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中国物理海洋学研究 70 年: 发展历程、学术成就概览

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摘要: 本文概略评述新中国成立 70 年来物理海洋学各分支研究领域的发展历程和若干学术成就。中国物理海洋学研究起步于海浪、潮汐、近海环流与水团, 以及以风暴潮为主的海洋气象灾害的研究。随着国力的增强, 研究领域不断拓展, 涌现了大量具有广泛影响力的研究成果, 其中包括: 提出了被国际广泛采用的“普遍风浪谱”和“涌浪谱”; 发展了第三代海浪数值模式; 提出了“准调和分析方法”和“潮汐潮流永久预报”等潮汐潮流的分析和预报方法; 发现并命名了“棉兰老潜流”, 揭示了东海黑潮的多核结构及其多尺度变异机理等, 系统描述了太平洋西边界流系; 提出了印度尼西亚贯穿流的南海分支(或称南海贯穿流); 不断完善了中国近海陆架环流系统, 在南海环流、黑潮及其分支、台湾暖流、闽浙沿岸流、黄海冷水团环流、黄海暖流、渤海环流, 以及陆架波方面均取得了深刻的认识; 从大气桥和海洋桥两个方面对太平洋-印度洋-大西洋洋际相互作用进行了系统的总结; 发展了浅海水团的研究方法, 基本摸清了中国近海水团的分布和消长特征与机制, 在大洋和极地水团分布及运动研究方面也做出了重要贡献; 阐明了南海中尺度涡的宏观特征和生成机制, 揭示了中尺度涡的三维结构, 定量评估了其全球物质与能量输运能力; 基本摸清了中国近海海洋锋的空间分布和季节变化特征, 提出了地形、正压不稳定和斜压不稳定等锋面动力学机制; 构建了“南海内波潜标观测网”, 实现了对内波生成-演变-消亡全过程机理的系统认识; 发展了湍流的剪切不稳定理论, 提出了海流“边缘不稳定”的概念, 开发了海洋湍流模式, 提出了湍流混合参数化的新方法等; 在海洋内部混合机制和能量来源方面取得了新的认识, 并阐述了混合对海洋深层环流、营养物质输运等过程的影响; 研发了全球浪-潮-流耦合模式, 推出一系列海洋与气候模式; 发展了可同化主要海洋观测数据的海洋数据同化系统和用于 ENSO 预报的耦合同化系统; 建立了达到国际水准的非地转(水槽/水池)和地转(旋转平台)物理模

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型实验平台;发展了 ENSO 预报的误差分析方法,建立了海洋和气候系统年代际变化的理论体系,揭示了中深层海洋对全球气候变化的响应;初步建成了中国近海海洋观测网;持续开展南北极调查研究;建立了台风、风暴潮、巨浪和海啸的业务化预报系统,为中国气象减灾提供保障;突破了国外的海洋技术封锁,研发了万米水深的深水水听器 and 海洋光学特性系列测量仪器;建立了溢油、危险化学品漂移扩散等预测模型,为伴随海洋资源开发所带来的风险事故的应急处理和预警预报提供科学支撑。文中引用的大量学术成果文献(每位第一作者优选不超过 3 篇)显示,经过 70 年的发展,中国物理海洋学研究培养了一支实力雄厚的科研队伍,这是最宝贵的成果。这支队伍必将成为中国物理海洋学研究攀登新高峰的主力军。

关键词: 物理海洋学;海浪;潮汐;海平面;大洋环流;水团;陆架与边缘海环流;海洋中尺度过程;湍流与混合;数值模拟与数据同化;实验室模拟;大洋与气候;海冰与极地考察;海洋气象与灾害;海洋物理学;海洋环境

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1 引言

物理海洋学是以物理学的理论、技术和方法,以海水的物理性质和运动为研究对象,阐释海洋中的物理现象及其变化规律,并研究海洋水体与大气圈、岩石圈和生物圈的相互作用的科学^[1-2]。它是海洋科学的一个分支,与大气科学、海洋化学、海洋地质学、海洋生物学有密切关系^[2]。物理海洋学涵盖的内容包括海浪、潮汐、海洋环流、中尺度涡旋、湍流、混合、气候变化等过程,采用的研究手段包括卫星和现场观测、数值模拟和理论分析,其研究成果在海洋灾害预警预报、海洋环境安全保障、海洋权益维护、海洋资源开发、海上工程、气候预测等方面具有重要应用。

新中国成立 70 年以来,随着国家实力的增强,中国的物理海洋学研究在调查观测、理论研究和数值模拟及预报方面取得了长足的进步,在海浪、潮汐与海平面、大洋环流、水团和陆架环流、海洋中尺度过程、湍流与混合、数值模拟与同化、实验室模拟、海气相互作用与气候、海冰与极地、海洋气象、海洋物理等方面取得了丰硕的成果,组织实施了针对中国近海、大洋和极地的多个大型观测计划和国际合作项目,成果在海洋环境安全保障中得到良好的应用。

物理海洋学是一门以调查观测为基础的学科。新中国成立早期,受国力所限,调查观测主要限于中国近海,于 1957-1960 年间先后开展了渤海同步观测和全国海洋普查^[3]。在此基础上,我们得以对中国近海的海流、水团、跃层分布以及它们的季节变化等有了一个概括的了解。进入 20 世纪 80 年代以来,随着改革开放,中国的物理海洋学家有机会进行国际交流,并逐渐开始走向大洋和极地:在 1980-2000 年间,通过中美、中日、中韩、中朝等国际合作,在热带

西太平洋、南海、东海、黄海等海域开展了科学考察研究,其中,中国台湾开展了黑潮边缘交换过程(Kuroshio Edge Exchange Processes, KEEP);参加了世界大洋环流实验(World Ocean Circulation Experiment, WOCE)、全球海平面观测系统(Global Sea Level Observing System, GLOSS)、热带海洋与大气研究计划(Tropical Ocean-Global Atmosphere, TOGA)等国际海洋计划^[4];大力推进了印度洋的观测^[5];1980 年,中国学者董兆乾和张青松前往澳大利亚南极凯西站进行考察;1984 和 1999 年,中国科考船开始挺进南极和北极海域^[2]。进入 21 世纪以来,相继启动了中国 Argo 实时观测网^[6]、“我国近海海洋综合调查与评价专项”^[7]、“全球变化与海气相互作用专项”^[8]、“南北极环境综合考察与评估专项”^[9-10]等一系列专项;发起了由中国学者主导的中-印尼国际合作^[11]、西北太平洋海洋环流与气候实验(Northwestern Pacific Ocean Circulation and Climate Experiment, NPOCE)国际计划等大型海洋科学考察^[12]。2017 年 8 月 28 日至 2018 年 5 月 18 日,完成了为期 263 d 的环球海洋综合科学考察,在印度洋、大西洋、南极周边海域和太平洋开展了水文气象断面调查、潜/浮标等定点观测、水下滑翔机观测等工作。

物理海洋学是一门建立在物理框架下的、具有很强实用性的学科。新中国成立初期,由于海洋环境安全和国民经济建设的迫切需要,中国的物理海洋学研究主要以海浪、潮汐、近海环流与水团,以及海洋气象灾害(特别是风暴潮)为主。1959 年,中国第一部有关潮汐分析和预报的手册《实用潮汐学》^[13]出版;1962 年,文圣常撰写的《海浪原理》^[14]专著问世,开创了中国的海浪研究;1964 年,毛汉礼等人首次提出中国近海跃层的研究方法,出版了《中国海温、盐、密度

跃层》^[15];同年,赫崇本编写了《中国近海的水系》(见《全国海洋综合调查报告》)^[3],是中国学者首次论述中国近海水系和水团结构及其季节变化的重要文献;1966年,专著《海流原理》^[16]出版,是中国最早系统介绍海洋环流的著作;在1955–1963年间,毛汉礼先后翻译了《动力海洋学》(J. Proudman 著)、《海洋》(H. U. Sverdrup 著)、《湾流》(H. Stommel 著),撰写了《海洋科学》^[17]等著作;赫崇本主持编写了《海洋学基础理论丛书》、《海洋学》、《潮汐学》,为中国物理海洋工作者的培养提供了教材。至此,中国物理海洋学研究初具规模,建立了自己的研究体系。20世纪80年代以来,《潮汐学》^[18]、《风暴潮导论》^[19]、《海雾》^[20]、《海浪理论与计算原理》^[21]、《潮汐和潮流的分析和预报》^[22]、《中国近海水文》^[23]等物理海洋学专著陆续出版,形成了具有中国特色的物理海洋学体系。随着中国走向大洋和极地需求的增强,中国积极发展大洋和极地的观测与研究,在太平洋西边界流^[24]、大洋环流与气候变化^[25–26]、极地海洋学^[27]等方面均做出了有影响力的成果,逐步进入了国际前沿研究领域。

在数值模拟和数据同化方面,中国学者提出了新型混合型海浪数值模拟方法,发展了第三代海浪模式^[28];提出了风暴潮预报方法,建立了超浅海风暴潮数值预报模型^[19];发展了第三代潮汐潮流预报系统^[29];推出了LASG/IAP气候系统海洋模式(LASG/IAP Climate System Ocean Model, LICOM)系列海洋环流模式^[30];发展了海浪–潮流–环流耦合数值模式FIOCOM^[31];发展了中等复杂的厄尔尼诺–南方涛动(El Niño-South Oscillation, ENSO)预测模型^[32];推出了FGOALS、FIOESM、BCC-CSM、BNU-ESM等气候耦合模式并参与国际耦合模式比较计划(Coupled Model Intercomparison Phase, CMIP)^[33]。

由于国外的技术封锁,中国在以海洋声、光、电等物理现象为基础的海洋探测应用技术方面走上了自主研发的道路,在海洋物理理论和技术研究中取得了突破,研制了一批具有自主知识产权的海洋探测装备和传感器,提升了中国海洋观测的技术保障能力。

经过70年的不懈奋斗,物理海洋学研究在实现“查清中国海,进军三大洋,登上南极洲”这一海洋梦想的过程中写下了浓重的一笔。本文将从海浪、潮汐与海平面变化、水团、陆架环流、海洋中尺度过程、湍流与混合、数值模拟和数据同化、实验室模拟、大洋环流与气候变化、大型观测、海冰与极地、海洋气象与灾害、海洋物理,以及海洋环境应用等诸

方面,以作者视野概略记述中国物理海洋学研究70年来取得的若干进展。

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2 海浪、潮汐与海平面

2.1 海浪

海浪是中国最早开展研究的物理海洋学分支之一。70年来,在波浪理论、现场观测、室内实验、数值模拟和预报等方面均取得了长足的进步。中国学者在不同时期进行过较系统的回顾和展望^[34–35]。2000年之后,在波浪破碎、海气界面通量、海浪–环流耦合等方面又取得了许多新的突破。

文圣常是中国海浪研究的开创者。他于1962年出版的专著《海浪原理》^[4],以及同余宙文合著的《海浪理论与计算原理》^[21]是中国海浪研究的奠基性著作。文圣常提出了随风时或风区成长的普遍风浪谱,被誉为“文氏风浪谱”,在波浪研究和预报中得到广泛应用^[34]。在波浪谱理论的发展过程中,其他学者通过引入不同参量和因子,或从非线性动力学角度,对海浪的频谱特征、生消过程、细结构等进行了解析^[34]。

