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# Key Scientific and Technical Issues in Earth System Science Towards Achieving Carbon Neutrality in China

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## Abstract

The carbon neutrality strategy will be the largest orderly human activity in this century, which requires strong scientific supports. This study introduces some key scientific questions and remaining knowledge gaps in earth system science (i.e. atmosphere, land, ocean science), and also discusses some key techniques and the associated challenges, including Earth System Model, climate metrics, greenhouse gasses monitoring techniques, carbon inventories from regional to global scales. On this basis, this study recommends to construct climate monitoring system and platform in China, better describe and understand the earth system coupling processes and mechanisms. To consolidate the techniques for carbon neutrality, this study also suggests to build carbon monitoring and inventory assessment platform and to improve the Earth System Model.


## Keywords

carbon neutrality; carbon source; carbon sink; greenhouse gas; climate change; earth system model; climate monitoring


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# 碳中和目标下的若干地球系统科学和技术问题分析

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**摘要** 碳中和作为21世纪最大规模的有序人类活动，亟待科学应对。文章从地球系统科学角度，讨论了支撑“碳达峰、碳中和”目标的大气、陆地和海洋相关的地球系统科学中的若干科学和技术问题及现存的知识不足。从地球系统模式、气候监测指标、温室气体监测技术、碳源/汇核算方法体系等方面，阐述了支撑碳中和的关键技术手段及现存的问题。基于目前存在的挑战和不足，建议深入理解气候系统多圈层相互作用过程和机制，完善地球系统理论与模式，从多圈层角度加强“碳达峰、碳中和”目标和气候变化理论基础；自主构建气候变化监测指标系统，研发温室气体监测与核查手段和平台，为碳中和目标提供先进的技术手段支撑。

**关键词** 碳中和，碳源，碳汇，温室气体，气候变化，地球系统模式，气候监测

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碳排放指以二氧化碳（$CO_2$）为代表的人为温室气体排放，其中包括 $CO_2$ 和非 $CO_2$ 气体，但均以 $CO_2$ 当量计。碳达峰是指一定空间范围（如全球或某级行政辖区）内的碳排放年总量在某个时间段

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呈现为工业化以来的最高峰值。政府间气候变化专门委员会（IPCC）指出，碳中和是指净零碳排放，即规定时期内人为移除与人为排入大气的 $CO_2$ 当量相互抵消[1]。根据《中华人民共和国气候变化第二次两年更新报告》[2]，我国 2014 年的碳排放量约为 11.2 Gt（1 Gt=$10^9$ t）$CO_2$ 当量，占同年全球排放量①的大约 22.3%，未来实现碳中和所需的碳减排压力远大于任何一个发达经济体。

实现碳中和涉及人为减排、能源结构调整、人工碳汇等手段的实施，这些本质上都属于有序人类活动[3]，其目标是包括中国在内的全球各国通过合理安排和组织，在满足社会经济发展需求的同时使自然环境在一定时空尺度内不发生明显退化，甚至能持续好转。在实施层面，人类社会通过降低碳排放的手段进行气候调控属于对自然环境的人工调控或者最优调控问题，也是自然控制论的研究范畴[4]。碳达峰与碳中和涉及诸多亟待解决的重要科学问题，本文主要阐述碳达峰与碳中和目标下地球系统中大气、陆地和海洋相关的若干关键科学问题及知识缺口，以及支撑碳中和的监测和评估方法。面向国家碳中和重大战略需求，科学界亟待解决这些问题，支撑我国建设世界科技强国。

## 1 温室气体及全球响应和反馈过程

### 1.1 地球系统响应温室气体增加的科学基础及不确定性

地表温度对温室气体排放具有接近实时的快速响应（按年计），长时间尺度的地表温度变化和累积温室气体排放有近线性的关系（图 1），即大约 550 Gt 的碳排放会对应 1℃的升温。自工业革命以来的温室气体排放累积导致了全球平均气温上升约 1.1℃。而未来的温度变化主要取决于未来的排放量，所以《巴黎协定》的 2℃控温目标实际上对应了未来的温室气体总排放量：粗略估计只有约 500 Gt 的排放空间[5]。

