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南大洋翻转环流与碳源汇过程的复杂性

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工业革命以来, 海洋持续吸收着人类活动排放的二氧化碳(CO_2), 有效缓解了大气中CO_2浓度的升高及其温室效应[1]. 环绕南极洲的南大洋(南纬35°以南的海洋)具有独特的经向翻转环流(MOC)结构[2,3], 是吸收和存储人类活动排放CO_2(C_{ant})的重要区域[4]. 其中, 南极底层水(AABW)的生成构成了全球MOC的深层分支, 将大气中的CO_2输运到深海, 并缓慢扩散到全球海洋的底层, 其体积总量约占全球海洋的30%~40%[5], 是海洋碳泵的重要组成部分[6~9]. 一系列基于观测数据的研究揭示AABW的体积通量正在显著减少[10~12]. *Science* “2023年度十大科学突破”之一(https://www.science.org/content/article/breakthrough-of-the-year-2023)以“地球碳泵正在减缓(Earth’s carbon pump is slowing)”为题进行了报道, 强调了AABW产率下降对海洋碳泵和气候变化的指示意义. 该报道推测海洋深层流动正在减缓, 致使海洋捕获并存储C_{ant}的功能减弱, 这将对气候变化产生正反馈作用, 导致全球变暖加速. 该报道凸显了海洋在气候变化中的重要性, 以及进一步加强深海科学研究、应对气候变化的紧迫性.

尽管该报道提出了重要的观点, 但有必要对其科学依据进行讨论和评估, 从而更加客观和全面地认识当前海洋和气候状态. 从专业的角度来看, “AABW减少–深海环流减缓–海洋碳泵减弱”这一逻辑主线上涉及诸多复杂的海洋和气候过程. 首先, AABW的变化无法代表全球海洋碳泵的总体变化, Zhang等人[9]估算AABW向深海输运的C_{ant}为68.6±12.8 Tg C, 仅占全球海洋吸收C_{ant}总量的~2.9%; 其次, 南大洋上层风生环流的变化与AABW驱动的深层环流变化并不相同, 前者对南大洋碳泵的总体贡献更大; 此外, 南大洋MOC的变化受多种气候过程支配, 在不同时期呈现不同的变化趋势; 最后, 海洋碳泵的强度取决于多种物理和生物地球化学因素的共同作用, 除海洋环流参与的溶解泵之外, 生物泵的变化也需要考虑. 目前, 科学界对这些过程的观测、数值模拟和理论认知还存在诸多不足, 也未能就其长期变化规律形成共识性结论, 对南大洋环流和海洋碳泵变化趋势的预测极为困难.

下面将依次讨论*Science*报道中涉及的4个环环相扣的主要科学问题, 分别为(1) AABW的形成与变化、(2) 南大洋风生环流变化、(3) 影响南大洋MOC变化的气候过程及(4) 海洋碳泵与环流的关系. 除了阐述科学界对上述问题已有的认知之外, 我们还将结合报道的主要科学基础[10~12]探讨现有观测数据和数值模式中的不确定性, 提出自己的观点并展望未来的发展方向, 以期帮助科学界和社会公众更加全面和客观地了解海洋环流与碳泵的关系及其变化规律.

1 AABW的形成与变化

受南极大陆冬季离岸风的影响, 南极沿岸存在无冰或少冰的区域, 称之为冰间湖. 冰间湖持续的结冰析盐导致海洋表层的盐分被转移到海洋内部, 增大海水密度, 形成陆架重水[13]. 陆架重水形成后会沿着陆架上的凹槽流向外海, 并穿过陆架坡折以重力流的形式跨大陆坡下沉到深海, 期间与上层暖水团混合, 最终形成AABW(图1)[14~17]. 目前已知的AABW形成地点主要有4个: 威德尔海[13]、罗斯海[18]、阿德利地[19]和普利兹湾[20]. 其中, 威德尔海和罗斯海是AABW最主要的产生地, 分别贡献了总量的~50%[6]和~25%[14,15]. 尽管AABW的形成对大气与深海之间的物质交换以及全球气候变化有重要影响, 但由于研究的困难性, 目前国际科学界对AABW形成和变化的认识不足. 这主要由两方面导致: 一方

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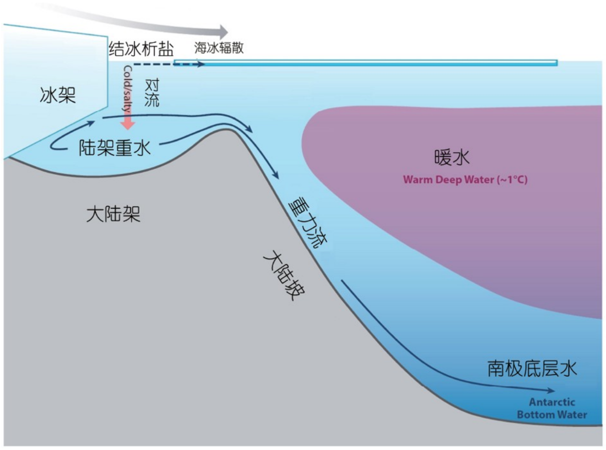

图 1 AABW形成过程示意图. 修改自Purkey等人[15]
Figure 1 Schematic of Antarctic Bottom Water formation along the Antarctic continental shelf and slope. Adapted from Purkey et al.[15]

面南极近岸自然环境恶劣，且AABW位于海洋底部，观测难度大, 当前的技术手段无法开展高效的观测[21]; 另一方面, 对AABW形成过程的数值模拟极为困难，若要实现对AABW形成过程的准确模拟, 模式网格分辨率至少要达到~2 km, 但是目前大多数模型达不到如此高分辨率[22].

