TIBETAN PLATEAU SNOW COVER VARYING WITH CLIMATE CHANGE: A REGIONAL CLIMATE PERSPECTIVE

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ABSTRACT:

The Tibetan Plateau (TP) is experiencing dramatic climate changes, which increases the geographical hazard risks affecting human lives and properties. As TP holding the largest cryosphere extent outside the polar region, frequent and serious snow disasters become the crucial topic in the TP disaster reduction and management. The primary task to cope with TP snow disasters is to understand the formation and evolution of snow cover as the basis to assess and predict geographical hazards. Considering time variability and spatial heterogeneity, the geographical detector analysis has been adopted to investigate the coupling relationships between snow cover and climate change in the different periods (1989-2018) and different geographical regions (Qaidam areas, Qiangtang areas and Hengduan Mountains). The following results are noted: (i) Regionalization provides a better climate explanation for snow cover compared with the non-regionalized whole plateau model, which verifies again that the snow cover distribution and its driving mechanism both have strong spatial heterogeneity. (ii) Temperature has a dominant influence on the snow cover in all three regions, showing that net surface energy flux balance is the major limitation to the snow cover so that temperature becomes the key factor of snow-related risk management. (iii) The impact of precipitation on snow cover is only significant in the Qaidam areas according to the interaction detector approach, where the combination of temperature and precipitation can explain more than 65% of the snow cover distribution. Thus the Qaidam areas requires risk monitoring related to both hydrological and thermal aspects.

1. INTRODUCTION

The third pole, Tibetan Plateau (TP), is the highest and most extensive highland in the world with an average elevation of over 4000 m asl and an area of approximately 2.5×10^6 km^2. The unique geographical environment equips TP with a unique role for the global and regional climate scale (Yao et al., 2012). In the past few decades, TP has experienced climate change featured by overall warming and moistening (Xu et al., 2008; Yang et al., 2014) associated with significant increases of geographical hazard risks like landslides, glacial lake outbursts, snow/ice disasters, etc., imposing serious threats to human life and property. However, research on the TP hazard is hindered by the lack of the understanding for the geographical environment and their quantitative relations with hazard triggers like climate contributing factors (Yao et al., 2019). Thus, the primary task to cope with the TP hazards is to understand the formation and evolution of geographical hazards, then we can further assess and predict geographical hazards.

As the largest cryosphere extent outside the polar regions, the snow cover on the TP is highly susceptible to climate change (Li et al., 2008; Kang et al., 2010). Snow cover, as the main form of cryosphere, is directly affected by climate change including changes of precipitation and temperature. Snow cover also exerts an influence on climate by changing the thermal conditions on the plateau through the snow albedo effect and the hydrological cycle (Li et al., 2018; Qian et al., 2011). These changes can further influence the Asian monsoon system and the atmospheric circulation, related with the flooding and drought in south-eastern Asia and even climate anomalies in North America (Chu et al., 2008). Besides feedbacks with the global climate system, the snow cover changes on the TP are also closely related to the lives of millions of people, as the TP functions as the Asian Water Tower (Immerzeel et al., 2010). Therefore, monitoring the snow cover changes on the TP and investigating their coupling relationships with climate change are crucial topics for understanding and possibly reducing climate disasters, and thus preserving a safe living environment.

The complex topography on the TP leads to the uneven spatial distribution of snow cover. The climate and its temporal variation on the TP also have great spatial heterogeneity. Furthermore, the snow-climate relationships can also vary in different regions. However, previous studies have mostly been focussing on the overall snow cover change as a response to climate change, giving less priority to the regional differentiation (Kang et al., 2010). This study addresses first the distribution of snow and climate change in different geographical regions and then explores the varying mechanisms of the snow-climate interaction on the TP, in order to provide information for snow cover change prediction and support to cope with snow related disasters.

2. THE SPATIO-TEMPORAL VARIATION OF SNOW COVER ON THE TIBETAN PLATEAU

2.1 Snow Cover Dataset

Ground observation stations on the TP are too few and sparse, which cannot obtain representative information of snow cover and climate. Thanks to the development of the remote sensing techniques, we can extract the snow cover extent in continuous

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time and with a full spatial coverage based on optical satellite images, which makes snow cover extent a readily visible indicator of climate change.

