刘辉志，杜群，许鲁君，等. 2024. 青藏高原东南缘不同类型生态系统碳、水交换特征[J]. 大气科学, 48(1): . LIU Huizhi, DU Qun, XU Lujun, et al. 2024. The Patterns of Carbon and Water Exchange Process over Different Types of Ecosystems in the Southeastern Margin of the Tibetan Plateau [J]. Chinese Journal of Atmospheric Sciences (in Chinese), 48(1): . doi:10.3878/j.issn.1006-9895.2309.23315

青藏高原东南缘不同类型生态系统碳、水交换特征

刘辉志[1,2] 杜群[1,3] 许鲁君[1,3] 刘阳[1,3] 蒙小妮[4] 邵雅梅[5] 郑颖祺[1,3]

1 中国科学院大气物理研究所大气边界层物理和大气化学国家重点实验室，北京 100029

2 云南大学，昆明 650500

3 中国科学院大学，北京 100049

4 北部湾环境演变与资源利用教育部重点实验室，南宁师范大学，南宁 530001

5 生态环境部南京环境科学研究所，南京，210042

摘要 青藏高原东南缘横断山脉地区是南亚和东亚季风的交汇处，也是大气变化的敏感区和热源区。开展该地区地气相互作用对区域水热过程影响机制及其参数化研究，对于研究青藏高原大气水汽传输的关键过程问题有重大意义。本文介绍了基于涡动观测法开展的青藏高原东南缘地区的地气相互作用观测试验，并总结了洱海湖面、丽江高山草甸及腾冲北海湿地的地气交换特征，以及利用数值模式开展复杂山地局地环流特征的研究工作。目前已初步明确和揭示青藏高原东南缘横断山脉不同类型下垫面的地气交换特征及其影响因素，主要结论如下：青藏高原东南缘高山草甸的碳、水交换过程受降水分布影响显著，“浮毯型”湿地（水面常年覆盖有“浮毯”状苔草草排）的碳、水交换除了受气象因素影响外，也受到下垫面植被和水体比例变化的影响。不同类型生态系统的碳、水交换过程在不同时间尺度的影响因子存在差别。风速始终是湖泊潜热和 CO_2 交换的关键影响因子，而降水在较长时间尺度对湖泊 CO_2 通量也有显著影响。此外，青藏高原东南缘的复杂地形对于生态系统的碳、水交换过程也有显著影响。复杂地形产生的不同类型的局地环流对于生态系统的碳、水交换过程有不同的影响。

关键词 地气相互作用 潜热通量 净碳交换 涡动相关

文章编号 1006-9895(2024)01-0000-00 **中图分类号** P **文献标识码** A

doi: 10.3878/j.issn.1006-9895.2309.23315

The Patterns of Carbon and Water Exchange Process over Different Types of Ecosystems in the Southeastern Margin of the Tibetan Plateau

Huizhi Liu[1,2], Qun Du[1,3], Lujun Xu[1,3], Yang Liu[1,3], Xiaoni Meng[4], Yamei Shao[1,3], Yingqi Zheng[1,3]

1 *State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry (LAPC), Institute of Atmospheric Physics, Chinese Academy of Science, Beijing* 100029

2 *Yunnan University, Kunming* 650500

3 *University of Chinese Academy of Sciences, Beijing* 100049

4 *Key Laboratory of Ministry of Education for Environment Change and Resources Use in Beibu Gulf, Nanning Normal University, Nanning* 530001

Abstract The Hengduan Mountains situated in the southeast margin of the Tibetan Plateau is in the conjunction area of the south Asia monsoon and southeast Asia monsoon, and it is also the heating area and sensitive area of the atmospheric change. It is of great importance for the understanding of the key processes of the atmospheric water resource in the Tibetan Plateau to investigate the effects and its parameterization schemes of the interaction between the land surface and the atmosphere on the water and energy exchange processes in this region. It is introduced about the land-atmospheric filed experiments developed in this area based on the continuous eddy covariance measurements. It is also analyzed about the patterns of the exchange process between the wetland/ lake/

作者简介 刘辉志，男，1967 年出生，博士，研究员，主要从事大气边界层和大气环境方面的研究。Email: huizhil@mail.iap.ac.cn

基金项目 第二次青藏高原综合科学考察研究任务 2019QZKK0105，国家自然科学基金项目 42161144010, 41975017

Funded by The Second Tibetan Plateau Scientific Expedition and Research (STEP) program (Grant 2019QZKK0105) and National Natural Science Foundation of China (NSFC) (Grants 42161144010, 41975017)

grassland surfaces and the atmosphere in Erhai lake, Lijiang alpine grassland and Tengchong Beihai wetland land surface process observation sites. In addition, the characteristics of local circulation simulated with numerical models are also investigated in complex mountainous areas. The characteristics of land-atmosphere surface exchange process and their influencing factors for different types in the southeastern edge of the Tibetan Plateau and Hengduan Mountains have been preliminarily identified and revealed. The main conclusions are as follows: the carbon and water exchange processes in alpine meadows in the southeastern edge of the Tibetan Plateau are significantly influenced by precipitation distribution. In addition to meteorological factors, the carbon and water exchange in "floating blanket" wetlands with grass floating on the surface like blanket for whole year is also affected by changes in underlying surface vegetation and water proportion. The influencing factors of carbon and water exchange processes in different types of ecosystems vary at different time scales. Wind speed is always a key factor influencing latent heat and CO_2 exchange in lakes, while precipitation also has a significant impact on CO_2 flux in lakes at longer time scales. Furthermore, the complex terrain in the southeastern edge of the Tibetan Plateau has a significant impact on the ecosystem carbon and water exchange processes. Different types of local circulations generated by complex terrain have different effects on the carbon and water exchange processes of ecosystems.
Keywords Land–atmosphere interaction, Latent heat flux, Net ecosystem exchange, Eddy covariance

1 引言

青藏高原东南缘位于横断山脉地区，该区域地形起伏、海拔高差大、地形地貌复杂多样。由于其所处地理位置的特殊性和地形地貌的复杂性，使得该地区既是东亚季风和南亚季风的交汇区，也是大气变化的热源区和敏感区（叶笃正和高由禧，1979）。青藏高原东南侧有来自相邻的印度洋、南海地区的异常显著的暖湿气流及水汽输送，并在高原东南侧构成异常水汽辐合区；该区域是引起我国乃至日本等地区天气气候异常的水汽输送关键区以及东亚陆－气相互作用最敏感区域之一（徐祥德等，2014）。青藏高原东南地区的陆面、大气的基本状况对邻近区域及东亚地区天气气候有着重要影响（苏锦兰等，2015；Dong et al., 2018）。

全球陆地约一半的面积位于非平坦、非均匀的复杂地形下，地气间的热力驱动流对大气边界层和复杂地形下局地天气气候的发展演化都起着非常重要的作用（Rotach et al., 2017）。地表-大气交换过程对气候系统的水分、能量和生物地球化学循环亦有重要影响（Kirshbaum et al., 2018）。青藏高原东南缘区域复杂地形的动力和热力作用是通过下垫面与大气间的动量交换、水文循环和物质交换等过程实现的，进而影响局地天气和气候（Henne et al., 2004；徐祥德等，2014）。青藏高原东南缘地区降水和温度的空间分布极不均匀，天气多变，区域气候差异特征显著。准确的估算非均匀地表的能量和水汽交换仍然面临很大挑战（Ma et al., 2023）。由于地形地貌复杂，自然环境恶劣，青藏高原东南横断山区各类观测资料极为缺乏，高质量的观测资料更少，限制了人们对该区域大气及陆面基本状况及其变化规律的认识。

山区复杂地形在不同时空尺度影响地气相互作用以及地气间物质、能量和热量通量的输送和混合过程等（Chow et al., 2013）。复杂山地的局地环流对地（湖）－气之间水热过程的影响过程，到目前仍是大气边界层研究的热点和难点（Mengelkamp et al., 2006）。Wagner 等（2014）指出，山谷逆温层和垂直环流的发展与下垫面强迫和背景稳定度密切相关；其中山谷的复杂地形尤其是山谷深度对区域及更大尺度上（包括山地和沿海地区）的热力分层及环流结构影响巨大。因此，开展复杂山地的地气相互作用特征的观测及数值模拟研究，改进数值模式中复杂地形的大气边界层的描述，对模拟复杂地形下的大气边界层中的垂直交换过程及自由大气中的环流发展是至关重要的。由于青藏高原东南地区缺乏地气相互作用高质量的观测资料，显著影响数值模式在该区域的准确性，该区域成为全球范围内数值预报准确率不确定性最高的区域之一。现有的数值预报模式对高原东部及下游地区模拟降水出现了显著的偏差（Yu et al., 2000）。研究青藏高原多尺度陆-气相互作用特征及其数值模拟，提高该区域数值模拟的准确性，不仅对局地气象预报和灾害预警至关重要，同时也与下游地区天气、气候预报的质量密切相关（Xu et al., 2002；吴绍洪等, 2012）。

