Du-zheng Ye scientific contribution and research methods (chapter 14)

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第 14 章　叶笃正的科学贡献及研究方法

叶笃正先生——风华正茂已是奠基人，古稀之年仍为开拓者

14.1　引　　言

自新中国的第一份气象记录诞生以来，回溯中国气象科学的发展历史，总会让人禁不住想起中国现代气象事业的开拓者——叶笃正先生。他 1935 年考入清华大学，开始了物理学的求知之路；1938 年历经艰难困苦远赴西南联合大学，开始了气象学的寻梦之旅。1945 年，叶笃正赴美留学，在芝加哥大学叩开了气象学的大门，有幸成为著名气象学家罗斯贝（C. G. Rossby）的学生。或许，自助者天助之。彼时世界气象界一流的科学家经常光顾芝加哥大学，使得叶笃正有机会目睹皮耶克尼斯、帕尔门等前辈大师的风采，聆听大师们的教诲，更有机会学习和观摩大师们的科学研究方法，这为他以后在学术之路上的精进创新打下了基础。世界著名气象学家、欧洲科学院院士霍斯金斯（B. Hoskins）是这样评价叶先生的“作为可能最后直接受教于罗斯贝的人，他不仅推动了气象学科许多方面的发展，同时也为中国气象及气候研究跻身世界前列奠定了基础（He was probably the last direct contact with Rossby, laid the ground for Chinese meteorological and climate research to take its place at the top level in the world）”（Hoskins, 2014）。叶笃正的科学研究工作包括大气 Rossby 波能量频散、大气环流动力学、东亚大气环流的季节突变、大气阻塞高压动力学、大气中的地转适应过程、青藏高原气象学及全球变化等多个领域，取得了许多创新性成果和开创性研究。回顾叶笃正的科学历程，梳理他的科学研究业绩，分析其中的研究方法特点，对于后辈学人弘扬科学精神，开拓创新思路无疑具有重要的启发意义。

14.2 大气能量频散

在叶笃正的众多贡献中，大气长波频散理论是最早提出并得到广泛认可的研究成果。波动是大气运动的基本特征之一。第二次世界大战前后，随着高空大气观测的发展，已经可以绘制出高空天气图，罗斯贝在5500m高空天气图上发现在北半球中高纬度存在数千公里波长的大气波动，其移动速度与他的简化数学模型估计大体一致。后来，这种大气长波被称为Rossby波。克里奥利（Coriolis）参数随纬度变化是其形成的动力学原因。叶笃正在罗斯贝长波理论的基础上，用类比的研究方法，参考物理学中色散或频散的概念，发现Rossby波相速度与波长有关，是频散波，导出了Rossby波群速度的公式。这是对罗斯贝长波理论的发展。该成果成为叶笃正博士论文 *On Energy Dispersion in the Atmosphere*（Yeh，1949）（图14-1）的核心内容，并于1948年在美国著名气象期刊上正式发表，在国际上引起气象学者的重视，被誉为动力气象学的经典文献之一（王舒，2008）。气象学大师罗斯贝对这篇论文非常重视，鉴于这一理论工作对动力气象学的重要性，他特意给著名气象学家恰尼（J. Charney）写信，要他基于他们正在做的数值预报试验，写一篇短论以支持叶笃正的结果（Harper，2008）。

图14-1 获得博士学位时的叶笃正先生

所谓能量频散，就是波动的能量随波的传播而被分散或重新聚集的现象。叶笃正引入群速度的概念，研究了在四种大气模式中的群速、相速和波长之间的关系。不同波长单波相速度不同，不同尺度单波又组成波列，一个波列的能量以群速度传播。在一般情况下，总会存在一个群速大于相速的波长范围，导致在初始波动下游形成新的波动（王舒，2008）。如果波动流场存在辐散，且大气中的水平温度不均匀，则会出现负的群速度，即只有“水平温度不均匀”才是上游形成新的波动条件。叶笃正通过积分一个正压涡度方程揭示了能量通过频散传播的过程，从理论上证实西风环流中的能量以远大于风速或波动相速度的群速度向下游传播，导致下游的天气迅速变化。这种现象已经在天气预报实践中被发现，俗称“上游（或下游）效应”。能量频散理论把这种经验上升到理论的高度，从而把天气预报的实践和理论结合起来，为提前预报高空等压面上大槽或大脊的变化

