中国高温、干旱及其复合事件的研究进展和展望

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摘要 干旱是全球最主要、影响最严重的气象灾害之一。随着全球变暖,干旱更易与高温同时发生,干旱与高温的正反馈过程导致极端事件持续更久、强度更强,形成高温干旱复合极端事件,对农业、生态环境等造成更为严重的影响。本文通过对中国高温、干旱及其复合事件研究进展的回顾,总结了中国高温、干旱及其复合事件的变化事实,并对影响中国高温、干旱的关键因子及物理机制进行了梳理;指出了当前研究存在的不足,并提出系统研究海温-陆面-海冰-大气多因子、多过程协同影响中国复合高温干旱事件的必要性;最后,对当前高温干旱的预测现状进行了简要回顾,指出在系统认识复合高温干旱事件发生发展机制的基础上,亟须发展动力-统计相结合的方法,以提升其预测水平。

关键词
热浪;
干旱;
极端事件;
复合高温干旱事件;
复合事件

地球分为湿润区、半湿润区、干旱区和半干旱区。干旱区和半干旱区长期处于年平均降水小于蒸散发的动态平衡,而湿润区和半湿润区则相反。作为全球最主要、影响最严重的气象灾害,干旱事件在上述任何地区都可能发生,同时也是中国频发的主要气象灾害之一。据统计,在中国,平均每年干旱致灾面积超过 2 000 万 hm^2,占农作物受灾面积一半以上,约占耕地总面积的 1/6(黄荣辉和杜振彩,2010;陈方藻等,2011;张强等,2015)。过去几十年,中国干旱频次和强度均发生了显著变化,对社会经济、区域水资源安全、生态环境等造成了深远影响。如 2022 年夏季,中国南方出现了历史罕见的持续性大范围干旱,长江流域的干旱为有完整监测资料以来最严重,全国共有 5 245.2 万人次受灾,农作物受灾面积达 609 万 hm^2,造成直接经济损失 512.8 亿元(数据来自应急管理部网站 https://www.mem.gov.cn/xw/yjglbgzdt/202301/t20230113_440478.shtml)。

高温热浪一般指较大范围的持续异常热天气气候事件。世界气象组织(WMO)指出,高温热浪会加剧健康风险和经济风险,导致人类死亡率、干旱和水质问题、野火、电力短缺及农业损失增加(https://wmo.int/topics/heatwave)。随着全球变暖,高温热浪频次增多、强度增强,对人类生存环境及人体健康的威胁加剧。2000—2019 年,高温热浪导致全球范围内平均每年约 489 000 人死亡(Zhao et al.,2021)。世界卫生组织(WHO)指出,在 2003 年欧洲热浪期间有超过 70 000 人死亡(https://www.who.int/health-topics/heatwaves/)。Yan et al.(2022)的研究显示,超过 17 000 例死亡与 2017 年中国夏季热浪有关。

在全球变化背景下,高温热浪易更易与干旱同时或相继发生,形成高温干旱复合极端事件,从而对农业、生态环境等造成更为严重的影响。干旱发生时,降水持续偏少,土壤偏干,而当高温与干旱同时

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Zhu Y L,Liu Y,Kong X H,et al.,2025.Research progress and prospect on the drought,heatwave,and compound drought and heatwave events in China[J].Trans Atmos Sci,48(1):26-36.DOI:10.13878/j.cnki.dqkxxb.20240911002.(in Chinese).

或相继发生时,土壤蒸发更快,植被水分流失加剧,局地可蒸散水分加速减少,气温偏高和降水偏少之间的正反馈会使得灾害更加严重(图 1;Hao et al.,2022)。此外,高温干旱共同作用使得虫害多发(Williams et al.,2010)、植被健康受损(Ciais et al.,2005),易导致树木死亡(Allen et al.,2010)以及森林野火灾害(Flannigan et al.,2009)。随着高温和干旱发生频次的增加(Chen and Sun,2017;Chen et al.,2020),在全球范围内二者同时或相继发生的概率在增加,对粮食安全、生态系统、社会经济等带来比单一高温或干旱更为严重的影响。在中国,近些年造成严重影响的极端干旱,有不少是复合高温干旱事件。如:2013 年 7 月上旬—8 月下旬,中国南方大部分地区出现破纪录的持续高温,其中多地同时发生中到重度干旱,给当地农业、生态和经济造成巨大损失(王文等,2017)。自气象灾害应急预案制定以来,中国气象局首次启动高温应急响应。2016 年夏季中国东北发生严重高温干旱事件,造成经济损失达 156 亿元(Li et al.,2018)。