图 1 青藏高原东南缘不同生态系统通量观测站，（a）丽江高山草甸通量观测站（27° 10′ N, 100° 14′ E），（b）洱海通量观测站（25°46′N, 100°10′E），（c）腾冲“浮毯”型湿地通量观测站（25° 07′ N, 98° 33′ E）

Fig.1 (a) Different types of ecosystems in southeast margin area of Tibetan Plateau, (b) The Lijiang alpine meadow flux site (27° 10′ N, 100° 14′ E), (c) The

Erhai Lake flux site (25° 46′ N, 100° 10′ E) , (d) Tengchong ‘floating blanket’ wetland flux site (25° 07′ N, 98° 33′ E)

2 青藏高原东南缘高山草甸地气交换特征

丽江位于青藏高原东南部横断山脉地区，位于青藏高原向东亚地区水汽输送通道上，对丽江水汽交换过程的理解将有助于更好的理解东亚水汽循环（Xu et al., 2002）。与青藏高原大部分地区不同（Gu et al., 2008），丽江位于亚热带，有更高的气温、更多的降水量。受全球变暖影响，丽江玉龙冰川区雪山明显减少，雪线已经上升（何和张，2004）。中国科学院大气物理研究所自 2012 年在丽江牦牛坪建立了高山草甸通量观测站，运行至今已积累多年连续观测资料（图 1）（Wang et al., 2016; Wang et al., 2017）。丽江站裸土的反照率低于草地，这是由于丽江站的土壤颜色较深造成，而这种现象与半干旱地区的草地观测结果相反（Wang et al., 2018）。丽江站的有效能量主要分配为潜热通量（表 1），在湿季，潜热通量占净辐射的 60%，而且这个比例在整个湿季保持稳定，这与其他草地生态系统不同，海北站潜热占净辐射的比例随着植被生长而增加（Gu et al., 2005）。

表 1 丽江站湿季、干季和整个生长季（2011 年 6 月到 2013 年 12 月）太阳辐射（S_m, MJ $m^{-2}day^{-1}$）、净辐射（Rn, MJ $m^{-2}day^{-1}$）、感热通量占净辐射的比例（H/Rn）、潜热通量占净辐射的比例（LE/Rn），海北站生整个季节是指 2002 年 DOY15 到 2023 年 DOY14 (Gu et al. 2005)。引自 Wang et al. (2016)。

Table1 The solar radiation (S_m, MJ m^{-2} day^{-1}), net radiation (Rn, MJ m^{-2} day^{-1}), H/Rn (the ratio of sensible heat to net radiation) and LE/Rn (the ratio of latent heat to net radiation) at Lijiang site for the wet seasons, the dry seasons and the whole years from June 2011 to December 2013 and at the Haibei alpine meadow for the growth period and the whole yar from DOY 15, 2002 to DOY 14, 2003 (Gu et al. 2005). From Wang et al. (2016).

Year/site	Period	S_m	Rn	H/Rn	LE/Rn
2011	湿季	11.0	6.3	0.24	0.60
2012	湿季	10.6	5.9	0.27	0.60
	干季	16.8	5.2	0.55	0.36
	全年	14.2	5.5	0.43	0.46
2013	湿季	11.1	6.2	0.25	0.62
	干季	16.9	5.3	0.52	0.38
	全年	14.4	5.7	0.40	0.49
海北站	生长季	21.1	11.9	0.17	0.44
	全年	17.6	7.4	0.31	0.31

丽江站的净碳吸收出现了正午受到抑制的现象，在晴朗天气下，高辐射和较高的气温是高山草甸生态系统净碳吸收在正午下降的原因，这种现象在半干旱区和地中海草原也都观测到（Fu et al. 2006; Aires et al. 2008）。云量的增加显著增强了丽江的净碳吸收，可能是由于光合有效辐射的散射辐射增加了，这在黑河流域的草原上也观察到了类似现象（Bai et al., 2012）。气温是影响高山草甸净碳吸收的主要控制因子（Wang et al., 2016; Saito et al., 2009）。气温升高导致青藏高原地区的高山草甸净碳吸收显著增加（Wang et al., 2023）。丽江高山草甸净碳交换各组分的年际变异主要由于气象因子（气温和降水等）的季节变化引起（Wang et al., 2017），这与欧洲和北美地区草甸的研究结果一致（Jensen et al., 2017; Teklemariam et al., 2010）。Shao 等（2014）认为气象因子的年际变化导致的植被功能改变是净碳交换各组分年际变异的主要原因。

图 2 丽江高山草甸通量观测站 2014-2016 年（a）累积降水，（b）5cm 深度土壤水含量，（c）累积净碳交换通量 NEE。阴影部分代表湿季。引自 Zheng et al. (2022)

Fig.2 (a) Cumulative precipitation, (b) SWC (Soil water content) at the depth of 5 cm (SWC-5 cm), and (c) cumulative NEE (net ecosystem exchange) for the year 2014, 2015, and 2016 in Lijiang alpine meadow flux site. The shaded area denotes wet season. From Zheng et al. (2022)

全球变暖引起降水变率增加，在极端干旱和湿润之间变动（Zhang et al., 2021）。丽江站的净碳吸收过程受干旱和降水分布影响而发生改变（Wang et al., 2016; Zheng et al., 2022）。2012 年的春季干旱导致丽江高山

草甸生长季缩短进而引起净碳吸收下降，这在其他生态系统也观测到类似现象（Kwon et al., 2008）。丽江高山草甸在 2015 年 6 月表现为微弱的碳源，这是由于上一年度的干旱导致，上一季度的土壤水分亏缺会抑制高山草甸的净碳吸收作用（Li et al., 2016）。降水分布会改变土壤水分状况，进而影响草原生态系统的碳收支（Sloat et al., 2015）。由于丽江站 2014 和 2015 年的降水更多分布在生长季，在 2014 和 2015 年生长季前的干季，只观测到两次土壤含水量的脉冲，而 2016 年的降水分布更为均匀，导致 2016 年净碳吸收更高（图 2）（Zheng et al., 2022）。生长季早期的降水事件能促进草原生态系统的土壤呼吸（Post and Knapp, 2020）。旱季降水量减少会抑制生态系统呼吸和光合作用，导致净 CO_2 吸收量总体下降，因为光合作用对土壤水分的敏感性高于生态系统呼吸（Wu et al., 2011; Zheng et al., 2022）。

3　青藏高原东南缘湖气相互作用特征

湖泊是全球变化的重要指示器（Adrian et al., 2009），通过复杂的生物物理和生物地球化学进程，对局地和区域尺度上的天气和气候产生重要影响（Shao et al., 2015）。我国是一个多湖的家，超过一半的湖泊分布于高原地区（Ma et al., 2012）。中国科学院大气物理研究所基于中日合作 JICA 项目建立的固定于洱海湖面上的观测平台，从 2012 年起在大理洱海开展了湖面—大气间相互作用的连续观测实验（图 1）（Liu et al., 2015）。洱海的反照率在 0.06 到 0.13 之间，并且干季大于湿季，可能是由于太阳高度角的变化（Du et al., 2018a; Liu et al., 2015）。洱海的反照率高于青藏高原腹地的鄂陵湖（Li et al., 2015），与鄱阳湖较为接近（Zhao and Liu, 2017）。洱海在夜间观测到正的潜热通量，表明洱海在夜间持续蒸发，在芬兰南部地区的湖泊也观测到相似现象（Nordbo et al., 2011）。夜间蒸发是湖泊水汽蒸发的主要贡献者（Liu et al., 2012）。洱海的潜热通量和感热通量存在相反的季节变化，潜热通量在雨季更高，而感热通量相反，并且潜热通量远大于感热通量（Du et al., 2018a）。洱海在 1-6 月份热量储存为负，湖泊在持续的释放热量，与我国亚热带地区的太湖相似（Wang et al., 2014）。洱海的年蒸发量在 1120.8 到 1228.5 mm 之间（Du et al., 2018a），高于青藏高原的纳木错湖（1025 mm）和青海湖（830 mm）的年蒸发量（Wang et al., 2020）。湖泊的蒸发量受纬度、海拔和湖泊面积影响，海拔越高、面积越小并且纬度越高的湖泊蒸发越小（Wang et al., 2020）。洱海的年蒸发量始终高于降水量，这与青藏高原的纳木错湖和青海湖相似，甚至后两者蒸发量和降水量的差距更大（Haginoya et al., 2009; Li et al., 2016）。

图 3 洱海能量通量各组分 2012-2015 年在季风前期、季风期和季风后期的月均值（△Q 储存热量，Rn 净辐射，LE 潜热通量，Hs 感热通量）。引自 Du et al. (2018b)

Fig.3 The monthly average energy fluxes (△Q , the storage heat flux in the lake; Rn , the net radiation flux; LE , the latent heat flux; and Hs, the sensible heat flux) during pre-monsoon, monsoon and post-monsoon periods from 2012 to 2015. From Du et al. (2018b)

