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物理海洋十大前沿科学问题

吴立新[1,2,3*], 陈显尧[1,2], 陈朝晖[1,2], 荆钊[1,2,3], 马晓慧[1,2,3], 甘波澜[1,2], 周春[1,2], 张志伟[1,2], 牟龙江[3], 宋德海[1,2], 钟文理[1,2], 祁第[4], 刘骥平[5], 刘志宇[6], 宋振亚[7], 杨海军[8]

1. 中国海洋大学深海圈层与地球系统前沿科学中心, 青岛 266100
2. 中国海洋大学物理海洋教育部重点实验室, 青岛 266100
3. 崂山国家实验室海洋大数据与人工智能研究部, 青岛 266237
4. 集美大学极地与海洋研究院, 厦门 361021
5. 中山大学大气科学学院, 珠海 519082
6. 厦门大学海洋与地球学院, 厦门 361102
7. 自然资源部第一海洋研究所, 青岛 266061
8. 复旦大学大气与海洋科学系, 上海 200438
* 联系人, E-mail: lxwu@ouc.edu.cn

物理海洋学主要通过分析海水的运动、海水的动力、物理与其他生物地球化学性质的分布与变化，研究海洋的动力与物理性质、过程和机制. 物理海洋学是深入了解海洋及其在地球系统中作用的基础学科. 在全球气候变暖的背景下，海洋吸收了整个气候系统中超过90%的热量盈余和超过30%的人类活动排放的温室气体，从根本上缓解了人类活动导致气候变暖的速率. 同时，海洋也是从季节到年际和年代际气候可预报性的根本源头. 因此，更加深入地理解海洋的动力与物理性质、过程和机制，是进一步明确海洋在全球变化中作用以及人类对地球气候系统影响作用的核心基础. 物理海洋学正从认识海洋的理论与实验科学，转向为认识海洋、经略海洋并重、多应用场景驱动的理论、技术与工程协同科学.

为此，我们详细梳理了近百年来物理海洋学的发展轨迹，从三个维度出发分析总结了当前物理海洋学发展面临的关键挑战. 三个维度包括: (1) 研究范式，即观测、数值模拟、理论分析与人工智能. 研发新的观测技术、加强海洋观测系统建设、获取海洋观测数据始终是物理海洋学发展的基础. 同时，由于任何观测系统都不能实现全部、实时覆盖全球海洋，需要借助计算机技术，包括计算流体力学和人工智能等一系列手段，模拟形成并全面了解整个海洋的变化过程. (2) 时空尺度，包括从秒和分钟到千年甚至万年、从厘米和米到千公里甚至万公里的各种时间和空间尺度. 海洋的变化涉及上述各种时空尺度运动之间的能量交换和相互作用. (3) 界面互作，既包括河口海岸与深海大洋、海水与冰之间的联系，也包括海洋与大气、海洋与陆地(包括海底)、海洋与生物圈之间的相互作用. 基于这三个维度，我们分析总结了物理海洋十大前沿科学问题.

吴立新 中国科学院院士、发展中国家科学院院士、欧洲科学院院士、美国地球物理学会会士、美国气象学会会士，现任崂山国家实验室主任，中国海洋大学副校长. 长期致力于海洋多尺度动力过程、海洋地球系统观测、模拟与预测研究.

1 跨尺度实时化全球海洋观测系统构建

观测是推动海洋系统认知革新的基础. 自1872年“挑战者”号环球科考航次以来，物理海洋学观测范式的每一次转变均引发了海洋认知的重大突破: 热带海洋与全球大气(TOGA)观测计划推动了对热带太平洋海气相互作用与厄尔尼诺与南方涛动(ENSO)循环的深入认识[1]，全球海洋环流实验(WOCE)计划首次绘制了全球大尺度环流的图景[2]，卫星遥感实现了对全球海洋表面中尺度动力环境的长期监测，海洋实时观测系统(Argo)浮标彻底改变了获取全球上层海洋水体状态的能力[3]，快速气候变化与大西洋经向翻转环流(RAPID-AMOC[4])、北大西洋亚极地翻转环流(OSNAP)等大洋断面观测揭示了大西洋翻转环流的变化特征[5]，黑潮延伸体系统研究(KESS)、跨等密度面与沿等密度面混合实验

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(DIMES)以及我国在南海建立的潜标观测网[6]等计划推动了多尺度动力过程能量串级的深入研究．每一次观测范式的跃迁在拓展海洋认知、提升气候预测能力的同时，也凸显了新的观测需求，包括对深层海洋(2500 m以深)、复杂地形周边及冰下等特殊环境的观测能力仍然有限，跨尺度解析亚中尺度、小尺度乃至微尺度过程的能力不足，实时观测数据获取能力有待提升．

构建跨尺度、立体化、实时化的新一代全球海洋观测系统(图1)，是探索深层海洋物质与能量循环、多尺度过程相互作用、全球气候变化以及极端气候事件演变等前沿问题的重要支撑，也是实现精细感知海洋系统耦合过程和精准预测全球气候变化与极端气候事件的坚实基础．

