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Comparison and Effects of Different Climate-Vegetation Models in Areas of Complex Terrain under Climate Change

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Abstract: Identifying the impacts of climate change is important for conservation of ecosystems under climate change, particularly in mountain regions. Holdridge life zone system and Köppen classification provide two effective methods to assess impacts of climate change on ecosystems, as typical climate-vegetation models. Meanwhile, these previous studies are insufficient to assess the complex terrain as well as there are some uncertainties in results while using the given methods. Analysis of the impacts of the prevailing climate conditions in an area on shifts of ecosystems may reduce uncertainties in projecting climate change. In this study, we used different models to depict changes in ecosystems at 1 km × 1 km resolution in Sichuan Province, China during 1961–2010. The results indicate that changes in climate data during the past 50 years were sufficient to cause shifts in the spatial distribution of ecosystems. The trend of shift was from low temperature ecosystems to high temperature ecosystems. Compared with Köppen classification, the Holdridge system has better adaptation to assess the impacts of climate change on ecosystems in low elevation (0–1000 m). Moreover, we found that changed areas in ecosystems were easily affected by climate change than unchanged areas by calculating current climate condition.

Keywords: Holdridge classification; Köppen classification; uncertainty; Sichuan Province, China

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1 Introduction

Many studies on climate change worldwide suggested that the global temperature is continuously increasing resulting in vanishing or decrease in vulnerable ecosystems in future (Diaz and Eischeid, 2007; Baker *et al*., 2010; Rubel and Kottek, 2010). The changes in ecosystems provide the largest challenges to conservation planning and ecosystem management. Assessing and identifying the changed area of ecosystems is therefore important for managing the ecosystem in a changing climate.

The climate-vegetation models can be an effective method to demonstrate the impacts of climate change on ecosystems. These models include sophisticated and non-sophisticated dynamic vegetation models. Although sophisticated dynamic models can provide accurately assessed impacts of climate change yet, they require more data and thus, many of the mechanisms of ecosystem dynamics are still not clear (Foley *et al*., 1998; Hurtt *et al*., 1998; Hallgren and Pitman, 2000). Therefore, the non-sophisticated dynamic models have been used widely in most of the studies conducted on ecosystem dynamics. Two such accepted methods, the Holdridge (1967) and Köppen (1900) systems, have been utilized to quantify shifts in ecosystems under climate change situation (Baker *et al*., 2010; Chakraborty *et al*., 2013). The Köppen system is the first international standard quantitative classification system for ecosystems, while the Holdridge system focuses on

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ecosystem function. Meanwhile, based on real life in China, the Holdridge system was modified and aggregated into eight large units (Zhang, 1993). The classification has also been used to demonstrate the impacts of climate change on ecosystems at different scales. Most studies suggested that changes in temperature were sufficient to cause shifts of ecosystem types in Europe, Asia and America (De Castro *et al*., 2007; Diaz and Eischeid, 2007; Chakraborty *et al*., 2013). The results of previous studies done in China showed that nival area and subtropical thorn woodland had a rapid decrease under climate change (Chen *et al*., 2003; Yue *et al*., 2005; Wang *et al*., 2011). However, these studies could not accurately assess the shifts in ecosystems in areas of complex terrain because of coarse resolution. Besides, uncertainties in assessing results are not to be trusted for regional conservation strategies.

With the development of thin-plate smoothing spline algorithm, this method can provide climate surfaces of high resolution. It also addresses some issues of the past studies. Additionally, comparison with different models and analysis in more detailed in the impacts of current climate conditions may reduce some uncertainties of assessing result. The major thrust of this study is to map the distribution of ecosystems at fine resolution as well as to compare with the results from different classifications in areas of complex terrain under climate change, and to analyze the impacts of current climate conditions and the rate of climate change on shifts of ecosystems.