湖泊在全球碳循环的重要性也不可忽视（Huotari et al., 2011）。洱海在年际尺度表现为碳源，并且其净 CO_2 排放高于美国五大湖之一的伊利湖（Shao et al., 2015）。风速是影响洱海 CO_2 通量的主要影响因子，当风速较大时，通过湍流引起的涡动和涡流影响气体交换速率，当风速较低时，通过对流调节气体交换速率（Eguster et al., 2003）。降水也被发现是影响洱海 CO_2 通量季节尺度的控制因子，这在美国五大湖之一的伊利湖也发现相似现象（Shao et al., 2015），可能是由于降水改变了湖泊营养物质的变化（Yu et al., 2014）。另一方面，降水也可能会促进 CO_2 排放，降水会加快碳从陆地向湖泊输送，从而增加有机碳的浓度并提高二氧化碳分压（Pumpanen et al., 2014）。湖面大气特征的变化会引起湖-气交换过程大气驱动因素的变化，进而影响湖-气交换过程（Huotari et al., 2011; Li et al., 2015）。在季风期，当带有暖湿气团的东南风经过青海湖，会导致湖气温差减少并转变为负值（Li et al., 2016）。而洱海在季风期开始前，湖气温差为负值，而在季风期湖气温差转变为正值（Du et al., 2018b）。洱海的潜热通量在季风期较高，而感热通量在季风后期较高，并且洱海在季风前期释放热量，季风后期储存热量（图 3）（Du et al., 2018b）。与洱海不同，位于青藏高原的纳木错湖的感热和潜热通量在季风前期和季风中期较小，在季风后期较高，季风后期湖泊向大气中释放大量的热量（Haginoya et al., 2009）。

与陆地下垫面不同，湖气间的潜热通量和感热通量的峰值出现在弱不稳定至近中性层结（Yusup and Liu, 2016; Li et al., 2015）。洱海在 1-6 月期间保持在弱稳定至稳定层结，之后转变为弱不稳定到不稳定层结（Meng et al., 2020）。与其他地区的湖泊（Yusup and Liu, 2016；Li et al., 2015）相比，洱海湖面近地层大气稳定度变化范围较小，强不稳定和强稳定出现的概率几乎为零，而在热带的大型湖泊（Verburg and Antenucci, 2010）和位于青藏高原的鄂陵湖（Li et al.,　2015），观测期间湖面近地层均持续处于不稳定状态。洱海在稳定条件下的潜热通量高于不稳定条件下，这是由于稳定层结下，较高的风速和水汽压差引起较大的蒸发（Meng et al., 2020），在瑞典北部的小型湖泊也观测到类似的结果（Heikinheimo et al., 1999）。

4　青藏高原东南缘“浮毯型”湿地地气交换特征

湿地是气候变化研究的“热点”区域，对气候变化响应敏感（Alekseychik et al., 2017）。腾冲北海湿地是我国西南高原唯一的“浮毯型”高原浅水湖泊湿地，其水面常年覆盖有“浮毯”状苔草草排，该湿地类型十分罕见。中国科学院大气物理研究所自 2015 年 6 月在腾冲湿地开展碳、水通量观测（图 1）（Du et al., 2021）。蒸散是湿地水循环的重要组成部分之一，但由于湿地类型存在差异，湿地的水文过程仍存在很大的不确定性（Tonti et al., 2018）。腾冲湿地的能量分配存在显著的季节变化，在湿季有效能量主要分配为潜热通量。在干季，潜热通量占净辐射的比例和感热通量占净辐射的比例差异较小（图 4）（Shao et al., 2022）。位于中纬度和高纬度地区的具有季风气候的湿地，随着湿季的开始，能量分配中的主导能量通常会从感热通量转变为潜热通量（Yan et al., 2020）。在青藏高原的高山草原和牧场，潜热通量在夏季的能量分配中占主导，而感热通量在其他季节的能量分配中起主导作用（Zhang et al., 2019；Ma et al., 2015）。腾冲湿地的植被和水体比例的变化对水汽和净碳交换过程均有显著影响，植被占下垫面的比例与净碳吸收和蒸发成正比（Du et al., 2021）。其他研究也发现植被对湿地净碳收支的影响，青海湖湿地的叶面积指数决定了净碳交换 85%的变异（Cao et al., 2017）。植被通过改变陆表特征包括粗糙度、反照率等进而影响湿地的能量分配和水分平衡（Forzieri et al., 2020）。Zhao 和 Liu 等（2018）也指出水体比例对于鄱阳湖的能量收支和分配有显著影响。

图 4 腾冲湿地不同季节逐月日变化（a）净辐射（Rn），（b）感热通量与净辐射的比值（H/Rn），（c）潜热通量与净辐射的比值（LE/Rn），（d）波文比（Bo），（e）储存热量与净辐射的比值（Qs/Rn）。引自 Shao et al. (2022)

Fig.4 Monthly average diurnal variation of (a) the net radiation (Rn), (b) the ratio of the sensible heat flux to the net radiation (H/Rn), (c) the ratio of the latent heat flux to the net radiation (LE/Rn), (d) Bowen ratio (Bo), and (e) the ratio of heat stored in the water to the net radiation (Qs/Rn) in the four seasons. From Shao et al. (2022)

5　青藏高原东南缘复杂地形局地环流对湖气碳、水通量的影响

山地附近湖区周边地形复杂多样，湖泊和陆地之间的热力和动力差异导致湖陆风环流的形成，产生复杂和独特的局地环流（Bartůňkova et al.，2014；Curry et al.，2015）。山地湖区周边地形复杂多样，形成的局地环流具有复杂性和独特性。目前，对山地湖区局地环流的研究多为个例分析，基于长时间序列观测资料进行的分析很少，山地湖区不同时间尺度的局地环流特征有待进一步揭示（Gerken et al.，2014）。Xu 等（2021）基于 Arrillaga 等（2016）和 Román-Cascón 等　（2019）的方法，对大理洱海盆地 2015 年白天和夜间的山谷风和湖陆风环流进行统计，根据风向和持续时间对湖陆风和山谷风环流进行筛选。发现该地区白天为湖风（风向范围：0°-170°）。夜间，大理盆地的局地环流主要受苍山山风和洱海陆风的共同影响。夜间局地环流表现为两种环流形势（图 5）。当苍山山风强盛于洱海陆风时，观测点附近主要受西南风影响，表现为 N1 型局地环流（图 5 a）。反之，当苍山山风较弱时，洱海南部气旋式环流北支到达湖泊中部西岸，观测点附近主要受东南风影响，表现为 N2 型局地环流（图 5 b）。N1 型山风主导局地环流和 N2 型陆风主导局地环流的风向分别定义为 180°-350°和 90°-170°。洱海使局地风速增加，与 Curry 等（2017）在北美南部湖泊的发现一致。洱海观测站处的湖风主要在日出后 1 小时形成，日落前消失，与意大利阿尔卑斯山的加尔达湖风较为相似（Giovannini et al., 2015）。

图 5 大理夜间水平适量（a）N1 型夜间山风环流（02:00 LST 12/08/2015）和（b）N2 夜间山风和陆风叠加环流（0200 LST 24/10/2015）。灰色的边框代表洱海。阴影表示海拔高度（单位：米）。风向和风速来自 WRF（The Weather Research and Forecasting Model）模式模拟资料。引自 Xu et al. (2021)

Fig.5 Wind fields for (a) an N1 nighttime breeze event (02:00 LST 12/08/2015) and (b) an N2 nighttime breeze event (0200 LST 24/10/2015). The gray outline shows Erhai Lake. Shadows indicate altitude (unit: m). Wind vectors and magnitudes are from WRF (The Weather Research and Forecasting Model) simulation data. From Xu et al. (2021)

复杂地形局地环流对湖泊物质和能量通量有不同的影响。Xu 等（2021）研究发现除 N2 型环流外，N1 型山风环流和白天湖风都减弱感热通量，且 N1 型山风环流的减弱效果更明显（图 6）。夜间山谷降温比山坡慢，使得山谷湍流混合作用减弱，大气边界层更趋于稳定（Fernando et al., 2015）。白天湖风和夜间 N2 型环流都促进潜热交换，N2 型环流的增强作用约为白天湖风环流的两倍，而 N1 型环流则减少潜热通量（Xu et al., 2021）。局地环流对潜热通量的交换主要是由于湖风引起了局地比湿和水汽压变化导致（Naor et al., 2017）。湖泊在复杂地形湖区的二氧化碳输送中也起着关键作用（Lin et al.，2018；Davis et al.，2020）。在夜间，山区植被通过呼吸作用排放 CO_2，山坡处的 CO_2 浓度高于洱海湖面，苍山的山风将山坡处的 CO_2 输送到洱海湖面，从而增加 CO_2 通量。在白天，湖风增加了局地风速，进而对 CO_2 交换过程产生影响（Xu et al., 2021）。

