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黑潮及其对中国近海的入侵研究综述

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摘要 本文综述了近20多年来黑潮及其对中国近海入侵的研究进展. 黑潮作为北太平洋最强西边界流, 具有流幅窄、流速快、流量大的特点, 其流量存在季节内至年代际等多时间尺度变率, 并受大尺度气候因子(如厄尔尼诺—南方涛动、太平洋年代际振荡)与局地动力过程(如风场、涡旋)共同调控. 黑潮主要通过吕宋海峡和台湾岛东北海域入侵中国近海: 在吕宋海峡, 入侵强度呈冬强夏弱的季节变化, 受季风、β效应、惯性效应及岛屿地形综合调控, 而且太平洋年代际振荡、厄尔尼诺—南方涛动、中尺度涡旋进一步调节入侵路径与强度; 在台湾岛东北海域, 黑潮形成近岸与离岸双分支结构, 表层与次表层入侵的季节变化不同, 动力机制主要受地形与斜压联合效应及位涡平流等调控. 黑潮入侵对中国近海产生多方面影响: 显著影响陆架环流、涡旋、锋面等多尺度动力过程; 改变温盐结构, 调节锋面混合与层化; 输入外源营养盐, 支撑高初级生产力, 影响生物群落结构与生态过程. 在可预测性研究方面, 数据同化及深度学习等方法为黑潮入侵预报提供了新技术; 上下游动力联动机制为提升预测能力提供了物理基础. 未来针对黑潮及其对中国近海入侵的研究, 需加强多过程耦合机制、跨尺度/跨流段联动及可预测性等方面的研究.

关键词 黑潮, 入侵, 南海, 东海

黑潮是全球海洋最强劲的西边界流之一, 对邻近边缘海(包括中国近海)的多尺度海洋动力过程、气候和生态环境等具有重要调控作用. 黑潮与其邻近边缘海的多时空尺度相互作用(包括物质与能量循环、水交换等)一直是海洋科学研究的前沿、重点和难点. 在过去的几十年间, 国内外海洋学者对黑潮本身流轴与流态的基本特征、时空演变规律及其动力、气候与生态效应开展了大量研究[1,2]. 本文侧重对黑潮及其通过入侵中国近海进而调控中国近海环流与生态环境等方面的系列研究进行归纳总结, 并对未来的研究方向提出展望.

1 黑潮基本特征与多尺度变异

黑潮作为太平洋北赤道流的北向分支, 发源于菲律宾以东约12°~15°N海域, 先后流经吕宋岛以东、吕宋海峡、台湾岛以东、东海陆架/陆坡、日本九州岛以南等海域, 并于约35°N向东进入北太平洋形成黑潮延伸体区(图1). 多源观测与数值模拟结果表明: 黑潮流幅宽约200 km, 最大流速超过1 m/s; 在东海段黑潮的年平均体积输运量介于19~24 Sv(1 Sv=10^6 m^3/s), 但存

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图 1 黑潮主轴及其对中国近海的入侵路径. 图中深红色粗线表示黑潮主轴，是基于全球漂流浮标(GDP)历史数据集绘制的气候态黑潮表层主轴；黑潮入侵南海三种路径根据Nan等人[18](2011)重绘，其中绿色线、橙色线、蓝色线分别表示黑潮入侵南海的越隙、泄漏和流套路径；黑潮从台湾岛东北部海域入侵东海的两种路径根据Yang等人[19](2011)重绘，其中KBBCNT表示台湾岛东北部的黑潮底部分支流，UW代表上升流；图中还以黑色虚线及空心箭头标出东海3个断面及其水体通量

Figure 1 Schematic diagram of the Kuroshio and its intrusion paths to the China's coastal seas. The thick dark red line indicates the climatological axis of the Kuroshio, derived from Global Drifter Program database. The green line, orange line and blue line represent the leaping path, the leaking path, and the looping path, respectively, adapted from Nan et al.[18](2011). The two intrusion paths of Kuroshio off the northeastern coast of Taiwan Island are redrawn from Yang et al.[19](2011). KBBCNT denotes the Kuroshio Bottom Branch Current to the Northeast of Taiwan Island; UW stands for upwelling. Three transects (black dashed lines) with hollow arrows illustrate water volume transports across each section in the East China Sea

在显著的空间差异性；黑潮自台湾岛东北海域进入东海后逐渐增强，在东海陆坡中部达到最强，随后朝吐噶喇海峡方向逐渐减弱[1].

黑潮的流量存在季节变化. 例如，吐噶喇海峡的观测结果表明黑潮流量冬夏季大而春秋季小[3]；菲律宾以东的潜标观测则显示黑潮流量在2018年和2019年的季节变化有所差异[4]. 黑潮流量还具有明显的季节内变化[5]，菲律宾以东海域200 m以上黑潮流量的变化周期约为56 d[6]，而18°N处黑潮存在50~60 d和约100 d的季节内变化周期[7]. 此外，黑潮流量还存在周期为2~7年的年际变化[3]、年代际变化[8]和与气候变化密切相关的长期变化趋势[9,10].