提供了科学依据。这曾经是20世纪80年代前气象台做中期天气预报（4～10天预报）的主要方法之一。例如，冬季东亚大规模冷空气入侵往往与中纬度大气长波调整有关；中国的天气预报人员在上游发现了几个关键区，如北大西洋沿岸、地中海等；北大西洋气压脊或地中海气旋发生明显变化，往往会导致几天后中国上空的环流场发生调整并伴随大范围的天气变化。

然而，高空气流不全是波状的，在中高纬度有时会出现移动缓慢甚至停滞的巨型Ω形状的高压，严重影响东西向气流的流动，被称之为阻塞高压（blockinghigh）。能量频散理论对阻塞高压天气系统的生成、维持和移动给出一种动力学解释，成为业务上预报持续性异常天气的理论基础之一。叶笃正的计算表明阻塞高压在高纬度地区的生命周期比在低纬度地区长，西移的速度随纬度的升高而减少，在一定程度上解释了阻塞高压为什么总是出现在高纬度。叶笃正还解释了另一些重要的现象，譬如中高纬地区西风气流上经常出现大槽大脊，而低纬度只有强度不大的东风波；低纬天气系统生命周期很短，中高纬的生命周期很长等现象（周家斌，2007）。

此外，叶笃正又进一步提出了起源于热带的扰动可以向中纬度传播的理论（周家斌，2007），并且这一扰动以波列的形式向东北方向传播，进而影响中高纬度的天气和气候。31年后，这个理论才由英国著名动力气象学家霍斯金斯的“大圆理论”所推广，成为对观测到的大气遥相关或遥响应现象的理论基础。在叶笃正提出能量频散理论及查尼等对地形和非绝热加热对大气准定常行星波的形成问题研究后，气象学家又分别从观测、数值模拟和理论分析对大气准定常行星波的性质展开研究，在准定常行星波的形成机制、水平传播和能量频散、垂直传播等方面取得了重要的研究成果。后来，这些成果又进一步推动大气环流异常的遥相关和平流层环流异常动力学的发展。长波能量频散理论与罗斯贝的长波理论及查尼的长波不稳定理论一起被认为是有关大气长波动力学的三个重要理论（谭本馗，2007）。

14.3 东亚大气环流季节突变

从观测事实出发归纳出大气环流的演变规律，是叶笃正常用的一种研究方法。新中国成立后中国高空气象观测网得到了快速的发展，到20世纪50年代中期中国的探空站已经超过了60个，高空风观测站多达150个。丰富的探测资料为东亚大气环流的研究提供了可能。为了改进和提高中国天气预报的准确性，理解东亚地区的大气环流状况，叶笃正以观测事实和理论分析为出发点，系统地研究了东亚大气环流的演变（王舒，2008）。1957年和1958年，叶笃正和顾震潮

等在瑞典地球物理杂志 *Tellus* 上发表了 *On the General Circulation over Eastern Asian* 的文章，分三期连载。该文主要阐释了东亚地区的大气环流状况及成因，概述了东半球冬季和夏季对流层中层（500hPa）的大气环流分布状况，发现了东亚环流的一些特征，论述了东亚大气环流的季节变化，影响东亚天气的主要天气系统，以及青藏高原对东亚大气环流和中国天气的影响（杨多文，2008）。其中，青藏高原对大气环流的影响随季节变化的观点与以往把高原的影响看成固定不变的观点有很大的不同（周家斌，2007）。该文就青藏高原是热源还是冷源的问题进行了讨论，指出青藏高原对大气环流的影响远超过北美的落基山脉。

1958 年叶笃正和朱抱真共同出版了《大气环流的若干基本问题》（叶笃正，1958）一书，它早于 Lorenz 的名著《大气环流的性质与理论》十年。该书系统讨论了北半球大气环流的特征和影响大气环流变化的主要因子，如大气中热量、角动量、能量的平衡，急流的形成与维持，西风带上低压槽和高压脊的形成等（叶笃正，1958）。1980 年，大气物理研究所与中央气象台、北京大学地球物理系合作建立“联合数值预报室”，将东亚大气环流等的研究成果用于中国气象局的业务预报模型，成为新中国气象科学发展的一个里程碑。