随着数值天气、气候模式分辨率的提高，湖泊的作用变得不可忽视(Zia et al., 2016)。湖－气耦合模式的发展成为数值天气的前沿问题之一（Subin et al., 2012）。Xu 等（2017）基于洱海通量观测资料，评估了湖气耦合模式 WRF3.7.1 在洱海的适用性，结果表明 WRF 模式高估了风速和地表的湍流混合作用。通过采用地形订正因子（Jimenez and Dudhia, 2012），引入次网格地形参数化对模型进行优化，提高了风速和地表通量模拟的准确性，表明在复杂地形上进行地形校正的必要性。

图 6 （A）（B）（C）分别为感热通量、潜热通量和 CO_2 通量差值日变化特征，其中（a）白天（11/08/2015）（b）N1 型（12/08/2015）（c）N2 型（24/10/2015），绿色实线为不同类型环流个例感热/潜热/ CO_2 通量日变化，黑色虚线为不同类型环流平均感热/潜热/ CO_2 通量变化，阴影为不同类型环流平均感热/潜热/ CO_2 通量变化标准差，红色虚线表示日出，灰色虚线表示日落

Fig.6 （A）（B）（C）are sensible heat flux (Hs), latent heat flux(LE) and CO_2 flux anomalies for (a) an example daytime breeze event (11/08/2015), (b) an example N1 breeze event (12/08/2015), and (c) an example N2 breeze event (24/10/2015) at the EC site are indicated with green lines. The vertical gray (red) solid lines indicate sunset (sunrise). The anomaly mean for all events is shown with black dots,
and the standard deviation is shown with shadow.

6 结论

青藏高原东南缘位于青藏高原关键的水汽输送通道上，地形地貌复杂，是数值模拟的难点区域。气候变暖背景下，不同类型生态系统对气候变化响应的程度和方式也有所不同。长期的通量观测资料将有助于提高对复杂地形区地气相互作用特征及其影响机制的认识。中国科学院大气物理研究所自 2012 年开始，利用涡动相关法在青藏高原东南缘不同生态系统（湿地、湖泊和草甸）开展了长期、连续和高质量的观测，获取了长时间序列的地表通量数据集。基于以上观测，已初步明确和揭示青藏高原东南缘横断山脉不同类型下垫面的地气交换特征及其影响因素。青藏高原东南缘高山草甸的碳、水交换过程受降水分布影响显著，“浮毯型”湿地的碳、水交换除了受气象因素影响外，也受到下垫面植被和水体比例变化的影响。不同类型生态系统的碳、水交换过程在不同时间尺度的影响因子存在差别。风速始终是湖泊潜热和 CO_2 交换的关键影响因子，而降水在较长时间尺度对湖泊 CO_2 通量也有显著影响。此外，青藏高原东南缘的复杂地形对于生态系统的碳、水交换过程也有显著影响。复杂地形产生的不同类型的局地环流对于生态系统的碳、水交换过程有不同的影响。通过对复杂地形区不同生态系统地交换过程及其影响机制的研究，将有助于改进青藏高原东南缘地区的地表参数化方案，提高该地区数值预报的准确性。

参考文献（References）

Adrian, R., O'Reilly, C.M., Zagarese, H., et al. 2009. Lakes as sentinels of climate change [J]. Limnol. Oceanogr. 54: 2283-2297, doi: 10.4319/lo.2009.54.6_part_2.2283.

Aires, L.M.I., Pio, C.A., Pereira, J.S. 2008. Carbon dioxide exchange above a Mediterranean C3/C4 grassland during two climatologically contrasting years [J]. Glob. Chang. Biol. 14: 539-555, doi: 10.1111/j.1365-2486.2007.01507.x.

Alekseychik, P., Mammarella, I., Karpov, D., et al. 2017. Net ecosystem exchange and energy fluxes measured with the eddy covariance technique in a western Siberian bog [J]. Atmos. Chem. Phys. 17: 9333-9345.

Arrillaga, J.A., Yagüe, C., Sastre, M., et al. 2016. A characterisation of sea-breeze events in the eastern Cantabrian coast (Spain) from observational data and WRF simulations [J]. Atmos. Res. 181: 265-280.

Bai, Y., Wang, J., Zhang, B., et al. 2012. Comparing the impact of cloudiness on carbon dioxide exchange in a grassland and a maize cropland in northwestern China [J]. Ecol. Res. 27: 615-623.

Bartůňková, K., Sokol, Z., Pop, L. 2014. Simulations of the influence of lake area on local temperature with the COSMO NWP model [J]. Atmos. Res. 147: 51-67.

Cao, S., Cao, G., Feng, Q., et al. 2017. Alpine wetland ecosystem carbon sink and its controls at the Qinghai Lake [J]. Environ Earth Sci 76, doi: 10.1007/s12665-017-6529-5.

Chow, F.K., DeWekker, S.F.J., Snyder, B.J., 2013. Mountain Weather Research and Forecasting [M]. Springer, Dordrech.

Curry, M., Hanesiak, J., Sills, D. 2015. A radar-based investigation of lake breezes in southern Manitoba [J], Canada. Atmos Ocean 53: 237-250.

Davis, Z.Y., Sills, D.M., McLaren, R. 2020. Enhanced NO2 and aerosol extinction observed in the tropospheric column behind lake-breeze fronts using MAX-DOAS [J]. Atmos. Environ. 5: 100066.

Dong, D., Tao, W., Lau, W.K.M., et al. 2019. Interdecadal Variation of Precipitation over the Hengduan Mountains during Rainy Seasons [J]. J. Clim. 32: 3743-3760, doi: 10.1175/JCLI-D-18-0670.1.

Du, Q., Liu, H., Liu, Y., et al. 2021. Water and carbon dioxide fluxes over a “floating blanket” wetland in southwest of China with eddy covariance method [J]. Agr. Forest. Meteorol. 311: 108689.

Du, Q., Liu, H., Xu, L., et al. 2018a. The monsoon effect on energy and carbon exchange processes over a highland lake in southwest of China [J]. Atmos. Chem. Phys. 18: 15087-15104, doi: 10.5194/acp-18-15087-2018.

Du, Q., Liu, H.Z., Liu, Y., et al. 2018b. Factors controlling evaporation and the CO_2 flux over an open water lake in southwest of China on multiple temporal scales [J]. Int. J. Climatol. 38: 4723-4739, doi: 10.1002/joc.5692.

Eugster, W., Kling, G., Jonas, T., et al. 2003. CO_2 exchange between air and water in an Arctic Alaskan and midlatitude Swiss lake: Importance of convective mixing [J]. J. Geophys. Res-Atmos. 108: 20, doi: 10.1029/2002jd002653.

Fernando, H. J. S., Pardyjak, E. R., Di Sabatino, S., et al. 2015. The Materhorn - unraveling the intricacies of mountain weather [J]. Bull. Am. Meteorol Soc. 96(11), 1945-1967, doi: 10.1175/BAMS-D-13-00131.1.

Forzieri, G., Miralles, D.G., Ciais, P., et al. 2020. Increased control of vegetation on global terrestrial energy fluxes [J]. Nat. Clim. Chang. 10: 356-362, doi: 10.1038/s41558-020-0717-0.

Fu, Y., Yu, G., Sun, X., et al. 2006. Depression of net ecosystem CO_2 exchange in semi-arid Leymus chinensis steppe and alpine shrub [J]. Agr. Forest. Meteorol. 137: 234-244, doi: 10.1016/j.agrformet.2006.02.009.

Gerken T., Biermann, T., Babel, W., et al. 2014. A modelling investigation into lake-breeze development and convection triggering in the Nam Co Lake basin, Tibetan Plateau [J]. Theor. Appl. Climatol., 117, doi: 10.1007/s00704-013-0987-9.

Giovannini, L., Laiti, L., Zardi, D., et al. 2015. Climatological characteristics of the Ora del Garda wind in the Alps [J]. Int. J. Climatol. 35: 4103-4115.

Gu, S., Tang, Y., Cui, X., et al. 2008. Characterizing evapotranspiration over a meadow ecosystem on the Qinghai - Tibetan Plateau [J]. J. Geophys. Res. Atmos. 113.

Gu, S., Tang, Y., Cui, X., et al. 2005. Energy exchange between the atmosphere and a meadow ecosystem on the Qinghai–Tibetan Plateau [J]. Agr. Forest. Meteorol. 129: 175-185.

Haginoya, S., Fujii, H., Kuwagata, T., et al. 2009. Air-Lake Interaction Features Found in Heat and Water Exchanges over Nam Co on the Tibetan Plateau [J]. Sola 5: 172-175, doi: 10.2151/sola.2009-044.

Han, B., Meng, X., Yang, Q., et al. 2020. Connections between daily surface temperature contrast and CO2 flux over a Tibetan Lake: A case study of Ngoring Lake [J]. J. Geophys. Res. Atmos. 125: e2019JD032277.

Henne, S., Furger, M., Nyeki, S., et al. 2004. Quantification of topographic venting of boundary layer air to the free troposphere [J]. Atmos Chem Phys 4: 497-509, doi: 10.5194/acp-4-497-2004.