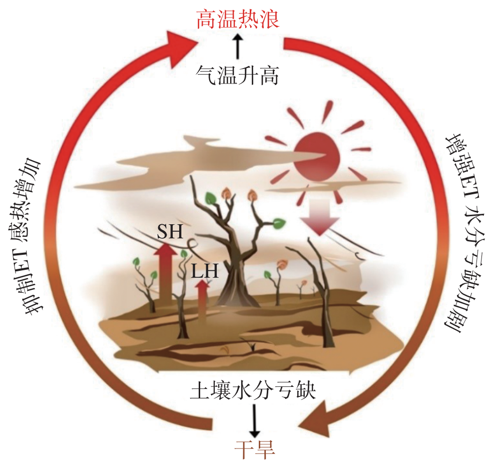

图 1　复合高温干旱事件中高温和干旱正反馈过程示意图(SH、LH、ET 分别代表感热、潜热和蒸散发)(改自 Hao et al.(2022))

Fig.1　Schematic diagram of the positive feedback loop between high temperature and soil moisture deficit during compound dry and hot events. SH, LH, and ET denote sensible heat, latent heat and evapotranspiration, respectively. Adapted from Hao et al.(2022)

1　高温干旱事件的定义和识别

根据研究角度的不同,干旱主要分为气象、水文和农业-生态干旱(周波涛和钱进,2021;王晨鹏等,2022;IPCC,2023),它们相互联系又有所区别。大部分干旱开始于降水的持续亏缺,表现为气象干旱;随着气象干旱状况持续,土壤湿度、径流量和地下水以及湖泊河流和水库等的陆地水储量异常偏少,导致水文干旱;随着大气蒸发需求增加,土壤变干,植物水分胁迫增加,导致农作物发育迟缓及减产、生态系统发育受阻及生产力下降等,进而引起农业-生态干旱(Van Loon et al.,2012;Apurv et al.,2017;袁星等,2020)。气象干旱是所有干旱事件的初期表现,而水文干旱和农业-生态干旱是气象干旱在水文系统和农业-生态系统中进一步发展加剧的现象。

气象干旱主要研究不同尺度干旱的变化特征和物理机制。常用的气象干旱指数很多,包括 PDSI(帕尔默干旱指数,Palmer drought severity index;Palmer,1965)、SPI(标准化降水指数,standardized precipitation index;McKee et al.,1993),以及后来考虑了蒸散发的 SPEI(标准化降水蒸散发指数,standardized precipitation evapotranspiration index;Vicente-Serrano et al.,2010)等。PDSI、SPI 和 SPEI 都可以通过计算其在不同时间尺度上的值来描述干旱状况。而由于考虑了降水和蒸散发的共同影响,SPEI 通常被认为可以更全面地反映干旱。由于土壤湿度可以直接影响农作物和生态系统的生长发育,农业-生态干旱常用 SMQ(土壤湿度分位数,soil moisture quantile;Sheffield et al.,2004;Wang et al.,2011,2018)作为干旱指数。水文干旱则利用水文变量来识别干旱,常用指数有 SRI(标准化径流指数,standardized runoff index;Shukla and Wood,2008)、SSI(标准化流量指数,standardized streamflow index;Vicente-Serrano et al.,2012;Yuan et al.,2017)等。

对于高温事件,也有多种不同的定义。一般根据温度阈值(如绝对温度或温度序列的分位数)来识别,所用变量有日最高气温、日最低气温等(Alexander et al.,2006;Barriopedro et al.,2023)。IPCC 第六次评估报告将热浪定义为连续两天至数月超过某一相对温度阈值的异常热事件(IPCC,2023)。对于不同地区而言,判断高温事件的阈值往往存在明显差异。此外,还有一些研究利用累积日平均气温或累积日最高气温定义高温事件的强度(Perkins and Alexander,2013;Russo et al.,2015)。

识别复合高温干旱事件通常有两种方法,一是在分别对高温和干旱事件判定后寻找其交集(Hao et al.,2022);二是通过定义新的复合高温干旱指数进行判定(Hao et al.,2018a;Feng et al.,2020)。相较而言,第一种方法更直观易懂。但由于高温和干旱的判定标准本身就不单一,在对复合高温干旱事