2 超高分辨率全球海洋数值模式与海洋数字孪生系统发展

高性能计算和人工智能技术的发展推动全球海洋环流模式进入“公里级”甚至更高分辨率的新阶段．这一变革带来了一系列物理海洋学的基础问题：重新评估传统大尺度假设在超高分辨率下的适用性；发展可避免“双重计算”的物理参数化方案，以保证模式海洋的能量守恒[7]；构建能够统一描述海洋湍流各向异性的闭合理论[8]；厘清大尺度、中尺度、亚中尺度与内波、潮汐潮流、与海浪等多尺度过程之间复杂的能量串级与逆串级机制[9]；明确超高分辨率下跨圈层间的耦合机制，并发展具有物理一致性的耦合方案[10]；发展基于人工智能预报结果的物理可解释性理论[11]．

这些挑战对观测和模拟数据的分辨率及处理能力提出了前所未有的要求．借助数据驱动的深度学习方法，以物理规律约束人工智能的学习过程，实现物理第一性原理与人工智能的深度融合，构建全球海洋超高分辨率数值模式与海洋数字孪生(图2)[12]，是提升海洋认知和预报能力，应对气候变化及保障海洋安全的重要方向．

3 海洋中小尺度动力过程及其物质能量输运与气候效应

海洋中蕴含着丰富的中尺度涡、亚中尺度过程、内波、潮汐与潮流、海浪和湍流混合等中小尺度动力过程(图3)，这些过程能够通过多种途径影响气候变化[13]：中小尺度动力过程能够通过自身输运作用以及多尺度过程之间的相互作用影响海洋中物质和热量的时空分布[14~17]，并通过水平和垂向输运直接影响二氧化碳等温室气体的埋藏过程与海洋生态系统的固碳能力来调控地球系统的碳循环[18,19]．

针对中小尺度动力过程的现场观测仍然匮乏，高分辨率的海洋动力-生物地球化学耦合模式发展不足，目前对中小尺度动力过程的气候效应的认识仍然非常有限．揭示海洋中小尺度动力过程对物质能量输运与气候变化的影响机制，不仅是当前物理海洋面临的前沿科学问题，也是提升地球系统模式预测预报精度、提高应对气候变化能力的关键挑战，同时也是准确预测海洋物理场分布变化特征的重要基础．

