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RegCM 区域气候模式系统在东亚地区的应用——回顾与展望

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摘要

由国际理论物理中心（ICTP）发展的 RegCM 系统，是东亚地区最常用的区域气候模式（RCM）之一。本文对 RegCM 系统及其在东亚地区的应用做了简要的回顾，包括对模式发展历史和未来发展规划的描述，以往和目前针对东亚地区的应用情况归纳，及对模式系统所表现出的优势和偏差的总结等。模式模拟偏差主要存在于冷季，其特征主要表现为高纬度地区存在暖偏差和南部区域存在的降水量低估，与大多数全球气候模式（GCM）模拟存在的偏差表现出相似性。最后介绍了该模式在国际联合区域气候降尺度试验（CORDEX）框架下的应用和未来发展计划。本文旨在为东亚地区 RegCM 系统的未来应用提供必要的参考。

1. 引言

在过去的几十年中，区域气候模式（RCM）在世界不同区域，被越来越多地应用于提供相对于全球气候模式（GCM）而言更小尺度的气候信息[1]。RegCM 系统是首个被用于气候降尺度的区域气候模式系统，起源于20世纪80年代末和90年代初，在美国的国家大气研究中心（NCAR）建立[2–4]，并且经过了一系列后续版本的发展，如RegCM2 [5,6]、RegCM2.5 [7]、RegCM3 [8]和最新版本RegCM4 [9]。RegCM 系统目前在意大利国际理论物理中心（ICTP）开发和维护。它是一个开源代码系统，被众多的科研团队广泛使用，形成了所称的区域气候研究网络，即RegCNET [10]。该模式可应用于世界各地[9]，并正在向耦合了海洋[11,12]、湖泊[13]、气溶胶[14]、沙漠沙尘[15]、化学[16]、水文[17]和陆面过程[18]的全耦合区域地球系统模式发展。

东亚具有复杂的地形、海岸线和土地利用分布，以及影响当地气候的区域环流（季风、热带风暴等），因而对于RCM 来说是非常有应用价值的大陆之一。随着经济的快速发展，其气候也受到很大的人为强迫影响，如气溶胶排放和土地利用变化[19,20]。此外，已被证明，以东亚季风为主的当地气候的很好模拟，依赖于模式分辨率，如夏季季风雨带的位置和时段的再现[21]。由于上述原因，从开发的早期阶段，RCM 即已应用于东亚区域[22–25]，并在此后得到更快发展。目前，东亚是国际联合区域气候降尺度试验框架（CORDEX）下的标准区域之一[26,27]，并已有大量的气候预估集合结果[28,29]。

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在应用于东亚地区的RCM中，如RIMES [30]、IPRC-RegCM [31]、PRECIS [32]、P-□ RCM [33]、MM5 [34]及WRF [35]等，RegCM系统是最常用的模式之一。文献[22,24]报道了其对该地区气候变化模拟的首次应用，尤其是后者以NCAR所发展的CCM1气候场作为模式侧边界驱动条件，分别选择当代和CO_2加倍的各五年进行积分，完成了首个50 km分辨率的东亚区域的预估模拟。之后，不同版本的RegCM系统在东亚地区得到了大量应用，包括从天气过程的研究和气候变化预估，到对气溶胶和土地利用变化影响的模拟等方面。这些研究还特别报道了一些模式的系统偏差，从而引起模式在性能改善方面具有实质性的进展。

多年来，该区域的RegCM用户群体稳步增长，除了在ICTP定期举办的两年一次的研讨会外，各地也相继组织了多个培训讲习班和培训课程，如2015年5月在菲律宾的马尼拉举行的研讨会，2006年7月在中国北京举行的第三届气候系统和气候变化国际研讨会期间的培训等。RegCM团队计划在CORDEX背景下，使模式在东亚地区更多地应用，并在其中特别强调气候系统不同组成部分之间的相互作用和反馈以及人为强迫对气候影响的研究。为此本文将给出过去和当前阶段，RegCM在东亚地区应用的简要回顾，及未来相关的模式发展计划，从而为未来的模式使用者提供此方面的基础参考文献。