科学界已经明确温室气体排放会导致气温上升[6-8]，并以此作为未来减排目标的主要科学依据。但是，不确定性依然存在[9]（图 1），主要来自以下方面：气温对温室气体的响应过程和机制的不确定性，包括碳循环的响应；地球系统中大气、陆地、冰冻圈、海洋等对温室气体的响应及其相互作用；冻土的反馈机制；$CO_2$ 及非 $CO_2$ 温室气体的核算及其反馈机制；地球系统的非线性响应及自然变率的贡献等。减小气温对温室气体响应过程和机制的不确定性将为未来精准核算碳收支提供科学基础。

除了地表温度上升外，全球变化表现为大气、海洋、陆地、冰冻圈、生物圈等各圈层的系统性变化，包括且不限于：海洋升温和酸化、陆面温度上升、高山冰川和北极海冰范围缩小、格陵兰和南极冰盖质量损失、海平面上升、极端事件加剧等，这些是全球变化的主要判别指标。目前，这些主要的全球性气候指标数据依然被欧美国家的政府机构或研究团体主导，我国的贡献甚少。同时，我国尚未建立关键气候变化核心指标的实时监测平台，这制约了我国施行快速、精准的气候变化政策，也制约了我国对碳达峰与碳中和目标的措施进行绩效评价。

### 1.2 全球海洋和大气响应全球气候变化的科学问题及知识缺口

#### 1.2.1 海洋的响应和反馈

全球变暖 90% 以上的热量都储存在海洋中。由于巨大的体量和比热容，海洋对温室气体的响应具有延时性[10]。即使碳中和目标可以达成，海洋变暖、海平面上升等依然会持续[8,11]，这对未来适应和减缓气候变化提出了更高的要求。

全球海洋物理状态的变化会改变海洋的碳收

① 根据《联合国气候变化报告 2019》（*United Nations Climate Change Annual Report 2019*）中的统计。

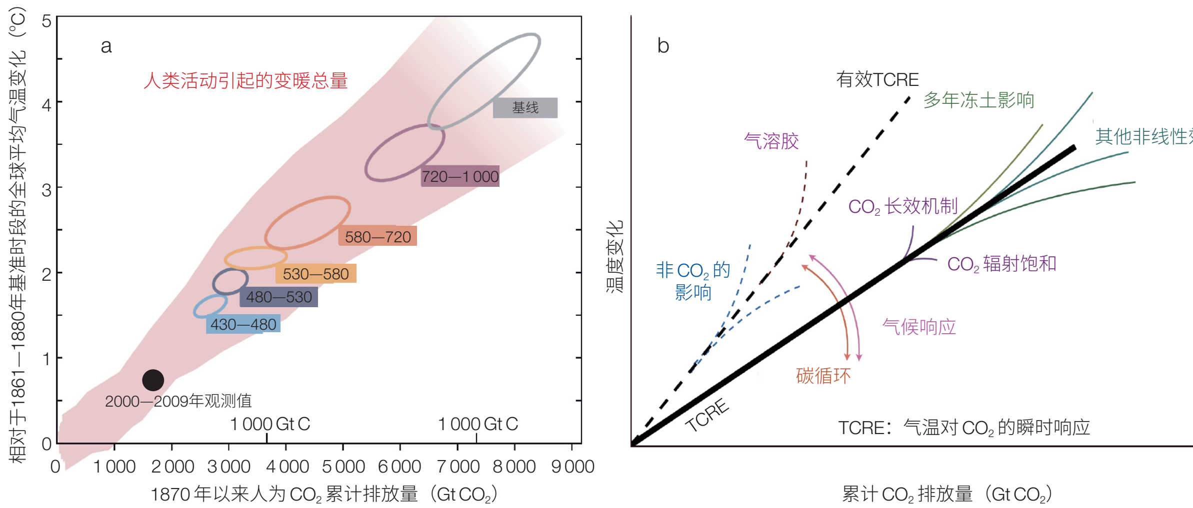


图 1　全球地表温度与累计 $CO_2$ 间的关系及其不确定性来源

Figure 1　Relationship between global mean surface temperature and cumulative $CO_2$ emissions, and uncertain processes affecting the relationship