在波浪统计方面,中国学者通过引入随机过程理

论,逐渐形成了三维海浪要素的统计分布理论,建立了海浪波面及波高的非正态模型,并对波群的统计性质开展了研究,还将“信息熵”的概念引入海浪统计^[34,36]。

在海浪理论方面,袁业立建立了非线性风浪在波数空间成长演化的广义 Schrödinger 方程,丁平兴、孙孚、尹宝树等在风浪非线性频散、非线性波浪的传播与变形、近岸波浪与潮汐风暴潮相互作用等方面进行了理论与数值研究^[34,37]。陈戈等利用卫星高度计与散射计资料揭示了全球“涌浪池”及其特性^[38]。

海浪研究的另一个重要进展是海浪及破碎在海水气交换、上层海洋混合中的作用。中国学者自 20 世纪 80 年代开始在此做了许多很有特色的工作^[34,39-42],开展了波-湍相互作用的水槽实验^[43]和现场观测研究^[44],以及海浪波生切应力作用研究^[45-46]。浪致混合理论的建立^[44,47],改进了现有混合参数化方案中上层海洋混合不足的问题,改善了海洋和气候模式对海洋上混合层的模拟^[44]。通过波-湍相互作用和波生辐射应力,海浪在台风、海冰、悬沙输运、风暴潮过程中也起关键作用。

在海浪数值模式及其应用方面,从 1986 年启动的“七五”国家科技攻关开始,先后研发了混合型海浪数值模式^[48]、第二代海浪数值预报模式 YW-SWP^[49]、第三代海浪数值模式 LAGFD-WAM^[28]和球坐标系下的 MASNUM 全球海浪数值模式^[50]。同时,基于卫星高度计和合成孔径雷达(Synthetic Aperture Radar, SAR)遥感的海浪同化也得到快速发展^[48],并用于业务化海浪数值预报^[51]。

2.2 潮汐与海平面变化

新中国成立前,中国的潮汐观测和研究十分薄弱,全国仅有 10 余个验潮站,其中 8 个只有高低潮记录,且大量资料因战乱遗失。1948 年编印的潮汐表只有吴淞等 5 个主港的每日高、低潮预报,有些预报值直接抄录国外潮汐表,预报精度也较低^[52]。新中国成立后,海军海道测量部门陆续建立了 20 多个长期验潮站。1964 年,国家海洋局成立,开始长期验潮站建设。目前,国家海洋部门业务化运行的长期验潮站共 120 多个,1999 年还在中山站附近建成中国首个南极永久性验潮站。

《实用潮汐学》是中国第一部有关潮汐分析和预报的手册,总结了从中国新中国成立初期采用达尔文调和分析法手工推算潮汐预报,到 20 世纪 50 年代末,引入前苏联杜瓦宁(А. И. Дуванин)非调和方法进行“潮流大面积预报”的工作^[13]。1958-1960 年间,根据全国海洋普查开展的 500 多站潮流观测,编制了

“潮流永久预报表”。1960 年初,方国洪提出了“准调和和分析方法”,被采用为国家标准沿用至今^[22,53]。郑文振和方国洪还给出了中国近海潮波传播示意图和初步的动力解释^[3]。

20 世纪 50 年代末,前苏联海洋学家 Борис 最先开展了中国近海的潮波数值模拟。1969 年,在方国洪的倡议下,成立了潮流预报协作研究组,开始了长达 10 年的潮汐潮流预报研究^[29]。期间,方国洪等建立了二维潮汐潮流数值模式和潮波方程的变分数值模式,提出了明显优于杜瓦宁法的潮流永久预报新方法,在 1973-1978 年间陆续编制了《中国近海潮流永久预报图表集》,实现了中国近海全海区、多层次潮流预报。中国学者还提出了 jv 模型、潮汐波面分析、不完整记录分析等方法,取得了很好的应用效果^[22,54]。以这些成果为基础的《潮汐学》^[18]和《潮汐和潮流的分析和预报》^[22]是这一时期的代表性著作。

20 世纪 90 年代后期,卫星高度计观测开始用于潮汐研究和模式同化^[55-58]。随着计算机的普及和发展,大区域、高精度、可视化的潮汐潮流预报系统成为主流,直接服务于国防和经济建设^[29,58]。现在,在中国海事服务网、国家海洋信息中心全球潮汐预报服务网、各地方海洋预报、气象、水利等部门网站均可以方便地查询沿海各地的潮汐潮流预报。手机应用软件也推出了潮汐潮流预报服务。基于数值模拟等方法,中国学者在潮波动力学方面也取得了丰硕的成果^[22,59-60]。

中国海平面变化研究始于 20 世纪 80 年代,1989 年开始发布《中国海平面公报》。2006 年,中国启动基准潮位核定工作,并于 2015 年颁布了《基准潮位核定技术指南》国家海洋行业标准。2009-2011 年在 56 个验潮站加装全球导航卫星系统(Global Navigation Satellite System, GNSS)设备,实时监测各站高程变化。2009 年起组织开展全国沿海省市海平面变化影响调查评估,并根据国务院领导要求,编制了《海平面上升影响评估专题报告》。2011 年 8 月,首次发射搭载高度计的海洋卫星 HY-2,实现了对全球海平面的持续监测。2014-2015 年开展全国海洋站水准连测。随着 21 世纪以来国家对气候变化的重视,中国在中国近海乃至全球海平面的监测、研究和影响评估及应对等方面取得了一系列进展^[61-62]。

3 大洋环流、水团和陆架环流

3.1 太平洋

新中国成立初期,由于远洋科学调查能力的欠缺

和国际局势的动荡,中国大洋环流的研究极为薄弱。20世纪50–60年代,毛汉礼等人率先开始了对大洋环流和西边界流的理论研究^[63]。部分学者注意到西北太平洋环流场及其海温对东亚气候的影响^[64–65]。改革开放之后,随着中日黑潮合作调查、中美联合调查,以及参与TOGA等国际研究计划^[66],中国对西太平洋的系统性科学探索得以起步。

1980–1990年间开展的中日黑潮联合调查,对黑潮认识和研究上取得了众多突破:揭示了黑潮多核结构、发现了东海黑潮逆流、揭示了东海黑潮流量季节与年际变化及其机理、揭示了东海黑潮热通量季节变化及物质通量变化等^[67–68]。在同一时期,中国海洋学家在热带西太平洋环流结构方面取得了一系列新的科学发现,发现并命名了“棉兰老潜流”^[24]、“吕宋潜流”^[69]和“北赤道潜流”^[70],探讨了它们的动力学机理^[71]和水团特性^[71],建立了西太平洋次表层环流体系^[24];开展了西太平洋上层环流的定量研究,估算了西太平洋北赤道流、棉兰老流和源地黑潮的流量^[71],开展了太平洋行星波动影响海洋环流的研究^[72–73]。

进入21世纪之后,随着远洋调查能力的增强,获得了对西太平洋环流动力过程更为深刻的认识,通过长期潜标观测证实了棉兰老潜流、吕宋潜流和北赤道潜流的存在,揭示了其多尺度变异规律^[74–76];指出西太平洋活跃的中尺度涡旋^[77–80]和风生Rossby波^[81]是环流高频变异的主要来源^[74,82];研究了太平洋和南海的相互作用过程,包括黑潮入侵、Rossby传播等^[25,83];探讨了中尺度涡旋与大尺度环流之间的复杂涡–流相互作用及其对环流的结构和形态的影响^[84–85];指出太平洋内区的真实环流结构与Sverdrup理论具有差异,发现了北赤道逆流之下向西流动的“北赤道次流”^[86]。

中国学者在西太平洋环流的低频变异及其与气候变化关系的研究方面也取得了众多成果:对太平洋赤道流分叉点多尺度变异机理^[87–88]、太平洋环流异常对水团分布的影响及其与ENSO的联系做出了解释^[75,89–94];指出在人类活动的影响之下,西太平洋环流逐渐显现出了复杂的响应趋势^[95–96],且在副热带西边界流区出现全球海洋增暖的“热斑”现象^[24]。

中国是较早对西太平洋暖池(全球最大的暖水库)开展研究的国家之一,分析了暖池的基本分布特征及其与ENSO的联系^[97–98],指出暖池是在现代地形和海洋–大气动力过程共同作用下形成的^[99]。近年,中国学者提出了暖池“热心”概念,揭示了西太平洋暖池“分裂”现象及其对ENSO的影响^[100]。

太平洋内部的副热带翻转环流(Subtropical Cell,

STC)和热带翻转环流(Tropical Cell, TC)对ENSO的低频变异有潜在作用。中国科学家完善了STC的动力学框架^[101],指出热带风场强迫是STC低频变异的主要原因^[102–104],并可影响ENSO的年代变异^[105];对STC下沉分支的变异机理也进行了探索^[106–107],发现TC表层和中层相对于赤道辐散、温跃层辐聚的三层结构^[108–109]。

3.2 印度洋

印度洋环流是全球大洋环流的重要组成部分。新中国成立初期,中国在印度洋开展的研究相对较少。改革开放之后,随着国家需求向印度洋延拓,中国学者逐渐开始印度洋海洋学研究。早期主要关注的问题大多集中在热带印度洋海气相互作用及其对季风的影响^[100]以及赤道印度洋–太平洋海气系统的耦合关系^[111–112],主要研究对象大多为海表温度,并提出了热带太平洋–印度洋海温联合模态的概念^[113]。中国台湾学者参与了1957–1965年间实施的国际印度洋科学考察计划(IIOE)。但总体而言,在2000年以前,中国对印度洋环流研究较为缺乏。

季风环流是印度洋环流系统区别于太平洋和大西洋的主要特征。在季风转换期间,赤道印度洋表现为自西向东的Wyrski急流。中国学者基于多种观测资料,对Wyrski急流的特征和变异机制进行了研究^[114],指出Wyrski急流分叉对东印度洋盐度平衡有重要作用^[115]。另外,在印度洋存在明显的上升流和下沉流区,中国学者对位于西南印度洋的隆起区^[116]、位于爪哇岛西侧的上升流^[117]和位于东南印度洋的下沉流^[118]开展了研究。2010年起,通过组织实施每年一次的国家自然科学基金委员会东印度洋共享航次,积累了丰富的水文站位调查和潜标海流剖面连续观测数据,在热带印度洋环流多尺度变异方面取得了许多新的认识^[119]。最近,印度洋经圈环流和南印度洋副热带环流也受到关注,中国学者利用卫星遥感、漂流浮标、Argo等观测资料和数值模拟等手段,对印度洋热带环流圈热盐输运^[120–121]、南印度洋副热带环流^[121–122]、副热带模态水^[123]等进行了研究。

