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秦岭山地气候变化的地形效应

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摘 要: 研究不同地形下的山地气候变化对于植被生长、不同动物种群的生存习性及对气候的应激性有重要意义。本文基于陕西秦岭地区 1959—2016 年 32 个国家站的日气温和降水资料, 采用 Anusplin 插值法、标准化降水蒸散指数 (SPEI)、稳健回归和 Theil-sen 回归法等方法分析了山区地形对气候变化的影响。结论如下: (1) 58 年来秦岭四个坡向上年均温度随着海拔的升高呈现显著下降趋势, 年降水随着海拔的升高呈现不同程度的上升趋势。温度随坡度的增加表现出下降趋势; 除秦岭南坡西段外, 降水随着坡度的增加呈现出上升趋势, 但均不显著。(2) 年尺度上, 秦岭山地南坡和南坡东段的气温呈显著增温趋势, 南坡西段和北坡呈不显著增温趋势; 四个方向上的降水均呈显著下降趋势。秦岭山地四个方向上的干湿等级为正常, 北坡和南坡西段的干湿状况一致, 58 年年均 SPEI 均为 0.07, 南坡东段较暖湿 (0.08), 南坡较暖干 (0.05)。(3) 季节尺度上, 秦岭山地四个方向上除了夏季外, 其他季节的气温均表现出不同程度的升温趋势, 降水均呈下降趋势。秦岭四个方向上四季干湿变化属于正常等级。秦岭北坡出现春季干暖化趋势; 南坡秋季较暖湿; 南坡东段和西段的冬季呈暖湿化特征; 南坡西段夏季呈现暖干化特征。

关键词: 山区气候; 地形效应; 气候变化; 秦岭

中图分类号: K903; P94

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全球气候变化对区域气候的影响是一个重点研究方向, 根据研究, 1880—2012 年, 全球海陆表面平均温度升高了 0.85 °C 且未来全球变暖将会持续^[1], 而气候变化会减缓区域气候而引起区域陆地生态的改变^[2-5]; 山体作为一种独特的地貌单元, 其自身的气候变化有着强烈的区域性和独特性, 地形作为山地最为突出和复杂的地理因子, 通过海拔、坡度和坡向在一定程度上影响着温度、降水、风速、日照和蒸散发等因素的改变, 从而造成山区复杂的气候模式^[6-7]。有研究表明^[8] 秦岭高山特有种——

巴山冷杉的生理特征因受南北坡不同的干湿特征而表现出明显的差异性。研究不同地形下的山地气候变化及干湿变化不仅可以有效预测区域气候对植被生长的影响, 还有助于了解不同种群生物的生存习性以及对不同尺度下气候变化表现出的敏感性, 从而获知种群最适宜生存的气候条件。由 Vicente-Serrano 等^[9-10] 提出的标准化降水蒸散发指数 (Standardized Precipitation Evapotranspiration Index, SPEI) 考虑了降水和温度因子, 具备多时间尺度优势且适用较好、应用广泛, 能够准确地表征气候的干

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湿变化。

近年来对秦岭地区气候变化的相关研究主要包括:秦岭南北坡的气候变化和春季气候变化^[11-12];利用树轮重建秦岭地区过去百年的气候变化^[13-16];秦岭山地气候变化对物候特征、植被覆盖、树轮宽度和河流径流量的影响与响应研究^[17-21]。傅抱璞基于考察资料和有限的测站资料研究了 1950—1970 年秦岭山地各个气候要素的特征^[22];陆福志建立了秦岭大巴山的气候格点数据集^[23]。然而,目前对于全球气候变化背景下秦岭地区不同坡度坡向下山地气候的特征及其干湿变化呈现怎样的趋势这个科学问题尚待解决。本文以位于陕西南部的秦岭腹地为研究对象,采用 Anusplin 插值法、稳健回归和 Theil-sen 回归等方法研究秦岭地区气候变化的地形特征及干湿变化特征,以此丰富山地气候学的理论研究并为局地气候变化提供理论基础和科学依据。

1 资料和方法

1.1 研究区概况

本文研究区主要为陕西省境内的秦岭腹地^[24](32°40′~34°35′N,105°30′~111°3′E),总面积约 6.19 万 km²,如图 1 所示。海拔范围为 195~3771.2 m,其中,太白山为秦岭山脉的主峰。秦岭山地与 1 月 0℃等温线、800 mm 等降水量线基本重合。秦岭山地南北气候差异明显,北坡属于暖温带半湿润气候,广泛分布暖温带落叶阔叶林;南坡为北亚热带湿润气候,分布着北亚热带常绿阔叶—落叶