2 Materials and Methods

2.1 Study site

Sichuan Province (26°03′–34°19′N, 97°22′–108°32′E), covered about 485 000 km^2, is situated in the southwest of China (Fig. 1). The topography of the province varies from the east (low elevation) to the west (high elevation) with inclination from the northwest to the southeast direction. The Longmen Mountain and Daliang Mountain regions are located in the east of the Sichuan Basin. They are elevated between 1000 m and 3000 m. Mountains and plateaus in the west of Sichuan and mountainous regions in the southwestern part have above 4000 m elevation. There are diversified types of topography in Sichuan including plain, hill, mountainous region and plateau. Mountainous areas dominate the province followed by plateau. Therefore, this region is sensitive to climate change because of complex topography. By assessing shifts of the distribution of ecosystems, we can select a more effective model to demonstrate the impacts of climate change in mountain areas.

2.2 Calculation methods

2.2.1 Holdridge life zone

The Holdrdige life zone can be determined by local climate. This classification system uses three climatic parameters: biotemperature (*Bt*), mean annual precipitation (*P*), and potential evapotranspiration (*PER*). In order to identify the life zone, the *Bt*, *P* and *PER* are transformed into their natural logarithm. This transformation of the values provides theoretical method for establishing divisions of equal weight. These values are calculated as follows:

$$Bt = \Sigma t \ / \ 12 \ (0℃ \le t \le 30℃) \tag{1}$$

$$PER = 58.53Bt \ / \ P \tag{2}$$

$$Bt' = \ln Bt \tag{3}$$

$$P'(x, y) = \ln P \tag{4}$$

$$PER'(x, y) = \ln PER \tag{5}$$

where *Bt* stands for the biotemperature, and *Bt* has been defined as positive temperature in Celsius, with temperature below 0℃ adjusted to 0℃ and above 30℃ adjusted to 30℃. The *PER* and *P* have been defined as the potential evapotranspiration and mean annual precipitation. *Bt*′, *PER*′ and *P*′ have been defined as the natural logarithm of *Bt*, *PER* and *P*. According to Holdridge chart (Holdridge, 1967), each life zone is depicted by a hexagon formed by intersecting intervals defined by *Bt*, *P* and *PER* plotted along logarithmic axes of a triangular coordinate system. This type of life zone is determined by the distance of hexagon center. The expression for calculating the distance is as follows:

$$d_i = \sqrt{\left(Bt' - Bt_i'\right)^2 + \left(P' - P_i'\right)^2 + \left(PER' - PER_i'\right)^2} \tag{6}$$

where d_i stands for the distance of region to the hexagon center, *i* indicates the each life zone. If d_i is equal minimum distance, the region is classified into the *i*th life zone. *Bt*′, *P*′, *PER*′ have been defined as the natural logarithm of *Bt*, *PER* and *P* in Holdridge chart. Similarly, Bt_i', P_i', PER_i' have been defined as the natural logarithm of *Bt*, *PER* and *P* in the *i*th zone.

Based on the real life zones in China, the Holdridge life zone was aggregated in following eight large types: tropical rainforest and monsoon forest (TRF), subtropical evergreen broadleaved forest (SEBF), warm-temperate deciduous broadleaved forest (WDBF), cool-temperate mixed coniferous and broadleaved forest (CMC), cool-temperate steppe (TS), cool-temperate desert (TD), cold-temperate coniferous forest (CCF) and Tibetan high-cold plateau-or alpine meadow (THP) (Zhang, 1993).

2.2.2 Köppen classification

The Köppen classification is based on the five vegetation groups determined by the French botanist (De Candolle, 1874). These five vegetation classes represent the following climates: A, the equatorial climates; B, the arid climates; C, the warm temperate climates; D, the snow climates and E, the polar climates. The A-, B-, C-, D- and E- classes are further divided based on seasonal precipitation. Although alternative classifications were proposed (Trewartha and Horn, 1980), the climate classification originally developed by Köppen and Geiger has already been used in many studies (Kottek *et al.*, 2006). Here, we also have used Köppen-Geiger classification to depict vegetation changes in Sichuan Province. The applied identification scheme for the Köppen-Geiger classes was described by the past studies.

In this paper, the authors proposed a program for determining Köppen and Holdridge zones in Python programming language. The results could be demonstrated by ArcGIS software 10.0.