印尼贯穿流是印度洋环流系统的另一个显著特点。它是全球在低纬度连接两个大洋的唯一水道,也是全球热盐环流的重要通道之一,可以通过改变热带–副热带交换、热带温跃层结构、暖池和冷舌平均温度梯度等的季节–年际变化来影响厄尔尼诺。中国学者较早地关注了印尼贯穿流与南海环流的关联^[25,124–129],提出了印尼贯穿流南海分支^[128]和南海贯穿流^[130],指出盐度在印尼贯穿流运输变化中具有重要作用^[131]。

3.3 洋际相互作用

随着覆盖全球的观测系统投入运行和地球系统模式的快速发展,物理海洋和气候学研究开始关注洋际相互作用,而不仅仅关注单个大洋。洋际相互作用主要通过大气桥和海洋桥实现。

近期,青岛海洋科学与技术试点国家实验室领衔全球众多学者在 *Science* 杂志刊发题为“Pantropical climate interactions”的综述文章,回顾和总结了目前热带太平洋-印度洋-大西洋气候系统之间相互作用的最新研究进展,指出热带印度洋和大西洋海温变化可通过引起太平洋海表面风场异常来调制潜热通量和热带海洋波动,从而影响太平洋气候系统^[132](图 1)。

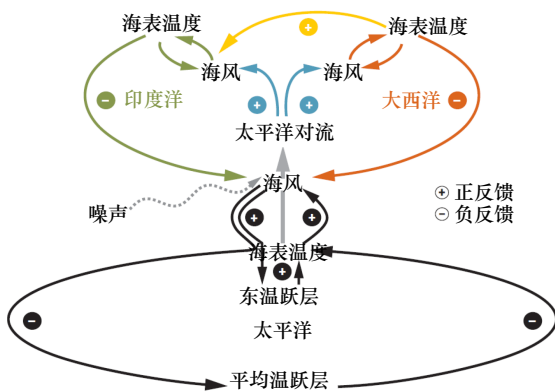


图 1 热带太平洋-印度洋-大西洋之间的海气反馈过程示意图^[132]

Fig. 1 Pantropical feedbacks affecting ENSO^[132]

大气桥过程通过某洋盆海温异常激发的热带大气波动、遥相关波列和风暴轴调整来调制另一洋盆的海表面热通量和海平面高度,并在某些海域通过海气相互作用局地放大或传播异常信号。中国学者指出,热带大西洋在近几十年主导了热带的低频变化^[132]。大西洋多年代际振荡激发的大气遥相关异常,可引起北太平洋的海平面气压和海表面温度异常,最终信号传向热带西太平洋,调制暖池的多年代际变化^[133]。热带印度洋与太平洋之间也能够通过大气桥在年际和年代际气候变化中相互影响^[134-136]。

海洋桥过程通过洋际物质能量交换、海洋长波和涡旋,来传递年际及以上时间尺度的异常信号。其中,印尼贯穿流是唯一一支发生在低纬度大洋间的流动,对大洋物质能量平衡及全球气候十分重要。中国学者提出了印尼贯穿流的南海分支,并发起了中-印尼国际合作项目南海-印尼海水交换及对鱼类季节性洄游的影响(The SCS-Indonesian Seas Transport/Exchange and Impact on Seasonal Fish Migration, SITE),对

其进行了观测研究^[11]。南海分支主要通过南海贯穿流^[130]实现,从吕宋海峡进入南海,以南海西边界的流的形式经卡里马塔海峡流入爪哇海,随后和印尼贯穿流主流汇合^[25]。另一方面,印尼贯穿流还是联系热带印度洋和太平洋的海洋信号通道,对印度洋偶极子(Indian Ocean Dipole, IOD)-ENSO 相互作用^[137]、利文流(Leeuwin Current, LC)年际异常等有重要意义^[120]。中国学者对印尼贯穿流变化的调制机理也进行了研究,指出局地降水在其中起到重要作用^[131]。

3.4 海洋水团

海洋水团是物理海洋学的基本问题和最早研究的对象之一。全国海洋普查(1958-1960年)推动了中国海洋水团研究,给出了中国近海水团的分布、消长等基本特征与规律^[3, 138]。赫崇本等^[139]和管秉贤^[140]先后对黄海冷水团的水文及环流特征进行了系统的描述。Chu^[141]给出台湾岛周边海域的水团特征。毛汉礼等^[15]利用 T-S 关系定量分析了中国近海水团,开创了近海水团研究的先河。徐斯等^[142]探讨了有界水团的混合问题,并提出了混合终点的概念,推论了 T-S 图解法的一些性质。

1980-2009 年的 30 年间,中国的海洋水团研究进入鼎盛时期,取得了许多成果。苏育嵩提出了“变性水团”的概念,定义了浅海变性水团,并提出聚类分析,用于中国近海水型分布和水系划分^[143]。聚类分析法,以及 Fisher 型逐步判别法、T-S 图解法、对应分析法和曲线族拟合法等方法,在中国近海水团研究中得到了应用与发展^[23, 143-146]。

2000 年以来,国家“908”专项(2003-2011 年)和一些重大、重点研究项目的实施,积累了中国近海丰富的高精度现场调查资料,进一步提升了对中国近海水团分布及季节变化的认识^[7, 147]。例如,一些学者更为深入地分析了北部湾^[148]、台湾海峡南部^[149]水团的分布及变化特征,研究了黄海冷水团^[150]的强度变化,划分了南海北部的水团^[151],并指出太平洋次表层水在南海北部的影响范围和作用^[152]。

在大洋和极地水团研究方面,中国学者做出了的重要贡献包括:太平洋次表层水^[153]、副热带模态水^[154-155]和高盐水^[105, 156-157]、印度洋副热带模态水^[123]、大西洋模态水^[158]、乃至全球海洋水团的潜沉^[159],以及南极和北极周边海域水团的分布及变化等方面^[160-162]。

3.5 陆架与边缘海环流

陆架与边缘海是海岸和大洋之间的过渡水域,通常水深较浅。其环流受陆架地形、大洋环流、风应力和河流入海冲淡水等的控制。东海是世界上最为广

阔的陆架海之一,黄海是半封闭的陆架海,其环流由太平洋西边界流黑潮及其分支台湾暖流、对马暖流、黄海冷水团、季风驱动的沿岸流、河流入海冲淡水尤其是长江巨量冲淡水驱动的海流等组成,具有显著的时空变化特征。早在20世纪50年代,管秉贤^[163]提出了中国沿岸表面海流系统的概念,这是中国较早将整个东中国陆架海(东海和黄海总称)环流当作一个系统去描述。此后,国内外学者对于东中国陆架环流的研究做了很多工作,并不断完善和深入。在1980–2000年间,通过中美、中日、中韩、中朝等国际合作,在热带西太平洋、南海、东海、黄海等海域开展了科学考察研究。中日之间经历10年的黑潮合作调查研究,出版了黑潮调查研究论文选集^[67–68]。

黄海显著的水文特征是夏季黄海冷水团及其产生的气旋式环流。冬季黄海冷水团消失,环流主要由受季风驱动向南流动的中国沿岸流和朝鲜沿岸流、以及作为补偿流的济州岛西南侧流向西北的黄海暖流组成。夏季,黄海冷水团可以诱发一个气旋型涡旋^[164],从而构成了黄、渤海环流系统^[165]。潮混合作用被认为是影响该环流系统的重要因子^[166–168]。而逆风北上的黄海暖流偏向黄海深槽的西侧流动^[169]。

东海陆架环流主要由沿陆架坡的黑潮、向东北流动的台湾暖流、随季风转变流向的闽浙沿岸流组成。台湾暖流终年存在,大量的研究集中在它的起源、归宿和时空变化以及分支上^[23, 170]。目前,被普遍接受的观点认为黑潮水在台湾东北侧的跨陆架入侵是台湾暖流的主要来源,沿内陆架的台湾暖流一直可以延续至长江河口水下河谷区域^[171],整个东海陆架的台湾暖流向东北流动,汇入对马暖流和黄海暖流^[23, 163]。黑潮在流经东海陆架时,与东海陆架环流发生水交换,对中国沿海水动力系统也有重要影响^[172–173]。胡敦欣还指出,黄东海上上升流是该海域底质沉积的重要驱动力之一^[164]。长江冲淡水对东中国陆架海环流有重要影响,扩展构成黄、东海典型的水文现象。研究指出,冬季受偏北风和浮力驱动,长江冲淡水出口门后向南输运,形成一条狭长的冲淡水带;夏季长江冲淡水近区主要受潮汐调制、远区受偏南风 and 陆架环流影响^[23, 174]。

南海是西太平洋最大边缘海,水域宽深、几近封闭,具备形成独具特色环流系统条件。1970–1980年代起,原国家海洋局和中国科学院南海海洋研究所先后开展了南海中部调查、南海海区综合调查研究和南沙调查,南海成为我国边缘海物理海洋学研究热点,在南海环流、黑潮与南海相互作用等方面取得了

许多成果,例如提出了黑潮入侵南海的流套结构等^[175],也拉开了南海中尺度涡研究的序幕^[66]。特别是近10年来,中国在南海环流特征研究方面取得了丰富的研究成果。台湾学者起步更早、贡献良多。这在后文各分领域中均有评述。

陆架波是风驱动大陆架浅海的典型动力过程。中国陆架波研究始于20世纪70年代。冯士筭^[176]根据中国近海陆架的特点,建立了考虑底摩擦的宽陆架海陆架波模型。陈大可和苏纪兰^[177]根据中国沿海验潮站及海流数据计算出夏季和冬季陆架波的周期和传播相速度。王佳等^[178]利用正压二维浅水非线性方程数值模式,计算出黄、东海存在两个自由陆架波,在黄海海域呈气旋式传播。Hsueh和Pang^[179]采用V字结构地形剖面,利用正压长波模型给出黄海沿岸陆架波的传播特点。Ding等^[180]利用数值模拟计算出南海北部陆架波的传播相速度为5.5~17.9 m/s。Yin等^[181]将强迫陆架波理论应用到东海陆架。Li等^[182]利用卫星高度计沿轨数据分解出了陆架波垂直岸方向的模态结构。

4 海洋中尺度过程

4.1 涡旋

水平直径在10~500 km之间、水平旋转且持续时间由数天至数月的中尺度涡旋广布全球海洋。认识到海洋速度场由中尺度涡旋主导,是现代物理海洋学发展中一个重要的概念突破,观测资料揭示海洋中90%的动能是以中尺度涡旋形式存在的。中国科学家早在1979年就评述了海洋中尺度涡研究的重要意义及进展^[183],并在1985年就报道了在南海中部观测到中尺度暖涡^[184]。

南海中尺度涡是中国学者研究的重点,经过众多研究机构、多年的系统观测与共同努力,基本确定了南海中尺度涡旋的宏观特征,包括涡旋在南海海盆的空间分布特征^[185–190]、涡旋统计特征的季节与年际变化^[186, 191–192]、涡旋的三维结构^[80, 193–197],以及涡旋运动学的特征^[183, 189, 191]。作为一个实例,图2给出中国海洋大学南海中尺度涡实验(2013–2014)的研究区和声学多普勒流速剖面仪(Acoustic Doppler Current Profiler, ADCP)锚系观测站位,以及由观测结果得出的暖涡从吕宋海峡西口向西传播过程中发生的耗散现象。

