Characteristics of Long-Term Climate Change and the Ecological Responses in Central China

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Measurements of air temperature and precipitation at 35 stations in Hubei Province, China, during 1962–2011 are used to investigate the regional climate change. There is an increasing trend for observed air temperature (0.23°C decade\(^{-1}\)), which is slightly higher than that from multiple model simulations/predictions [phase 5 of CMIP (CMIP5) datasets] (0.16°C decade\(^{-1}\)). The observed precipitation increases at the rate of 11.4 mm decade\(^{-1}\), while the CMIP5 results indicate a much lower decreasing trend (0.8 mm decade\(^{-1}\)) in this region. To examine the ecological responses to the climate changes in Hubei Province, annual gross primary productivity (GPP) and net primary productivity (NPP) products during 2000–10 and leaf area index (LAI) products during 1981–2011 are also analyzed. It is discovered that GPP, NPP, and LAI increase at the rate of 1.8 TgC yr\(^{-1}\) yr\(^{-1}\), 1.1 TgC yr\(^{-1}\) yr\(^{-1}\), and 0.14 m\(^2\) m\(^{-2}\) decade\(^{-1}\), respectively. A linear model is further used to conduct the correlation analyses between climatic parameters (i.e., air temperature and precipitation) and ecological indicators (i.e., GPP, NPP, and LAI). The results indicate that the air temperature has a significant positive correlation with LAI (\(R^2 = 0.311\)) and GPP (\(R^2 = 0.189\)); precipitation is positively correlated with NPP (\(R^2 = 0.209\)). Thus, it is concluded that the air temperature exerts a stronger effect on the ecosystem than precipitation in Hubei Province over the past decades.

KEYWORDS: Climate variability; Ecosystem effects; Vegetation–atmosphere interactions

1. Introduction

Terrestrial ecosystems and the climate system are closely coupled (Cao and Woodward 1998), which significantly affects the geophysical, geochemical, and geobiological processes of land surfaces (Meir et al. 2006; Park et al. 2010; Bernal et al. 2012). The changes in climate can strongly influence the vegetation distribution (Gonzalez et al. 2010; Gottfried et al. 2012; Shafran-Nathan et al. 2013) and terrestrial carbon balance (Peng et al. 2013). Correspondingly, the ecological feedbacks of terrestrial ecosystems will significantly accelerate climate change over the twenty-first century (Cox et al. 2000). During 1951–2012, the average temperature over global land and ocean surfaces has already risen by 0.72°C (IPCC 2013). It is widely considered that this rapid warming trend may be a current and future threat to vegetation biodiversity and productivity (McCarty 2001; Hay et al. 2011). Particularly, the observed air temperature in China has increased by 1.2°C since 1960s (Piao et al. 2010), which is twice as much as the global average. How such a significant warming trend will affect the climatic conditions and ecological environment in China has become a notable issue (Risley et al. 2011; Sun et al. 2015).

Previous studies mainly focused on vegetation responses to climate change at the national scale and suggested that vegetation activity in most regions of China has increased in the late twentieth century (Piao et al. 2006). Especially in the arid region of northwestern China, the significant changes in climate may lead to the changes in vegetation growth (Zhao et al. 2011). In southern China, the subtropical forests are threatened by their lack of resilience against long-term climate change (Zhou et al. 2013).

To evaluate the effects of climate change on terrestrial ecosystems, the gross primary production (GPP) and the net primary production (NPP) are widely used in literature (Fang et al. 2013). For example, one study focused on the between model
variation of GPP’s latitudinal patterns, which had showed that there existed higher spatial correlations between GPP and precipitation (Beer et al. 2010). Churkina and Running (1998) used the biogeochemical model to assess the relative importance of climatic controls in limiting NPP on a global scale, and the results suggested that climatic factors play important roles in limiting productivity for most vegetation biomes. In addition, the leaf area index (LAI) is another key biophysical variable for measuring the energy balance, evapotranspiration, and carbon sequestration (Propastin and Kappas 2012). The interactions between LAI and climate indicators suggest that LAI depends on climatic factors closely (Hoff and Rambal 2003). Therefore, it is necessary to study the relationships between climatic factors and these ecological indicators in a changing climate (Kimball et al. 2007).