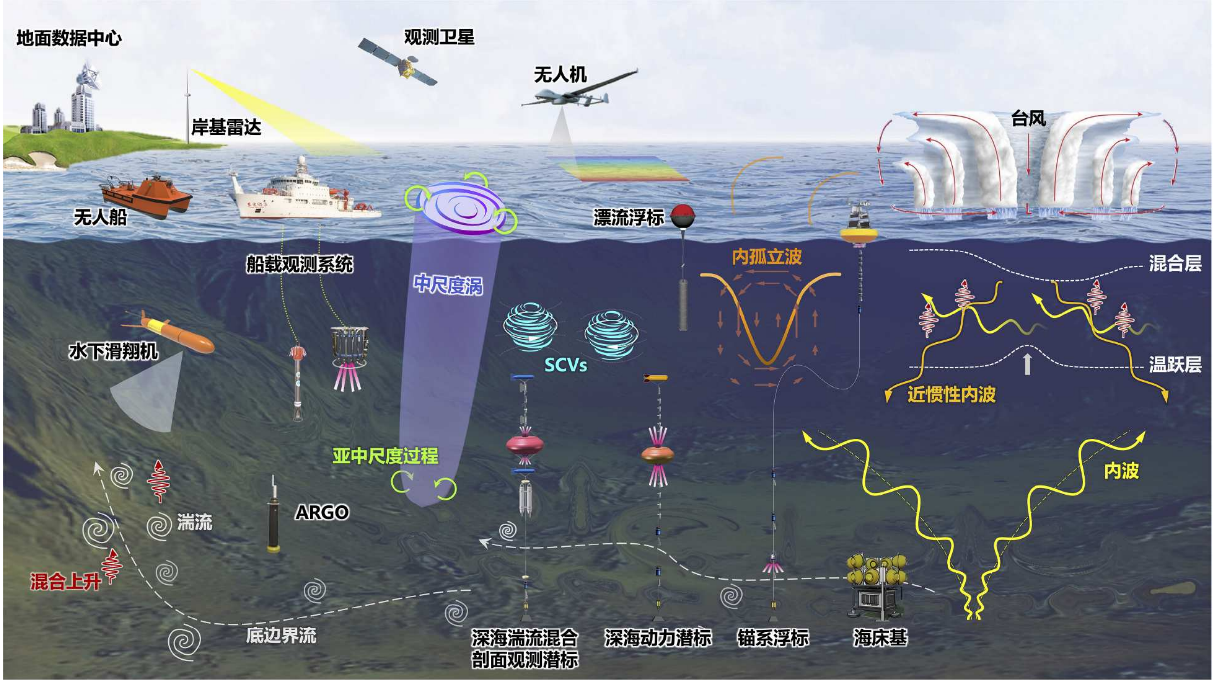

图 1　实时化全球海洋观测系统
Figure 1　A real-time global ocean observing system

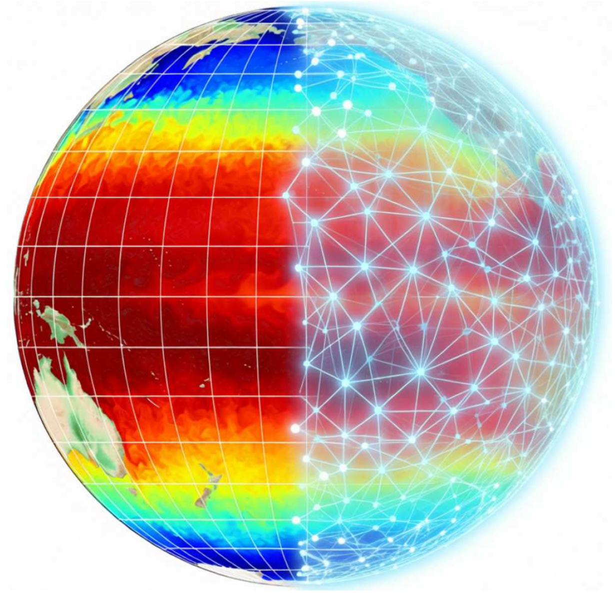

图 2 数据与理论协同驱动的超高分辨率全球海洋数值模式
Figure 2 Ultra-high-resolution data-and theory-driven ocean model

4 多尺度海气相互作用的机理与极端气候事件

海洋主要通过海气界面的热量、动量和淡水通量交换调控全球能量平衡与水循环. 当前海气相互作用理论主要集中于千公里以上的大尺度过程, 对中尺度(10~100 km)、亚中尺度(1~10 km)以及小尺度(0.1~1 km)的海气耦合机制缺乏深入认识, 制约了对关键海洋过程和极端气候事件的模拟能力, 成为影响气候预测精度的关键瓶颈(图4)[20]. 近年来的观测研究表明, 中尺度海洋涡旋与大气的相互作用能够通过改变海洋混合层结构影响副热带模态水的生成效率, 调节海洋对气候系统的记忆功能[21]; 中尺度涡旋和风场强迫共同作用可以导致次表层海洋热浪及其极端事件的发生[22]; 亚中尺度海洋过程造成的垂向热量输送可以超过中尺度涡旋数倍, 显著影响海洋上层热量分布及其与大气之间的能量交换[15]; 小尺度海浪能够直接影响海气界面的热量、动量和淡水通量[23]. 这些过程对台风、副热带风暴、大气河以及海洋热浪等极端天气气候事件的生成与演变也具有重要的调制作用[24,25].

因此, 系统揭示跨尺度海气耦合机理及其对气候系统(特别是极端气候事件)的调控规律, 是突破现有气候预测理论局限、提升气候预测能力和气候变化预估可靠性的核心途径, 也是全球变化研究领域亟需攻克的前沿科学问题.

5 复杂海底地形调控下的海洋能量物质循环

海洋是一个涵盖多种时空尺度运动的复杂巨系统, 上至海盆尺度的大洋环流, 下至微尺度的湍流混合. 为了维持机械能守恒, 海洋从大尺度风场和浮力强迫中获取的能量需要通过微尺度三维湍流实现耗散[26], 而两者的空间尺度相差6~9个数量级. 一方面, 能量从大尺度向小尺度的传递对于维持海洋能量收支平衡, 激发深海大洋湍流混合有着重要作用[27~29]. 另一方面, 深海大洋湍流混合通过驱动深海三维环流, 调控海洋的热量物质输运, 进而影响到整个气候系统[30]. 在这一跨尺度的能量传递链条中, 海洋中尺度过程所处的地转平衡状态形成了能量从大尺度向小尺度传递的动力屏障(图5)[31]. 能量如何突破中尺度地转平衡屏障, 向更小尺度传递, 是理解海洋中能量输运和传递过程的前沿科学问题.

复杂海底地形通过流固相互作用可以为打破地转平衡

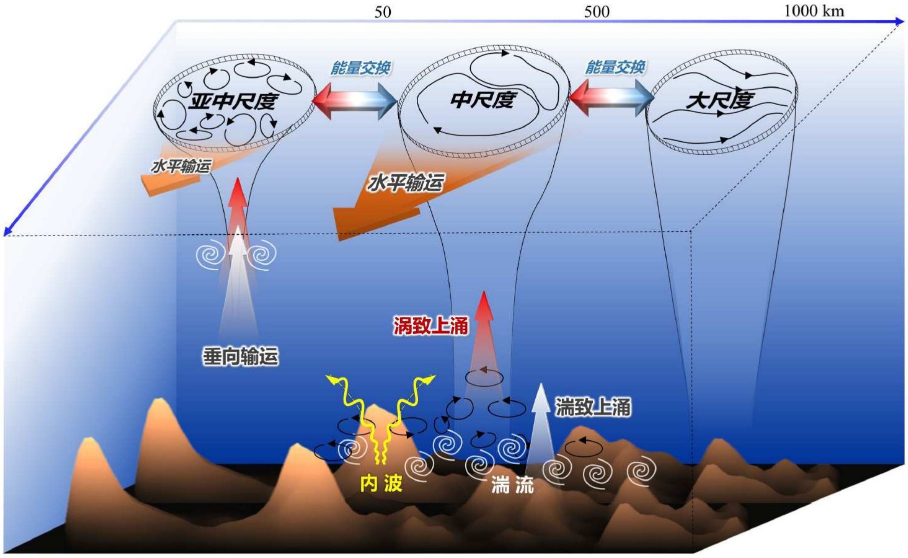

图 3 海洋中小尺度动力过程及其物质能量输运与气候效应
Figure 3 Transportation of energy and materials and climatic effects of meso-and submesoscale oceanic processes