中国学者提出了南海中尺度涡产生的多种可能机制^[183, 193, 198–204]。近期,将南海中尺度涡视为群体运动现象,先后提出和发展了长寿涡列、驻波模态和Rossby

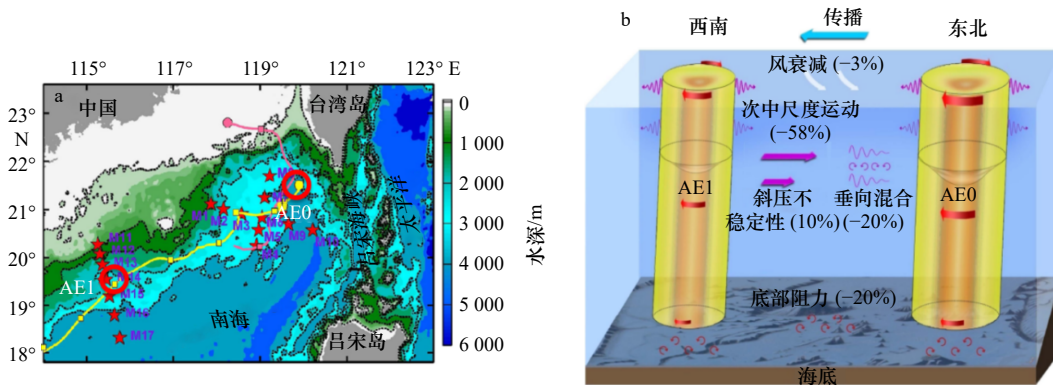


图 2 中国海洋大学南海中尺度涡实验 (2013–2014 年)

Fig. 2 South China Sea Mesoscale Eddy Experiment (S-MEE) by Ocean University of China in 2013/2014

a. 研究区, 红星代表 ADCP 锚系观测站位, 填色图表示水深, 黑色虚线分别表示 100 m、500 m、1 000 m、2 000 m 和 3 000 m 等深线, 黄线和粉红线分别代表实验期间一个暖涡和一个冷涡的运动轨迹; b. 该暖涡从吕宋海峡西口向西传播过程中发生的耗散, 各动力学过程对涡旋耗散的贡献见图 2 中黑色标识^[197]

a. Locations of the S-MEE mooring arrays (red stars). The color shading shows bathymetry with black dashed lines indicating the isobaths of 100 m, 500 m, 1 000 m, 2 000 m and 3 000 m, respectively; yellow and magenta lines denote the trajectories of an anticyclonic eddy (AE) and a cyclonic eddy (CE), respectively. b. Schematic diagram of the eddy dissipation processes. Contribution of each dynamical process to the eddy dissipation is illustrated in this schematic^[197]

标准模等概念^[183, 205]。在西太平洋海域, 对涡旋与大尺度环流, 如西太平洋赤道流系^[206]、副热带逆流^[207]、黑潮及其延伸体^[24]、副热带回流圈^[208]之间的相互作用, 以及涡旋对模态水潜沉的影响^[209], 对台湾以东黑潮流量的影响^[210]等方面进行了研究。

自 20 世纪 90 年代始, 卫星高度计极大推进了对全球范围内中尺度涡旋结构与演变的认识。中国学者利用卫星高度计、Argo 浮标等数据开展了一系列研究, 揭示了大洋中尺度涡的三维结构^[211], 定量评估了中尺度涡的全球物质与能量输送能力^[212–215], 揭示了中尺度涡在气候系统中扮演着与大尺度环流同等重要的角色。中国学者还开展了大西洋^[216]、印度洋^[217]、南大洋^[218]等海域中尺度涡的研究, 并探索利用卫星数据反演中尺度涡全水深三维结构^[211, 214], 以及利用人工智能预测中尺度涡变异^[219]。

4.2 锋面

海洋锋是海洋中不同水系或水团的交界面, 在中国近海十分显著, 是中国物理海洋学及海洋交叉学科中的重要课题之一^[220]。

毛汉礼等^[221]利用盐度水平分布的季节变化来表征长江冲淡水及其混合特征。1986–1993 年原国家海洋局和日本科学技术厅联合开展“中日黑潮合作调查研究”项目, 对东海黑潮锋及锋面涡做了详细观测^[220, 222]。1989–2000 年中国台湾开展了 KEEP 计划, 利用多学科联合观测, 给出“东海黑潮表层水与东海陆架水之间通过锋面过程进行水量和物质交换”的科学认知^[223]。2003–2011 年“我国近海海洋综合调

查与评价(简称‘908’)”专项的实施, 实现了高技术支持下的综合调查与科学研究相结合, 给出了中国各海区海洋温度、盐度、密度等大范围、高精度基础数据, 描述了锋面分布的基本特征和季节变化^[7, 147]。陈大可还指出, 由于锋面能够产生垂向物质输运, 因而锋区附近具有较高的生物生产力水平^[224]。

随着调查数据的积累、遥感技术的发展和数模分辨率的提高, 对中国近海锋面的研究越来越深入, 如中国近海锋面的季节变化规律总结^[220, 225]、锋面弯曲导致的不稳定现象^[225]以及针对局部特殊动力过程导致的锋面结构变化的研究^[220, 225–227]。中国近海海温锋区位置相对固定, 锋面强度和范围具有季节性变化周期。冬季的海温锋形态成熟, 黑潮流域与邻近陆架海域的锋面相互作用清晰可见。夏季受太阳辐射影响, 离岸远海的海温锋(如南海陆架锋、吕宋海峡黑潮入侵锋、东海黑潮锋等)基本消失, 仅在沿岸地区和浅滩边缘存在由潮混合产生的海温锋^[220, 225]。在锋面动力学机理研究方面, 中国学者指出地形、正压不稳定、斜压不稳定等均对东海黑潮锋面的弯曲有重要影响^[225]。此外, 潮致混合形成密度(温度、盐度)锋面, 并伴生锋面次级环流, 是引起上升流的动力机制之一^[168, 228]。由于缺乏更高时空分辨率的观测, 目前对中国近海锋面的预报研究较少, 主要集中于黑潮锋的预报^[225]。

4.3 内波

内波是发生在海洋内部的波动。20 世纪 40 年代, 海洋调查仪器的进步使内波研究进入快速发展时

期,尤其是在60–70年代,以Garrett和Munk基于观测调查给出大洋内波谱模型(GM72和GM75)为标志,国际海洋内波研究进入全盛时期。相对而言,我国海洋内波研究开展较晚,中国学者于1963年在舟山群岛海域通过开展短期定点观测,获得了东海浅海内波的周期、波向、波速和波长等内波基本特征^[229]。在70–90年代,观测发现渤海、黄海和南海的近海海域也存在着活跃的海洋内波,并描绘了这些海域内波的基本特征^[230–233],分析了黄海地形对内波传播的调制作用^[234]。中国学者还通过构建内波理论方程、数值模式和小型水槽试验对海洋内波开展了一些探索研究^[235–236]。通过上述研究,中国学者在20世纪末对周边海域浅海内波的基本结构特征有了初步认知。

在21世纪初叶,中国学者对中国周边海域内波开展了系列研究,实现了对周边海域内波气候态发生特征的认知。利用卫星高度计和SAR遥感数据,分析了西北太平洋第一岛链内潮的生成和传播^[237],给出了中国周边南海、东海和黄海内孤立波的生成源地、发生区域、传播方向和演变过程等统计特征^[238–240]。中国台湾学者与美国合作在南海北部陆架区开展了亚洲海国际声学试验(Asia Seas International Acoustic Experiment, ASIAEX),分析了南海北部内孤立波和内潮的短期发生特点、动力结构特征和能量空间变化,探讨了南海北部内波生成与吕宋海峡天文潮的关系^[241–242];之后,中国台湾学者与美国再次合作开展了WISE/VANS与IWISE等观测试验,获得了南海北

部内孤立波的生成演变过程、季节变化规律和第二模态内孤立波的发生特征^[243]。利用数值模拟和理论分析,中国学者进一步探究了南海北部内孤立波生成过程机制及黑潮对吕宋海峡内波生成的影响^[240,244–245]。图3为利用由卫星图像中提取的3500余个内波波包绘制的南海内波与传播方向分布^[240]。

2010年后,在国家“863”计划和海洋局专项等项目的支持下,中国海洋大学构建了“南海内波潜标观测网”,实现了对南海北部内波生成–演变–消亡全过程超过9年的连续观测,布放回收潜标100余套次,最多同时在位18套全水深观测潜标,获取了3000余个内孤立波的生命全周期观测数据,在此基础上明晰了南海北部内孤立波的生成–演变–消亡过程与机制,探讨了ENSO事件对南海北部内孤立波的影响,剖析了内波与中尺度涡的相互作用过程^[246–250]。中国科学院在吕宋海峡西侧和陆架区开展了内波潜标观测,并分析了南海内潮的季节变化特征及其在南北方向上的差异^[251–253]。自然资源部第一海洋研究所在东沙岛西侧开展了内波潜标观测,在此基础上分析了东沙岛西侧内孤立波的动力学特征和发生规律^[254]。基于KdV理论模型结合压力逆式回声仪(Pressure Inverted Echo Sounder, PIES)观测,中国学者进一步探讨了南海北部内潮向内孤立波的演变过程^[255]。在数值模拟方面,中国学者在构建三维内波数值模式的基础上对周边海域内波的生成开展了量化分析,探究了其传播过程及其影响因素,明晰了其耗散区域,系统讨论了

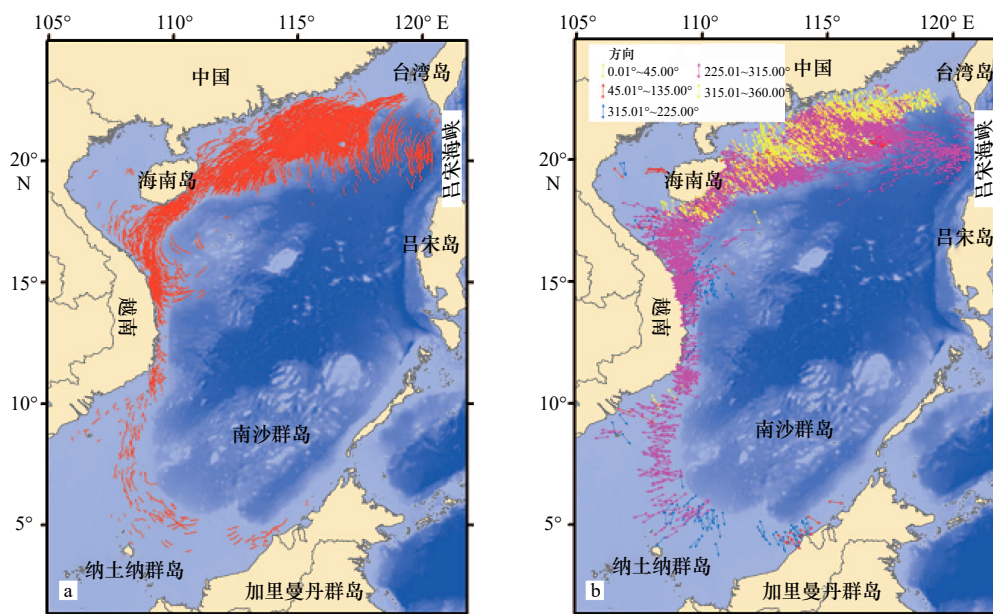


图3 利用卫星图像绘制的南海内波(a)与传播方向(b)分布图^[240]

