南海环流多尺度动力过程演变特征与机制研究进展

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摘 要: 作为西太平洋最大的边缘热带海盆，南海具有季节性海盆尺度风生环流特性，具有越东偶极子、南海西边界流、黑潮入侵分支等主流系(空间尺度>100 km)，也具有丰富的中尺度涡旋、锋面、上升流等中尺度过程(空间尺度约为 O(10～100 km))和活跃的亚中尺度过程(O(1～10 km))等，而这些多尺度运动之间的能量转化是全球海洋能量循环的主要组成部分。本文主要概述了南海贯穿流特征、南海陆架陆坡流和西边界流特征、主流系对中尺度涡旋的影响、(亚)中尺度对湍流混合的影响四个方面取得的研究进展。目前的研究已发现主流系主要通过斜压不稳定将能量传递给中尺度过程，中尺度涡旋能量主要通过正压不稳定、剪切不稳定等过程将能量传递给小尺度过程。但是，多尺度运动之间能量传递过程的观测、南海中小尺度过程的能量逆级串过程及其对局地天气与气候的影响仍需进一步研究。

关键词: 南海；多尺度动力过程；能量传递

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南海是西太平洋边缘最大的边缘海，连接着太平洋和印度洋。其中南海贯穿流是太平洋-印度洋水交换的重要分支，在南海热量、盐度运输中起到重要作用[1-2]。南海贯穿流的跨海盆输运将从太平洋进入的低温高盐度水体变为高温低盐度水体随后流出南海，通过与印尼贯穿流接触的 2 个分支调节着印尼贯穿流的变率[2-8]，从而影响太平洋向印度洋的水体、热量输运，调节 2 个大洋间的物质、能量平衡。

南海地处东亚季风区，其稳定强大的季风性大气环流是南海上层环流的主要驱动力[9]。冬季盛行东北季风，南海环流总体表现为一个大的气旋式环流；夏季盛行西南季风，总环流大致表现为北部气旋式而南部反气旋式的偶极子式环流特征，并在二者中间的越南中部沿岸形成离岸东向急流[1,10-19]。由于风应力旋度是南海上层环流的主要驱动力，黑潮入侵与吕宋海峡水交换的相对贡献较小，因此，南海上层海盆尺度环流的形成可以通过准稳态 Sverdrup 平衡以及斜压 Rossby 波的快速调整得到很好的解释[20-22]。

除具有明显的季节性环流之外，南海环流还具有多尺度特性，如：具有大尺度(空间尺度>100 km)的西边界流、中尺度(空间尺度约为 O(10～100 km))涡旋/锋面/上升流、亚中尺度(O(1～10 km))过程及湍流混合(空间尺度 O(0.01～100 m))等多种运动。从动力角度上看，大尺度运动满足地转平衡，中尺度运动满

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足准地转平衡，而亚中尺度过程打破了地转平衡理论，伴随有强的垂向速度（O（10～100 m/s））。

近些年来，海洋环流的多尺度特征这一科学问题成为了海洋学家们关注的热点。海洋环流多尺度演变特征的研究可加强我们对海洋能量从大中尺度串级到小尺度这一完整过程的认识[23-28]。基于此，本文主要从南海贯穿流特征、南海陆架陆坡流和西边界流特征、主流系对中尺度涡旋的影响、（亚）中尺度对湍流混合的影响四个方面取得的进展展开论述。

1 南海贯穿流的跨海盆输运

南海贯穿流是太平洋-印度洋贯穿流的重要分支[19,29-30]。太平洋水经吕宋海峡进入南海之后成为南海贯穿流的主要来源。南海贯穿流通过2个分支通向印度尼西亚海域，其中第一分支为流经卡里马塔海峡到达爪哇海，第二分支经过民都洛-锡布图通道从而到达苏拉威西海。

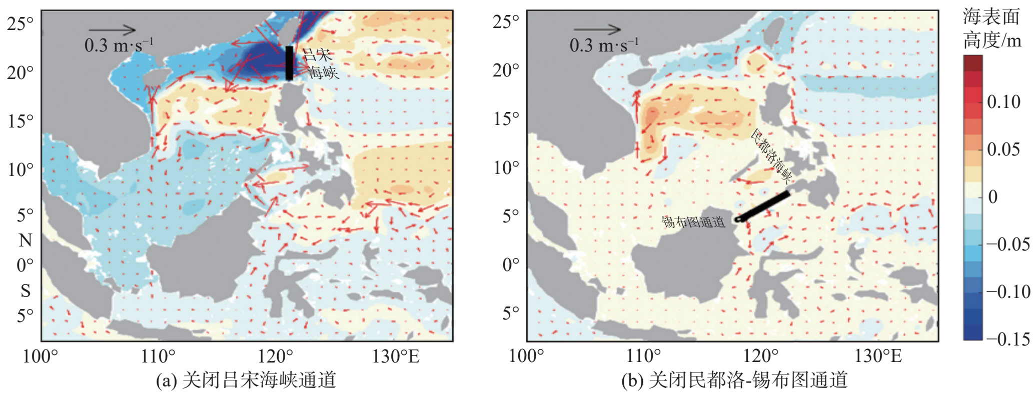
吕宋海峡位于南海的东北侧，处于台湾岛与吕宋岛之间，海槛深度约为2 200～2 400 m，最大水深超过3 000 m，是直接沟通南海和西北太平洋的唯一深水通道，也是南海与外海间体积、热量、盐度输运最大的通道，吕宋海峡的水交换对南海环流的维持有重要的影响[17,31-33]。观测以及数值模式结果表明[6,34-38]，从太平洋经吕宋海峡流入南海的总流量为2～6 Sv，且有明显的季节和年际变化，表现为冬季和El Niño期间流量较大，夏季和La Niña期间流量较小。此外，吕宋海峡的水交换具有明显的垂向分层结构特征[39]，具体表现为上层（小于500～750 m）为太平洋水进入南海，流量约为3～6 Sv [33,40-41]，中层（约750～1 500 m）是南海水出流进入太平洋，中层水流出吕宋海峡的流量约为1～2 Sv[41]。吕宋海峡底层水交换为密度较大的太平洋深层水穿过两千多米水深的吕宋海峡海槛进入南海，其深层水交换流量为1～2 Sv，是南海深层环流的主要驱动力[42-44]。基于14 a的卫星观测海底压力时间序列，Zhu等[45]研究表明吕宋海峡深层水交换流量在2003年到2016年间以每十年0.43 Sv的速度减弱，该减弱趋势可能对南海深层产生深远影响。