黑潮流轴在不同时间尺度的变化受到不同动力过程的调控. 其低频变率(年际、年代际、长期趋势)主要受外海大尺度风应力旋度、厄尔尼诺—南方涛动(ENSO)、太平洋年代际振荡(PDO)和北太平洋环流振荡(NPGO)、海洋层结等因子的变化控制[8~12]. 黑潮的季节内变率主要受局地风场、中尺度涡旋等过程的调控[13~16]. 在季节尺度上, 黑潮上层的流速变化由局地风应力主导，下层变化则受伊豆—小笠原海岭以西的风应力旋度调控[17].

2 黑潮入侵中国近海的路径与动力机制

2.1 南海

2.1.1 入侵路径

黑潮入侵南海的路径形态多样，早期研究多基于流场形态进行分类. Nan等人[18](2011)基于海表地转涡度指数提出了经典的三种路径类型(图1)，成为后续研究的重要基础：(1) 越隙路径(leaping path)：黑潮主流轴以较为平直的形态跨越吕宋海峡，未显著进入南海，主要表现为“跨越”式通过；(2) 泄漏路径(leaking path)：黑潮部分水体以分支形式向西渗入南海，持续时间较短但频率较高，也称之为分支路径；(3) 流套路径(looping path)：黑潮在吕宋海峡形成气旋式或反气旋式环流，部分水体以涡旋形式进入南海，影响范围较大.

在此基础上，一些学者进一步提出黑潮冷、暖涡指数(KCI/KWI)识别冷涡路径、暖涡路径与分支路径[20]；或基于流线的方法将入侵路径进一步细分[21]；还有近期一项研究结合海表特征和水团性质进一步完善路径的识别方法[22].

2.1.2 入侵特征

表现出明显的季节变化. 冬季入侵较强，主要呈现“泄漏”或“流套”路径；夏季入侵较弱，多以“越隙”路径为主[23]，表层入侵通常在9月开始，于11~12月达到高峰，次年3月后减弱[24]；春季仍可能出现入侵现象[25]. 同时，由于黑潮的入侵，吕宋海峡的水体输运量(流量)具有季节、年际和年代际变化特征[26~28](表S1).

2.1.3 调控机制

在季节尺度上, 更多受局地过程影响(季风、β效应和惯性效应；表S1)，例如季风通过调整近岸海面高度，调节涡度平衡和气旋性切变层内的正摩擦应力力矩，导致入侵冬强夏弱[21]；在年际以上尺度，更多受外海强迫的影响，例如PDO通过调节北赤道流分岔点位置，影

响吕宋岛以东黑潮强度，正位相时促进入侵[29]. ENSO的作用则受PDO位相调制，在PDO负位相时影响更显著；厄尔尼诺事件通过削弱东北季风、增强斜压不稳定性来增加路径不稳定性，而拉尼娜事件有利于流套路径的维持[30]. 此外, 中尺度涡旋是影响入侵的重要因子; 暖涡倾向于增强黑潮主轴, 而冷涡则可通过行星涡度的挤压、负相对涡度的平流或黑潮主干的截断促进入侵[31]; 涡旋与黑潮的碰撞位置也会影响路径形态. 吕宋海峡内的岛屿可以减弱黑潮惯性、调节经向平流, 促进入侵并影响涡旋脱落[32,33]；黑潮入侵能够调整位涡, 并将上层中尺度能量下传, 调制深层地形罗斯贝波向南海传播, 从而影响南海北部深层环流[34,35].

2.2 东海

2.2.1 入侵路径

台湾岛东北海域是黑潮入侵东海的关键区域. 相较于吕宋海峡处的黑潮, 该段黑潮主轴相对稳定. 受地形影响，黑潮在此形成反气旋弯曲并产生双分支结构(图1)：一支为台湾岛东北的黑潮底部分支流(KBBCNT), 向西北延伸至长江口外, 形成浙江沿海底层高盐水; 另一支为黑潮分支流(KBC), 沿100 m等深线东偏[19]. 此外, 东海陆架黑潮底部分支流有时也可分为近岸黑潮分支流(NKBC)和离岸黑潮分支流(OKBC)[36], 其中OKBC来源于黑潮60~120 m之间的水团并沿着~100 m等深线流动，而NKBC来源于黑潮120~250 m之间的水团并从台湾岛东北海域的近底缓慢“爬升”到浙江沿岸(图2)[37,38].

2.2.2 入侵特征

呈现明显的季节变化，且表层与次表层有所不同. 表层水体在春夏季主要限于陆架外缘，秋冬季则增强并向陆架深入，10月达最强，有时可进入台湾海峡[39]; 次表层水入侵则为夏强冬弱. 在年际尺度上，跨200 m等深线入侵强度存在约8年的周期[40].