（a）地表温度与 $CO_2$ 累积排放量；其中，实心黑色椭圆表示观测到的至 2005 年的 $CO_2$ 累计排放和 2000—2009 年这 10 年观测到的温度，而不同颜色的椭圆表示基于气候模型在不同未来温室气体排放情景下的 2100 年气温和 1870—2100 年累计 $CO_2$ 的对应关系，椭圆旁的数字表示 2100 年的大气 $CO_2$ 浓度（单位为 ppm）（图简化自 IPCC-AR5）；（b）影响估计地表温度对温室气体响应关系的主要不确定性来源[9]

(a) Global mean surface temperature increases as a function of cumulative total global $CO_2$ emissions; the filled black ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000–2009 with associated uncertainties. Ellipses show total anthropogenic warming in 2100 versus cumulative $CO_2$ emissions from 1870 to 2100 from a simple climate model (median climate response) under different scenarios (figure from IPCC-AR5); (b) Uncertain processes affecting relationship between increasing global mean surface temperature and cumulative $CO_2$ emissions[9]

支（例如，海洋吸收 $CO_2$ 的“生物泵”和“物理泵”），对碳中和目标的实现有重要影响。海水增暖后，其固碳能力会下降。例如，近几十年南大洋内部热含量的增长十分显著[12]，这可能导致南大洋固碳能力减弱[10]。大西洋经圈翻转环流减弱也可能会削弱深对流过程的固碳能力[13]。在碳中和气候状态下，海洋层结上层减弱、中深层加强，这对海洋储碳能力的影响尚不明确。北冰洋海底拥有巨大的碳埋藏量，一方面，北冰洋海水增暖使得这些冰状水合物极易融化分解，从而释放出 $CO_2$；另一方面，全球变暖导致北极海冰范围缩小，使得海表冷水与大气的接触增加，从而增强海水的储碳的能力，二者最终会导致北极碳收支发生何种变化也不明确。

### 1.2.2 大气的响应和反馈

我国碳中和目标的实现主要依赖于科技的进步和经济发展方式的转型，但同时也会受到我国未来气候走向的直接影响。例如，植树造林，以及利用太阳能、风能等新能源都是实现碳中和的重要举措，而在多大程度和范围内能够采取上述举措主要依赖于气温、降水、辐射、风速等基本的天气和气候状况；即使对于传统的水力发电，其在未来的能源供给能力也依赖于气候，特别是降水的走向。在极端天气条件下，如异常的“副高活动”“极涡活动”等带来的大范围风能、光能异常，可能导致大规模电力供应不足问题，如 2020 年冬季美国得克萨斯州的能源灾难问题。因此，在进行我国碳中和规划和碳汇的估算时必须考虑未来 40 年内气候走向这一要素。

温室气体浓度变化对气候的影响主要分为 2 类不同时间尺度的过程[14]：受大气 $CO_2$ 强迫影响的快速调整过程、受全球平均温度变化影响的缓慢调整过程。在温室气体浓度上升阶段，两者同步增长，该情形下的气候变化研究相对较清楚[15,16]；而在下降阶段，

全球平均温度的增长将放缓，而科学界对该阶段的气候影响认识不够[10,17]。此外，《巴黎协定》只给出了21世纪的温度控制目标，但实现目标的温室气体排放路径却有很多种可能[18]；同时，以不同的温室气体排放路径实现相同的温度目标，气候的响应也存在差异[19,20]。

#### 1.2.3 地球系统内部变率的影响

气候变化一部分是由温室气体排放、土地利用等人类活动引起的气候系统外强迫改变所造成的变化；另一部分则是由气候系统内部的大气、海洋、陆地、冰雪等圈层相互作用所引起的内部变率造成的变化[21]。过去40年，内部变率对东亚一些地区气温等要素变化的作用可以超过人类活动的作用[22,23]。内部变率引发的气候变化与人类活动外强迫导致的变化相比具有更大的不确定性，是造成未来30—50年气候变化不确定性的重要来源[21]。因此，在考虑我国碳中和相关政策时，必须关注气候系统内部变率的作用，特别是由其引起的不确定性。目前，有关全球碳汇格局、时间尺度、演化趋势及其与气候系统互馈机理等方面的科学认识尚存在重大缺失，亟待进一步深入研究。

