Exploring the relationship between polar motion and a natural river's runoff based on Granger causality

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Abstract Assessing the sensitivity of cold and mountain hydrological systems to climate change needs long-term hydrological data. The data in cold and mountain regions are either available on the very short-term, or absolutely unavailable due to high elevation and cold environments, which are hard to access for conducting field observations. In order to explore the possibility of whether we can seek assistance from some already existing long-term data in other disciplines to fill the blank of data of river flow in these regions, the relationship between the runoff of Yarlung Zangbo, a natural river in Tibet, China, and polar motion, which has data records from 1864 up to the present, is explored. First, the action path framework was structured based on geophysical principles. The Granger causality test was conducted at monthly, seasonal and annual time scales. It is found that on a monthly scale the X component of polar motion influences the runoff at the lag being from the 1st to the 21st month, with the 9th month being an exception. The Y component of polar motion influences the runoff at the lag from the 1st to the 9th month and from the 17th to the 24th month. At seasonal scale, the influence of the X component of polar motion on river runoff can be seen in the 2nd season (i.e. from the 4th month to the 6th month). The influence of the Y component of polar motion on river runoff can be seen at seasonal scale from the 4th to the 6th season (i.e. from the 10th month to 18th month). We cannot see evidence of Granger causality from polar motion to river runoff at annual scales. For the Granger influence of river runoff to polar motion, it is found that at monthly scale the influences are prominent at the lag being from the 3rd to the 25th months for the X component and from the 3rd to the 25th for the Y component. At seasonal scale, these influences can be seen at the lag from the 2nd to the 8th season (corresponding to the 4th to 24th months) for the X component and at the lag from the 1st to the 8th season (corresponding to from the 1st to the 24th month) for the Y component. Again, at the annual scale no evidence of Granger causality can be found from runoff to polar motion. The different behaviours at monthly, seasonal and annual scale suggest that using the monthly data of polar motion to obtain the monthly runoff data is more practicable than to borrow the data from polar motion for river runoff at seasonal and annual scale.

Key words runoff; polar motion; Granger causality; Yarlung Zangbo

INTRODUCTION

Climate change is noticed more and more by people today. Cold and mountain regions are especially attractive as hydrological systems in cold and mountain regions are to a certain degree more sensitive to climate change than those in other regions. Cold and mountain regions provide a good platform for the study because they are less disturbed by human activities. In other regions, due to the combination of the influences, it is hard to differentiate the influence due to human activities and that due to climate change. However, to study the response of climate change on hydrological processes in cold and mountain regions poses challenges, because the data in cold and mountain regions are either very short-term or absolutely unavailable due to the high elevation and cold environment which are hard to access for conducting field-observations.

The geocentric position of the Earth's rotation axis is one of the important indexes to describe rotation of the Earth. Variations in the geocentric position of the Earth's rotation axis (polar motion) cause deformation within the Earth. Although the variation is small (causing peak-to-peak variation in radical motion of typically 10–20 mm, Wahr, 1980), the influence on atmospheric movement is possibly large due to the vast difference between mass of the Earth and mass of the atmosphere based on the conservation of angular momentum of the Earth–atmosphere system (Peng & Lu, 1981). As the movement of the atmosphere is the driving force for hydrological regimes, there should be a relationship from polar motion to water storage, which is mainly reflected by river discharge. The possible action path from the polar motion to runoff is shown in Fig. 1. The action from polar motion to atmospheric movement is delivered by a deformation force, whose formulas were deduced (Wahr, 1980; Peng & Lu, 1981) and are shown in Fig. 1. Peng &

Lu (1981) calculate the deformation forces could reach 2940 cm^2/s^2 (45°N 110°E area, in the summer of 1954). For effects from polar motion deformation force on the precipitation, there is no report and still some uncertainty. But we suggest the deformation force causes a movement of the atmosphere, and may then affect the precipitation. These processes will ultimately influence catchment hydrological change.

On the other hand, the change of river flow reflects the change of water mass. Terrestrial water storage and ocean bottom pressure change are major contributors to the observed polar motion excitations, second only to atmospheric mass movement (Jin *et al.*, 2010). There may be a relationship from runoff to polar motion. Rivers are easily disturbed by human activities. The best place to explore the relationship is in cold and mountain regions. In the cold and mountain regions, the surface runoff is closely related to the regional water storage, including glacial, snowpack and soil water, among others. The possible action path from runoff to polar motion is shown in Fig. 2.