The snow cover dataset adopted in this study is based on optical instrument remote sensing on the Tibetan Plateau (1989-2018) (Zheng & Chu, 2019), which provides per-day snow cover extent (within the annual snow accumulation period from October to April of the following year) with 1 km spatial resolution.

2.2 Spatio-temporal distribution characteristics of snow cover on the TP

Snow cover days (SCDs) are counted for the annual snow cover accumulation period periods (per 1 km^2 pixel) from 1989 to 2018; that is the proportion of SCDs in the annual snow accumulation period (Fig. 1). The result shows that SCDs reveal an obvious spatial heterogeneity with regional characteristics: south-eastern TP shows the largest SCDs, compared with the middle-west TP with less SCDs than south-eastern TP and Qaidam Basin with little snow.

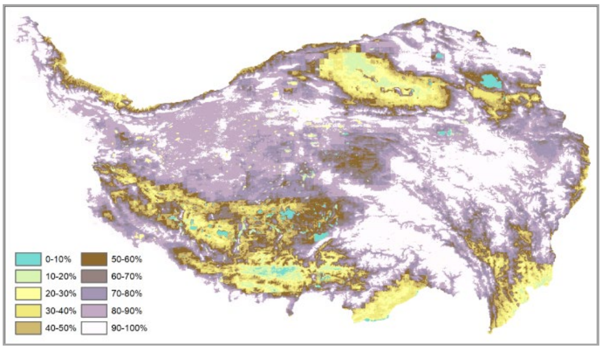

Figure 1. The proportion of SCDs in the annual snow accumulation period on the TP (1989 − 2018)

Qaidam Basin, south-western TP, Yarlung Zangbo Canyon and the south Hengduan Mountains have rather short snow days, where the SCDs are less than 60 days and no more than 30% of the annual snow accumulation period. Although they are all featured by less SCDs, their causes are different: (i) Affected by arid climate, the precipitation on the Qaidam Basin is rare and mostly instantaneous snow, which is difficult to maintain the snow cover. (ii) For the Yarlung Zangbo Canyon and the south Hengduan Mountains, the temperature is relatively higher compared with the other parts on the TP, which is not favorable for snow formation. (iii) In contrast, the south-western TP is a rather cold region supporting snow cover formation and maintenance. But controlled by the cold high pressure center in the winter, there is less water vapour transport into this region, responsible for the observed limited snow accumulation.

The regions with large SCDs are mainly distributed in the high altitude mountainous areas, including Karakoram, Kunlun, Himalaya, Tanggula, Nyenchen Tanglha, Qilian and Hengduan Mountains, etc. In these regions, the annual SCDs can reach more than 120 days. These regions are also under the different situation. Those alpine regions in the middle and western TP (i.e. Karakoram, Kunlun, Himalaya and Qilian Mountains) are covered with permanent snow all the year around according to the extremely cold climate, while the eastern TP is benefit by the favourable water vapour condition. The topographic uplift on the south-west side of the TP blocks the southern warm and moist air flow to enter the hinterland of the TP. As a result, the warm and moist air flow is forced to move eastward along the Himalaya Mountains and northward along the Hengduan Mountains. The abundant water vapour forms snow, which rapidly accumulates on the eastern TP, resulting in the snowy eastern TP.

The spatial heterogeneity of snow cover on the TP is not only reflected by the spatial differences of SCDs, but also shown in the varying trend of annual SCDs in different regions (Fig. 2). According to the combination of Fig. 1 and Fig. 2(a), it is found that the regions with less SCDs (around 20% of the TP area), such as Qaidam Basin and south-western TP, show a trend towards a smaller number of SCDs; while SCD numbers on 80% of the TP area reveal a growth trend. Especially regions with large SCD numbers, as the Karakoram and Nyenchen Tanglha Mountains, are subjected to a rapid increase of SCDs, reaching more than 5 days per year. That is, ‘snowy regions become snowier', which indicates that the polarization of the SCDs on the TP is getting more serious. After further significance testing ($p < 0.05$) (Fig. 2(b)), SCDs have changed significantly in the 34.77% of the TP. Most of them (34.12%) show significant SCD growth, mainly on the Karakoram, Nyenchen Tanglha and Qilian Mountains. But the opposite is not significant: only 0.64% of the area (the hinterland of the Qaidam Basin) has the significant trend of decreasing SCDs. The SCD variation in the south-western TP is not significant.