*Science*报道的主要科学依据是Lee等人[10]以及Gunn等人[12]对AABW的研究结果. 其中, Gunn等人[12]主要是基于罗斯海以及阿德利地下游的走航断面观测，结合数值模式估算AABW体积通量，并根据近几十年数次重复观测的结果估算长期趋势. 由于观测数据少且不全面，关于AABW通量变化的研究结论具有一定的不确定性. 罗斯海的断面观测只重复了3次, 分别是1992、2011和2018年, 估算的AABW通量呈现出非常大的变化，其中2011年相对1992年下降了65%，并在2018年恢复到接近1992年的通量. 然而，该研究选用的观测断面靠近罗斯海重力流出口，根据最新的研究[17]，罗斯海重力流受潮汐影响大，在靠近重力流出口处，AABW通量存在显著的大小潮周期变化. 理论上讲，断面观测时间处在大潮或小潮期间，结果会有很大的不同，这些差异可以显著地影响长期趋势的相关结论. 阿德利地下游的AABW通量观测则有更多的重复断面(7个)，结果显示，从1994年到2018年底层水通量下降了77%. 同时, 走航断面距离重力流出口较远, 观测结果的噪声较小, 结果也相对可信.

尽管对罗斯海底层水通量的观测较少，但目前各方面证据都支持该区域AABW产率下降的总体趋势. 例如，罗斯海陆架重水确实存在盐度变淡趋势，并从2014年之后逐渐恢复[23,24]，这在一定程度上可以反映陆架重水体积的变化，并直接影响AABW通量. 因此，罗斯海底层水通量可能确实有Gunn等人[12]发现的变化趋势，但其具体变化幅度很难确定. 另外，威德尔海是AABW最大的生成源地，但Gunn等人[12]的研究没有涉及威德尔底层水通量的变化，因而相关结论无法代表AABW整体通量的变化. Zhou等人[25]通过温盐断面观测的AABW横截面积的变化推测威德尔海底层水体积自1992年以来下降了~30%，但由于缺少流速观测，结论同样存在一定的不确定性. Lee等人[10]利用历史积累的开阔大洋水文观测数据集(WOA18)约束海洋模式，从而诊断海洋环流，得到AABW通量的年代际变化信号. 根据研究结果，自20世纪70年代中期以来AABW通量在南大洋下降了10%~20%. 因为所采用的数据比较全面，并且环流信息是根据温盐水文数据诊断而来, 这一结论相对可靠.

尽管目前对AABW体积通量的估计存在较大的不确定性，但大量现有研究均支持AABW产率下降的结论. 在全球变暖背景下，南极冰盖融化释放的淡水会持续抑制陆架重水的形成[26]，AABW产率也会相应地下降，对气候变暖以及深海碳存储产生重要影响. 因此，深入认识AABW的形成与变化对理解未来气候变化有重要意义.

2 南大洋风生环流变化

AABW并非南大洋生成的唯一水团. 实际上，南大洋MOC具有复杂的“双圈”结构(图2)[2,3]，AABW的形成是其深层环流圈的主要组成部分. 南大洋西风带驱动的上升流将较冷的绕极深层水带到表层，其中一部分水向北运动并吸收大气热量, 在南极绕极流(ACC)流域及其北侧潜沉, 转化为南极中层水(AAIW)和亚南极模态水(SAMW)，构成了南大洋MOC的上层环流圈. 与深层环流圈不同，上层环流圈主要由南大洋的风场所驱动. 伴随着南大洋-南极系统的气候演变，上述风生环流发生了显著变化[27]，呈现出与AABW所在的深层MOC截然不同的变化规律, 均对全球海洋碳泵产生了重要的影响.

观测资料表明，过去半个世纪中，南大洋的大气环流发生了明显变化, 驱动了南大洋上层环流和碳泵变化. 其中, 最为突出的现象是从20世纪80年代持续到21世纪初期的西风带加强且向南移动，也表现为南半球环状模(SAM)的正向趋势[28~32]. 这种环南极的大尺度风场变化带动了南大洋乃至整个南半球风生环流的整体加速[33~36]. 该时期南大洋的上层环