驱动吕宋海峡水交换的主要机制包括季风、地形的强迫和黑潮的入侵，以及中尺度涡旋的影响[17,41,46-47]。南海季风活动影响着南海上层环流的基本状况，决定南海上层环流季节转换[19]。黑潮入侵南海的动力机制可归结为风场驱动[48]、跨太平洋-南海的压力梯度[49]、迟滞效应[50]、位涡守恒[51]和涡旋活动[52]。Wang等[42]指出南海深层的热盐环流上升运动对调控上层风驱环流有重要的作用。作为南海环流的上游通道，吕宋海峡的输运变化在南海水交换过程中起着重要作用，实际上下游出流通道也是南海环流的重要组成部分，目前对于南海南部出流海峡通道的研究较多集中在卡里马塔海峡，而对于民都洛海峡的水交换研究较少。

卡里马塔海峡为连接南海和爪哇海的通道，其宽约350 km，最大水深约50 m，方国洪等[29]研究指出卡里马塔海峡是南海南部海区的主要出流通道，对于维持南海的热盐平衡起着重要作用[2]。从2007年至2016年中国-印度尼西亚-美国三方合作开展的南海-印尼海水交换观测项目（The SCS-Indonesian Seas Transport/Exchange, SITE）开展了对卡里马塔海峡流速的持续观测[53-55]。近十年（2007年至2016年）的观测数据表明卡里马塔海峡的年平均流量为−0.74 Sv，从南海流向爪哇海，冬季平均流量达到−2 Sv, 而夏季则从爪哇海流向南海，平均流量为0.69 Sv [56]。影响卡里马塔海峡水交换的主要因素为局地风场的强迫，其季节及年际变化主要受东亚季风的影响[6,30]。虽然卡里马塔海峡的年平均流量较小，但其淡水输运量却高达−30.87 mSv，相当于冬季印度尼西亚海降水量的42%[57]。数值模式研究表明，和另一分支民都洛海峡相比，卡里马塔海峡年平均淡水输运量超过民都洛海峡的2倍，占年进入南海淡水总量的26.3%[56]，因此卡里马塔海峡的水交换对南海跨海盆的淡水输运起到重要作用。

民都洛海峡为南海与苏禄海的连接通道，其深度约为500 m。卡里马塔海峡和台湾海峡的深度都小于100 m，只涉及南海表层环流。因此，民都洛海峡是南海的主要出流通道之一，也是南海环流温跃层和温跃层深度以下唯一的出流通道。模式模拟和卫星遥感数据研究表明，民都洛海峡多年平均的南向输送约为3 Sv[2,33,41,58-59]。2007年至2009年菲律宾海峡动力学实验（PhilEx）计划期间的潜标数据提供了目前唯一观测到的民都洛海峡流速剖面[60]，其2008年向南流量为0.1 Sv，这与潜标的位置及观测年份有关。由于缺乏对民

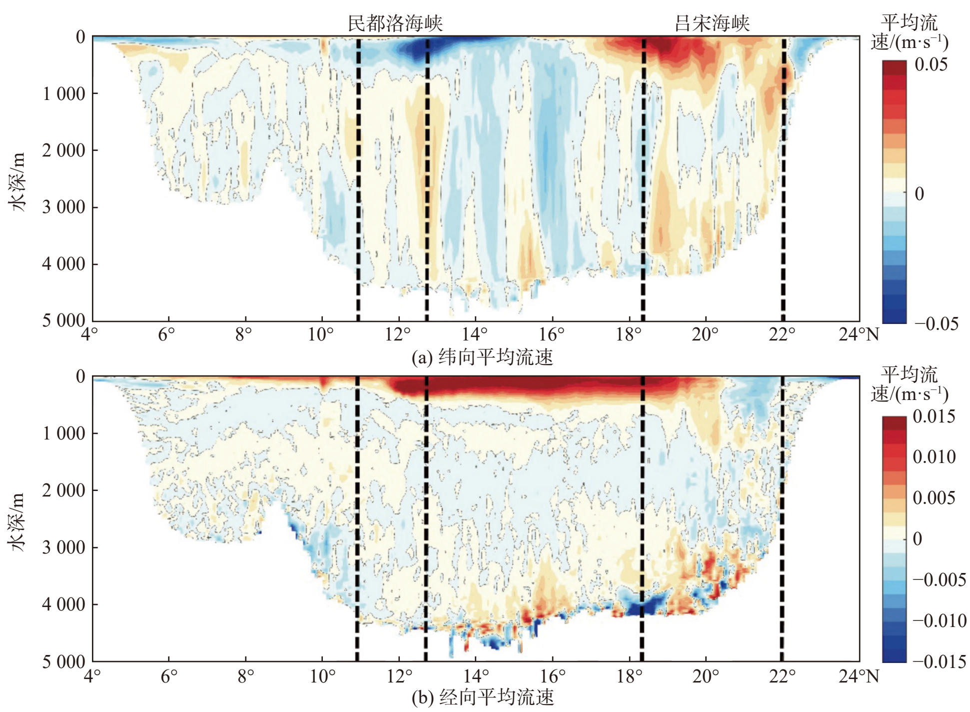
都洛海峡的长期观测，所以，目前尚不清楚民都洛海峡水交换对南海环流的相对贡献和水文变化特征。关闭海峡的模式敏感性实验有助于理解海峡与环流之间的动态关系[4,61-62]。基于高分辨率海洋模式的研究表明，如果民都洛-锡布图通道关闭，则吕宋海峡的流量减少 75%，上层环流特别是南海贯穿流大幅减弱[63]（图 1）。由于上层与中层环流的垂向耦合[46]，关闭民都洛-锡布图通道后南海上层环流减弱使得南海中层反气旋式环流也减弱，而深层环流没有显著改变[64]（图 2）。



注：本图来源于 Li 等[63]