2.3 Data sources

2.3.1 Climate data

We used monthly temperature and precipitation data, and the selected spatial resolution was high enough to reflect the impacts of complex terrain (Hijmans *et al.*, 2005). These data were obtained from the Institute of Plateau Meteorology in Chengdu City. We applied the Anusplin 4.36, a spline software of spatial interpolation that explicitly accumulated the relation between elevation and climate data and downscaled the climate data at 1 km × 1 km resolution. Further, we fitted a second-order spline using elevation as a covariate because this produced the lowest generalized cross validation (GCV) and generalised max likelihood (GML) as compared with other settings (e.g., third-order spline, fourth-order spline). Temperature and precipitation data were selected from 241 weather stations that were scattered around Sichuan Province. Figure 1 shows the distribution of meteorological observation stations.

Considering the impact of climate change, we chose three time periods to represent the changes in ecosystems under climate change in Sichuan Province, such as 1990 (representing the 30-year average for 1961–1990), 2000 (representing the 30-year average for 1971–2000), and 2010 (representing the 30-year average for 1981–2010). The values of Bt, P, and PER in three periods are calculated by mean temperature and precipitation.

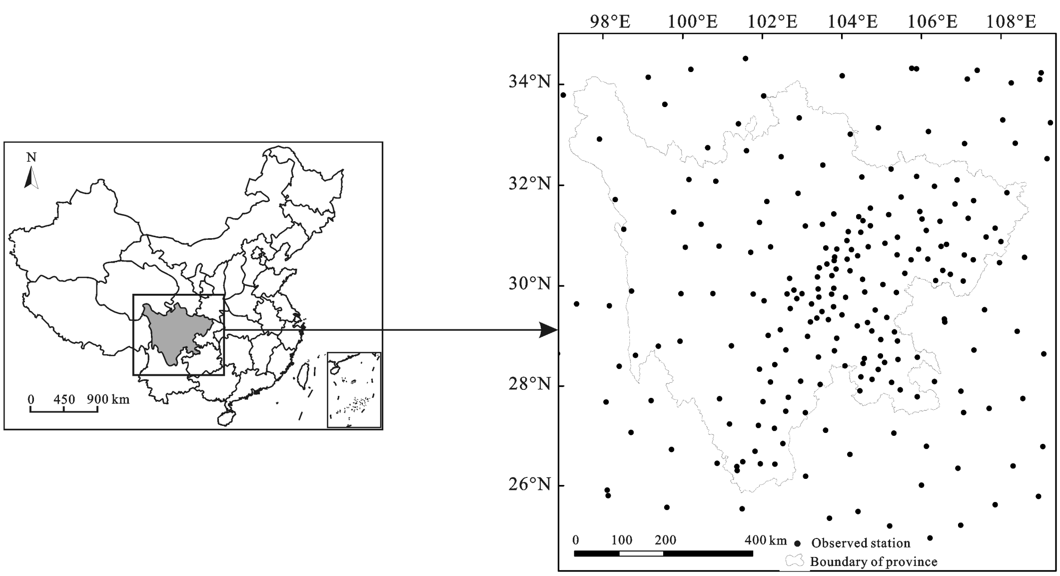

Fig. 1 Distribution of meteorological observation stations in Sichuan Province, China

The Kappa statistic is a useful index of differences and similarities between bioclimatic zone and ecosystem (Monserud and Leemans, 1992). In our research, the Kappa values of different life zones and Köppen climates were calculated by comparing bioclimatic zone with 1 km × 1 km scale vegetation database that represents the distribution of ecosystems in period 1981–2010.

2.3.2 Validation

Before studying the changes in bioclimatic types under climate change, we validated the climate surface by comparing it with data, gathered from meteorological observation stations. The mean monthly temperature and precipitation were computed in successive 100 m elevation belts from 100 m to 5000 m during 1981–2010. Meanwhile, the authors used the method of regression analysis to calculate differences between climate surfaces and observations data. The result shows that the correlation between them is very good for temperature (Fig. 2). However, the values of precipitation surfaces are not high quality by using spline method. As the bioclimatic types are mainly determined by temperature, there are not significant impacts on shifts of types.