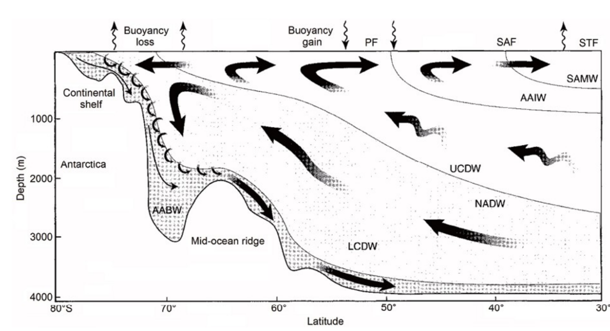

图 2 南大洋翻转环流的“双圈”结构. 引自Speer等人[2]
Figure 2 Schematic two-cell meridional overturning circulation in the Southern Ocean. Adapted from Speer et al.[2]

流很可能在加强，观测证据(包括氟氯烃数据)显示上升流加强[27]、SAMW厚度增加[37]、AAIW显著变暖且盐度下降[38,39]，ACC北侧暖水汇聚下沉[40,41]等．数值模拟结果显示，自20世纪70年代中期以来，风驱动的南大洋上层MOC加强了3~4 Sv，而AABW所在的深层MOC相应收缩，并减弱了相同的幅度[9]．上层和深层环流不同的变化趋势对海洋碳泵的综合影响难以估算．一方面，南大洋部分区域的海表面温度(SST)呈下降趋势[42]，这有助于吸收大气CO_2并储存到AAIW和SAMW之中；另一方面，上升流把深海的CO_2带到表层并释放到大气中，会起到碳源作用．观测数据表明，南大洋自工业革命以来持续吸收人为CO_2，在1981~2004年间的共吸收17.5±2.5 Pg C，且主要存储在AAIW和SAMW之中[43,44]．

3 影响南大洋MOC变化的气候过程

南大洋环流的变化主要受气候变暖背景下大气风场变化和冰盖融化的影响，而气候变化是由人类活动和自然变率共同决定．例如，南大洋西风带在20世纪80年代以来的加强和南移，既有南极臭氧层空洞和温室效应的强迫作用[29,31]，也有局地和低纬度自然变率的影响[42,45,46]，这为理解和预测南大洋气候变化带来了很大的挑战．不同来源气候过程的作用也进一步增加了南大洋MOC变化的复杂性，使其在不同时期呈现不同的变化趋势．

人类活动排放CO_2造成的温室效应是气候变暖和冰盖融化的根本原因，这也促使南半球Hadley环流扩张，西风带加强并向南移动[31]．上述趋势和规律很可能将持续到21世纪末期，这被IPCC第六次评估报告认为具有高信度[47]．20世纪70年代后期显现的南极平流层臭氧空洞也能驱动西风带的加强和南移[28~32]，且在2010年之前的南大洋大气环流变化中贡献很大(特别是夏季)．但随着近年来空洞的逐渐消失，其作用正在逐渐削弱．当前的南大洋气候正处于温室效应强迫日益加强和臭氧空洞逐渐削弱的微妙制衡之中，为短期气候预测带来了困难．

热带气候的遥相关作用(图3)是南大洋-南极气候自然变率重要来源[46]．太平洋和大西洋的低纬度气候变率能够激发大气行星Rossby波列，调控高纬度大气环流，特别是阿蒙森低压的状态[48,49]．南极西部气温的快速增暖、2015年之前的海冰扩张以及其后的迅速消融、近几十年中南极冰盖的变薄、1980~2010年期间西风带的加强和南移等变化现象，均与年代际太平洋振荡(IPO)和大西洋多年代振荡(AMO)的相位转换有关[45,48,50~53]．另外，南大洋对流自身的自然变率也对2015年之前南大洋部分区域表层海温(SST)变冷和海冰扩张有一定贡献[42]．

4 海洋碳泵与环流的关系

海洋碳泵与海洋环流之间联系密切，但海洋环流只是决定碳泵强度的诸多因素之一．虽然大气中的CO_2首先由海洋

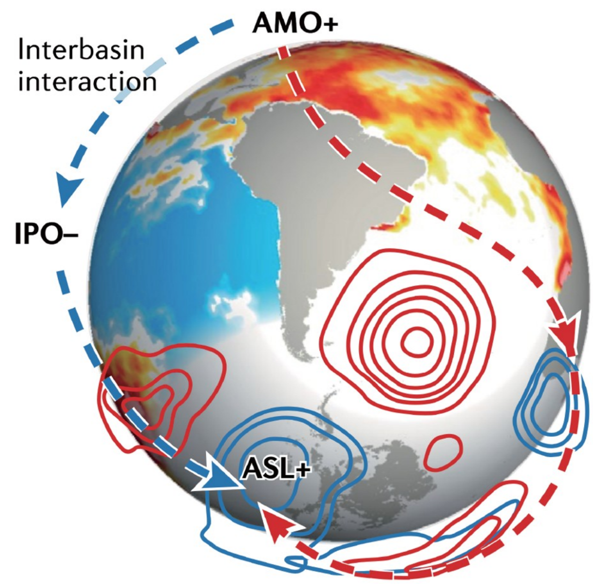

图 3 太平洋和大西洋气候对南大洋-南极气候系统的遥相关示意图．太平洋IPO负相位(IPO−)和大西洋AMO正相位(AMO+)通过激发大气Rossby波列，加强阿蒙森低压(ASL)进而导致西风带加强和南移．引自Li 等人[46]

