全球气候变化下海洋环流多尺度演变:联动协同与环境生态效应初探

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摘要:海洋环流是海洋系统物质能量收支、配置、平衡、维持和变化的关键通道与机制。从全球海洋视角,基于目前海洋环流多变率动力过程与趋势演变的认知,重点综述气候变化下海洋环流的海盆尺度三维联动特征机制、洋际交换与协同、世界大洋经向输运变化以及相关的海洋气候与环境生态效应,依据研究现状和需求,提出研究建议。结果表明:全球一致性变暖路径与进程调控下,受驱动因子的演变与胁迫,海洋环流变化对副热带中高纬地区年际、年代际气候与环境变迁具有突出作用影响,并可产生显著环境生态效应和严重致灾风险。建议加大专精特新观测仪器自主研发,通过国际合作加大中高纬海洋环流多尺度动力过程综合调查的参与度和主导性,增强多学科融合交叉研究力度,有效提升深层次海洋环流变异及动力、环境、生态灾害影响的气候变化综合风险预测预评估和防治能力,为海洋领域能源开发、生态系统保护、气候变化应对与灾害风险治理提供必要的动力学参考。

关键词:翻转流;边界流;潜流;上升流;绕极流;贯穿流;热盐环流;中高纬灾害风险

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Multiscale Evolution of Ocean Circulation Under Global Climate Change: Linkage, Synergy and Environmental Ecological Effects

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Abstract: Ocean circulation is a key channel and mechanism for the budget, allocation, balance, maintenance, and change of ocean material and energy. From the global ocean perspective, based on the current understanding of multi-scale processes and trend evolution of ocean circulation dynamics, this paper focuses on the overview of basin-scale three-dimensional linkage mechanism, interoceanic exchange and synergy, meridional transport changes and related

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marine climate and environmental ecological effects of ocean circulation under global climate change, and puts forward heuristic suggestions according to the current research status and deficiencies. The results show that under the regulation of global consistent warming pattern and process, due to the evolution and stress of driving forces, the changes of ocean circulation play an important role in regulating the inter-annual and inter-decadal climate and environment variations and can generate outstanding environmental ecological effects and serious disaster risks in subtropical mid to high latitude regions. It is suggested to increase the independent research and development of refined, special and new observation instruments, enhance the leadership and participation of mid to high latitude comprehensive marine investigation of multi-scale dynamic processes of deeper ocean circulation through international cooperation, highlight the integration and cross-disciplinary research efforts, and effectively improve the capability for forecasts, projection, assessment and prevention of the comprehensive risks of climate change affected by ocean circulation variability and the dynamic environmental and ecological disasters, with the aim of providing necessary hydrodynamic reference for marine energy development, climate change adaptation and disaster risk governance in the marine field.

Keywords: Overturning current, Boundary current, Undercurrent, Upwelling, Circumpolar current, Throughflow, Thermohaline circulation, Mid to high latitude disaster risks

0 引言

海洋是地球气候系统的重要成员[1],海洋环流则是系统内物质能量输运、维持和再配置的关键动力载体[2],进而成为海洋沉积地形分布、融冰速率、经济鱼类密集、海洋生产力分区和海洋可再生能源开发的主要动力途径[3-5],作为海洋与天气气候模式的重要塑造力[6-7],海洋环流更是海洋与气候孕灾、成灾、灾变与协同致灾的直接动力基础[8]。尤其海洋充当地球系统中最大的碳库,在全球气候变化中起着控制性作用。其中海洋环流通过热量配置以及调控海洋对大气中 CO_2 的收支,影响着全球气候变化的方向、路径与进程[3,9]。20 世纪 90 年代以来,随着世界大洋环流实验(WOCE)的实施,各大洋西边界流得到观测,海洋环流要素得到量化,全球海洋环流的物理图景逐步建立[10]。同时,有关海洋环流结构与变化,及其通过参与生物地球化学循环和海气相互作用等过程影响海洋与气候、生物生态和冰冻圈的认识也不断丰富,取得了较大进展。深入认识海洋环流多尺度特征、趋势演变及其海洋气候与环境生态效应,是当前践行人与自然和谐共生的生态文明思想和实现海洋气候与环境生态安全保障的重要组成部分。需指出的是,受陆地分隔等大地形、季风和行星风系、淡水和热盐通量及局地多尺度热动力过程等综合影响,不同洋盆各类型环流体系和分支具有独特性,差异明显[11]。为系统透析和深化对海洋环流本身复杂性及其气候与生态影响风险的相关认知,本文试图基于海洋的连通性与海洋环流链接,从全球海洋系统整体性视角,突出大尺度海洋环流的联动效应以及气候变化下的低频尺度演变,分别从全球气候变化下海洋环流的洋域三维联动效应、洋际交换协同效应以及气候环境生态效应 3 个方面简述海洋环流变化的多尺度变率特征与气候趋向及关键影响风险研究的基本现状。并围绕以上主要科学问题探讨提出相关研究的不足、未来需求与研究建议,以期为我国海洋高质量可持续发展、海洋强国建设的安全保障、海洋命运共同体构建以及深度参与全球海洋治理提供科学参考和科技支撑。