件进行判定时有更多不同的组合标准，所以识别的复合高温干旱事件可能会随判定标准的不同而发生变化（Yu and Zhai，2020a；Tian et al.，2021）。第二种做法一般用降水和温度的组合来定义新的指数，如利用降水和温度的边缘累积密度分布构建标准化干热指数（Hao et al.，2018a）。

2　中国高温和干旱的变化与机制研究

近几十年来，我国大部分地区极端高温频次增多、强度增强，持续时间也明显增加（Wei and Chen，2011；Wang and Fu，2013）。干旱变化与高温有所不同，有着明显的区域特征（秦大河，2015；Zhang and Zhou，2015；Shi et al.，2018）。20世纪60年代以来，华北和西南的干旱更加严重，西北地区则因降水增加而有所缓解（Li et al.，2014；马柱国等，2018；张强等，2020）。20世纪90年代后期以来，中国东部（尤其是东北）干旱发生频次增多、强度增强（邹旭恺等，2010；Yu et al.，2014；Zhang et al.，2019）。

目前，关于中国高温和干旱变化的影响机制已取得了一些认识。高温或干旱区上空往往会伴随显著的反气旋性环流异常（卫捷和孙建华，2007；Chen and Lu，2015；王文等，2017）。除局地环流因素的直接影响外，大尺度环流模态异常也可通过影响区域环流，进而诱发高温或干旱事件的发生。如通过沿急流传播的丝绸之路遥相关或环球遥相关，北大西洋涛动可以为华北高温事件（Sun，2012；Hong et al.，2017；王文等，2017）以及华北干旱（Du et al.，2020）提供有利的环流背景。此外，除了大气环流的直接调控，海温、海冰和陆面过程均可通过调整大尺度环流影响区域系统，进而影响高温或干旱事件的发生。

中国的高温和干旱与全球多个海温模态存在显著联系（Li C X et al.，2020；Wei et al.，2020）。厄尔尼诺-南方涛动（ENSO）可以调控中国东部高温的年际变化（Zhou et al.，2014；Chen and Zhou，2018；Luo and Lau，2019）。在厄尔尼诺衰减年的夏季，海气相互作用使得西北太平洋副热带高压增强，导致中国江南和西南地区被异常反气旋控制，有利于高温热浪的发生（Hu et al.，2013；马双梅等，2021）。2019年8—10月中国东部发生的严重干旱也是由热带中东太平洋偏暖所致（Ma et al.，2020）。太平洋年代际振荡通过调控东亚地区的大气环流（杨修群等，2004；马柱国和邵丽娟，2006；Zhu et al.，2011，2015），进而影响华北干旱的年代际变化。大西洋海温异常可以激发向下游传播的Rossby波，对江南高温（Sun，2014）、中国北方干旱（Han et al.，2019；Wang et al.，2019）、西南干旱（Feng et al.，2014；Yuan et al.，2022）等产生显著影响。大西洋多年代际振荡可以显著调制中国东北干旱的发生频次（Qian et al.，2014；Hu et al.，2021；Yue et al.，2021），并通过调整年代际气温（Hong et al.，2017；Sun et al.，2019）影响中国高温热浪强度和频次（Li H X et al.，2020）的年代际变化。印度洋海盆一致增暖可以激发东传的开尔文波，有利于华南地区反气旋性环流异常的形成和增强，进而使中国南方极端热事件增多、持续时间增长（Hu et al.，2012；Liu et al.，2015；曾刚和高琳慧，2017）。

北极海冰异常也可以显著调节北半球中高纬度大气环流和行星波活动，进而对中纬度的极端气候产生影响（Cohen et al.，2014；Tang et al.，2014；Coumou et al.，2018）。北极海冰减少可以激发往东南方向传播的罗斯贝波，造成夏季中国西南出现异常反气旋，导致高温热浪发生（Wu and Francis，2019；Deng et al.，2020）。冬春季北极海冰减少可以通过欧亚遥相关型影响贝加尔湖高压，使得中国东北上空出现异常反气旋并盛行下沉运动，有利于干旱事件的发生（Wang and He，2015；Li et al.，2018；Du et al.，2022）。