2.2.3 调控机制

包括局地过程和外海过程(表S2; 图3). 局地过程方面, 在台湾岛东北海域, 斜压性与地形的联合效应(JEBAR)与位涡平流(APV)项之间的平衡调控着入侵强度[41]; 黑潮与陆坡碰撞可导致海水沿等位涡面上翻, 形成自底层至表层的反气旋式入侵结构[42]. 在季节尺度上, 入侵强度更多受局地过程的影响, 受季风、黑潮与陆坡相互作用、局地涡度等多过程共同调制. 例如, 风应力通过埃克曼输运直接影响近岸黑潮分支流，秋季

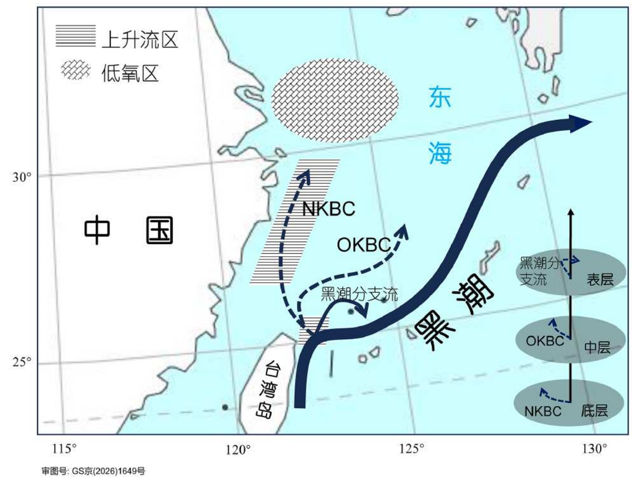

图 2 黑潮及其对东海的入侵路径与上升流区、低氧区位置. 黑潮入侵东海及其各层次分支流的路径是根据杨德周等人[37](2017)改绘; NKBC、OKBC分别表示近岸黑潮分支流与离岸黑潮分支流

Figure 2 Schematic diagram of the Kuroshio and its intrusion paths to the East China Sea (ECS), together with upwelling zones and hypoxic zones. The intrusion pathways of the Kuroshio and its multi-layer branches into the ECS are redrawn from Yang et al.[37](2017); NKBC and OKBC denote the nearshore Kuroshio branch and offshore Kuroshio branch, respectively

风场减弱导致该分支流衰退[36]；局地涡度平衡由JEBAR、底摩擦和非线性平流共同维持，影响分支流的季节变化[43]. 在年际及以上尺度变化上, 入侵强度更多受外海强迫的影响，例如入侵强度8年的周期变化受PDO调控的风应力旋度影响；海盆尺度的风应力产生的赤道向输运需要通过东海和日本海之间的极向输运来平衡，这一平衡主要由黑潮入侵东海和台湾海峡输运共同实现[44]. 中尺度涡旋的作用也较为显著, 副热带逆流区的涡旋可通过减少黑潮输运量来增强入侵东海, 不同海域的涡旋分别作用于黑潮的不同区段，进而影响入侵路径和强度[45].

3 黑潮入侵对中国近海的影响

作为连接西太平洋与中国近海陆架系统的关键动力纽带，黑潮通过多尺度环流调制、锋面与湍流混合增强以及物质输运，显著地影响南海北部与东海陆架的多尺度动力过程、锋面混合与层化、物质输运及生态系统功能.

3.1 对中国近海多尺度动力过程的影响

黑潮入侵可显著影响中国近海的多尺度动力过程, 包括陆架环流与水体交换、中尺度涡旋、亚中尺度锋

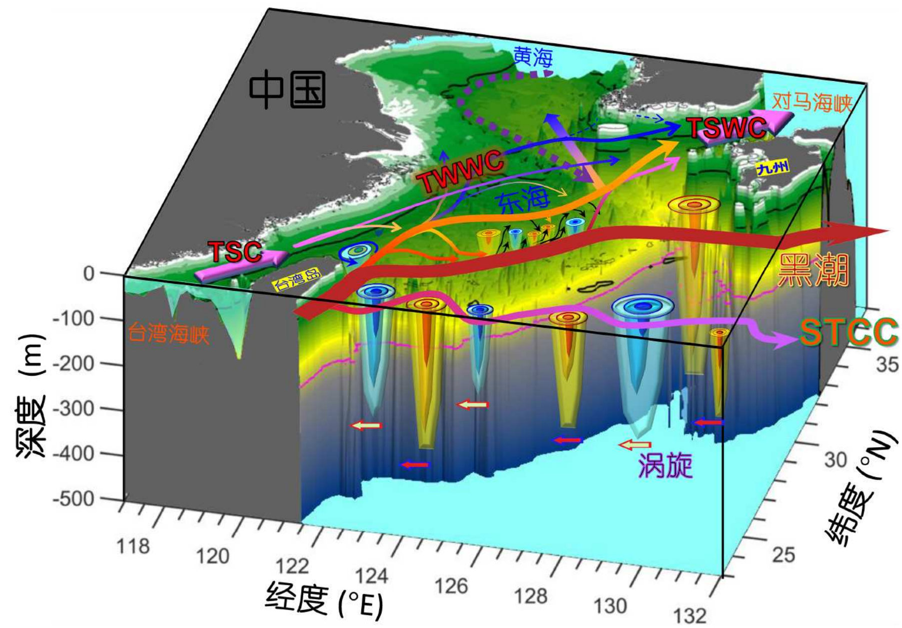

图 3 黑潮与东海陆架环流相互作用的三维示意图. 改自Liu等人[1](2021). TSC: 台湾海峡海流; TWWC: 台湾暖流; TSWC: 对马暖流; STCC: 太平洋副热带逆流. 在图中移除了琉球群岛等岛屿, 以便更清楚地展现东海的黑潮主流、台湾岛以东的太平洋副热带逆流以及相关的中尺度涡旋; 此外, 台湾海峡海流与对马暖流的详细流态、水深浅于30 m的沿岸与河口环流, 以及来自长江的冲淡水与黄海冷水团的形态均未在此图中展示

