

西亚陆面热力异常的成因及气候效应研究进展*

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摘要: 全球变暖背景下, 西亚地区作为陆地增暖的热点区域引起了广泛关注。观测表明, 西亚陆面温度不仅存在显著的增暖趋势, 还存在明显的年代际变化和较大的年际变率。关注西亚陆面热力异常现象及其成因和气候效应, 对应对气候变化具有重要的现实意义。本文回顾了近年来围绕西亚陆面热力异常开展的研究工作, 从西亚热力异常的观测事实出发, 综述了引起西亚热力异常的大气环流变异和外强迫信号, 以及西亚热力异常对局地气候、印度季风、关键大尺度环流系统和大气遥相关模态以及中国气候的影响。然而, 西亚地区的地形状况和陆面热力时空变化十分复杂, 关于其热力异常的主导成因、局地陆气相互作用的机理和热力异常对不同时间尺度大气环流的影响机制仍有待深入研究, 进而从陆面热力异常的视角加深对全球和区域气候变化的认识, 为气候预测提供更坚实的理论依据。

关键词: 西亚, 陆面热力异常, 陆气相互作用, 物理成因, 气候效应

引言

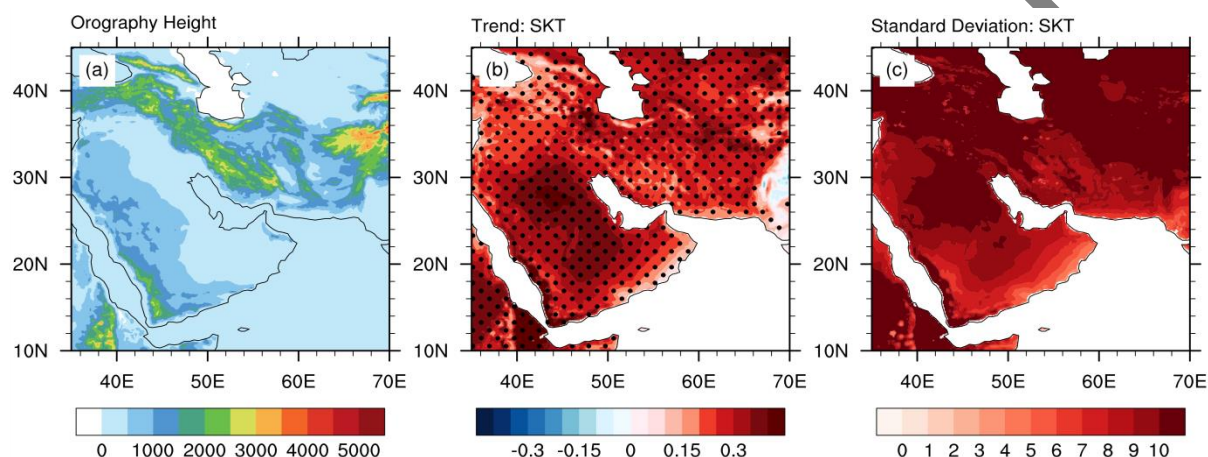
陆面是地球气候系统极其复杂且至关重要的组成部分, 发生于陆面的各种过程及其与大气的相互作用对天气、气候、生态环境和人类生产生活具有重要影响 (Pielke Sr and Niyogi, 2009; Betts, 2009; 黄荣辉等, 2013; 张强等, 2017)。作为大气运动重要的下边界, 陆面对地气间的能量交换过程起到关键的调控作用 (Cohen and Rind, 1991; Walland and Simmonds, 1996; Matsui et al, 2003; Amenu et al, 2005; Orłowsky and Seneviratne, 2010; Gao et al, 2010; Williams et al, 2012)。土壤温/湿度能通过热通量影响地表温度, 进而通过调节地表感热通量及向上长波辐射影响陆面对大气的热力强迫 (Santanello et al, 2018)。因此, 陆面热力异常能对大气环流及气候状况产生十分重要的影响, 在某些区域或时段甚至起关键性作用 (Seneviratne et al, 2006; 2010; 李建平等, 2013)。全球变暖背景下, 陆面整体增暖幅度大于海表 (Sutton et al, 2007; Dong et al, 2009; Boer, 2011), 陆面热力异常时常伴随极端天气气候事件的发生 (Fischer et al, 2007; Schumacher et al, 2019; Zhang et al, 2019a; 2020); 从陆面热力异常的视角理解全球和区域气候变化问题已成为陆面过程研究的一个重要关注点 (Schubert et al, 2014; Chen, 2022)。

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近年来，西亚地区作为陆面增暖的热点区域引起了科学界的广泛关注（Giorgi, 2006; Hansen et al, 2010; Cohen, 2012; Zhou et al, 2015; 2016; Hong et al, 2017）。西亚位于亚洲西南部，其地形以高原、山地和沙漠为主，整体海拔较高，气候干燥；西亚陆面温度不仅呈现长期增暖趋势，还具有明显的年代际变化并伴有较强的年际变率（Hasanean and Almazroui, 2017; Ehsan et al, 2020; 图 1）。一方面，西亚陆面热力状况受大气环流变异、海温强迫、陆面反馈和人类活动等影响；另一方面，西亚陆面热力异常能通过热驱动环流影响周边气候，甚至通过大气遥相关影响下游气候。本文将回顾西亚陆面热力异常特征、成因及气候效应的研究进展（图 2），以为未来研究提供参考。