Based on this assumption, the Yarlung Zangbo River in Tibet, China, was selected to study the relationship between polar motion and river runoff. The Granger test is used to explore the relationship. As polar motion has data records from 1849 up to the present, if we can identify the relationship between the polar motion and runoff, it may help us to obtain long-term data to better understand the response of hydrological processes in cold and mountain regions to climate change.

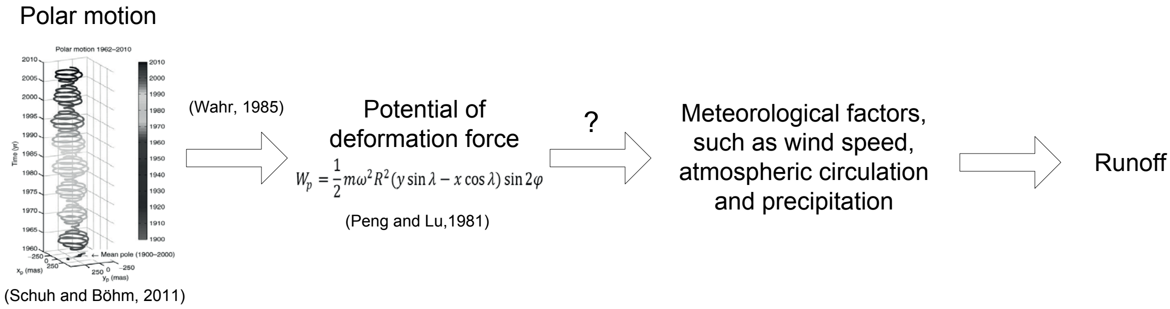

Fig. 1 The possible action path from the polar motion to runoff (the question mark in the figure means there are unknowns about the paths from deformation force to precipitation, which need to be further researched in the future)

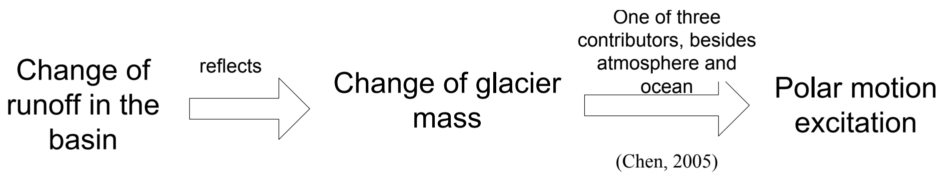

Fig. 2 The possible action path from runoff to polar motion.

METHOD

Granger causality, which attempts to identify the causal relationships between different time series, was first developed for use in econometrics (Granger, 1969). Now it is widely used in climate and hydrological studies (Elsner, 2007; He *et al.*, 2007; Attanasio *et al.*, 2012). For a time series analysis, if future values of Y can be better predicted by using past values of both variables X and Y, rather than only the past values of variables Y, we can define the variables X is the Granger Cause of variables Y. We consider the two models: the autoregressive (AR) model of order k and the vector autoregressive (VAR) model of the same order k:

$$y_t = C_1 + \sum_{i=1}^{k} \alpha_i \Delta y_{t-i} + \varepsilon_{t0} \tag{1}$$

$$y_t = C_2 + \sum_{i=1}^{k} \beta_i \Delta y_{t-i} + \sum_{i=1}^{k} \gamma_i \Delta x_{t-i} + \varepsilon_{t1} \tag{2}$$

where the C_1 and C_2 are the constants, α, β, γ are the coefficients of the models, ε_{t0} and ε_{t1} are the residuals of the two models. The null hypothesis of noncausality corresponds to:

$$H_0 : \gamma_1 = \gamma_2 = \ldots = \gamma_k = 0 \tag{3}$$

Estimating the parameters of the models (1) and (2) by ordinary least squares (OLS), we apply the F-test to evaluate the significance.

$$F = \frac{(RSS_{AR} - RSS_{VAR}) / q}{RSS_{VAR} / (n-m)} \tag{4}$$

where RSS_{AR} is the residuals sum of squares of the AR model (1), RSS_{AVR} is the residuals sum of square of the VAR model (2), q is the number of coefficients of the AR model (q = k), m is the number of coefficients of the VAR model (m = 2k+1), and n is the number of observations. Under the assumption that the time series are stationary, the test statistics in equation (4) asymptotically converge to F(q,n-m) distribution under H_0. A significant statistics implies that the null hypothesis of noncausality is rejected. We take the significance level (p) as 5% in the analysis.