1958 年，叶笃正、陶诗言和李麦村联名在《气象学报》上发表了《在六月和十月大气环流的突变现象》，其英文版收录于 1959 年罗斯贝纪念专辑中。该文通过分析 1956 年 5 ~6 月和 9 ~10 月几个代表性经度上的纬向风–气压剖面图，归纳后发现东亚上空西风急流中心位置在 6 月和 10 月有明显的突变（周家斌，2007）。大气环流冬、夏流型的转变在短时间内便可以完成，反映了大气环流的突变性。这一发现对中国天气预报的发展具有重要意义。叶笃正等科学家比其他国家早 20 多年就提出了东亚大气环流季节转换的突变性，他在东亚大气环流方面做出的开创性研究极大地提高了中国在国际气象学界的地位（章基嘉，1985；曾庆存，2005）。

阻塞形势是北半球冬季的主要天气系统之一，它的建立和崩溃常常伴随着大范围环流形势的强烈转变，它的长期维持能产生大范围天气、气候的反常现象。20 世纪 60 年代，叶笃正等对阻塞高压进行了更深入的归纳、分析和研究，其结果总结在 1962 年出版的《北半球冬季阻塞形势的研究》中，作者为叶笃正、陶诗言、朱抱真等。该书从气候、天气、动力及数值预报方面对阻塞高压进行了综合研究，系统阐述了阻塞高压的形成、维持及崩溃等动力过程。这一研究成果被应用于中国寒潮天气的预报中（周家斌，2007）。1963 年叶笃正等进一步探讨了不稳定扰动如何停止发展，指出扰动能对基本气流产生非线性反馈，当扰动不再能从基本流场得到能量（位能或动能）时，扰动便停止发展，从而形成阻塞高压或切断低压。这为研究东亚天气的持续性异常提供了理论依据，而直到 1976

年冬季北美出现极其寒冷的天气时，国外的学者才开始提出相关的理论，阻塞形势才成为国际上一个重要的研究方向。

14.4 转盘实验

实验是科学研究必不可少的环节之一。早在 19 世纪就有人在实验室做过大气环流模拟实验。20 世纪 50 年代，Fultz 和 Hide 等人曾进行了一系列的转盘模拟实验。叶笃正认为除了理论推演和观测事实分析，可以用流体力学实验方法模拟研究大气环流的动力学问题，因为描述大气和流体运动的数学方程是相似的。1972 年，在叶笃正的主持下，中国科学院大气物理研究所建立了大气环流转盘模拟实验室。实验装置为三个不同半径的有机玻璃壁。外壁 E1 和 E2 之间盛以热水，内壁（E3）环以内盛以冷水，以此来维持实验区外壁 E2 和 E3 之间实验流体的温差。实验区的外圈相当于较热的低纬度，内圈相当于较冷的极地地区。实验区内可以局部加热，也可以置入地形模型等。从而使实验槽中的流体作类似于大气中各种形态的运动（杨多文，2008）。叶笃正主要集中研究了青藏高原大地形及其夏季作为热源对大气环流的影响规律，使我们对东亚大气环流问题有了更深入的理解，而至今该转盘装置及其相关研究仍然是大气科学重要的研究手段之一（图 14-2）。

图 14-2　叶笃正先生晚年仍非常关心转盘实验的进展

20 世纪 70 年代，叶笃正在旋转流体中模拟了青藏高原对大气环流的动力和热力作用。在实验中虽然青藏高原的模型不过是个理想的半椭球体，但对东亚大气环流的多种影响都在这个旋转的转盘实验中被模拟出来。这些实验使人们对高原和东亚环流之间的联系有了进一步的认识。1974 年叶笃正和张捷迁还指出，当高原加热到一定程度后会出现温度脉冲现象，即随着加热增强，脉冲的幅度增强和次数增多，这说明高原上有对流活动。这与夏季青藏高原在南亚高压控制下对流活动旺盛的观测事实一致。此外，实验还证明，对流云是夏季高原向上输送热量的有效载体（叶笃正，1974）。

