

## Article

# The Effect of Climate Factors on 400 Years of Traditional Chinese Residential Building Roof Design: A Study from Southwest China

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**Abstract:** Indigenous people have used architecture over millennia to adapt to climatic factors and achieve stable and comfortable living. These adaptations can still inform the design of contemporary regional architecture. In order to explore the relationship between traditional dwellings and climatic factors, we examine buildings in four provinces and cities in southwest China. A database was created using detailed data obtained from the literature on indicators of climatic factors (e.g., temperature, precipitation, temperature difference, wind speed, solar radiation) and architectural elements (e.g., roof slope and eave length). Thorough statistical analysis shows that (1) MPWM has the most significant correlation with the slope angle of traditional building roofs but is not recommended as a predictor in multivariate equations. (2) Temperature and wind speed were significant correlates of roof slope, and a multiple regression model dominated by AMT and AWS serves as a good predictor of roof slope. (3) Solar radiation was not correlated with roof slope but was the largest correlate of eaves length in traditional buildings. AMSR and AWS also dominantly affect eaves length in a regression relationship. These results serve not only as a reference to catalog the use of traditional passive technologies but can guide the design of green buildings. However, more research is needed to refine the use of passive technologies to adapt to climate change

**Keywords:** traditional dwellings; roof slope; eaves length; climate adaptation; passive technology; regression analysis



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## 1. Introduction

### 1.1. Motivation

Massive energy consumption in the last century has led to the pollution of the natural environment and a gradual deterioration of the climate. The construction sector has the highest carbon emissions of any industry in China [1], and global CO<sub>2</sub> emissions from the energy sector reached a record high of 36.3 billion tons in 2021. A green transformation within the construction sector is crucial if we are to meet the Paris Agreement target of limiting global warming to 1.5 °C [2].

After years of research and practical efforts by countries around the world, a more mature system to save energy and reduce emissions in buildings was formed. First, the common international ISO7730 and ASHRAE standards were created to measure energy consumption from the perspective of thermal comfort. Second, the design of passive strategies to reduce heat and cold loads in buildings is now a primary focus of architectural design [3]; and third, active strategies give sufficient supply to equipment according to its heating and cooling requirements. Nevertheless, China's building energy consumption was 2.27 billion tce (ton of standard coal equivalent) in 2020, with the operation phase accounting

for 21.7% and electricity carbon emissions accounting for 53% of the total building operation carbon emissions. Furthermore, carbon emission from electrical generation is increasing rapidly, with thermal carbon emission also steadily rising [4]. Active energy-efficient buildings are the preferred energy-saving design, and their energy consumption continues to grow dramatically. Although the single active design can be further optimized, a passive design provides a good opportunity for architects to exert their creativity while reducing energy consumption. Traditional Chinese architecture, a product of thousands of years of productive life, utilizes passive design techniques worthy of consideration in modern architecture, especially in roof construction.

### *1.2. Passive Techniques of Traditional Architecture*

China's topography is complex, and many researchers have documented how traditional architecture was designed to incorporate local climate and cultural characteristics. In 2008, Chen Zhan proposed that the passive techniques used in conventional dwellings have a wide range of applications [5]. He Jingtang explored and verified the effectiveness of roof ventilation and heat dissipation, two ecological energy-saving techniques used in traditional subtropical dwellings [6]. Sun Feifei proposed corresponding passive design concepts for Chinese vernacular dwellings [7], and Ji Weidong analyzed the design of low-energy technology applications in traditional Chinese dwellings [8]. Today, Chinese passive technology is still adaptable to modern architectural designs [9] and follows four principles:

1. The conventional spatial layout considers daylight, monsoons, cold currents, and water.
2. Natural phenomena are considered, such as the wind effect, the chimney effect, and the effect of regional climate.
3. Ecological building materials like bamboo, crop blocks, earth, and stone are used.
4. Traditional architectural practices, such as insulation and water recycling, are used [10].

### *1.3. Past Research*

A survey conducted in Australia identified the roof as the second most environmentally influenced building element [11]. Roof design is the most prominent and typical energy-saving technique in the passive design of traditional Chinese houses. Most conventional building roofs are sloping, tile-pitched roofs, which ensures effective rainwater drainage from the roof. Projecting eaves also keep rainwater away from walls and obstruct direct sunlight. At the same time, roof tiles also transfer heat during exposure to direct sunlight, and the top floors are occasionally furnished with attics to warm lower floors.

Passive technology and the climate adaptation of traditional buildings attracted extensive attention from scholars worldwide, beginning in the 1940s when Professor Liu Dunzhen first studied Chinese residential buildings [12–14]. In 2003, Zheng Lipeng found that rainfall intensity determines the roof form [15], and Tan Liangbin described the influence of natural factors such as solar radiation, temperature, precipitation, and wind on residential building roofs [16]. Li Jie connected roof slope, structure, material, and construction process with climate change [17] and mentioned that the maximum rainfall in a certain period is the main factor influencing roof slope [18,19]. Yan Haiyan argues that the roofs of traditional buildings have poor insulation properties, as the longer eaves prevent heat absorption through the walls and mitigate excessive temperatures in summer [20]. Traditional buildings often use the attic as a buffer space to insulate against solar radiation in the summer and to trap heat in the winter [21]. Moreover, Wang Degen suggests that temperature and precipitation primarily influence the appearance of traditional dwellings [22]. These technical experiences gained from human adaptation to the natural environment still retain scientific value today and can support the design of energy-efficient buildings. However, the above research studies are qualitative, and few quantitative studies have been conducted. Zhang Tao used linear regression to investigate the relationship between roof slope and rainfall, sunlight, and temperature in residential buildings across the country,