Figure 3 Teleconnection patterns triggered by decadal sea surface temperature variability. The atmospheric Rossby wave train induced by a positive phase of the Atlantic Multidecadal Oscillation (AMO, red arrow) and a negative phase of the Interdecadal Pacific Oscillation (IPO, blue arrow) strengthens the Amundsen low-pressure system (ASL) and leads to the strengthening and westward shift of westerlies, adapted from Li et al.[46]

表层吸收，但海洋上层的储碳空间有限，只有将海洋上层的溶解无机碳(DIC)输送至深层，才能长时间与大气隔绝，实现碳封存，并促使上层海洋进一步吸收大气中的CO_2．海洋碳泵包括溶解度泵(solubility pump)和生物泵(biological pump)，它们发挥着输运、转化与存储碳的作用[54]．溶解度泵通常指高纬海区在冷空气和强风的作用下，表层海水快速降温，CO_2溶解度增大，海洋通过海—气交换从大气吸收大量CO_2；这些CO_2伴随深层水团的形成和下沉进入大洋深部，实现了对大气CO_2的封存．溶解泵主要受海温、海水化学性质和海洋环流的控制．生物泵始于海洋真光层，浮游植物通过光合作用，将无机碳转化为有机碳，其中，颗粒有机碳(POC)通过沉降等过程输送至深海，而溶解有机碳(DOC)则向下扩散或随着深层水的形成进入深海，但在输送过程中部分有机碳会被再矿化成DIC释放到周围水体中．生物泵的效率受光照、温度、表层营养盐供给、海洋动力场等因素的共同影响．

MOC连通了上层与深层海洋，显著影响海洋碳汇[55]．当前深海DIC的储量约为表层海洋的55倍[1,56]，而生物泵主导了DIC垂向梯度结构特征，对DIC垂向梯度的贡献量高达90%．南大洋上升流能将底层高浓度自然源DIC和营养盐带至表层，同时促进CO_2的吸收(生物泵)和释放(溶解度泵)：一方面

深层上涌的海水受热升温导致CO_2溶解度降低，促进自然源DIC中的CO_2向大气排放，形成碳源；另一方面，底层上涌的营养盐有利于提高表层海洋的初级生产力，从而通过生物泵作用将DIC转化为有机碳向深海输出，进而增强碳汇. 因此，海洋碳汇(源)的强弱取决于光合浮游植物能否充分利用下层供应的营养盐将上升流携带的DIC再次输送至深海[57,58]. 例如，在地质历史时期，MOC的减弱和生物泵的增强形成的强碳汇被认为是导致冰期大气CO_2浓度下降的主要原因[59]. 在当前气候状态下，受光照或铁含量等因素的限制，真光层的营养盐不能被浮游植物充分利用，导致“原存营养盐(preformed nutrient)”在表层积累，这意味着海洋生物泵未能完全将底层上涌的CO_2再次输送至深海，导致CO_2的“泄漏”[3,4].

从溶解度泵的角度讲，MOC上升分支能够将高自然源碳的深层海水输送至表层，形成自然源CO_2的源；同时，其下沉分支携带人为CO_2潜沉到海洋内部，形成人为源CO_2的汇. 因此，MOC对海洋碳泵的总体作用取决于自然源碳源与人为源碳汇的综合影响. 例如，在20世纪90年代，因南大洋西风带增强且向南偏移[28~32]，MOC显著增强，其对碳汇的影响是：自然源和人为源CO_2的排放和吸收分别增加了0.9和0.2 Pg C a^{-1}，净结果为海洋碳汇减少0.7 Pg C a^{-1}[60]. 而进入21世纪后，由于MOC减弱，海洋对自然源CO_2的排放每年减少0.6 Pg C，但对人为源CO_2的吸收也相应减少了0.1 Pg C，净结果是海洋碳汇增加了0.5 Pg C a^{-1}[61]. 若未来上层环流持续减弱，虽然短期内会增强海洋碳汇，但是在更长的时间尺度上，MOC减弱一方面会减少C_{ant}的吸收，另一方面会促使营养盐在深海大量累积，进而降低表层营养供给，导致生物泵效率下降，最终可能形成一个海洋碳汇与气候之间的正反馈循环[62].

5 讨论与展望

以上论述表明，由于相关海洋、气候和生物地球化学过程的复杂性，“AABW减少–深海环流减缓–海洋碳泵减弱”这一主线结论尚缺乏足够的科学证据. 事实上，尽管AABW产率的下降暗示了大洋底层流动的减弱，但南大洋上层风生MOC有相应的加强，所以还不能认为南大洋(或全球)MOC已经显著减缓. 而且，在气候变化背景下，MOC与碳源汇之间存在非线性对应关系，两者之间在不同时间尺度上呈现不同的反馈关系；除了海洋环流参与的溶解度泵之外，还要考虑生物地球化学过程主导的生物泵的变化. 要想准确预测上述过程的长期变化，我们尚需在科学认识和模式模拟能力两方面都取得长足进步. 目前，断言全球海洋碳泵正在减弱还为时尚早.