2. 东亚地区 RegCM 研究回顾

表1 [22–24,28,36–102]按研究类型和针对的子区域进行分类，给出东亚地区RegCM系统应用研究列表。模式在该区域的模拟表现是最受关注的，因此开展了大量使用再分析数据或GCM结果驱动，进行模式性能评估和优化的研究。这些研究表明，RegCM能够很好地再现该地区当代气候的主要特征。令人特别感兴趣的结论是该模式能够显著改善GCM对东亚夏季风模拟的常见偏差。事实上不同版本的GCM模拟的东亚季风降水中心偏差较大，与观测中的相比通常偏北偏西（即降水中心在青藏高原东部而不是中国东南部）。Gao等[36]通过采用GCM驱动不同分辨率RegCM2的系列试验，发现偏差主要是由于GCM的粗分辨率引起的。如图1 [21]所示，随着分辨率的提高，模拟的降水模态与观测具有越来越高的一致性，从而得出需要60 km或更高分辨率，才能准确地模拟出东亚雨带及其季节演变的重要结论。

表1 中国和东亚区域所开展的RegCM模拟列表

RegCM simulation	References	Grid size	Duration	Domain and region of interest
Present-day simulation, parameterization testing, and model validation	Liu et al. [24]	50 km	3 months	EAS
	Liu et al. [38]	50 km	3 months	EAS
	Zhao et al. [23]	60 km	4 months	EAS
	Giorgi et al. [39]	60 km	13 months	EAS
	Lv and Chen [40]	40 km	2 × 3 months	North China
	Kato et al. [41]	50 km, 25 km	Months long	EAS
	Chen and Fu [42]	60 km	3 years	East China
	Luo et al. [43]	60 km	4 months	EAS
	Li and Ding [44]	60 km	5 years	China (modified version)
	Chow et al. [45]	60 km	3 months	EAS
	Bao et al. [46]	50 km	4 × 3 months	West China
	Ju and Wang [47]	60 km	11 years	China
	Ding et al. [48]	60 km	10 years	China (modified version)
	Gao et al. [36]	45–360 km	2 × 6 × 5 years	E-EAS, China
	Im et al. [49]	60 km/20 km	30 years	EAS/Korea (double nested)
	Zhang et al. [50]	50 km	15 years	E-EAS
	Wang and Yu [51]	60 km	2 × 10 years	Tibetan Plateau
	Zou and Xie [52]	60 km	2 × 41 years	China
	Zou et al. [53]	50 km	80 × 4 months	South China, West Pacific, East Indian Ocean, the South China Sea
	Gao et al. [54]	25 km	5 × 1 years	E-EAS, China
	Gao et al. [55]	25 km	20 years	E-EAS, China