注：打点区域通过 0.05 显著性水平检验。

图 1 1951—2021 年西亚 (a) 地形 (单位: m), (b, c) 陆面温度 (ERA5) 的 (b) 线性趋势 (单位: $K \cdot year^{-1}$) 和 (c) 标准差 (单位: K)

Fig.1 Topography (m) (a), linear trend ($K \cdot year^{-1}$) (b) and standard deviation (K) (c) of land surface temperature over West Asia during 1951~2021 based on ERA5 data, in which dotted areas are statistically significant above the 95% confidence level.

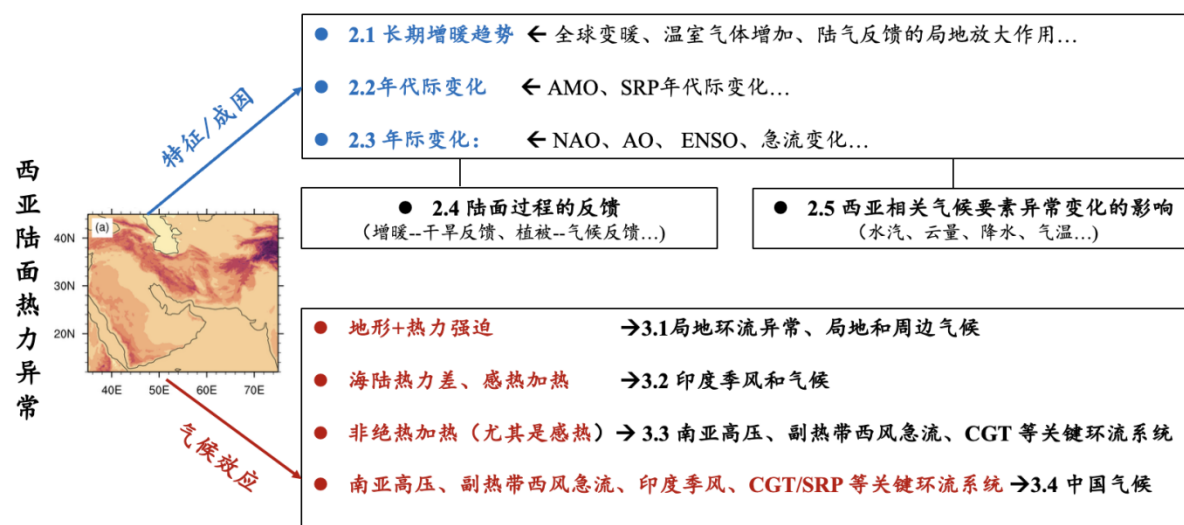


图 2 西亚陆面热力异常与成因及气候效应研究进展总结

Fig. 2 Summary of recent advance in research on West Asian land surface thermal anomalies together with its possible causes and climatic effects.

1 西亚陆面热力异常特征及成因研究

目前关于西亚陆面热力异常特征及成因研究，主要针对不同时间尺度上西亚陆面热力异常及相关要素的变化特征和成因进行了分析，并探讨了陆面反馈对西亚陆面热力异常的作用。

1.1 西亚陆面热力异常长期趋势及成因的研究

近几十年来西亚陆面增暖趋势显著，其中暖季较冷季增暖更强，最强的增暖季节为春季（Cohen et al, 2012; Alizadeh and Babaei, 2022）。根据以往研究，干燥的气候背景是西亚增暖突出的重要原因。Huang et al (2012) 发现，全球变暖背景下半干旱区的增暖趋势更强，这种现象可能是环流动力调整、海温异常、陆面过程和区域人类活动等多种因素共同作用的结果。Zhou et al (2015; 2016) 指出，全球中低纬度陆面温度随着植被增长减缓呈现急剧上升，尤其在阿拉伯半岛等沙漠地区的增暖率最强，西亚干旱地区存在明显的增暖放大效应。进一步分析表明，人类活动导致的温室气体排放有利于增强向下的长波辐射，使大气变得更潮湿和更暖，而干旱区气候对水汽变化极为敏感，因而出现更强的增暖，表明人类活动对西亚增暖的贡献不容忽视（Zhou et al, 2015; 2016）。