but the small sample size limits the study's validity [23]. In 2022, Zhang Xin conducted a regression analysis of data from forty typical residential buildings in various climate types across the country and found the roof slope and window-to-wall ratio were largely unaffected by climate [24]. Moreover, a meta-analysis by Yang Wenting reviewed 55 studies of residential dwellings worldwide and noticed that climate strategies were described based only on one or a few local dwellings and that these cases may not fully represent all regional characteristics [25]. Moreover, these studies inconsistently identify influencing factors and lack a quantitative methodology where multiple factors are studied simultaneously. In order to better apply these techniques from traditional buildings, quantitative studies are needed to fully describe the relationship between the regional climatic factors and building elements and improve the use of these techniques.

#### 1.4. Goals and Research Questions

This paper addresses these shortcomings by focusing on the relationship between various climatic factors and the roofing elements of traditional residential buildings within southwest China. We use multiple regression methods to incorporate roof slope and eaves length into an analytical model along with numerous climatic variables in order to comprehensively assess the role of various factors such as temperature, rainfall, and wind speed in the variation of roof slope and eaves. This analysis will provide a more accurate predictive model that may be instructive for a particular climate zone or region, confirm the relationship between traditional building elements and climatic factors, and improve the proper use of passive techniques for traditional buildings.

This paper considers the following issues:

1. Do climatic factors influence traditional roof elements (i.e., roof slope and eaves length)?
2. What are the relationships between the slope of a traditional roof, the length of the eaves, and various climatic factors?
3. Which climatic factors have the greatest influence on traditional roof construction?
4. Can a system be developed to recommend a building roof style suitable for a particular local climate?

## 2. Method

The research framework of this paper consists of data collection, data testing, statistical analysis, and model testing. We review the previous relevant literature and published mapping bibliographies to identify 124 buildings. WorldClim.org was used to obtain the corresponding indicator data by latitude and longitude, and these data were stored in a database (Table S1: database). Statistical tests, including normal distribution tests, were conducted on all variable data in the database using the one-sample Kolmogorov–Smirnov (K–S) test to select appropriate coefficients for correlation analysis. After correlation and regression analyses, further analysis was performed with bivariate correlation analysis, regression analysis (variance partitioning), and model selection to determine relevant impact factors. Finally, models are tested to establish their validity, reliability, and generalizability.

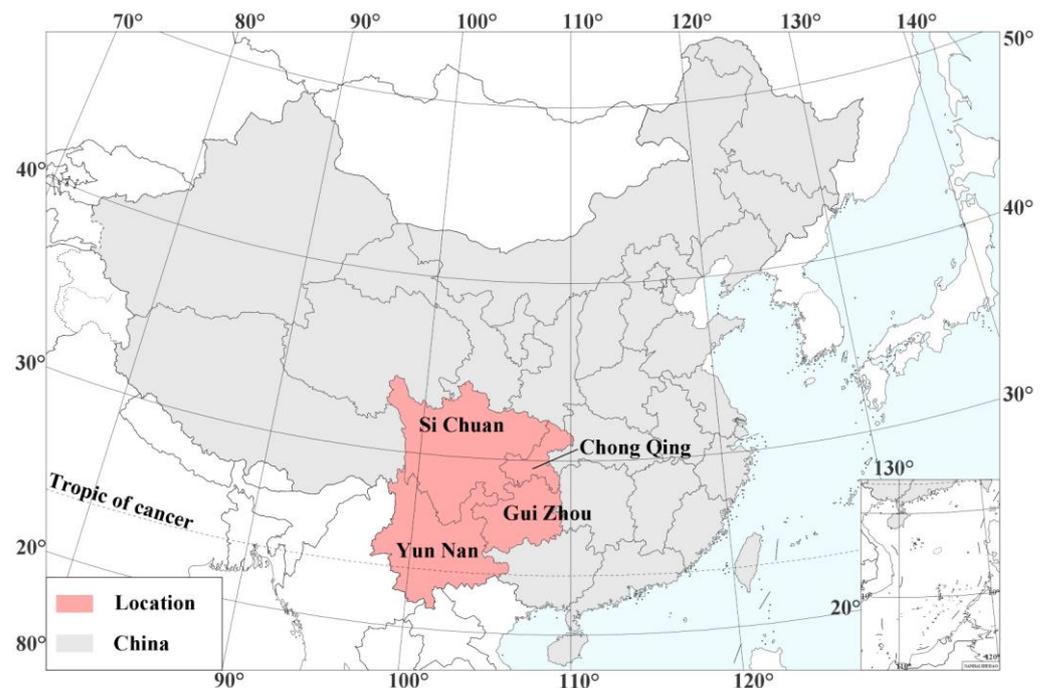
### 2.1. Data Collection

#### 2.1.1. Location Selection

Four provinces and municipalities in southwest China (Chongqing, Sichuan, Guizhou, and Yunnan) were selected for the study for the following reasons (Figure 1):

- (1) These locations possess a relatively consistent climate. Except for a small area of alpine boreal climate, the region is dominated by a subtropical monsoon climate. Average temperatures range from 10 °C to 20 °C, average annual precipitation is generally between 700 mm and 1400 mm, and there is little snowfall. We expect that conclusions drawn from the region will apply to most of China and other countries within the monsoon zone.