1 气候变化下海洋环流热动力学驱动因子演变特征

海洋环流一般由海洋内部热盐或淡水通量引起的密度不均匀(浮力强迫)和海面风应力等外强

迫导致的动量通量(包括内潮和湍动混合动力过程等)驱动[12-13]。为理解海盆尺度和全球三维海洋环流的多尺度运动,尤其是低频尺度动力特征和趋势规律,本节首先简述气候变化下海洋环流的主要强迫和胁迫因子及相关要素的演变特征。

1.1　全球升温背景下海洋暖化、淡化与酸化特征

联合国政府间气候变化专门委员会(IPCC)第六次评估报告(AR6)指出,近年来,全球大幅度升温,2001—2020 年平均温升较工业化前(1850—1900 年)增加 0.99℃,而 2011—2020 年相比工业化前增暖了 1.09℃。气候正在全球性迅速变暖[14],在此背景下低层极赤温差呈现减小趋势[15]。海洋是地球气候系统最重要的组成部分。海洋吸积的热量通过海洋经向环流输送至中高纬度海域,是维持地球系统能量平衡的重要机制,调节着全球气候变化。通过海洋不同气候态的对比研究证实全球海洋暖化显著[16],不同洋盆尺度南北海洋热力梯度变化存在差异,尤其对副热带西风急流具有重要调控作用[17]。

作为气候系统的核心过程之一,水循环是联系地球各圈层能量转移的重要渠道,也是不同水体交换、迁移运动的驱动机制[18]。对淡水通量(蒸发与降水之差)的分析表明,气候变暖虽倾向于增强全球水循环,然而极区体现了更强的物质能量与水分循环特征,导致高纬度地区更为淡化,中低纬度地区则趋于咸化。这种趋势可弱化海洋经向盐度梯度,减缓海洋的垂向混合,增强高纬度海洋暖化,推进全球海洋变暖一致性进程[19-20]。同时,受当前全球水循环"干更干、湿更湿"模式驱动,海洋呈现"咸更咸、淡更淡"的发展态势[21],上层海洋层结加大[22],也对大洋通风过程和海洋深层混合产生重要影响,更易于上层海洋全球性暖化[23-24]。

海洋是吸收和存储大气 CO_2 极其重要的汇区[25],大气 CO_2 排放的增加,在造成气候变暖的同时,也增强了海洋对 CO_2 的吸收,进而导致海洋酸化,特别是,由于海洋环流的变化以及对大气 CO_2 的输运,海洋酸化逐步由开放海域向海岸带以及海洋深层次发展。海洋酸化对海洋生物多样性和生态系统功能产生了严重影响[26]。目前预测结果显示,在全球变暖背景下,海洋酸化速率和幅度均大于海洋的暖化程度[27],值得提出的是,海洋暖化会影响海气 CO_2 通量[28],一定程度加剧气候变暖,海洋暖化和酸化的互作关系是海洋气候变化研究的重要科学问题。

1.2　全球升温背景下季风与行星风系演变特征

季风为海陆热力驱动下的大尺度环流,对大洋边界流变异具有重要作用[29]。气候变化可能影响季风环流的位置、强度和持续时间[30]。数据和模式结果分析显示,南亚夏季风(印度洋夏季风)在气候变暖背景下呈减弱趋势[31-34]。东亚季风近几十年呈现显著的年代际变化特征[35-36],特别是东亚夏季风自 20 世纪 70 年代末表现减弱趋势[37],但其变化更倾向于位置的改变[38]。分析表明,澳洲季风和北美季风同样趋于减弱[39-40]。季风还受到其他因子的调控,如北大西洋的升温,则有利于北美以及南美和非洲季风的增强[41-42],这种不同驱动因子多尺度变率的叠加为全球季风未来演变的分析评估带来一定困难。

作为对全球变暖的响应,热带大气环流中纬向 Walker 环流呈减弱趋势[43]。Hadley 环流与 Ferrel 环流表现为减弱,且倾向于向北扩张[44-45]。气候变化下南北半球高纬度西风带向极迁移明显且呈增强趋势[46-49],但半球间存在不对称性,南半球西风变化幅度较大[50]。另外,分析显示信风总体有增强迹象[51],而赤道信风趋于减弱[52]。