3 Results

3.1 Distribution of ecosystems in Sichuan Province

As the shifts in Köppen climates have been already analyzed in other study (Fig. 3; d, e, f) (Lu *et al.*, 2015), we found more changes in Holdridge life zones in our study. There are six life zones in Sichuan Province. All life zones are illustrated with providing legend to all of them (Fig. 3; a, b, c). The life zone with the largest area is CCF zone, which covers 34.31% of the total area of Sichuan Province. The life zone with the smallest area coverage is TS, covering only 0.31% of the total area of Sichuan Province. According to life zones distribution characteristics, the life zones at the high altitudes can be classified as premontane life zone, montane life zone, subalpine life zone and alpine life zone, distributed from the east to west in Sichuan Province. The western Sichuan Province is extremely heterogeneous with five life zones. The THP zone occurs only in the western mountains where ecosystem corresponds to alpine meadow. Compared with other studies (Zhang, 1993; Baker *et al.*, 2010), our results provide to resolve life zones for geographical setting in the southern Sichuan Province.

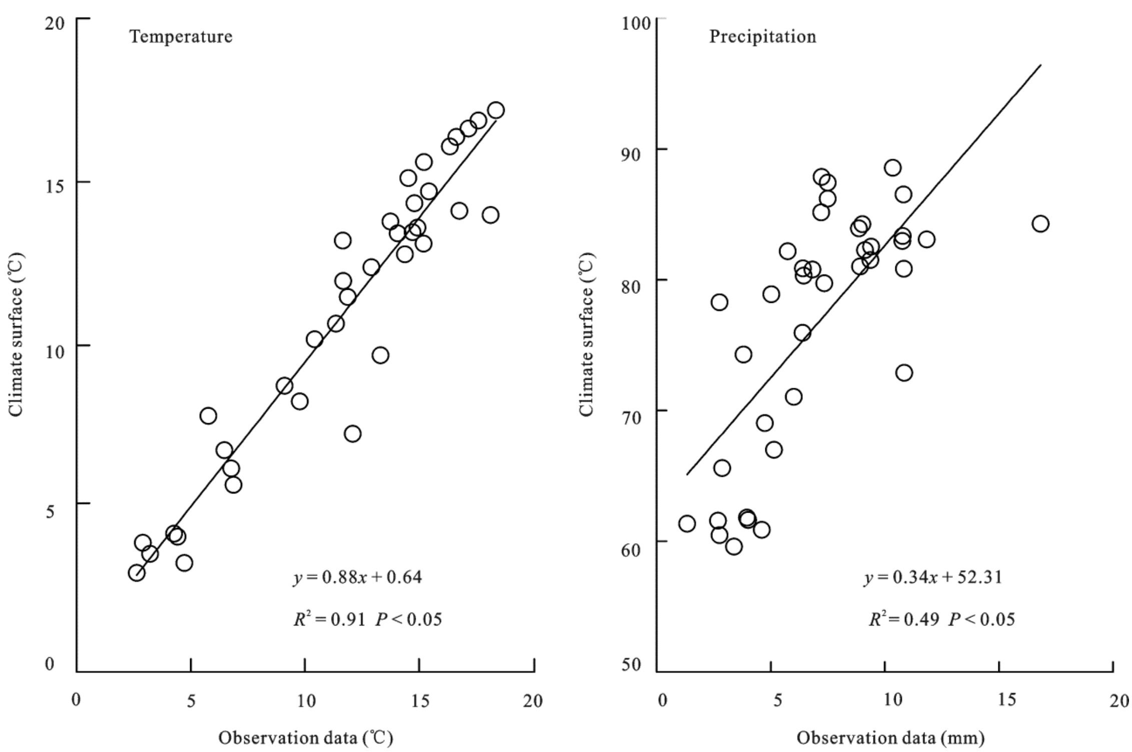

Fig. 2 Difference between climate surfaces data and observation data

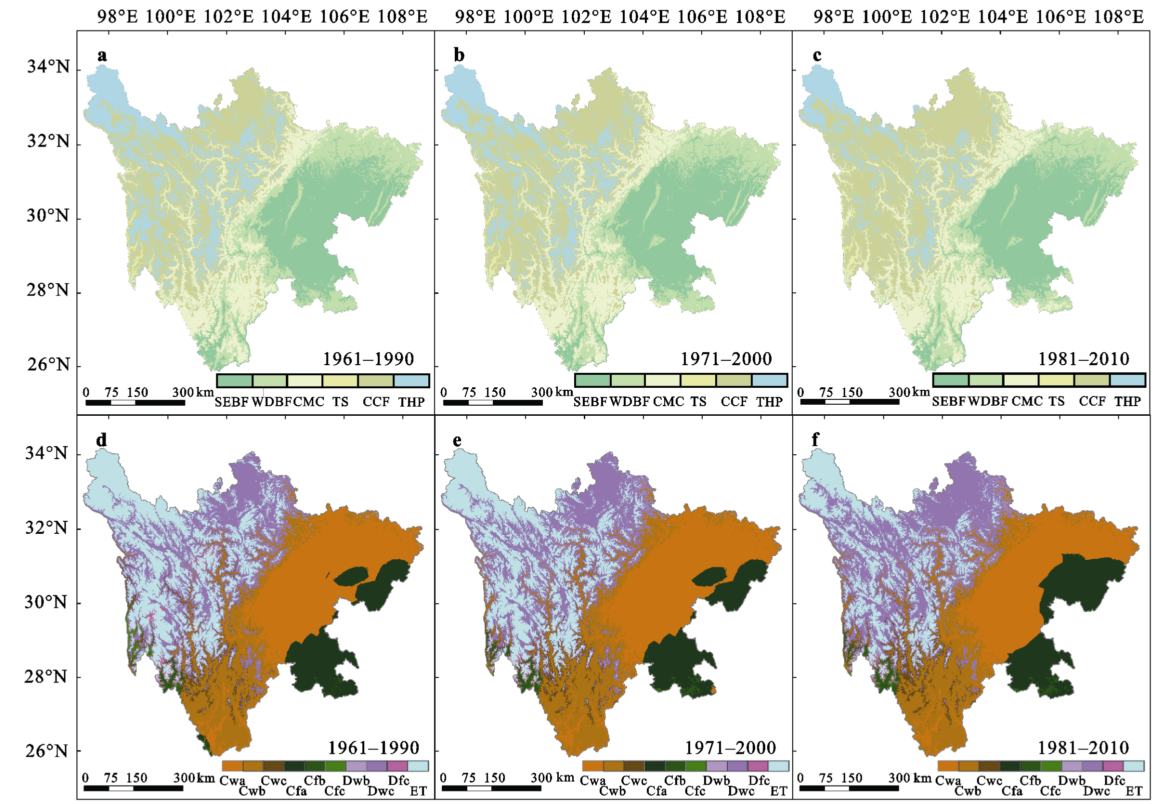