图 1　模式中关闭吕宋海峡和关闭民都洛-锡布图通道后南海海表面高度及表层流场变化

Fig. 1　Distribution of sea surface height and surface flow field in the South China Sea after the closure of Luzon Strait and Mindoro-Sibutu Channel in the model



注：本图来源于 Li 等[64]。

图 2　关闭民都洛-锡布图通道后南海纬向平均流速以及经向平均流速垂向结构分布的变化

Fig. 2　The vertical structure distribution of the zonal mean velocity and meridional mean velocity in the South China Sea after the closure of Mindoro-Sibutu Channel

此外，民都洛-锡布图通道为低频海浪从西太平洋传播到南海提供了路径[62,65-66]。与厄尔尼诺-南方涛动（El Niño-Southern Oscillation，ENSO）相关的西太平洋赤道 Rossby 波到达菲律宾沿岸后激发沿岸 Kelvin 波。沿岸 Kelvin 波主要通过民都洛-锡布图海峡进入南海，调节南海东部海平面高度，将 ENSO 信号传递到南海，进而影响吕宋海峡的入流，影响多层环流的年际变化[64]。因此，民都洛海峡的水交换对南海与西太平洋间海洋波动的传播起到至关重要的作用。

2 南海北部陆坡流与西边界流演变特征

南海西边界流与北部陆坡环流是南海贯穿流的重要组成部分，其形成与变化不仅与东亚季风息息相关，还受到吕宋海峡、民都洛海峡等的跨海盆输运，以及黑潮入侵、涡旋活动的调制。尤其是西边界流，其季节与年际变化均与吕宋海峡通量变化有较强的关联[67]。

2.1 南海西边界流

受风应力与β效应影响，南海环流存在显著的西向强化现象，被称为南海西边界流[9,68-69]，其深度可达600 m，最大流速超过1 m/s, 是南海环流的主要组成部分[67,70-71]。 Chen 和 Xue[72] 利用理想数值模型研究指出南海存在强的西边界流，而其他一些边缘海（如墨西哥湾）却未被观测到存在强西边界流，其主要原因是其他一些边缘海缺少风、流和地形的合理配置。

南海西边界流具有显著的季节变化特征：冬季向南，夏季向北。冬季南海西边界流路径和形态分布显示，南海西边界流起源于南海北部并沿陆坡向西南流动，在越南东部沿岸流速加强、流辐变窄，到达南部海盆后形成气旋型环流结构[13]。夏季，受局地风应力旋度和越南沿岸地形影响[73-75]，西边界流由南向北运动，在越南沿岸分离形成东向急流，并伴随偶极子的形成[19]。

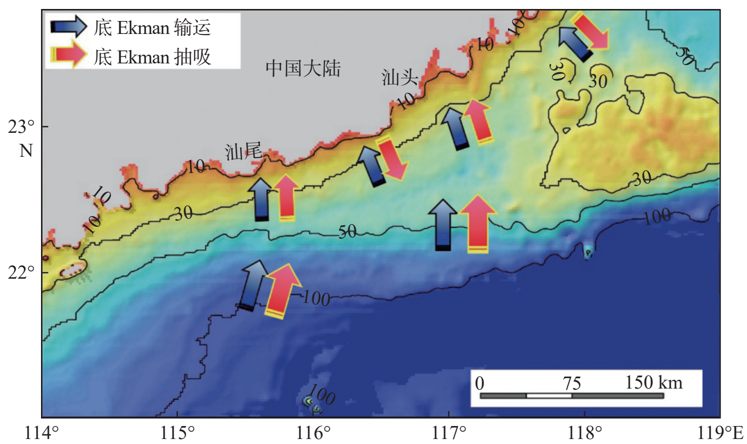
除此之外，南海西边界流还有显著的年际变化特征[67]。在厄尔尼诺年份，冬季受东亚季风减弱的影响，海盆尺度气旋环流减弱[69]，西边界流强度与范围均显著减弱，其在南部海盆的年际变化比北部海盆更为显著，不封闭的“U”型环流结构在厄尔尼诺发展期的冬季可变为封闭的“O”型气旋环流结构[76]。夏季受季风与吕宋海峡入侵变化的共同调制，东向急流的位置和强度及其伴随的偶极子的强弱有显著变化[68,77-79]。越南沿岸的东向急流与西边界流的北向分支呈反相关变化，厄尔尼诺发展期的夏季，较强的夏季风和吕宋海峡输运有利于更强的东向急流，而厄尔尼诺衰退期的夏季，较弱的夏季风与吕宋海峡输运有利于更强的北向分支[80]。

2.2 南海北部陆架陆坡流

南海暖流、夏季沿岸上升流系统以及冬季沿岸下降流系统构成了典型的南海北部陆架流系[81]。南海暖流是一支出现在广东外海、流向东北的海流，由于其流向与冬季东北风方向相反，也被称为“冬季逆风海流”[82]。南海暖流的形成机制目前还存在争议，其大体分为4种观点：①南海暖流是由黑潮入侵和与南海北部地形相互作用所产生[83-87]；②风应力松弛为南海暖流的形成提供一种瞬变的作用力，是南海暖流产生的主要原因，而黑潮入侵起到加强的作用[69,88]；③风应力引起的 Ekman 输送受到海岸的阻挡使海水在海南岛以东海域产生堆积，从而使得在海南岛以东到浙东近海形成明显的沿陆架等深线走向的坡度形成暖流[89-90]；④其他观点，譬如：Fang 等[13] 认为顺流的海面坡度在形成南海暖流中具有控制作用；Ye[91] 认为南海北部冬季环流主要是由斜压作用导致的密度流；Yang 等[92] 认为台湾海峡常年的北向流是产生南海暖流的主要机制。

南海北部陆架和粤港澳大湾区近岸海洋环流系统表现出明显的季节性变化。夏季，以东北向陆架流为主；冬季以西南向陆架流为主，跨陆架水交换表现出明显的夏季上升流和冬季下降流特征[93-94]。南海北部