总体言之,全球变化背景下,受人类无序活动影响,地球气候系统热能量增加[53],系统临界状态明显,海洋热带化极向扩张,低纬度分异梯度(海洋热力对比和驱动力)总体趋于减弱[54],且同步一致性倾向增强[55],大气强迫体现为热带环流的普遍减弱,以及副热带环流极向迁移和偏高纬度的增强[48]。当前需关注的是,在全球一致性变化进程中,受环境梯度的影响,气候变暖的扰动激发,使得中高纬度地区的响应日趋显著,尤其地球气候系统状态平衡的能级和级联调整与转换过程中的不确定性、突发性和联合致灾危险性将可能在相应地区加剧,严重影响人类的生存和发展,因此,从地质学[56]和星系尺度(如,卫星尺度、行星尺度和恒星尺

度)，特别是结合月地、日地系统结构和稳定性[57-58]，考虑自然变率和可控人类活动，针对地球气候系统动力演化和宜居性研究亟待开展。

2 气候变化下洋域海洋环流体系及三维联动效应

对海洋三维环流的认识，是深入理解海洋动力学，以及评估海洋对地球气候响应与反馈及海洋生态系统影响的基础和关键。本节围绕海盆尺度大洋环流的纬向配置、垂向交换和经向输运特征，分析气候变暖背景下大洋环流体系的三维联动效应和趋势变化。整体洋盆的环流体系一般由位于副热带(热带环流或赤道流可看作为其低纬度边界)或亚极地海洋的大型涡旋式环流圈(如副热带环流、亚极地环流和南半球的巨型环流[59])支配，其西边界则为西边界流系统，其中低纬度西边界流源于赤道流系及其分岔。为体现洋盆尺度环流的三维动力结构与联动效应，这里讨论的环流类型主要包括大洋内部整体环流圈以及赤道流、潜流、上升流、下降流、大洋边界流等。

数据与模式分析发现，南北半球副热带环流存在极向扩展趋向[60-61]。其中，20 世纪 70—80 年代，北太平洋副极地和副热带环流圈增强了约 10%[62]。北太平洋副热带环流圈的增强主要源于风应力的加大[63]。卫星和 ARGO 数据分析显示，南太平洋副热带环流圈在 2000 年代期间呈增强趋势，其中上层 1 000 m 增强幅度约为 20%～30%，深层增幅约为 10%～30%[64]。耦合模式分析表明，气候变暖会加快南极融冰，加大南大洋的热吸收，并增强南大洋副热带环流圈[65]。北大西洋副热带环流在 20 世纪 90 年代中期存在由强变弱的突变，模式诊断显示，除了大气强迫本身外，还与北大西洋涛动(NAO)密切相关[66]。相比而言，南大西洋副热带环流圈趋于增强，并具有极向扩展趋势[67]。另外，南半球环状模正位相和西风加大背景下，南半球的巨型环流圈趋于增强[68-69]。总体上，海洋副热带环流的气候趋势对应大气强迫的演变特征。

2.1 纬向配置

由于信风等驱动因子的相似性，热带大西洋和热带太平洋盛行东西纬向的环流，且在季节和年际变化尺度具有诸多共有特点[70]。模式结果显示，受 Walker 环流减弱的影响，赤道环流趋于减弱[71]。然而，就热带大洋平均环流而言，对其的能量(以全球积分总动能为表征)分析表明，在表层风驱动增强下可表现出显著增强趋势，由于缺乏深层环流数据且仅考虑风强迫下(未考虑浮力强迫、潮汐引发的湍动混合等[72-73])的机械能输入与转换部分，其积分结果存在诸多不确定性[74]。模式结果的分析评估进一步表明，海洋层结在加速大洋副热带环流圈的同时，也增强了南大洋纬向环流。另外，海洋暖化可加速全球海洋 77%的上层环流，而对深层环流主要起减缓作用[75]。

赤道太平洋因其大的纬向跨度，在全球气候系统中具有重要地位。其平均态的微小变动足以驱动大幅度局地和远地气候影响。一般而言，赤道太平洋平均态以海表温度的纬向梯度来表征，并与大气在年际尺度上强烈耦合。有数据分析显示，赤道纬向风应力的减弱将造成赤道太平洋上层海洋西向动量的减弱，引起东向赤道潜流(虽为多种机制驱动，这里可看作为表层环流在深层的回流形式)的增强，并作为东边界上升流的源流之一，进一步导致赤道东太平洋的降温，最终增强海表温度的纬向梯度[76]，以上过程尚未被模式成功模拟。此外，大西洋赤道潜流近期有增强趋势[77]，并受到海洋波动的影响[78]。分析表明，印度洋偶极子的伴随风场对印度洋赤道潜流具有维持作用[79]。然而，由于基础数据的不足和模式性能限制，目前对海洋深层次输运的分析甚为匮乏[80]，这对海洋热储存能力以及海平面上升的气候变化评估造成极大影响。由此可见，大洋环流的纬向三维配置特征规律还存在很大不确定性。研究结果总体表明，低纬度海洋环流可能趋于弱化，而热带和副热带上层海洋环流主要以增强为主，且中高纬度更为明显，然而，随着气候变暖的加剧，海洋环流的纬向配置临界特征日趋显著。相关科学问题是今后海洋环流气候变化研究的关键。