Fig. 3 Changes in bioclimatic zones in Sichuan Province. a, b, and c represent Holdridge life zone; d, e and f represent Köppen classification. SEBF, WDBF, CMC, TS, CCF, and THP represent subtropical evergreen broadleaved forest, warm-temperate deciduous broadleaved forest, cool-temperate mixed coniferous and broadleaved forest, cool-temperate steppe, cold-temperate coniferous forest, and alpine meadow. Similarly, Cwa (b, c), Cfa (b, c), Dwb (c), Dfc and ET represent warm temperate climate with dry winter and hot (warm, cool) summer, warm temperate climate, fully humid with hot (warm, cool) summer, snow climate with dry winter and warm (cool) summer, snow climate, fully humid and cool summer, and tundra climate, respectively

According to result of Kappa statistic, although the values of SEBF and THP are higher than other life zones, our study shows that it is lower than other documents (Chen *et al*., 2003; Yue *et al*., 2005; Wang *et al*., 2011). The result may be partially related to 1) some errors involved in vegetation data or Holdridge system at fine resolution; 2) the original ecosystems had been replaced under climate change; and 3) different definitions of ecosystems and climate classifications were used. As the climate is one of the environmental factors that determine the distribution of ecosystem, the climate-vegetable model cannot reflect completely the real vegetation.