1.2 西亚陆面热力异常年代际变化特征及成因的研究

伴随着显著的增暖趋势，西亚陆面年代际增暖现象也十分明显（Hong et al, 2017; Sun et al, 2019a, b）。例如，1979—2009 年阿拉伯半岛增暖为 $0.6^{\circ}\text{C} \cdot (10 \text{ a}^{-1})$ ，夏季阿拉伯半岛地表气温在 20 世纪 80 年代出现显著的年代际增暖（Hasanean and Almazroui, 2017; Ehsan et al, 2020）。由于地理位置相近，不少学者发现夏季西亚和欧洲在 20 世纪 90 年代均出现年代际增暖，并将其作为一个整体来研究。Hong et al (2017) 指出，西亚—欧洲增暖受到大西洋多年代际振荡（Atlantic multidecadal oscillation, AMO）及丝绸之路遥相关模态（Silk Road pattern, SRP）年代际变化的调控。考虑到 AMO 周期大约为 65~80 a 且已在 20 世纪 90 年代中期转变为正位相，西亚—欧洲的年代际增暖将会持续。进一步，Sun et al (2019b) 采用大气数值模式进行集合试验，验证 AMO 正位相能激发类 SRP，导致西亚—欧洲上空出现异常反气旋性环流，增强暖平流和向下短波辐射，引起地表增暖。此外，Ehsan et al (2020) 通过分析观测和再分析数据，并利用耦合大气-海洋模式模拟发现，只要北大西洋持续异常增暖，西亚年代际增暖现象就将持续。Sun et al (2019a) 应用气候反馈-响应分析方法对导致西亚—欧洲年代际增暖的辐射和非辐射过程的贡献进行了定量诊断。结果表明，辐射过程是导致增暖的主要原因，包括云量、 CO_2 浓度和水汽含量的作用，其中最主要的驱动因素为云量；而地表感热、潜热和动力过程结合的非辐射过程贡献则相对较小。

1.3 西亚陆面热力异常年际变化特征及成因的研究

年际尺度上，西亚陆面温度呈现出较大的变率（Yang et al, 2021）。研究发现，在所有季节，西亚陆面温度深受热带海温变化的影响，且与厄尔尼诺-南方涛动（El Niño-Southern oscillation, ENSO）、北大西洋涛动（North Atlantic oscillation, NAO）和北极涛动（Arctic oscillation, AO）密切相关（Attada et al, 2019a）。一些研究还指出，西亚陆面温度异常通常伴随着由中亚传来的波列引发的位势高度异常（Saeed et al, 2011a; Watanabe and Yamazaki, 2014a），这种年际尺度上的遥相关可能与 ENSO 有关（Watanabe and Yamazaki, 2014b）。此外，夏季西亚陆面温度变化也与副热带西风急流的强度密切相关，副热带西风急流可以通过调控中纬度 Rossby 波列影响西亚地表温度（Attada et al, 2018）。近期，Song et al（2022）探究了春季西亚—欧洲陆面温度年际变化主模态与大尺度大气遥相关模态的关系，发现西亚陆面热力异常与 NAO 的变化密切相关，当 NAO 为负位相时，伴随西亚上空的异常反气旋性环流，地表的辐射加热有利于增暖。

1.4 陆面反馈在西亚陆面热力异常中的作用

近期，有研究从陆面过程对区域气候反馈的角度探讨了西亚陆面增暖的成因。例如，Barlow et al（2016）从植被反馈的角度出发，提出由于干旱加剧造成的植被减少可能对大气产生重要反馈，包括地表反照率变化导致的能量平衡反馈、蒸腾变化导致的水分收敛反馈、风蚀和扬尘效应等，并认为在变暖的气候中，西亚的植被反馈可能变得更加重要。Cook et al（2021）也发现了温室气体引起的西亚增暖放大现象，但将其主要归因于较干旱地区缺少潜热降温（蒸发冷却）的作用，强调了陆面水热状态对增暖的贡献，与 Zittis et al（2014）的观点一致。这些研究表明，西亚的干旱特征有利于陆面异常增暖，而陆面温度的异常升高往往对应降水的异常减少（Tanarhte et al, 2012），导致干旱进一步加剧（Barlow et al, 2002; Sobhani et al, 2020），形成增暖—干旱正反馈。

1.5 西亚陆面热力相关气候要素异常的成因研究

西亚陆面热力异常与该区域相关要素变化之间也存在紧密联系（Song et al, 2025），例如当地的水汽输送、降水和气温异常（Hasanean and Almazroui, 2017; Almazroui et al, 2012; Attada et al, 2018; Kostopoulou et al, 2014; Athar, 2015; Ehsan et al, 2019; Tuel et al, 2022）。除了之前提到的 NAO（Donat et al, 2014; Al Senafi and Anis, 2015; Saeed et al, 2023）、AMO（Sheffield and Wood, 2008; Ehsan et al, 2020）、急流（Attada et al, 2018; Niranjana et al, 2016; Rana et al, 2019）、ENSO（Chakraborty et al, 2006; Abid et al, 2018; Almazroui et al, 2019; Hoell et al, 2014; 2015; 2017; 2018）的影响，也有研究指出了遥相关模态（Feldstein and Dayan, 2008; Almazroui et al, 2019; Saeed et al, 2023）、印度洋偶极子（Indian Ocean dipole, IOD）（Chakraborty et al, 2006; Athar, 2015; Al Senafi and Anis, 2015）、青藏高原（Lu et al, 2018）、欧亚积雪（He et al, 2024）、南亚季风