Figure 3 Three-dimensional schematic of the interactive Kuroshio and East China Sea shelf currents. Redrawn from Liu et al.[1](2021). TSC, TWWC, TSWC, and STCC denote the Taiwan Strait Current, the Taiwan Warm Current, the Tsushima Warm Current, and the Subtropical Countercurrent in the Pacific, respectively. The Ryukyu Islands and other islands are removed to provide a clearer review of the Kuroshio's main stream in the East China Sea, the subtropical countercurrent east of Taiwan Island, and the associated mesoscale eddies. Also not shown are the detailed structures of TSC and TSWC, the coastal and estuarine circulations in waters shallower than 30 m, and the Changjiang River plume and the Yellow Sea cold water mass

面等.

黑潮入侵东海显著影响东海陆架环流系统的物质与能量平衡. 该系统通过台湾海峡净流入约1.7 Sv, 对马海峡净流出约3.03 Sv, 其差额主要由黑潮在陆架坡折处约1.4 Sv的入侵通量补偿(图1), 以维持体积守恒[44,46,47]. 作为主要输出流系, 对马暖流的重要来源即为黑潮入侵, 主要包括台湾暖流的延伸、九州岛西南的黑潮分离流(图1中深红色点线)及台湾岛东北的黑潮分支流, 但是它们的相对贡献存在明显的季节变化特征[2]. 黑潮对南海的不同入侵形态也影响着吕宋海峡的“三明治”结构水体交换[48]: 在上层(500 m以浅), 黑潮以约9 Sv的流量流入南海; 在中层(500~1500 m), 水体净输运方向转为流出南海, 流量约5 Sv; 至深层(1500 m以深), 再次转变为太平洋深层水流入南海, 流量约2 Sv. 针对中层水交换, 进一步研究发现: 在500 m深处, 大部分水体沿黑潮入侵路径进入吕宋海峡北部后折返回太平洋; 而在1250 m深处, 超过60%的北部流出水体最终将回流至南海[49].

黑潮与中尺度涡的相互作用是调节南海北部涡度场的关键机制: 当台湾岛以东海域气旋涡切断黑潮主流时, 会增强吕宋海峡黑潮流套并增加南海北部负涡度[31]. 从黑潮脱落的反气旋涡携带占上层输运总量6.8%~10.8%的水体, 可沿陆坡西南向传至西沙群岛附近[50]; 新近的研究进一步表明, 部分反气旋涡在南海北部可通过背景流能量供给(如Ekman抽吸)实现再强化, 生命周期延长至6~8个月, 显著改变入侵水团的滞留时间[51].

黑潮的高温高盐水入侵中国近海, 与陆架低温低盐水相遇形成尺度与强度不同的温盐锋面. 除位于东海陆架坡折处的黑潮锋面外, 还有闽浙沿岸锋面、台湾沿岸锋面等[52]. 除上述大尺度锋面外, 在黑潮入侵影响下, 南海北部与东海陆架还存在中小尺度锋面. 大尺度锋面结构发生不稳定也会诱导生成穿刺锋面[53]或锋面波[54]等亚中尺度、小尺度过程. 这些次生的中、小尺度动力过程对中国近海的物质与能量输运可能有潜在的重要影响, 但具体贡献尚有待进一步量化.

3.2 对中国近海锋面混合与层化的影响

黑潮入侵将高温高盐的西太平洋水体输送至中国近海, 显著改变了中国近海的温盐结构, 这种结构性调整主要体现在锋面混合与层结调控两个方面, 不仅影响陆架环流形态, 也为亚中尺度不稳定与垂向混合的发生提供了有利条件. 在黑潮与海底地形存在相互作用的海域, 高温高盐的黑潮水与低温低盐的陆架水相遇, 形成强温盐锋面, 这类区域通常伴随活跃的湍流混合, 是海洋能量与物质交换的关键区[55]. 近年来的研究表明, 黑潮入侵相关的混合过程在空间上高度非均匀, 并呈现出明显的亚中尺度特征.

在长江口区域, 盐度锋面由长江冲淡水、苏北沿岸流和黑潮入侵共同作用形成. 在潮流作用调控下, 该锋面所伴随的混合与层结特征十分复杂(图4). 过去几十年间, 长江口锋面的研究大多聚焦长江冲淡水(河口羽流)的扩散特征与机制, 而针对锋面区混合的研究较少, 主要受观测与模拟方面的挑战所致. 关于长江口锋面混合的研究可追溯至毛汉礼等人[56](1963), 但此后多数工作主要依赖数值模拟或基于水文观测资料来间接估算海水的混合[57,58], 而针对混合的直接现场观测为数不多.