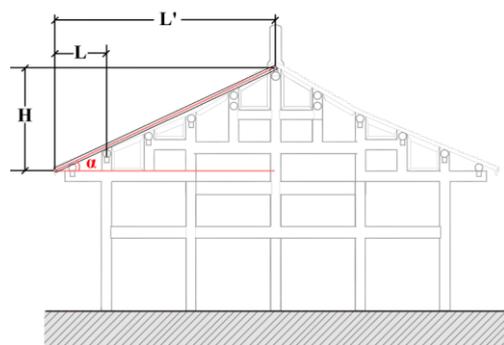
- (2) Traditional roof construction, such as slope and eaves length, varies extensively in this region. Climatic elements should also differ due to the complexity of the terrain, which should facilitate pattern identification.
- (3) There are few regional cultural differences. The culture, topography, customs, and language of Yunnan, Guizhou, Sichuan, and Chongqing are all similar. The culture inhabiting this region is a highly compatible fusion culture formed from an attitude of inclusivity. By incorporating advanced cultural elements, a separate system has formed that is suited to the natural and economic conditions of the region.
- (4) Traditional buildings are everywhere, with wood, lime, bricks, and tiles as the main building materials, and roofs are generally tiled and sloping. These locally sourced materials are economical but are also harmonious with the environment and reflect the local atmosphere.
- (5) Energy consumption in buildings is growing, especially in the south. Although most building energy consumption in China is concentrated within economic zones like Beijing and Shanghai, new building construction is shifting southwards. Development of this southwestern region is promising, and its future energy requirements should not be underestimated.



**Figure 1.** Location of chosen sites.

### 2.1.2. Indicators

Two types of variables are included in this study. Roof slope and picket length are the two dependent variables that define the form of the roof. Roof slope is represented by the slope angle, which is calculated as  $\alpha = \arctan\left(\frac{\text{Elevation distance (H)}}{\text{Horizontal distance (L')}}\right)$  (Figure 2). As the heights of the residential buildings do not vary greatly, the length of the eaves of the buildings  $L$  was also counted on this basis.



**Figure 2.** Architectural elements.

Roof construction variables are evaluated against eleven independent climatic indicators derived from temperature, rainfall, solar radiation, and wind speed. These include the annual mean temperature (AMT), maximum temperature of the warmest month (MT), mean diurnal range (MDR), annual temperature range (ATR), isothermality (ISO), annual precipitation (AP), Maximum Precipitation of Wettest Month (MP), annual wind speed (AWS), annual maximum wind speed (AMWS), annual solar radiation (ASR), and annual maximum solar radiation (AMSR) (Table 1). Because historical climate data are influenced by a combination of natural climatic fluctuations and human activity, we used modern reanalysis data from 1970 to 2000. This region is mostly inland and had little environmental intervention prior to 1970. Because natural variability in wind speed depends strongly on local topography and atmospheric circulation, we can presume this parameter has not changed significantly, even from global warming in recent decades [26]. Solar radiation is dependent on the number of hours of local sunshine. In turn, temperature and precipitation show a specific variation pattern over this period [27,28]. This suggests that climate data from 50 years ago may reflect that of the last few hundred years from the Ming and Qing dynasties (1636–1912). Because the topography has not changed substantially between 1600 and 2000, we expect climate characteristics of this region to have also been similar.

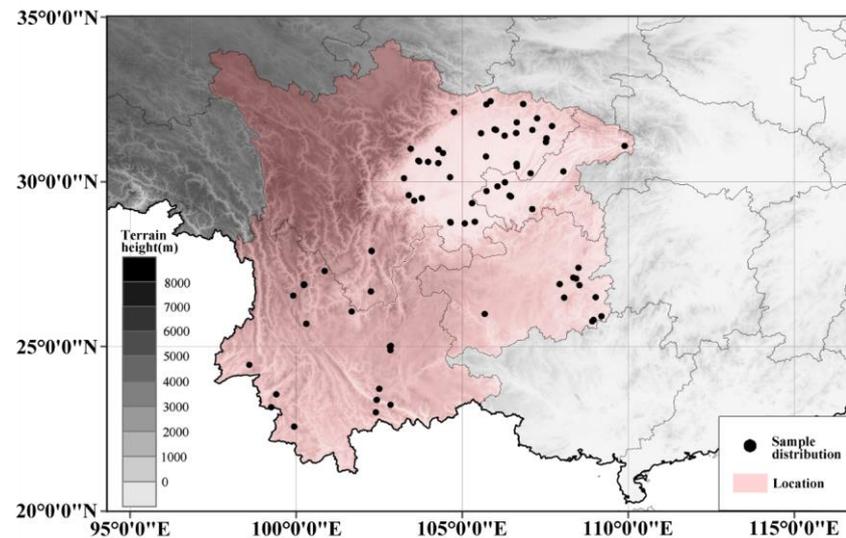
**Table 1.** Definition of climate-independent variables.