2.2 垂向交换

通风过程是海表混合层水体向大洋内部输送和输出的重要通道机制[81]，分析表明，南极绕极流

通过大洋内部通风过程成为其他洋盆海洋水团的主要容纳器。另外,气候变化导致的通风异常可通过潜沉和对流浮露等通风过程影响远地的大气[82]。由于自然变率、气候变化的复合以及区域性差异的影响,未来海洋通风过程的趋势演变也存在很大的不确定性[83]。目前,受数据限制,相关的研究存在较大欠缺,尤其针对全球海洋水体交换,围绕海洋水团[84]形成(年龄)、分布、变性和生消的动态演化和深层次特征规律研究尚待深入系统开展。

上升流系统是大洋垂向交换的重要机制,主要位于太平洋和大西洋,海盆尺度的配置决定了上升流生态系统的特点,信风使得海洋热量和质量在海盆西部累积,造成海盆东、西部温跃层的加深和上抬。分析表明,大洋东边界的上升流通过大气强迫、温跃层形势、生物地球化学循环以及食物网链动力学耦合综合影响上升流生态系统,并具有显著的年际和年代际变率[85]。特别是,由于热量和质量在纬向上的再配置,加之赤道低与副热带环流区高的温跃层经向模态,以及不同的营养盐分布和高纬度混合与锋区影响,使得不同东边界上升流生态系统具有经向依赖性[85]。预估分析显示,气候变化增强了上升流风场,尤其中高纬度东边界上升流普遍呈现持续期加大、强度增加趋势[86-87]。然而,大洋东边界上升流生态系统在风场动力强迫、营养盐深度调控、海洋酸化、缺氧和气候变率等多因子胁迫下对气候和全球变化的响应较为复杂[88],不同区域上升流系统气候变化有待系统研究。同时,相关模拟预估分析能力尚待提升[89]。相较于东边界上升流系统的生态重要性,西边界上升流的研究较少,分析显示,就全球尺度而言,绝大部分西边界上升流加强[90]。另外,有利于下降流的风场也趋于增强,但趋势不显著[91],由于数据的不足,下降流相关研究较少。鉴于海洋环流作用下的垂向交换是海洋气候以及全球气候变化进程研究的重要课题,尤其应结合海陆气相互作用,将气候变化下中高纬度大尺度的和深层次海洋环流与垂向交换的机制机理和分析评估作为今后研究的重点。

2.3　经向输运

东西边界流受到风驱动、斜压强迫、地形影响与年际和年代际气候变率调控[92],具有多尺度特征[93],并在海洋经向热输送中具有举足轻重的地位。由于西向强化和极向输运的重要作用以及对周边区域气候产生的严重影响,海洋西边界强流得到更多的关注[94]。黑潮和湾流分别为太平洋和大西洋副热带西边界流系统,模式分析显示,气候变暖背景下,由于热盐响应和风强迫的差异[95],湾流呈现减弱趋势,黑潮则趋于增强[96-97]。而印度洋的安格拉斯流,因受到海洋涡旋的调控,并无趋势性变化[98]。但在季风驱动和地形地貌的影响下,印度洋边界流可通过季节性上升和下降流对生物地球化学循环和生物生态系统产生显著影响[99]。分析表明,大西洋的巴西海流极向扩展和增强趋势明显[100],同时,东澳大利亚流向南扩展显著,但强度趋势变化不明显[101]。值得关注的是,东西边界流是理解和观测气候变化影响与气候变化区域响应的关键动力过程。目前相关的观测研究仍有待加强[102],特别是针对中高纬度和深层次边界流的探测和监测体系亟待建立和完善。