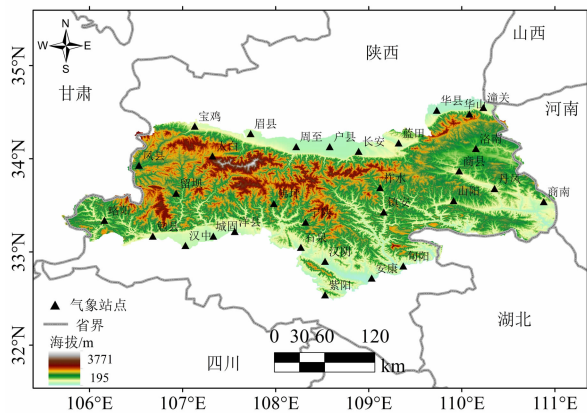


图 1 研究区地理位置和气象站点的分布
Fig. 1 Location of study area and the distribution of meteorological stations

阔叶混交林^[17,21]。

1.2 数据来源

1959—2016 年秦岭地区 32 个国家站日气温和降水数据均来自陕西省气象局,32 个气象站点根据不同坡向分组如表 1 所示。

表 1 秦岭山脉气象站点资料

Tab. 1 Information of meteorological stations in the Qinling Mountains				
坡向	站点名称	纬度/°N	经度/°E	海拔/m
北坡	宝鸡	34.35	107.13	612.4
	眉县	34.27	107.73	517.6
	周至	34.13	108.22	436.0
	户县	34.13	108.58	414.8
	长安	34.08	108.89	445.0
	蓝田	34.17	109.32	540.2
	华县	34.52	109.73	341.5
	华阴	34.55	110.09	351.3
	华山	34.48	110.08	2064.9
南坡	潼关	34.55	110.23	556.3
	石泉	33.05	108.27	484.9
	安康	32.72	109.03	290.8
	汉阴	32.9	108.53	413.1
	旬阳	32.85	109.37	285.5
	紫阳	32.54	108.53	503.8
	宁陕	33.32	108.32	802.4
南坡西段	留坝	33.63	106.93	1032.1
	略阳	33.34	106.16	794.2
	佛坪	33.52	107.98	827.2
	勉县	33.17	106.68	548.1
	汉中	33.07	107.03	509.5
	城固	33.17	107.33	486.4
	洋县	33.22	107.56	468.6
	凤县	33.93	106.53	985.9
	太白	34.03	107.32	1543.6
南坡东段	商县	33.87	109.97	742.2
	柞水	33.69	109.12	818.2
	镇安	33.43	109.16	693.7
	山阳	33.55	109.91	660.2
	商南	33.54	110.88	523.0
	丹凤	33.68	110.35	581.4
	洛南	34.11	110.15	963.4

2 研究方法

2.1 Anusplin 插值法

Anusplin 最早是由澳大利亚学者 Hutchinson 在总结前人经验基础上研发的,它是基于普通薄盘和局部薄盘样条函数插值理论^[25]。Anusplin 的优点是除了样条自变量外,还允许引入线性协变量,如海拔对气温的影响。局部薄盘光滑样条的理论模型表述如下:

$$z_i = f(x_i) + b^T y_i + e_i (i = 1, \dots, N) \quad (1)$$

式中, z_i 为位于空间 i 点的因变量; x_i 为样条独立变量; f 为要估算的关于 x_i 未知光滑函数; y_i 为独立协变量; b 为 y_i 的系数; e_i 为具有期望值为 0 的自变量随机误差^[26]。

2.2 趋势分析法

本文采用稳健回归和 Theil-sen 回归对秦岭山地 58 年来不同坡向上的气候变化趋势进行分析。稳健回归 (Robust Regression) 是将对异常值十分敏感的经典最小二乘回归中的目标函数进行修改^[27]。稳健回归还可以用于异常点检测,或者是找出某些对模型影响最大的样本点。Theil-sen 回归 (Sen's slope) 为了量化秦岭山地不同坡度上的气候变化趋势的大小,使用非参数方法 Sen's slope 方法^[28-32],它是一个参数中值估计器,它适用泛化中值,对多维的异常点 (outliers 外点) 有很强的稳健性。Sen's slope 可以用来判断时间序列趋势的升降同时降低潜在数据偏态分布的敏感性,当 $SS > 0$ 时,时间序列呈上升趋势,反之呈下降趋势。Sen's slope 的计算公式如下:

$$SS = \text{median} \left[\frac{a_j - a_i}{j - i} \right] (j - i) \quad (2)$$

式中, median 为中值函数; a_j 为 j 时间对应的气候因子值; a_i 为 i 时间对应的气候因子值。

在本文中,在 T -test 的 P 值均小于 0.01 且稳健回归系数和 Theil-sen 回归系数趋势一致时,表示气候变化趋势具有显著性。

2.3 标准化降水蒸散指数 (SPEI)