(Tyrllis et al, 2013; Babaeian and Rezazadeh, 2018; Attada et al, 2019b) 和太平洋年代际变化 (Ma et al, 2023) 的显著作用。多项研究指出, 不同热带和副热带海区的海温异常可以通过协同调控水汽输送与大气环流结构, 对西亚陆面热力异常产生显著影响。Chakraborty et al (2006) 和 Hochman et al (2024) 指出, 当 El Niño 和 IOD 正位相事件同时发生时, 输送到阿拉伯半岛的大气净水汽通量更多, 进而造成降水偏多的异常响应。类似地, Syed et al (2006) 发现, 在 NAO 正位相和暖 ENSO 共同作用下, 冰岛低压东伸、西伯利亚高压减弱, 导致西亚上空形成异常低压槽, 有利于该地区冬季降水增多。此外, Hasanean and Almazroui (2017) 指出, 夏季热带北大西洋和热带南大西洋的海温变化会影响印太暖池的海温, 进而影响印度季风低压的强度, 最终造成阿拉伯半岛地表气温异常。

2 西亚陆面热力异常的气候效应研究

西亚陆面热力异常既受到大气环流变异的控制, 又能对大气环流和气候产生重要的反馈作用。近年来, 关于西亚陆面热力异常气候效应的研究逐渐增多, 学者重点探讨了其对局地及周边地区气候、印度季风活动、关键环流系统、大气遥相关以及中国气候的影响。

2.1 西亚陆面热力异常对局地和周边气候的影响

西亚包括伊朗高原、扎格罗斯山脉、阿拉伯高原和亚美尼亚高原等高海拔地区。高耸的地形能对大气产生机械强迫 (Simpson et al, 2015) 及隔热作用 (Boos and Kuang, 2010)。研究发现, 扎格罗斯山脉的阻挡和抬升作用有利于增强苏丹降水系统, 导致扎格罗斯的南坡、东南坡和陡坡出现强降水 (Kiani et al, 2019)。此外, 由于地形抬升引起的加热作用, 特定等压面在高原上往往比周围非抬升地形的温度更高 (Hu and Boos, 2017a; 2017b), 抬升的陆面热力异常也能对较高层大气产生直接的非绝热加热, 进而对局地环流和周围气候产生影响。Zaitchik et al (2007) 指出, 扎格罗斯山脉夏季地表异常加热会激发近地层热低压和上升运动, 抽吸伊朗高原西侧爬坡气流, 加强中东平原的地中海季风, 形成闭合的平原-高原环流, 导致中东平原的异常下沉气流、绝热增暖和降水减少。Gevorgya and Melkonyan (2015) 发现, 由于强的陆气温差, 艾美尼亚高原上空的大气比周围离地面较远的大气更容易受到地表加热的影响; 同时, 巨大的山脉阻挡了来自里海和黑海的偏东、偏北冷空气, 促使高原内部的绝热变暖和陆面加热。近年来陆面增暖有利于亚美尼亚高原上空热驱动环流进一步增强。而在人类活动导致的陆面过程对大气的热力强迫方面, Marcella and Eltahir (2012) 指出西亚地区人类灌溉和沙尘排放的准确表述对合理模拟当地气候十分重要。

2.2 西亚陆面热力异常对印度季风及印度次大陆气候的影响

西亚地区临近印度季风区, 西亚陆面热力异常能通过调节海陆热力差异影响印度季风及印度次大陆气候。观测分析和数值模拟均表明, 伊朗高原热力异常是驱动印度季风的关键强迫 (He et al, 2019; Zhang et al, 2019b; Hu et al, 2022), 其中感热加热为伊朗高原的重要加热形式, 春夏季为

主导加热。夏季伊朗高原地表感热加热能激发近地面气旋性环流，有利于增强来自阿拉伯海的西南水汽输送，导致巴基斯坦、印度北部及青藏高原西南坡降水增多，而阿拉伯半岛降水减少（Wu et al, 2012；刘屹岷等，2017）。值得注意的是，季风降水伴随的潜热释放也能进一步加热大气，表明潜热加热在伊朗高原对印度季风的热力调节过程中起到了重要的反馈作用。还有研究指出，夏季扎格罗斯山脉隆起的隔热作用也有利于印度季风的发展，扎格罗斯山脉的存在有利于青藏高原南部的对流层高层温度升高，进而驱动印度季风（Tang et al, 2013）。此外，季风爆发前阿拉伯半岛陆面感热加热对印度季风爆发的作用也不容忽视（张亚妮等，2013）。根据热力适应定理（刘屹岷等，1999；吴国雄和刘屹岷，2000），阿拉伯半岛感热加热强迫对流层低层出现气旋性环流而中层出现反气旋性环流，促使阿拉伯海上空的副热带高压西撤至阿拉伯半岛上空，位涡纬向非对称不稳定逐渐发展，有助于形成印度季风爆发涡旋。