Climatic factor	AMT	MTWM	MDR	ATR
Explanation	The arithmetic means of the daily average temperatures for each day of the year	Maximum value of annual maximum temperature month temperature for each year	The average of the difference between the highest and lowest temperatures for each day of the year	Difference between the highest monthly average temperature and the lowest monthly average temperature in a year
Climatic factor	ISO	AP	MPWM	AWS
Explanation	The ratio of the annual mean diurnal range in temperature to the annual temperature range *100%	The sum of the average monthly precipitation during the year	Precipitation in the wettest month of the year	The sum of the observed wind speeds for each month of the year
Climatic factor	AMWS	ASR	AMSR	—
Explanation	Wind speed in the month of the year with the highest observed wind speed	The sum of solar radiation observed in each month of the year	Solar radiation in the month of the year when the maximum solar radiation is observed	—

### 2.1.3. Data Sources

Strain data for roofs are derived with a certain degree of reliability from published mapping bibliographies or books on building structures [29–37]. Climate data were pri-

marily sourced from WorldClim.org, a global database of high spatial resolution weather and climate data. These data can be used for mapping and spatial modeling and provide data for research and related activities. The latitude and longitude of a mapped building provide a link to the global climate map with 30'' accuracy. Therefore, climate data will be identical for buildings in the same village or location. See Figure 3 for a geographical representation of building data.



**Figure 3.** Sample distribution in China. The distribution of the sample is concentrated in areas of intense human activity, while the northwestern part is a highland terrain, where no local buildings were selected in view of the high environmental impact and the small number of buildings.

### 3. Results

#### 3.1. Data Testing

After sufficient data were obtained, a one-sample Kolmogorov–Smirnov (K–S) test was performed using SPSS Statistics 26. All samples had a  $p$ -value of less than 0.05 and were determined to be non-normally distributed. Because the distribution was not normal, Spearman’s correlation coefficient was used to analyze the correlation.

#### 3.2. Statistical Analysis

##### 3.2.1. Correlation Analysis

Spearman’s correlation coefficient was used for correlation analysis, with results shown in Table 2. AWS and MDR negatively correlate with the roof slope angle ( $\alpha$ ), while all other factors correlate positively. The climatic factors affecting roof slope are as follows: MPWM:  $p = 0.000003$ , AMT:  $p = 0.000010$ , AWS:  $p = 0.000016$ , AMWS:  $p = 0.000168$ , MTWM:  $p = 0.005108$ , AP:  $p = 0.005737$ , and MDR:  $p = 0.093187$  (values displayed in Table 2 are rounded). All climate factors negatively correlate with eaves length, with  $p = 0.00169$  for AMSR,  $p = 0.00347$  for ASR,  $p = 0.03285$  for AMT, and  $p = 0.04935$  for AWS.

Climatic elements with  $p < 0.01$  correlate significantly with the roofing element, whereas variables with  $p < 0.05$  show a weaker correlation. Although other climatic features could exert some influence, especially when multiple factors are combined, these other factors have large  $p$ -values and small correlation coefficients.

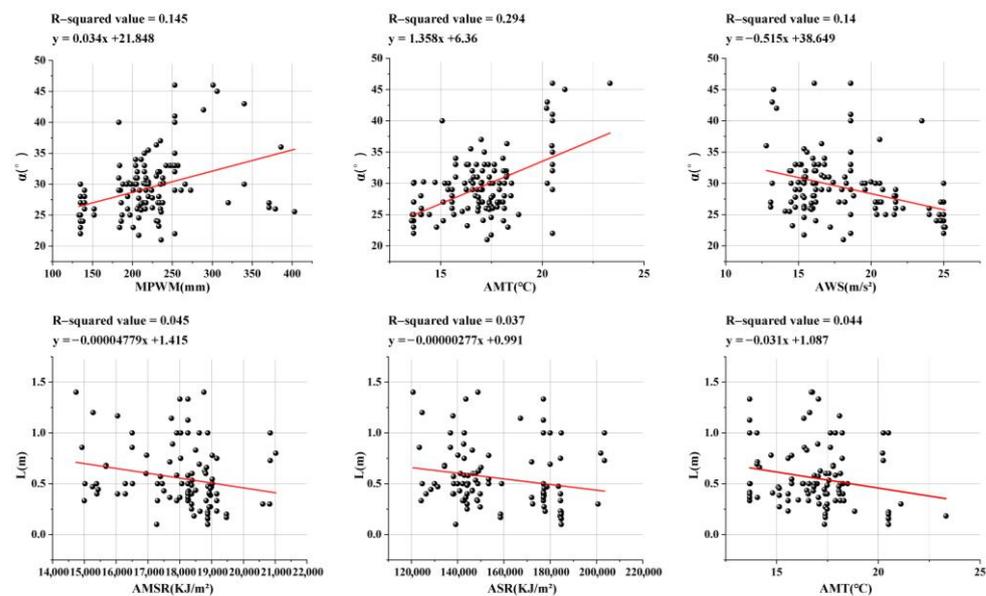
**Table 2.** The relationship between the climatic element and the roofing element.

Variables		$\alpha$	L	AMT	MDR	ISO	AP	TAR
$\alpha$	Spearman Coefficient	1.000	0.174	0.386 **	−0.151	−0.047	0.247 **	0.021
	Sig.		0.078	0.000	0.093	0.601	0.006	0.820
L	Spearman Coefficient	0.174	1.000	−0.210 *	−0.096	−0.176	−0.169	0.155
	Sig.	0.078		0.033	0.337	0.075	0.088	0.117
Variables		MTWM	MPWM	AWS	ASR	AMWS	AMSR	—
$\alpha$	Spearman Coefficient	0.250 **	0.408 **	−0.377 **	−0.070	−0.332 **	0.013	—
	Sig.	0.005	0.000	0.000	0.440	0.000	0.884	—
L	Spearman Coefficient	−0.065	−0.020	−0.194 *	−0.285 **	−0.152	−0.306 **	—
	Sig.	0.515	0.842	0.049	0.003	0.126	0.002	—

\*\*  $p < 0.01$ , \*  $p < 0.05$  (two-tailed).