为了揭示秦岭地区气候变化的干湿特征,本文使用 SPEI 值来反映季节干湿情况。对于干湿等级的划分,参考 GB/T20481-2006《气象干旱等级》和

借鉴刘珂等^[11,33]对干湿等级的划分方法,具体划分标准如表 2 所示。

表 2 SPEI 干湿等级划分

Tab. 2 Dry-wet classification of SPEI

SPEI 值	干湿等级
≥ 2.0	极端湿润
$1.5 \leq \text{SPEI} < 2.0$	严重湿润
$1.0 \leq \text{SPEI} < 1.5$	中等湿润
$0.5 \leq \text{SPEI} < 1.0$	轻度湿润
$-0.5 \leq \text{SPEI} < 0.5$	正常
$-1.0 \leq \text{SPEI} < -0.5$	轻微干旱
$-1.5 \leq \text{SPEI} < -1.0$	中等干旱
$-2.0 \leq \text{SPEI} < -1.5$	严重干旱
≤ -2.0	极端干旱

3 结果与分析

3.1 秦岭山地气候的地形效应

为了探究秦岭山地气候变化的地形效应,利用 ARCGIS10.3 通过分别匹配气温和降水与海拔、坡度图层,得到图 2、图 3,分别为秦岭不同海拔和坡度上年均温和年降水在秦岭四个坡向上的变化规律。由图 2 可知,秦岭 58 年来年均温度随着海拔的升高呈现显著下降趋势,年降水随着海拔的升高呈现不同程度的上升趋势。其中,秦岭南坡东段气温直减率最大,为 $0.63 \text{ } ^\circ\text{C}/(100 \text{ m})$,北坡、南坡和南坡西段的气温直减率分别为 0.43 、 0.45 和 $0.49 \text{ } ^\circ\text{C}/(100 \text{ m})$ 。秦岭南坡西段的年降水变化最为稳定,速率为 $2.95 \text{ mm}/(100 \text{ m})$,北坡、南坡和南坡东段的上升率分别为 14.19 、 15.7 和 $14.52 \text{ mm}/(100 \text{ m})$ 。从图 2 中还可知,秦岭地区的气候变化在高海拔地区的变化不稳定,尤其是降水变化。坡度在一定程度上可影响气候因子的变化,从而引起山地植被和景观发生变化。由图 3 可知,温度随坡度的增加表现出下降趋势;除了南坡西段,降水随着坡度的增加表现出上升趋势,但均不显著。