北极地区某些关键区域海冰对中国高温干旱具有重要影响。春季巴伦支海海冰的减少可激发欧亚波列，在西南地区引发异常反气旋，导致热浪发生（Deng et al.，2020）。夏季巴伦支海海冰异常偏多的情况可持续到秋季，并引发西南地区的干旱，这种联系在20世纪90年代后期尤为显著（宦杜斌等，2022）。中国东北地区的干旱状况在20世纪90年代中期后加剧，可能与春季巴伦支海海冰变化有关（Li et al.，2018，2022；Du et al.，2022；Hu et al.，2023）。春季巴伦支海海冰减少可能通过陆气相互作用和北极-欧亚环流型异常加剧我国东北夏季高温干旱（Li et al.，2018；Du et al.，2022）。除了巴伦支海海冰的影响外，其他区域（如白令海和喀拉-拉普捷夫海）的海冰异常也可通过调整大尺度环流来影响中国东部的干旱（Liu et al.，2020，2023）。前期格陵兰海海冰异常可以通过遥相关波列对西北地区春夏季高温干旱产生影响（王岱等，2021；Liu and Chen，2024）。

陆气相互作用对高温和干旱事件的形成和发展也有重要影响（张井勇和吴凌云，2011；Wang and

Dickinson,2012;管晓丹等,2018)。局地陆气反馈使得土壤干燥度增加,大气中的热量累积,从而触发高温热浪的发生或使其增强(Miralles et al.,2014;Seo and Ha,2022)。除局地陆气反馈外,其他关键区的陆气相互作用也可以通过激发大气遥相关波列引起高温或干旱的发生,如:欧亚大陆春季土壤湿度异常能显著影响华北夏季高温(Liu et al.,2014;Zhang et al.,2015);中亚 5 月土壤温度偏高预示东北夏季高温日数偏多(Yang et al.,2024);青藏高原春季土壤温度偏低可导致下游夏季长江流域出现严重干旱(Xue et al.,2018);前期春季上游贝加尔湖南部地区土壤偏湿对 2017 年东北地区的春夏连旱事件有显著影响(Zeng and Yuan,2021)。此外,前期欧亚大陆积雪异常也可通过改变陆表反照率调整大气环流,进而影响东北夏季高温干旱事件的发生(Li et al.,2018)。

除了气候系统内部变率调控外,人类活动对极端气候的影响也日益凸显。工业革命以来的人类活动已经导致大气、海洋和陆地变暖这一结论是毋庸置疑的,人类活动引起的温室气体排放是观测到的全球(几乎确定)和大部分陆地(很可能)极端温度事件变化、陆地强降水增强的主要驱动因子(IPCC,2023)。在区域极端事件的变化中也能检测到人类活动信号。如:过去几十年亚洲中高纬极端强降水增加(Dong et al.,2020)、2012—2014 年加利福尼亚的异常干旱(Williams et al.,2015)、2014 年欧洲高温热浪(Uhe et al.,2016)、非洲东部近年来干旱的加剧(Hoell et al.,2017)等均与人类活动密切相关。在中国,过去几十年极端高温事件的增多增强也可检测到人类活动的影响(Sun et al.,2014;Lu et al.,2016;Ma et al.,2017;Yin et al.,2017;Wang et al.,2018;Chen et al.,2019)。另外也有研究指出,近几十年中国区域干旱发生频次增加、强度增强,人类活动在其中可能起到了重要作用(Chen and Sun,2017;Wang and Yuan,2021)。