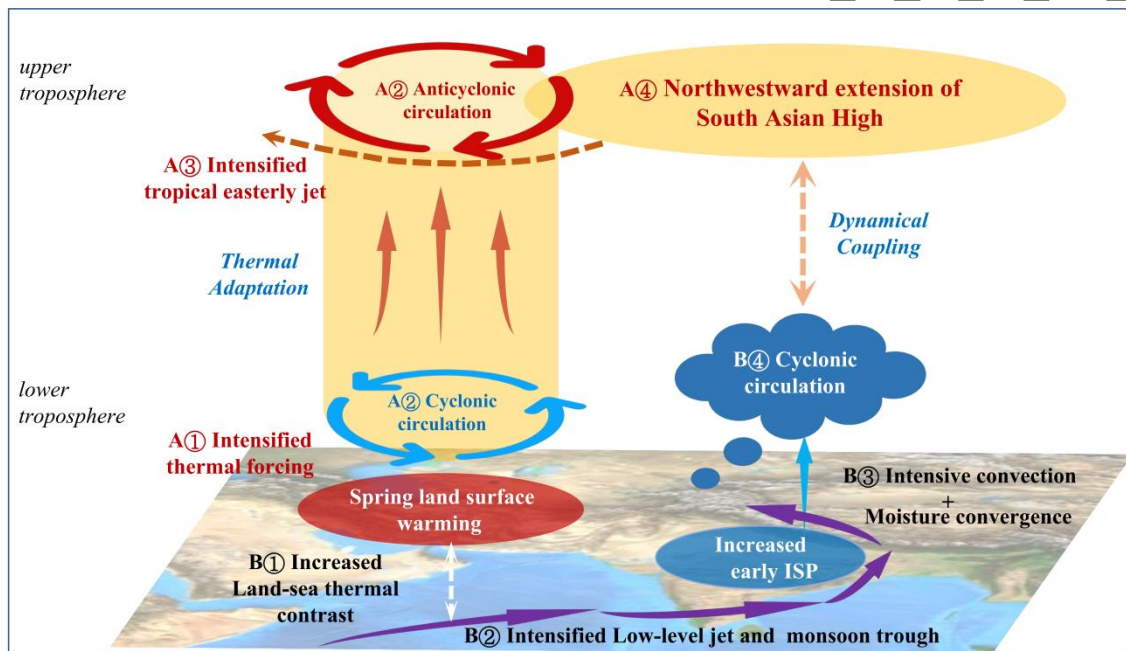


图 3 西亚春季陆面热力异常影响印度初夏季风降水物理机制示意。（引自 Yang and Chen, 2022）

Fig. 3 Schematic diagram of mechanisms via which anomalous spring land surface warming over West Asia affects early summer Indian monsoon precipitation. (cited from Yang and Chen, 2022)

最近，越来越多研究关注前期春季西亚陆面热力异常对印度季风降水的影响。观测表明，春季西亚地区正以每十年 $0.5\text{ }^{\circ}\text{C}$ 的速度升温，西亚增暖能促使低空急流不断北移，造成巴基斯坦等印度季风边缘区的夏季降水增多，洪涝风险随之增加（Li et al, 2023）。此外，西亚增暖也有利于增强季风槽及印度北部的水汽辐合和上升运动，并能激发对流层高层反气旋性异常环流，有利于热带东风急流增强和南亚高压西伸北进；初夏，印度北部上空增强的南亚高压与中低层气旋性异常环流动力耦合，降水随之偏多（Yang and Chen, 2022）。

2.3 西亚陆面热力异常对关键环流系统和大气遥相关的影响

伊朗高原上空的副热带高压是西亚对流层中高层夏季环流的主要特征之一，简称伊朗高压（Zarrin et al, 2010）。研究指出，扎格罗斯山脉对伊朗高压的形成和维持起重要作用，如若将其去除，非绝热加热的大小和空间分布显著变化，垂直平流和对流层中层的反气旋均明显减弱，伊朗高压消失于伊朗西部（Zarrin et al, 2011）。同样受大地形的动力和热力作用，夏季南亚高压根据中心位置的不同，分为青藏高原型和伊朗高压型两个平衡态，西亚陆面热力异常对南亚高压的形态和强度也有着显著影响（Zhang et al, 2002; Shi and Qian, 2016）。伴随南亚高压趋向于伊朗高原，印度夏季风降水也随之增多（Wei et al, 2014; 2015）。对于前期陆面热力信号的作用，Zhang et al (2019b) 发现，初夏南亚高压的位置受到春末伊朗高原地表感热异常的强烈影响，当春末伊朗高原感热偏强时，春末—初夏印度北部对流层低层出现异常气旋，伴随大气上升运动和水汽辐合，导致印度北部潜热释放增强，对流层高层视热源垂直梯度减小，初夏南亚高压向西北方向移动。