## 2 我国陆地和海洋碳源/汇贡献和不确定性

### 2.1 中国陆地生态系统碳源/汇综述

陆地生态系统是我国最重要的碳汇之一[24]，系列研究利用不同的模型和方法，估算了我国区域陆地碳汇强度。这些研究对于量化我国陆地碳汇的贡献发挥了重要的作用。例如，Wang 等[24]发现2010—2016年我国陆地生态系统年均吸收了同时期人为碳排放的45%，揭示了我国陆地生态圈的巨大碳汇作用。然而，目前对于我国区域陆地碳汇强度估算仍然存在着较大的不确定性，不同研究者对于碳汇强度估算存在明显的差异（表1）[24-30]。

#### 2.1.1 森林碳汇的不确定性

21世纪前10年我国森林年碳汇总量平均约为173.9 Tg C/yr（1 Tg C=$10^{12}$ g），其中生物量、死有机质和土壤有机碳（SOC）的年碳储量变化分别为约150.2 Tg C/yr、9.0 Tg C/yr和24.7 Tg C/yr。但是，不同研究之间的结果差异较大。生物量碳库的不确定性主要来自不同研究所采用的森林面积不同，

表1　中国陆地生态系统碳汇强度估计

Table 1　Estimation of carbon sink of terrestrial ecosystem in China

| 模型方法 | 碳汇强度（Pg C/yr） | 研究时期 | 文献来源 |
|---|---|---|---|
| 自下而上（即基于调查数据的回归模型和基于过程的生态系统模型） | 0.186 | 1980—1999年 | [25] |
| | 0.179 | 1961—2005年 | [26] |
| | 0.966 | 2001—2010年 | [27] |
| | 0.330 | 2006—2009年 | [28] |
| | 0.118 | 1980—2010年 | [29] |
| 自上而下（即大气反演模型） | 0.35 | 1996—2005年 | [25] |
| | 0.33 | 2001—2010年 | [30] |
| | 0.45 | 2006—2009年 | [28] |
| | 0.66, 1.11* | 2010—2016年 | [24] |

*基于不同的大气$CO_2$浓度观测值

*Based on different $CO_2$ concentration observations

从1.428亿公顷[31]到1.882亿公顷[32]不等。一部分研究采用的森林面积数据来源于国家森林资源连续清查，另一部分研究采用了我国1∶1 000 000植被图确定森林面积，而二者对于森林的定义存在显著区别。此外，多数研究只评估乔木林生物量碳储量变化，而较少涉及经济林、竹林、灌木林、稀疏林及森林之外的林木，也较少涉及死有机质和SOC碳库变化，难以全面衡量森林生态系统的碳汇功能。另外，SOC储量变化估算结果的不确定性与所评估的土层厚度不一致有很大关系[33,34]。

#### 2.1.2 田间管理提高农业碳汇能力

农田生态系统作为全球碳库中最活跃的部分，受耕作、灌溉、施肥等人类活动的影响最大，对大气碳含量影响也较为明显。目前的研究更多地关注了农田SOC储量变化，而对于SOC储量变化与非$CO_2$温室气体排放之间平衡的研究相对较少。在农田生态系统中，作为土壤肥力关键指标的SOC含量，对粮食生产和缓解气候变化起着重要作用[35]。气候变暖和极端气候事件频发可能会导致SOC损失加剧，而提高作物产量、增加秸秆还田及少免耕等农业生产措施则会显著增加农田SOC[36-38]。

#### 2.1.3 湿地保护与碳汇

我国自然湿地的SOC储量达8—17 Pg C，约占全国陆地SOC总储量的1/10—1/8，约占全球陆地SOC总储量的3.8%[39,40]。我国自然湿地甲烷（$CH_4$）年排放量估计为1.9—3.86 Tg C[41-43]。