热带低纬度和极地高纬度净辐射的不对等造成地球系统能量的失衡。而地球系统的能量平衡则主要由经向环流来维持。其中,热盐环流是海洋中经向能量输送的动力承载,以高纬度水团下沉和低纬度水团上升为特征,不同尺度的变化主要由浮力通量和风应力驱动,承担着全球大洋 90%的水体输送量[103-104]。相比于北太平洋和北印度洋,北大西洋具有盐度更高(高密度)的海水[105-106],大西洋翻转环流(又称大洋传送带)以其层次深、强度大而成为全球大洋热盐环流的代表,它是地球系统年代际气候变率和气候突变的重要机制[107-109],同时,大西洋翻转环流被认为是地球气候系统(网络)重要的临界要素,大西洋温盐环流与其他临界要素之间的关联和遥相关是分析地球气候系统稳定性(如,跃迁和崩溃等)的关键科学问题[110]。分析表明,大西洋翻转环流年代际变化明显,且与海表温度、对流活动、NAO 和北极融冰等气候要素间存在着协调关系[111-113]。气候变化下全球大洋热盐环流演变的评估尤为重要。数据与模式预估分析显示,大西洋经向翻转环流具有减弱倾向[114-116],其中北极快

速融冰后对北大西洋的淡水注入有利于翻转环流的减弱[117]，而南大西洋底层水的暖化使得上层翻转环流圈增强了约5%～10%，进而可能抵消其减弱趋势[118]。近期有分析表明，过去30年北大西洋经向翻转环流状态稳定[119-120]。目前，有关大西洋经向翻转环流的长期演变特征尚无定论[121-122]。模式分析显示，气候变暖背景下，印太翻转环流增强约30%[123]，其中印度洋一致性增暖对其具有重要贡献[124]。太平洋浅层经向翻转流对上层海洋热含量的年际和年代际纬向配置具有重要影响，同时，不同纬度热传输的异常变化与风驱动下西传的Rossby波有关[125]。数据和模式分析表明，整体而言，全球大洋热盐环流自20世纪80年代以来具有增强的演变特征[126]，然而，鉴于全球大洋热盐环流属于多平衡态系统[127-128]，其气候变化综合评估仍依赖于观测数据的丰富和数值模拟手段的加强[129-131]。

总而言之，全球变暖可基于地球气候系统热力配置，提高强迫因子分异驱动和负反馈(耗散配置)机制，如导致气候变暖暂缓[132]，海洋环流联动效应和多尺度变化是其重要的动力体现，尤其是海洋热带化和副热带环流极向扩张或中高纬度多尺度变异增强等。然而需进一步关注的是，气候变暖增强海洋副热带整体环流圈同时，强化西边界流对表层水的极向输运[133]，加大海洋深层次通风过程[134]，并通过海洋热盐环流等洋际交换的协同效应[135-136]，不断降低海洋经向和纬向热力梯度，减小海洋垂向热力差异[137]，增进地球气候系统临界状态转变，尤其是纬度配置，加快全球一致性变暖进程。相关机制机理研究尚有待系统建立和深入开展。下面围绕海洋环流的洋际交换及协同效应做进一步探讨。

3 气候变化下海洋环流的洋际交换及协同效应

印度尼西亚海、南极绕极区、阿古哈斯回折区和白令海峡为洋际交换提供了重要枢纽通道[138]。鉴于地球气候系统的整体性和海洋子系统的统一性，本节主要围绕贯穿流、绕极流、热盐翻转环流等，简述气候变化下海洋环流的洋际交换和协同效应。受地理位置(气候分区)、陆地分隔、形状(如，经向跨度)等大地形的影响，全球海洋表层热收支的不平衡通过海洋的连通性由洋盆间的海洋环流来补偿。印尼贯穿流链接太平洋和印度洋，除了表层热盐环流由太平洋向印度洋输运外，中层(约1 000 m)西边界强流及其翻转也起了重要作用[139]。模式分析表明，印尼贯穿流呈现显著减弱趋势[140]，且通过洋盆间的波动过程与大西洋经向翻转环流减弱产生动力关联[141]。印尼贯穿流对全球和区域气候的重要性体现于其对洋际海洋热量再分配和大气环流的影响[142-146]，然而，由于复杂地形和时空变化的多样性，对其观测具有较大挑战[147]，进而影响到有关多尺度变化的评估[148]。

南极绕极流是全球海洋最大的环流，它不仅链接三大洋盆，增强洋际交换和调控全球经向翻转环流的发展演化[149]，而且通过显著的等密度线倾斜将深海与大气连通，同时，对大气热量和CO_2的海洋吸收起着关键作用[150]。风强迫是绕极流输运变化的主要动力[151]，且绕极流对南半球环状模变化的响应敏感[152]，有分析显示，受西风加强的影响[48]，绕极流具有向南迁移迹象和总体增强趋势[153-155]，并通过加快深层暖水的涌升为南极冰融提供热量[156]。