14.5 大气运动的演变与适应

大气运动也是各种矛盾斗争的统一体，分析其中的主要矛盾及其转化过程是认识天气变化本质的途径之一。例如，风场与气压场就是一对矛盾。传统理论认为，大气运动是大气质量分布不均匀的结果，大气质量分布不均匀产生气压梯度，从而引起大气的运动（风）。风场与气压场之间，风是被动的，气压是主动的。当气压场发生变化后，风场也要随之发生变化，以满足所谓的地转关系（曾庆存，1988）。1936 年，罗斯贝首先提出了与传统观点相反的观点。他认为在大气或海洋的一部分运动中，质量分布不是运动的原因，而是运动的结果。于是他分析了一个初始只有速度，而无压力梯度相平衡的带状气流的演变。他发现流速变化不大，同时产生了与科氏（Coriolis）力相平衡的气压梯度。他认为，气压场与风场是相互适应的，主要是气压场向风场适应，即气压的分布是动力的结果（周家斌，2007）。1945 年 A. Cahn 进一步分析发现，气压场向风场适应是通过重力波的频散来完成的，即重力波将有限空间内的气压场与风场之间不平衡的能量散布到整个空间，使得单位空间中的不平衡能量趋于零，不平衡现象就消失了。1957 年叶笃正在日本《气象集志》（*Journal of Meteorological Society of Japan*）上发表了 *On the Formation of Quai-Geostrophic Motion in the Atmosphere* 一文，指出风和气压的适应取决于运动的空间尺度范围。通过对地转适应物理过程的分析，他发现在较大尺度运动的地转适应过程中，主要是风场向气压场适应；而在较小尺度运动的地转适应中，主要是气压场向风场适应（杨多文，2008）。这从理论上阐明了适应过程与运动尺度的关系。

大气运动适应过程中的一个重要机制是重力–惯性波的频散。在一般数值预报模式中，这种波被当做“气象噪音”而滤掉。其中一种方法就是采用准地转假定，因为在准地转运动中不存在重力–惯性波。由此看来，重力–惯性波的存在是和地转偏差分不开的。1958 年 A. C. МонИн 指出，大气中的重力波是地转

偏差激发出来的。1964 年叶笃正和李麦村在《中国科学》上发表《重力波激发强非地转运动的过程》一文，指出重力惯性波的集中导致了强烈的非地转运动。在有限空间中的非地转扰动，不能恢复到准地转状态，反而在一段时间后有增大的趋势，叶笃正通过比较扰动出现的时间与重力惯性波的移动，证明扰动的增大是重力波集中的结果。

大气中的中小尺度天气系统常常能引起灾害性天气。地转关系对于中小尺度运动或低纬度天气系统并不适应。然而，这些情况是否存在类似于中高纬度大型运动的地转关系呢？在 1964 年叶笃正、李麦村所著《中小尺度运动中风场和气压场的适应》一书中对运动方程各项量级进行了分析，发现无论尺度如何，运动的演变一般都是在力的准平衡情况下进行的。对于大尺度的运动，这种准平衡状态就是地转关系。在中尺度运动中，科氏力、气压梯度力和惯性力三者处于准平衡状态；在小尺度运动中，惯性力和气压梯度力处于准平衡状态。当这种准平衡状态遭到破坏后，必定有一种机制使运动恢复到准平衡状态，否则就不能经常观测到这种准平衡状态的运动。因此，在中小尺度运动中也有一种风场和气压场的适应过程。这种适应和地转适应一样，也是通过重力波的频散来实现的。在大尺度运动中，平衡状态是地转关系，风沿等压线吹。在中小尺度运动中，平衡状态是风与能量之间的平衡关系，风沿等能量线吹。这为中小尺度天气分析提供了理论依据。

14.6 青藏高原气象学的创立

科学的进步离不开原始创新，而每一次创新结果的提出离不开观测研究和细致的分析，从量变到质变的飞跃与叶笃正自身动力学的积累以及敏锐的洞察力等分不开（符淙斌，2006）。

地形是大气运动的重要强迫源之一。20 世纪 30 年代后期，人们发现在北美的落基山、南美的安第斯山和青藏高原的东边，都有一个准静止的西风带大槽。40 年代，西风带长波理论出现之后，不少人认为，大地形东边的长波槽是其动力扰动的结果。50 年代，叶笃正和一批中国气象学者开始研究青藏高原对东亚环流和天气的影响。当时高原观测站稀少，也没有先进的气象仪器，叶笃正利用两次科考队收集的数据，发现了青藏高原的南支急流、北支急流以及北半球强大的西风急流。这些研究总结在 1956 年出版的专著《青藏高原对东亚大气环流及中国天气的影响》及 1959 年出版的《西藏高原气象学》中，标志着青藏高原气象学的创立（钱正安，1996；孙烨，2012）。

