

## The history of vegetation and climate changes of Yunnan in response to the uplift of Tibetan Plateau during the Neogene\*

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As we all know, during the Neogene the uplift of the Tibetan Plateau caused profound changes in the regional landforms and climate, and influenced the development of the Asian monsoons. The Neogene global cooling is a crucial event of geology history when the aridity in the Asian interior enhanced and the Asian monsoons intensified. In order to understand the Neogene vegetation succession and climate changes of Yunnan, previous investigations have explored the vegetation and climate based on palaeobotanical data. Based on the plant fossil assemblages' fluctuations from 11 localities, we attempt to quantitatively reconstruct the palaeoenvironmental evolutions of Yunnan, and to explore the terrestrial environmental changes in response to development of the Asian monsoons. By using the palaeobotanical evidence, this research will provide a new attempt at exploring the palaeoclimate changes of Yunnan, revealing regional differences of Neogene climatic changes between Central Europe and Yunnan, and detecting the signals of the Asian monsoons on the southeastern edge of Tibetan Plateau during the Neogene.

**Keywords:** Palaeovegetation; Climatic changes; Asian monsoon; Tibetan Plateau; Neogene; Yunnan.

### 1. Introduction

Neogene (23.03-2.59 Ma) is a crucial phase of global climate changes. In Asian, regional climate and environment changed profoundly by the uplift of Tibetan Plateau [1, 2, 3, 4, 5, 6]. The uplift of Tibetan Plateau gradually influenced the basic pattern of the atmospheric circulation in the northern hemisphere, triggered the onset of the Asian monsoon system, and become an important

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climate factor affecting the environmental change and biological evolution in Asia [7]. During the Neogene, Asian monsoons experienced significant and complicated evolution, among which the late Miocene is one of the key points of the evolution [3, 8, 9]. The strengthening of monsoons caused climate changed significantly in Asia and aridity in the Asian interior enhanced [4]. During the Late Miocene, the vegetation in Pakistan appeared C3 plants decreasing and C4 plants increasing [10, 11, 12] while on the northeastern edge of Tibetan Plateau the vegetation changed from forest to steppe [13].

A large number of investigations focus on the regional differences of Neogene climatic changes among North America [e.g. 14, 15, 16], Northern Australia [e.g. 17, 18] and Europe [e.g. 19, 20, 21, 22] were carried out. The quantitative researches on the Neogene climate in China have been accumulating since the 2000s [6, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Yunnan is located on southeastern edge of Tibetan Plateau (Figure 1), and its climate is influenced by the Asian monsoons and characterize by wet and dry season. The unique geographical position, special climate condition and abundant botanical resources make Yunnan one of the most important regions for studying the climate and vegetation changes caused by uplift of the Tibetan Plateau [32, 33, 34, 35]. In recent years, a series of similar quantitative researches on the Neogene climate in Yunnan have been accumulating since the 2000s [5, 30, 33, 34, 35, 36, 37].

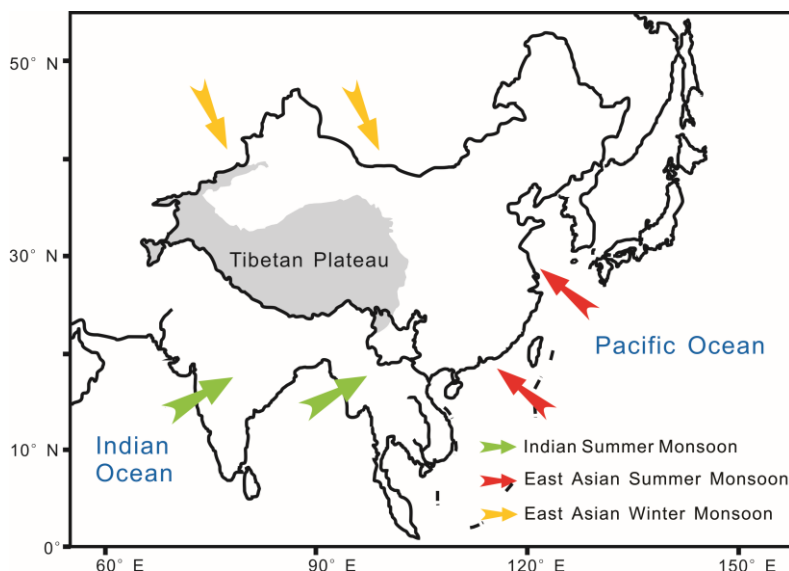


Fig. 1. A map of the modern Asian monsoon system, the Tibetan Plateau and the position of Yunnan (Modified from [4]).