The prerequisite of testing for Granger causality is that the time series should be stationary, since the nonstationary time series can involve spurious causality results (Stock & Watson, 1989; Sims *et al.*, 1990). If the time series is not stationary, we should make the time series be stationary though computing its first order difference, or even second order difference. The Augmented Dickey-Fuller (ADF) test (Dickey & Fuller, 1981) is used to test the stationary of the time series before doing the Granger causality analysis:

$$\Delta w_t = q_0 + q_1 t + \varphi w_{t-1} + \sum\nolimits_{j=1}^{p^*} \mu_j \Delta w_{t-j} + v_t \tag{5}$$

where, q_0, q_1, φ, and μ_j are the parameters. $q_1 t$ is the trend item. $\sum\nolimits_{j=1}^{p^*} \mu_j \Delta w_{t-j}$ is the lagged first differences item of the time series, either X or Y as mentioned above, and v_t is white noise. If $\varphi = 0$ and $q_1 = 0$, then w_t has a unit root and a stochastic linear trend. Alternatively, if $\varphi < 0$, then the series is linear trend stationary. The null hypothesis is that the series is stationary. The ADF statistics is:

$$ADF = \frac{\hat{\varphi}}{se(\hat{\varphi})} \tag{6}$$

where $\hat{\varphi}$ is the OLS estimate of φ, and $se(\hat{\varphi})$ is the standard error of $\hat{\varphi}$. A detailed description of ADF can be seen in Attanasio (2012).

DATA

The Yarlung Zangbo River, which is also called upper Brahmaputra River and located in Qinghai-Tibet Plateau, is seldom disturbed by human activities. Thus, we take the Yarlung Zangbo River runoff data gauged in Nuxia hydrological station as the sample to explore the Granger causality. Figure 3 shows the location of the Yarlung Zangbo River and Nuxia hydrological station. The area of Nuxia hydrological station catchment is 191 235 km^2. Here we use the polar motion X-component (mas), polar motion Y-component (mas), and the Yarlung Zangbo River runoff (m^3/s) from January 1978 to December 2006, as shown in Fig. 4. Three different time scales, i.e. monthly, seasonal and annual, are calculated to explore the Granger causality. The seasonal time series is made by averaging the three corresponding months' data. The annual time series is the annual average of the monthly time data.

RESULTS

Stationary test

Before doing the Granger causality test, the stationarity of the time series is checked. The stationarity of the three different time series is tested by the ADF test and the results are shown in