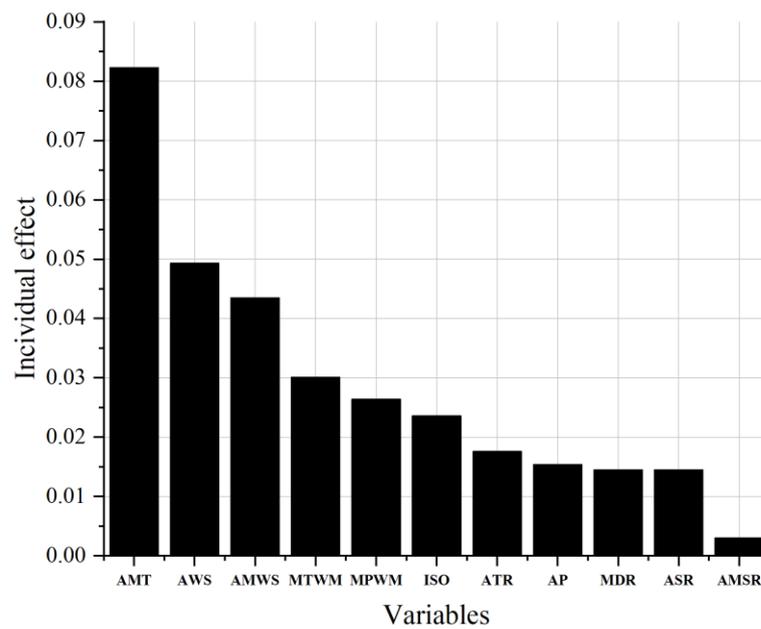
### 3.2.2. One-to-One Regression Analysis

After correlation analysis, we attempted to fit highly-correlative climatic variables and the corresponding building elements to a linear model to identify clear trends. The results are shown in Figure 4.

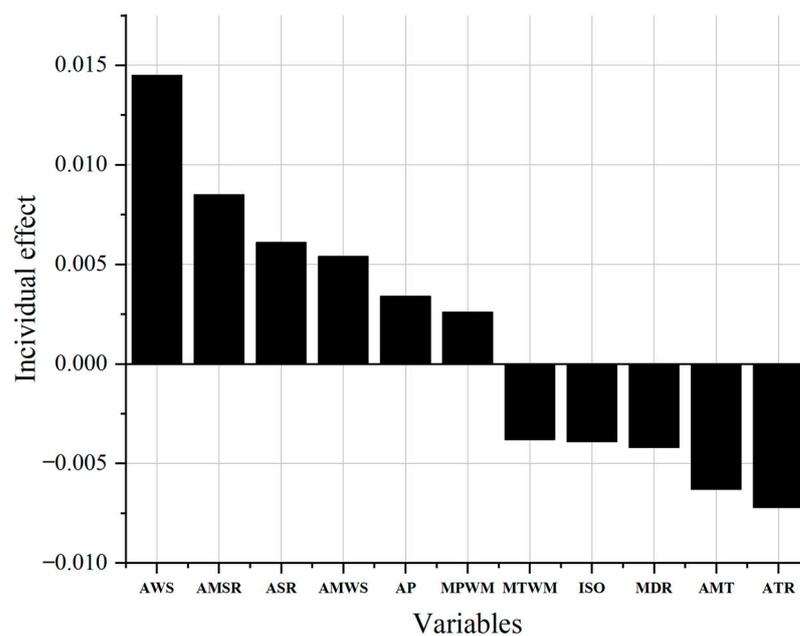
**Figure 4.** Linear fit to one-to-one variables.

### 3.2.3. Multiple Regression Analysis and Variance Partitioning Analysis

Correlation analysis explores the relationship between the independent variables of the building elements and climatic factors, with different variables predicting the magnitude of the same dependent variable. However, it was difficult to rank the extent to which climatic factors influenced the roof elements, particularly when strong or complex correlations exist among predictors and response variables. To address this, we used the R package rdacca.hp to explore the influence of each climate factor on the strain variables [38]. The relationship between climatic variables and roof slope in multiple regression is shown in Figure 5. In Figure 6, it shows which climatic factor influence the eaves length most.



**Figure 5.** The relative importance of individual climate variables in predicting roof slope by rdacca.hp [38].



**Figure 6.** The relative importance of individual climate variables in predicting eaves length by rdacca.hp [38]. If the individual effect is a negative number which means the independent variable have little effect on the strain variable.

AMT had the highest individual importance on roof slope (8.23%), followed by AWS (4.93%), AMWS (4.35%), MTWM (3.01%), and MPWM (2.64%). Alternatively, AWS (1.45%) exerts the greatest influence on eaves length, followed by AMSR (0.85%), ASR (0.61%), AMWS (0.54%), and AP (0.26%).

### 3.2.4. Model Selection

Multiple forward stepwise regressions were conducted for the two building elements and climate variables to select the best model.