3.2 Changed areas in different classification systems

In this study, we analyzed the shifts in bioclimatic types that were caused by temperature increase for a common base of comparison. Although, the major distribution of bioclimatic zones would not significantly change in Sichuan Province, we found that changes in temperature were sufficient to cause shifts in two models. Unlike other documents to analyze shifts in China, we did not find new bioclimatic types and none of bioclimatic types had disappeared in the past 50 years (Fig. 3). For Holdridge system, between 1961 and 1990 relative to the period of 1981–2010, the area of SEBF, CMC, and CCF would increase about 4.15%, 10.76%, and 16.43%, respectively. Contrary, the relative area of WDBF, TS and THP would decrease about 2.39%, 36.14% and 40.23%, respectively. The maximum shift mainly refers to THP, while the maximum shift was observed from THP to CCF. From 1961 to 2010, we found that only 59.77% of total area of THP, which did persist into the future, was spatially distributed in the higher altitudinal regions. For Koppen classification, the area of C and D climate class would increase about 3.90% and 23.13%, respectively. At the same time, the area of E would decrease about 31.43% in the past 50 years. Moreover, we calculated the shifts in bioclimatic types in two times as well as compared with changed areas between classification systems. The changed areas in different classification systems were calculated in successive 100-meter intervals. As shown in Fig. 4, the differences of Bt, mean monthly temperature, and the warmest temperature increased with increasing elevation. Meanwhile, the difference of mean monthly temperature rise was higher than Bt rise above ~2000 m elevation in most periods. Comparison of changed areas with different classifications generally shows good general agreement at most altitudinal belts. Meanwhile, the changed area increased with increasing elevation and temperature in different classifications. The changed area has reached 64 834 km^2 in life zones and 63 348 km^2 in Köppen climates between 1961–1990 and 1981–2010. However, the changed area in life zones above 2500 m elevation was lower than changed area in Köppen climates. For distribution of changed areas, their altitudinal belts were from 400 m to 4900 m in Holdridge and from 1100 m to 4600 m in Köppen classification.

3.3 Characteristic of climate in changed and unchanged areas

Considering the temperature warming rate in different altitudinal belts, the temperature and the difference of temperature increase between unchanged and changed areas were also calculated between 1961–1990 and 1981–2010 in successive 100-meter intervals. We selected different types that were obviously shifted under climate change to analyze these differences of temperature conditions (Fig. 5). In Holdridge system, we found that the Bt in CCF and THP decreased with increasing elevation as well as the values of Bt in changed areas were greater than those in unchanged areas. However, the values of Bt increase in changed areas were not greater than the values in unchanged areas, such as CCF (Fig. 5a). In Köppen classification, the changes of E class in the warmest temperature between changed and unchanged areas were consistent with changes in THP of Holdridge system.