Hubei Province is located at the Yangtze River basin in central China, which belongs to the typical subtropical monsoon zone. The impacts of climate warming on precipitation during 1961–2000 has been examined in this region, suggesting a significant positive trend in summer precipitation and a positive trend in rainstorm frequency (Jiang et al. 2007). Few studies regarding the regional climate change and the risk of climate-induced flood hazard in recent decades show that the ecological systems in this region are especially sensitive to changes in air temperature and precipitation (Su et al. 2006; Wang et al. 2014b). However, there are no more studies focusing on analyzing the temperature changes and ecological responses in this region. Because the ecological responses to climate change varied greatly from one place to another, the particular analyses in central China become very meaningful.

In this paper, we focus on the spatial–temporal trends of climate change in Hubei Province over the last 50 years as well as the ecological responses (e.g., the change trends of terrestrial GPP/NPP and LAI) to this climate change. The air temperature and precipitation datasets from 35 meteorological stations and multiple model simulation/prediction results from phase 5 of CMIP (CMIP5) during 1962–2011 are analyzed to show the climate change trends. Meanwhile, the 1-km annual GPP and NPP datasets from the MODIS products during 2000–10 and the AVHRR Boston University (BU) LAI products during 1981–2011 are also selected to show the ecological conditions. Furthermore, we conduct the correlation analyses between climatic parameters and ecological indicators to evaluate the effects of climate change on the ecosystems.

2. Data and methods

2.1. Study area

Hubei Province is located between 29°05′–33°20′N and 108°21′–116°07′E in China (Figure 1). This area belongs to the subtropical monsoon climate zone, which is characterized by well-marked seasons with hot and rainy summer and cold and dry winter (Chen et al. 2012; Wang et al. 2013). The annual-mean air temperature is 15°–17°C and annual rainfall is 1100–1300 mm (Wang et al. 2014a). According to the China’s Sixth National Population Census, the population in Hubei Province has increased by 124.77% from 25.80 million in 1949 to 57.99 million in 2010. Because of the convenient traffic system and the science and education strength, Hubei Province is regarded as the political, economic, and
cultural center in central China. The statistical results from the land-cover maps (Figure 2) show that vegetation accounts for the largest proportion of the study area: the proportion of vegetation coverage reaches 97.57% in 2012, 0.08% higher than that in 2003 (97.49%). Among various vegetation species, deciduous broad-leaf vegetation (40.08%) and annual grass vegetation (38.12%) are the dominant types. Furthermore, the area of water increases from 0.91% to 0.97% during 2003–12, while urban and bare lands decrease from 1.60% to 1.46%.

2.2. Data processing

2.2.1. Observed meteorological data

The observed meteorological data in this study are derived from the “Yearly Surface Climate Variables of China” (National Meteorological Information Center 2005) provided by the China Meteorological Administration (CMA). The dataset contains daily measurements from January 1951 to the present, with a total of 752 stations throughout mainland China, which consist of 38 climate variables, such as air temperature, precipitation, sunshine hours, relative humidity, and air pressure. All data have been carefully quality controlled using a series of quality assurance tests (extreme value checks, time consistency checks, etc.) (Xu et al. 2009). Among the meteorological stations, there are 21 stations within the territory of Hubei Province. After removing data with excessive departures from climatology and historical records, the number of stations declines to 18. For increasing the density of stations to receive more accurate interpolation results, 17 other stations (closely surrounded the study area) are also included in the process of numerical calculation (Figure 1). All of these 35 meteorological stations are distributed fairly evenly in the study area and provide the most accurate meteorological data under current conditions.
In this work, the annual-mean air temperature and annual precipitation from 1962 to 2011 are calculated from the daily measurements to represent the climate change trends. There are many spatial interpolation methods such as inverse distance weighting (IDW), Thiessen polygon, and ordinary kriging for investigating the spatial distributions of the meteorological factors (Ruelland et al. 2008). However, these traditional methods only focus on the spatial factors (e.g., longitude and latitude) and ignore the topographic factors, which will make the distribution of air temperature and precipitation more complex, especially in mountain areas. Thus, the cokriging geostatistical interpolation technique is used for the spatial interpolation of air temperature and precipitation in this study. By choosing the elevation of each meteorological station as the covariable and implementing repeated exploratory spatial data analysis, cross validation, error analysis, and parameter modification, the cokriging method will ultimately get better interpolation results. The detailed description about the cokriging interpolation technique can be found at Apaydin et al. (2011).