Matsuno等人[59~61]的系列工作是东海陆架较早的湍流混合直接观测研究(表1), 但主要聚焦在长江冲淡水的远岸段. 在长江冲淡水的近岸段, 公开报道的湍流混合观测研究至今仍较少. 其中, Wang等人[62](2020)基于2014年在长江口2~3 天的直接现场观测发现, 河口近岸海区的湍流混合在垂向上呈三层结构: 河口羽流层、中层及底部台湾暖流层; 三层水体的湍流混合强度及层化结构均受涨落潮过程的显著调制. 基于2015年9月的长江口现场观测, Zhang和Wu[63](2018)发现黑潮分支水入侵陆架形成的盐度锋面在潮流应变调制下生成活跃的对流混合, 由此增强的垂向混合促进了底边界层泥沙的悬浮; 基于同一观测资料, Tu等人[64](2024)从直接观测上呈现了黑潮入侵长江口羽流所形成的底部锋面的剪切不稳定, 指出该剪切不稳定引发了强烈的湍流混合, 耗散率和垂向扩散率分别达$O(10^{-4}\ \mathrm{m^2\ s^{-3}})$与$O(10^{-1}\ \mathrm{m^2\ s^{-1}})$.

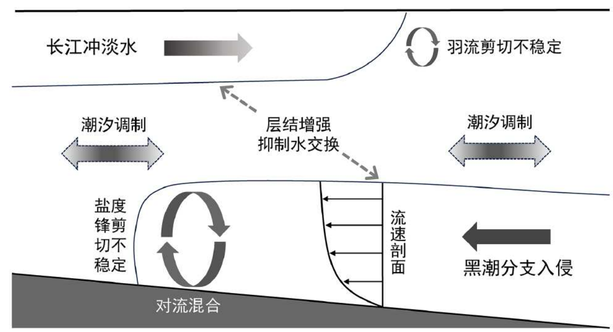

图 4 长江冲淡水和黑潮分支流入侵共同调控下的东海陆架动力特征示意图

Figure 4 Schematic diagram of dynamic characteristics on the East China Sea continental shelf under the joint regulation of the Changjiang diluted water and the intrusion of Kuroshio branch current

黑潮入侵对层化结构的影响同样显著, 但具有明显的区域差异. 夏季东海有着明显的三层结构(图4): 均匀的表层和底边界层被陡变的温跃层分隔[65,66]. 在长江冲淡水区域, 表层低盐水与底层入侵的黑潮水共同增强垂向层结, 抑制水体交换, 为夏季底层低氧区的形成提供了关键物理背景[67~69].

3.3 对海洋生态与生物地球化学过程的影响

黑潮入侵通过多尺度动力过程调控中国近海的温盐及层化环境, 同时为海域输送外源营养盐、有机碳等关键生源物质, 深刻影响了南海北部与东海陆架的海洋生物地球化学循环、初级生产过程、群落结构演

表 1 东海陆架/陆架坡折锋面湍流混合直接观测

Table 1 Direct observations of turbulent mixing at the shelf/shelf-break fronts in the East China Sea

参考文献	观测位置	观测时间(年.月.日)	观测仪器
[59]	东海陆架坡折区	1991.8.25~26 1992.7.13~14	Micro-Scale Profiler (MSP)
[60]	东海陆架坡折区	2001.10、2002.5	TurboMAP
[61]	东海外陆架	2003.7.18、2004.7.15	TurboMAP5
[62]	东海内陆架(长江口)	2014.10.31~11.1 2014.6.9	TurboMAP
[63] [64]	东海内陆架(长江口)	2015.9.22~23	MSS-90L/ADV

变及渔业资源补充，是中国近海生态系统维持的关键外部动力驱动因子.

3.3.1　营养盐的输送与补给

黑潮次表层水是东海陆架外缘营养盐的重要来源，尤其在台湾岛东北海域的平流通道，但其对近岸(如闽浙沿海)的贡献与陆源输入相当，贡献了闽浙沿海和东海绝大部分的溶解无机氮与磷酸盐[70]．其输送机制主要包括:

(1) 平流与垂向交换: 黑潮向邻近陆架输送营养盐主要依靠直接平流输运[71]，以及由湍流混合[72]和上升流驱动的垂向交换[73,74]．这两种途径的主导性存在显著区域差异[75,76]. 其中，台湾岛东北陆坡以黑潮次表层水的直接跨等深线平流为主，是黑潮营养盐进入东海陆架的核心通道；而浙江沿岸上升流区(27°N~30°N, 121°E~124°E)则以风生上升流驱动的垂向营养盐输送为主要途径(图2)．黑潮对南海北部初级生产力有重要贡献, 其营养盐供给呈现明显季节性变化: 冬季，黑潮通过吕宋海峡的流套输运和锋面混合显著增加上层营养盐，其诱导的气旋涡是维持该海域冬季藻华的关键营养盐来源之一; 夏季入侵减弱, 南海北部的营养盐则主要转为受西南季风驱动的上升流控制，与东海模式形成鲜明对比[77].