3 结论与讨论

综上所述,海洋、海冰、陆面要素异常均可通过复杂的大气动力学过程影响大尺度和区域环流,调制中国高温和干旱事件的发生发展,且在高温和干

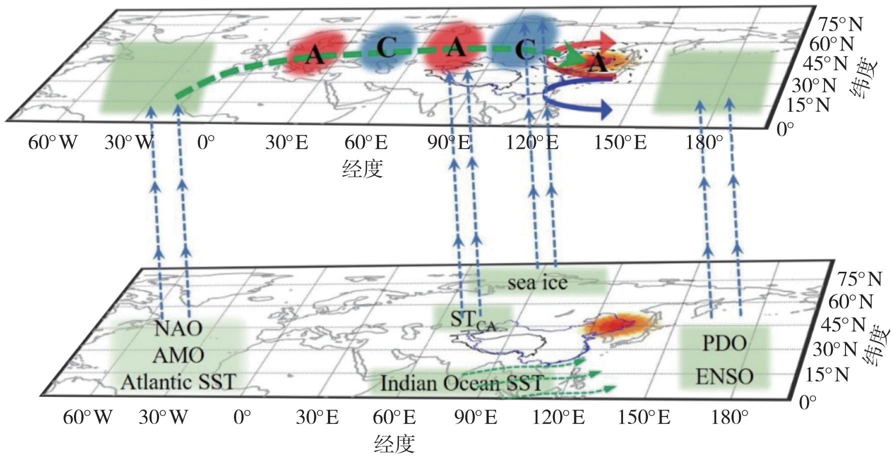

图 2 海-陆-冰-气协同影响中国东北高温、干旱的物理机制示意图(下层所示为海-陆-冰关键区,上层所示为对流层上层的环流异常,两层之间蓝色虚线箭头表示海-陆-冰关键区异常对上层环流的影响;浅绿色阴影区代表关键区异常信号,蓝色和红色弧形箭头表示影响东北地区的异常环流;下层绿色细虚线箭头表示来自印度洋的水汽输送,上层绿色粗虚线箭头表示波列传播路径;"A"和"C"分别代表反气旋性和气旋性环流异常,"ST_{CA}"代表中亚地区土壤温度)

Fig.2 Schematic diagram illustrating the physical mechanisms underlying the synergistic influence of sea-land-ice-air systems on the dry/hot events in Northeast China.The bottom map shows key regions of the sea-land-ice systems that significantly impact Northeast China,while the top map depicts the atmospheric circulation anomalies in the upper troposphere modulating the climate in Northeast China.Blue dashed arrows between the two maps represent the influence of regional sea-land-ice anomalies on upper-level circulations.Light green shadings indicate anomalies in key regions.Blue and red curved arrows show anomalous circulations that influence Northeast China.Dashed thin green arrows in the bottom map represent water vapor transport from the Indian Ocean.The dashed thick green arrow in the top map show the propagation path of the wave train from the upstream."A" and "C" denote anticyclonic and cyclonic anomalous,respectively.ST_{CA} represents soil temperature in Central Asia

旱事件的变化中可检测到人类活动的影响。但是当前的机制研究多从海气、陆气、冰气相互作用之中的某一方面展开。而事实上,极端事件的发生,往往受到多圈层、多因子的共同调制,影响机制极其复杂,研究单一因素的影响对全面理解极端事件的变化机制有很大的局限性。如 2022 年盛夏中国南方出现的严重高温干旱复合事件,除了受到西太平洋副热带高压偏强、中纬度西风带和热带海温异常的共同影响(孙博等,2023)外,局地陆气耦合过程(Ni et al.,2024)和上游青藏高原的热力异常也是重要影响因素(Xu et al.,2022),同时人类活动则大大增加了此类事件的发生概率(Chen et al.,2024)。虽然已有个别研究对多因子的协同影响开展了探索,如 Sun et al.(2022)指出巴伦支海海冰减少与拉尼娜共同作用导致了 2020/2021 年华南持续性干旱的发生,但要对极端事件的复杂发生机制获得系统认知,仍有许多未解答的问题。另一方面,目前的机制研究多是针对高温或干旱事件单独开展的,对高温干旱复合极端事件的研究仍然相对有限(Hao et al.,2018a,2022;Feng et al.,2020;Liu et al.,2022;Zeng et al.,2024),尤其对多要素协同影响其发生发展物理机制的研究更少。另外,高温和干旱之间具体存在怎样的关系,如在什么样的天气气候背景下,高温和干旱之间的正反馈过程可以发生并得以持续,影响高温、干旱及复合高温干旱事件的环流特征有何区别与联系,也是值得深入研究的问题。

因此,在近几十年中国地区高温和干旱不断加剧(Chen and Sun,2017;Chen et al.,2020)、复合高温干旱极端事件明显增多增强(Hao et al.,2018b;Yu and Zhai,2020b)的背景下,亟须系统开展复合高温干旱极端事件的变化机制和归因研究。对复合高温干旱事件发生规律与机制的系统认识,可为改进极端天气气候事件的预测提供科学基础,为国家防灾减灾政策措施的制定和实施提供重要科技支撑。具体而言,需要从海-陆-冰-气多圈层协同影响的角度开展中国复合高温干旱极端事件的变化机制研究,并进一步探究人类活动等外强迫因子在其中的作用及贡献,为职能部门防灾减灾及气候变化应对工作提供科技支撑。