Fig. 3 The distribution map (a) and the propagation direction map (b) of internal waves in the South China Sea^[240]

内波与中尺度涡的相互作用过程与机制^[256-258]。

5 湍流与混合

湍流是一种无规则、多尺度、有结构的流体运动状态,是自然界、工程领域和日常生活中随处可见的现象。由于高度非线性,湍流是物理学界尚未解决的经典科学难题之一。湍流以“集装箱”式运输的效率极高,以能量耗散、质量扩散、热扩散、涡黏性等表征的运输能力是层流的成千上万倍,尤其是湍流的大尺度拟序结构能够极大地影响运输过程。海洋湍流能量的维持需要外源,跨等密度面混合所需要的能量主要来自风和潮汐提供的机械能^[259-260]。此外,非破碎浪致混合能够通过波-湍相互作用强化湍流^[44]。湍流混合是维系全球大洋环流能量平衡的关键因子,在调控海洋热量与物质的分布、海洋生物地球化学过程,乃至全球气候变化研究等方面皆起十分重要的作用。

5.1 海洋湍流

中国海洋湍流研究起步较晚,这主要受限于观测技术的发展。早期的研究工作主要围绕湍流模式理论的发展^[47, 261-262],建立了正压浅海湍流运动的雷诺应力封闭模型^[263]与准地转斜压湍流两层模式^[264],提出了把混合层与动力不稳定相结合的海洋垂向湍流混合参数化新方法^[265]。近年来在全球海洋模式中湍流参数化方案的改进^[41, 266]、湍流的大涡模拟^[267-268]、非破碎海浪生湍流机制等方面开展了一些工作。在海洋湍流的基础理论研究方面也取得了一些进展,如发展了“从湍流到湍流”的剪切不稳定理论^[269],提出了海洋流动的“边缘不稳定”概念^[270]。在海洋湍流的观测方面,在近海^[271-276]、远海^[277-278]与深海^[279]都开展了卓有成效的工作。在海洋边界层湍流特征与机理方面,开展了海洋上边界层^[280]及其湍动能^[281]、朗缪尔湍流及其台风影响^[282-283]、海洋底边界层湍流^[284-285]等研究。同时,开展了强潮驱动的湍流混合^[286]、波浪环境下湍流雷诺应力的估算^[287]、海冰下水体湍扩散系数^[288]与黏性系数估计^[289]、小尺度流速剪切控制机理^[290]以及中尺度湍流波数谱特征^[291]等若干研究。图4所示为海洋大尺度湍流的有序结构实例:海洋带状流^[292]。

5.2 海洋混合

海洋中蕴含着大尺度环流、中尺度过程、亚中尺度运动、微尺度混合等丰富的多尺度动力过程,其中跨等密度面混合过程是调控全球经向翻转环流的动力源泉。受多种机制影响,微尺度混合呈现显著的时

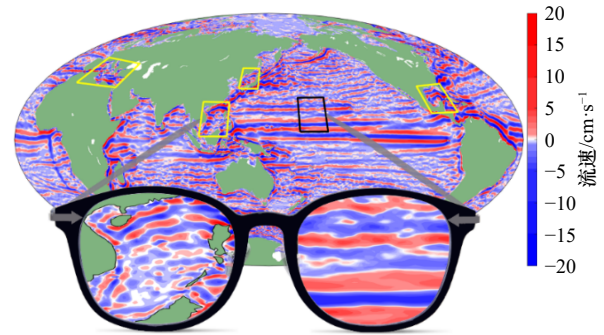


图4 海洋带状流: 湍动海洋中的有序结构

Fig. 4 Ocean strip flow: organized structures in turbulent oceans

红色为东向流,蓝色为西向流

Shading indicates flow direction: Red is eastward current and blue westward current

空间歇性。中国学者围绕混合的时空特征、影响机制及其对大尺度环流和生物地球化学过程的调制作用等问题开展了大量研究。从研究区域看,涵盖了黄海^[168]、东海^[293]、南海^[294-303]、吕宋海峡^[304]、北太平洋西边界流区^[278, 305]、赤道太平洋冷舌区^[306]、南大洋普里兹湾^[307]等海区。从影响机制看,研究指出非破碎的表面波^[43]和波浪-湍流相互作用^[44, 308]均可以促进混合,进而影响上混合层的深度^[309]。考虑该机制对湍流能量收支的作用^[47, 310],可以显著改进海洋模式中的 Mellor-Yamada 和 KPP 等混合参数化方案^[311-312],进而改善海洋模式对海洋表层温度^[313]、上层温度^[314]及海洋环流^[44]的模拟能力,提高对热带气旋路径预报能力^[315],改善气候模型的性能^[316]。此外,朗缪尔环流^[315]、双扩散对流^[317]等过程也会影响海洋混合。而在浅海陆架区^[318]和河口区^[276, 319],还需考虑径流淡水和潮流对混合的影响。中国学者还重点研究了海洋内部混合的不同能量来源,如内潮能量^[267, 320]、风输入的近惯性能量^[321]、中尺度涡能量^[322-323]等,以及影响混合的多种过程,如内潮^[324]、内孤立波^[325]、近惯性内波^[326]、中尺度涡^[302, 327]、非线性波-波相互作用^[328-331]、低频流与内波间的能量交换^[332]等,进而阐明混合对水团演变及深层环流^[333-334]、营养物质的垂向运输^[335]、底边界层沉积物再悬浮^[336]等过程的影响。

6 数值模拟、数据同化与实验室模拟

6.1 海洋与气候数值模式

海洋数值模式通过求解地球流体力学方程来模拟海水的运动及海洋状态的演化。从其刻画的运动形态时空尺度不同,可分为海洋环流、海浪、潮汐、

风暴潮等数值模式,通过与大气、陆面、海冰、生物地球化学等过程耦合,组成气候或地球系统模式^[31,44]。中国海洋环流模式原以应用国外模式为主。21世纪初,中国科学院大气物理研究所大气和地球流体力学数值模拟国家重点实验室基于早期自主开发的准全球多层海洋环流模式^[337-338],推出了海洋环流模式 LICOM 1.0^[30]。此后,又陆续推出 LICOM2.0^[339]和 LICOM3.0^[340]。LICOM 系列及早期的海洋环流模式在不同时期分别与多个大气环流模式耦合,组成海气耦合模式,并逐渐完善形成“全球海洋-大气-陆地系统模式”(GOALS)^[341-343]、“灵活的”耦合气候模式的原始版本(FGCM-0)^[344]和不同版本的“灵活性全球海洋-大气-陆地系统模式”(FGOALS)^[345]。目前,基于 LICOM3.0 的全球涡分辨海洋预报系统(LICOM Forecast System, LFS)开发工作正在快速推进。中国学者提出了海洋动力系统数值模式体系概念,基于多运动形态相互作用理论,发展了全球涡分辨率海浪-潮流-环流耦合数值模式 FIO-COM,并在多个领域实现了业务化应用^[346]。

中国从20世纪70年代末开始发展气候模式,并将其应用于气候过程的模拟研究^[31]。近年来,随着中国综合国力的增强,在地球系统模式研发和模拟上的投入逐年加大,气候模拟研究队伍逐步壮大。2007年之前,我国参加 CMIP1、CMIP2 和 CMIP3 的地球系统模式仅有中国科学院大气物理研究所的 GOALS/FGOALS 系列^[342,344],而到2013年,FGOALS 系列之外^[347-348],新增国家气候中心的 BCC-CSM 系列^[349]、自然资源部第一海洋研究所的 FIO-ESM^[44]和北京师范大学的 BNU-ESM^[350]等共6个模式版本参与到 CMIP5 中。在正在开展的 CMIP6 耦合模式计划中,预计中国7家单位共8个模式研发团队将参与其中。其中,FIO-ESM 是参与 CMIP5 计划中唯一包含海浪分量模式的地球系统模式。

运行效率是高分辨率海洋数值模式发展和应用中的一个重要挑战。模式水平分辨率每提高一倍,计算量会增加约1个数量级,模式输出数据量会增加1个数量级^[31]。在海洋模式计算方案方面,华东师范大学研究团队提出了高精度、无频散和低耗散的平流计算格式 HSIMT,显著改进了海洋数值模式中物质输运模拟的精确性和稳定性,已被海洋数值模式 COAWST/ROMS 采用^[350]。在海洋模式算法方面,清华大学研究团队提出了高可扩展的海洋环流模式正压求解方案,改进了海洋环流模式的计算性能,使 POP 海洋环流模式在万核规模有了近6倍的性能加

速,这一方案被美国国家大气研究中心(National Center for Atmospheric Research, NCAR)的 CESM 地球系统模式作为海洋分量模式默认求解器采用^[351]。在高效并行技术方面,自然资源部第一海洋研究所研究团队提出了非规则并行剖分方案,可使得模式并行剖分达到负载近绝对均衡,并行规模可达10万核^[352],随后基于中国神威·太湖之光超级计算机,突破了主从核系统计算框架设计和循环折叠优化等若干关键技术,应用到 MASNUM 海浪模式全机并行规模超千万核,浮点并行效率提高至36%。

6.2 海洋数据同化

数据同化技术通过将观测数据与数值模式的有机结合,以改进数值模拟和预测预报的精度。该技术在海洋领域的应用研究发端于20世纪80年代。1998年国际上发起了“全球海洋数据同化试验(Global Ocean Data Assimilation Experiment, GODAE)”计划,中国相继开展了工作。韩桂军等^[353]及吕咸青和刘文剑^[354]讨论了伴随方法在理想试验中和简单的数值试验算例中的应用。卫星遥感的发展和 Argo 观测网的运行促进了同化技术的发展。Zhu 等^[355]和基于三维变分方法研发了完整的海洋数据同化系统,是当时世界上少数几个可以同化主要海洋观测数据的海洋数据同化系统,在国内外多家科研和业务部门推广应用^[356-357]。Xie 和 Zhu^[358]研发了基于等密度面模式的 Argo 同化技术,解决了同化密度引起的强非线性问题。Zheng 和 Zhu^[359]基于中等复杂程度耦合模式研发了耦合同化系统,国内多家业务部门将其应用于 ENSO 预报。Yan 等^[360]基于集合同化方法构建并在网站发布了印度洋和太平洋海洋再分析数据集,并用于评估观测系统^[361]。Han 等^[362]发布了中国近海再分析数据集。Cheng 和 Zhu^[363]基于集合同化方法和观测构建了一套格点化的全球历史温度数据集,已被应用于全球海洋变暖估算、未来气候变化预估、海平面变化以及区域气候变化研究。