自然状态下，湿地生态系统都表现为碳汇[44-46]。但受人类活动影响，湿地被排干，其SOC分解速率加快，导致温室气体排放量增加，从而将湿地生态系统由碳汇转变为巨大碳源[47]。我国近半个世纪的湿地垦殖导致的碳损失量达每年173.2 Tg C[40]；同时，$CH_4$排放量总共减少约10.3 Tg[41]。不同区域、不同类型的湿地，其$CH_4$排放通量和固碳速率均有差异。因此，制定合理的湿地恢复政策，挖掘我国自然湿地的低碳汇价值，对于实现碳中和具有积极意义。

### 2.2 海洋碳收支和海洋增汇

海洋是巨大的碳汇和碳库，人类活动排放的$CO_2$约有1/4—1/3被海洋吸收。海洋碳汇主要有海岸带高等植被（包括红树林、盐沼、海草床等）、微型生物碳汇（“生物泵”与“微型生物碳泵”）、以海藻养殖为主体的渔业碳汇等。海洋水体中蕴含巨大的可长久储存的惰性溶解有机碳（RDOC），其总量与大气碳量相当，而RDOC主要来自微型生物碳泵的贡献[48,49]。海洋碳源/汇在不同海区有较大差别，急需综合考虑海区的外部碳输入和向外输出等因素，估测我国近海的碳源/汇情况[49]。目前，国际上还缺乏统一的海洋碳汇评估标准，急需强化不同生境海洋碳汇复杂过程和机制的深入研究，并在此基础上建立不同类型海洋碳汇的核查技术体系，大力研发海洋增汇技术，积极探索实施海洋增汇工程。目前，有潜力的增汇措施主要包括陆海统筹减排增汇、海洋缺氧环境减排增汇、滨海湿地减排增汇、养殖环境减排增汇、珊瑚礁生态系统减排增汇、海洋地质碳封存等[51]。

## 3 地球系统科学支撑碳中和的关键技术手段及现存的关键问题

### 3.1 基于地球系统模型模拟和预估气候变化，支撑碳中和路径和目标

地球系统模式能够定量刻画大气、陆地、海洋碳循环等地球系统各部分之间的相互作用过程，是认识、理解全球碳循环过程和机制，以及模拟和预估气候变化的核心工具。通过设置不同的碳中和目标约束（如何减排、如何增汇等），地球系统模式得到最有效、最合理的碳中和路径，从而为寻找碳中和最优科学路径提供强有力的技术和工具支持。当前，我国具有自主知识产权的第二代中国科学院地球系统模式（CAS-ESM2）实现了碳循环和气候的完全耦合[52]，可以模拟地球各主要分系统对不同碳中和路径的响

应，包括陆地和海洋碳通量变化、陆表植被和水文变化、气候变化等。然而，当前地球系统模式在功能和性能上还需进一步完善，特别是提升对人为过程、植被动态演变、火干扰、氮循环等过程的描述[53]。

## 3.2 天空地一体化温室气体观测系统

### 3.2.1 卫星遥感观测

卫星遥感观测可以在碳源/汇核查方面发挥重要作用。我国于2016年发射了第一颗 $CO_2$ 监测科学实验卫星[54]，又陆续发射风云三号D星和高分五号大气成分监测卫星[55]。由于幅宽较小（10—20 km）且重访周期长，国际上现有卫星主要在全球尺度碳源/汇反演中发挥作用，还无法满足点源、城市、区域尺度监测需求。

新一代的温室气体监测卫星的主要发展方向包括[56]：① 提高观测的时空分辨率。例如，增加跨轨扫描宽度（> 100 km）以提高覆盖范围（中国风云三号G星、大气环境监测卫星2星），提高时间分辨率（欧洲 $CO_2M$ 多星组网、美国GEOCARB静止轨道卫星），采用激光雷达（欧洲MERLIN、中国“环境一号”卫星）实现昼夜观测，以及温室气体和污染气体协同观测。② 发展先进的遥感反演算法、快速高精度辐射传输模式和改进分子光谱学数据库。③ 进一步发展卫星数据同化方法，实现人为温室气体源汇清单反演能力。