3.2 秦岭山地不同坡向年均气候变化趋势

秦岭山地沿不同坡向年均气候变化趋势如图 4

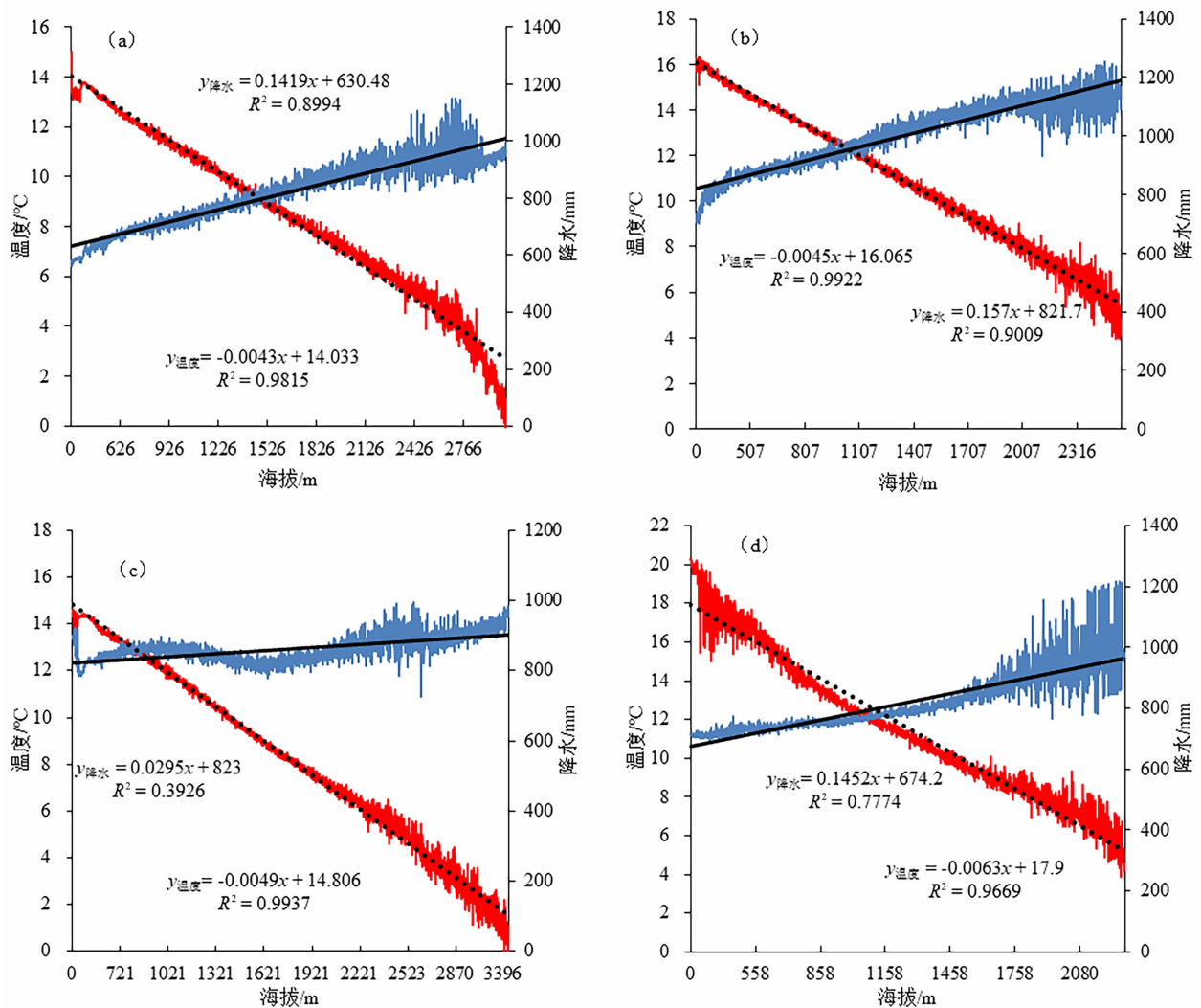


图 2 秦岭山地不同坡向 1959—2016 年年均气温和降水与海拔的关系

(a,b,c,d 分别代表秦岭北坡、南坡、南坡西段和南坡东段)

Fig.2 Relationship of annual mean temperature and precipitation with elevation in different aspects of the Qinling Mountains from 1959 to 2016 (a,b,c,d represent the northern slope, the southern slope, the western section of the southern slope and the eastern section of the southern slope, respectively)

所示,1959—2016 年秦岭山地南坡和南坡东段的气温呈现显著增温趋势,四个方向上的降水均呈显著减少趋势。其中,秦岭山地北坡、南坡、南坡西段和南坡东段 1959—2016 年年均温为 12.47℃、15.57℃、12.74℃和 12.64℃,稳健回归系数分别为 0.2、0.1、0.2 和 0.2℃/(10a) ($p < 0.01$),Sen's slope 系数分别为 -0.1、0.2、-0.1 和 0.1℃/(10a)。四个方向上年降水量分别为 644.4、887、803.9 和 745 mm,稳健回归系数分别为 -12、-4、-9.8 和 -2.9 mm/(10a) ($p < 0.01$),Sen's slope 系数分别为 -170、-30、-120 和 -150 mm/(10a)。结合表 3 可知,秦岭山地四个方向上的干湿等级为