2.2.2. Multiple model simulations and predictions from the WCRP CMIP5

The WCRP CMIP is the analog of the Atmospheric Model Intercomparison Project (AMIP) for the global coupled ocean–atmosphere circulation models
CMIP5 not only can evaluate how realistic the models are in simulating the historical climate conditions but also can predict the future climate changes on decadal time scales (Taylor et al. 2012). Although CMIP5 models provide only simulation outputs and have independent internal variability and starting conditions that will be different from the observed weather patterns, the comparison of overall changing trends between observations and simulations/predictions can provide useful information for better understanding the changing climate (Arora et al. 2013; Terando et al. 2012b).

The simulated (1850–2005) and the projected (2006–2100) meteorological data from six models (CanESM2, CCSM4, INM-CM4, MIROC-ESM-CHEM, MPI-ESM-LR, and MRI-CGCM3; see Table 1) are used in this study (Kharin et al. 2013). These datasets are freely available online (at https://pcmdi9.llnl.gov/projects/cmip5/). Monthly air temperature and precipitation datasets from the above six models are used to examine the climate change trend in Hubei. The IDW method is used to interpolate these models into unified grids (0.5° latitude by 0.5° longitude), and the annual-mean air temperature and annual precipitation are calculated to analyze the long-term variable characters.

### 2.2.3. MODIS GPP/NPP

The MODIS primary production product (MOD17) is the first regular, near-real-time GPP/NPP dataset for monitoring global vegetation at a 1-km resolution every 8 days. The improved Collection 5 MOD17 can establish the uncertainties of datasets using a systematic and statistically robust method (Zhao et al. 2005), which includes two subproducts: 1) MOD17A2, storing 8-day composite GPP, net photosynthesis (PsnNet); and 2) MOD17A3, which contains annual GPP/NPP. The composite MOD17A2 is an 8-day summation of GPP and PsnNet, and the annual GPP/NPP products for MOD17A3 are annual summations of two variables. Thus, the Collection 5 MOD17A3 products (annual GPP and NPP) from 2000 to 2010 are selected in this study (which can be downloaded at http://ladsweb.nascom.nasa.gov/data/search.html).

### 2.2.4. AVHRR BU LAI

Based on the third-generation GIMMS NDVI from AVHRR sensors (NDVI3g) products and an Artificial Neural Network (ANN) model, Ranga B. Myneni’s
group at Boston University generated the AVHRR BU LAI datasets with the following attributes: 15-day temporal frequency, \(1/12\)° resolution, and a temporal span from July 1981 to December 2011 (http://sites.bu.edu/cliveg/datacodes/) (Zhu et al. 2013). The datasets are first aggregated from 15-day sets to monthly sets by using maximum value composites (MVC) method and then averaged to annual sets. Both the annual-mean LAI and LAI during growing season (between May and October) in Hubei from 1981 to 2011 are calculated in this study.

### 2.2.5. Trend analysis

To evaluate the effects of climate change on the local ecosystem, trend analysis is introduced to this study. We use a linear model because this approach is simple and computationally efficient. Before the trend analysis, homogeneity of climatic parameters and ecological indicators are calculated using Levene’s tests. Results of the tests indicate that all datasets are homogeneous at a significance level of 95%.

For observed meteorological data, we use least squares regression to fit a linear trend to the data and account for temporal autocorrelation by operating the autoregressive moving average (ARMA) process (Terando et al. 2012a). The ARMA process can be characterized by its mathematical expectation \(\mu\) and its autocovariance function (ACVF). And through the ACVF, the autocorrelation function (ACF) can be further calculated. Especially, the ACVF and ACF provide a useful measure of the degree of dependence among the values of a time series at different times (Brockwell and Davis 2002). After accounting for autocorrelation, a station’s trend will be considered statistically significant if the 95% confidence interval around the linear trend does not contain zero. In addition, we also account for an inflated null hypothesis rejection rate by calculating adjusted \(p\) values that are pooled across all station trends (Benjamini and Hochberg 1995). Overall, 35 meteorological stations remained in the trend analysis upon completion of the filtering process (see Table 2).