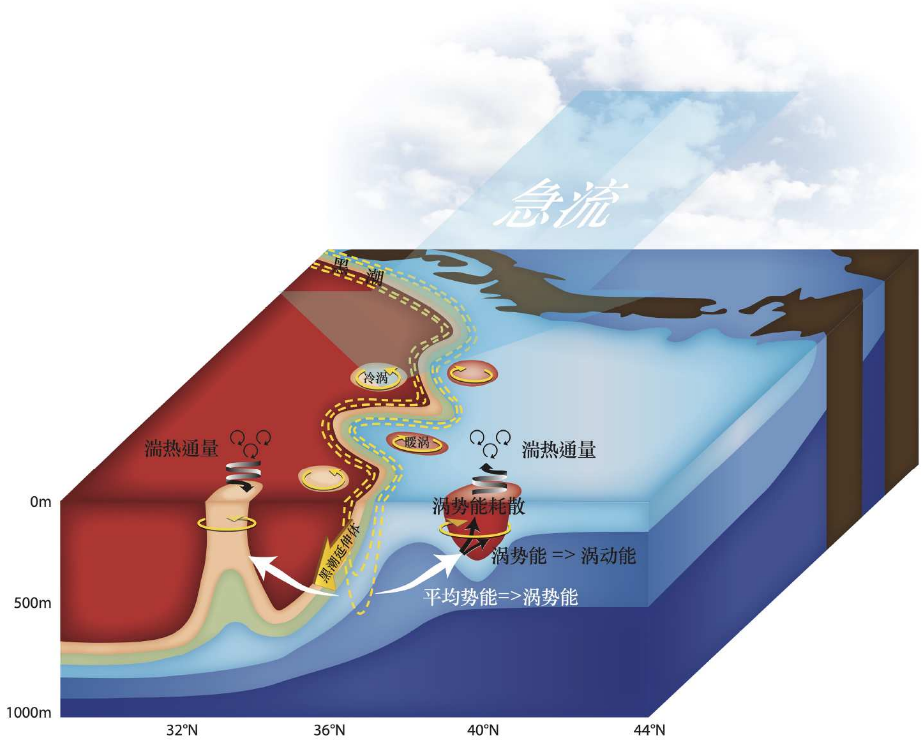

图 4 多尺度海气相互作用的机理与极端气候事件[20]
Figure 4 Mechanisms of multiscale ocean–atmosphere interactions and extreme climate events[20]

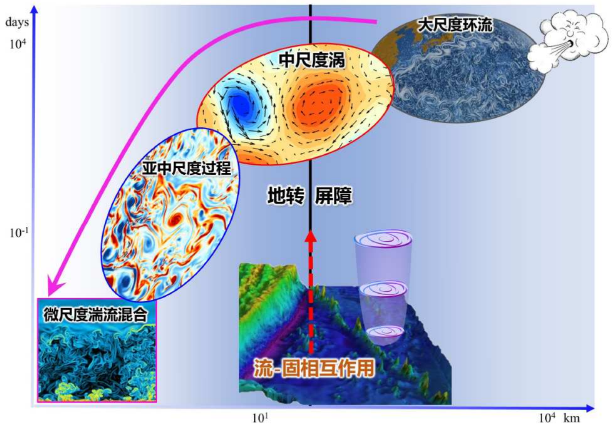

图 5 复杂海底地形调控下的海洋能量物质循环
Figure 5 Energy and material cycles modulated by seafloor topography

提供有利条件，驱动能量从海洋中尺度过程向更小尺度过程传递[32]．但是如何量化流固相互作用对跨尺度能量传递的贡献，厘清其在全球尺度上的空间分布及其对深海三维环流的影响机制，并在海洋和气候模式中准确参数化这些过程是当前物理海洋学研究的重要挑战．

6 极地快速变化的关键过程与气候效应

极地海洋是全球气候系统的“放大器”和“指示器”，其快速变化涉及一系列复杂的物理、化学和生物过程[33]，量化这些过程及其之间的相互作用，需要明确外部辐射强迫变化下海冰-反照率-温度反馈[34]、大气温度递减率反馈[35]、水汽和云-辐射反馈[36]、海洋和大气环流向极热输送[37]、海冰热力学过程、海洋中小尺度过程与海冰的相互作用以及海洋-冰架相互作用等关键过程的贡献与变化(图6)[38]．

目前地球系统模式基本涵盖了主要的大尺度反馈过程，但是模式模拟预测全球变暖下的极地海冰和海洋变化仍然与观测显著不同．这主要是极地快速变化导致海冰物理特性及与海洋大气相互作用发生了巨大的变化[39,40]，增加了海冰和海洋模式物理参数化和模拟的不确定性．发展适应海冰和海洋多尺度快速变化的海冰耦合模式，揭示海洋-海冰-冰架相互作用机制，提升海冰变化及其对海洋环流影响的模拟能力，是当前海洋和冰冻圈科学中亟待解决的关键问题．

7 深层海洋环流结构、成因与变异驱动机制

深层海洋(2500 m以深)的海水主要源于沿南极陆坡下沉形成的南极底层水，以及从格陵兰岛-冰岛-苏格兰海脊流出的溢流[5,41]．深层海水形成时会携带表层大气中的热量和二