### 3.2.2 地面温室气体通量观测技术

过去20多年，全球范围内形成了碳通量观测网络（FLUXNET），为全球碳收支与全球变化研究提供了高质量的温室气体地面通量长期观测数据[57]。面向碳中和的需求，也应把温室气体地面通量的监测网作为整个碳核算监测体系的重要组成部分。该监测网络的建设应关注5个方面：① 加强典型城市下垫面的通量监测；② 推动观测方法、数据处理、仪器操作和维护的规范化和标准化建设，提升地面观测通量数据的质量和可靠性；③ 强化非二通量先进测量技术的研发和加强 $CO_2$ 与主要非 $CO_2$ 温室气体（$CH_4$ 和 $N_2O$）的地面通量同步观测；④ 加快自主技术仪器设备的研发；⑤ 加强基于自主技术气体分析仪的温室气体和污染气体地面通量观测研究。

### 3.2.3 发展人为碳排放观测技术

目前的观测技术在观测非 $CO_2$ 温室气体方面还有较大欠缺。虽然所有7种温室气体都有可满足精度需求的较成熟检测方法，但还存在体积大、成本高、运维难度大、在线化程度低等缺点，因此不利于获得广泛的高分辨观测数据。例如，氧化亚氮（$N_2O$）、六氟化硫（$SF_6$）、三氟化氮（$NF_3$）需要带有电子捕获检测器的气相色谱仪，而氢氟碳化物（HFCs）、全氟碳化物（PFCs）需要气相色谱质谱联用仪。另外，不同高度的浓度观测所代表下垫面通量贡献区有显著的差异，因此基于雷达、高塔、飞机、探空的垂直分布观测也至关重要。

### 3.2.4 加强城市碳监测平台建设

城市占陆地面积不到3%，却直接排放了全球约44%的 $CO_2$，间接影响了近80%的能源相关的 $CO_2$ 排放，是估计人为碳排放的关键区域。在城市尺度上，$CO_2$ 排放清单的统计数据和排放因子、时空分配方案等具有较大的不确定性，不同清单的差异可达70%—300%[58]，并且无法识别和定位未知的排放源。城市尺度的 $CO_2$ 浓度排放监测和反演可以提供独立的手段校准碳排放清单数据，服务于城市清单碳排放总量验证，追踪城市碳排放清单的遗漏。

## 3.3 温室气体源-汇清单核算方法

根据IPCC的国家温室气体清单指南，温室气体的人为源汇清单可用3个层级的方法编制；其中，第一、二层级是排放因子法，第三层级是过程模型法，都统一属于“自下而上”（bottom-up）方法。排放因子法目前还是各个国家或地方政府编制温室气体清单的通行方法。由于活动水平资料难以快速更新，且排放因子数据通常是一些有限条件观测数据的平均值，

排放因子法往往不能比较客观地反映温室气体源-汇的动态变化与空间分布。相比而言，过程模型法则可以克服排放因子法的上述不足。但是，过程模型的构建和检验，以及其驱动数据的准备，难度相对较大，这导致过程模型法仅在极少数发达国家及我国的部分土地利用类型（如农田、湿地等）温室气体源-汇清单编制中得到应用。另外，对于土地覆被和土地利用变化引起的温室气体源-汇变化，以及畜牧业的温室气体排放，过程模型法的应用仍然具有挑战性。