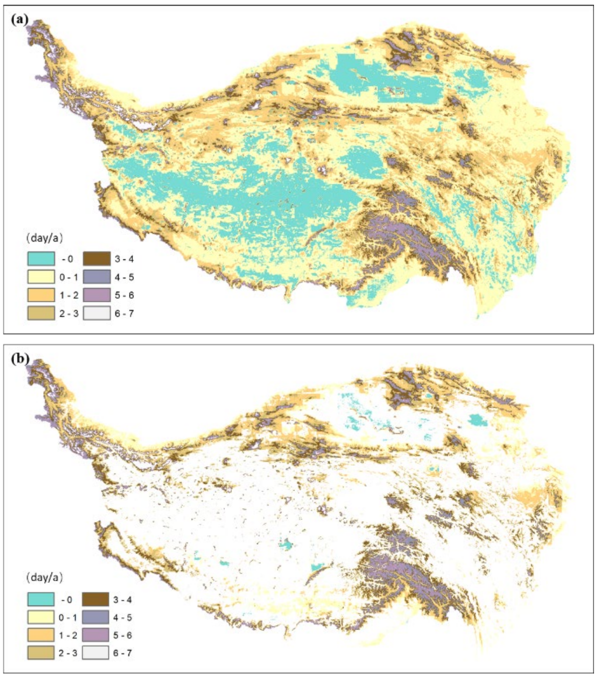

Figure 2. (a) The annual trend of SCDs on the TP (1989 − 2018) and (b) the region with 95% confidence level ($p < 0.05$)

Given the above, snow cover is an important indicator for the climate and environmental change. Based on the satellite remote sensing data, we can achieve the periodic full-coverage dynamic monitoring for the TP snow cover, especially for these regions with significant SCD trend, no matter the SCDs are extending or shortening. It helps to obtain the location and additional information of risk areas in time to provide targeted preventive action to reduce disasters.

3. CLIMATE SPATIAL HETEROGENEITY AND REGIONALIZATION

3.1 Meteorological Dataset

China Meteorological Forcing Dataset (CMFD) (He et al., 2020) is introduced to explore the response of snow cover to climate change. It is a high spatial-temporal resolution gridded (0.1°) near-surface meteorological dataset of China, which integrates multi-source data on the in-situ observation of meteorological stations, including remote sensing products and the reanalysis dataset. Seven near-surface meteorological variables are provided in CMFD and used for measuring the climate-snow coupling relationships in this study, including the near surface (2-meter) air temperature (temp), surface pressure (pres), specific humidity (shum), 10-meter wind speed (wind), downward shortwave radiation (srad), downward longwave radiation (lrad) and precipitation rate (prec). Compared with the traditional combination of temperature and precipitation, CMFD provides a more nuanced view of the thermal, hydrological and atmospheric climate conditions on the TP by seven near-surface meteorological variables, which makes it possible to accurately depict the climate-snow coupling relationships.

3.2 The Geographical Division of TP

To obtain a geographical division closely related to both snow cover change and climate change, we mainly concerned the regional hydro-thermal condition, which largely determine the distribution of snow cover. By clustering the temperature and precipitation, we divided TP into three main climate regions, Qaidam areas (Region I), Qiangtang areas (Region II) and Hengduan Mountains (Region III) (Fig. 3).

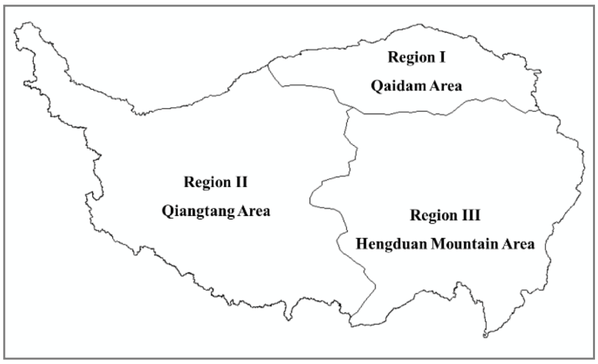

Figure 3. The geographical division of three climatic regions

According to the distribution of three climate regions in the temperature-precipitation feature space, they are in the totally different energy/water-limited conditions under the Budyko dryness framework (Budyko, 1974) (Fig. 4). The climate conditions are measured by the aridity ratio A:

$$A = \frac{P}{PET}, \tag{1}$$

It characterizes the surface flux ratio of precipitation (P) versus potential evapotranspiration (PET) relating water demand and water supply (Feng et al., 2022), where PET has been estimated by a modified Thornthwaite formula (Holland, 1978; Gordon et al., 2005), where T is the Kelvin temperature and the estimated PET is in cm/year:

$$PET = 1.2 \cdot 10^9 \cdot e^{\frac{-4.62 \cdot 10^3}{T}}, \tag{2}$$

In Figure 4, each colour is for its corresponding region, yellow for Qaidam areas, blue for Qiangtang areas and green for Hengduan Mountains. For each region, we divided the study period (1989-2018) into three decades, calculated their decadal statistics and plotted the trajectory of their temperature-precipitation trajectory. Shown in Figure 4, Region I is extremely arid (A<0.5) with warming and moistening in the past 30 years. The precipitation in Region II has increased from 200 to 350mm/a. Although Region II is still under the arid condition, the dryness condition within Region II has already improved a lot during the past three decades. Different with Region I and Region II, Region III is under the energy-limited condition. With the simultaneous increase of temperature and precipitation, the dryness condition in Region III is relatively stable. From rather dry area (Region I) to relative wet area (Region III), they also well correspond to the distribution of SCDs from less to more (Fig.1). In each region, the pattern of the snow cover vary with climate conditions should also be different. Thus, in the following section, we will quantitatively explore snow-climate interactions varying in these three geographical regions on the TP, and investigate the climate controlling factors behind the snow cover change.

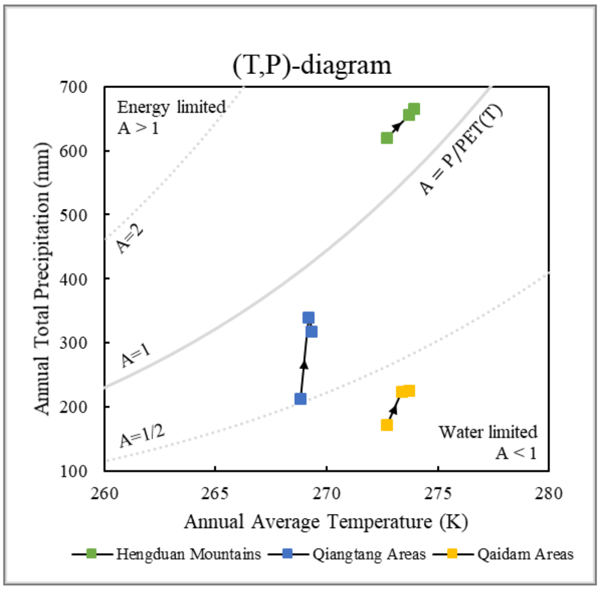

Figure 4. The hydro-thermal climatic conditions in three climatic regions and their decadal variations from 1980s to 2010s.

4. THE COUPLING RELATIONSHIP BETWEEN SNOW COVER AND CLIMATE CHANGE

4.1 The Geographical Detector

We introduce the Geographical Detector Statistical Method (Wang et al., 2017) to reveal the specific climate driving force affecting the spatial differentiation of snow cover from the perspectives of the whole plateau and three geographical regions separately.

The basic idea of geographical detector is that spatial heterogeneity can be expressed by strata, that is, classes or subareas. The study area is characterized by spatial stratified heterogeneity if the variance within strata is less than the variance between strata. If the spatial distribution of two variables tends to be consistent, these two variables have statistical correlation. Geographical detectors can be used to measure the spatial heterogeneity among data, test the coupling relationship between two variables and investigate interaction between multiple explanatory variables to the response variable. This analysis has been widely used in natural sciences, social sciences and environmental sciences (Du et al., 2016; Guo et al., 2022).