上升流系统主要包括粤东上升流与琼东上升流。夏季沿岸西南风被认为是南海北部上升流产生的主要机制[95-98]。同时上升流的空间分布受到地形、沿岸流、冲淡水等因素的调制[99-101]。在脉冲状西南风作用下，下层上升流和上层剪切混合过程使得盐度收支空间分布不均匀，造成珠江冲淡水脱离出孤立的低盐水，在遥感图像和航次观测大面分布图中表现为斑块状的珠江冲淡水[102]。当粤东上升流充分发展时，上升流锋面处由于热成风作用形成射流，当珠江冲淡水东向延展时被卷入此射流，进而形成射流状珠江冲淡水[103]。当粤东上升流较弱时，东向延展的珠江冲淡水穿过粤东上升流和浅滩上升流之间的地带；当粤东上升流充分发展时，其锋面处强地转流向外海延展，此时珠江冲淡水将向浅滩上升流以东海域迁移[104]。Gan 等[94] 研究了在理想风的条件下南海北部加宽的陆架地形对上升流的影响，发现粤东区域加宽的陆架地形诱导了西向压强梯度力，进而加强了汕头附近风生上升流的强度。Liu 和 Gan[105] 基于观测和多层嵌套模式进一步指出，台湾海峡风场可以通过建立大尺度背景环流维持南海北部跨陆架水交换。沿岸流在变化的地形区域通过底 Ekman 输运与底 Ekman 抽吸驱动驱使地形诱导的上升流，调制南海北部上升流的空间分布，并对上升流年际变化产生影响[81,106]（见图 3）。



注：本图来源于 Wang 等[106]；图中等值线数据为水深，单位为 m。

图 3　南海北部底 Ekman 输运与底 Ekman 抽吸对地形诱导上升流的贡献示意图

Fig. 3　Schematic diagram of the contribution of bottom Ekman transport and Ekaman suction to topographic induced upwelling in the northern South China Sea

冬季，在东北季风作用下，广东沿岸出现水位的堆积，产生东南方向的压强梯度力，从而产生西南方向的沿岸流[22]。堆积的冷水在近岸下沉，形成南海北部下沉流[107]。马文涛等[108] 通过模型模拟发现南海的溶解有机碳与季风关系密切，冬季强混合可引起陆坡区域溶解有机碳浓度的增高。Gan 等[93] 通过数值模拟实验研究粤东加宽陆架地形对冬季下降流的加强作用，结果表明：粤东区域西向收敛的地形导致沿岸流加速，形成增强的向沿岸压强梯度力，进而导致加强的向岸地转输运；同时西向加强的沿岸流增加了东向的底摩擦力，增强了底层 Ekman 离岸输送。

3　南海背景流对中尺度涡旋的调制研究

3.1　中尺度涡与黑潮入侵的动力关联

中尺度涡能够在任何季节从黑潮脱落并进入南海，并且冬季发生的频率更高[31,109]。利用 1.5 层约化重力

准地转模型研究在迟滞状态下西边界流流经宽口缝隙时中尺度涡对西边界流的影响，发现迟滞现象为周期性的由入侵和跨越造成的涡度平衡所控制，而在迟滞状态时中尺度涡从东边海盆靠近豁口会对西边界流在豁口内的路径产生显著的影响[110-111]。

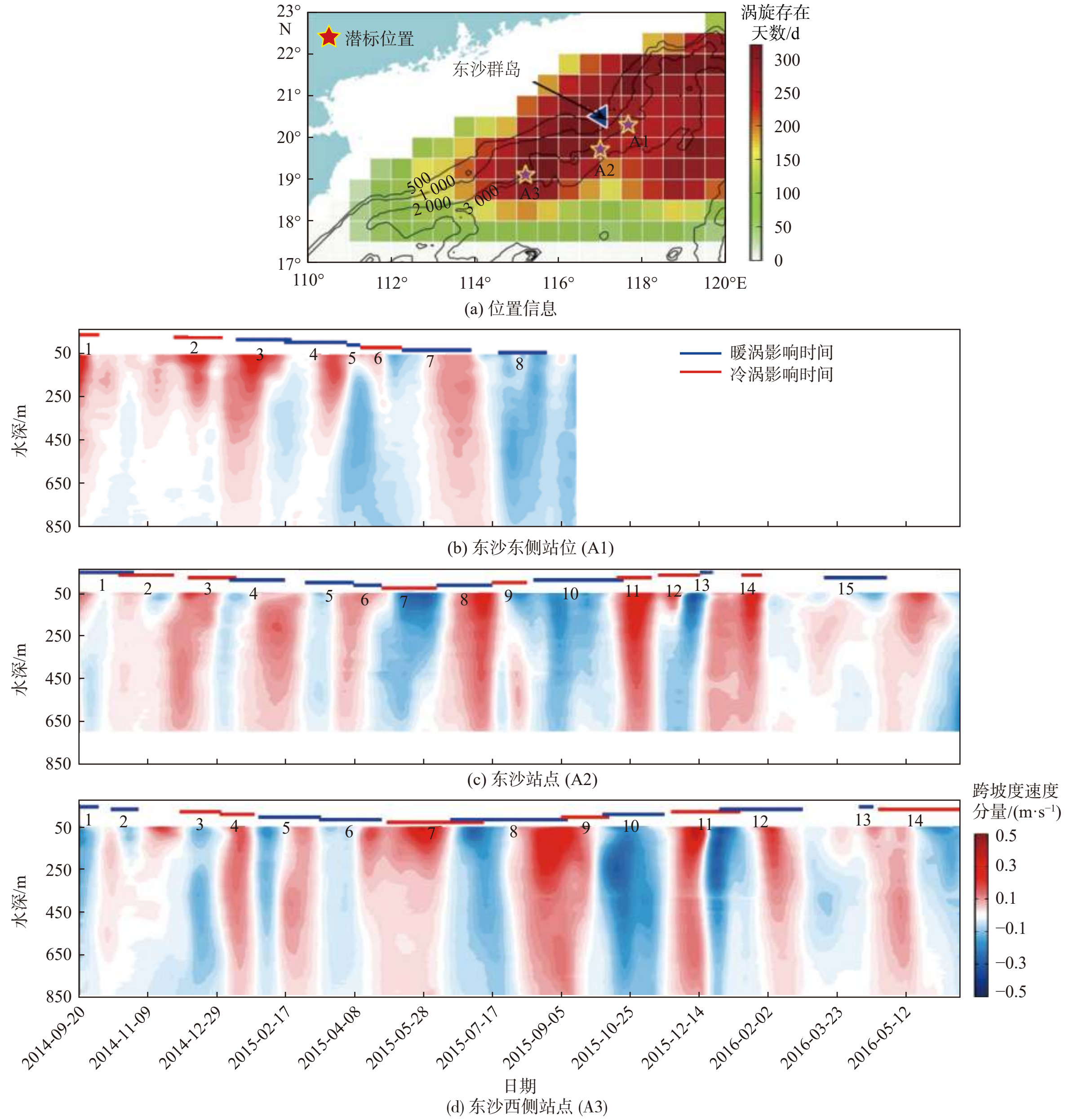
西太平洋的中尺度涡能否穿越黑潮进入南海一直是一个重要的科学问题。Song 等[112] 认为，从理论上，中尺度涡无法穿越稳定的跨越式黑潮，但是，Yuan 等[113] 认为当黑潮处于入侵形态的时候，无论是气旋涡还是反气旋涡均能够穿越黑潮进入南海。Xie 等[114] 发现西太平洋信号能够以罗斯贝波的形式进入南海。Zu 等[115] 通过能量诊断计算发现，2006 年冬季的一个反气旋涡能够长时间维持在台湾岛西南部的主要是由黑潮通过斜压不稳定将平均动能向涡动能转化所致。另外，黑潮以次表层流速极大值入侵的方式调控南海北部斜压不稳定性，当黑潮次表层流速极大值入侵增强时，南海北部背景环流的垂向剪切也会加强，进而通过斜压转换过程增强大尺度能量向中尺度能量的转化，激发南海北部活跃的中尺度涡活动[116]。