正常,北坡和南坡西段的干湿状况一致,58 年来年均 SPEI 为 0.07,南坡东段较暖湿,南坡较暖干。

表 3 秦岭不同坡向年均 SPEI 值

Tab.3 Annual SPEI values in different slopes of the Qinling Mountains

坡向	SPEI
北坡	0.07
南坡	0.05
南坡西段	0.07
南坡东段	0.08

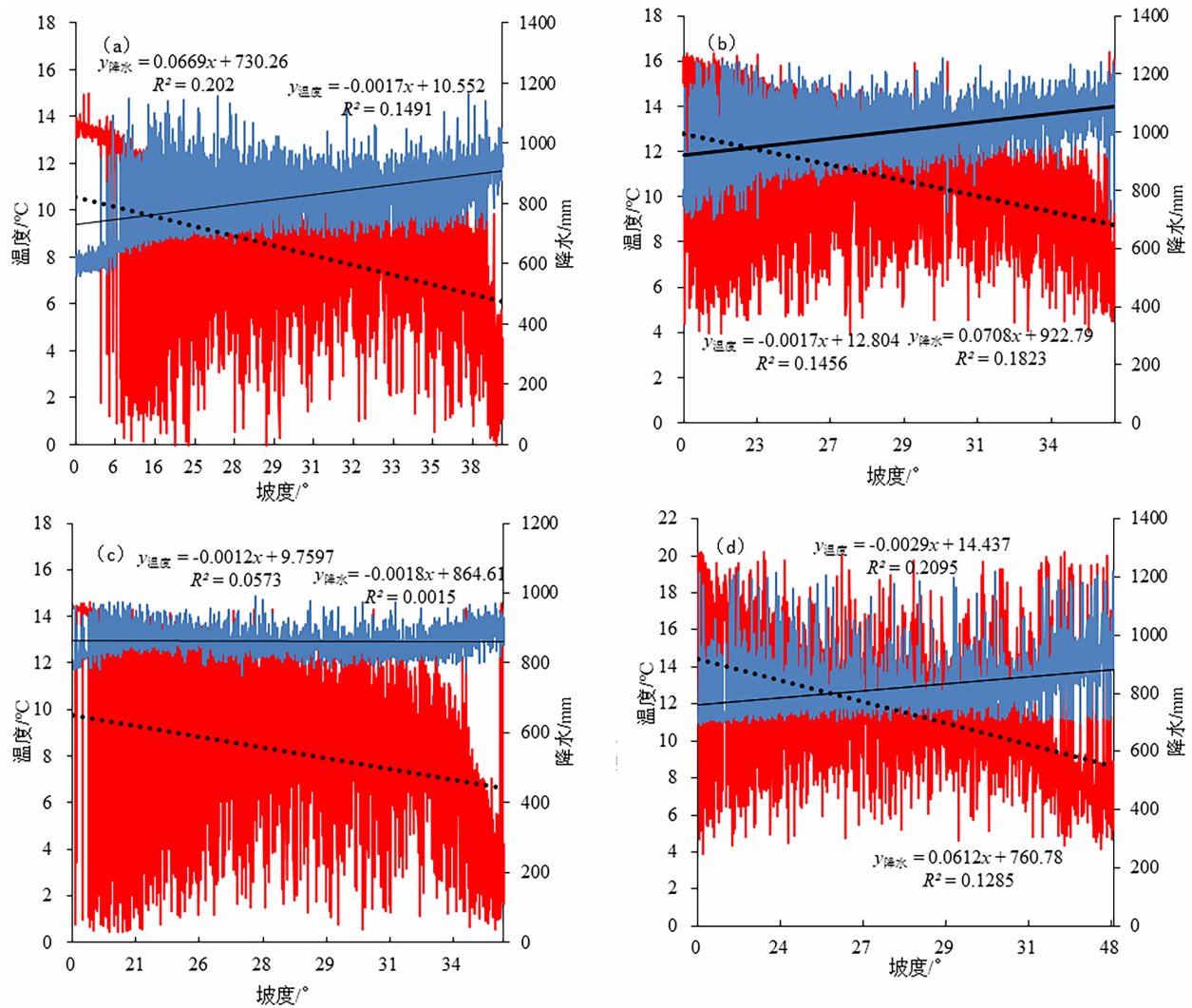


图3 秦岭山地不同坡向上1959—2016年年均气温和降水与坡度的关系

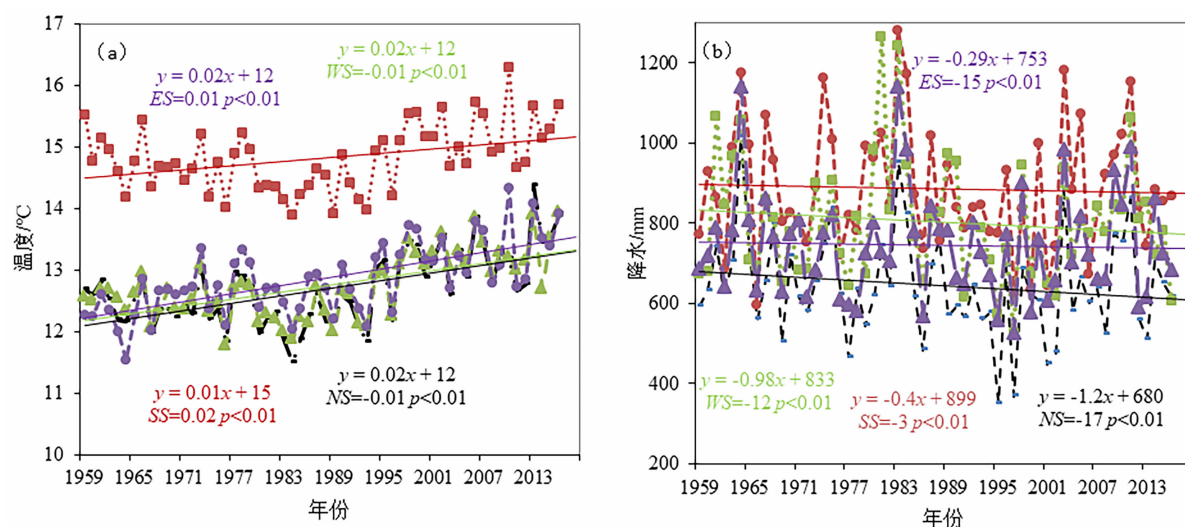
(a,b,c,d 分别代表秦岭北坡、南坡、南坡西段和南坡东段)