北大西洋是全球海洋通过海气相互作用关联大气与深海的显著区域。其中，最重要的海洋动力体现是北大西洋经向翻转环流，它是全球热盐环流的重要组成和源流，前面主要针对热盐翻转环流洋盆尺度的变化变率和趋势演变作了探讨，这里主要简述其通过洋际交换的协同作用与影响。热盐翻转环流受到浮力(密度梯度)强迫、垂向混合、局地风驱动、边界波动、湾流和深层西边界流输运及内部Sverdrup平衡调整的影响[157]，主要通过浅层、深层和贯穿3个组分和跨密度面混合一个过程连通全球三维海洋[158-164]，并经能量、水分、热盐和碳循环与热辐射调整及深海交换过程影响区域气候变率、半球间的遥相关和全球气候变化[165-166]，其中，由翻转环流主导的极向热传输的半球不对称性，会对气候产生重要影响[167]。同时，经向翻转环流与海洋深层的层化密切相关，该大尺度环流通过经向的热输运以及调控与大气CO_2的交换，极大地影响着地

球气候系统的变化,在海平面上升、北极融冰、厄尔尼诺—南方涛动(ENSO)事件暴发、台风(飓风)产生以及极端气温等灾害中具有重大作用[168-169]。目前由于观测数据的缺乏,针对中、深层次经向翻转环流变化机制机理相关的理论和模拟还十分薄弱[170],对经向翻转环流的整体认识仍有待系统加强。总之,有关海洋环流洋际交换的协同效应研究,应更多地关注海洋环流引起的海洋环境梯度配置以及气候与环境改变[171],尤其是跨界面多圈层和多尺度变化及其反馈机制。

4　气候变化下海洋环流变异的海洋气候与环境生态效应

围绕热盐环流对气候、生态和社会经济等的影响预估表明,翻转环流的减弱降低了人类排放的 CO_2 进入深海的强度,进而调控未来海洋对热盐的配置[172]和 CO_2 的吸收[173-174]。热盐环流的减缓和停止会影响全球季风[175],引起北半球低温气候和全球海平面上升,至 2150 年,北大西洋沿岸海平面将上升约 80 cm,对沿海和海岸带的保护形成巨大挑战,同时由于生物生理热盐耐受所限,造成鱼类等海洋资源缺失严重[176-178]。

气候变化通过改变上升流系统物理、生物地球化学和生态特性,影响海洋生态系统的初级生产力,以及不同营养层次的生物产量和生物多样性,如,物种丰度[179-180]。东边界上升流系统是全球海洋经济和生态服务功能的重要贡献者。对东边界上升流系统强度、频率和持续性的分析表明,温室气体的排放加大了昼夜温差[181],从而增强了有利于上升流加强和持续的风场[182-185]。增强的上升流区会引发严重的海洋缺氧现象,影响海洋营养盐和碳循环、生态生境和海洋生物生产力[186-187]。需指出的是,上升流过程还会进一步作用于气候变化,减缓海洋暖化[181],降低海洋热浪发生[188]。研究发现,印度洋上升流区冷水的涌升以及表层的西向平流对印度洋偶极子(IOD)气候模态的触发具有重要作用[189]。并且,海洋环流通过涌升和下降过程影响深层次海洋热输送,模式分析显示,气候变暖背景下,暖水涌升和冷水下沉过程处于崩溃,而通过半球间的翻转(暖水下沉)过程增强,使得深海趋于暖化[190]。另外,沿岸下降流在保持海水暖化的情形下,可增强海气温湿差异,加大台风登陆的影响[191]。

大西洋和太平洋西边界流在北半球环状模建立与气候影响中起着关键性作用[4]。分析表明,西边界流还对海洋深层次暖化具有促进作用[192]。西澳大利亚边界流强度在厄尔尼诺—ENSO 的调制下,对鱼类等脆弱性生态系统产生严重影响,由于气候变化下极端 ENSO 事件趋多[193],会进一步降低渔获量和典型生态系统的恢复力,增强灭绝风险[194]。然而气候变暖背景下针对不同气候区、生境类型、营养层次和深度范围的相关综合风险评估还十分缺乏。

值得关注的是海洋环流对生态环境具有重要影响。海洋整体环流圈内大海洋垃圾带是 Ekman 动力学在表层环流的重要体现[195-197]。数值模拟分析显示,受北太平洋副热带涡旋洋流系统的主导作用,日本福岛核泄漏在海洋的传输路径首先向东到达东太平洋,而后向南向西扩散至西太平洋[198]。包括核污水排放等后续相关的观测和监测研究具有重要的科学与实践意义。