Xu [36] described the Late Pliocene palynofloras of Eryuan, Yangyi and Longling, western Yunnan and respectively quantitatively reconstructed the climates of three localities. Zhao et al. [37] reported plant megafossils from the Early-Middle Miocene Nanlin Formation of the Mangdan coal-mine, including 11 taxa of angiosperms, *Corylopsis*, *Ficus*, *Hypericum*, *Lauraceae*, *Lithocarpus*, *Magnolia*, *Myrica*, *Nyssa*, *Sabia*, *Symplocos* and *Zanthoxylum*, suggesting an evergreen broad-leaved forest growing in Mangdan region. Kou et al. [5] recorded the pollen assemblages from Eryuan during the Late Pliocene of western Yunnan, and compared those with two contemporary palynofloras from Yangyi and Longling. They suggested the palaeotemperature was higher than present among three localities while the a doubling of the palaeoprecipitation in the Longling area between the Late Pliocene and the present. Later, Xu et al. [33] described the Late Miocene palynoflora from Lühe coal-mine, reflecting a subtropical climate condition. Xia et al. [34] quantitatively analysed the Xiaolongtan flora which supported a southern, humid subtropical climate, being more humid and having a slightly higher mean annual temperature than today. Zhang et al. [35] summarized the history of vegetation succession in four sites in southern part of Yunnan during the Middle Miocene, suggesting that the vegetation there was composed of mixed evergreen and deciduous broad-leaved forests growing under subtropical conditions. Li et al. [30] reported the Late Miocene palynoflora in Wenshan basin resembles that of modern evergreen broad-leaved forests in subtropical East Asia.

In this study, based on assemblages of pollen/fruits/seeds which were employed from prior researches and their NLRs in China we reconstruct the climate trends in Yunnan during the Neogene by applying the CA and we focus on seasonal ranges of temperature and precipitation in particular. The aims of our study were: (1) to design the palaeotemperature and palaeoprecipitation curves of Yunnan based on prior botanical data and bioclimatic analyses; (2) to reveal regional differences of Neogene climatic changes between Central Europe and Yunnan; (2) to detect the signals of the Asian monsoon on the southeastern edge of Tibetan Plateau in Neogene.

## **2. Materials and Methods**

Pollen/fruits/seeds taxa making up different assemblages at 11 widely distributed Yunnan fossil plant sites (Figure 2, Table 1) were used for the reconstructing changes in temperature and precipitation during Neogene. This study summarized almost all the known quantitative researches on the Neogene climate in Yunnan.

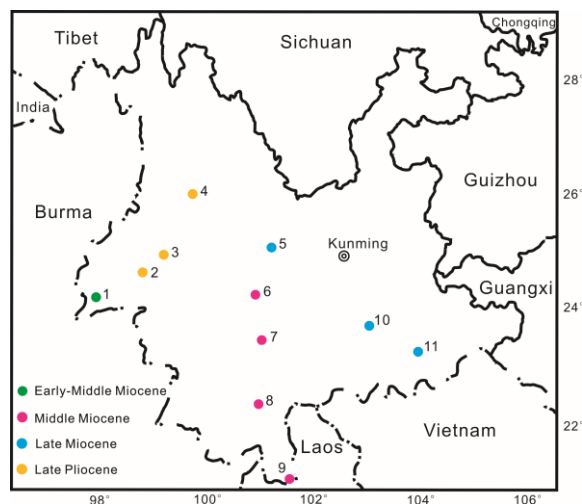


Fig. 2. Map showing the position of the 11 localities of Yunnan where prior quantitative researches have been investigated. (1. Mangdan, 2. Longling, 3. Yangyi, 4. Eryuan, 5. LüHe, 6. Jingdong, 7. Zhenyuan, 8. Puwen, 9. Mengla, 10. Kaiyuan, 11. Wenshan.)

Table 1. List of fossil localities in Yunnan (Site numbers as in Figure 1).