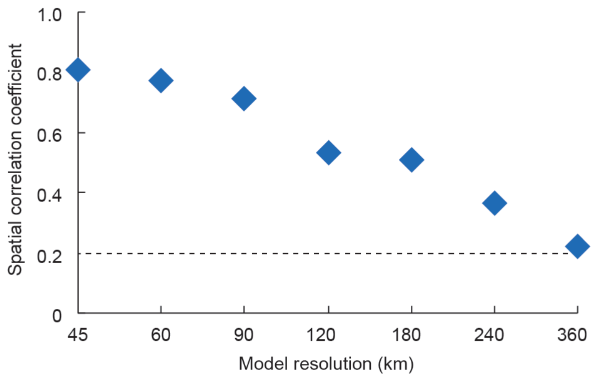

图 1. 不同模式水平分辨率下中国年平均降水量模拟和观测间的空间相关系数（虚线为0.99显著水平）。基于文献[21]绘制。

这些发现已经被RegCM4 [37]和其他RCM [103]的进一步试验所证实。

为确定东亚区域的最优模式配置，开展了物理参数化方案不同选项及模式参数方面的许多测试工作。例如，研究发现Emanuel 积云对流方案在RegCM3[45]和采用CLM 陆面方案的RegCM4.4较新版本中都有较好的表现[54]。一般来说，RegCM 系统在季风（暖季）温度和降水的再现方面有较好的模拟能力，但在冷季如高纬度地区的暖偏差、南方降水量的低估和北方降水量的高估这种相对较大的误差（与大多数GCM 结果相似）仍然存在。如参考文献[54]所指出的，RegCM4未能较好地模拟出中国南方冬季的降水中心，与大多数GCMs 一样[104,105]。类似偏差在ERA-interim再分析数据中也存在，尽管偏差程度较小，表明模式在模拟该区域冬季降水方面所存在的困难。此外，也有研究指出地表发射率等地表特征有可能改善冬季气温的模拟[106]。

RegCM 系统被广泛应用于东亚地区GCM气候变化预估结果的降尺度研究。通常与驱动GCM 相比，RegCM 不仅能够给出更详细的地理分布，也能够更好地再现当代大尺度降水特征。在未来降水变化预估方面，Gao 等[61,65]的研究表明，RegCM 不仅给出了降水变化信号与地形有关的更精细结构，而且模拟出与驱动GCM 明显不同的大尺度分布型。在这些研究中，虽然驱动的GCM 与其他大多数GCM 预估结果一致，均表现出季风降水显著增加，但RegCM4 预估出了更多降水减少的区域。同时当RegCM 由不同的GCM 驱动时，中国东部会表现出不同的变化。这些结果表明，在这一人口密集地区的季风降水预估仍然存在较大的不确定性，因而需要更多GCM/RCM 的集合进一步认识此问题。RegCM 也是第一批使用双重嵌套法，在一些东亚子区域（如日本和韩国）运行的较高分辨率的RCM 之一[41,60,63]，更好地说明了这种方法在描述地形和海岸线是如何影响局地气候变化信号方面的优势。

RegCM 系统在东亚的另一重要应用，是开展与较长历史时期的农业活动和高密度人口有关的土地利用的气候效应研究。所进行的试验包括在试验区域使用理想化的简单植被变化，即从一种类型变化到另一种类型（如从沙漠到森林或反之），对比潜在植被覆盖与当前土地利用，以及20世纪末的几十年来经济快速发展导致的土地利用变化等的研究。所有研究均表明土地利用对该地区气候有显著影响，然而不同试验所得到空间分布结果和影响程度有一定不同，因此这同样也需要进行多RCM 的集合和对比研究。此外，一般国际数据库中的覆被数据在中国区域通常显示出较大的偏差。如在CLM 默认数据集的土地类型中，青藏高原上主要为裸土覆盖[107]，但实际上该区域中的主导植被是草地。研究表明，使用基于本地数据集的更可靠的土地覆盖数据，可以有效改进模式模拟[108]。

近几十年来，随着当地工业和经济发展所带来的污染排放量迅速增加，人为气溶胶对气候的影响日益引起人们的关注。RegCM 系统是第一个用于研究这个问题的RCM，也是第一个在东亚地区将气溶胶辐射的直接和间接效应耦合到RCM 的模式[82–84]。其模拟结果表明，气溶胶有明显的降温和抑制降水作用，特别是工业化程度最高的地区，如中国西南地区中部的四川盆地。由于气溶胶效应的复杂性，需要开展进一步研究，以更好地定量评估气溶胶颗粒对降水的影响，特别是在其与云的相互作用方面，而RegCM 系统已开展的工作为此打下了良好基础。东亚也是最主要的沙尘源区之一，如中国西部和蒙古沙漠等，多个沙尘气溶胶的模拟结果表明，RegCM 系统对于近地面浓度的时空变化、质量负荷、光学厚度和主要源区的沙尘气溶胶排放的再现具有较好的模拟能力[87]。