14.6.1 地形热力效应

青藏高原是热源还是冷源，多年来一直是个重要的科学问题。在 1957 年由叶笃正、罗四维、朱抱真等编写的《西藏高原及其附近的流场结构和对流层大气的热量平衡》中首次提出青藏高原夏季是一个热源，冬季其西南角有一部分是热源，其余地区可能是冷源的论断，并对冷热源的概念加以解释，质疑了前人定义的偏颇之处。书中进一步阐明了形成热源、冷源的热量源自辐射、湍流、凝结和蒸发等的净热量积累（叶笃正，1957）。叶笃正曾在《青藏高原气象学》（叶笃正，1979）中指出高原热力作用可分为高原地面和高原大气的冷源和热源两种，凡是把热量供给大气的高原地面称为热源；反之，称之为冷源。同样，当高原上空的大气把热量输送给四周大气时，则称高原大气为热源；反之为冷源。他们认为大气热量收支主要包括来自地面加热的热辐射、地面的湍流热输送、太阳的热辐射以及当地凝结降水的加热等（Yeh，1985）。1979 年，叶笃正等进一步指出，高原大气冷热源的变化在垂直环流上扮演着重要的角色。1991 年《美国气象学会通报》在介绍叶笃正的成就时说道："他是世界上第一个确认青藏高原的热力效应并且用数学方法加以表述的，而在此之前人们主要是把青藏高原作为动力机械强迫来对待。"2003 年的《世界气象组织通报》进一步指出："叶笃正是提出世界上最大的高原夏季是热源，冬季是冷源的第一人"。

14.6.2 地形动力效应

由于高原地区独特的地形及动力和热力作用，形成了高原及周边地区特殊的天气气候。中国大范围的干旱、洪涝等都直接或间接地与青藏高原的存在有关。叶笃正对高原动力学问题进行了系统的论述和分析，指出高原动力作用包括机械作用和摩擦作用两种（叶笃正，1956）。高原的机械作用表现为：冬季，西风气流经过高原时，6km 以下的低层气流被迫分成南北两支，沿等高线绕流，形成了高原区域极为明显的北脊南槽的环流形势，绕流气流到达高原背风面之后又重新汇合，冬季的南支槽是带来南方冬季降水的重要天气系统。夏季，东风气流经过高原时也有分支绕流的现象，但不如冬季明显。高层气流则会爬坡，当气压系统被迫爬越高原时，因气柱缩短而增压，这将使低压系统减弱或填塞，但高压系统会变得更加强大；当气压系统移出高原时，气柱因拉长而减压，低压系统将加深或发展，高压系统则会减弱或消亡。所谓的高原摩擦效应是指气流经过高原时在高原侧边界会产生摩擦作用，使得气流流速减慢，而离高原较远处气流则正常行

进，从而侧边界附近的气流出现水平切变，产生地方性涡度。冬季，在高原北部西风侧边界，常出现反气旋性涡旋，而南部则伴有气旋性涡旋产生；夏季，高原北部仍为西风侧边界，常有中尺度反气旋生成，而高原南部转为东风侧边界，也常伴有中尺度反气旋涡旋。这些都对临近地区的天气气候产生重要影响。20 世纪 80 年代以后基于各种地形坐标系和参数化方案的高原数值预报模式逐渐发展起来，更多的学者开始投入到高原数值模式的研究中，进一步推动了高原气象学的发展，引起了世界各国科学家的关注（杨伟愚，1990）。

14.7 全球变化与有序人类适应

叶笃正是最早提出全球变化研究的主要科学家之一。1984 年在第一次全球变化大会上他做了题为 *Climate Change–a Global and Multidisciplinary Theme*（气候变化——一个全球性的多学科科学问题）的报告（Yeh，1985）。第一次指出 10～100 年应当是全球变化研究集中关注的时间尺度，讨论了气候变化和全球变化的联系和区别。1986 年，国际科联正式批准建立国际地圈–生物圈计划（简称 IGBP），标志着全球气候变化科学新领域的诞生，并参与了国际地圈生物圈计划的制订。他进一步指出，全球变化对东亚，特别是中国生存环境变化和可持续发展会产生影响，包括全球增暖对东亚季风的影响、对水资源和气候灾害出现频率和强度的影响、对农业的影响以及对海平面高度变化的影响等。另外，他指出了具有全球意义的区域性生存环境问题，其中包括季风气候、生态系统相互作用、人类活动、生存环境的敏感带及变化的突变性等。