Two statistics tools in the geographical detectors, factor detector and interaction detector, are employed to analyse the spatial correlation between snow cover and climate change. Factor Detector uses q-statistic to measure the determinant power of an explanatory variable X of Y:

$$q = 1 - \frac{SSW}{SST} = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}, \tag{3}$$

where the study area is stratified into h = 1, ···, L stratum for both the explanatory and response variable X and Y; N and N_h are the numbers of the sample within the whole study area and stratum h; σ^2 and σ_h^2 are the variances of the whole study area and stratum h. It is also renamed as SSW, Within Sum of Squares, and SST, Total Sum of Squares. The value of q is within [0, 1]. If Y is stratified by an explanatory variable X, the larger the value of q statistics corresponds to the stronger the explanatory power of factor X to attribute to Y; $q = 0$ indicates that there is no coupling between Y and X; while $q = 1$ indicates that Y is completely determined by X.

Considering the complex relationship between multiple climatic factors and snow cover, the interaction detector is also used to identify the interactive influence of explanatory factors X1, X2 and more X on a response variable Y. This detector relies on the calculation and comparison of q(X1), q(X2) and q(X1 ∩ X2) to evaluate whether the interactive influence of variables X1 and X2 on response variable Y are independent, or whether they strengthen or weaken the explanatory power for the response variable Y when acting together.

4.2 Implementation Process

First, we sampled the distribution of snow cover on the TP from the probability distribution. Next, we selected seven typical climate variables (see Section 3.1) and used Jenks Natural Breaks (Fisher, 1958; Jenks & Caspall, 1971) to define the strata as the input of the samples. Factor detector and interaction detector were used to test the coupling relationships between a single climate variable / combination of climate variables and the response variable SCDs with q-statistics. Then the dominant factors and dominant interactive factor pairs in each region were identified by a higher q-value, which is a stronger explanatory power to snow cover differentiation.

The above procedures were carried out in all three decadal periods (1989-1998, 1999-2008, 2009-2018) in the whole plateau and separately for the three geographical regions, namely Qaidam areas (Region I), Qiangtang areas (region II), and Hengduan Mountains (Region III), respectively. Finally, we obtained the decadal responses of the snow cover to climate change on the TP, for both scales of the whole-plateau and its geographical sub-regions, shown in Table 1 and Table 2.

4.3 The Dominant Climatic Factors of TP Snow Cover Variation

The determinant power (q value) of explanatory climate variables in the regionalized analysis have significant increased comparing with the non-regionalized analysis which regards the whole plateau as one region (Table 1). Especially, the q value of the dominant factor in Region I and III are around 0.40 − 0.60, which can explain about 50% spatial differentiation of the snow cover. By contrast, it reveals a rather low q value with climate strata in Region II. It is consistent with the preceding analysis (Section 2.2) that the snow spatial pattern in Region II is mainly determined by large topography, but not by climate. Thus it can be seen that the snow cover distribution and its driving mechanism both have strong spatial heterogeneity, thus it is necessary to discuss by regionalization.

It appears that temperature is the climate factor showing the closest relation with the spatial pattern of snow cover on the TP in all three regions and all three periods. Downward longwave radiation and downward shortwave radiation also have significant influences on the snow cover in the most regions. That is, the net surface energy flux balance is the major limitation to the snow cover on the TP.

For Region I (Qaidam areas), the dominant climatic factor is temperature, and the secondary dominant climatic factor is downward longwave radiation, which both reflect the thermal condition of the ground. Compared with other alpine regions on the TP, Qaidam Basin is relatively warm, so that the thermal condition becomes the decisive condition for the formation, development and persistence of local snow cover.

The dominant climatic factor of snow cover in Region III is air pressure. As the region with the largest snow extent on the TP, Region III covers a large area of long-term stable snow. The thermal effect of snow cover is sufficient to affect the local pressure. The air temperature also has an almost equally large influence on the snow distribution. That is, both temperature and pressure reveal a significant negative correlation with snow cover.