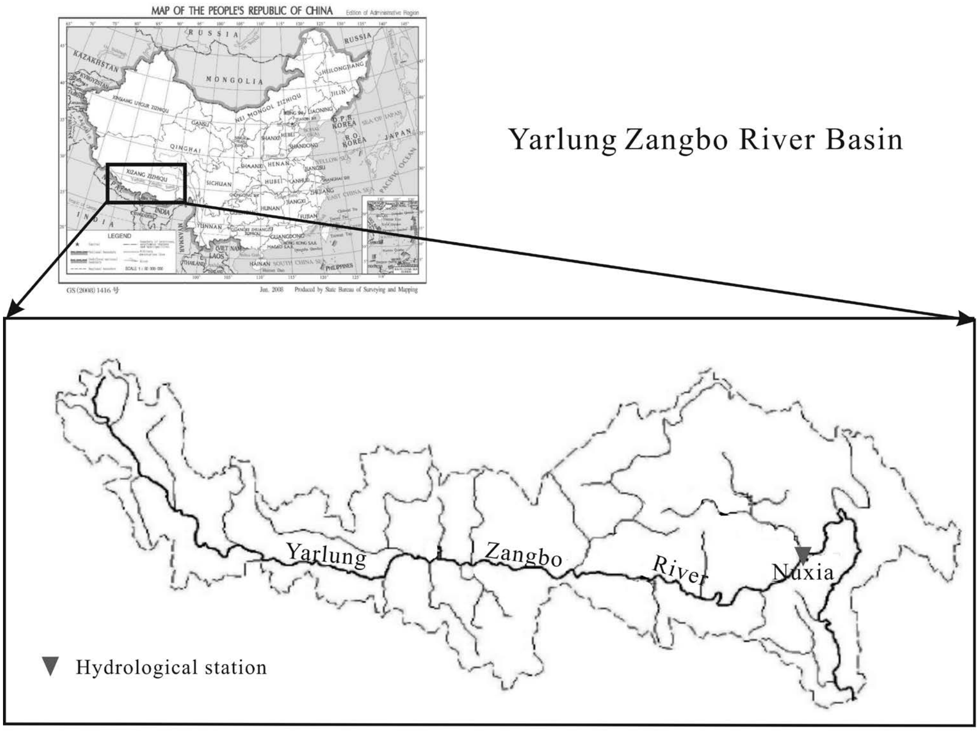

Fig. 3 The location of the Yarlung Zangbo River basin and Nuxia hydrological station.

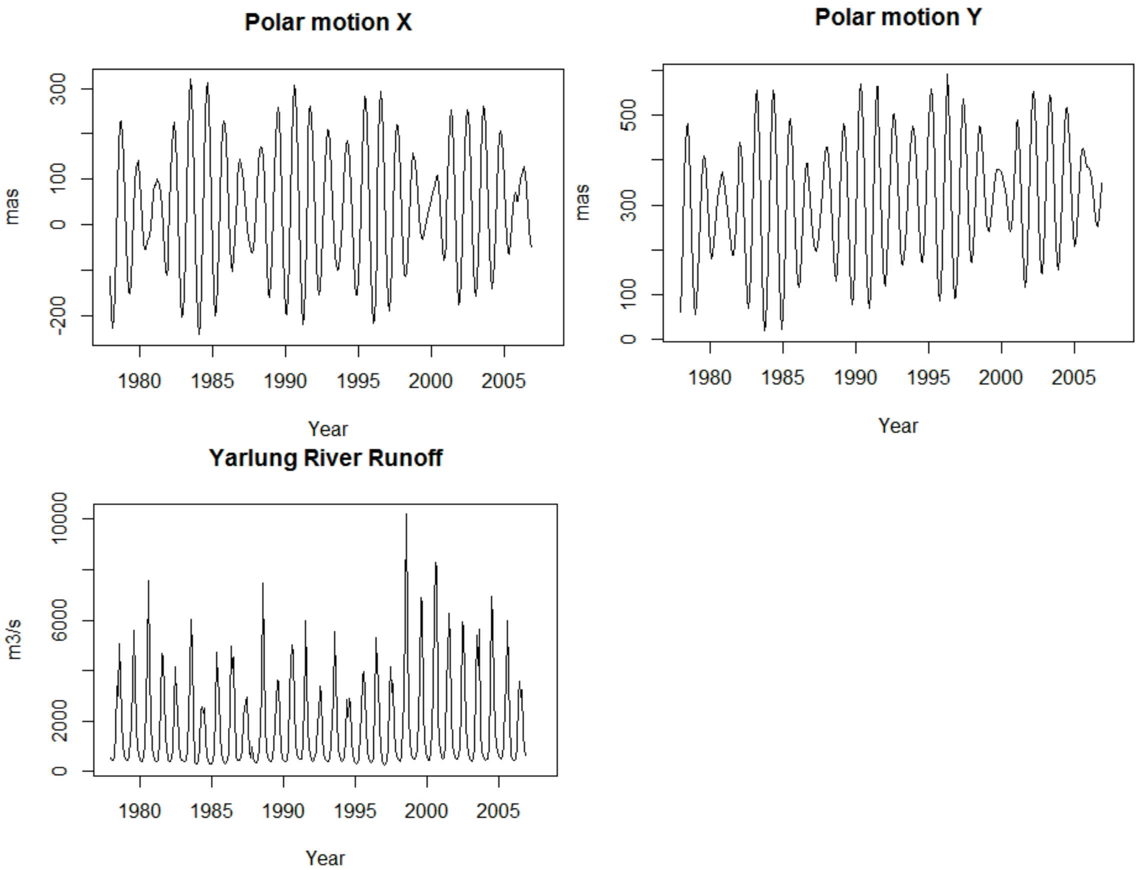

Fig. 4 The plots of the polar motion X (mas), polar motion Y (mas) and the Yarlung Zangbo River runoff (m^3/s) from Jan. 1978 to Dec. 2006