西亚对流层高空存在副热带西风急流。西亚急流的南北位置与急流波导（Hoskins and Ambrizzi, 1993）的 Rossby 波活动均能影响下游大气环流和气候。研究发现，夏季地中海和北大西洋—斯堪的纳维亚半岛对流层高层的负涡度源区和 E-P 通量强辐散区为 Rossby 波源区，波源区的位置和强度变化会引起其激发的沿西亚急流东传的 Rossby 波活动异常。当西亚急流位置偏南时，其中的 Rossby 波活动偏弱（杨莲梅和张庆云，2008）。而偏南的西亚急流有利于沿青藏高原南麓穿过印度次大陆的异常西南暖湿气流从低纬度进入中亚和新疆北部，促进当地降水（Zhao et al, 2014）。此外，西亚上空的异常波动也能被急流捕获进而传播到下游。近期研究表明，西亚北部的陆面热力异常能在西亚西北部强迫出异常高压和由沿急流东传的波列，且这种高层环流响应应具有明显的位相锁定；而伊朗高原地形导致的局地基本气流的纬向变化是维持西亚北部位相锁定的一个重要原因（Wang et al, 2019）。

大气环流遥相关是空间上相距较远的区域环流之间存在显著时间相关性的现象，其形成与外强迫激发的 Rossby 波密切相关（Hoskins and Karoly, 1981; Simmons et al, 1983; Li and Ji, 1997）。Ding and Wang (2005) 提出的北半球夏季环球遥相关（circumglobal teleconnection, CGT）作为一种典型的大气环流遥相关模态，是以西亚（35°~40°N、60°~70°E）为参考区域计算所得北半球夏季 200 hPa 位势高度的单点相关。CGT 呈现环球定常纬向 5 波分布，包括位于西亚、东亚、北太平洋、北美、西欧和欧洲俄罗斯上空的 6 个显著波活动中心。研究指出，CGT 呈现多尺度分布，沿北非—亚洲急流分布的 SRP（Lu et al, 2002; Enomoto et al, 2003; Enomoto, 2004）可以被看作 CGT 的区域性表现（Krishnan and Sugi, 2001; Yasui and Watanabe, 2010; Zhou et al, 2019）。根据定义，CGT 与西亚地区的大气低频环流密切相关。已有研究证明，这个波包起源于西亚，进而沿西风急流向东传播（Enomoto et al, 2003; Enomoto, 2004; Sato and Takahashi, 2006; Chen and Huang, 2012），即西亚的非绝热加热有助于 CGT 形成（Enomoto et al, 2003; Saeed et al, 2011b）。例如，Saeed et al (2011b) 发现，西亚上空降水/对流增强引起的低层热低压增强，可激发出类 CGT 模态，延伸至

亚洲季风区。此外,不少研究还指出,印度夏季风加热有利于在其西北部形成 Gill 型 Rossby 波(Gill, 1980),认为 CGT 可能是中纬度西风带对印度季风热源响应的结果(Ding and Wang, 2005; Chen and Huang, 2012; Lin, 2009; Wang et al, 2012; Lee and Ha, 2015; Dutta and Neena, 2022)。从陆面热力直接强迫出发,有分析发现春季西亚陆面热力异常可能通过影响初夏 CGT 进而影响中国东北冷涡活动,西亚陆面异常增暖往往对应东北冷涡活动偏弱,表明西亚的陆面热力状况作为下垫面条件对 CGT 的形成和维持具有潜在贡献(王迪等, 2018)。最新研究证实,西亚陆面热力反馈是导致 20 世纪 90 年代以来初夏 CGT 显著增强的重要驱动力(Banerjee et al, 2025)。针对西亚和印度地区的非绝热加热对 CGT 的相对贡献问题, Yasui and Watanabe (2010) 应用简单线性大气模式进行数值试验发现,对稳定 CGT 响应贡献最大的同期非绝热加热关键区位于西亚,并认为西亚的非绝热加热可能与 CGT 相耦合,而印度地区非绝热加热的作用相对较弱。

2.4 西亚陆面热力异常对中国气候的影响研究

西亚陆面热力异常导致的南亚高压位置及强度变化不仅影响印度夏季风,也会影响东亚夏季风(Sun et al, 2010),进而对中国降水 and 气温产生影响(张琼和吴国雄, 2001; 钱永甫等, 2002; Wei et al, 2014; 2015; Ren et al, 2015)。一方面,伴随南亚高压的增强和东伸,西太平洋副热带高压加强并西进,进而影响中国降水(Jiang et al, 2011; Guan et al, 2018; Wei et al, 2019a)。另一方面,受西亚陆面热力调控的印度夏季风进程和强弱的变化能够影响向东亚传输的水汽,引起降水异常变化(Zhang, 2001; Liu and Huang, 2019)。同时,印度季风潜热加热也能通过调节南亚高压的活动进一步影响中国降水(Wei et al, 2014; 2019b)。此外,对于中国西北的非季风区,伊朗高原的感热加热、南亚高压的强度及位置变化也可以通过调节大尺度环流和水汽输送影响中国西北的降水和气温(杨莲梅, 2003; 王前等, 2017; 赵勇等, 2018, 陈佳毅和赵勇, 2023)。