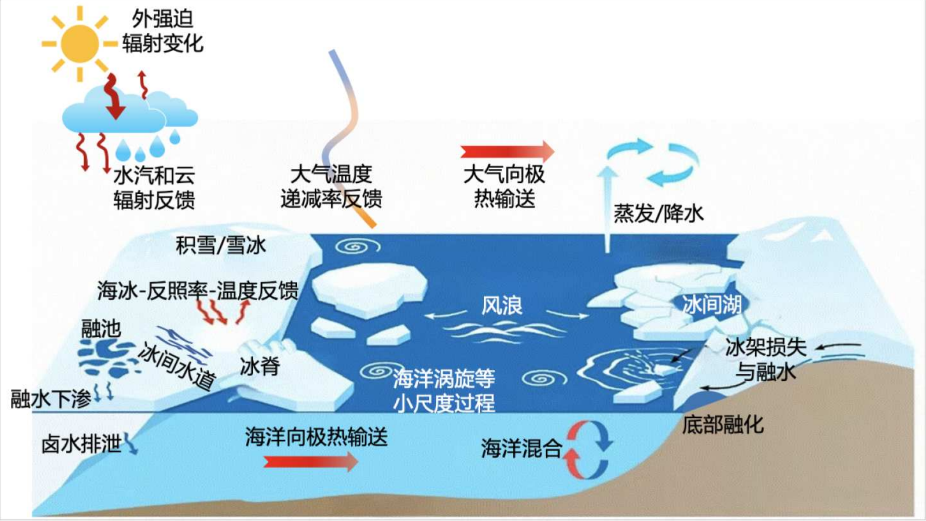

图 6 极地快速变化的关键过程
Figure 6 Key processes of polar rapid changes

氧化碳进入深层海洋，并通过深层海洋环流扩散和输运至全球大洋，构成了全球气候系统中最大的热、碳储库[42,43]．深层海洋环流的变异会通过调制深层海洋的储热、蓄碳能力，直接影响全球气候变化(图7)[44,45]．

在深海大洋，南极底层水与北大西洋深层水之间的“竞争”是塑造深层海洋环流结构及其变异的主要原因，也是大洋热盐环流的关键驱动机制之一．近几十年来，南极冰盖、格陵兰冰盖和北极海冰均呈现加速融化趋势，融冰形成的淡水注入导致南极底层水和北大西洋深层水同时呈现减缓的趋势[46]．作为大洋热盐环流的重要组成部分，两极中深层和底层水体形成的同时减缓将会对全球海洋造成怎样的影响、地球系统的碳循环过程将产生怎样的响应，全球气候将如何反馈，仍然有待深入探索．亟需借助深海Argo等观测技术的发展，获取更多现场观测数据，深化对深层海洋环流变异机制的认识．

8 大洋热盐环流变化临界点关键过程与可预测性

大洋热盐环流可能存在多种稳定态，从一个稳定态向另一个稳定态的变化会经历环流系统的临界点，即在该阈值附近，微小的外强迫作用就会导致系统产生本质性的变化(图8)[48,49]．进一步地，大洋热盐环流的临界变化可能会触发其他地球气候系统的临界翻转，导致地球气候出现不稳定状态[50]．

地球气候的长期演化记录表明，历史时期的海洋环流可能已经历过不同的稳定态[51,52]．然而，由于缺乏直接的观测证据，不同的稳定态之间的切换机制以及所对应的气候系统的背景条件特征仍不明确[53]．在现代全球气候持续受到温室气体排放导致的辐射强迫作用下，大洋热盐环流是否会在百年或千年的时间尺度上出现临界不稳定，仍然存在重大争议[54]．利用气候模式进行的敏感性实验虽然能够展示出气候系统在海冰、冰架和冰盖快速融化形成的淡水注入的情况下出现停滞，并触发热盐环流的临界不稳定[51]，但是其物理过程尚未得到观测证实．阐明大洋热盐环流系统的临界不稳定特征与翻转机制仍是深入理解人类活动影响气候变化作用的核心挑战之一．

9 复合胁迫作用下河口-近海系统的韧性调控

河口-近海区域是陆地-海洋-大气耦合的关键界面，其物质通量(有机碳、营养盐、沉积物等)在河流输入、潮汐混合、海浪以及极端天气气候事件(风暴潮、河流洪水)等因素的协同驱动下，形成了具有高度非线性的物理-生态耦合系统(图9)[55]．全球气候变暖以及人类活动(如河流建坝、岸滩围垦、污染排放、海水养殖)的复合胁迫作用扰动了自然状态下的界面交换过程，削弱了河口-近海系统原有的缓冲能力，并降低了其应对环境变化的韧性[56]，使得其水文特性、生物地球化学循环和生态系统均发生深刻改变[57]．

传统物理海洋学模型通常将水文动力、生物地球化学和生态过程分别处理，难以真实反映河口-近海系统中多界面、多尺度过程对自然与人类活动复合胁迫作用的非线性反馈机制，制约了对河口-近海系统韧性变化机制的理解、预测与调控能力[58]．亟需发展跨学科综合观测与高分辨率耦合模型，通过精细化辨析多尺度界面过程、量化韧性指标，揭示自然与人类活动的复合胁迫作用的级联效应，实现能够捕捉“极端事件-界面过程-系统功能”连锁反应的海岸带预测体系，为海岸带的适应性管理提供科学依据[59]．