由于直接观测大尺度海洋环流极为困难，我们对全球和南大洋MOC长期变化的研究很大程度上依赖于气候模式. 然而，过高的计算成本导致全球气候模式分辨率太低[63]，稀疏的历史观测所提供的物理约束又极为有限. 因此，当前的气候模式(如CMIP5和CMIP6)对南大洋和南极的模拟水平明显低于中低纬度区域. 以AABW的形成为例，Heuzé[63]分析了35个CMIP6气候模式，其中只有两个模式在罗斯海出现了重力流，而作为AABW最重要源地的威德尔海则没有任何一个模式模拟出重力流过程. 这些缺陷使得大多数气候模式通过外海虚假的深对流产生AABW，导致模式中AABW的形成过程与真实海洋中完全不同. 另一种模拟方式是采用非耦合的海洋模式，从而减少计算成本，实现更高分辨率的模拟. 当前这类模式的分辨率在南极近岸区域最高可以达到5公里左右，能够模拟出重力流过程[64,65]. 但由于南极近海罗斯贝变形半径较小，5 km的分辨率还是无法有效地模拟重力流下沉的中尺度过程[22]. 根据Han等人[17]的研究结果，地形罗斯贝波和潮汐对重力流下沉以及所产生的AABW温盐属性具有重要影响，因此，准确模拟AABW的形成需要进一步提高分辨率.

气候模式中，南大洋气候对外部强迫因素的响应也存在偏差[66]. 例如，气候模式普遍低估西风带加强并南移现象，模拟的大气环流变化主要局限于南极附近，而不像观测中那样覆盖整个南半球[36]，这势必影响上层风生环流和碳泵的模拟. 此外，目前物理与生物地球化学耦合模式的发展水平严重落后于海洋物理模式的水平，主流耦合模型的分辨率大多数约为100 km，远远达不到准确模拟AABW所需要的分辨率. 生物地球化学模型本身对碳泵过程的模拟和预估存在很大的不确定性[67]；例如，当前气候模式(CMIP6)对未来气候变化下生物泵通量变化的预估范围为−41%~+1.8%. 这主要是因为与生物泵相关的诸多过程在模式中被简化或忽略了[67]. 当前，对海洋碳汇变化趋势的估算主要依靠诊断模型和观测数据[61]，而观测数据的稀缺性导致海洋碳汇估算不够准确.

鉴于现场测量的困难性，观测数据短期内很难显著增加；受计算能力和模式物理框架的限制，气候模式的模拟能力也很难迅速改善，观测与数值模拟能力的提升是一个长期而艰难的过程. 为更好地模拟和估算海洋环流和碳汇的变化趋势，将人工智能技术，特别是融合物理信息的人工智能技术[68,69]结合到相关研究中，或许是一个可行的方向. 例如，通过结合人工智能手段，Zhong等人[70]估算的1992~2021年南大洋平均的碳汇效率为−0.87 Pg C yr^{-1}，表明以往对南大洋碳汇可能有所高估.

回顾历史，自20世纪60年代以来，受日益增长的大气CO_2浓度的驱动，海洋持续发挥着碳汇作用；展望未来，随各国减排政策的实施，大气CO_2浓度的增长趋势预期放缓，海洋对C_{ant}的吸收速率也将相应降低. 同时，由于前文所述大洋环流的改变，以及增温、酸化等因素的影响，海洋碳汇能力预期也会下降[71]. 最后，现场观测是理解海洋环流动力过程及其与生物地球化学过程耦合机制的基石，已有的研究[12,17,72,73]加深了对AABW形成机制的认识，为未来实施更高效的观测奠定了基础. 目前，我国在南极海洋学领域的研究相对薄弱，随着南极罗斯海“秦岭”新站的建设，未来我国也有望在南大洋MOC和碳泵研究方面起到更重要的作用.