何元庆，章典. 2004. 气候变暖是玉龙雪山冰川退缩的主要原因 [J]. 冰川冻土, 26: 230-231. He Yuanqing, Zhang Dian. 2004. Climatic Warming is the Major Reason for Glacier Retreat on Mt. Yulong [J], China. Journal of Glaciology and Geocryology (in Chinese), 26: 230-231.

Huotari, J., Ojala, A., Peltomaa, E., et al. 2011. Long - term direct CO_2 flux measurements over a boreal lake: Five years of eddy covariance data [J]. Geophys. Res. Lett. 38: 113-120, doi: 10.1029/2011GL048753.

Jensen, R., Herbst, M., Friborg, T.J.A. 2017. Direct and indirect controls of the interannual variability in atmospheric CO_2 exchange of three contrasting ecosystems in Denmark [J]. Agr. Forest. Meteorol. 233: 12-31.

Jiménez, P.A., Dudhia, J. 2012. Improving the representation of resolved and unresolved topographic effects on surface wind in the WRF model [J]. J. Appl. Meteorol. Climatol. 51: 300-316.

Kirshbaum, D.J., Adler, B., Kalthoff, N., et al. 2018. Moist Orographic Convection: Physical Mechanisms and Links to Surface-Exchange Processes [J]. Atmosphere 9, doi: 10.3390/atmos9030080.

Kwon, H., Pendall, E., Ewers, B.E., et al. 2008. Spring drought regulates summer net ecosystem CO_2 exchange in a sagebrush-steppe ecosystem [J]. Agr. Forest. Meteorol. 148: 381-391, doi: 10.1016/j.agrformet.2007.09.010.

Li, L., Fan, W., Kang, X., et al. 2016a. Responses of greenhouse gas fluxes to climate extremes in a semiarid grassland [J]. Atmos. Environ. 142: 32-42.

Li, X.Y., Ma, Y.J., Huang, Y.M., et al. 2016b. Evaporation and surface energy budget over the largest high-altitude saline lake on the Qinghai-Tibet Plateau [J]. J. Geophys. Res-Atmos. 121: 10470-10485, doi: 10.1002/2016jd025027.

Li, Z., Lyu, S., Ao, Y., et al. 2015. Long-term energy flux and radiation balance observations over Lake Ngoring, Tibetan Plateau [J]. Atmos. Res. 155: 13-25, doi: 10.1016/j.atmosres.2014.11.019.

Lin, J.C., Mitchell, L., Crosman, E., et al. 2018. CO_2 and carbon emissions from cities: Linkages to air quality, socioeconomic activity, and stakeholders in the Salt Lake City urban area [J]. B. Am. Meteorol. Soc. 99: 2325-2339.

Liu, H., Zhang, Q., Dowler, G. 2012. Environmental Controls on the Surface Energy Budget over a Large Southern Inland Water in the United States: An Analysis of One-Year Eddy Covariance Flux Data [J]. J. Hydrometeorol. 13: 1893-1910, doi: 10.1175/jhm-d-12-020.1.

Liu, H.Z., Feng, J.W., Sun, J.H., et al. 2015. Eddy covariance measurements of water vapor and CO2 fluxes above the Erhai Lake [J]. Sci. China. Earth. Sci. 58: 317-328, doi: 10.1007/s11430-014-4828-1.

Ma, Y., Wang, B., Zhong, L., et al. 2012. The regional surface heating field over the heterogeneous landscape of the Tibetan Plateau using MODIS and in-situ data [J]. Adv. Atmos. Sci. 29: 47-53, doi: 10.1007/s00376-011-1008-5.

Ma, Y., Yao, T., Zhong, L., et al. 2023. Comprehensive study of energy and water exchange over the Tibetan Plateau: A review and perspective: From GAME/Tibet and CAMP/Tibet to TORP, TPEORP, and TPEITORP [J]. Earth-Sci. Rev. 237: 104312, doi: 10.1016/j.earscirev.2023.104312.

Meng, X., Liu, H., Du, Q., et al. 2020. Factors controlling the latent and sensible heat fluxes over erhai lake under different atmospheric surface layer stability conditions [J]. Atmos. Ocean. Sci. Lett. 13: 400-406.

Mengelkamp, H.T., Beyrich, F., Heinemann, G., et al. 2006. Evaporation over a heterogeneous land surface - The EVA-GRIPS project [J]. B. Am. Meteorol. Soc. 87: 775-+, doi: 10.1175/bams-87-6-775.

Naor, R., Potchter, O., Shafir, H., et al. 2017. An observational study of the summer Mediterranean Sea breeze front penetration into the complex topography of the Jordan Rift Valley [J]. Theor. Appl. Clmatol. 127: 275-284.

Nordbo, A., Launiainen, S., Mammarella, I., et al. 2011. Long-term energy flux measurements and energy balance over a small boreal lake using eddy covariance technique [J]. J. Geophys. Res-Atmos. 116: 1-17, doi: 10.1029/2010jd014542.

Post, A.K., Knapp, A.K. 2020. The importance of extreme rainfall events and their timing in a semi‐arid grassland [J]. J. Ecol. 108: 2431-2443, doi:

Pumpanen, J., Linden, A., Miettinen, H., et al. 2014. Precipitation and net ecosystem exchange are the most important drivers of DOC flux in upland boreal catchments [J]. J. Geophys. Res-Biogeo. 119: 1861-1878, doi: 10.1002/2014jg002705.

Román-Cascón, C., Yagüe, C., Arrillaga, J., et al. 2019. Comparing mountain breezes and their impacts on CO2 mixing ratios at three contrasting areas [J]. Atmos. Res. 221: 111-126, doi:

Rotach, M.W., Stiperski, I., Fuhrer, O., et al. 2017. Investigating exchange processes over complex topography [J]. B. Am. Meteorol. Soc. 98: 787-805, doi: 10.1175/bams-d-15-00246.1.

Rucong, Y., Wei, L., Xuehong, Z., et al. 2000. Climatic features related to eastern China summer rainfalls in the NCAR CCM3 [J]. Adv. Atmos. Sci. 17: 503-518.

Saito, M., Kato, T., Tang, Y. 2009. Temperature controls ecosystem CO2 exchange of an alpine meadow on the northeastern Tibetan Plateau [J]. Glob. Chang. Biol. 15: 221-228.

Shao, C., Chen, J., Stepien, C.A., et al. 2015. Diurnal to annual changes in latent, sensible heat, and CO2 fluxes over a Laurentian Great Lake: A case study in Western Lake Erie [J]. J. Geophys. Res-Biogeo. 120: 1587-1604, doi: 10.1002/2015JG003025.

Shao, J., Zhou, X., He, H., et al. 2014. Partitioning climatic and biotic effects on interannual variability of ecosystem carbon exchange in three ecosystems [J]. Ecosystems 17: 1186-1201.

Shao, Y., Liu, H., Du, Q., et al. 2022. Seasonal variation and controlling factors of evapotranspiration over a “floating blanket” wetland in southwest China [J]. J. Hydrol. 612: 128316.

Sloat, L.L., Henderson, A.N., Lamanna, C., et al. 2015. The effect of the foresummer drought on carbon exchange in subalpine meadows [J]. Ecosystems 18: 533-545.

Subin, Z.M., Riley, W.J., Mironov, D. 2012. An improved lake model for climate simulations: Model structure, evaluation, and sensitivity analyses in CESM1 [J]. J. Adv. Model. Earth Syst 4, doi: 10.1029/2011ms000072.

苏锦兰，李建，杨桂荣，等. 2015. 横断山系云岭余脉点苍山东西侧小时降水特性对比分析[J]. 气象, 1:17-24. Su Jinlan, Li Jian, Yang Guirong, et al. 2015. Comparative Analysis on Hourly Precipitation Features on the East and West Sides of Yunling Diancang Mountain in Hengduan Mountains [J]. Meteorological Monthly (in Chinese), 1:17-24.

Teklemariam, T.A., Lafleur, P.M., Moore, T.R., et al. 2010. The direct and indirect effects of inter-annual meteorological variability on ecosystem carbon dioxide exchange at a temperate ombrotrophic bog [J]. Agr. Forest. Meteorol. 150: 1402-1411.

Tonti, N.E., Gassmann, M.I., Perez, C.F. 2018. First results of energy and mass exchange in a salt marsh on southeastern South America [J]. Agr. Forest. Meteorol. 263: 59-68, doi: 10.1016/j.agrformet.2018.08.001.

Venäläinen, A., Frech, M., Heikinheimo, M., et al. 1999. Comparison of latent and sensible heat fluxes over boreal lakes with concurrent fluxes over a forest: implications for regional averaging [J]. Agr. Forest. Meteorol. 98-99: 535-546, doi: 10.1016/S0168-1923(99)00100-8.

Verburg, P., Antenucci, J.P. 2010. Persistent unstable atmospheric boundary layer enhances sensible and latent heat loss in a tropical great lake: Lake Tanganyika [J]. J. Geophys. Res-Atmos. 115: 13, doi: 10.1029/2009jd012839.