Study Areas	Study Periods	Dominant Factor (q-value)	Secondary Dominant Factor (q-value)
All regions Tibetan Plateau	1989 − 1998	Pres (0.2485)	Temp (0.2416)
	1999 − 2008	Temp (0.2238)	Pres (0.1454)
	2009 − 2018	Temp (0.2504)	Lrad (0.1308)
Region I Qaidam Areas	1989 − 1998	Pres (0.4829)	Temp (0.3916)
	1999 − 2008	Temp (0.5144)	Lrad (0.4387)
	2009 − 2018	Temp (0.5914)	Lrad (0.5057)
Region II Qiangtang Areas	1989 − 1998	Temp (0.2460)	Lrad (0.1551)
	1999 − 2008	Temp (0.2789)	Srad (0.2490)
	2009 − 2018	Temp (0.2852)	Lrad (0.2207)
Region III Hengduan Mountains	1989 − 1998	Pres (0.5522)	Temp (0.5479)
	1999 − 2008	Pres (0.4653)	Temp (0.3852)
	2009 − 2018	Temp (0.4892)	Pres (0.4106)

Table 1. The dominant climatic factors of snow cover variations for the whole plateau and three climatic regions

Considering the interaction of climate factors on the snow cover, the interaction detector shows that the interaction of any two climatic factors on the snow cover on the TP is greater than the solo effect of a single climatic variable (Table 2). Compared with the single dominant climatic factor, the dominant interactive climatic factor pairs add to the influence of precipitation, air specific humidity and wind speed. As Table 2 shows, Region I is mainly affected by the combination of temperature and precipitation. The correlation between climate and snow spatial differentiation is quite high in the Qaidam areas (Region I), where the combination of temperature and precipitation explains 65% of the snow cover distribution. Region II (Qiangtang areas) is mainly affected by the combination of air temperature and wind speed. The combined dominant factors of Region III (Hengduan Mountains) vary over decades, but the pressure always played a decisive role in the snow spatial differentiation.

Study Areas	Study Periods	Dominant Interactive Factor Pair (q-value)	Secondary Dominant Interactive Factor Pair (q-value)
All regions Tibetan Plateau	1989 – 1998	prec ∩ temp (0.5023)	prec ∩ pres (0.4630)
	1999 – 2008	pres ∩ srad (0.4461)	temp ∩ wind (0.4328)
	2009 – 2018	temp ∩ wind (0.4469)	srad ∩ temp (0.4218)
Region I Qaidam Areas	1989 – 1998	prec ∩ pres (0.6500)	pres ∩ shum (0.6352)
	1999 – 2008	temp ∩ wind (0.6689)	srad ∩ temp (0.6093)
	2009 – 2018	prec ∩ temp (0.6951)	lrad ∩ temp (0.6857)
Region II Qiangtang Areas	1989 – 1998	temp ∩ wind (0.3618)	prec ∩ temp (0.3509)
	1999 – 2008	srad ∩ temp (0.4671)	lrad ∩ srad (0.4424)
	2009 – 2018	temp ∩ wind (0.4269)	srad ∩ temp (0.3965)
Region III Hengduan Mountains	1989 – 1998	pres ∩ wind (0.6556)	pres ∩ temp (0.6453)
	1999 – 2008	pres ∩ srad (0.5670)	prec ∩ pres (0.5422)
	2009 – 2018	pres ∩ srad (0.5769)	pres ∩ temp (0.5628)

Table 2. Dominant interactional climatic factor pairs of snow cover variations for the whole plateau and three climatic regions

5. CONCLUSION

Quantifying the coupling relationship between snow cover and climate variables in different regions can provide information for snow cover change prediction and can support to cope with snow related disasters, flood/drought disasters and other extremes caused by snow cover changing on the TP, which ultimately provides support for protecting the safety of life and property of residents of the watershed. The results show that the regionalized analysis improves the climate-based explanation for snow cover change than the non-regionalized analysis for the whole plateau, which verifies again that the snow cover distribution and its driving mechanisms both have strong spatial heterogeneity. Thus, it is necessary to pay attention to the regional differentiation of the snow cover on the TP, to carry out a targeted monitoring and management policy. Temperature has a dominant influence on the snow cover in all three regions. The spatial distributions of snow cover in the Qaidam areas and Hengduan Mountains are both significantly related to the temperature strata, showing that the net surface energy flux balance provides a major limitation to the snow cover. Thus, temperature becomes the key factor of snow-related risk management. Note that the impact of precipitation on snow cover is only significant in the Qaidam areas according to the interaction detector approach, where the combination of temperature and precipitation can explain 65% of the snow cover distribution. Thus the Qaidam areas requires risk monitoring related to both hydrological and thermal aspects.

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