此外, CGT/SRP 通过将印度季风和东亚夏季风连接起来(Ding and Wang, 2005; Lu et al, 2002; Enomoto et al, 2003; Lee et al, 2011; Wu et al, 2016; Liu and Huang, 2019; Dutta and Neena, 2022),进而影响中国气候(Hsu and Lin, 2007; Huang et al, 2011; Kosaka et al, 2011; Wang and He, 2015; 林大伟等, 2016; Bueh et al, 2016; Zhang et al, 2019c; Na and Lu, 2023)。同时,与西亚陆面热力异常密切相关的南亚高压变化也能引起与 CGT 具有较高时空相似性的遥相关模态,进而影响东亚夏季风降水;东亚夏季风降水产生的非绝热加热反馈对 CGT 的维持也有重要作用(Zhou et al, 2020),说明西亚热力异常引起的季风降水潜热反馈不容忽视。着眼于西亚热力异常对 CGT 的直接强迫作用,研究发现,西亚春季陆面热力异常不仅能导致初夏 CGT 异常和中国北方环流异常,还能对当地降水和气温产生影响。西亚异常增暖通过加热上空大气引起斜压不稳定,触发沿西风急流向东传播的 Rossby 波,形成环北半球的低频波列。从春季到初夏,由于陆面热力强迫的作用和基本气流与异常波列的相互作用,异常波列逐渐增强和演变,在初夏呈现类似 CGT 的分布,增强的 CGT 位于东亚的波活动中心影响中国北方的环流及气候(陈海山等, 2018; Yang et al, 2021)。从年代际变化的角度深入分析发现,1990 年之后西亚春季陆面热力异常与初夏 CGT 及东北降水的关系明显加强,

这种变化可能与西风急流的年代际转变有关（Sun et al, 2024）。最新研究还发现，2022 年盛夏长江流域破纪录的高温热浪也与前期西亚非绝热加热密不可分，巴基斯坦地区降水偏多引起的异常加热可以通过增强 CGT 引起南亚高压东伸，有利于长江流域高温的持续（Tang et al, 2023; Fu et al, 2024）。上述研究表明，近年来西亚陆面热力异常对我国气候的影响日益显著，加强对这一地区的监测与研究将有助于提高对我国气候预测水平。

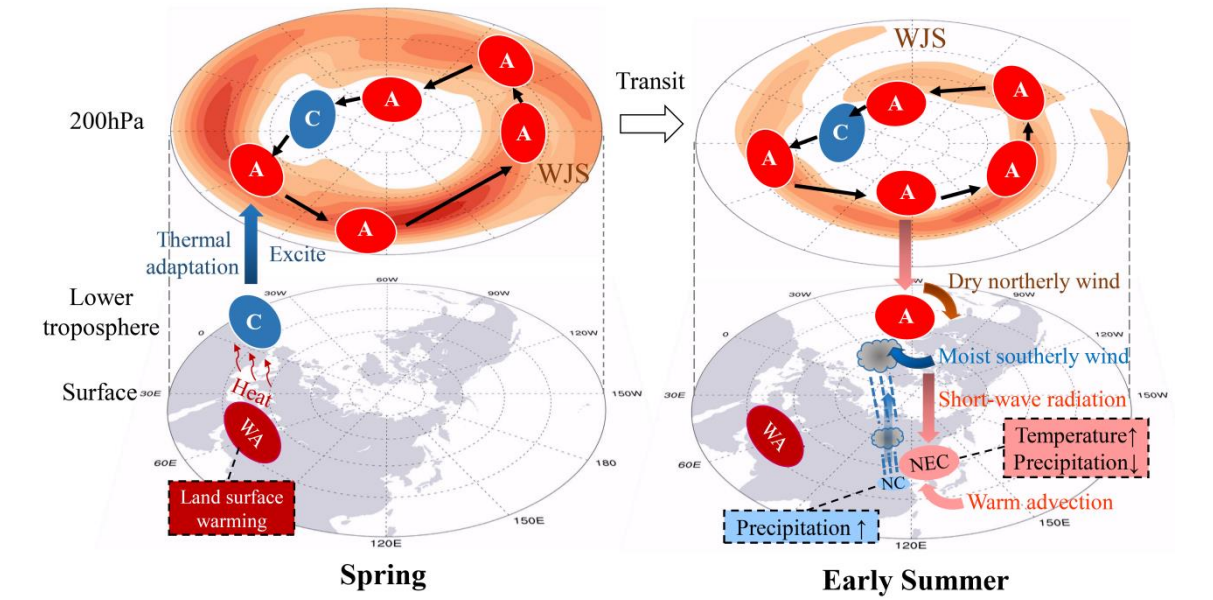


图 4 西亚春季陆面热力异常影响我国北方初夏气候物理机制示意（引自 Yang et al, 2021）
Fig. 4 Schematic diagram on mechanisms in which spring land surface warming over West Asia affects early summer climate over northern China. The WA, NC and NEC represent the locations of West Asia, North China and Northeast China. The A and C in the circle represent the anticyclonic and cyclonic circulation anomalies. The thick arrows represent the wind directions and the thin arrows in 200hPa show the directions of Rossby wave propagation. The filled contour areas in 200hPa show westerly jet streams (WJS, dark/light color corresponds to strong/weak WJS). (cited from Yang et al, 2021)