近20年来,在海洋和气候研究中使用的数据同化方法主要包括最优插值、变分同化和滤波方法。滤波同化方法是当前研究热点,在早期线性滤波研究的基础上,针对非线性问题发展起来了变形 Kalman 滤波等一系列同化方法,解决了滤波同化中的一些关键问题,目前已应用于业务化模式^[364-367]。

6.3 实验室模拟

实验室物理模型实验,是将物理过程进行抽象简化,利用真实流体进行模拟实验。在避免数值模型的人为假设的同时,也具有实验成本低、可控制和可重

复性高等优点,是海洋科学研究不可或缺的重要手段,但也存在耗费高、量化不足的问题。由于研究海洋现象的尺度不同,物理模型实验通常分为非地转实验(主要是水槽/水池)和地转实验(旋转平台)。

非地转实验水槽(池)建设方面,中国涉海高校和单位发展了一系列具有国际一流水准、能满足多种海洋实验需求的大型实验设施群。自然资源部第一海洋研究所、交通运输部天津水运工程科学研究院、大连理工大学、浙江大学、中国海洋大学、中国科学院深海科学与工程研究所、天津大学、南京信息工程

大学、广东海洋大学等单位均建有水槽实验室,这些实验设施具有模拟风场、波浪、海流、海洋内波等多种或其中几种水动力环境的能力,可有效应用于海洋内波^[368-372]、海气相互作用^[43]、海浪机理^[373]以及海洋工程等领域的教学和实验研究。

中国在旋转水池的建设和研究上起步较晚,但是随着近年来中国在海洋领域的投入不断加强,目前已经有包括中国海洋大学、南京信息工程大学、中国科学院大气物理研究所、浙江大学在内的多家单位都建立了自己的旋转实验平台,见表 1。

表 1 国内主要地球流体旋转实验平台

Tab. 1 Major geophysical hydrodynamic rotational experimental platforms in China

实验室名称	所属单位	直径	深度	旋转周期
地转平台实验室	中国海洋大学	40 cm; 2 m	40 cm; 40 cm	—
行星流体力学实验转台	南京信息工程大学	1 m	40 cm	>2 s
大气和海洋环流移动模拟实验平台系统	中国科学院大气物理研究所	0.8~1.5 m	—	>4 s
地球流体力学旋转水槽	浙江大学	3 m	50 cm	>3 s

由于可以通过旋转平台模拟科氏力的作用,因此旋转平台试验可以更真实地模拟地球流体动力过程,例如旋转框架下层化湍流过程^[374]、海洋中尺度过程^[374]及次中尺度过程^[375]、内波的演变与发展过程^[372, 376-378]等。

目前,中国的实验平台仍不能满足不断扩大的科研试验需求,不久的将来,中国有望建成世界上最大的地球流体旋转平台(图 5),直径约 14 m,最大注水深度约 1.2 m,旋转周期约为 30~1 000 s,将会为中国的物理海洋学发展添加新的推力。

7 大尺度海洋-大气相互作用

海洋-大气相互作用是地球各圈层耦合中最活跃部分,中国学者对该领域研究贡献良多。

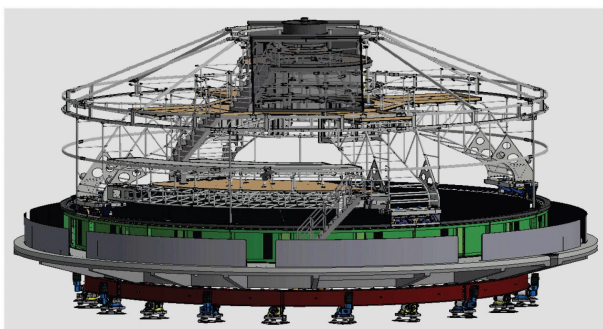


图 5 大型实验平台主体设计

Fig. 5 Schematic design diagram of large experimental platform

ENSO 是气候系统中最剧烈的年际尺度振荡,对全球大部分地区的天气和气候系统有着重要影响^[379]。Fu 等^[380]发现厄尔尼诺存在一种在日界线附近为主要增暖区的新形态,它的产生与副热带海气相互作用^[381]、热带高频强西风异常现象^[382]有密切联系。Cai 等^[132]指出热带印度洋变化可加速厄尔尼诺的消亡,并有助于厄尔尼诺向拉尼娜的位相转变;热带大西洋赤道及北部海域的海温变化对 ENSO 事件的多样性具有重要贡献。Mu 和 Duan^[383]提出条件非线性最优扰动(Conditional Nonlinear Optimal Perturbation, CNOP)法,能够刻画大气和海洋系统中的非线性运动特征,已被广泛应用于 ENSO 等事件的预报。张荣华等建立的中等复杂程度海气耦合模式(IOCAS ICM),为国际学术界提供 ENSO 实时预报结果^[32]。

在热带印度洋,中国学者提出了印度洋海盆模态(IOB)^[384],指出 IOB 能够影响亚洲夏季风^[384-386]和西北太平洋台风活动^[121]。Liu 等^[386]和 Zheng 等^[387]预测了未来气候变化情境下的 IOD 和 IOB 变化。杜岩等^[121]还指出印度洋热带环流圈热盐输运对区域气候模态有重要影响。

在年代际气候变化研究方面,吴立新团队建立了能够分离中低纬海洋-大气通道在年代际气候变率中作用的模式动力实验体系、中高纬海洋热盐环流变异影响热带海洋-大气耦合系统的动力学框架及大西

洋海洋环流与海温年际-年代际变化的预测模型,系统阐述了副热带环流在太平洋气候系统年代际变化中的调控机理,揭示了北大西洋年代际变化模态是海-气耦合模态,阐述了海洋层结变化以及海洋 Rossby 波调整对于中纬度年代际气候变率受全球变暖影响的作用机理^[387-393]。刘征宇等阐述了海洋动力过程尤其是行星波动在确定气候系统年代际变率的时间尺度中的作用,发展了分离不同海洋大气动力过程在太平洋气候系统年代际变化中相对作用的数值模式方法,详细论述了在年代际时间尺度上热带外气候变率影响热带气候系统的不同动力过程,发展了利用数值模式研究中纬度大气环流对海洋变率响应的初值方法,改进了定量估计中纬度海洋对大气反馈作用的统计分析方法^[394-397]。谢尚平和日本合作者在2000年前后阐述泛大西洋年代际气候振荡机理;发展了热带大西洋年代际变率的海气耦合动力模型;提出风-蒸发-海表温度(Wind-Evaporation-SST, WES)反馈机制,在气候研究中得到广泛应用^[398]。构建了全球变暖下热带降水变化的理论框架,并提出全球变暖背景下不均匀性决定降雨变化区域分布的观点,得到观测和数值模拟的一致证实^[399-400],还提出赤道太平洋海面温度冷却作用是近15年来全球变暖停滞的主要因素,指出太平洋年代际振荡在20世纪末的位相转换可通过调制全球平均温度,造成全球变暖停滞现象^[401-402]。Zhang等^[403]基于观测资料揭示了大西洋温盐及热含量的时空演变过程,指出大西洋深层西边界流及深层赤道开尔文波是大西洋深海热量传输的主要路径,且传输过程具有60年的周期特征。

Liu等^[404]发现了北太平洋黑潮延伸体为中心的马蹄型海温异常对大气环流的反馈作用。揭示了影响台湾以东黑潮变异的北太平洋副热带海域年代际变化的机理,定量给出黑潮延伸体海洋异常信号在海洋温跃层内传播到台湾以东的海洋内部通道;为确定北太平洋动力过程在气候变化中的作用提供了理论依据。揭示了太平洋副热带逆流与副热带模态水之间的联系;发现全球变暖背景下,北半球副热带模态水减少导致的副热带逆流减弱和SST增暖空间分布的非均匀性;为依据海洋动力过程预测未来气候提出了新的理论依据^[405-406]。

杨海军等阐述北大西洋热盐环流对温室气体浓度变化的响应;揭示了大西洋经向翻转环流基于海气耦合模型的年代际变化机制;阐明了风通过海冰及垂直扩散作用对大西洋经向翻转环流的影响^[407-408]。

近期南大洋的显著增暖备受关注。Chen和

Tung^[409]研究发现北大西洋和南大洋的深层水域中的热量增加,使得21世纪以来全球变暖出现停滞。Gao等^[410]预计风应力的增加将推动亚南极模态水的加深和南半球热含量的增加,从而减缓全球表层温度增暖的速度。Xue等^[411]观测发现风速变化对南大洋夏季海洋酸化速率有着重要的调控作用,大大提高了对南大洋酸化机制的认识,为预测南大洋碳吸收和评估其对生态系统的影响提供了重要的理论依据。

8 海冰、极地

1969年的渤海大冰封事件造成的中国重大经济损失,是推动中国海冰监测与研究的关键契机^[412]。随后,中国学者在海冰数值模式中的热力学与动力学过程^[413-415]、冰-海耦合^[416-418]等方面取得了进展,并用于业务化海冰预报。工程海冰学也随之得到发展^[419],在海洋平台上开展全方位立体工程海冰现场监测研究^[420],建立了被国际标准采纳的柔性海洋平台结构冰力时程函数和冰力谱^[421],在冰与结构物作用力的物理模拟^[422]和工程海冰数值模拟方面也取得很大进展^[423]。1980年1月,董兆乾和张青松前往澳大利亚南极凯西站进行考察,拉开了中国极地物理海洋学调查与研究的序幕^[424-425]。1984年,“向阳红10”号考察船执行我国首次南极科学考察,开始在长城站沿海^[426]及南设得兰群岛周边海域进行水文调查^[427]。1989年中山站建成后,调查与研究海域扩展到普里兹湾及其邻近海域^[9, 428],并开展了冰架^[429]、冰间湖^[430]与海洋相互作用的研究。近些年来,罗斯海与阿蒙森海成为新的调查区域。以往南大洋海盆区的研究多集中在锋面^[431]与南极绕极流^[432]。最近在混合^[307]、亚南极模态水^[410]/南极中层水^[433]长期变化等方面均取得了突出成果。

中国首次北极考察于1999年由“雪龙”号执行,其中第5次(2012年)和第8次(2017年)北极考察分别通过了东北和西北航道,其他航次的调查区域均集中在白令海、白令海峡、楚科奇海和加拿大海盆,初步摸清了调查海域的水文情况^[10],对北冰洋水团变化、环流等进行了研究^[160, 434-436]。

中国学者在南大洋与北冰洋开展的理论研究^[437]和数值模拟^[438-442],加深了对极地物理海洋学的认识,取得的研究成果揭示出极地海洋在全球变化中的重要作用^[62, 409]。

中国极地海冰观测与极地考察同步发展。1981年张青松^[443]观测了南极固定冰的形成和破碎过程。之后,在长城站和中山站附近开展了固定冰层理学、

形态学和热力学的观测研究^[444-445]。1996 年效存德和秦大河^[446] 获得了北极中心区域海冰形态和雪层剖面特征的空间分布。随后,在北极冰面边界层研究^[447]、海冰形态学定量化^[448]、积雪和海冰层理结构^[449]、海冰物质平衡^[450]、海冰和融池的空间分布^[451] 以及海冰光学等方面^[452] 都取得了突出的观测研究成果。通过优化同化方案发展了海冰预报模式^[453]。利用卫星观测产品,发展了刻画冰间湖产冰率^[454] 和水道分布^[455] 的遥感算法。我国多个地球系统模式参与了预估南北极海冰变化的国际比较计划^[44, 456]。研究表明,北极海冰的快速减少会对中国天气气候过程产生重要的影响^[457-458]。