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推荐阅读文献

1 Wang W L, Fu W, Le Moigne F A C, et al. Biological carbon pump estimate based on multidecadal hydrographic data. Nature, 2023, 624: 579–585
2 Speer K, Rintoul S R, Sloyan B. The diabatic deacon cell. J Phys Oceanogr, 2000, 30: 3212–3222
3 Marshall J, Speer K. Closure of the meridional overturning circulation through Southern Ocean upwelling. Nat Geosci, 2012, 5: 171–180
4 Gruber N, Landschützer P, Lovenduski N S. The variable Southern Ocean carbon sink. Annu Rev Mar Sci, 2019, 11: 159–186
5 Johnson G C. Quantifying Antarctic Bottom Water and North Atlantic Deep Water volumes. J Geophys Res, 2008, 113: 2007JC004477
6 Orsi A H, Johnson G C, Bullister J L. Circulation, mixing, and production of Antarctic Bottom Water. Prog Oceanography, 1999, 43: 55–109
7 Arrigo K R, van Dijken G L, Bushinsky S. Primary production in the Southern Ocean, 1997–2006. J Geophys Res, 2008, 113: 2007JC004551
8 Nissen C, Timmermann R, Hoppema M, et al. Abruptly attenuated carbon sequestration with Weddell Sea dense waters by 2100. Nat Commun, 2022, 13: 3402
9 Zhang S, Wu Y, Cai W J, et al. Transport of anthropogenic carbon from the Antarctic shelf to deep Southern Ocean triggers acidification. Glob Biogeochem Cycle, 2023, 37: e2023GB007921
10 Lee S K, Lumpkin R, Gomez F, et al. Human-induced changes in the global meridional overturning circulation are emerging from the Southern Ocean. Commun Earth Environ, 2023, 4: 69
11 Johnson G C. Antarctic bottom water warming and circulation slowdown in the Argentine basin from analyses of deep Argo and historical shipboard temperature data. Geophys Res Lett, 2022, 49: e2022GL100526
12 Gunn K L, Rintoul S R, England M H, et al. Recent reduced abyssal overturning and ventilation in the Australian Antarctic Basin. Nat Clim Chang, 2023, 13: 537–544
13 Foldvik A, Gammelsrød T, Østerhus S, et al. Ice shelf water overflow and bottom water formation in the southern Weddell Sea. J Geophys Res, 2004, 109: 2003JC002008
14 Orsi A H, Smethie Jr. W M, Bullister J L. On the total input of Antarctic waters to the deep ocean: A preliminary estimate from chlorofluorocarbon measurements. J Geophys Res, 2002, 107: 3122
15 Purkey S G, Smethie Jr. W M, Gebbie G, et al. A synoptic view of the ventilation and circulation of Antarctic bottom water from chlorofluorocarbons and natural tracers. Annu Rev Mar Sci, 2018, 10: 503–527
16 Solodoch A, Stewart A L, Hogg A M C, et al. How does Antarctic bottom water cross the Southern Ocean? Geophys Res Lett, 2022, 49: e2021GL097211
17 Han X, Stewart A L, Chen D, et al. Circum-Antarctic bottom water formation mediated by tides and topographic waves. Nat Commun, 2024, 15: 2049
18 Gordon A L, Orsi A H, Muench R, et al. Western Ross Sea continental slope gravity currents. Deep Sea Res Part II-Topical Studies Oceanogr, 2009, 56: 796–817
19 Williams G D, Bindoff N L, Marsland S J, et al. Formation and export of dense shelf water from the Adélie Depression, East Antarctica. J Geophys Res, 2008, 113: 2007JC004346
20 Ohshima K I, Fukamachi Y, Williams G D, et al. Antarctic Bottom Water production by intense sea-ice formation in the Cape Darnley polynya. Nat Geosci, 2013, 6: 235–240
21 Silvano A, Purkey S, Gordon A L, et al. Observing Antarctic bottom water in the Southern Ocean. Front Mar Sci, 2023, 10: 1221701
22 Mensah V, Nakayama Y, Fujii M, et al. Dense water downslope flow and AABW production in a numerical model: Sensitivity to horizontal and vertical resolution in the region off Cape Darnley polynya. Ocean Model, 2021, 165: 101843
23 Castagno P, Capozzi V, DiTullio G R, et al. Rebound of shelf water salinity in the Ross Sea. Nat Commun, 2019, 10: 5441
24 Silvano A, Foppert A, Rintoul S R, et al. Recent recovery of Antarctic Bottom Water formation in the Ross Sea driven by climate anomalies. Nat Geosci, 2020, 13: 780–786
25 Zhou S, Meijers A J S, Meredith M P, et al. Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes. Nat Clim Chang, 2023, 13: 701–709
26 Li Q, England M H, Hogg A M C, et al. Abyssal Ocean overturning slowdown and warming driven by Antarctic meltwater. Nature, 2023, 615: 841–847
27 Waugh D W, Primeau F, DeVries T, et al. Recent changes in the ventilation of the Southern Oceans. Science, 2013, 339: 568–570