3.2 中尺度涡与南海西边界流的动力关联

Wang 等[117] 分析 2004 年 1 月至 4 月南海北部陆坡区域的一个浮标发现：该浮标一直被反气旋涡所捕获（78 d），并且该浮标除了受反气旋涡的控制而旋转外，同时也受到大尺度环流的调制；该反气旋涡个例表现出显著的涡-流相互作用的特征。中国科学院南海海洋研究所在西沙海域长时间连续潜标的布放，为认识南海西边界流与中尺度涡的相互作用提供了极大助力。Wang 等[118] 利用潜标观测资料定量评估了中尺度涡对西沙海域西边界流能量变化的贡献，发现该海区西边界流季节内能量的波动主要受中尺度涡的调制，并且中尺度涡对其能量的贡献最大能够达到 90%。Zhu 等[119] 通过观测重构南海西边界流流量数据[120]，很好地推动了南海西边界流变率的研究。Xu 等[121] 最新研究发现，南海北部流场变率以 10～110 d 变率为主导。Chu 等[72] 发现 2010 年西沙出现极端暖涡，涡流相互作用的能量诊断表明，西边界流通过正压、斜压转换将能量传递给涡旋，其中季风期间正压转换更强，从而导致涡旋不断北移并增大、增强。Qiu 等[122] 基于模型的结果显示该区域的暖涡发生了形变，该形变过程主要由西边界流的斜压不稳定能量传递引起。Su 等[123] 对入侵陆坡的涡旋进行了统计分析，发现能量密度大的涡旋更易进入东沙、西沙等陆坡区域；潜标及模型结果揭示，在南海西边界流影响下，反气旋在陆坡区域有所增强，而气旋能量削弱。Hu 等[124] 研究发现，越南东侧的中尺度涡形成与沿岸急流紧密相关。

3.3 南海西边界流区域中尺度涡旋引起的跨陆坡输运

Wang 等[116,125-128] 进行了一系列涡致跨陆坡输运的研究，比如：基于大量现场观测，在东沙群岛附近发现了中层跨陆坡急流的存在，并利用数值模型解释了其动力成因[126]；基于模型对南海北部跨陆坡流动的诊断研究发现，西沙群岛海域以东的陆坡区域以爬坡运动为主，而在西沙群岛以西以下坡运动为主；通过动力诊断分析发现，沿陆坡方向的正压压强梯度力是控制跨陆坡运动的主要动力因子[127]；2018 年基于陆坡潜标阵列的分析发现，中尺度涡结构的不对称性以及非线性特征能够引起显著的跨陆坡水体输运[125]（图 4），并且该涡致跨陆坡运动占总体运动标准差的 74.6%[116]；该跨陆坡运动中 10～20 d 的扰动分量能够显著激发东沙群岛附近的深海地形罗斯贝波[128]。Chen 等[129] 通过分析高度计、CTD 和 Argo 资料观测到的中尺度涡旋，发现由于上层海洋的强混合和深海很小的温盐梯度的存在，涡旋引起的温盐输运分别主要发生在温跃层和盐跃层；较大的极向涡致热输运发生在夏季的越南东部海域、冬季的吕宋岛西部海域，而较大的赤道向涡致热输运发生在冬季的吕宋海峡西部海域。Yang 等[130] 观测发现，从黑潮脱落的涡旋能够裹挟黑潮高盐水体输运到南海北部。



注：本图来源于 Wang 等[125]；图 a 中的等值线数据为水深，单位为 m；图 b 至图 d 中的数字为涡旋编号，跨陆坡速度分量正值表示向岸。

图 4　南海北部涡致跨陆坡速度

Fig. 4　Eddy-induced cross slope velocity in the northern South China Sea

4　南海(亚)中尺度过程对湍流混合的影响

海洋湍流混合能改变水团性质，重新分布营养物质和微生物，在海洋热量、动量的传递和能量的平衡过程中扮演着重要的角色。南海是全球中小尺度过程最活跃的海域之一，正压潮与吕宋海峡陡峭地形相互作用，不仅产生出强大的内潮波[131-136]，而且激发出大振幅的内孤立波[137-142]。此外，盛行的季风和频繁的热带气旋使得南海的近惯性内波非常活跃[143-146]。这些中小尺度过程可以为南海湍流混合提供大量能量。