1989 年叶笃正对于全球变化学科提出了纲领性的问题。他与符淙斌共同撰写了 *A Discussion on the Predictability of Global Change*（全球变化可预报性的研究）一文（Yeh，1989），发表在 *Climate Change*（气候变化）上。文章主要探讨了 3 个问题：①我们需要预报什么？针对这一问题他们提出把地球作为一个系统作出预报，而不是只对其中个别分量（如大气、海洋等）单独做出预报。问题是，我们应该怎样定义地球系统呢？我们需要预报的最重要元素是什么？他们建议全球变化预报问题可以分两步走：第一步，分别制作全球变化某些主要分量的预报，如可再生的地球资源的预报或者地面状态的预报；第二步，制作全球变化的集成预报，即把地球系统作为一个整体来预报。②可预报性问题。预报能力与 3 个因子有关，即系统的记忆能力、外源状况和学科发展水平。他们认为全球气候模式的成功可以归结为非线性记忆。太阳辐射才是地球系统真正的外源，其他地球系统内部的源可看作内源。对于十年到百年尺度的变化，内源主要是人类活动。③适应问题。地球系统的不同成分变化的速度各不相同。“牵一发而动全

身”，一个成分发生变化，其他也会发生变化。如果适应过程很快，最先改变的成分会受到其他成分的影响。这就产生一个相互适应的过程，从而使地球系统发生连贯变化。而不同组分之间的非线性相互适应过程还可能使地球系统发生突变。显然，这 3 个问题是研究全球变化问题的关键（叶笃正，2001）。

叶笃正等指出，应该把“适应气候变化”和“可持续发展”有机结合起来。就气候变化而言，适应是指自然系统或人类社会系统对预期的变化或其影响做出适当的响应，以趋利避害。叶笃正和吕建华在 2003 年发表了《对未来全球变化影响的适应和可持续发展》（叶笃正，2003），文中强调了对未来全球变化影响的适应和可持续发展的联系，阐述了两点应对全球变化影响的措施：首先是减少温室气体和破坏臭氧层物质的排放，以缓和、减轻全球变化的压力；其次尽管人类采取减缓措施，但由于滞后作用，全球变化的大趋势在未来 100 年中仍将不可逆转地持续下去，这就迫使人类社会必须适应这样的全球变化趋势。因此，全球变化的适应问题，就是根据全球变化对于世界各地的不同影响，应采取什么措施减轻其不利影响，充分利用其有利的作用的问题。对于可持续发展而言，就是建立在社会、经济、人口、资源、环境相互协调和共同发展基础上的一种发展，旨在既能相对满足当代人的需求，又不能对后代人的发展构成危害。以前这两个问题的研究互不相干，部分原因是由于之前的全球变化研究更侧重于地球科学的基础，而可持续发展则侧重于社会经济以及具体的实践应用。因而他强调了全球变化和可持续发展的重要联系。他们明确指出，一方面，全球变化的适应必须以改变肆意破坏环境的生产、生活方式为前提，对于已发生并且不可逆转的全球变化趋势，应有不同的适应方式，但必须遵循可持续发展原则；另一方面，可持续发展的概念是以过去和现在的气候背景、环境状况为依据提出的，似乎较少考虑未来几十年到一百年全球变化的趋势，这具有很大的局限性（叶笃正，2003，2008）。因此，如果脱离了对未来全球变化趋势的估计，也就不能适应变化了的气候和环境背景，可持续发展就如刻舟求剑。对于未来不确定的气候变化，人类活动对气候的适应本身也在影响气候。据此，叶笃正在《我们应该如何应对气候变化》（叶笃正，2007）一文中提出了几条对策：如鉴于人类活动本身的适应变化及与气候变化的不断相互作用，应每隔 3 ~ 5 年重新开展对未来最有可能发生的气候变化的研究；应着重关注区域异常或极端天气现象的气候变化；强调相关领域协作研究的重要性等。