28 Cai W, Cowan T. Trends in southern hemisphere circulation in IPCC AR4 Models over 1950–99: Ozone depletion versus greenhouse forcing. J Clim, 2007, 20: 681–693
29 Thompson D W J, Solomon S, Kushner P J, et al. Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. Nat Geosci, 2011, 4: 741–749
30 Polvani L M, Waugh D W, Correa G J P, et al. Stratospheric ozone depletion: The main driver of twentieth-century atmospheric circulation changes in the southern hemisphere. J Clim, 2011, 24: 795–812
31 Swart N C, Fyfe J C. Observed and simulated changes in the Southern Hemisphere surface westerly wind-stress. Geophys Res Lett, 2012, 39
32 Swart N C, Gille S T, Fyfe J C, et al. Recent Southern Ocean warming and freshening driven by greenhouse gas emissions and ozone depletion. Nat Geosci, 2018, 11: 836–841
33 Roemmich D, Gilson J, Sutton P, et al. Multidecadal change of the South Pacific gyre circulation. J Phys Oceanography, 2016, 46: 1871–1883
34 Qu T, Fukumori I, Fine R A. Spin-up of the Southern Hemisphere super gyre. JGR Oceans, 2019, 124: 154–170
35 Hu S, Sprintall J, Guan C, et al. Deep-reaching acceleration of global mean Ocean circulation over the past two decades. Sci Adv, 2020, 6: eaax7727
36 Duan J, Li Y, Wang F, et al. Rapid sea-level rise in the southern-hemisphere subtropical oceans. J Clim, 2021, 34: 9401–9423
37 Gao L, Rintoul S R, Yu W. Recent wind-driven change in Subantarctic Mode Water and its impact on Ocean heat storage. Nat Clim Change, 2018, 8: 58–63
38 Schmidtko S, Johnson G C. Multidecadal warming and shoaling of Antarctic intermediate water. J Clim, 2012, 25: 207–221
39 Durack P J, Wijffels S E. Fifty-year trends in global Ocean salinities and their relationship to broad-scale warming. J Clim, 2010, 23: 4342–4362
40 Armour K C, Marshall J, Scott J R, et al. Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. Nat Geosci, 2016, 9: 549–554
41 Böning C W, Dispert A, Visbeck M, et al. The response of the Antarctic Circumpolar Current to recent climate change. Nat Geosci, 2008, 1: 864–869
42 Zhang L, Delworth T L, Cooke W, et al. Natural variability of Southern Ocean convection as a driver of observed climate trends. Nat Clim Change, 2019, 9: 59–65
43 Sabine C L, Feely R A, Gruber N, et al. The oceanic sink for anthropogenic CO_2. Science, 2004, 305: 367–371
44 Khatiwala S, Tanhua T, Mikaloff Fletcher S, et al. Global ocean storage of anthropogenic carbon. Biogeosciences, 2013, 10: 2169–2191
45 Ding Q, Steig E J, Battisti D S, et al. Winter warming in West Antarctica caused by central tropical Pacific warming. Nat Geosci, 2011, 4: 398–403
46 Li X, Cai W, Meehl G A, et al. Tropical teleconnection impacts on Antarctic climate changes. Nat Rev Earth Environ, 2021, 2: 680–698
47 IPCC, 2021: Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pirani A, et al., eds. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2021
48 Ding Q, Steig E J. Temperature change on the Antarctic peninsula linked to the tropical Pacific. J Clim, 2013, 26: 7570–7585
49 Simpkins G R, Peings Y, Magnusdottir G. Pacific influences on tropical Atlantic teleconnections to the southern hemisphere high latitudes. J Clim, 2016, 29: 6425–6444
50 Meehl G A, Hu A, Santer B D, et al. Contribution of the Interdecadal Pacific Oscillation to twentieth-century global surface temperature trends. Nat Clim Change, 2016, 6: 1005–1008
51 Yuan X, Martinson D G. Antarctic sea ice extent variability and its global connectivity. J Clim, 2000, 13: 1697–1717
52 Simpkins G R, McGregor S, Taschetto A S, et al. Tropical connections to climatic change in the extratropical southern hemisphere: The role of Atlantic SST trends. J Clim, 2014, 27: 4923–4936
53 Purich A, Cai W, England M H, et al. Evidence for link between modelled trends in Antarctic sea ice and underestimated westerly wind changes. Nat Commun, 2016, 7: 10409
54 Dai M H. Carbon sink. In: Jin Z J, Jiang Y, Dai M H, et al., eds. Introduction to Caron Neutrality (in Chinese). Beijing: Peking University Press, 2023 [戴民汉. 海洋碳汇. 见: 金之钧, 江亿, 戴民汉, 等. 碳中和概论. 北京: 北京大学出版社, 2023]
55 Bernardello R, Marinov I, Palter J B, et al. Impact of Weddell Sea deep convection on natural and anthropogenic carbon in a climate model. Geophys Res Lett, 2014, 41: 7262–7269
56 Boyd P W, Claustre H, Levy M, et al. Multi-faceted particle pumps drive carbon sequestration in the Ocean. Nature, 2019, 568: 327–335
57 Dai M, Cao Z, Guo X, et al. Why are some marginal seas sources of atmospheric CO_2? Geophys Res Lett, 2013, 40: 2154–2158
58 Siddiqui C, Rixen T, Lahajnar N, et al. Regional and global impact of CO_2 uptake in the Benguela Upwelling System through preformed nutrients. Nat Commun, 2023, 14: 2582
59 Sigman D M, Boyle E A. Glacial/interglacial variations in atmospheric carbon dioxide. Nature, 2000, 407: 859–869
60 Le Quere C, Rodenbeck C, Buitenhuis E T, et al. Saturation of the Southern Ocean CO_2 sink due to recent climate change. Science, 2007, 316: 1735–1738