In this study, the slope of linear fitting \(b\) is used for representing the changing trend, and the Pearson correlation coefficient \(r\) (two tailed) is calculated to measure the relationship between climatic parameters (e.g., air temperature and precipitation) and ecological indicators (e.g., GPP/NPP and LAI). The absolute value of \(r\) ranges from 0 (uncorrelated) to 1 (perfectly correlated), which indicates the different correlation strength: \(0 \leq |r| < 0.3\), weakly correlated; \(0.3 \leq |r| < 0.5\), moderately correlated; \(0.5 \leq |r| < 0.8\), significantly correlated; and \(0.8 \leq |r| < 1\), strongly correlated (Zou et al. 2003).

#### Table 2. Percentage of stations with statistically significant linear trends after accounting for serial correlation and adjusting for pooled hypothesis testing for climatic parameters.

<table>
<thead>
<tr>
<th>Climatic parameter</th>
<th>Time period</th>
<th>Increasing trend</th>
<th>Decreasing trend</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Total (P &lt; 0.01)</td>
<td>(P &lt; 0.05)</td>
</tr>
<tr>
<td>Air temperature ((n = 35))</td>
<td>1962–2011</td>
<td>97.1</td>
<td>80.0</td>
</tr>
<tr>
<td>Precipitation ((n = 35))</td>
<td>1962–2011</td>
<td>74.3</td>
<td>—</td>
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</table>
3. Results and discussion

3.1. Long-term variations of climatic parameters in Hubei Province

In this section, the air temperature and precipitation datasets from 35 meteorological stations are used to analyze the temporal and spatial pattern of climate change in Hubei Province from 1962 to 2011. The annual-mean air temperature is about 16.1°C, with a maximum of 17.3°C in 2006 (1.2°C above the mean) and a minimum of 15.3°C in 1984 (0.8°C below the mean). There is a significantly increasing trend for air temperature (at the 99% confidence level) in this area (Figure 3a); the average air temperature rises by 0.9°C from 1962 to 2011 at a rate of 0.2°C decade⁻¹, and this rate further increases to 0.4°C decade⁻¹ since 1980s. The decadal-mean air temperature during 1962–2011 is generally increasing: 15.8°C (1962–71), 15.9°C (1972–81), 15.8°C (1982–91), 16.4°C (1992–2001), and 16.7°C (2002–11). However, precipitation shows no significantly linear trend (Figure 3b). The annual-mean precipitation during 1962–2011 is 1134 mm, with a maximum of 1534 mm in 1983 (400 mm above the mean) and a minimum of 772 mm in 1966 (362 mm below the mean). Since the early 1960s, the precipitation increases gradually at a rate of 47 mm decade⁻¹ until it reaches the peak value in 1980s, then the precipitation begins to decrease at a rate of 25 mm decade⁻¹ to the 2010s. The decadal-mean precipitation over the last 50 years is 1102 mm for 1962–71, 1092 mm for 1972–81, 1197 mm for 1982–91, 1131 mm for 1992–2001, and 1148 mm for 2002–11, respectively.

Figures 4 and 5 show the spatial pattern of climate change in Hubei Province from 1962 to 2011, which is calculated from the interpolation results of observed meteorological parameters. The spatial distribution of mean air temperature reveals an increasing trend from the north to the south (Figure 4a). The areas with high temperature are in the southwest and southeast, and areas with low temperature are in the northwest. Figure 4b shows that the mean precipitation increases gradually from the northwest to the southeast. The regions with abundant precipitation are in the southeast and southwest, and regions with less precipitation are in the northwest. Figure 5 describes the linear fit of both air temperature and precipitation changes in Hubei Province from 1962 to 2011. The significance level for spatial trends is tested, and the results are displayed in Table 3. The results indicate that the air temperature increases significantly throughout the entire Hubei Province over the last 50 years; the slope of the air temperature increases from the west to the east (slope ranges from 0.0015°C yr⁻¹ to 19.7241°C yr⁻¹). Furthermore, the precipitation in Hubei Province increases in majority regions, while decreasing mainly in the southwest (slope range from −3.4162°C yr⁻¹ to 3.6611°C yr⁻¹), but the trends are not statistically significant.

In addition to analyzing the change trends of observed meteorology data, we also examine the CMIP5 models to verify whether the changing trends simulated from CMIP5 can match the observed measurements. Figure 6 describes the change trends of air temperature and precipitation in Hubei Province from 1962 to 2011, which are calculated from six models (CanESM2, CCSM4, INM-CM4, MIROC-ESM-CHEM, MPI-ESM-LR, and MRI-CGCM3). All the above models show increasing trends for air temperature and half of them (CanESM2, CCSM4, and MPI-ESM-LR) at the 99% confidence level. However, only INM-CM4 and MIROC-ESM-CHEM show the increasing trend for precipitation, the other four...
models (CanESM2, CCSM4, MPI-ESM-LR, and MRI-CGCM3) all suggest a slightly decreasing trend during the whole study period, and the variation tendency for precipitation calculated from multiple models is also not statistically significant.