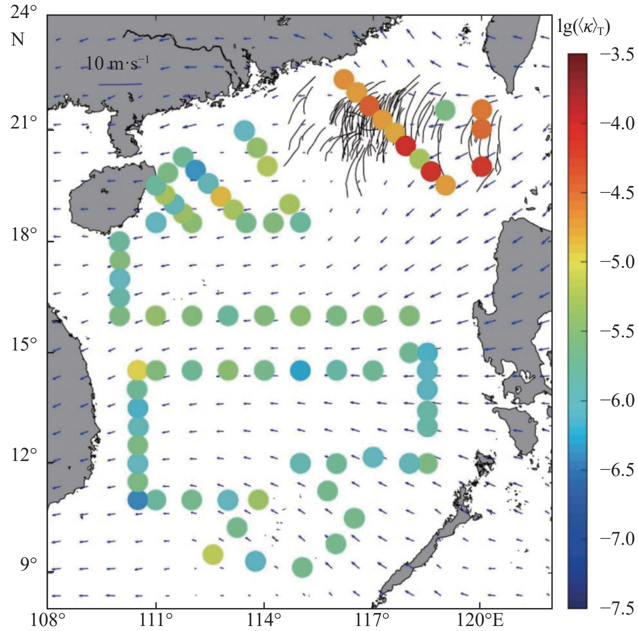
4.1 内潮对湍流混合的调制

内潮是南海湍流混合重要能量来源之一，正压潮与吕宋海峡陡峭地形相互作用产生大量的内潮波，其中高模态内潮波易于局地耗散，低模态内潮波易于传播[131,133-134]。Niwa 和 Hibiya[134] 估计吕宋海峡半日潮的转换率为 14 GW，其中 50% 以内潮波的形式辐射出去（4.2 GW 进入南海，3.2 GW 进入西太平洋）；Jan 等[133] 估计半日潮和全日潮的转换率分别为 11 GW 和 19 GW，共计 30 GW，其中约 40% 以内潮波的形式辐射出去（7 GW 进入南海，6 GW 进入西太平洋）；Alford 等[137] 估计吕宋海峡内潮的转换率为 24.1 GW，其中 60% 以内潮波的形式辐射出去（向西和向东的总能量通量分别为 7.89 GW 和 6.05 GW）。向西传入南海的内潮波可以穿越深海海盆，到达南海北部陆架和越南海岸[136]。

内潮波在深海盆传播过程中会发生非线性波-波相互作用（如参数化次调和不稳定），将能量传递到更高模态的内波[147-149]。到达陆架、陆坡的内潮波则与地形相互作用，部分能量因底地形摩擦直接耗散，另一部分能量反射回深海或继续向更浅的陆架海域传播[150-152]。南海北部大陆坡相对于全日潮为临界地形，相对于半日潮为亚临界地形，全日潮的能量更易于反射回深海，而半日潮的能量则倾向于向更浅海域传播[153]。通过与地形的线性相互作用和非线性相互作用，南海内潮波将大量的能量级串到高模态内波，从而为南海湍流混合提供大量能量。

海洋数值模式、细结构参数化方案等间接方法的研究均表明南海湍流混合的时空分布和南海内潮波分布均与南海地形相关[142,154-157]。Wang 等[157] 基于海洋数值模式的研究表明，产生于吕宋海峡的内潮是南海内潮耗散的主要能量来源，内潮引起的强湍流混合主要发生在吕宋海峡、陆架坡折处和海底边界层。Sun 等[156] 利用细结构参数化方案研究了南海北部（118°30′E, 20°54′N）湍流混合的时间变化特征，结果表明南海北部湍流混合的季节性变化与内潮波和风致近惯性内波有关。Liu 等[155] 采用细结构参数化方案估算了南海 18°N 断面的湍流混合，结果表明，内潮波主导着深层湍流混合，在粗糙地形海域内潮波可以增强整个水深的湍流混合。Lu 等[154] 也采用细结构参数化方案研究了南海湍流混合的空间分布特征，结果表明，强湍流混合主要出现在内潮生成区的吕宋海峡和强非线性相互作用的东沙群岛海域。Wang 等[142] 利用声学多普勒流速仪（Acoustic Doppler Velocimetry，ADV）观测数据间接估算了南海北部陆坡处底边界层的湍流混合，结果表明，底边界层的湍流混合强度受内潮影响，在观测期间其湍动能耗散率从 7.6×10^{-6} W/kg 增加至 5.6×10^{-4} W/kg。

另外，直接的湍流微结构观测亦表明南海湍流混合的时空分布与南海内潮分布和南海地形相关[158-167]。Shang 等[160] 利用湍流微结构数据分析了南海上层湍流混合的空间分布特征，结果表明南海上层湍流混合自北向南逐渐减弱，这种空间分布与吕宋海峡形成的内潮波在南海的分布和传播路径相关（见图 5）。南海的一个强湍流混合区是内潮波的生成区——吕宋海峡，Lozovatsky 等[162] 观测发现吕宋海峡附近密跃层的平均湍动能耗散率高达 10^{-7} W/kg，比开放大洋高 2 个数量级，Tsutsumi 等[165] 的观测也表明吕宋海峡海脊处的湍动能耗散率和垂向扩散率比开放大洋高 2 个数量级。南海另一个强湍流混合区是南海北部发生强非线性相互作用的陆架和陆坡区。St. Laurent[164] 的观测结果表明南海北部陆架坡折区的湍动能耗散率高达 10^{-6} W/kg，强湍流混合与斜压潮和底地形有关；Yang等[167] 的观测结果表明半日潮和全日潮引起的剪切不稳定控制着南海陆架上的强湍流混合；Cui 等[158] 分析南海北部多个跨陆架陆坡的断面观测数据认为，密度跃层中存在强湍流混合的湍流斑块，这些湍流斑块的强湍流混合由高频内波引起的对流驱动，主要出现在陆架坡折处；St. Laurent 等[163] 的湍流混合微结构观测结果表明，源自吕宋海峡的内波能量大部分耗散于南海北部的陆架和陆坡海域，在波浪振幅最大的东沙群岛海域，湍流能量耗散高达 1 W/m^2。



