aquifer interactions	Improve simulations of groundwater dynamics and streamflow
Improve simulations channel/floodplain routing by implementing 1-D diffusive wave models	Improve simulations of streamflow, especially backwater effects
Improve data sets on bedrock depth and bedrock permeability	Improve simulations of soil moisture and groundwater dynamics
Improve data sets on physical characteristics of rivers (e.g., slope, roughness, hydraulic geometry)	Improve simulations of streamflow and stream-aquifer interactions

挑战性工作（五）： TMS 模拟平台




陆面模拟系统
(区域/全球陆面水文-气象-生态预报系统)
数值天气/气候/地球系统模式
(GRAPES / CWRF / CAS-ESM /…)
高分辨率的陆面气象驱动数据集
高分辨率陆面基础数据
陆面模式 (CoLM)
高性能计算
陆面参数最优估算系统
陆面数据同化系统
数据可视化系统和发布平台


Thank You !

中山大学号


三沙市 气象局 （永兴岛）