9 海洋气象

9.1 台风

中国受台风(或热带气旋)影响严重,自新中国成立以来就十分重视台风的研究工作,并积极参与国际交流与合作。1972 年,全国台风科研协作组织成立,推动了《台风年鉴》(1989 年后改名为《热带气旋年鉴》)的整编工作^[459]。该年鉴是世界气象组织(World Meteorological Organization, WMO)全球热带气旋资料集(International Best Track Archive for Climate Stewardship, IBTrACS)之一,也是全球唯一收录登陆台风降水及大风数据的资料集。2008 年,中国台风最佳路径资料集被纳入 IBTrACS^[460],参与国际资料交换和比较计划。

20 世纪 90 年代起,国内外开展多次大规模的台风现场试验,促进了台风尤其是异常台风的研究。在国家科技攻关“85-906”项目和国际热带气旋研究合作项目支持下,我国学者在台风的突变现象和预报技术方面取得了新的进展^[461-462]。经过几代学者的努力,大大提高了对台风机制^[463-466]、台风与海洋相互作用等的认识^[467],在台风资料同化^[468-469]、物理过程参数化^[470]、台风监测和预报^[315, 471-472] 等关键技术上实现了突破,为中国台风灾害防御提供了有力的科技支撑。

9.2 风暴潮

中国是西北太平洋沿岸风暴潮灾害最严重的国家。新中国成立以来,中国风暴潮理论、预报和防灾减灾能力得到很大提升,因风暴潮灾害造成的死亡人数大幅减少。1970 年,国家海洋环境预报中心开始发布风暴潮预报,国内风暴潮研究也逐步开展。秦曾灏和冯士筴^[473] 建立的浅海风暴潮理论,为中国风暴潮预报奠定了理论基础。孙文心等^[474] 基于该理论首次开展了风暴潮的数值模拟。1982 年,冯士筴^[19] 编

著的《风暴潮导论》系统论述了风暴潮理论和预报方法。1990 年前后,王喜年等开始了中国第一代业务化台风风暴潮数值预报工作^[475]。于福江等开发了覆盖中国海的温带风暴潮数值预报系统,并于 2003 年投入业务化运行^[476]。尹宝树等建立考虑天文潮和海浪共同作用的渤海风暴潮和海浪模型^[37]。王培涛、陈永平等先后发展了风暴潮集合数值预报系统,避免了台风路径预报不确定性对风暴潮预报的制约^[477-478]。

9.3 巨浪

巨浪指由强烈大气扰动,如热带气旋、温带气旋和强冷空气等天气系统以及海浪自身调制引起的灾害性海浪。自 20 世纪 50 年代中国启动海浪研究以来,就对巨浪十分关注。赵九章等在海浪观测方面开展了大量开创性工作^[479],后人基于观测对巨浪灾害进行了个例分析,并收集整理了巨浪灾害史料集^[480-482]。80-90 年代,中国学者基于文氏二代谱模式^[48] 和 LAGFD-WAM 三代谱模式^[28] 对巨浪过程进行了模拟^[49, 483-484]。2000 年之后,中国学者在巨浪的生成及演变方面取得了系列进展。例如,畸形波传播及模拟^[482, 485]、风暴潮-海浪耦合机理^[482]、年代际巨浪演化规律^[486] 等。

9.4 海啸

海啸是由海底地震等因素引起的海水大规模波动形成的一种大洋长波,破坏力极强。中国受到灾害性海啸的影响极为少见,但在南海马尼拉海沟等海域的潜在海啸,仍有可能对中国造成一定威胁,受到学者们的关注^[487]。

中国自 20 世纪 70 年代以来,开展了中国历史海啸灾害资料的整编与分析工作。1983 年,中国加入太平洋海啸预警系统国际协调组。90 年代后期,原国家海洋局组织建立了太平洋海啸资料数据库、太平洋海啸传播数值预报模式和越洋、近海海啸数值预报模型,并应用于中国一些核电站的环境评价中^[487-488]。国家海洋环境预报中心于福江等开发了基于 GPU 并行框架的 CTSU 数值模式,建立了基于情景数据库的定量海啸预警系统。上述定量化预警技术已在由中国牵头建设的南海海啸预警中心实现业务化运行^[489]。

10 海洋物理

海洋物理是研究声、光、电磁等信号在海洋中传播规律、与海洋相互作用机制,以及利用它们探测海洋的一门科学^[490]。

海洋声学是现代海洋技术的物理基础。中国海洋声学研究始于 1958 年,汪德昭带领一批北京大学

的大三学生在三亚的南海研究站与前苏联水声学家开展合作研究。1996年,中美在远黄海开展了第一次国际合作实验。期间,中国学者在广义相积分简正波理论(WKBZ)、浅海声场和声传播、浅海海底参数反演、浅海射线简正波混响理论与技术等方面取得重要进展。1997年,第一届国际浅海声学会议在北京举办,会上关定华对1958–1996年间中国在浅海声学研究中取得的进展进行了总结^[491]。

在2012年第三届国际海洋声学会议上,张仁和综述了1997–2012年间中国浅海声学的研究进展^[492],主要包括:基于WKBZ理论发展的波束位移射线简正波理论(BDRM)、耦合简正波抛物方程计算模型(CMPE3D)和耦合简正波声场模型(DGMCM3D);提出了多物理量联合海底参数反演方法;建立了相干混响模型;描述了海洋内波引起的声场起伏;提出了浅海声学被动层析方法和声源定位方法;将沿海声层析应用于中国近岸多站位组网观测实验,并完成了沿海声层析数据和近岸水动力模式的数据同化研究^[493]。

2012年后,中国在深海声学研究方面取得了一系列重要进展^[494],突破了10 000 m水深水听器关键技术,打破了国外对我国深水水听器的技术封锁。从此,中国具备了深海大范围水声信号长时间采集的能力,获得了马里亚纳海沟9 300 m深处的人工地震信号、南海和西太平洋深海复杂地形下的远程声信号传播数据,实现了1 000 km级的超远程声传播与水声通信,发展了基于大深度声场的水下目标定位方法。此外,根据台风过程中海洋环境噪声记录,建立了风生噪声模型;基于射线理论解释了海底地形对声传播的影响机理;建立了适用于深海的海洋混响本底及异地混响模型;揭示了中尺度涡旋、内波和海浪引起的声场起伏统计特性及其影响机理。

海洋光学主要研究光在海水中的传播以及海水的性质,是海洋遥感和探测的物理基础。新中国成立以来,中国在海洋光学理论、海水光学特性调查和仪器研发,以及以光学为核心手段的海洋探测技术方面均取得了长足的进步。

在海洋光学理论研究方面,建立了变换辐射传递模型,解决了海水光学传递函数、水中窄光束传输等典型问题^[495];针对卫星海洋光学遥感信息提取和反演,中国学者在海洋水体不同波段的遥感模型、波浪对水下光场影响^[496]等方面都提出了自己的见解。

在海水光学特性调查方面,中国自1974年起在南海开展海洋光学测量^[497]。从20世纪90年代起,进一步完善了光学特性测量和数据处理方法,并开始规

模化调查^[498–499],完成了海洋水色卫星定标检验海上同步光学调查(1998–2012年)、“908”专项光学调查(2003–2012年)、“全球变化与海气相互作用专项”光学调查等大型光学调查(2011–2020年),获取了中国近海水体的光吸收、光散射、光离水辐射特性及其季节变化的相关数据^[500–501]。

在海水光学特性测量仪器研发方面,20世纪60–80年代在第一机械工业部和原国家海洋局支持下,研制了海水透明度计、小角度海水散射仪、走航式海面照度计、海水光学多参数测量仪等海洋光学仪器^[502]。20世纪80年代以来,在国家“九五”至“十二五”“863”计划的支持下,中国海水光学特性测量仪器得以迅速发展,研发了深水照度计、海洋光学多参数测量仪、海面和海水层光学测量系统、海洋光学浮标、多波段透射率仪、浊度计、海洋高光谱辐射实时观测系统、阵列式多角度水体体散射函数测量仪等仪器^[503–506]。

在海洋探测应用技术方面,自主研制了多普勒激光雷达^[507]、深海原位激光拉曼光谱仪^[508],在拉曼-荧光联合原位探测、激光诱导击穿光谱原位探测等方面也取得了突破^[509–510]。在水下视觉技术与三维目标定位^[511–513],以及激光通信方面,突破了照明与成像方式、激光扫描、通信链路、调制编码、宽视场窄带接收技术等一系列关键技术,取得了重要进展并多次开展海试^[514–516]。

11 大型观测计划、大型项目

经过近70年的发展,在全国海洋普查、中国近海海洋综合调查、大洋专项、极地专项、中国科学院先导项目等一系列以海洋调查和能力建设为主体任务的国家重大专项的支持下,中国逐渐建立了由卫星、飞机、调查船、岸基监测站、浮标和志愿船等组成的近海海洋立体观测体系。

在国产调查仪器装备应用方面,早在20世纪50–60年代,主要以人工观测为主,观测效率低;20世纪80年代以后,开始大量进口国外自记自容式海洋调查仪器装备,提高了观测效率;20世纪90年代以来,开始了海洋调查仪器装备国产化研制和海试应用,积累了一定的技术基础,但是由于缺乏对核心技术的把握,国产海洋调查仪器装备的市场占有率尚低。

自20世纪90年代开始,中国开始布设定点连续观测的海床基、潜标和浮标,多以单个、分散和短期为主。21世纪以来,中国定点连续观测逐步向阵列化发展,对中国近海、西太–南海–东印度洋进行了区域针对性调查,积累了海洋调查布局区域控制和整体

协同方面的系列经验。

中国于 2002 年正式加入全球 Argo 计划, 至 2018 年底, 已在全球海洋中维持了约 100 个活跃浮标组成的 Argo 区域, 建立了以深海大洋观测为主的中国 Argo 实时观测网^[6]。2013 年至今, 中国科学院海洋研究所建成了西太平洋实时科学观测网并实现稳定运行(图 6), 实现了对西太平洋上层赤道流系、西边界流和中深层环流的同步连续观测和深海潜标数据的长周期实时传输^[517-518]。中国海洋大学自 2009 年以来在南海布放潜标 350 余套次, 构建了目前国际上规模最大的区域海洋潜标观测网——南海潜标观测网, 并于 2016 年实现全面覆盖南海深海盆的深海多尺度动力过程长期连续观测^[519]。青岛海洋科学与技术试点国家实验室提出“透明海洋”重大科学计划, 以构建一个长期的、连续的、实时的立体观测网等为目标^[520], 并于 2015 年底开始在黑潮延伸体附近海域布放深海潜标。中国在南北极环境综合考察与评估专项等的支持下, 发展了极地在线近岸海洋环境监测系统、极地潜标和极地大型海-气耦合浮标等海床基观测系统^[521]。在国际合作调查方面, 自然资源部第一海洋研究所先后开展了 SITE 和“印尼贯穿流海域水体输运、内波和混合观测研究(Transport, Internal Waves and Mixing in the Indonesian Throughflow regions and impacts on seasonal fish migration, TIMIT)”^[11]、“印尼爪哇沿岸上升流潜标观测”^[522] 等中-印尼国际合作项目以及“安达曼海上层海洋及海气相互作用观测研究”^[523] 等中-泰国际合作项目。此外, 中国科学家积极参加第二次国际印度洋科学考察计划(Interna-