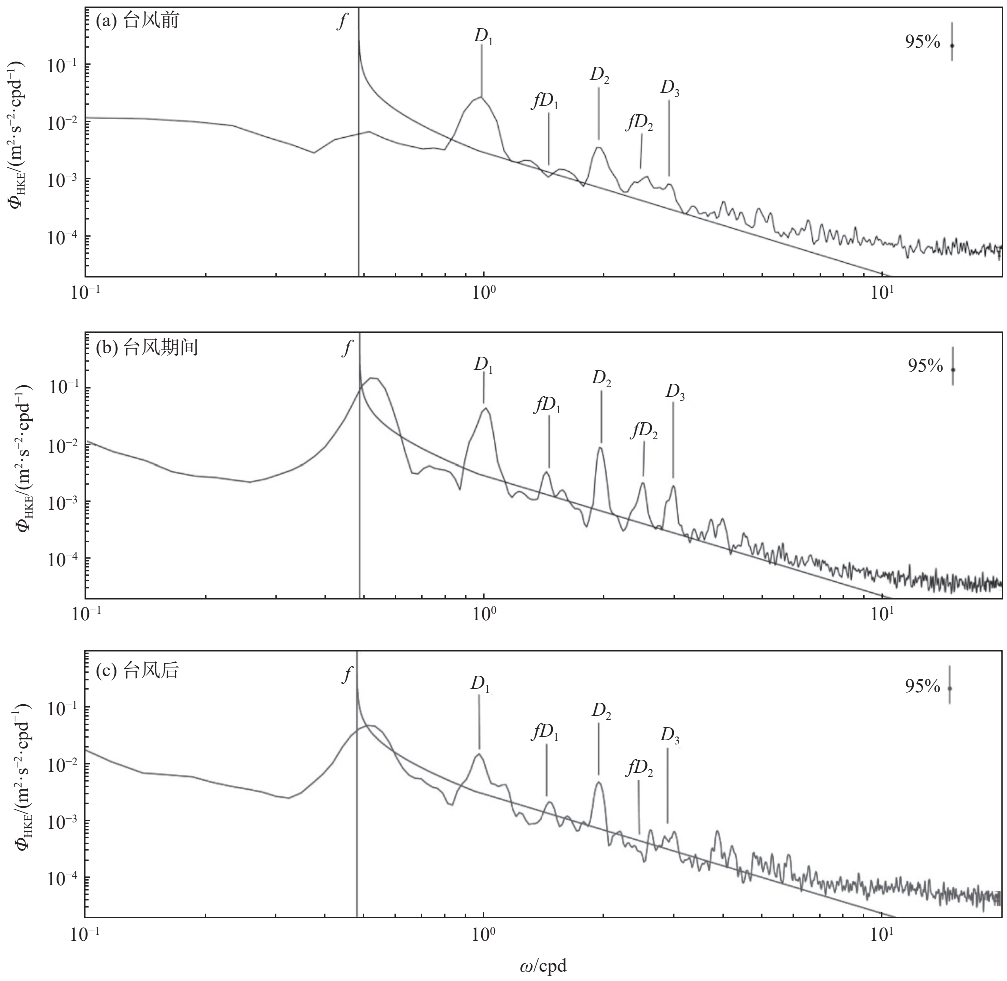
注：本图来源于 Shang 等[160]；图中蓝色箭头为 10 m 高度平均风速，黑色曲线为卫星图像观测到的内波。

图 5　南海温跃层平均垂向扩散率($\langle k \rangle_T$)的空间分布

Fig. 5　Spatial distribution of the average vertical diffusivity of the thermocline in the South China Sea

4.2　近惯性内波对湍流混合的调制

近惯性内波是南海湍流混合的另一个重要能量来源，盛行的季风和频繁的热带气旋导致南海的近惯性内波非常活跃，观测已表明，在南海夏季风盛行期间出现显著的近惯性内波、过境的热带气旋也常伴随着强烈的近惯性内波[78,168-169]。热带气旋引起的近惯性内波与热带气旋强度、移动速度和最大风力半径等有关[143,169-171]，同时受到中尺度涡和背景流等的影响[100,172-174]。Yang 和 Hou[171] 通过潜标观测到热带气旋引起的近惯性内波的垂向范围达到 300 m，垂向相速度和群速度分别为 0.27 和 0.08 cm/s；Sun 等[145] 和 Huang 等[172] 的观测发现中尺度涡和背景流可以导致近惯性内波频率发生偏移；Li 等[173] 的观测表明地形惯性波和陆坡流可以增强热带气旋引起的近惯性内波。热带气旋引起的近惯性内波以第二模态为主，其指数衰减时间为几天到十几天[143,169,171-172,175-176]。近惯性内波在衰减期间通常会发生非线性相互作用，将能量传递到更高模态的内波[176-178]。Guan 等[176] 的观测表明，热带气旋引起近惯性内波(频率为 f)伴随着强高谐频内波(频率为 $fD1$, $fD1=f+D1$，其中 $D1$ 为全日潮频率)，这些高谐频内波由近惯性内波和全日潮之间的非线性相互作用产生；Lin 等[178] 的观测表明，热带气旋引起的强近惯性波也可以与半日潮(频率为 $D2$)发生非线性相互作用，产生高谐频内波(频率为 $fD2$，$fD2=f+D2$)；Liang 等[177] 的观测表明，热带气旋引起近惯性内波亦可以激发全日内潮和半日内潮之间的非线性相互作用，产生高谐频内波(频率为 $D3$，$D3=D1+D2$，图 6)。近惯性内波及其期间通过非线性相互作用产生的高谐频内波往往具有强剪切[179]，使得水体容易发生剪切不稳定，从而产生强湍流混合[155-156]。Sun 等[156] 基于细结构参数化方案的研究发现，南海北部的强湍流混合与风致近惯性内波有关；Liu 等[155] 基于细结构参数化方案的研究结果表明近惯性内波对南海 18°N 断面上层的强湍流混合起到重要作用。



注：本图来源于 Liang 等[177]；f 为近惯性内波频率；$D1$ 为全日潮频率；$D2$ 为半日潮频率；$fD1$、$fD2$ 和 $D3$ 为高谐频内波频率，$fD1=f+D1$，$fD2=f+D2$, $D3=D1+D2$；右上角的垂直点线表示 95% 的置信区间。

图 6 台风前、台风期间和台风后观测站位（110°31′12″E，13°59′24″N）48～152 m 水深的平均动能谱

Fig. 6 Average kinetic energy spectrum between 48—152 m at observation station（110°31′12″E，13°59′24″N）before, during and after the typhoon