将RegCM 与气候系统的其他组成部分（包括不同的海洋模型、植被模型和地下水模型等）进行耦合的研究在中国也有相当程度的开展，如Zou等[97]的研究结果表明，与海洋耦合后的RegCM，可以极大提高模式对西北太平洋降水的气候态和年际变率的模拟能力。RegCM 的其他应用还包括古气候研究和季节预测试验，关于后者，如Zhang等[101]发现RegCM 在一些特定地区和年份的预测技巧有所改善，但总体而言在应用模式进行实时季节预测方面仍需开展进一步研究。

3. 模式在东亚地区未来发展和应用的展望

Gao等[54,55]推荐了RegCM4.4 在东亚地区的物理和参数的配置。具体来说，当使用Emanuel 积云对流方案和CLM 陆面方案，以及基于中国数据集更新的土地覆盖数据[108]时，模式在该区域上表现“最佳”。与此同时，RegCM 系统正在进行各种与东亚地区应用直接相关的发展。与Giorgi等[9]所描述的版本相比，增加了Tiedtke[109]、Kain和Fritsch[110]两种新的积云对流方案，它们在热带地区对流模拟中表现出很好的效果。RegCM 也参照中尺度模式MM5，完成了非静力平衡版动力框架的构建[111]，同时引入了可以显示表示云水、云冰及雨雪等变量的一套完整的云微物理方案[112]。以上使得模式能够应用于几公里尺度的高分辨率模拟试验中。

关于耦合模式的发展，MIT-OGCM 海洋模式的更新版本现在已经耦合到RegCM4 中，并在各个地区进行了测试，同时CLM陆面模式升级到了4.5版本[18]，此版本额外增加了城市环境和动态植被及其对气候强迫响应的选项。与陆地水文模型CHYM 的耦合[17]也已经完成，目前正进行测试。海洋生物地球化学模型的耦合也正在进行中。

除了第2节讨论的问题外，已有计划在东亚和中国区域更加广泛的应用模式的新版本。非静力平衡的模拟能够在几公里的分辨率下进行，但到目前为止，由于巨大的计算成本，在整个东亚地区进行这种模拟可能是困难的。然而对某些特定区域的模拟将有助于更好地了解当地的气候状况，并为影响评估研究提供局地尺度的气候变化预估结果。通过使用RegCM4中提供的陆地次网格方案[113]，还可以使用更高精度的地表覆盖数据，模式的这种性能目前同样在某种程度上还未充分利用。利用新的云微物理方案对RegCM4进行的一些初步测试表明，云量模拟的改进降低了高纬度地区冷季的暖偏差，虽然这个结论尚需进一步验证，但最终结果将为其他RCM 和GCM 的发展提供有用的建议。作为下阶段CORDEX 活动的一部分，各大陆尺度CORDEX 区域的RCM 分辨率将提高到10~20 km[1]，因此需要进一步测试和优化高分辨率下RegCM4的模拟性能。未来在CORDEX 框架下模拟的进行、RCM 之间的相互比较，将有助于更好地理解模式结果，从而为其模拟能力在该区域的进一步发展提供帮助。

综上所述，在东亚地区利用RegCM 系统已经开展了众多试验，为该地区的气候模拟研究提供了非常有价值的结果。该模式的应用和发展将继续促进该地区的气候研究，包括气候变化预估、土地利用对气候变化的影响、气溶胶和污染研究（分布、传输和对气候的影响）以及古气候和季节预测等各个方面。预计新一代的RegCM 在东亚地区的模拟将为政府间气候变化专门委员会（IPCC）第六次评估报告（AR6）、CORDEX以及影响评估和脆弱性研究等方面提供有效的帮助。

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Compliance with ethics guidelines

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