Wagner, J.S., Gohm, A., Rotach, M.W. 2014. The Impact of Horizontal Model Grid Resolution on the Boundary Layer Structure over an Idealized Valley [J]. Mon. Weather. Rev. 142: 3446-3465, doi: 10.1175/mwr-d-14-00002.1.

Wang, B., Ma, Y., Su, B., et al. 2020. Quantifying the evaporation amounts of 75 high-elevation large dimictic lakes on the Tibetan Plateau [J]. Sci. Adv. 6: eade8558, doi: 10.1126/sciadv.aay8558.

Wang, Y., Xiao, J., Ma, Y., et al. 2023. Persistent and enhanced carbon sequestration capacity of alpine grasslands on Earth's Third Pole [J]. Sci. Adv. 9: eade6875, doi: 10.1126/sciadv.ade6875.

Wang, L., Liu, H., Shao, Y., et al. 2018. Water and CO_2 fluxes over semiarid alpine steppe and humid alpine meadow ecosystems on the Tibetan Plateau [J]. Theor. Appl. Clmatol. 131: 1-10.

Wang, L., Liu, H., Sun, J., et al. 2016. Water and carbon dioxide fluxes over an alpine meadow in southwest China and the impact of a spring drought event [J]. Int. J. Biometerol. 60: 195-205.

Wang, L., Liu, H., Sun, J., et al. 2017. Biophysical effects on the interannual variation in carbon dioxide exchange of an alpine meadow on the Tibetan Plateau [J]. Atmos. Chem. Phys. 17: 5119-5129.

Wang, W., Xiao, W., Cao, C., et al. 2014. Temporal and spatial variations in radiation and energy balance across a large freshwater lake in China [J]. J. Hydrol. 511: 811-824, doi: 10.1016/j.jhydrol.2014.02.012.

吴绍洪，潘韬，曹杰，等. 2012. 西南纵向岭谷地形对季风的"通道-阻隔"作用 [J]. 地理研究, 1: 1-13. Wu Shaohong, Pan Tao, Cao Jie, et al. 2012. Barrier-corridor effect of longitudinal range-gorge terrain on monsoons in Southwest China [J]. Geographical Research (in Chinese), 1: 1-13.

Wu, Z., Dijkstra, P., Koch, G.W., et al. 2011. Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation [J]. Glob. Chang. Biol. 17: 927-942, doi: 10.1111/j.1365-2486.2010.02302.x.

Xu, L., Liu, H., Du, Q., et al. 2021. Characteristics of lake breezes and their impacts on energy and carbon fluxes in mountainous areas [J]. Adv. Atmos. Sci. 38: 603-614.

Xu, L., Liu, H., Du, Q., et al. 2017. Evaluation of the WRF - lake model over a highland freshwater lake in southwest China [J]. J. Geophys. Res-Atmos. 121: 13898-14005, doi: 10.1002/2016JD025396.

Xu, X., Zhou, M., Chen, J., et al. 2002. A comprehensive physical pattern of land-air dynamic and thermal structure on the Qinghai-Xizang Plateau [J]. Science in China Series D: Earth Sciences 45: 577-594, doi: 10.1360/02yd9060.

徐祥德，王寅钧，赵天良,等. 2014. 高原东南缘大气近地层湍能特征与边界层动力、热力结构相关特征 [J]. 气象 40: 1165-1173. Xu Xiangde, Wang Yinjun, Zhao Tianliang, et al. 2014. Relationship Between Turbulent Energy in the Near-Surface Layer and Atmospheric Boundary Layer Thermodynamic Structure over the Southeastern Side of Tibetan Plateau [J]. Meteorological Monthly (in Chinese), 40: 1165-1173.

叶笃正，高由禧. 1979. 青藏高原气象学 [M]. 北京：科学出版社. Ye Duzheng, Gao Youxi. 1979. Meteorology of the Qinghai-Tibet Plateau. Beijing: Science Press.

Yu, G., Jiang, Y., Song, G., et al. 2014. Variation of Microcystis and microcystins coupling nitrogen and phosphorus nutrients in Lake Erhai, a drinking-water source in Southwest Plateau, China [J]. Environ. Sci. Pollut. R. 21: 9887-9898.

Yusup, Y., Liu, H. 2016. Effects of atmospheric surface layer stability on turbulent fluxes of heat and water vapor across the water–atmosphere interface [J]. J. Hydrometeorol. 17: 2835-2851.

Zhang, W., Furtado, K., Wu, P., et al. 2021. Increasing precipitation variability on daily-to-multiyear time scales in a warmer world [J]. Sci. Adv. 7: eabf8021.

Zhao, X., Liu, Y. 2017. Phase transition of surface energy exchange in China's largest freshwater lake [J]. Agr. Forest. Meteorol. 244: 98-110, doi: 10.1016/j.agrformet.2017.05.024.

Zhao, X., Liu, Y. 2018. Variability of Surface Heat Fluxes and Its Driving Forces at Different Time Scales Over a Large Ephemeral Lake in China [J]. J. Geophys. Res-Atmos. 123: 4939-4957, doi: 10.1029/2017jd027437.

Zheng, Y., Liu, H., Du, Q., et al. 2022. Effects of precipitation seasonal distribution on net ecosystem CO_2 exchange over an alpine meadow in the southeastern Tibetan Plateau [J]. Int. J. Biometerol. 66: 1561-1573.

Zia, A., Bomblies, A., Schroth, A.W., et al. 2016. Coupled impacts of climate and land use change across a river–lake continuum: insights from an integrated assessment model of Lake Champlain's Missisquoi Basin, 2000–2040 [J]. Environ. Res. Lett. 11: 114026.

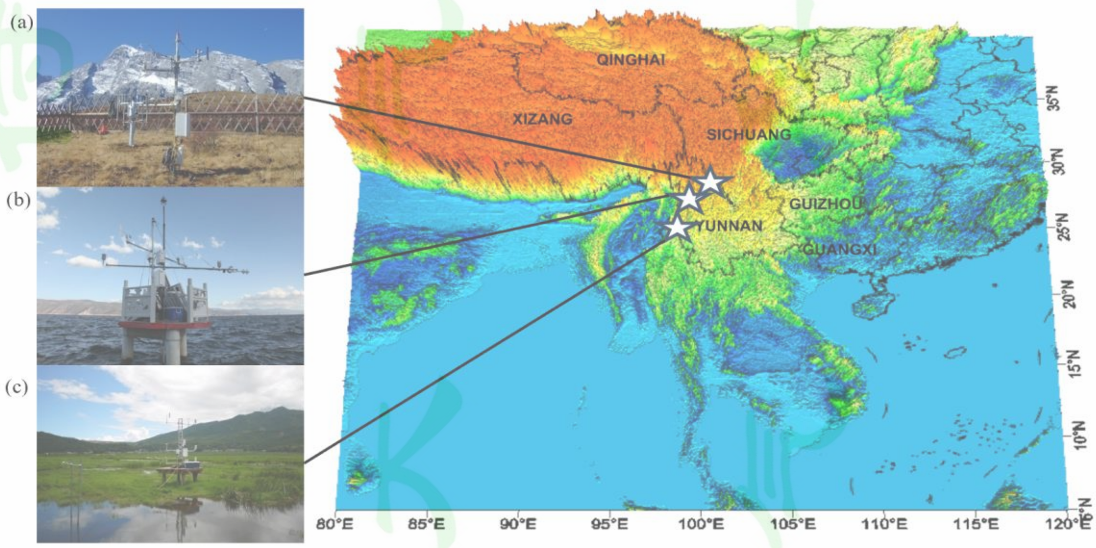


图 1 青藏高原东南缘不同生态系统通量观测站，（a）丽江高山草甸通量观测站（27°10′N, 100°14′E），（b）洱海通量观测站（25°46′ N, 100°10′ E ），（c）腾冲“浮毯”型湿地通量观测站（25°07′N, 98°33′E）

Fig.1 (a) Different types of ecosystems in southeast margin area of Tibetan Plateau, (b) The Lijiang alpine meadow flux site (27°10′N, 100°14′E), (c) The Erhai Lake flux site (25°46′ N, 100°10′ E) , (d) Tengchong ‘floating blanket’ wetland flux site (25°07′N, 98°33′E)