4.3 中尺度涡旋/亚中尺度过程对湍流混合的调制

近期研究表明中尺度涡旋对湍流混合也有影响。Yang 等[180] 研究发现涡旋边界上的垂向混合率比涡旋中心处高 5～7 倍。在利用水下滑翔机数据研究中尺度涡旋结构的基础上，Qi 等[181] 发现在涡旋边界存在锋面的区域垂向混合强，而在温度梯度较小的涡旋西边界处垂向混合较弱。Yang 等[130] 利用数值模型模拟了中尺度涡旋在陆坡区域耗散至亚中尺度过程并最终以湍流混合形式耗散掉的过程，发现中尺度涡旋边界上湍动能耗散率较强。

亚中尺度过程是中尺度过程与湍流混合之间能量传递的桥梁。亚中尺度过程一方面从中尺度过程或海气界面处强迫吸收能量，另一方面伴随出现能量耗散。Ramachandran 等[182] 的数值模式结果显示中尺度与亚中尺度耦合能引起垂向通量的增强；Callies 等[183] 用数值模式分析了亚中尺度强迫产生湍流的 2 种机制：中尺度驱动的表面锋生和斜压混合层不稳定,并肯定了这 2 种机制在不同尺度能量传递中的贡献。

南海北部表层和次表层均存在亚中尺度结构。甘子均和蔡树群[184] 分析表明南海北部的罗斯贝半径约

为 50～100 km，即确定南海的亚中尺度空间尺度基本小于 50 km。Zheng 等[185] 对南海亚中尺度过程研究进行了综述，把亚中尺度过程分为亚中尺度波动（内波、内潮）、涡管（涡旋、地形波等）和陆架过程（河口锋）等。Dong 和 Zhong[186] 统计 4 a 的高分辨率数值模拟结果发现，南海北部亚中尺度过程在冬季较强、夏季较弱，认为强的流应变和深的混合层可能会引起锋生。锋生过程能吸收中尺度涡旋的能量以达到稳定状态，也可通过不稳定激发亚中尺度过程，在这些能量级串过程中伴随着强的能量耗散[28]。Qiu 等[122] 利用水下滑翔机观测也发现中尺度涡旋边界上有锋生现象，布放的漂流浮标也观测到了亚中尺度涡旋。Lin 等[187] 利用 Massachusetts Institute of Technology General Circulation Model（MITgcm）结果发现潮汐对亚中尺度过程的能量变化有重要影响。Zhang 等[188] 基于潜标阵列观测揭示了南海次表层的亚中尺度相干涡旋特征。

近年来，国内对亚中尺度过程及湍流混合做了很多观测。中山大学海洋科学学院大气海洋相互作用团队与南方海洋科学与工程广东省实验室（珠海）于 2021 年组织了 3 次中尺度涡旋与湍流混合、亚中尺度过程与湍流混合的观测。基于 MVP（Moving Vessel Profile）拖曳及 VMP（Vertical Microstructure Profiler）湍流剖面仪观测了亚中尺度过程与湍流混合，发现：在暖涡和冷涡交界处，湍动能耗散率较强；在背景流速剪切较大的区域，其湍动能耗散率也较大。该观测为亚中尺度过程引起的湍流混合参数化研究提供了支持。

5　结　语

本文回顾了南海贯穿流特征、西边界流特征、主流系与中尺度相互作用特征、中小尺度相互作用等方面取得的研究成果和进展状况。大尺度环流主要通过斜压不稳定将能量传递给中尺度过程，中尺度涡旋的能量主要通过正压不稳定、剪切不稳定等过程将能量传递给小尺度过程。但是，目前在南海的多尺度相互作用研究方面遇到了一些亟待解决的瓶颈问题，主要体现在以下 2 方面。

1）“大尺度-中尺度-小尺度”之间能量传递过程的观测存在难点。南海具有显著的季风强迫、复杂的地形以及由黑潮入侵等因素激发出的南海上层丰富的亚中尺度活动[40,189]。但是，由于亚中尺度活动的时空范围都很小，对亚中尺度现象的观测十分困难。传统的船载断面观测分辨率低且无法获得长期连续的观测数据，但高分辨率的数值模式可以模拟出连续的亚中尺度现象，并可以被用来分析其动力过程[187-188]。中尺度涡旋能量如何通过亚中尺度运动耗散，以及亚中尺度过程是否会导致锋面的能量向小尺度耗散，并如何将能量串级至湍流尺度，到目前为止尚不清楚。

2）南海中小尺度过程研究对局地天气与气候的影响仍不明确。Wang 等[190] 基于高分辨率数值模型发现赤道太平洋亚中尺度涡旋对 ENSO 发展起重要的抑制作用。目前在南海，亚中尺度过程对全球气候的影响尚不明确，急需建立高分辨率数值模式开展研究。

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Progress in the Dynamic Process and Mechanisms of Multi-Scale Currents in the South China Sea

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Abstract: South China Sea (SCS) is one of the largest marginal sea in the western Pacific Ocean. SCS large-scale currents (*O*(100 km)) include seasonal wind-driven basin-scale currents, Kuroshio branches, SCS western boundary currents, and so on. Mesoscale process (*O*(10—100 km)) in terms of eddies, fronts, upwelling and submesoscale process (*O*(1—10 km)) are also active in SCS. The energy transformation among above multi-scale process plays vital roles in global oceanic energy balance. Some achievements are on the dynamic characteristics of SCS throughflow, continental shelf and slope currents, SCS western boundary current, the impact of SCS western boundary current on mesoscale eddies, and the influence of mesoscale eddies on turbulence, etc. Forward energy cascade process has been revealed that the SCS western boundary current releases its energy to mesoscale eddies via baroclinic instability, while the mesoscale eddies cascade energy to submesoscale process or smaller scale process through barotropic instability, in terms of shear instability. The issues of advanced observation of the energy transformation process among multi-scale motions, inverse energy cascade from small scale process to (sub)mesoscale process, and the contributions of submesoscale process to the SCS weather and climate remain unclear and merits near future study.

Key words: South China Sea；multi-scale dynamic process；oceanic energy balance
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