(2) 时空变异及涡旋调制: 黑潮营养盐输送的时空变异受到PDO、季风系统等气候因子，以及中尺度涡旋的卷夹(水平)与泵吸(垂向)机制共同调制，从而对中国近海生态系统产生复杂的多尺度影响．黑潮向中国近海输送硝酸盐和磷酸盐的年均通量分别可达170.8和12.7 k mol s^{-1}, 其通量主要受流场调控[78]. 这一输送过程并非稳定单一，而是一个受多时空尺度因素调控的复杂系统. 多化学示踪物分析表明, 黑潮输入的高活性营养盐可能通过增加有机质沉降，强化东海陆架沉积物的反硝化过程，可导致东海外陆架低氧区(图2)面积扩大[68], 但具体幅度需进一步验证. 在年际尺度上，黑潮及其上游的硝酸盐输送(尤其100~800 m 的次表层及中层水)表现出强烈波动，这与不同来源水体(如南海水、西太平洋水)的流量变化及混合过程密切相关．在季节尺度上, 东海的营养盐通量呈现规律性变化, 在所研究断面的统计上，东向硝酸盐输送秋季最大、冬季最小，这一季节位相与黑潮主流速的季节性变化总体一致[79]. 在南海北部, 季节差异更为显著: 冬季黑潮入侵通过流套输运和锋面混合提升营养盐，其诱导的气旋涡泵吸是维持藻华的核心机制; 夏季入侵减弱，营养盐供给以西南季风上升流为主，但黑潮卷夹及涡旋平流仍起次要作用, 机制与冬季截然不同.

3.3.2　对初级生产力和生态系统结构的调控

黑潮的外源营养盐输入是维持东海陆架高初级生产力的核心基础[80]．不同海域的初级生产过程主导因子存在显著空间分异：浙江近岸海域叶绿素a浓度主要受沿岸上升流控制，但其营养盐基底部分源于黑潮平流，而东海陆架外缘的次表层叶绿素最大值则由黑潮入侵的动力过程主导[74].

东海陆架是典型的受陆源输入影响的边缘海，反硝化作用强烈, 会造成海域活性氮的净损失; 而生物固氮作用可将大气中的氮气转化为生物可利用的活性氮, 是维持海洋氮收支平衡的关键过程. 相关研究表明, 黑潮入侵可显著增强东海夏季的生物固氮作用，年固氮贡献量达0.13~0.22 Tg N, 可在一定程度上补充海域因反硝化作用而损失的氮源，对陆架区夏季初级生产力构成重要补充[81].

在生物群落结构层面，黑潮入侵表现出明显的选择性输送与环境筛选效应．在台湾岛以东黑潮上升流区(图2)，浮游植物以微微型种群为主，原绿球藻丰度从近岸向远岸递增，而聚球藻和微型真核生物则呈相反的分布格局，反映了黑潮动力过程对浮游植物群落结构的筛选作用[82]．进一步的研究发现，春夏季期间，东海近岸黑潮分支流(NKBC)将高盐水体及附带的微微型藻类输送至长江口邻近水域，是调控该海域微微型浮游植物群落动态(尤其是原绿球藻和低光型聚球藻)、并潜在影响该区域赤潮发生过程的关键物理输送与生态调控过程[83].

对近海渔业资源而言，黑潮入侵具有显著的双重调控效应，其影响覆盖了日本鳗鲡、剑尖乌贼、带鱼等多种中国近海核心经济物种. 一方面, 黑潮入侵形成的暖水路径与中尺度涡旋为经济物种的鱼卵、仔稚鱼提供了适宜的存活环境与洄游通道，有利于渔业资源补充，补充比例与ENSO事件存在相关性，在黑潮流套路径和暖核涡旋发生时期资源补充效果最佳[84]；另一方面，黑潮暖水的入侵范围直接决定了经济物种产卵场的形成，其中剑尖乌贼是东海南部陆架区的核心经济头足类，其产卵场、索饵场的形成与黑潮入侵台湾岛东北海域准永久性上升流(常称“东海冷穹”)的过程高度耦合，是黑潮生态效应在渔业资源上的典型指示物种，相关研究已明确其资源量与黑潮入侵强度的定量关系——当沿岸水覆盖抑制黑潮暖水入侵时，剑尖

乌贼的年单位捕捞量会显著偏低[85].

4 黑潮入侵中国近海的可预测性

黑潮入侵中国近海的可预测性研究方法在不断演进. 早期研究主要依靠数值模拟, 例如Isobe等人[86](2010)采用近岸海洋模式对九州丰后水道的黑潮入侵事件实现了2~3个月的提前预测. 在数据同化方面, Liu等人[87](2023)通过集合卡尔曼滤波同化副热带逆流区和北赤道流区的海面高度数据, 显著改善了对黑潮流套脱落事件的预报技巧. 近年来, 条件非线性最优扰动、信息流因果分析等新方法为识别关键前兆提供了新途径. 例如, 条件非线性最优扰动方法揭示, 触发黑潮入侵南海的关键前兆是吕宋海峡南部的反气旋涡旋, 该涡旋的西北向移动和增长是导致黑潮路径由“越隙”转为“泄漏”的重要信号[88]. 人工智能模型也在黑潮预测中展现出较大潜力. 已有研究结合经验正交函数(EOF)、自适应噪声完全集合经验模态分解(CEEMDAN)与长短期记忆网络(LSTM)构建混合模型, 实现了对日本以南黑潮路径的120 d预测, 相关系数达0.739[89]. 此外, 基于信息流因果的LSTM模型有效预测了东海黑潮体积输运的短期变化[90]; 基于深度学习的黑潮集合预报系统(KurNet)在黑潮入侵南海路径的分类预测中, 准确率达71.9%, 还能输出各类路径类型的概率分布[91]; 并且建立了黑潮智能预报系统(KIPS), 可便捷地预报未来10 d黑潮区域(12°N~36°N, 116°E~141°E)的三维温、盐、流场以及海面高度[92].