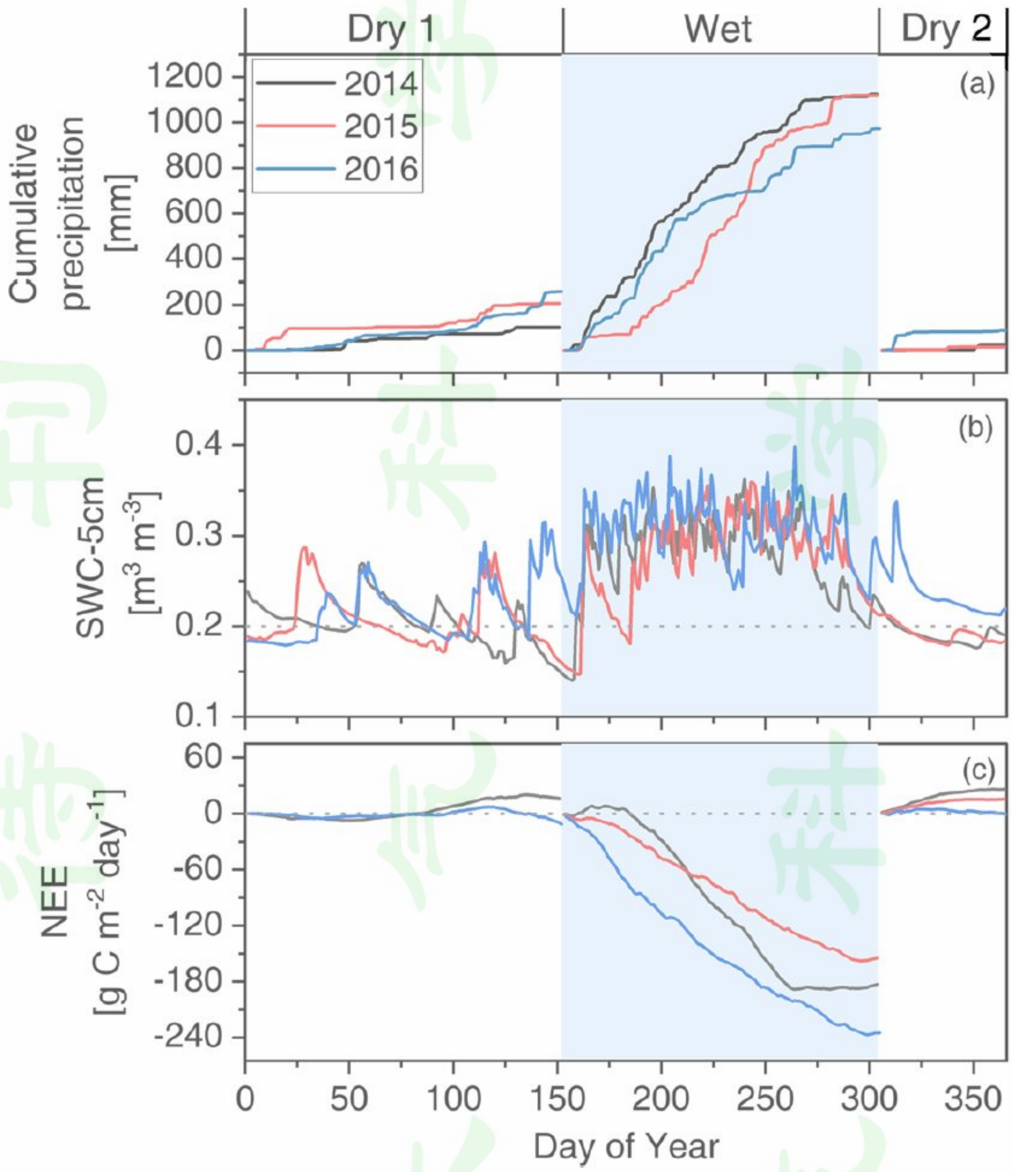


图 2 丽江高山草甸通量观测站 2014-2016 年（a）累积降水，（b）5cm 深度土壤水含量，（c）累积净碳交换通量 NEE。阴影部分代表湿季。引自 Zheng et al. (2022)

Fig.2 (a) Cumulative precipitation, (b) SWC (Soil water content) at the depth of 5 cm (SWC-5 cm), and (c) cumulative NEE (net ecosystem exchange) for the year 2014, 2015, and 2016 in Lijiang alpine meadow flux site. The shaded area denotes wet season. From Zheng et al. (2022)

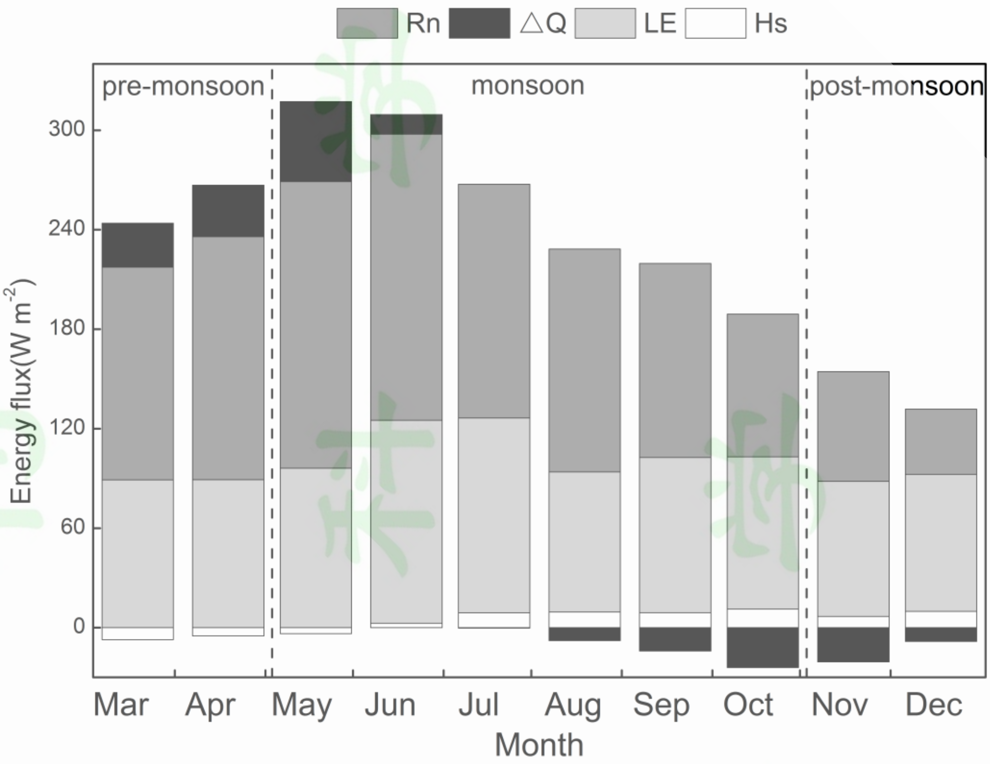


图 3 洱海能量通量各组分 2012-2015 年在季风前期、季风期和季风后期的月均值（△Q 储存热量，Rn 净辐射，LE 潜热通量，Hs 感热通量）。引自 Du et al. (2018b)

Fig.3 The monthly average energy fluxes (△Q , the storage heat flux in the lake; Rn , the net radiation flux; LE , the latent heat flux; and Hs, the sensible heat flux) during pre-monsoon, monsoon and post-monsoon periods from 2012 to 2015. From Du et al. (2018b)

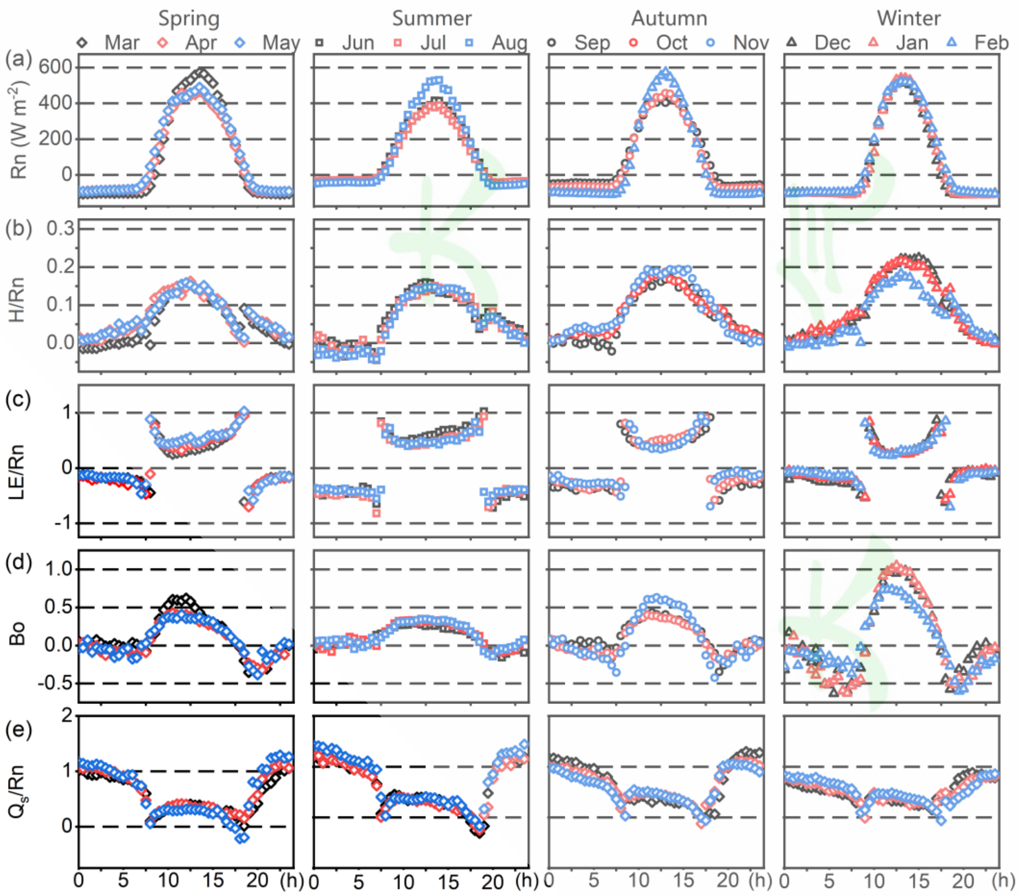


图 4 腾冲湿地不同季节逐月日变化（a）净辐射（Rn），（b）感热通量与净辐射的比值（H/Rn），（c）潜热通量与净辐射的比值（LE/Rn），（d）波文比（Bo），（e）储存热量与净辐射的比值（Qs/Rn）。引自 Shao et al. (2022)