综上所述,全球变暖背景下,海洋环流造成的海洋气候与环境生态的关键风险在于,其通过界面交换、收支过程、纬度配置与海洋通风调节海洋高纬度和深层次暖化,调控海洋酸化[199],同时,海洋环流作为海洋碳循环和海洋含氧量变化的关键物理过程[200-201],会严重影响海洋生态系统的健康、生物多样性维持以及海洋生产力发展[202-203],并引发海洋热浪、台风、极地融冰、海平面上升、海洋缺氧与珊瑚白化等气候环境与生态灾害[204-206]。然而,由于对环流本身观测事实和历史演变特征规律认识的不足,针对海洋环流变异与影响的关键风险评估仍存在很大的不确定性。目前,尤其应防范海洋热带化背景下极端灾害风险的极向扩展,对于我国,致灾危险性的北移,如热带、副热带中高纬度地区可能是今后极端灾害防控的重要关注点。

5　存在不足

作为热量、动量、气体、水分、营养物质、海洋生物、污染物和辐射物等能量物质输运的关键动力载

体,海洋环流是海洋系统外源胁迫、热盐和生物地球化学平衡的大尺度动力学体现,调节着天气和气候环境变化,维持和影响着海洋生命体系和生态系统的结构安全与功能健康。海洋中的运动受到多种强迫因子的胁迫驱动,并具有显著的多时空尺度特征。认识海洋环流的三维体系结构以及季内扰动振荡、季节差异、年际和年代际变率与气候演变趋势等多尺度特征是海洋变化与气候环境效应研究的关键科学问题。为了深入理解海洋环流的环境生态与气候学意义,综合本文有关气候变化下海洋环流的洋域三维联动效应、洋际交换协同效应以及气候环境生态效应3个方面主要科学问题的研究现状,提出相关研究的不足和未来需求方向。从而为我国海洋动力学研究与发展提供必要的科学依据,也为我国海洋领域应对气候变化以及全球变化下海洋与气候综合风险治理能力的提升提供科技支撑。

5.1 观测研究

自20世纪初,海洋环流的观测经历了海洋物理状态片段性描述向全球化和长时序监测方向发展的历程,且以欧美发达国家海洋科考为主,海流测量方法和仪器也日益成熟。随着热带海洋与全球大气(TOGA)、世界大洋环流实验(WOCE)、气候变率及其可预报性(CLIVAR)、全球海洋观测系统(GOOS)和全球海洋观测计划(ARGO)等全球性核心观测计划以及热带太平洋观测系统2020(TPOS2020)和印度洋海洋观测系统(IndOOS)、西南太平洋海洋环流与气候试验(SPICE)和西北太平洋海洋环流与气候试验(NPOCE)等区域性观测计划的陆续实施,物理海洋学在海洋边界流系统观测、海洋内部经向翻转环流及其跨等密度面混合等方面获得了长足进展[207-215],并为海洋与全球能量平衡以及水分和碳循环等研究提供了坚实的海洋动力学基础数据。我国也不断参与和发起其中相关观测计划,取得了丰富的成果。然而,目前仍不能满足气候变化和全球变暖的热动力机制机理分析与环境生态影响及风险预评估要求,同时,针对不同尺度过程、多维度层次(特别是中高纬和深层次[216])、特殊环境和精度要求的精细化观测还十分不足。主流设备的进口依赖性较强,设备的可靠性、通用性和安全性等总体性能有待进一步提高。另外,通过定点测流、船载走航、漂浮测流、移动深潜、卫星遥测反演等多平台综合性监测、观测、探测和勘测体系尚待完善,传感、平台和数据处理等技术的信息化、智能化、集成化和标准化程度仍待持续提升,同时,空天地海一体化、网络化构建需逐步提上日程,进而不断增强我国深海、远洋和极地探测能力[217],助力我国在“深空”“深海”“深地”“深蓝”(简称“四深”)领域的综合竞争力。

5.2 理论分析和应用研究

地球气候系统异常复杂,海洋环流受到诸多驱动因子胁迫,由于数据的尚待丰富,目前针对海洋环流多尺度动力过程,围绕其动力结构、外源胁迫、因应同频、相因共振、作用通道、耦合叠加、选择性响应、层次(尺度)限制、动力机制、反馈时效以及未来趋势演变等产生的不确定性缺乏深入剖析,全球变暖所引发的海洋变化趋势中容易忽略波导和涡流所引起的背景环流变化的复杂多样性[218-220],重要的是,全球气候一致性变化进程中,尤其气候变暖背景下中高纬度地区各要素的不稳定和不确定等非线性特征突出,多尺度演变特征和区域性差异显著,正确认识全球气候一致性变化、方向、路径和进程与海洋环流多尺度演变之间的因应本质是关键。当前,海洋环流气候变化临界特征明显,相关结果结论尚需谨慎揭示与阐释,尤其应结合全球气候一致性变化与进程,认识全球海洋环流多尺度演变的复杂性波动响应和归趋。同时,对垂向涡度通量和流速[221]、湍动混合等精准量化不足。在气候变化下信号扰动振荡叠加放大传输的大尺度效应、作用贡献量、对比分类分析和危险性风险程度评估[72,222]方面欠缺确定性或作用隶属的测度理论方法。此外,对深层次海洋环流和垂向交换机制以及极区等中高纬海洋环流的认识还相当有限[49,223-224]。预报模型中的数据同化为海洋状态演变的精准描述提供了保证[225],然而,精细化数据的匮乏会引起模型初始化偏差,造成分析结果结论的不确定性,妨碍对气候变化下环流动力演变的深入认识和理解以及综合环流理论的完善。目前,协同