Figure 7 compares the multiple model results from CMIP5 with the results from the meteorological stations. We use standard nonparametric tests [i.e., Kolmogorov–Smirnov (K–S) test] to examine the difference for population distribution between
observational datasets and the model’s outputs. The annual-mean air temperature from the stations is 16.1°C, and the decadal-mean air temperature increases by 0.9°C from 1962 to 2011 at a rate of 0.2°C decade\(^{-1}\). Compared with the observed air temperature, the values from CMIP5 are much lower. The annual-mean air temperature from CMIP5 is 13.8°C, and the decadal-mean air temperature increases by 0.6°C from 1962 to 2011 at a rate of 0.2°C decade\(^{-1}\). Although there are significant differences in population distribution between stations and CMIP5, the mean annual air temperature trends from both datasets are highly consistent. Meanwhile, the
annual-mean precipitation from the stations is 1134 mm, and the decadal-mean precipitation increases by 45 mm from 1962 to 2011 at a rate of 11 mm decade$^{-1}$.

However, the precipitation datasets from CMIP5 show that the annual-mean precipitation during 1962–2011 is 1233 mm, and the decadal-mean precipitation decreases by 4 mm from 1962 to 2011 at a rate of 1 mm decade$^{-1}$. Through uncertainty analysis, neither the increasing trend for observed precipitation nor the decreasing trend for CMIP5 precipitation is statistically significant.

To summarize from the above analysis, the air temperature shows an increasing trend during 1962–2011, which can get strong evidence from the observed
meteorological data. Furthermore, this increasing trend can also be simulated explicitly by CMIP5 multiple models. This is consistent with the global warming that most previous studies have demonstrated. However, the temporal change of the precipitation in Hubei Province is not so simple. The results from observational stations suggest a slightly increasing trend of precipitation, whereas the datasets from multiple models suggest a slightly decreasing trend. This inconsistency may be due to the uncertainties in the process of spatial interpolation and the differences in the model resolutions. Most importantly, the CMIP5 models may not have all the right processes, or they may be improperly parameterized. But it is encouraging that the CMIP5 models, like the observations, do not indicate statistically significant precipitation trends. When it comes to the spatial change trends, we can find that the areas with higher air temperature are accompanied with abundant precipitation, and these areas are mainly located to the southeast of Hubei Province. In contrast, the areas with lower air temperature also have less precipitation, and these areas are mainly located in the northwest. Moreover, the increasing rates for both air temperature and precipitation increase from west to east. These spatial characteristics may be caused by the following factors: the latitude, terrain, and distance from the ocean, for example, the terrain decreases from the northwest to the southeast, and the distance from the ocean increases from the east to the west. In a future study, much work still needs to be carried out for improving the data accuracy of spatial interpolation and model predictions for comprehensive understanding of the above differences.

3.2. Long-term variation characters of ecological indicators

GPP and NPP are the most widely used ecological indicators for terrestrial ecosystem performance. Figure 8 shows the annual variations of GPP and NPP in Hubei Province during 2000–10, which are calculated from the annual 1-km improved GPP/NPP products (MOD17A3). The mean annual GPP is 219 TgC yr\(^{-1}\), with a maximum of 232 TgC yr\(^{-1}\) in 2002 (13 TgC yr\(^{-1}\) above the mean) and a minimum of 202 TgC yr\(^{-1}\) in 2001 (17 TgC yr\(^{-1}\) below the mean). The annual GPP increases from 203 TgC yr\(^{-1}\) in 2000 to 221 TgC yr\(^{-1}\) in 2010 at a rate of 2 TgC yr\(^{-1}\) yr\(^{-1}\). At the same time, annual-mean NPP from 2000 to 2010 in Hubei Province is 110 TgC yr\(^{-1}\), with a maximum of 120 TgC yr\(^{-1}\) in 2002 (10 TgC yr\(^{-1}\) above the mean) and a minimum of 100 TgC yr\(^{-1}\) in 2001 (10 TgC yr\(^{-1}\) below the mean). Annual NPP also increases by 11 TgC yr\(^{-1}\) from 2000 (102 TgC yr\(^{-1}\)) to 2010 (113 TgC yr\(^{-1}\)) at a rate of 1 TgC yr\(^{-1}\) yr\(^{-1}\).
Figure 9 shows the spatial distribution of both the annual-mean GPP and NPP in Hubei Province. Both the annual GPP and NPP have higher values in the west and the southeast, which is mostly covered by broadleaf vegetation with sufficient light, water, and soil fertility; low GPP and NPP values occur in the central and northern part of Hubei Province where plain and hills are the dominant landforms. Furthermore, the spatial change trends of the annual GPP and NPP within the terrestrial ecosystem in Hubei Province from 2000 to 2010 are shown in Figure 10, and the corresponding significance test results are shown in Table 3. The results indicate that both GPP and NPP decrease in the south and increase in the north. The largest increasing rate for GPP and NPP values are observed in the northwest and the most obvious decline is located in the southeast and southwest.