The final equations obtained (parameters shown in Tables 3 and 4) had overall significance  $p$ -values of 0.011 and 0.000, respectively, indicating that the fits were statistically significant and that at least one of the independent variables has a significant effect on the dependent variable. We find a correlation of 0.357 between the independent variables and roof slope, indicating that the three variables together explained 35.7% of the roof slope, and the independent variables monitored in the study were able to predict roof architecture variables. The adjusted coefficient correlation was 0.341, which indicates the goodness of fit of the regression equation. The correlation of the three variables on the eaves length was 0.125, which together explained 12.5% of the eaves length with an adjusted coefficient correlation was 0.098. All variables in the regression model were statistically significant.

**Table 3.** Fit parameters for roof slope regression model.

	Unstandardized Coefficient		Standardization Coefficient		
	B	Std. Error	Beta	t	p
(Constant)	15.002	5.787	—	2.592	0.011
AMT	0.976	0.244	0.390	4.001	0.000
MDR	0.802	0.240	0.346	3.337	0.001
AWS	−0.507	0.176	−0.369	−2.889	0.005

**Table 4.** Fit parameters for roof length regression model.

	Unstandardized Coefficient		Standardization Coefficient		
	B	Std. Error	Beta	t	p
(Constant)	2.261	0.476		4.750	0.000
AMSR	$-1.767 \times 10^{-5}$	0.000	−0.078	−0.739	0.461
AMT	−0.056	0.019	−0.374	−2.974	0.004
AWS	−0.024	0.010	−0.298	−2.307	0.023

Next, the regression coefficients were examined. The regression coefficients were 0.802 for DTR and 0.976 for AMT for roof slope angle, indicating that these variables positively correlated with the dependent variable  $\alpha$ . Conversely, the regression coefficient for AWS was  $-0.507$ , indicating AWS negatively correlates with  $\alpha$ . AMT, DTR, and AWS each displayed  $p$ -values of 0.000, 0.001, and 0.005, respectively, all less than 0.1, indicating that all three variables significantly affect the dependent variable  $\alpha$ .

Thus, we derive the following roof slope regression model:

$$\alpha = 15.002 + 0.976 \times \text{AMT} + 0.802 \times \text{MDR} - 0.507 \times \text{AWS}, \quad (1)$$

For eaves length (L), the regression coefficients for AMSR, AMT, and AWS were  $-1.767 \times 10^{-5}$ ,  $-0.056$ , and  $-0.024$ , respectively, indicating that these variables negatively correlated with L. These parameters have  $p$ -values of 0.461, 0.004, and 0.023 for AMSR, AMT, and AWS, respectively. All three variables had some effect on the dependent variable L, while AMT and AWS were significant predictors.

The eaves length regression model can be written as follows:

$$L = 1.428 + (-1.767 \times 10^{-5}) \times \text{AMSR} - 0.056 \times \text{AMT} - 0.024 \times \text{AWS}, \quad (2)$$

### 3.3. Model Testing

After conducting statistical analyses, regression model validity was confirmed by analysis of model covariance, generalizability, and normality. The covariance diagnosis was first performed (Tables 5 and 6). In both final models,  $VIF < 5$ , and there are no problems with co-linearity.  $R^2$  and adjusted  $R^2$  for the final model (1) and model (2) show a difference of approximately 0.016 and 0.027. This relatively small variance indicates good

generalizability for all models. This justifies the assumption that the hypothesis is feasible under dependent errors and the variables studied in this analysis can sufficiently explain the explanatory variables. Finally, Using a PP diagram, the regression model probabilities show a normal distribution. Together, these indicate that the model is stable, valid, and generalizable and that all regression statistics are valid.

**Table 5.** Co-linearity analysis of spatial properties variables ( $\alpha$ ).

	Tolerance	VIF <sup>a</sup>
AMT	0.565	1.771
MDR	0.497	2.012
AWS	0.329	3.037

<sup>a</sup> Variance inflation factor (VIF).

**Table 6.** Co-linearity analysis of spatial properties variables (L).

	Tolerance	VIF <sup>a</sup>
AMSR	0.790	1.265
AMT	0.558	1.791
AWS	0.528	1.893

<sup>a</sup> Variance inflation factor (VIF).

It is worth noting that although the regression analysis supports the correlation analysis, this is not always the case. A correlation analysis is a bivariate relationship, whereas a regression analysis considers the combined effect of multiple variables. Thus a correlation between variables does not necessitate a regression relationship and vice versa.

### 3.4. Summary of the Findings

This analysis identified a significant positive effect of mean annual temperature on the traditional residential building roof slope and was the most influential factor in the multiple regression, whereas roof slope and annual wind speed negatively correlate. Annual mean temperature and wind speed significantly influence roof slope. Maximum annual precipitation had the strongest correlation with roof slope; however, its correlation coefficient was insignificant in the regression analysis, and its impact is not as great as the temperature and wind speed.

For eaves length, the annual solar radiation and maximum solar radiation are the most significant correlates, followed by the annual mean temperature and wind speed. All climate values negatively correlate with the eaves length, and the solar radiation and wind speed both show a significant impact in regression analysis.

The model for roof slope and climatic factors is considerably better than the model for eaves length and climatic factors. This is unavoidable as the length of the roof eaves is, in general, seen to be more subjectively influenced by human factors.