Tables 1, 2 and 3. The value of p*, which is the model order, is selected by using Akaike information criteria (Akaike, 1974). The maximum p for the monthly scale, the seasonal time series and the annual time series is 30, 12 and 6, respectively.

For the monthly time scale (Table 1), polar motion X (X), polar motion Y (Y), and runoff (Q) are nonstationary at a significance level of 5%. Thus, we calculated the first order difference for the series to obtain the polar motion X-component first order difference (ΔX), the polar motion Y-component first order difference (ΔY), and the Yarlung Zangbo River runoff first order difference (ΔQ). After making the first order difference, these three series behave as stationary, with rejection of the null hypothesis. For the seasonal time scale, Table 2 shows that the time series are not stationary, so accepting the null hypothesis. However, after making the first order difference these three time series turn to be stationary. The same case is for the annual time scale.

Table 1 ADF test for the monthly time series (maximum p = 30) with a significant level being 5%

Monthly	ADF statistics	Lags p*	Probability (%)
X	–1.68	29	44.04
Y	–1.58	26	48.97
Q	– 2.27	22	18.12
ΔX	–6.35	28	0.00
ΔY	–6.82	25	0.00
ΔQ	–7.40	25	0.00

Table 2 ADF test for the seasonal time series (maximum p = 12) with a significant level being 5%

Seasonal	ADF statistics	Lags p*	Probability (%)
X	–1.85	9	35.47
Y	–1.21	9	66.63
Q	–2.04	7	26.81
ΔX	–7.38	8	0.00
ΔY	–7.31	8	0.00
ΔQ	–8.34	6	0.00

Table 3 ADF test for the annual time series (maximum p = 6) with a significant level being 5%

Annual	ADF statistics	Lags p*	Probability (%)
X	–0.64	5	84.18
Y	–1.18	5	66.49
Q	–2.43	3	14.31
ΔX	–5.00	4	0.06
ΔY	–6.30	4	0.00
ΔQ	–9.70	0	0.00

Granger causality from polar motion to runoff

In order to understand the relationship between the change of river runoff and polar motion well, we do the Granger causality from both sides. That is from polar motion to the runoff, as in Fig. 5, and from the runoff to the polar motion, as in Fig. 6, at three time scales.

In order to balance the efficiency and freedom of the model, Granger causality tests are performed for the lagged order, k, from 1 to 36 in a monthly time scale, from 1 to 12 in the seasonal time scale, and from 1 to 3 for the annual time scale. Figure 5 shows the Granger causality results from polar motion to the river runoff.

At a monthly scale (Fig. 5(a),(b)), the polar motion X Granger causes the river runoff that is detectable from the 1st to the 21st month with the 9th month as an exception. For the polar motion Y, Granger causality can be detected from the 1st to the 9th month and from the 17th to the 24th month. At a seasonal scale (Fig. 5(c),(d)), from the polar motion X to the river runoff, the null hypothesis is rejected only at the 2nd season (i.e. from the 4th month to the 6th month). The influence of the Y component of polar motion on the river runoff can be seen at a seasonal scale from the 4th to the 6th season (i.e. from the 10th month to the 18th month). At the annual time scale, the statistics are insignificant. There is no Granger causality at the annual time scale.