为了应对全球变暖、土地退化等全球变化的负面影响，为了实现可持续发展这一战略目标，以叶笃正为代表的科学家提出了“有序的人类活动”和“有序适应”的概念，进一步强调人类活动对环境的能动作用。在 2003 年气候变化国际研讨会开幕的当天，叶笃正作了题为《有序人类活动》的报告（叶笃正，

2001）。他认为，人类活动已经给环境带来了不可逆转的影响，尤其是近 100 年，人类工业的发展是以破坏生存环境为代价的。而以往的人类活动多是无序的，今后人类应当约束自己，从事有序的活动。他所推崇的“有序人类活动”就是以可持续发展为目标和判断指标，同时也提供可持续发展的理论方法和实际措施（叶笃正，2008）。若从保护人类生存环境的角度出发，什么样的人类活动才算有序的呢？叶笃正等认为通过合理安排和组织人类活动，使自然环境在长时间、大范围内不发生明显变化，甚至能持续好转，同时又能满足当时社会经济发展对自然资源和环境的需求。这个概念为可持续发展指出了一条明确的道路，引起众多科学家的共鸣。对于如何开展有序人类活动的研究，叶笃正等提出了三个研究方法（叶笃正，2006）。首先是将社会科学和自然科学相结合；其次是建立人类活动–生存环境模式系统；最后是建立示范区，进行长期的监测研究。同时，应用卫星遥感监测结果进行数学模拟研究，并应用观测资料监测模式结果的可靠性作为改进模式的依据之一。这充分体现了叶笃正的科学研究方法体系。

14.8　与用户结合：未来的天气气候预测体系

天气气候预测中的不确定性是不可避免的。它一方面给用户或有关决策者带来很大的困难，同时也给科学工作者提出了新的研究课题。叶笃正从气象预测面临的实际应用困难中，敏锐地看到了新的科研发展方向，提出将气象预测过程同用户决策过程有机地结合起来，充分利用来自用户的知识和风险管理经验，形成一套相互作用协同发展的、更具实际应用价值的气象预测体系。叶笃正强调：新的气象预测体系，必须使天气气候预测成为有效的决策基础。一方面需要加强天气和气候系统本身的研究，使得预测所赖以进行的理论基础更加完善；另一方面则应通过和应用者协作，对各种可能天气气候变化的风险及其应对措施进行评估，针对不同用户研制有用的预测报告。用户则可从应用角度分析何种天气气候情形下预测易于出现何种差错，从风险角度总结如何使用预测并提炼对预测系统的进一步需求，加以总结并进而模式化，从而改进预测体系。这样的预测体系不仅仅由气象学知识构成，而是包含了各种用户各自的知识体系。

在叶笃正提出的上述思想指导下，近年中国气象局在其行业专项框架内部署了若干相应的研究项目。这些项目研究的成果，已开始应用于国家和地方气象、水文预测部门（石育中，2013）。叶笃正直至晚年，仍能从实际应用的角度考虑问题，提出创新的科研发展方向，是其一生科研实践的结晶使然。叶笃正，无疑为后来者树立了一个在科研领域不断创新开拓的不朽典范（Yan，2012）。

14.9 结　　语

纵观叶笃正一生的科学生涯，充满了开拓创新。他将西方的分析方法与中国传统的系统论思想结合，倡导多学科交叉的研究方法。他注重观测事实，反复强调“事实是最重要的”这一罗斯贝的谆谆教诲；他将归纳法和演绎法结合起来，从观测数据入手，分析、归纳、总结，发现新的现象、新的规律，然后通过严谨的理论推演揭示其中的物理机制，最后再利用物理实验或数值模拟再现所研究的过程，证实或检验这些发现；他善于理论联系实际，将动力气象学的理论成功地应用于东亚天气气候的研究，推动了中国天气气候预测业务的发展；他视野开阔，纵横于多个学科领域，提出全球变化的重要科学问题，引领了当代地球科学研究的潮流；他关心人类的生存环境，强调地球环境变化中人与自然的关系，创造性地提出“人类有序适应”的理念，成为当今国科联（ICSU）未来地球伙伴计划的重要内容之一。2011 年 12 月科技部创新方法研究会将首届“创新方法成就奖”颁发给叶笃正先生。叶笃正先生虽然已经离去，但他提倡的科学精神和科学研究方法将永远启迪后辈学人，奋进创新。

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