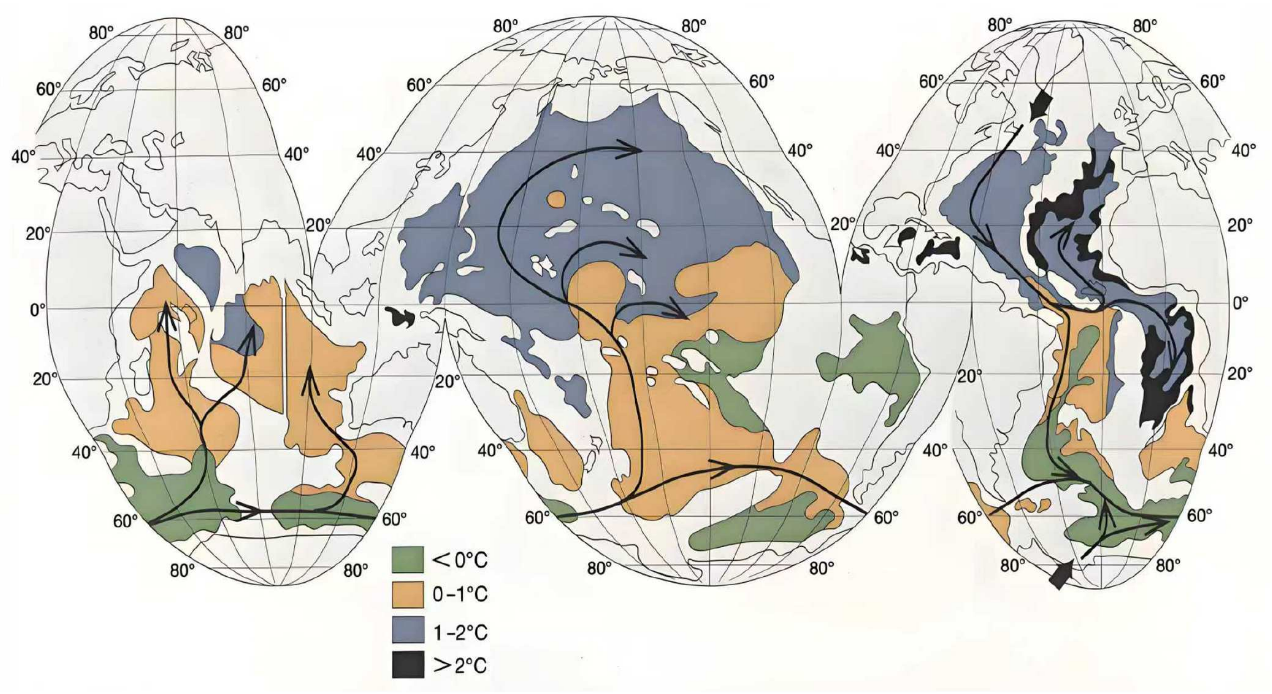

图 7 深海环流[47]
Figure 7 Abyssal currents in the world's ocean[47]

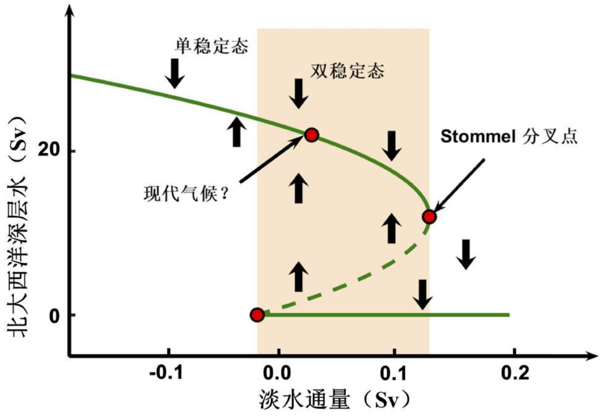

图 8 大洋热盐环流变化的临界点[51]
Figure 8 Tipping point of ocean thermohaline circulation[51]

10 海洋动力过程对碳-氮-氧生物地球化学循环的影响

海洋动力过程(包括混合、上升/下沉和通风等)深刻影响海水中碳、氮、氧的分布与输运，并与初级生产、再矿化和微生物代谢等生物地球化学过程一起形成复杂的耦合系统(图10)[61,62]. 当外部强迫接近阈值并引发动力过程转变时, 这种动力-生地化耦合可能触发碳、氧与营养盐循环的收支与时空分布的结构性响应与反馈，并进而影响气候系统的稳定性[63,64].

观测研究表明，锋面、亚中尺度涡与中尺度涡能够在短时间尺度上迅速调配营养盐与溶解性气体、改变初级生产与再矿化深度[65,66]，但其对全球碳、氮、氧收支的净效应仍缺乏一致量化. 在持续增暖与淡化背景下，大西洋经向翻转环流与南极底层水可能的减弱会抑制深层通风与向深海的碳、氧输送，降低深层碳储存与含氧量并提高中层缺氧风险[67]，但是这些长期物理变化趋势及其对生物地球化学循环的具体反馈仍缺少直接观测证据与明确归因. 阐明海洋动力过程主导的碳、氮、氧循环的长期变化机制及其对全球变暖的反馈作用，建立面向关键通道的持续观测与一体化模拟框架，是深入理解气候变化下海洋反馈机制及维护海洋健康与生态系统稳定性的核心挑战之一.