Period	Site	Location	Formation	Site coordinate	Type of flora	References
Early-Middle Miocene	1	Mangdan	Nanlin	21.4° N, 97.8° E	Fruits/Seeds	Zhao et al. 2004
	6	Jingdong	Dajie	24.3° N, 101.0° E	Pollen	Zhang et al. 2012
Middle Miocene	7	Zhenyuan	Dajie	23.6° N, 101.2° E	Pollen	Zhang et al. 2012
	8	Puwen	Dajie	22.5° N, 101.0° E	Pollen	Zhang et al. 2012
	9	Mengla	Dajie	21.3° N, 101.7° E	Pollen	Zhang et al. 2012
Late Miocene	5	LüHe	Shihuiba	25.0° N, 101.5° E	Pollen	Xu et al., 2008
	10	Kaiyuan	Xiaolongtan	23.5° N, 103.2° E	Pollen	Xia et al., 2009
	11	Wenshan	Xiaolongtan	23.4° N, 104.2° E	Pollen	Li et al., 2015
Late Pliocene	2	Longling	Mangbang	24.7° N, 98.8° E	Pollen	Xu, 2002
	3	Yangyi	Yangyi	25.0° N, 99.3° E	Pollen	Xu, 2002
	4	Eryuan	Sanying	26.0° N, 99.8° E	Pollen	Kou et al., 2006

As a mountainous plateau which is strongly influenced by the uplift of Tibetan Plateau, Yunnan possesses complicated topography, multivariate climates and diverse plants. Geographically, it represents only 4% of China, but it contains 45.9 % species of vascular plant [38]. The Asian Winter Monsoon blocked by the growing Tibetan Plateau, which caused the winter here gradually warmer and warmer since Middle Miocene [35].

It has a complex terrain with a climate pattern influenced by monsoon systems. Mainly two types of modern vegetation exist in Yunnan. One type widely distributes in north and middle part of Yunnan where exists subtropical

evergreen broad-leaved forest dominated by *Castanopsis*, evergreen *Quercus*, Lauraceae Theaceae and so on, indicative of humid and dry seasons. The other type only distributes in the southern edge of Yunnan where grows tropical rainforest and seasonal rainforest dominated by species of families such as Moraceae, Meliaceae, Sapindaceae, Palmae and so on, suggesting tropical climate [7, 29].

For the quantitative analyses of Neogene climate changes of Yunnan, 11 assemblages including 1 fruits/seeds and 10 pollen floras from 11 fossil localities have been summarized from the references. The 11 localities are listed in Table 1 together with information on their stratigraphy and sedimentology, with references concerning the type of floras.

Coexistence Approach (CA) [39] is used for quantitative bioclimatic analysis of the 11 assemblages. Based on the assumption that the climatic requirements of a fossil taxon are similar to those of its Nearest Living Relative (NLR). Analyzing the geographic distributions of all NLRs [40], the climatic parameters and coexistence intervals of the fossil taxa in a palynoflora are obtained. The modern climatic parameters of NLRs used in CA are extracted from the surface meteorological data of China[42]. Seven parameters of temperature and precipitation have been determined. These are: MAT = the mean annual temperature, MWMT = the mean temperature of the warmest month, MCMT=the mean temperature of the coldestmonth, DT=the difference in temperature between the coldest and warmest months, MAP= the mean annual precipitation, MMaP=the mean maximum monthly precipitation, and MMiP= the mean minimum monthly precipitation.

### 3. Results

Seven parameters of temperature and precipitation were estimated based on pollen/fruits/seeds data at all 11 sites during the Neogene (Table 2). The pattern and ranges of temperature and precipitation are presented as below (Figure 3).

Table 2. Comparison of climatic parameters of 11 fossil localities in Yunnan extended from the Early-Middle Miocene to the Late Pliocene.

Period	Site	Location	MAT	MWMT	MCMT	DT	MAP	MMaP	MMiP
Early-Middle Miocene	1	Mangdan	18.8-20.5	27.6-28.0	7.9-11.3	15.2-17.9	1170.0-1300.0		
	6	Jingdong	11.5-17.3	19.8-28.0	-0.2-5.9	12.3-24.6	793.9-1389.4	172.4-245.2	6.9-22.1
	7	Zhenyuan	11.5-20.8	18.7-28.0	-0.2-5.9	12.1-26.0	793.9-1389.4	172.4-245.2	5.7-22.1
	8	Puwen	11.5-21.9	18.7-28.0	-0.2-5.9	12.1-24.6	793.9-1389.4	139.0-245.2	4.9-23.6
Middle Miocene	9	Mengla	11.5-21.9	18.7-28.5	-0.2-5.9	12.1-26.0	793.9-1389.4	137.3-245.2	4.5-22.1
	5	LüHe	13.3-20.9	22.5-27.5	2.5-12.6	12.1-24.8	803.6-1254.7	179.4-249.6	10.2-18.5
	10	Kaiyuan	16.7-19.2	25.4-26.0	7.7-8.7		1215.0-1639.0	224.0-248.0	19.0-24.0
Late Miocene	11	Wenshan	16.6-17.5	27.5-29.7	2.4-5.5		1432.3-1598.9	228.7-266.0	21.7-48.1
	2	Longling	18.6-22.1	22.8-27.5	9.7-15.1	12.3-18.1	815.8-1254.7	172.4-249.6	9.8-11.3
Late Pliocene	3	Yangyi	13.3-20.9	22.5-27.5	1.9-12.6	12.3-25.5	797.5-1254.7	172.4-249.6	7.2-12.7
	4	Eryuan	13.3-18.6	24.6-27.5	1.9-12.1	14.2-16.6	619.9-1484.3	143.8-245.6	12.7-16.4