“自上而下”方法通过观测大气温室气体浓度，结合气象场资料和大气传输模式，利用同化技术反演估算区域源-汇及变化状况[59-61]。IPCC 最新版的温室气体清单指南[62]首次提出，该方法反演估算的温室气体源-汇状况，作为完全独立的数据，可以被用来验证排放因子法或过程模型法编制的温室气体清单。当前，$CO_2$ 同化系统发展趋势主要表现在 4 个方面：① 联合同化地基观测和卫星遥感的 $XCO_2$（大气 $CO_2$ 柱浓度）数据。② 联合同化大气 $CO_2$ 浓度、站点通量、遥感地表参数等数据[61]。③ 同时优化生态系统和化石燃料燃烧的 $CO_2$ 通量[63]。现有的全球碳同化系统基本上都假设化石燃料燃烧的 $CO_2$ 通量数据无误差，仅优化生态系统 $CO_2$ 通量，但事实并非如此[64]。$^{14}CO_2$ 是公认的理想化石燃料燃烧排放指示信号[65]。④ 通过污染气体和 $CO_2$ 的联合同化，以优化化石燃料燃烧 $CO_2$ 排放[66]。

## 4 结论和建议

实施碳中和目标将是我国 21 世纪最大规模的人类有序活动，涉及地球系统多圈层相互作用，必将触发地球环境演变，并催生新的科学前沿。本文总结了涉及碳中和的地球系统科学的若干科学技术问题，展望了发展趋势。基于上述讨论，提出 3 点科学建议。

（1）自主构建气候变化监测指标系统，深入理解气候系统多圈层相互作用过程和机制，为碳中和目标的实现提供科学基础。针对我国尚未建立关键气候变化核心指标实时监测平台的问题，建议积极统筹各方力量，建立我国自主可控的气候变化核心监测指标集和平台，以实现全球气候变化核心数据的自主化并形成国际影响力，动态评估全球气候状况，为应对气候变化提供科学数据基础。对气候系统多圈层相互作用过程和机制的理解，是精准设置减排目标、准确评估气候变化影响和风险的基础。因此，要实现碳中和目标，需要全面加强全球碳汇格局、时间尺度、演化趋势及其与气候系统的互馈机理等方面的重要基础科学研究。

（2）自主研发温室气体监测与核查技术和平台，为碳中和目标提供先进的科技支撑。目前，我国缺乏温室气体源汇评估的自主核查校验方法和技术平台。建议：① 在监测数据获取能力方面，突破温室气体空间监测技术、地面监测网、垂直探测、自主先进探测技术、非 $CO_2$ 监测技术，推进城市碳监测平台建设，形成天空地一体化的温室气体监测能力。② 在方法体系方面，研发基于天地一体化观测的多尺度温室气体清单校核方法。融合“自上而下”反演方法与高分辨率“自下而上”动态清单方法，实现人为源-汇变化的精细化监测，为国家相关政策的制定提供科学依据。③ 需要全面认识和调查海洋和陆地的生物及其物理固碳能力，全面监测我国的碳源/汇。

（3）进一步完善地球系统模式，以国家“地球系统数值模拟装置”为核心，建设国家碳中和核算-评估-决策支持中心，用科技能力建设支撑碳中和战略的实施。需要研发和优化可正确刻画碳循环复杂过程的地球系统模型，结合不同减排情景和不同的人类活动影响，预估 2030 年和 2060 年的全球及我国碳收支特征，以及我国不同陆地生态系统对碳中和的贡献；研究规划最优碳中和路径的方法论，评估生态工程可能的方案和转换能源结构的最优途径，为我国 2060 年前实现碳中和目标提供强有力的科技支撑。

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# Key Scientific and Technical Issues in Earth System Science Towards Achieving Carbon Neutrality in China

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**Abstract** The carbon neutrality strategy will be the largest orderly human activity in this century, which requires strong scientific supports. This study introduces some key scientific questions and remaining knowledge gaps in earth system science (i.e. atmosphere, land, ocean science), and also discusses some key techniques and the associated challenges, including Earth System Model, climate

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metrics, greenhouse gasses monitoring techniques, carbon inventories from regional to global scales. On this basis, this study recommends to construct climate monitoring system and platform in China, better describe and understand the earth system coupling processes and mechanisms. To consolidate the techniques for carbon neutrality, this study also suggests to build carbon monitoring and inventory assessment platform and to improve the Earth System Model.

**Keywords** carbon neutrality, carbon source, carbon sink, greenhouse gas, climate change, earth system model, climate monitoring

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