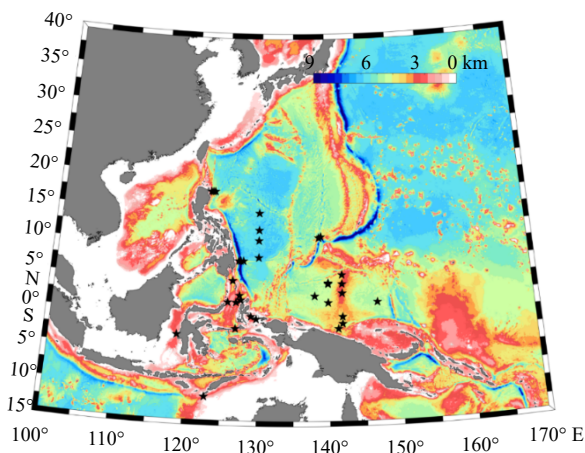


图 6 西太平洋科学观测网潜标和浮标位置图
(黑色五角星)

Fig. 6 Locations of subsurface moorings and buoys in the western Pacific (black pentacle)

tional Indian Ocean Expedition-2, IIOE-2), 在 IIOE-2 的发起、规划、实施等阶段都发挥了重要作用, 并与日本、美国科学家共同发起了东印度洋上升流研究计划(Eastern Indian Ocean Upwelling Research Initiative, EIOURI)^[5]。

海洋声学调查方面, 中国开展了覆盖了南海、西北太平洋和部分印度洋区域的多个海洋声学调查专项。迄今已成功研制了深海声学潜标, 取得了一大批珍贵海洋声学数据, 形成了一整套海洋声学调查规范。

海洋光学调查方面, 1998 年, 中国引进了第一台水色剖面仪, 这一时期在东海和黄海开展了实验性的光学调查及研究工作。2002 年, 发射了第一颗海洋水色卫星 HY-1A。卫星在轨运行期间, 在黄海、东海及南海开展了多次用于卫星传感器辐射定标和真实性检验的海洋光学调查工作。2006 年开始的“我国近海海洋综合调查与评价”专项, 开展了 4 个季节覆盖中国近海海区的 37 个航次光学调查与研究。此后, 通过国家专项的实施, 将光学调查与研究工作的范围向南海、东印度洋和西太平洋扩展。

目前, 中国海洋调查区域以管辖海域为主。经过近 70 年的发展, 形成了一定规模的海洋调查与测量船队, 在海洋调查专项的持续支持下, 培养了大批专业海洋调查与测量人员, 快速形成了从近海向深远海调查的格局。但是中国对全球海洋调查仍处于起步阶段, 在西太平洋、东印度洋和南北极等重点海域较为系统的海洋调查方兴未艾。

12 海洋环境及应用

新中国成立以来, 中国石油化工产业、海洋资源勘探开发技术迅速发展, 海洋开发利用范围和强度不断扩大, 导致各类海上溢油、危险化学品(以下简称危化品)泄漏事故多发, 对海洋生态环境和国民经济都造成了不良影响。物理海洋学对这些事故的应急处理和危险预报等方面起着至关重要的作用。

中国学者在海洋溢油模拟预测理论和应用方面, 开展了大量工作。早期受计算能力的限制, 多应用参数化的方法, 由风场和海面流场推测油膜轨迹^[524]。之后, 海洋水动力模型和计算方案被引入了海面油膜漂移预测^[525-526]。安伟等^[527]通过集成三维水动力模块、气象模块、环境敏感区域模块和决策支持模块, 建立了中国近海溢油漂移预测系统。李彤和谢志宜^[528]应用“油粒子”模型得到了较传统平流扩散模型精度更好的油膜轨迹预测结果。李燕等^[529]将数据同化技术应用到了溢油预测模型中, 进一步提高了模拟

精度。王永刚等建立了一个包含多种过程的溢油漂移预测模型并业务化运行^[530]。乔方利等^[531]建立了全球长时间尺度溢油预测方法,并在2018年东海“桑吉”轮溢油事件中应用。

中国针对海洋中泄漏危化品扩散的数值模拟研究起步于20世纪世纪末^[532]。早期,大多采用简单的二维模型对易溶保守液体化学品的污染扩散进行数值计算^[533-534]。进入21世纪,危化品漂移扩散的数值模拟转向三维,危化品的种类和扩散模型也趋于多元化^[535]。余江等^[536]根据密度、溶解度、挥发性等特征,建立了危化品分类方法,对提高泄漏危化品漂移扩散的模拟有重要的参考价值。

13 结语

本文以翔实的科学事实、大量数据和文献评述新中国成立70年来物理海洋学各领域研究(主要包括物理海洋和海洋气象,也涉猎海洋物理与海洋观测)从无到有、从小到大、从弱到强,发展壮大历史轨迹。可以说这是一部丰富生动、遵循了唯理与实证科学精神的探索史。

在这70年发展历程中,有一段史实值得回忆。1964年,国家海洋局成立。国家赋予的使命概括为3句话15个字,即“查清中国海,进军三大洋,登上南极洲”。这是当年的国家海洋战略,也是当年中国人民的海洋强国梦。从本文评述可见,经过半个世纪三代人艰苦卓绝、可歌可泣的努力奋斗,当年的梦想不仅成为现实,而且已经超越。

70年的实践表明,国家的海洋战略是学科发展的灯塔,国家经济建设、国防建设和维护海洋权益的刚

性需求是海洋学科发展的不竭原动力,国家实力是学科发展的坚强后盾,遍布全国的众多研究群体是学科发展的生力军,通过国际交流与合作研究分享国外科研新思路、新方法、新数据和新成果是学科发展不可或缺推动力。这即是宝贵的历史经验,也对未来发展有重要参考价值。

总结历史的辉煌成就是为了开创更加美好的未来。可以预期,在中国“加快建设海洋强国”和“走向深海大洋”战略规划指引下,随着国家综合实力不断增强,物理海洋学研究作为探索海洋科学的第一梯队,必将迎来更大、更好的发展机遇。“今日非昨日,明日更辉煌”。

本文以已发表的科研成果为依据,从一个侧面评述中国物理海洋学研究70年来的发展概况。这些科研成果是学科发展史重要组成部分,但不是全部。由于文章篇幅限制,没能列出所有收集到的研究成果(每位第一作者以3篇为限)。一叶扁舟盛不下大海,仅能承载有限的记忆。本文对国家重大专项调查和攻关项目、获奖项目以及突出贡献科学家等的记述欠详或缺失。这些局限性有待于撰写长篇幅专著来突破。

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Physical oceanography research in China over past 70 years: Overview of development history and academic achievements

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Abstract: This paper reviews development history and academic achievements of the research of physical oceanography branches in China over past 70 years since foundation of new China. The physical oceanography research in China began with studies of sea waves, tides, offshore circulation, water masses, and ocean meteorologic disasters with emphasis on the storm surge. With the rise of China, the research fields have been gradually expanded. Meanwhile, a great deal of significant research results have been achieved, such as, developed general wind wave spectra and swell spectra that are adapted broadly by the international community as well as the third generation sea wave numerical models; establishment of analytical and forecast methods for tides and tidal currents including quasi-harmonic analytical methods and permanent forecast methods of tides and tidal currents; discovered and named Mindanao Undercurrent, revealed multi-core structures and mechanisms of multi-scale variability of the Kuroshio in the East China Sea, and systematically described the circulation system of the western boundary of the Pacific; proposed the South China Sea Branch of Indonesian Throughflow (the South China Sea Throughflow); gradually improved continental shelf circulation systems of China offshore waters, and obtained deep understandings on the South China Sea circulation, the Kuroshio and its branches, Taiwan Warm Current, Zhejiang-Fujian Coastal Current, the Yellow Sea Cold Water Mass Circulation, the Yellow Sea Warm Current, the Bohai Sea Circulation and continental shelf trapped waves; systematically summed up inter-ocean interactions of the Pacific Ocean-the Indian Ocean-the Atlantic Ocean through the atmospheric and oceanic bridges; developed methods for the water mass analysis of shallow seas, generally clarified features and mechanisms of distribution and evolution of water masses in China offshore waters, and had contributions to studies of distribution and movement of water masses in deep oceans and polar oceans; clarified general features and generation mechanisms of mesoscale eddies in the South China Sea, explored 3-D structure of eddies, and quantitatively estimated material and energy transportation abilities of eddies in global oceans; basically clarified spatial distribution and seasonal variability features of ocean fronts in China offshore waters, proposed frontogenesis mechanisms including topography, barotropic and baroclinic instabilities; built mooring observation net for internal waves in the South China Sea, achieved systematic under-

standing of mechanisms for the full process of generation-evolution-dissipation of internal waves; development of shear instability theories of turbulence and ocean turbulence models, proposed a concept of current edge instability and new methods for turbulence-mixing parameterization; obtained new understandings for ocean interior mixing mechanisms and energy sources, and clarified effects of mixing on the deep layer circulation and nutrient material transportation processes; developed the Global Wave-Tide-Current Coupling Model, and a series of ocean and climate models; developed ocean data assimilation systems that may assimilate the majority of ocean observation data and coupling assimilation systems used for ENSO prediction; built physical model experiment platforms with ageostrophic water tanks/pools and geostrophic rotation platforms that satisfy the international standards; developed error analysis methods for ENSO prediction, built theory systems for inter-decadal variability of ocean and climate systems, explored response of mid-deep ocean layers to global climate change; primarily built ocean observation net in China offshore waters; continued Arctic and Antarctic expeditions; built operational forecast systems for typhoon, storm surge, extremely high waves and tsunami to provide supports for reducing meteorologic disasters in China; broke through foreign blockade to ocean technologies, successfully developed 10 km deepwater hydrophone and a series of instruments for observing ocean optical features; developed prediction models for oil spilling and dangerous/chemical material drifting and spreading in order to provide scientific supports to emergence processes and warning/forecast of risk events that are brought along ocean resources development. A great deal of literatures of academic results cited in this paper (maximum 3 papers selected for each first author) show that the development of physical oceanography research over past 70 years has trained a research team with solid strength. This is the most precious achievement. This research team will serve as a principal force to scale new heights in physical oceanography in China.

Key words: physical oceanography; ocean waves; tides; sea level; ocean general circulation; water mass; coastal ocean circulation; meso-scale processes; turbulence and mixing; numerical modeling; data assimilation; laboratory simulation; air-sea interaction; climate; sea ice; Arctic and Antarctic expeditions; ocean meteorology and disasters; ocean physics; marine environment