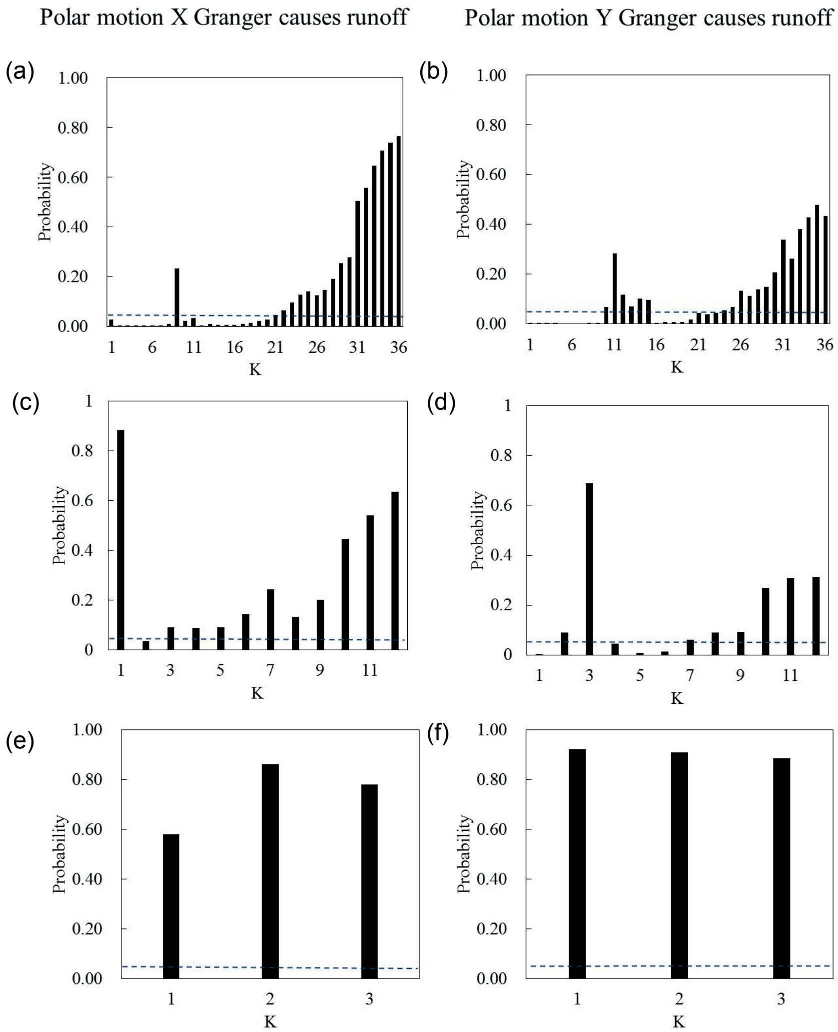

Fig. 5 The Granger causality test results from polar motion X (left) and Y (right) to runoff at monthly scale (upper panel), seasonal scale (middle panel) and annual scale (lower panel).

Granger causality from runoff to polar motion

The Granger causality from the river runoff to the polar motion is also performed as shown in Fig. 6. At a monthly scale, the Granger causality is prominent at the lag from the 3rd to the 25th months for the X component and from the 3rd to the 25th for the Y component. For the seasonal scale, these influences can be seen at the lag from 2nd and 8th season (corresponding to the 4th to 24th months) for X component and at the lag from 1st to 8th season (corresponding to from 1th to 24th month) for Y component. The annual time scale does not have the Granger causality. The melting water occupies 38% of the Yarlung Zangbo River runoff at the Nuxia hydrological station (Liu, 1999; Jia *et al.*, 2008). The runoff contains much information of the snow pack and soil water change. The polar ice sheets and mountain glaciers change are primary driving forces of Earth rotational changes (Chen *et al.*, 2011). This may be a reason for strong Granger causality from river runoff to polar motion. The phenomenon that the Granger causality occurs in the monthly and seasonal time scale rather than annual time scale is in accordance with the fact that the change in continental water storage plays a major role in the seasonal polar motion (Chen & Wilson, 2005).