## 4. Discussion

Here, we examine the relationship between climatic factors and traditional building roofs in southwest China. We find that five climatic variables of interest (temperature, wind speed, solar radiation, precipitation, and temperature range) are linked to roof slope and eaves length. After correlation and regression analysis, the relationship between these two sets of variables reveals a statistically significant relationship between the roofing and climatic attributes of traditional residential buildings.

### 4.1. Influence

First, we confirm that building roofs are influenced to some extent by climatic factors using quantitative analysis, which is an improvement over previous qualitative studies. Using multiple linear regression, which includes the climatic variables, the  $p$ -values for these two regression models were 0.011 and 0.000, respectively, indicating that our model is valid and at least one climatic factor had a significant effect on traditional roof architecture.

#### 4.2. Relationship between the Factors

Secondly, We explore the relationship between various climatic factors and building elements. For example, roof slope, precipitation, and temperature show a positive correlation, confirming a previous observation that roof slope was steeper in areas with higher annual rainfall [23]. We find that wind speed, however, negatively correlates with slope, in contrast to previous studies. Studies on tiled sloping roofs indicated that flatter roofs tend to experience higher negative wind pressure on the face, which causes more severe damage to the tiled roof [23]. However, in general, where wind speed is high, the additional external force on the building may cause damage over time, so roofs are characterized by a low and flat profile to prevent the elements from exceeding their load-bearing capacity. The negative wind pressure coefficient at the front roof measurement points consistently decreases as roof slope increases while the positive pressure increases, and this change is essentially independent of wind angle. At the same time, a smaller roof slope reduces the volume factor of the double-sloped roof model and lessens energy consumption [39–41]. Moreover, there are fewer examples of buildings being lifted by wind suction, especially when the slope angle is above  $26^\circ$  [15]. Therefore, the windward side of traditional residential houses is mainly subject to positive pressure [42]. When the roof slope angle is between  $21^\circ$  and  $46^\circ$ , higher wind speeds necessitate shallower roof slopes to prevent wind pressure damage. Additionally, the wind can exert a drifting effect, which is worsened by an uneven distribution of roofing material and a steeper roof slope [43]. This effect lowers pressure on the roof and alleviates the need for a steep roof slope. At higher wind speeds, additional rain load increases from precipitation which causes greater resistance in shallower roofs [44]. Finally, we observe that higher wind speeds lower pressure on the roof, with an additional increase in impact as windspeed increases. Conversely, the lower the roof slope, the more resistant the house will be to wind speeds.

We also find that AMSR, ASR, AMT, and AWS negatively correlate with the roof eaves length. In previous qualitative studies of traditional Chinese architecture, it was assumed that eaves were one of the most important means of combating the summer heat and that a higher annual solar radiation and temperature would correlate with a greater eaves length to lower wall and indoor temperatures in the summer [45]. However, although buildings are exposed to sunlight throughout the year, its effect on buildings can depend on the season. Sunlight penetrating a south-facing façade in the winter provides passive solar radiation to increase the comfort level of the home, whereas, in summer, this sunlight leads to excessive heat build-up [46]. Passive technology, therefore, needs to strike a balance and adapt to seasonal differences. From this perspective, sites located in a subtropical monsoon climate with hot summers and extreme humidity require a moderate amount of light in the summer to reduce humidity, and so building eaves are built with smaller projection lengths to increase solar radiation. At the same time, AMT is related to solar radiation, and in the southwest monsoon climate, the higher temperature and humidity are more likely to cause persistent dampness. AWS is a significant correlate, although it is hard to find a direct correlation between eaves length and wind. The relationship between eaves length and wind pressure is not significant [47]. However, the increased roof ventilation enhances the roof thermal insulation [48] and reduces the need for eaves cooling in summer, which allows for a shorter eaves length.

#### 4.3. Significant Factors and Models

We also explore which climatic factors significantly influence the roof slopes of traditional buildings. The Spearman's correlation coefficients generated from the analysis of roof slope are as follows: MPWM:  $p < 0.01$ , AMT:  $p < 0.01$ , AWS:  $p < 0.01$ , AMWS:  $p < 0.01$ , MTWM:  $p < 0.01$ , AP:  $p < 0.01$ . The values from variance partitioning analysis are AMT: 8.23%, AWS: 4.93%, AMWS: 4.35%, MTWM: 3.01%, and MPWM: 2.64%. MPWM shows the strongest correlation in our analysis, similar to other qualitative studies of roof slopes [18,49]. Li Siyang's 2021 study on the roof slope of traditional buildings in northern China demonstrated the adaptation of roof slope to climate change over the past millen-