To analyze the long-term ecological responses to climate changes in Hubei Province, the AVHRR BU LAI products are used in this section; the datasets from May to October especially are extracted to represent the growing season. Figure 11 shows the change trends of LAI during the growing season from 1981 to 2011. Approximately 97.57% of all pixels in Hubei Province are covered by vegetation (see Figure 2), so there is not much difference between the mean LAI in the whole study area and the mean LAI in the valued pixels; annual-mean LAI in the entire...
Figure 7. Trend comparisons for (a) the average air temperature and (b) the precipitation from CMIP5 and the meteorology stations in Hubei from 1962 to 2011. In the legend, the letter $b$ refers to regression coefficient, and letter $r$ refers to correlation coefficient. Significance levels: ** $p < 0.01$. 

K-S Test

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<th>Kolmogorov-Smirnov Z</th>
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K-S Test

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regions during 1981–2011 is 2.30 m\(^2\) m\(^{-2}\), and the annual-mean LAI in valued pixels is 2.35 m\(^2\) m\(^{-2}\). Moreover, the LAI increases in the entire region or in the valued pixels during the last 30 years. The mean LAI during the growing season throughout the Hubei Province increases from 1.98 (1982) to 2.40 m\(^2\) m\(^{-2}\) (2011) at a rate of 0.14 m\(^2\) m\(^{-2}\) decade\(^{-1}\). Similarly, the mean LAI during the growing season in valued pixels ranges from 2.02 (1982) to 2.44 m\(^2\) m\(^{-2}\) (2011), which increases by 0.42 m\(^2\) m\(^{-2}\) at a rate of 0.14 m\(^2\) m\(^{-2}\) decade\(^{-1}\).

Figure 12 describes the spatial distribution of annual-mean LAI and its changing trends during 1981–2011. It is clear that the LAI value is higher in the west and the southeast of the study area, and values are lower in the central and northern part, which is generally the same with the spatial distribution of annual-mean GPP and NPP (see Figure 9). In addition, there are 64% of pixels showing an increasing trend for LAI in Hubei Province from 1981 to 2011 (see Table 3), and the most significant increasing trend existed in the southwest ($p < 0.01$).

### 3.3. The correlations between climatic parameters and ecological indicators

It is known that the climate exerts an undeniable influence on the regional vegetation activity. To evaluate the effects of climate change on the terrestrial ecosystem in Hubei Province, the correlations between climatic parameters (i.e., air temperature and precipitation) and ecological indicators (i.e., GPP, NPP, and LAI) are analyzed in this section. Figure 13 shows the different types of correlations between air temperature/precipitation and GPP/NPP/LAI under various
scenarios. The strength of the correlation is determined by the squared value of Pearson correlation coefficient $r$ (i.e., $R^2$) (see section 2.2.5). A weakly positive correlation is found between the annual NPP and air temperature, and the annual GPP is moderately positively correlated with the mean air temperature (Figure 13a). Meanwhile, both the annual total GPP and the annual total NPP are moderately positively correlated with the annual precipitation (Figure 13b). Furthermore, there is no clear correlation between the annual-mean LAI of valued pixels (i.e., the areas covered with vegetation) and the precipitation, but the annual-mean LAI of valued pixels has a significantly positive correlation with the air temperature ($p < 0.01$) (Figures 13c,d).
If only focusing on the results of correlation analysis, we will find that the air temperature plays significant roles in both LAI and GPP, whereas the precipitation only affects NPP. It seems that the air temperature exerts a stronger effect on the ecosystem than the precipitation in Hubei Province during the past decades. In fact, a series of previous studies have examined the correlative link between air temperature and vegetation productivity among various ecosystems. For example, Nemani et al.
Figure 11. The temporal change trends of the mean LAI during growing season in (a) the entire Hubei areas and (b) the valued pixels from 1981 to 2011.
presented a global investigation of vegetation responses to climatic changes by analyzing 18 years (1982–99) of both climatic data and satellite observations of vegetation activity. The results indicated that global changes in climate, especially the continuously increasing temperature, had eased several critical climatic constraints to plant growth. Meanwhile, the increase of NPP in China from 1982 to 1999 has been found to be corresponded closely with changes in temperature (Fang et al. 2003).