61 Devries T, Holzer M, Primeau F. Recent increase in oceanic carbon uptake driven by weaker upper-ocean overturning. Nature, 2017, 542: 215–218
62 Liu Y, Moore J K, Primeau F, et al. Reduced CO_2 uptake and growing nutrient sequestration from slowing overturning circulation. Nat Clim Chang, 2023, 13: 83–90
63 Heuzé C. Antarctic bottom water and north Atlantic deep water in CMIP6 models. Ocean Sci, 2021, 17: 59–90
64 Morrison A K, Hogg A M C, England M H, et al. Warm Circumpolar Deep Water transport toward Antarctica driven by local dense water export in canyons. Sci Adv, 2020, 6: eaav2516
65 Li S, Liu W, Allen R J, et al. Ocean heat uptake and interbasin redistribution driven by anthropogenic aerosols and greenhouse gases. Nat Geosci, 2023, 16: 695–703
66 Neely Iii R R, Marsh D R, Smith K L, et al. Biases in southern hemisphere climate trends induced by coarsely specifying the temporal resolution of stratospheric ozone. Geophys Res Lett, 2014, 41: 8602–8610
67 Henson S A, Laufkötter C, Leung S, et al. Uncertain response of ocean biological carbon export in a changing world. Nat Geosci, 2022, 15: 248–254
68 Liang X S, Chen D, Zhang R. Quantitative causality, causality-aided discovery, and causal machine learning. Ocean-Land-Atmos Res, 2023, 2: 0026
69 Li Z, Kovachki N, Azizzadenesheli K, et al. Fourier neural operator for parametric partial differential equations,. arXiv: 2010.08895, 2020
70 Zhong G, Li X, Song J, et al. The Southern Ocean carbon sink has been overestimated in the past three decades. Commun Earth Environ, 2024, 5: 398
71 Gruber N, Bakker D C E, DeVries T, et al. Trends and variability in the Ocean carbon sink. Nat Rev Earth Environ, 2023, 4: 119–134
72 Han X, Stewart A L, Chen D, et al. Topographic Rossby wave-modulated oscillations of dense overflows. JGR Oceans, 2022, 127: e2022JC018702
73 Han X, Stewart A L, Chen D, et al. Controls of topographic Rossby wave properties and downslope transport in dense overflows. J Phys Oceanography, 2023, 53: 1805–1820

Summary for "南大洋翻转环流与碳源汇过程的复杂性"

Complexity in the Southern Ocean meridional overturning circulation and carbon source/sink

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The ocean has taken in a significant amount of anthropogenic carbon dioxide (C_{ant}) since the Industrial Revolution, which effectively mitigates the greenhouse effect on the globe's climate. Among others, the Southern Ocean surrounding Antarctica, defined broadly as the oceanic areas south of 35°S, has absorbed approximately 40% of the anthropogenic CO_2 through its deep-reaching meridional overturning circulation (MOC). The formation of Antarctic bottom water (AABW) propels the lower cell of the Southern Ocean overturning, carrying C_{ant} to the abyssal ocean and playing an essential role in the global ocean carbon pump. In 2023, studies based on observations indicated a reduction in the volume of the coldest component of the AABW since the 1970s, which was subsequently reported by Science using the title 'Earth's carbon pump is slowing'. It is indicated that deep ocean currents are weakening, resulting in a reduced capacity to capture C_{ant}, which will exacerbate climate warming. By emphasizing the essential role of the ocean in climate change, this report highlights the necessity of enhancing the research effort of the deep ocean.

However, the sequence of AABW reduction leading to a slowdown in deep-ocean circulation and a weakening of the ocean carbon pump encompasses many intricate oceanic and climatic processes, over which the scientific communities have not reached consensus views. There remain major gaps in the understanding of these issues across observational, modeling, and theoretical studies. To complement the perspective provided by this report and to better inform the decision-makers and the public, the scientific basis should be clarified. The present paper provides a review of four pertinent scientific issues to enhance the understanding of decision-makers and the public. (1) The formation and changes of AABW, (2) Changes in wind-driven Southern Ocean circulation, (3) Climate change impacts on the Southern Ocean, and (4) The relationship between ocean carbon pump and ocean circulation. In addition to an updated review of established understanding, uncertainties in observations and model simulations are also discussed. We demonstrate that while the reduction in AABW production suggests a deceleration of deep-ocean MOC, the wind-driven upper-layer MOC in the Southern Ocean has intensified due to changes in westerly winds. Estimating the total impact of the upper and lower MOCs on the carbon pump of the Southern Ocean and the global ocean presents significant challenges. Furthermore, the responsiveness of the ocean carbon pump to changes in ocean circulation is also subject to temporal variation. The biological pump, governed by biogeochemical processes, plays a crucial role alongside the solubility pump in ocean circulation, significantly influencing the overall dynamics of the ocean carbon pump in a changing climate.

Owing to the difficulties in the observation of ocean circulations, our understanding of the changing MOC relies predominantly upon climate models. Yet, realistically simulating the high-latitude ocean circulation and formation of deep-ocean water masses is still a challenging task for the state-of-the-art climate models. Most models cannot resolve fundamental processes in the formation of the AABW, such as gravity currents along the continental slope. In addition, systematic biases have been detected in the externally forced changes of the Southern Ocean climate in climate models. The strengthening of westerly winds is underestimated in models compared to observations, which inevitably affect the simulated changes in ocean circulation and carbon pump. Improving scientific understanding and model simulation is essential for making accurate predictions regarding changes in the MOC and carbon pump. Consequently, it appears premature to assert a slowdown of the carbon pump.

meridional overturning circulation, Antarctic bottom water, ocean carbon pump, climate change

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