Fig. 3 Relationship of annual mean temperature and precipitation with slope in different aspects of the Qinling Mountains from 1959 to 2016 (a,b,c,d represent the northern slope, the southern slope, the western section of the southern slope and the eastern section of the southern slope, respectively)

3.3 秦岭山地不同坡向四季气候变化趋势

秦岭山地沿不同方向上四季气候变化趋势如图5所示,58年来秦岭山地四个方向上除了南坡夏季呈显著下降趋势,其他三个季节的气温均表现出不同程度的升温趋势;降水除了夏季呈上升趋势外,其他三个季节均呈减少趋势。其中,南坡气温在四季中均高于其他三个坡向上的气温,南坡四季平均气温分别为15.1℃、25.1℃、14.9℃和4.2℃,南坡气温四季稳健系数分别为0.2、-0.005、0.1和0.2℃/(10a) ($p < 0.01$), Sen's slope 系数分别为-0.06、-2.5、-0.6和-0.3℃/(10a),由此可以得出南坡夏季气温呈显著下降趋势;南坡降水除了

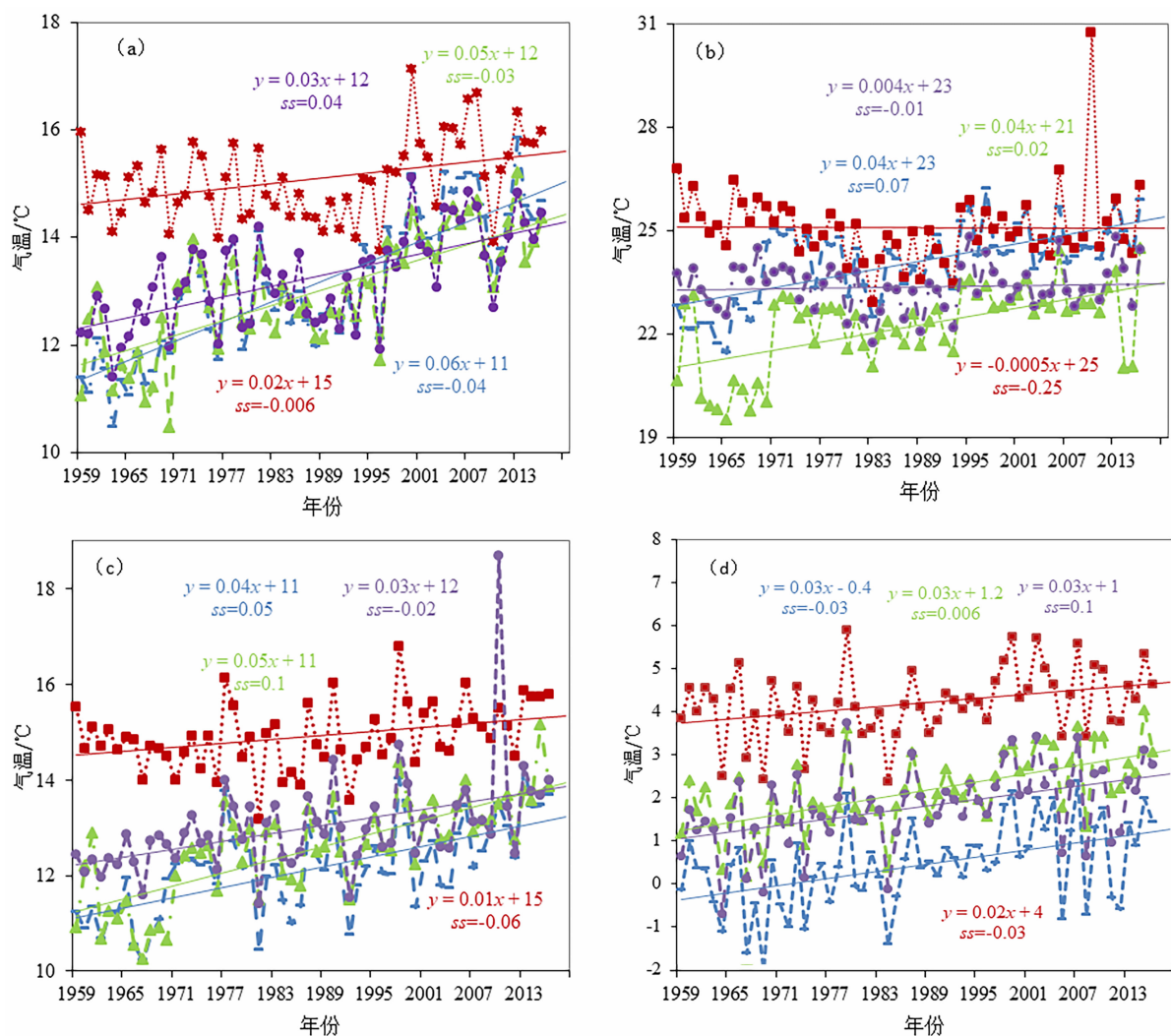
冬季外,均高于其他三个坡向上的降水,南坡四季降水量分别为193.7、407、262.1和24.2mm,南坡四季稳健系数分别为-5、20、-10和-0.9mm/(10a) ($p < 0.01$), Sen's slope 系数分别为-80、-40、-140和-10mm/(10a),由此可以看出南坡降水除了夏季外,均呈显著下降趋势。北坡除了冬季外,均低于其他三个坡向上的降水,北坡四季降水分别为145.6、264.4、196.5和23.9mm,北坡四季降水稳健系数分别为-6、10、-5和0.6mm/(10a) ($p < 0.01$), Sen's slope 系数分别为-50、0.2、30和-20mm/(10a)。结合表4可以看出,秦岭四个方向上四季干湿变化等级属于正常。其中,秦岭北坡