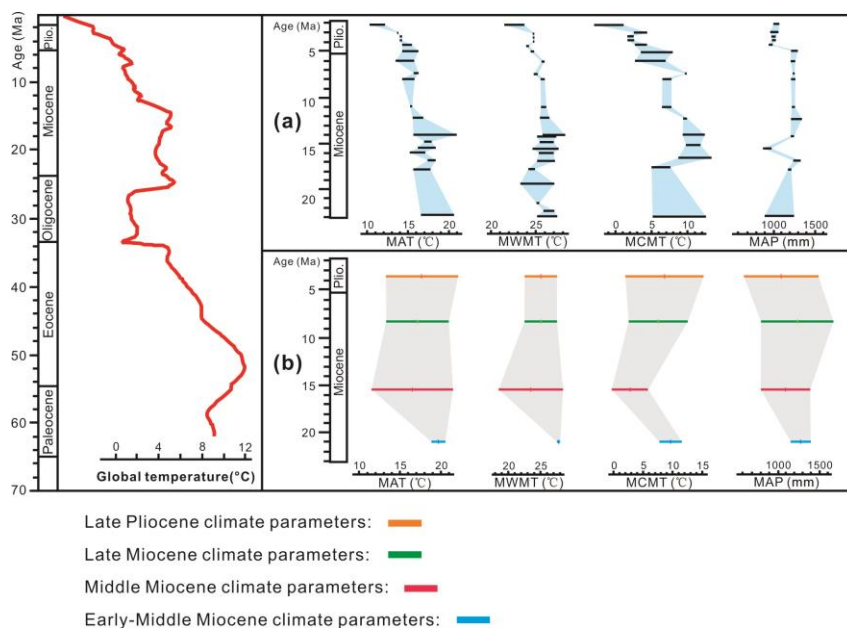


Fig. 3 The Neogene climatic comparison between Yunnan and Central Europe. The global temperature curve is modified from Zachos et al. (2001). a. The temperature and precipitation curves for Central Europe (modified from Mosbrugger et al., 2005). b. The temperature and precipitation curves for Yunnan.

### 3.1. MAT

Firstly, the curve showed a cooling trend from the Early-Middle to Middle Miocene with median values of MAT decreasing by 3.0 °C (from 19.7 to 16.7 °C) (Table 3). Secondly, a warming period from the Middle to Late Miocene

is characterized by MAT increasing by 0.4 °C (from 16.7 to 17.1 °C). Finally, the warming trend continued from the Late Miocene to Late Pliocene, MAT sequentially increased by 0.6 °C (from 17.1 to 17.7 °C). Generally speaking, the MAT curve showed a series of warming and cooling fluctuations. Taken as a whole, MAT curve indicated that the warmest period of Yunnan during Neogene occurred in Early-Middle Miocene, and the MAT dropped by 2.0 °C (from 19.7 to 17.7 °C).

Table 3. The Neogene temperature and precipitation evolution of Yunnan.