近年来研究发现, 黑潮上下游之间存在着紧密的动力关联, 例如, 日本以南黑潮与黑潮延伸体的流态存在显著的因果关联[93]. 黑潮上下游的联动主要通过三个关键过程实现: 首先, 中尺度涡旋通过影响特定流段的黑潮强度, 进而调控其上下游的黑潮流态[87,94]; 其次, 大尺度风场激发海洋罗斯贝波, 调节着黑潮上下游系统的周期变化[11,95]; 第三, 黑潮路径的蛇形摆动在东海陆坡诱发季节内周期的地形罗斯贝波[96,97]. 值得注意的是, 基于信息流的因果分析显示, 黑潮下游的东海入侵可通过台湾岛东岸的沿岸俘获波向上游传递, 这种波以约1.22 km d^{-1}的速度南传, 约220 d后抵达吕宋海峡, 并通过调制台湾岛东南部的涡旋活动来增强或减弱该处的黑潮入侵强度, 表明沿岸俘获波是连接黑潮上下游变异的关键动力纽带[98].

黑潮入侵中国近海的变异规律可通过上下游动力联系进行预测. 对于入侵南海的情形, 北赤道流分叉点南移和菲律宾以东的异常气旋风会增加黑潮上游流量, 从而抑制其向南海的入侵; 同时, 台湾岛以东的涡旋会调控其入侵流态[99,100]. 对于台湾岛东北海域的入侵, 观测发现东海陆坡存在周期约36 d、群速度约15.5 km d^{-1}并向西南传播的地形罗斯贝波, 该波动到达台湾岛东北部后会加强此处的黑潮入侵[96]. 因此, 解析黑潮入侵与上下游系统间的动力联系, 可为其变异提供预测依据(图5).

当前, 我国在南海、西太平洋等关键海区构建的立体观测网日益完善, 通过“海洋多尺度动力过程观测潜标”、流速—压力型倒置回声仪等先进观测设备与技术, 获取了大量第一手资料, 深化了对黑潮与边缘海相互作用的认识, 为提升黑潮入侵中国近海的预报能力提供了关键动力学支撑[101~104].

5 总结与展望

黑潮作为北太平洋最强的西边界流, 其对中国近海的入侵是多路径、多层次、多尺度、多调控因子的

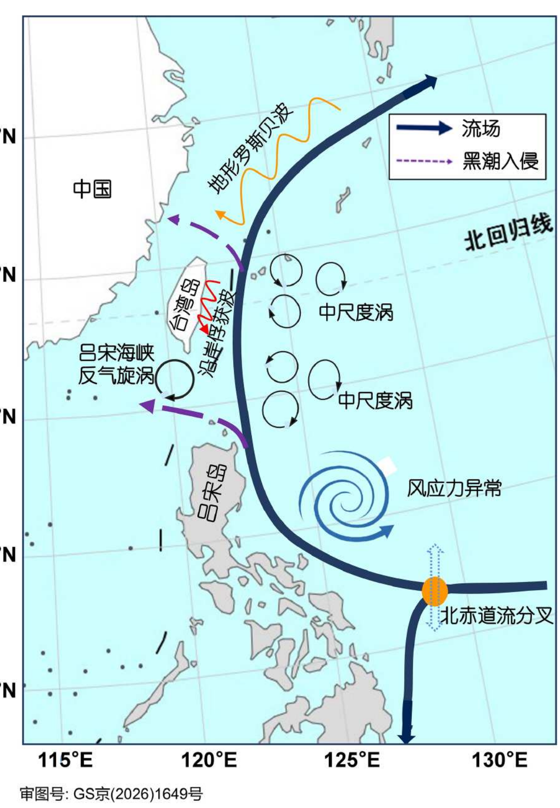

图 5 黑潮上、下游的动力联系

Figure 5 The dynamical linkage between the upstream and downstream of Kuroshio

复杂过程. 黑潮主要通过吕宋海峡和台湾岛东北海域分别入侵南海和东海. 在吕宋海峡, 入侵路径以"泄漏路径"为主, 入侵强度受季风强迫呈现冬强夏弱的季节特征; 在年代际时间尺度上, 通过影响北赤道流分岔点的位置, PDO的调制作用显著; 相较之下, ENSO的影响则不稳定; 除了大尺度风场, 西边界流自身的非线性不稳定性、岛屿的存在, 以及中尺度涡旋的撞击也是影响黑潮入侵路径和强度多尺度变化的重要机制. 在台湾岛东北海域, 入侵路径形成近岸与离岸双分支结构; 表层入侵受黑潮强度控制, 次表层入侵受埃克曼输运调控, 二者季节变化有所不同; 年际变化与PDO负相关. 入侵机制以地形与斜压联合效应为主, 风场与中尺度涡旋起调制作用.

