**Supplementary materials to**

**“Macro-economic cycles related to climate change in dynastic China” by Zhudeng Wei, Arlene Miller Rosen, Xiuqi Fang, Yun Su and Xuezhen Zhang**

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**Part A. Reconstruction of economic grade series**

**1. Background and precondition.**

The socio-economic history of imperial China was featured cyclical fluctuation ([Fu, 1981-1989](#_ENREF_4)). The question is how to express such macro-cycle quantitatively throughout the past two-millennium. Although scattered economic statistics are often available in the literatures, there remains a large degree of controversy among historians as to precisely what the absolute numbers mean, indicating by the varied estimates ranging from grain yields to the population size, due to the Chinese historical specialties. However, there is a substantial degree of agreement on the relative changes in describing the rise and fall of social and economic phenomenon.

In fact, the recorded relative changes of economic phase under one dynastic cycle in the abundant historical literatures are also well described semantically by lots of famous historians and economic historians of China. The macro-economic series we are going to reconstruct is to convey the relative shift of economic phases on an empire-wide scale. As suggested by [Skinner (1985](#_ENREF_11)), “That such macrocycles of development and decline or prosperity and depression have not been widely recognized in the historical literature on China follows, I surmise, from the usual focus on the empire as a whole or on its component political divisions. Economic macrocycles are a systemic property of macroregional economies-not of provinces and not of the Chinese empire per se-and consequently their contours become clear only when regional economies are taken as the units of analysis”. Inspired by his work, we consider the general performance of the economic system by taking the empire as the units of analysis, in a perspective of economic state.

**2. Economic records described in books**

In all, 1091 descriptions of the pre 1910 Chinese economy were extracted from 25 books (some of which are multi-volume publications) dealing with the economic history of China written by leading scholars and published in the last thirty years (see Appendix). These books have covered several authoritative publications on China’s economic history, especially the books on general Chinese economic history.

There are several advantages in using secondary materials. First, they provide more authoritative and convincing statements because descriptions in those books are based on systematical analysis on abundant original materials. The records and conclusions cited from these books could be used as useful and reliable expert’s opinions for assessing economic state of ancient China. Second, what we need is a macroscopic grasp of the general economic performance and these books can basically meet the requirement. In fact, many of the word descriptions are based on or cited directly from the original materials, particularly before the Song Dynasty when available original materials are relatively short. Finally, information from different opinions can complement and calibrate with each other, by which we can avoid one-sided judgement to some extent. However, it may bring some troubles like the intertextuality-dependence of later writers on their predecessors’ efforts. The study believes the more citation the statement has, the higher recognition it gets. The other major challenges may be from the influence of different writing style for authors and varied temporal scale in describing the phase change of economic state. To overcome this problem as much as possible, we use the semantic analysis based on the opinions of the majority combined with integration of multiple temporal-resolution descriptions to reconstruct the economic series.

Extracted information from these books includes the authors’ statements of empire-wide economic fluctuations (mainly state and relative phase transition), descriptions and statistics of the population, arable-land reclamation, peasant livelihoods, and governmental finances, among other information.

**3. Semantic analysis and description categorization**

The Semantic Differential (SD) technique was first developed by [Osgood (1957](#_ENREF_8)) in order to identify emotional meaning of words, and has been proved to be a useful and effective tool in indexing qualitative word description. Three logical basis of the semantic differential is as follows: (1) the process of description or judgment can be conceived as the allocation of a concept to an experiential continuum, definable by a pair of polar terms; (2) many different experiential continua, or ways in which meanings can vary, are essentially equivalent and hence may be represented by a single dimension; (3) a limited number of such continua can be sued to define a semantic space within which the meaning of any concept can be specified ([Snider and Osgood, 1969](#_ENREF_12)). Because of its flexibility and simplicity, Semantic Differential has been widely used in the areas such as Linguistics, Psychology ([Asch, 1946](#_ENREF_1)), and Anthropology. It is also widely used by historical climatologists in China to reconstruct quantitative time series from qualitative word descriptions recorded in literatures ([Zhang, 1996](#_ENREF_17)). Successful cases include the reconstruction of the dryness/wetness index ([CMA, 1981](#_ENREF_3); [Zheng et al., 2006](#_ENREF_19)), the harvests series ([Su et al., 2014](#_ENREF_13); [Yin et al., 2014](#_ENREF_16)), and the fiscal series ([Wei et al., 2014](#_ENREF_15)). Thanks to the richness, relative uniformity, and clarity of the words expression of economic fluctuation in the abundant literatures, this method can also be used to rebuild the series of economic state index.