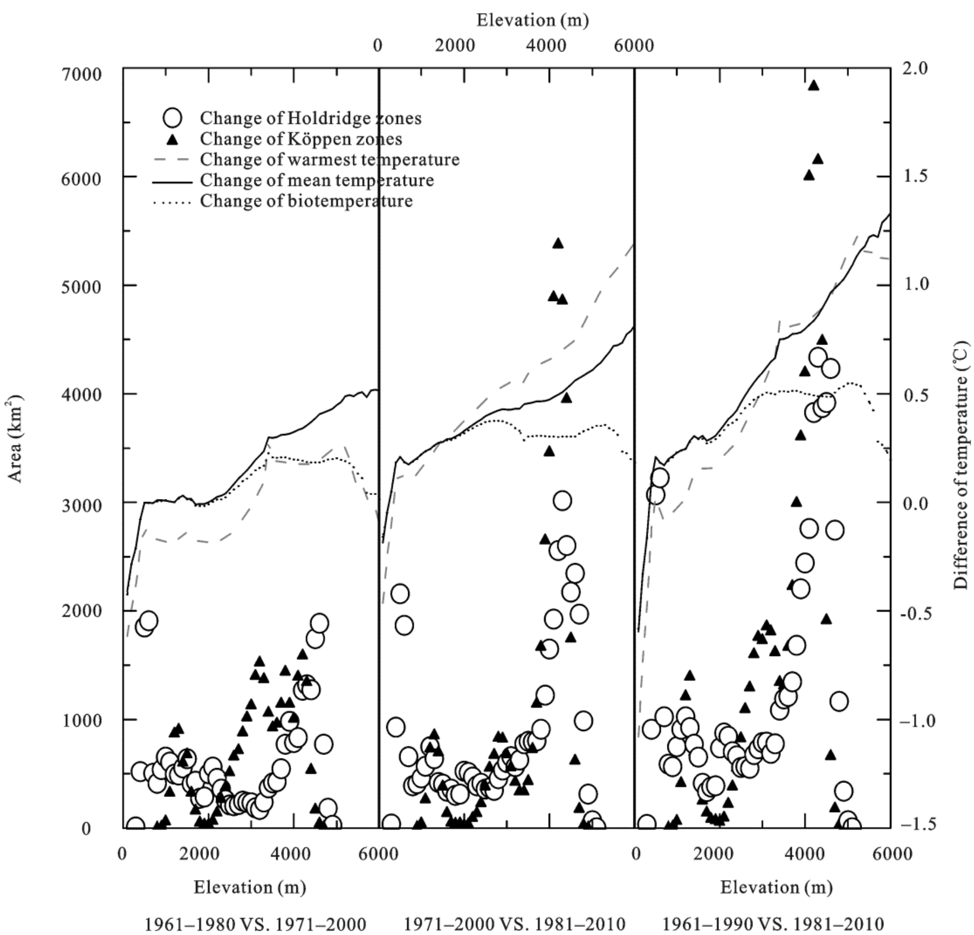

Fig. 4 Relationship among changed area in different classifications, temperature increase and elevation in different periods. Calculated and plotted in successive 100-meter interval

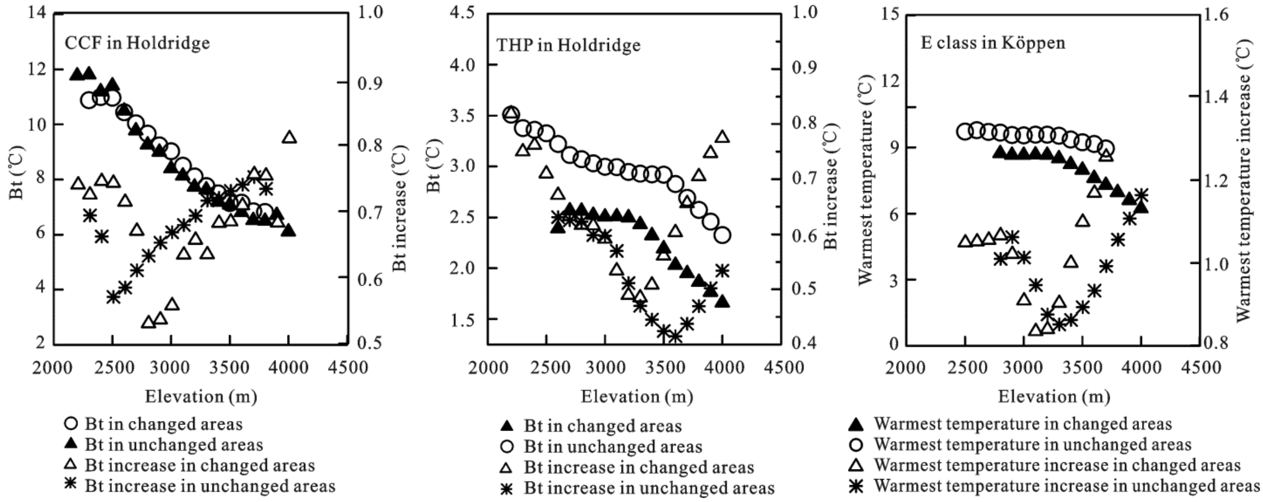

Fig. 5 Changes in temperature between changed areas and unchanged areas in different classifications