目前关于复合高温干旱的有限研究多从季节或月尺度开展(Hao et al.,2018a;Zeng et al.,2024),但实际上持续数日的复合高温干旱事件也可带来重要的影响。尤其在中纬度地区,气候系统存在明显的准双周振荡(Quasi-Biweekly Oscillation,QBWO)。季节或月尺度的研究不能揭示出极端天气气候事件在更短时间尺度上的演变特征,因此有必要利用更为精细的日资料对其变化规律和演变过程开展研究。

另外,尽管高温干旱事件的影响不断加剧,然而目前对高温干旱事件的预测水平仍然相当有限(Hao et al.,2018b,2019;Domeisen et al.,2023)。这一方面是由于当前模式对天气气候的预测能力本身有诸多局限(Wang et al.,2022)。动力模式对一周以内的天气具有较高的预报水平;通过结合统计方法,对季节尺度的短期气候预测也有一定技巧。而周至月尺度的次季节预测以及多年至年代际预测是当前天气气候预测领域的难点,同时又是防灾减灾的迫切需求。另一方面,对高温干旱事件发生发展机制的认识严重不足,而模式距离完整再现其复杂机制更是有较大差距。因此,要提升对复合高温干旱事件的预测水平,需要在系统认识复合高温干旱事件发生机制的基础上,改进动力模式对关键物理过程的模拟和预测水平。同时应结合统计预测和机器学习方法,构建有效的动力-统计机器学习相结合的预测模型。

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· **ARTICLE** ·

Research progress and prospect on the drought, heatwave, and compound drought and heatwave events in China

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Abstract Drought, as one of the leading and most severe meteorological disasters globally, occurs frequently in China. Between 2001 and 2020, approximately 48% of the crop area affected by meteorological disasters in China were due to drought (Li et al., 2021). Heatwaves are believed to be increasing under global warming, while droughts exhibit more regionalized patterns. The simultaneous occurrence of drought and heatwave has become more frequent, mainly due to increase in high temperature events driven by global warming. High temperature and soil moisture deficit can reinforce each other, likely leading to more frequent, longer-lasting, and stronger extreme events, known as compound drought and heatwave events (CDHEs). CDHEs have more severe and persistent impact on agriculture and ecological environment through the positive feedback between drought and high temperature. This work provides a brief review of research progress on drought, heatwave, and CDHE events in China. First, the various definitions of drought, heatwave, and CDHE are summarized. The influencing factors, including sea surface temperature (SST) and sea ice, land surface conditions, atmospheric circulation patterns, and the underlying physical processes, are then reviewed.

Northeast China (NEC) is a typical region where drought, heatwave, and CDHE events often occur. Previous studies have identified several factors that influence these events in NEC. As an example, we integrate the effects of sea-land-ice-air system on NEC drought, heatwave, and CDHE events based on prior research, constructing a simplified physical framework. The key mechanisms can be briefly depicted as follows:

Local anomalous anticyclone plays a central role in drought, heatwave, and CDHE events. These local circulation anomalies can be induced by Rossby wave train in the upper atmosphere, which are influenced by climate variations in the upstream, including the North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO), North Atlantic SST, polar sea ice, and soil temperature in Central Asia. Additionally, phenomena like El Niño and Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) can significantly affect the drought, heatwave, CDHE events in NEC.

Despite the identification of several local, regional, remote natural climate systems contributing to drought, heatwave, CDHE events in China, a comprehensive understanding of the synergistic physical and dynamical mechanisms behind these events remains lacking. These processes are complicated by the interplay between regional SST, sea ice, land surface conditions, and atmospheric dynamics. In addition to natural climate systems, anthropogenic activity are proposed to significantly drive the increasing frequency and intensity of drought, heatwave, CDHE events in China. However, the relative contribution of natural climate variation and anthropogenic forcing remain unclear and require further investigation.

Although the impact of drought, heatwave, CDHE events is growing rapidly, predictive skills remain limited. Numerical weather forecast based on state-of-the-art models have a skill horizon of only about one week. These limitations arise from our incomplete understanding of the underlying physical processes and the imperfect representation of the real world by current numerical models. The first step in improving prediction skills is to systematically enhance our understanding of the physical processes driving extreme climate events. Developing effective dynamical-statistical methods, including deep-learning techniques, is essential for improving the predictability of drought, heatwave, CDHE events over various timescales, addressing the urgent need to prevent disasters and reduce damages under global warming.

Keywords　heatwave; drought; extreme event; compound drought and heatwave event (CDHE); compound event

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