Table 1 shows examples of the criteria used to convert qualitative descriptions into quantitative grades based on semantic analysis. Economic level is divided into five grades using the vocabulary of collapse, depression, average conditions, prosperity, and climax to summarise descriptions with similar semantics and is graded to 1 to 5, respectively (Table 1). The entries of economic state alone are not sufficiently identifiable temporally nor numerous enough to yield a continuous high-resolution series. Therefore, this study classifies vocabulary descriptions into three groups. Group 1 conveyed the macro-economic state (MS) and could directly determine the economic grade. Group 2 indicated directional relative change in macro-economic processes (RMP) and helped rank records based on before-and-after economic condition comparisons. Lastly, group 3 indicated both state and directional changes of certain indices (primarily the peasants’ livelihoods and state fiscal situations (LFS)) and played a supplementary role given the lack records in the previous two groups during certain periods. Their capability and suitability in terms of reflecting the overall macroeconomic volatility is arranged in descending order. In particular, the LFS reflects volatility of specific indicators more than the fluctuations of the economy as a whole, and its changes may be out of sync with that conveyed by the MS and RMP. However, the entries of the first two groups account for 95% of the total data set (the number of entries for the MS, RMP, and LFS groups is 458 (42%), 576 (52.8%), and 57 (5.2%), respectively).

**Table 1** Examples of the vocabulary used to describe ancient economic fluctuations

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Level | MS | RMP | | LFS | |
| Upward | Downward | Livelihoods | Finance |
| Collapse  (1) | Totally collapsed, vanished; in ruins, a dead end; extremely desolate; cannibalism; unbearably languished | Collapse continued without any improvement | Quickly plummeted; sudden interruption; dropped to the lowest | Fail to survive; hunger to the point of cannibalism; unprecedented heavy corvée | Extreme lack of wealth; financial exhaustion and collapse |
| Depression  (2) | On the verge of collapse; economic crisis; brokenness; depressed; destitute | Recovered up to a limit; little improvement; slightly better than the economic collapse | Large reduction in production; rapid deteriorating | Shortage of food and clothing; extreme poverty; widespread bankruptcy; small-scale armed struggle | Extreme deficient; financial deterioration; constraints |
| Average  (3) | Adequately fed; normal economic production; lived and worked in peace; slack; mild economic chaos | Began to improve; production had been restored; developing recovery | Stagnated; wandering and backward; increasingly depressed; recession; no longer prosperous | Reluctantly ensuring basic needs; slight improvement; heavy burden; mild bankruptcy; displaced | On the right track; near balance; financially worse than sufficiency |
| Prosperity  (4) | Thriving; preliminary prosperity; well-off situation; stable economic situation | Rapidly developed; fundamental improvement; full recovery; continually moving forward | Began to decline; no longer at the peak, somewhat retreating | Better ensuring basic needs; recuperating; alleviated tax burden; beginning of bankruptcy before more serious issues | Accumulating wealth; sufficient food reserves to relieve tax; plenitude before excess |
| Climax  (5) | Strong economic strength; considerable wealth; unprecedented prosperity; affluence; peak; heyday | A great leap forward; increased nearly vertically; lasting prosperity | Maintained prosperity but failed to develop further | Basic needs could be met for the majority; lived in happiness and health | Excess wealth; sufficient treasury; strong finance; food was accumulated until it became mouldy |

**4. Integrating descriptions with multi-time resolutions**

The reconstruction has at least two key steps. The first step is to identify the interval of historical descriptions. The time resolution of many entries, as shown in Table 2, is obscure. They exhibit multi-temporal resolution from one year to several hundred years due to an inconsistent temporal perspective on the economic process among various authors.

Considering that most authors evaluate the relative change in the economy in the unit of an emperor’s reign, entries with nearly identical timescales can be reckoned as possessing the same starting and ending time and thus combined together in the database (e.g. No. 5 to 8 in Table 2). Therefore, one of the tasks is distinguishing the record’s time resolution by identifying the beginning and ending time of each entry to obtain the interval of the description. The second step is judging the economic level of entries and determining the final economic level of a decade (e.g. AD 11-20). The method of multi-time-resolution data integration involves two main steps: (1) reconstructing the trend-controlling series to determine the rough distribution of the economic grade as references for refining the time resolution of series; and (2) refining the time resolution of the trend-controlling series to up to one decade to generate 10-yr-resolution series.