注：“NS”代表北坡斜率，“SS”代表南坡斜率，“WS”代表南坡西段斜率，“ES”代表南坡东段斜率。NS, north slope; SS, south slope; WS, the western section of the southern slope; ES, the eastern section of the southern slope.

图4 秦岭山地不同坡向 1959—2016 年年均气温和降水变化趋势图

Fig. 4 Trend of annual mean temperature and precipitation in different aspects of the Qinling Mountains from 1959 to 2016



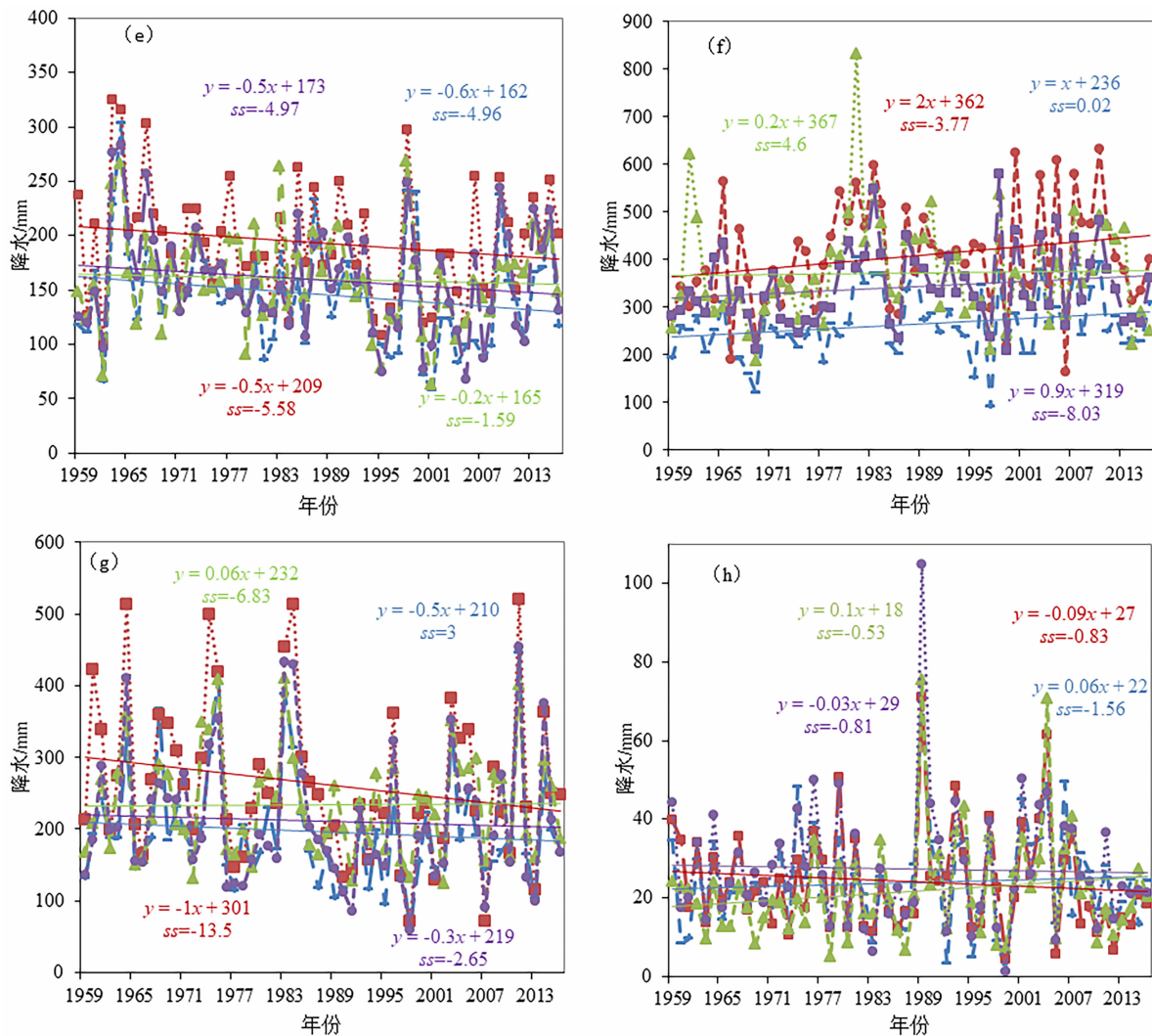


图5 秦岭山地不同坡向 1959—2016 年四季气温和降水变化趋势图

(a, b, c, d 为春夏秋冬的气温; e, f, g, h 为春夏秋冬的降水)