运用观测数据和数据驱动重建，是提升模式性能的重要手段[226]。而围绕三维海洋环流体系的整体认识以及针对包括人类活动在内的外源胁迫、自然变率和气候变化归因的多圈层耦合的气候模型有待完备，有关海洋观测[227]和预测的国际合作和多学科交叉研究尚待进一步加强。因而，有关海洋环流的观测、科学分析和研究结果结论的不确定性对全球变化下区域海洋与气候动力学的认识和理解以及区域海洋与气候变化综合风险评估带来诸多挑战和机遇。

6　研究建议

结合以上研究现状和不足，提出当前海洋环流有效观测、复合理论方法和高分辨率模型相关科学问题的几点研究建议。

(1)加快专精特新海洋观测仪器研发，加强国际合作，规划升级全球海洋与气候联合立体探监测网络异构平台，提高中高纬深远海的海陆空实时综合观测与研究水平。

基于海洋环流理论发展、生态动力学模型与气候变化模式性能提升对观测数据的要求，开展中高纬度关键海域动力环境综合监测、探测和观测，重点包括海洋辐射和污染物分布、微生物多样性以及大气气溶胶沉降等调查，注重中深层环流变化、深层动力混合、海洋次表层过程、跨界面交换与输运通量等的探测与观测实验以及海洋气候和环境生态安全临界点实时监测。致力于发展空天地海一体化观测网络集成与多功能整合。

(2)深化气候变化下中高纬海洋环流变异与海洋气候和环境生态系统互作互馈机制机理理论研究，深入认知和探究全球气候一致性和非均匀性(包括方向、路径和进程等)变化与海洋环流多时空尺度演变因应本质及临界特征规律，为提升海洋环流与气候环境生态效应的气候诊断、归因和预估能力提供理论基础和技术支撑。

丰富中高纬度多外源胁迫、多尺度海洋环流动力学和海陆气相互作用理论研究，深化深层水交换和跨尺度，如风和潮汐导致的湍动混合[158]，扰动激发、耦合、传播联动的海洋深层次机制研究，结合大数据结构与密集驱动，更侧重复杂响应反馈机制机理和因果关系[228]的数学物理新理论、新方法和新技术创新，同时，基于系统论和复杂科学理论，建立和完善全球气候变化下海洋环流系统的临界特征规律和临界隶属测度理论与应用。针对模型分辨率和小尺度过程体现，发展人工智能海洋气候数据处理、机器学习和数字孪生新工具、模式参数化和同化方案新技术，提高信噪比，不断改进提高超算系统模型、算法和算力，有效提升气候模式性能，为复杂气候系统变化的检测和归因提供科技支撑。

(3)促进多学科交叉融合，服务“双碳”战略目标实现，重点开展中高纬海洋环流与海洋气候和环境生态安全综合研究，为全球气候变化和区域适应与应对路径一体化方案提供科学依据。

开展气候影响下中高纬度大洋环流变化，特别是崩坏和气候突变、趋势演变等与海气相互作用、深远海极区极端和复杂环境变迁、生态系统演替及海洋气候与环境生态安全综合研究。重点围绕海洋碳循环，尤其是海洋增汇，如碳泵机制和海洋含氧量变化等海气动力过程，深远海水交换的动力环境、大洋能量传递的极区影响、上升流区生态系统演变以及海洋动力影响下生态灾害(赤潮、绿潮等)、台风登陆、污染物(尤其是溢油、垃圾和辐射物质)[229]输运等海洋环境安全问题，综合物理、化学和生物学科前沿，开展海洋与气候环境交叉学科新技术方法(如，生物基因技术、同位素技术、动态仿生仿真等)研究。构建海洋与气候变化检测诊断、归因溯源、预测预估、影响区划和风险治理的一体化路径方案与技术体系，有效提高防灾减灾救灾和急难险重突发公共事件处置保障能力，为我国海洋高质量发展、海洋气候与环境生态安全保障提供必要的科学参考和科技支撑服务，有效助推新时代海洋命运共同体构建，提升具有中国特色的全球海洋治理话语权。

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