Period	MAT min-max (mid)	MWMT min-max (mid)	MCMT min-max (mid)	DT min-max (mid)
Early-Mid Miocene	18.8-20.5 (19.7)	27.6-28.0 (27.8)	7.9-11.3 (9.6)	15.2-17.9 (16.6)
Middle Miocene	11.5-21.9 (16.7)	18.7-28.5 (23.6)	-0.2-5.9 (2.9)	12.1 -26.0 (19.1)
Late Miocene	13.3-20.9 (17.1)	22.5-29.7 (26.1)	2.4-12.6 (7.5)	12.1-24.8 (18.5)
Late Pliocene	13.3-22.1 (17.7)	22.8-27.5 (25.2) (25.15)	1.9-15.1 (8.5)	12.3-25.5 (18.9)
Period	MAP min-max (mid)	MMaP min-max (mid)	MMiP min-max (mid)	
Early-Mid Miocene	1170.0-1300.0 (1235.0)			
Middle Miocene	793.9-1389.4 (1091.7)	137.3-245.2 (191.3)	4.5-23.6 (14.1)	
Late Miocene	803.6-1639.0 (1221.3)	179.4-266.0 (222.7)	10.2-48.1 (14.6)	
Late Pliocene	619.9-1484.3 (1052.1)	143.8-249.6 (196.7)	7.2-16.4 (11.8)	

### 3.2. MWMT

Firstly, from the Early-Middle to Middle Miocene, the median values of MWMT decreasing by 4.2 °C (from 27.8 to 23.6 °C). Secondly, it increased by 2.5 °C from the Middle to Late Miocene (from 23.6 to 26.1 °C). Finally, it dropped by 0.9 °C from the Late Miocene to Late Pliocene (from 26.1 to 25.2 °C). Taken as a whole, MWMT curve suggested a general cooling trend during the whole Neogene dropping by 2.6 °C (from 27.8 to 25.2 °C) (Table 3).

### 3.3. MCMT

Firstly, the curve showed a cooling trend from the Early-Middle to Middle Miocene with median values of MCMT decreasing by 6.7 °C (from 9.6 to 2.9 °C). Secondly, a warming period from the Middle to Late Miocene is characterized by MCMT increasing by 4.6 °C (from 2.9 to 7.5 °C). Finally, the warming trend of MCMT continued from the Late Miocene to Late Pliocene, with median values sequentially increasing by 1.0 °C (from 7.5 to 8.5 °C). Generally speaking, the MCMT curve showed a series of warming and cooling fluctuations. Taken as a whole, MCMT curve indicated that the warmest period during Neogene occurred in the Early-Middle Miocene, and the MCMT dropped by 1.1 °C from the Early-Middle Miocene to Late Pliocene (from 9.6 to 8.5 °C) (Table 3).

### 3.4. *DT*

Firstly, from the Early-Middle to Middle Miocene, the median values of *DT* increasing by 2.5 °C (from 16.6 to 19.1 °C). Secondly, it decreased by 0.6 °C from the Middle to Late Miocene (from 19.1 to 18.5 °C). Finally, it increased by 0.4 °C from the Late Miocene to Late Pliocene (from 18.5 to 18.9 °C). Generally speaking, the *DT* curve showed a series of warming and cooling fluctuations. Taken as a whole, *DT* curve indicated that the warmest priod during Neogene occurred in Middle Miocene, and the *DT* increased by 2.3 °C from the Early-Middle Miocene to Late Pliocene (from 16.6 to 18.9 °C) (Table 3).

### 3.5. *MAP*

Firstly, the curve of *MAP* showed a drying trend from the Early-Middle to Middle Miocene with median values decreasing by 143.3 mm (from 1235.0 to 1091.7 mm). Secondly, a wetting priod from the Middle to Late Miocene is characterized by *MAP* increasing by 129.6 mm (from 1091.7 to 1221.3 mm). Finally, it decreased by 169.2 mm from the Late Miocene to Late Pliocene (from 1221.3 to 1052.1 mm). Generally speaking, the *MAP* curve showed a series of drying and wetting fluctuations. Taken as a whole, the *MAP* curve indicated that the wettest priod during Neogene occurred in Early-Middle Miocene, and the *MAP* dropped by 182.9 mm from the Early-Middle Miocene to Late Pliocene (from 1235.0 to 1052.1 mm) (Table 3).

### 3.6. *MMaP*

Firstly, the curve of *MMaP* showed a wetting trend from the Middle to Late Miocene with median values increasing by 31.4 mm (from 191.3 to 222.7 mm). Secondly, a drying priod from the Late Miocene to Late Pliocene is characterized by *MMaP* decreasing by 26.0 mm (from 222.7 to 196.7 mm). Taken as a whole, the *MMaP* curve indicated that the wettest priod during Neogene occurred in Late Miocene, and the *MMaP* increased by 5.4 mm from the Early-Middle Miocene to Late Pliocene (from 191.3 to 196.7 mm) (Table 3).