nium driven by fluctuations in extreme snowfall events [50]. From this perspective, the relationship between maximum precipitation and roof slope in southwest China hints at the relationship between the effects of extreme weather on building roofs in diverse climates. In addition, AMT is the second most relevant factor, with the outdoor temperature being the strongest predictor of indoor temperature and indoor humidity, especially when outdoor temperatures are high [51,52]. It is generally recognized that the climate is cooler in northern China, where roof slopes are smaller, and hotter in the south, where roof slopes are larger. Likewise, AMT shows a positive correlation with the roof slope for three reasons. First, high-angle-pitched roofs demonstrate optimal heat transfer compared to low-angle-pitched roofs [53]. At a slope of  $10^\circ$ , the heat transfer coefficient increases by only 1%. However, at a slope of  $30^\circ$ , the coefficient increases by 15.4%, and at a slope of  $45^\circ$ , it increases by 41.4% [54]. As the slope angle increases, the heat transfer coefficient of the roof also increases accordingly so that a higher slope will effectively reduce the indoor temperature in the summer [55]. Secondly, under certain wind speed conditions, ventilation performance increases with a steeper roof slope [56]. Thirdly, traditional buildings are mostly equipped with attics so that a greater roof slope corresponds to greater attic space and better thermal insulation. Of course, temperature also includes many indirect correlations closely related to humidity and the monsoon [52,57]. Nevertheless, the predicted model is still valid for this monsoon climate zone. At last, AWS is the third most relevant factor. Though there is some discrepancy between the multiple regression models and the above findings. It shows the role of AMT and AWS in multiple linear regression at the same time. The precipitation, however, does not show a good fit in the model for two reasons. Firstly, the climate precipitation at the site is relatively consistent and shows a minor effect on roof slope in the multiple regression compared to temperature and wind speed. As a caveat, we notice the selected buildings are mostly southern-facing with roof slope angles  $\geq 21^\circ$ . Because there is already an adequate drainage slope, changes in the rainfall variable show little correlation to roof slope. Finally, although MDR, ATR, and ISO reflect the topography of the site and correlate with solar radiation, temperature, wind speed, and precipitation, they do not show significant influence in the multiple regression model (performed using the R package *rdacca.hp*).

The eaves length Spearman's correlation coefficients are as follows: AMSR:  $p < 0.01$ , ASR:  $p < 0.01$ , AMT:  $p < 0.05$ , AWS:  $p < 0.05$ . The values from variance partitioning analysis are AWS: 1.45%, AMSR: 0.85%, ASR: 0.61%, AMWS: 0.54%, and AP: 0.26%.

Instead, AMSR and ASR are the first and second correlates of eaves length and negatively correlate. According to previous studies, the climatic elements to which roofs are subjected mainly include the effects of daytime solar radiation incidence, nocturnal long-wave radiation dissipation, and precipitation [58]. However, some of these relationships were not recapitulated in our analysis. We speculate that rainfall has less influence because of topological complexity at the site, the presence of high wind speeds, the weak ability of pickets to block precipitation, and the wet environment. AMT and AWS are the third and fourth correlates, though AWS shows more importance in multiple regression. AWS, ASR, and AMSR each show importance in multiple regression. AWS, AMT, and AMSR constitute a regression model that predicts the length of the eaves under the passive technology of traditional residential buildings. It is worth noting that eaves are related to solar altitude angle and latitude [23], and the sunlight coverage in each season is considered in the design [59].

#### 4.4. Points of Progress and Limitations

These results will have direct implications for the utilization of traditional passive building technologies, particularly in the Sichuan and Chongqing regions of southern China and in the subtropical monsoon climate zone. Currently, most research on traditional technologies has been qualitative and focused on the principles of the technology so that others may continue to implement it. However, quantitative analysis is essential to improve the efficacy of this technology and predict its climatic suitability. Secondly, major changes in

climate are predicted to occur throughout the 21st century, which will likely impact indoor housing conditions [60]. With the increased incidence of extreme weather and climate events, adaptation to climate change will remain a pressing issue in urban areas in the coming decades [61]. Encouragingly, research on green roofs also continues to progress. In these areas, the analysis of the relationship between climate change and the built fabric is necessary for the sustainability and resilience of cities [62].

As with any study, there are many limitations to these findings. First, only the south-western part of China was included in our analysis. Although the climatic characteristics are somewhat broad, they are not representative of the entire geographical area of China and certainly not the entire world. More case studies are needed to verify the universality of these findings. Secondly, a simple linear relationship between climate factors and building factors likely does not exist, and more exploration is needed to determine whether suitable building factors can be accurately predicted based on climatic conditions. Furthermore, although most of the buildings selected are tile-roofed buildings built during the Ming and Qing dynasties, there is still a significant delay between the construction dates and the analysis of the satellite climatic data. Nevertheless, we expect we have identified general trends in the climatic adaptation of traditional residential building roofs.

## 5. Conclusions

Few quantitative studies have explored the climate-resilient characteristics of traditional residential buildings, as sample error and regional differences can limit the utility of their findings in different regions. However, this is an effective way to explore the current impact of multiple climate variables on traditional buildings. The results validate ideas previously derived from qualitative studies and support their more precise use.

The contributions our study made are as follows:

1. We establish the correlation of roof slope with climatic factors such as temperature, wind speed, and precipitation. Eaves length, in turn, is influenced by solar radiation, temperature, and wind speed.
2. MPWM is considered the most important correlate of roof slope in traditional buildings, while AMT and AWS are considered significant correlates. AMT, AWS, and AMWS show importance in the regression equation. The regression equation dominated by AMT, AWS, and MDR can predict the roof slope of traditional houses under different climatic conditions.
3. AMSR and ASR are the most important correlation factors for the eaves of traditional buildings, though AMT and AWS also significantly correlate. AMSR, ASR, and AWS show importance in the regression equation, and the regression equations for AMSR, AMT, and AWS are good predictors of eaves length.
4. These two strain variables significantly inform the approach to roof design. The regression equation is helpful for the application of passive roofing techniques on traditional residential buildings in the subtropical monsoon region, especially in the Yunnan, Guizhou, Sichuan, and Chongqing regions of China.

This paper provides quantitative evidence to support the development of green buildings due to the sustainability of this approach in both urban and rural settings and the wide variety of conventional passive methods that can be implemented in their design.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings13020300/s1>.

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