3 总结与展望

本文回顾了全球变暖背景下西亚地区陆面热力异常的特征、成因及气候效应的研究进展。从地理位置来看，西亚地区是连接亚—欧—非三大洲的枢纽地带，关注西亚热力异常现象和前兆信号以及对大气的反馈影响，有助于进一步理解和应对气候变化。从气候背景来看，西亚属于半干旱—干旱气候区，在增暖的大前提下，较干旱的区域更缺乏潜热降温的作用，并对由增暖导致的水汽变化较敏感，因而存在增暖放大效应。同时，由于西亚的平均海拔较高，包括伊朗高原、扎格罗斯山脉等高海拔地区，高地形的隔热效应有利于内部绝热增温，而抬升的陆面增暖又能够直接加热较高层大气，进而影响周围环流，甚至通过遥相关影响下游气候。因此，探究西亚陆面热力异常的成因和气候效应具有重要的现实意义和科学价值。

然而，由于观测资料的缺乏，此前研究通常选用再分析的土壤温度、地表温度、感热通量或距地 2 m 气温等变量来表征西亚陆面热力状况，但这些变量具有不同的物理意义，不同再分析资料之间也存在系统性差异。未来研究可以加强基于多源数据对不同时段的西亚热力异常特征进行多角度对比分析，并明确其物理内涵，将有利于更全面认识西亚陆面热力异常的基本特征。从现有的研究来看，这个区域的热力异常主要通过非绝热加热来影响大气环流进而对气候产生影响。对于干旱区而言，非绝热加热的重要分量是地表感热加热，加强相关地表通量观测并结合多源资料分析将有助于深入理解其气候效应。此外，西亚陆面热力异常存在明显的季节差异，虽然相较于冷季，西亚地区暖季的增暖趋势更为显著，目前的研究也大多关注暖季的增暖现象，但西亚冷季热力异常的现象和特征也值得深入探究。

此外，尽管已有不少研究关注了西亚热力异常的成因和气候效应，但仍需从海-陆-气耦合的角度深入理解西亚热力异常在气候系统中的作用。一方面，目前对于西亚热力异常的多尺度变异机理缺乏深刻理解，以往研究主要强调了人类活动和 AMO 大尺度信号对西亚陆面增暖趋势的影响，对其年际和年代际变化的关注还不够，相关机制尚不明晰。但是，深入理解其年际和年代际变化机理，对于短期气候预测至关重要。比如，海温、海冰外强迫通过动力、热力过程影响西亚陆面热力异常的物理机制是什么？局地陆气相互作用在西亚陆面热力异常年际、年代际变化中起什么作用？还有待进一步探究。另一方面，目前对于西亚热力异常的气候效应仍缺乏系统性认识。此前研究强调了印度季风及降水的显著响应，但主要从季节预测的角度进行分析，对于受西亚前期陆面热力异常影响的季风爆发和发展具体过程仍未得到充分研究。

还值得注意的是，由于印度季风与南海季风、东亚季风存在密切的关联，西亚陆面热力异常是否与南海和东亚季风存在关联也有待深入研究。西亚地区靠近第三极，全球变暖背景下大地形的热力异常协同影响季风环流的机制也值得进一步探究。在西亚热力异常激发热驱动环流和低频波列，进而影响中国北方环流和气候的过程中，强迫波与基本气流之间的相互作用对 CGT 的影响仍需深入研究。此外，作为西亚热力异常-中国北方气候遥相关中的关键过程，印度季风降水加热在遥相关中起到怎样的作用，值得深入研究，以进一步加深对中国北方气候变异的理 解，助力提升降水和气温的预测水平。

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Research Progress on Causes and Climatic Effects of West Asia

Land Surface Thermal Anomalies

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Abstract: Under the background of global warming, West Asia has emerged as a prominent hotspot of land surface warming. Observational records reveal significant long-term warming trends in land surface temperature (LST) over this region, accompanied by notable decadal shifts and substantial interannual variability. Understanding the basic features, drivers and climatic effect of land surface thermal anomalies over West Asia is of great practical significance for addressing climate change challenges. This review synthesizes recent studies on land surface thermal anomalies over West Asia, beginning with observational evidence and examining the associated atmospheric circulation variations and external forcings. It further explores the impacts of these thermal anomalies on regional climate, Indian monsoon and climate, large-scale circulation systems and atmospheric teleconnection patterns, and climate anomalies in China. Nevertheless, the complex topography and high spatiotemporal heterogeneity of land surface thermal conditions over West Asia necessitate further investigation. Critical research gaps including identifying the dominant causes of LST anomalies, elucidating the mechanisms of local land-atmosphere interactions. Advancing the understanding of global and regional climate change through the lens of land surface thermal anomalies will strengthen the scientific foundation for reliable climate prediction.

Keywords: West Asia, land surface thermal anomalies, land-atmosphere interaction, physical causes, climatic effects.