4 Discussion

4.1 Changed areas of different climate models

Unlike other documents to assess the impacts of climate change by using the climate vegetation model, our results could objectively demonstrate how bioclimatic types change through space and time in mountain areas as well as we can highlight the difference between Holdridge life zone and Köppen classification. By using climate vegetation model, we found that the trend of biological response in two models tended to be warmer as well as being distributed over a greater altitudinal range. Compared with other document, the shifts of bioclimatic types in two models were consistent with observations of impacts of climatic change on ecosystems in China (Chen *et al.*, 2003). However, we can find detailed description of it in western Sichuan Province because of different resolution levels. In real ecosystems, broadleaved forest expanded its distribution and moved to northwest direction in north of China (Chen, 2000). In addition, the previous studies observed that the 'tree-line' is shifting towards the higher elevation in the eastern Qinghai-Tibet Plateau (Gou *et al.*, 2012). These results suggested that the climate change could change the spatial patterns of ecosystems. However, the real ecosystems did not seem to have influenced much under recent climatic change. We suggest that the results of finer resolution most closely agreed with real change in mountains.

Compared of changed area with two classifications, they displayed good correlation in most altitudinal belts. However, the altitudinal belts of changed areas are dramatically different, as the Holdridge system can reflect shift in elevation range from 500 m to 1000 m while it does not appear in Köppen climatic zones. This is because that the Holdridge system includes subtropical life zone. It is found that the changes in climate conditions have caused shifts in migration or phenology in many regions (Inouye *et al.*, 2000; Peñuelas and Boada, 2003). Therefore, it is important to assess the impacts of climate change in low altitude regions.

4.2 Influence of current climate conditions on shift

The current climatic conditions, in a region, have a strong influence on changes in ecosystems under climate change. In this study, we found that the values of temperature in changed areas were greater than that of in unchanged areas while, the rate of increase in temperature were similar in both areas. Therefore, this study tries to find out that that whether the current condition in ecosystems would be easily affected by environmental factors or not. The previous studies suggested that the areas, vulnerable to climate change are those locations where original ecosystem is disappeared (Saxon *et al.*, 2005). Despite of uncertainty in climate change, our results indicate that the current climate condition in ecosystems must be considered in addition to the rate of temperature increase. Moreover, by calculating the difference between current climate condition and temperature threshold in each bioclimatic type, it can address the limitations of assessment and the impacts of climate change on ecosystems.

4.3 Conservation planning for ecosystems

The shifts in ecosystem types provide one of the largest challenges to managers and conservation planning. Managing ecosystems in the face of uncertain in projection climate change require from different perspectives (Lawler, 2009). It is extremely difficult to improve climate-vegetation models due to imperfect knowledge of mechanisms underlying ecosystems distributions and ecosystems responses to climate change. In our study, we need focus on current climate condition in ecosystem for conservation planning. In addition, the Köppen classification was able to identify larger area where bioclimate had been changed in elevation, ranges from 4000 m to 4500 m. Considering uncertainty in climate change and shifts in bioclimatic types, we suggest that identifying the larger area of change can be important for conservation because, the ecosystem was extremely difficult to restore. According to our results, the Holdridge system can provide more details for the impacts of climate change on ecosystems at elevation ranges from 0 to 1000 m in Sichuan Province. Thus, the Holdridge system can assess the impacts of climate change on ecosystem in the lower altitudinal regions for conservation planning.

5 Conclusions

This study reveals that there were no any ecological zones disappeared and new zones emerged during 1961–2010. Similarly, the distribution of life zone was not changed obviously. The trend of shift was from the low temperature zone to the high temperature zone. The maximum shift mainly refers to alpine meadow, while the maximum shift was observed from alpine meadow to cold-temperate coniferous forest. The alpine meadow would decrease about 40.23%. Therefore, this ecosystem should be considered for conservation ecosystem under climate change.

Compared with different classifications, the Holdridge system can reflect the impacts of climate change on ecosystems at elevation, ranges from 100 m to 1000 m. Meanwhile, the Köppen classification was able to provide larger area at elevation, ranges from 4000 m to 4500 m in Sichuan Province.

The difference in changed and unchanged areas shows that the values of current temperature in changed areas were greater than those of in unchanged areas. It means that these ecosystems in changed areas can be shifted more easily when environmental factors are changed. Therefore, ecosystem management should be focused on these regions.

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