### 3.7. *MMiP*

Firstly, the curve of *MMiP* showed a wetting trend from the Middle to Late Miocene with median values increasing by 0.5 mm (from 14.1 to 14.6 mm). Secondly, a drying priod from the Late Miocene to Late Pliocene is characterized by *MMiP* decreasing by 26.0 mm (from 14.6 to 11.8 mm). Taken as a whole, the *MMiP* curve indicated that the wettest priod during Neogene



occurred in Late Miocene, and the MMiP decreased by 2.3 mm from the Early-Middle Miocene to Late Pliocene (from 14.1 to 11.8 mm) (Table 3).

#### 4. Discussion

##### 4.1. *The climate changes in Yunnan during Neogene comparison with those in Central Europe*

The Neogene temperature and precipitation curves of Yunnan were compared with those from the global marine temperature record and from Central Europe [19, 42] (Figure 3). It revealed that:

MAT: In contrast to the Neogene cooling [19, 42], MAT curves of Yunnan exhibited cooling first and then warming. Generally speaking, the decrease in MAT in Yunnan was gentler than in Central Europe since the Early-Middle Miocene. MAT dropped by 2.0 °C in Yunnan (from 19.7 to 17.7 °C) and by approximately 7.4 °C in Central Europe (from 18.5 to 11.1 °C). The temperature was 6.6 °C higher in Yunnan than in Central Europe during the Late Pliocene (17.7 vs. 11.1 °C), while it was 1.2 °C higher in Yunnan than in Central Europe during the Early-Middle Miocene (19.7 vs. 18.5 °C) (Figure 3).

MWMT: The decrease in MWMT in Yunnan and that in Central Europe were more or less similar. MWMT dropped by 2.6 °C (from 27.8 to 25.2 °C) in Yunnan and by 3.4 °C (from 26.1 to 22.7 °C) in Central Europe since the Early-Middle Miocene (Figure 3).

MCMT: The decrease in MCMT in Yunnan was much gentler than in Central Europe. MCMT only dropped by 1.1 °C from the Early-Middle Miocene to Late Pliocene (from 9.6 to 8.5 °C) in Yunnan, while it dropped by 9.8 °C (from 8.9 to -0.9 °C) in Central Europe during the Neogene. The MCMT in Yunnan and that in Central Europe were more or less similar during the Early-Middle Miocene (9.6 vs. 8.9 °C), but difference of winter temperatures between East China and Central Europe was 9.4 °C (8.5 vs. -0.9 °C) during the Late Pliocene (Figure 3).

MAP: In Central Europe, the MAP curve showed a series of wetting and drying fluctuations (Mosbrugger et al., 2005). Taken as a whole, MAP curve of Yunnan indicated that regional drying happened in Early-Middle Miocene with MAP dropped by 182.9 mm from the Early-Middle Miocene to Late Pliocene (from 1235.0 to 1052.1 mm). Generally speaking, the decrease in MAP in Central Europe was gentler than in Central Europe since the Early-Middle Miocene. (Figure 3).

#### 4.2. *The signals of the Asian monsoon on the southeastern edge of Tibetan Plateau in Neogene*

All three temperature curves (MAT, MWMT, MCMT) exhibit cooling trends from Early-Middle to Middle Miocene, then warming from Middle Miocene to Late Pliocene. The decrease of temperature in Middle Miocene might signal the strengthening of the Asian Winter Monsoon [4]. Since Middle Miocene temperature curves all showed increasing trends which most likely caused by the uplift of the Tibetan Plateau, which has succeeded in blocking the Asian Winter Monsoon since the Middle Miocene.

The precipitation curve (MAP) exhibited drying trend from Early-Middle to Middle Miocene, and this phenomenon might be influenced by the enhanced aridity in the Asian interior [4].

### 5. Conclusion

The compared palaeoclimatic studies in Yunnan, at the southeastern edge of the Tibetan Plateau, lead to the following conclusions:

1. In contrast to the global cooling, Yunnan palaeoclimate exhibited cooling first and then warming during the Neogene. The decrease in MAT in Yunnan was gentler than in Central Europe since the Early-Middle Miocene.
2. The winter temperature changes were more obvious than the summer temperature changes in Yunnan since the Miocene.
3. The decrease of palaeotemperature might signal the strengthening of the Asian Winter Monsoon in Middle Miocene. In our study the climate exhibited warming trends which most likely caused by the uplift of the Tibetan Plateau, which has succeeded in blocking the Asian Winter Monsoon since the Middle Miocene.

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