11 结语

上述问题涵盖了物理海洋学的主要研究范式、研究方向与基础理论问题. 我们相信，部分问题会在未来的5~10年内得到解决，例如超高分辨率的全球海洋模式会随着量子计算与人工智能的飞速发展成为可能；深层海洋环流结构及其变异会随着深海自持式剖面浮标与深海实时通信潜标等一系列新型观测技术手段的出现而获得新的观测，推进理论认识的突破与创新. 有些问题可能需要更长的时间才能够形成显著的进展，例如海底流固耦合过程及其对气候系统的影响、海洋动力过程与生物地球化学循环的关系等问题. 但是,

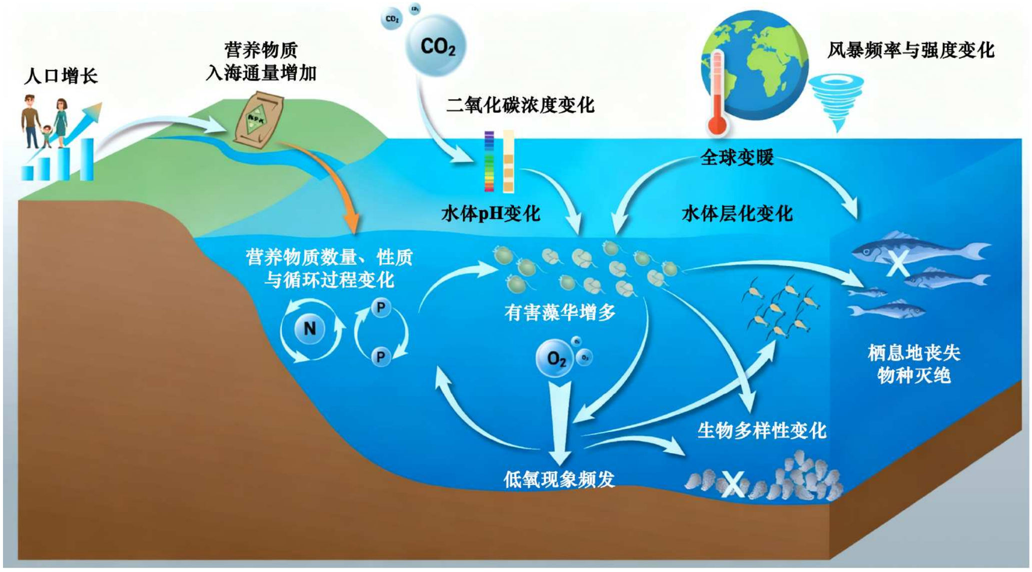

图 9 复合胁迫作用下河口-近海系统的韧性调控[60]
Figure 9 The complexity of interactions of multiple stressors in aquatic systems[60]

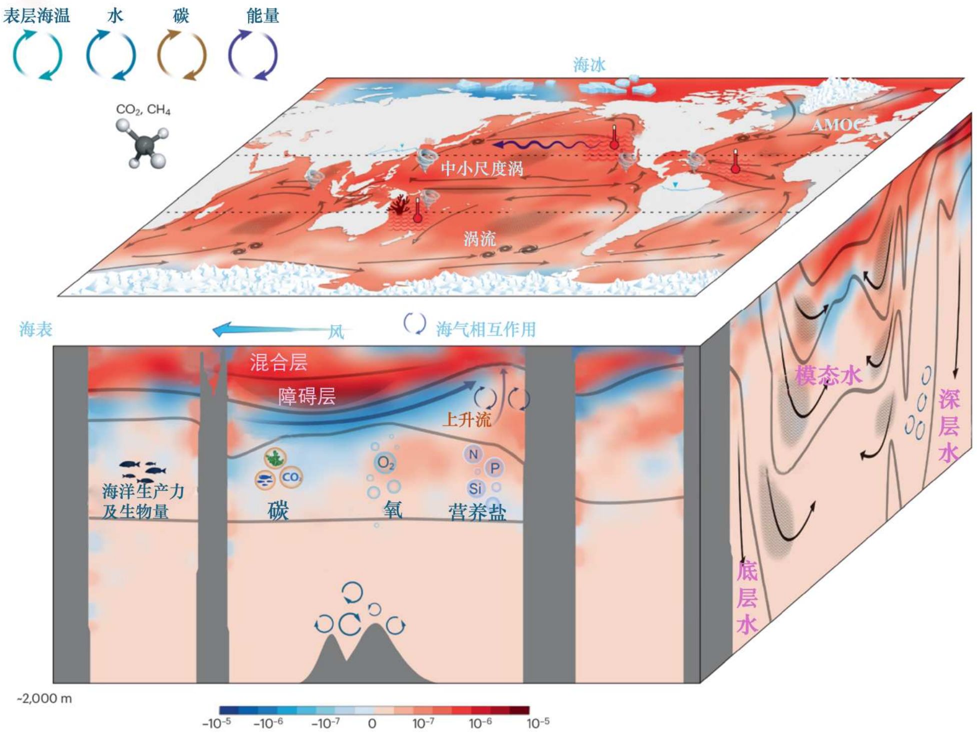

图 10 海洋动力过程对碳-氮-氧生物地球化学循环的影响[68]
Figure 10 Impacts of ocean dynamical processes on physical and biogeochemical ocean systems[68]

持续地关注并研究这些问题, 将极大地丰富我们对于全球海洋的认识, 推动物理海洋学的发展.