Fig. 5 Trend of seasonal temperature and precipitation in different aspects of the Qinling Mountains from 1959 to 2016 (a, b, c, d are the spring, summer, autumn and winter of temperature; e, f, g, h are the spring, summer, autumn and winter of precipitation)

出现春季干暖化趋势;南坡秋季较其他季节相对暖湿;南坡东段和西段的冬季均表现出暖湿化特征;南坡西段夏季较其他坡向呈现暖干特征。总体而言,秦岭山地季节尺度上,南坡较北坡春季暖湿,冬季暖干;南坡西段较东段的夏秋干,冬季较湿润。

4 结论

(1) 秦岭 58 年来年均温度随着海拔的升高呈现显著下降趋势,年降水随着海拔的升高呈现不同程度的上升趋势。温度随坡度的增加表现出下降趋势;除南坡西段外,降水随着坡度的增加表现出上升

表4 秦岭不同坡向季均 SPEI 值

Tab. 4 Seasonal SPEI values in different slopes of the Qinling Mountains

季节	SPEI			
	北坡	南坡	南坡西段	南坡东段
春季	0	0.01	0.01	0.01
夏季	0.01	0.01	0	0.01
秋季	0.02	0.02	0.01	0.02
冬季	0.04	0.01	0.05	0.04

趋势,但均不显著。

(2) 年尺度上,58 年来秦岭山地南坡和南坡东

段气温呈现显著增温趋势,四个方向上的降水均呈显著减少趋势。秦岭山地四个方向上的干湿等级为正常,北坡和南坡西段的干湿状况一致,南坡东段较暖湿,南坡较暖干。

(3)季节尺度上,秦岭山地四个方向上除夏季外,其他季节的气温均表现出不同程度的升温趋势,降水均呈下降趋势。秦岭四个方向上四季干湿变化等级属于正常。秦岭北坡出现春季干暖化趋势;南坡秋季较其他季节相对暖湿;南坡东段和西段的冬季呈暖湿化特征;南坡西段夏季呈现暖干特征。总体而言南坡较北坡春季暖湿,冬季暖干;南坡西段较东段夏秋较干,冬季较湿润。

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Topographic Characteristic of Climate Change in the Qinling Mountains, China

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Abstract: The study of the impacts of climate change in mountainous area in different terrains, is of great significance to vegetation growth, habits of different animal populations and environment. Using 32 meteorological stations' daily observed temperature and precipitation since 1959 to 2016, the influence of mountain topography on climate change were studied with the Anusplin interpolation method, Standardized Precipitation Evapotranspiration Index (*SPEI*), Robust Regression method and Theil-sen regression method. The results showed that over the past 58 years, the annual average temperature of the four slopes in the Qinling Mountains had shown a significant decreasing trend with the elevation, while the annual precipitation had shown an increasing trend in varying degrees with the elevation. The temperature indicated a decreasing trend with the increase of slope. Except for the western section of southern slope, the precipitation demonstrated an increasing trend with increasing of slope, but it was not significant. On an annual scale, the temperature on the southern slope and eastern section of southern slopes in the Qinling Mountains manifested a significant warming trend, while the temperature on the western section of southern slope and northern slopes revealed insignificant warming trend. Precipitation on four slopes revealed a significant decreasing trend. The dry and wet grade of four slopes in the Qinling Mountains was normal. The dry and wet conditions of the northern slope and the western section of southern slope were the same, which the annual *SPEI* for 58 years was 0.07, the eastern section of southern slope was warmer and wetter (*SPEI* = 0.08), and the southern slope was warmer and drier (*SPEI* = 0.05). On the seasonal scale, except for summer, the temperature on four slopes of the Qinling Mountains, all indicated varying degrees of warming trend, and the precipitation indicated a decreasing trend. The four slopes of the Qinling Mountains had normal dry and wet changes. The northern slope of the Qinling Mountains manifested a trend of dry warming in spring. The southern slope was warmer and wetter in autumn. In the winter on the eastern and western sections of southern slopes were characterized by warm and humid. The western section of southern slope showed a warm and dry feature in summer.

Key words: alpine climate; topographic effect; climate change; the Qinling Mountains