Fig.4 Monthly average diurnal variation of (a) the net radiation (Rn), (b) the ratio of the sensible heat flux to the net radiation (H/Rn), (c) the ratio of the latent heat flux to the net radiation (LE/Rn), (d) Bowen ratio (Bo), and (e) the ratio of heat stored in the water to the net radiation (Qs/Rn) in the four seasons. From Shao et al. (2022)

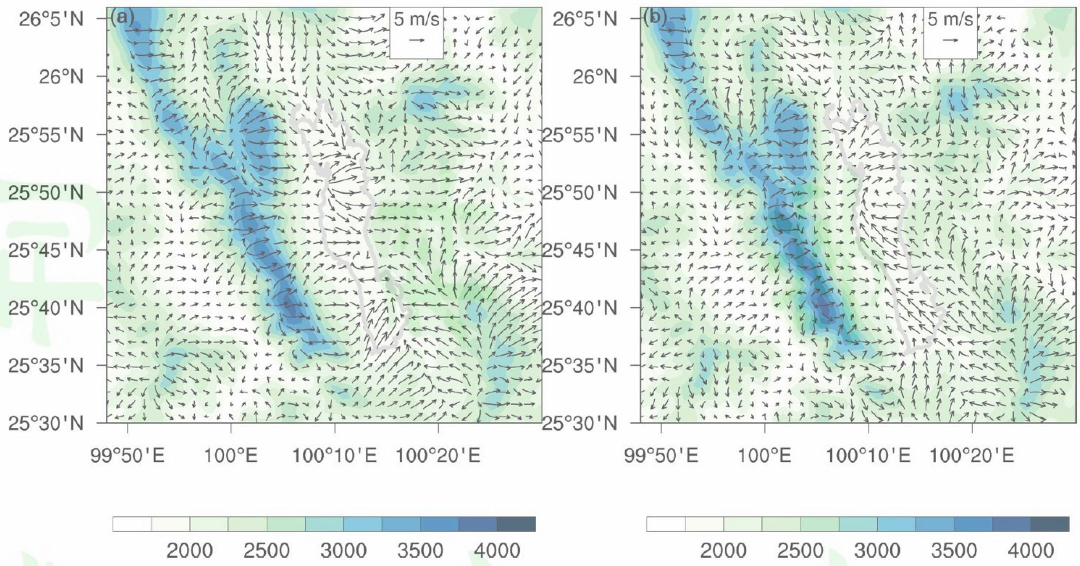
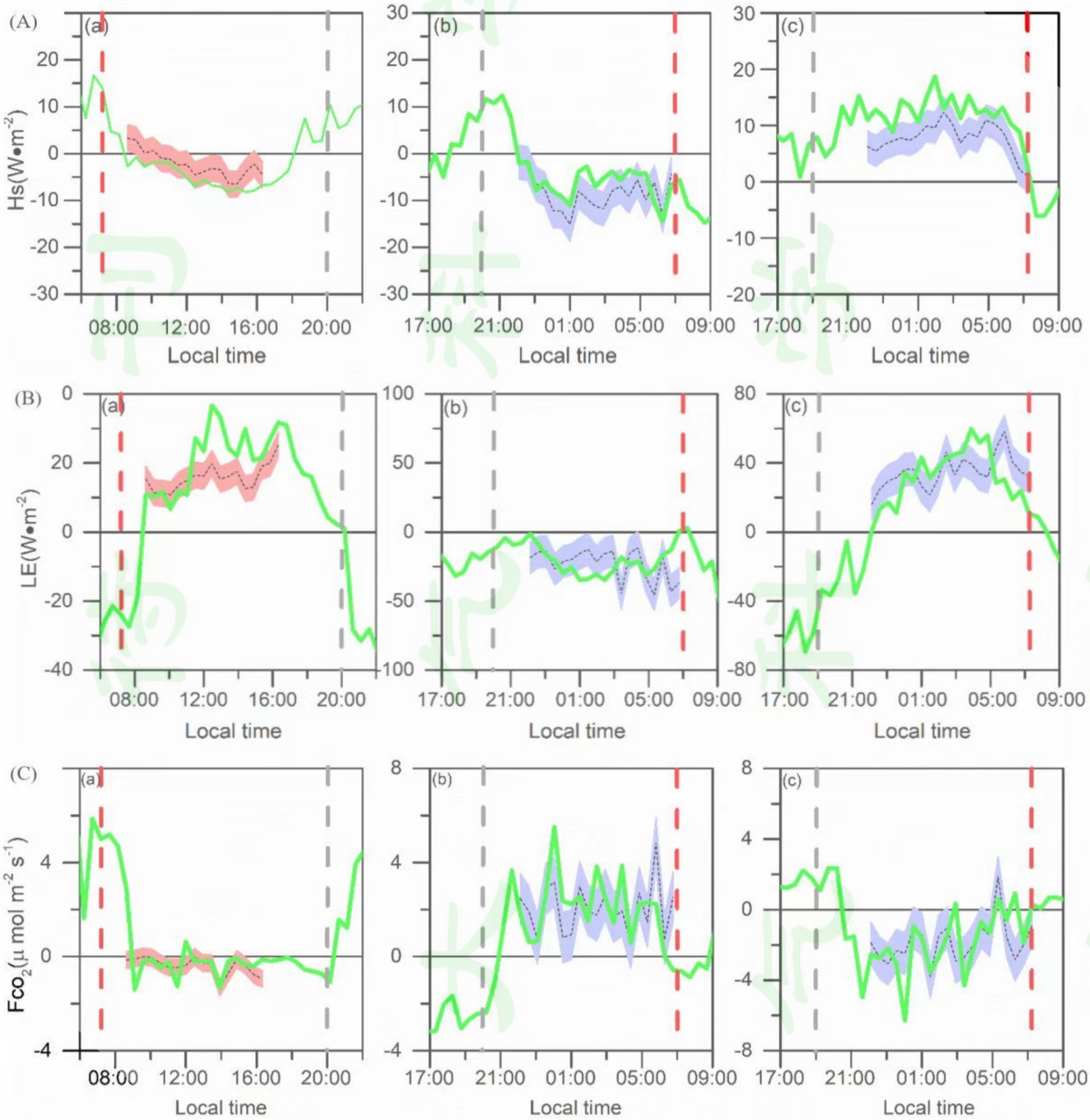


图 5 大理夜间水平适量（a）N1 型夜间山风环流（02:00 LST 12/08/2015）和（b）N2 夜间山风和陆风叠加环流（0200 LST 24/10/2015）。灰色的边框代表洱海。阴影表示海拔高度（单位：米）。风向和风速来自 WRF（The Weather Research and Forecasting Model）模式模拟资料。引自 Xu et al. (2021)

Fig.5 Wind fields for (a) an N1 nighttime breeze event (02:00 LST 12/08/2015) and (b) an N2 nighttime breeze event (0200 LST 24/10/2015). The gray outline shows Erhai Lake. Shadows indicate altitude (unit: m). Wind vectors and magnitudes are from WRF (The Weather Research and Forecasting Model) simulation data. From Xu et al. (2021)

图 6 （A）（B）（C）分别为感热通量、潜热通量和 CO_2 通量差值日变化特征，



其中（a）白天（11/08/2015）（b）N1 型（12/08/2015）（c）N2 型（24/10/2015），绿色实线为不同类型环流个例感热/潜热/ CO_2 通量日变化，黑色虚线为不同类型环流平均感热/潜热/ CO_2 通量变化，阴影为不同类型环流平均感热/潜热/ CO_2 通量变化标准差，红色虚线表示日出，灰色虚线表示日落

Fig.6 （A）（B）（C）are sensible heat flux (Hs), latent heat flux(LE) and CO_2 flux anomalies for (a) an example daytime breeze event (11/08/2015), (b) an example N1 breeze event (12/08/2015), and (c) an example N2 breeze event (24/10/2015) at the EC site are indicated with green lines. The vertical gray (red) solid lines indicate sunset (sunrise). The anomaly mean for all events is shown with black dots,

and the standard deviation is shown with shadow.