同时, 我们也清楚地认识到上述前沿科学问题不可能覆盖物理海洋学的各个角落. 随着更多的观测现象、更多的理论发展, 一定会涌现出一批新的、超出“十大”前沿科学问题范围的新挑战和新前沿, 正如我们回望老一辈的物理海洋学家分析定点的温度-盐度剖面观测以及更早的学者认为深层海洋几乎是静止的一样. “物理海洋十大前沿科学问题”的初

衷是沿着这些主要方向深入研究，在持续推进物理海洋学乃至地球系统科学发展的进程中，持续用新的问题替换“已得以解决”的问题，实现关心海洋、认识海洋和经略海洋的目标.

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Summary for “物理海洋十大前沿科学问题”

Ten priorities for Physical Oceanography

Lixin Wu[1,2,3*], Xianyao Chen[1,2], Zhaohui Chen[1,2], Zhao Jing[1,2,3], Xiaohui Ma[1,2,3], Bolan Gan[1,2], Chun Zhou[1,2], Zhiwei Zhang[1,2], Longjiang Mu[3], Dehai Song[1,2], Wenli Zhong[1,2], Di Qi[4], Jiping Liu[5], Zhiyu Liu[6], Zhenya Song[7] & Haijun Yang[8]

[1] *Frontier Science Center for Deep Ocean Multispheres and Earth System, Ocean University of China, Qingdao 266100, China*
[2] *Physical Oceanography Laboratory, Ministry of Education, Ocean University of China, Qingdao 266100, China*
[3] *Research Division of Ocean Big Data and Artifical Intelligence, Laoshan Laboratory, Qingdao 266237, China*
[4] *Polar and Marine Research Institute, Jimei University, Xiamen 361021, China*
[5] *School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai 519082, China*
[6] *College of Ocean and Earth Sciences, Xiamen University, Xiamen 361102, China*
[7] *First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China*
[8] *Department of Atmospheric and Oceanic Sciences, Fudan University, Shanghai 200438, China*
* Corresponding author, E-mail: lxwu@ouc.edu.cn

Physical Oceanography is a fundamental discipline for gaining an in-depth understanding of the ocean and its role in the Earth system. It primarily studies the dynamic and physical properties, processes, and mechanisms of the ocean by analyzing movements, distributions, variation of physical and biogeochemical properties of seawater. Over the past century, physical oceanography has evolved from observing, discovering, and understanding regional-scale phenomena into a science that systematically reveals the ocean’s variability and its role in the Earth system from a global perspective, relying on observations, theories, and numerical models. Driven by the needs of human social development, continuous innovations in observational technologies, rapid improvements in computing capabilities, and the widespread application of artificial intelligence theories and methods, physical oceanography has become an interdisciplinary science integrating theories, technologies, and engineering, which equally emphasizes ocean exploration and ocean governance and is driven by multiple application scenarios.

Ocean plays a unique role in global climate change. In the past century, global climate has been continuously warming under the forcing of greenhouse gas emissions from human activities. During this process, the ocean fundamentally mitigates the rate of global anthropogenic warming, by absorbing more than 90% of the excess heat in the entire climate system and over 30% of the greenhouse gases emitted by human activities. Obviously, a better understanding of the dynamic and physical properties, processes, and mechanisms of the ocean is the core foundation for further clarifying the ocean’s role in global change and the impact of human activities on the Earth’s climate system.

In this context, we systematically reviewed developments and trends of physical oceanography, summarized grand challenges of physical oceanography from three dimensions—research paradigms, spatiotemporal scales, and interface interactions, as follows:

(1) Research paradigm: it encompasses observation, numerical simulation, theoretical analysis, and artificial intelligence. Developing new observational technologies, enhancing the construction of ocean observation systems, and acquiring ocean observational data have always been the foundation of the development of physical oceanography. Meanwhile, since no observation system can achieve full and real-time coverage of the global ocean, it is necessary to rely on computer technologies, including computational fluid dynamics and artificial intelligence, to simulate and fully understand the variation processes of the entire ocean.

(2) Spatiotemporal scale: global ocean experiences multi-scales temporal and spatial variability, ranging from seconds, minutes to thousands or even tens of thousands of years, and from centimeters, meters to thousands or even tens of thousands of kilometers. Oceanic changes involve energy exchange and interaction between movements across the aforementioned spatiotemporal scales.

(3) Interface interaction: it includes not only connections between estuarine and coastal areas and the deep ocean, and between seawater and ice, but also interactions between the ocean and the atmosphere, the ocean and the land (including the seabed), and the ocean and the biosphere.

Based on these three dimensions, we refined our understanding into Ten priorities for Physical Oceanography. They are: (1) construction of a cross-scale, real-time global ocean observation system; (2) development of ultra-high-resolution global ocean numerical models and ocean digital twin; (3) meso-and small-scale dynamic processes in the ocean, and their material and energy transport and climatic effects; (4) mechanisms of multi-scale air-sea interaction and extreme climate events; (5) marine energy and material cycles regulated by complex seabed topography; (6) key processes and climatic effects of rapid polar changes; (7) structure, causes, and driving mechanisms of deep ocean circulation; (8) tipping point of thermohaline circulation and its predictability; (9) resilience regulation of estuarine-coastal systems under compound stress; (10) impacts of marine dynamic processes on carbon-nitrogen-oxygen biogeochemical cycles

Ten priorities for Physical Oceanography outlines the core development directions of physical oceanography in the coming period and will promote a deeper understanding of the ocean and its role in the Earth system.

Physical Oceanography, multiscale processes, interactions, artificial intelligence

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