黑潮入侵对中国近海温盐结构、营养盐循环和生态系统产生多方面影响: 维持东海陆架环流物质平衡, 通量呈秋大夏小的季节变化; 形成强温盐锋面并增强湍流混合; 输入高盐、低温、低氧且富营养盐的次表层水, 贡献大部分底层低氧水体, 并强化层结; 为东海提供关键营养盐, 支撑高初级生产力, 影响浮游植物群落结构, 同时对渔业资源具有重要调控作用. 在观测方面, 未来需要加强多要素协同观测, 利用Argo浮标、水下滑翔机与遥感技术同步监测入侵路径、营养盐通量及生态响应; 在机制理解方面, 亟需解析亚中尺度、涡旋等过程对营养盐输运及渔场的调控机制; 在数值模拟方面, 需要发展高分辨率物理—生态耦合模式, 模拟黑潮入侵的生态级联效应.

值得注意的是, 黑潮不同流段以及对南海和东海的入侵并不是独立的. 近期一批研究开始关注黑潮上下游联动机制, 发现黑潮系统存在显著上、下游遥相关, 上游变异(如吕宋海峡)可影响下游(如东海); 反之亦然.未来研究需要重点关注波动、涡旋等联动通道并量化其贡献, 揭示气候尺度(例如ENSO)与天气尺度(例如台风、涡旋)过程的相互作用, 建立多尺度耦合动力理论框架, 从而明晰黑潮入侵的可预测性. 同时, 随着数据同化与人工智能技术的提升, 构建海洋观测数据库, 建立与拓展海底观测网的实时同化与预警, 发展融合动力模式与人工智能技术的集合预报, 开发物理约束的深度学习预测模型, 并且延伸物理预测至生态要素, 实现营养盐、藻华等的业务化预报. 目前正在开展的"第二次黑潮及周边海域国际合作研究(CSK-2)"国际大科学计划有望搭建一个重要的国际合作平台, 促进对于黑潮以及周边海域影响的理解.

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补充材料

表S1 黑潮入侵南海的特征与机制总结
表S2 黑潮入侵东海的特征与机制总结

本文以上补充材料见网络版csb.scichina.com. 补充材料为作者提供的原始数据, 作者对其学术质量和内容负责.

Summary for "黑潮及其对中国近海的入侵研究综述"

A review of the Kuroshio and its intrusion into China's Coastal Seas

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As the strongest western boundary current in the North Pacific Ocean, the Kuroshio is characterized by a narrow and swift current carrying a large amount of volume transport. It starts from the northern branch of the North Equatorial Current at the Philippine coast, flows along the eastern borders of the Luzon Island, Luzon Strait, Taiwan Island, East China Sea shelf/slope and the southern coasts of Japan, separates from the Japanese coast at ~35°N and eventually enters the open Pacific Ocean. The intensity of the Kuroshio transport generally increases as it flows along its path; moreover, the Kuroshio transport also exhibits variability across multiple time scales, from intraseasonal to decadal, regulated by both large-scale climatic factors, such as El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), and local dynamic processes (such as wind fields and eddies). Given its large size and transport, the Kuroshio exerts a significant impact on oceanic and atmospheric dynamics and energetics, at both global and regional scales, as well as on ocean ecological and biogeochemical processes. This paper aims to provide a review of the research progress on the Kuroshio and its intrusion into China's coastal waters over the past two decades. The Kuroshio intrudes into China's coastal waters primarily through the Luzon Strait and the northeast of Taiwan Island. In the Luzon Strait, the intrusion intensity shows a seasonal pattern of being strong in winter and weak in summer, regulated by the monsoon wind, β-effect, inertial effect, and island topography. Furthermore, the PDO, ENSO, and mesoscale eddies further modulate the intrusion path and intensity. In the waters northeast of Taiwan Island, the Kuroshio forms a two-branch structure consisting of nearshore and offshore branches, with different seasonal variations of surface and subsurface intrusions. The dynamic mechanisms are mainly governed by the joint effect of baroclinicity and relief (JEBAR) and the advection of potential vorticity (APV). The intrusion of the Kuroshio exerts a number of conspicuous impacts on China's coastal waters. Firstly, it significantly influences the multi-scale dynamical processes in the China seas, including shelf circulations, mesoscale eddies, submesoscale fronts, etc. Secondly, it can also markedly change the thermohaline structure and hence affect the stratification and mixing in China's coastal waters. Thirdly, the Kuroshio intrusion has a profound impact on the Chinese coastal ecological and biogeochemical processes; for example, the Kuroshio brings a significant amount of nutrient-rich subsurface water to China's coastal waters, supports high-level primary productivity and modulates the coastal biological community structure and ecological processes, etc. In terms of predictability research, methods such as data assimilation and deep learning have provided new techniques for forecasting the Kuroshio intrusion, while the dynamical linkage between upstream and downstream segments of the Kuroshio offers a physical basis for improving the prediction capability. In the next step, to achieve better understanding of the Kuroshio and its intrusion into China's coastal waters requires more in-depth studies on (i) the coupling of multi-scale dynamics, (ii) the interactions of cross-scale dynamics and the linkages among different segments of the Kuroshio along its axis, and (iii) the predictability of the Kuroshio intrusion.

Kuroshio, intrusion, South China Sea, East China Sea

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