Although the $R^2$ values calculated from correlation analysis can explain the correlated relationship between climatic parameters and ecological indicators, there are
also some comingled factors, such as irrigation, that should be taken into account. In the context of agriculture, it is widely known that irrigation results in higher crop yields, which makes contributions to the global agricultural primary productivity (Haberl et al. 2007). Ozdogan (2011) explored the potential contribution of irrigation to global NPP and found that irrigation played an important role in boosting primary productivity of croplands in water limited areas. In this paper, the study area is located at the Yangtze River basin, which belongs to the typical subtropical monsoon zone. The abundant land surface water resources and plenty of summer precipitation make this region not water limited. Furthermore, we have checked a series of agriculture yearbooks to compare the irrigated acres’ changes in Hubei Province during the period 2000–10. The statistical results show that there is no obvious expansion in irrigated areas during the study period. Thus, it could be concluded that the irrigation has not played an important role in our study. However, the resolution of the datasets in the current study is not high enough, and more observational datasets regarding the climate changes and the ecological conditions, as well as detailed information concerning human activities, should be further examined in the future.

Figure 13. The correlation analysis between the GPP/NPP/LAI and the air temperature/precipitation: (a) annual total GPP/NPP and annual-mean air temperature, (b) annual total GPP/NPP and annual precipitation, (c) mean air temperature/total precipitation during the growing season and annual-mean LAI of the valued pixels, and (d) annual-mean air temperature/annual precipitation and annual-mean LAI of the valued pixels. Significance levels: ** \( p < 0.01 \).
4. Conclusions

This study analyzed the observational evidences and model results of regional climate changes and the associated ecological responses in Hubei Province, China. The main conclusions can be summarized as follows: 1) The observed meteorology datasets show a significantly increasing trend for air temperature during the last 50 years (0.23°C decade\(^{-1}\), \(p < 0.01\)), and the warming tendency can also be simulated explicitly by CMIP5 multiple models (0.16°C decade\(^{-1}\), \(p < 0.01\)). However, there is no statistically significant trend for precipitation; the observed data show an increasing rate of 11.4 mm decade\(^{-1}\), while the CMIP5 results indicate a lower decreasing trend (0.8 mm decade\(^{-1}\)). 2) Both the GPP/NPP datasets during 2000–10 and the LAI products during 1981–2011 show increasing trends in Hubei Province, and the increasing rates are 1.8 TgC yr\(^{-1}\) yr\(^{-1}\), 1.1 TgC yr\(^{-1}\) yr\(^{-1}\), and 0.14 m\(^2\) m\(^{-2}\) decade\(^{-1}\) respectively. 3) The air temperature plays a significant effect on both LAI (\(R^2 = 0.311, p < 0.01\)) and GPP (\(R^2 = 0.189\)), while the precipitation is only positively correlated with the NPP (\(R^2 = 0.209\)), so air temperature may be the main climatic factor influencing the ecosystem performance in Hubei Province over the past decades.

Paying attention to the long-term climate change and its ecological responses will contribute to the sustainable development of society, economy, and environment in China. The analyses in this article improve our comprehensive and accurate understanding of climate change characters and the ecological conditions in this region, which will provide a valuable basis for regional climate assessment and ecological protection. Certainly, there are still some limitations existing in our works; more accurate reasons for disparities between observational datasets and multiple model results need to be examined in further research. And the further research should be conducted for quantitatively examining the climate change and the ecological responses using high-resolution products and high-precision simulation and prediction methods. In addition, the effects of human activities on regional climate change and the ecological response should also be taken into account in future.

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