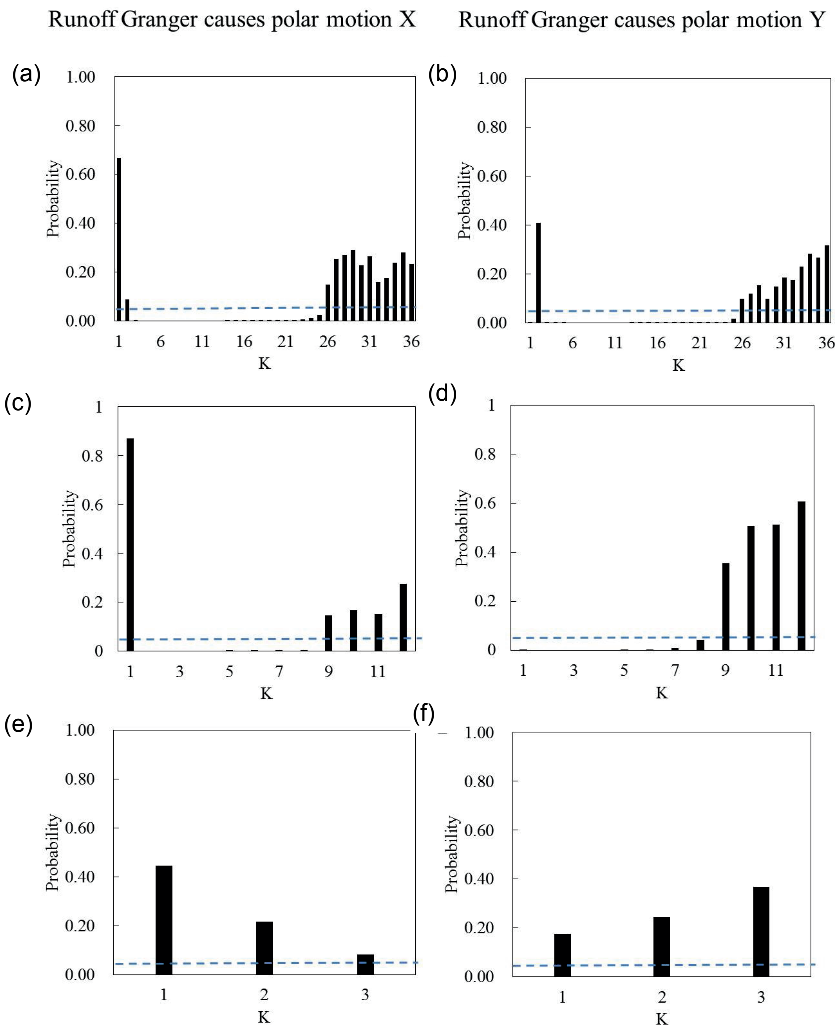

Fig. 6 The Granger causality test results from river runoff to polar motion X (left) and Y (right) at monthly scale (upper panel), seasonal scale (middle panel) and annual scale (lower panel).

DISCUSSION

Different time scale

In this study, we test three different time scales, including the monthly, seasonal and annual scale. There is obvious Granger causality at the monthly and a weaker one at the seasonal scale, but not in the annual scale, between the runoff and polar motion. For the runoff strongly related to snow pack, which is one of most important factors in water storage. The difference in these three time scales conforms to the documented results that the change in continental water storage plays a major role in the seasonal instead of annual polar motion (Chen & Wilson, 2005). For this point, the relationship between polar motion and runoff behaves stronger on the monthly and seasonal scale instead of the annual scale. This suggests the polar motion data may help us to improve the hydrological prediction in the monthly or seasonal time scale.

Global scale and local scale

As polar motion is the movement of the whole Earth, the influence of it on river runoff, or *vice versa*, should also be relative to the rivers on a global scale. It seems that there is contradiction for exploring the relationship between the global polar motion and the local Yarlung Zangbo River runoff, especially for the causality from the local runoff to global polar motion. However, as most rivers in the world are disturbed by human activities, it will be very hard to separate the influence by human beings from those by such natural factors as polar motion. With this limitation, choosing a large and undisturbed river, such as the Yarlung Zangbo River, is one of the alternative choices to explore the relationship between the runoff and polar motion. Moreover, what makes the statistical Granger causality is the relationship between the pattern of river runoff time series and that of polar motion time series. Thus, we do not need to consider too much whether the magnitude of river runoff is not fit for the magnitude of polar motion.

CONCLUSION

The polar motion data, which strongly relates to the snow and glacier change, is a good data source for the cold and mountain regions. In this study, we have explored the relationship between polar motion and Yarlung Zangbo River runoff and found there is evident Granger causality between them in the monthly and seasonal data. These test results provide us with the foundation to use the polar motion data in these sparse data areas to explore hydrological change. Thus, we propose that polar motion data could be used to predict the runoff on a monthly time scale to offer us more information to explore the hydrological response to climate changes in cold and mountain regions.

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