**Table 2** Historical economic descriptions with multi-time resolutions among different authors

|  |  |  |  |
| --- | --- | --- | --- |
| No. | Interval (AD) | Entries and their source | Group |
| 1 | 17-25 | The economy collapsed after the red-browed and Lulin peasant uprising ([Fu, 1981-1989](#_ENREF_4)). | MS |
| 2 | 17-25 | At the end of the Western Han Dynasty, especially after the peasant uprising, the national economy had totally collapsed ([Shi and Hu, 1994](#_ENREF_10)). | MS |
| 3 | 25-220 | The Eastern Han Dynasty was not a rich dynasty ([Peng, 2007](#_ENREF_9)). | MS |
| 4 | 25-220 | The economy of the Eastern Han Dynasty had not been as prosperous as that of the Western Han Dynasty ([Zhou, 2007](#_ENREF_21)). | RMP |
| 5 | 25-88 | An economic recovery period; the socio-economic situation gradually improved in the early stage of the Eastern Han Dynasty ([Shi and Hu, 1994](#_ENREF_10)). | RMP |
| 6 | 25-88 | Throughout the Eastern Han Dynasty, only Emperors Guangwu, Ming, and Zhang cared about reducing the burden on peasants, and the economy was successfully restored and began to move forward. | RMP |
| 7 | 25-88 | After more than half a century’s efforts on the parts of Emperors Guangwu, Ming, and Zhang, the social economy shifted from recovery to prosperity ([Zhao, 2002](#_ENREF_18)). | RMP |
| 8 | 25-88 | During the early stage of the Eastern Han Dynasty, the economy gradually recovered and developed ([Tian and Qi, 1998](#_ENREF_14)). | RMP |
| 9 | 25-57 | During the generation of Emperor Guangwu, the social economy was unbearably destitute, devastated everywhere, and extremely desolated ([Fu, 1981-1989](#_ENREF_4)). | MS |
| 10 | 25-57 | Throughout the Jianwu Age, there was no fundamental change in the economic devastation, which was [covered with wounds and scars](http://www.iciba.com/covered_all_over_with_wounds_and_scars) ([Tian and Qi, 1998](#_ENREF_14)). | RMP |
| 11 | 25-36 | At the beginning, the Eastern Han Dynasty faced a serious economic situation: production could not be carried out normally, famine remained during the wars, there was a significant population loss, and the national economy languished unbearably ([Shi and Hu, 1994](#_ENREF_10)). | MS |
| 12 | 25-36 | In the early years of Guangwu, the social economy was dilapidated and production had not been restored; “people survive on wild millet and flax” ([Tian and Qi, 1998](#_ENREF_14)). | MS |
| 13 | 36-36 | The country was reunified after the 12th yr in Jianwu and then began to focus on economic recovery and development ([Shi and Hu, 1994](#_ENREF_10)). | RMP |
| 14 | 37-88 | The first 50 yr of the Eastern Han Dynasty (after the unification wars) was a period of economic recovery ([Zhu and Shi, 1995](#_ENREF_22)). | RMP |
| 15 | 37-88 | After the middle of Emperor Gangwu’s reign, the number of wars decreased and the economy gradually recovered and began to shift to prosperity ([Zhou, 2007](#_ENREF_21)). | RMP |
| 16 | 37-57 | After the reunification of the country, Liu Xiu adopted a series of rehabilitated policies and achieved the objective of promoting the restoration and development of social economic production ([Li, 1991](#_ENREF_5)). | RMP |
| 17 | 37-57 | After the reunification, Liu Xiu adopted a respite policy, and social production was restored rapidly; people could engage in production peacefully ([Tian and Qi, 1998](#_ENREF_14)). | RMP |
| 18 | 58-105 | Beginning in the Yongping Age (AD 58-75) of Emperor Ming, the economy began to show some degree of prosperity, but this prosperity did not last long before declining after Emperor Zhang and He ([Fu, 1981-1989](#_ENREF_4)). | MS |
| 19 | 58-75 | The national economy displayed prosperity during the reign of Emperor Ming ([Shi and Hu, 1994](#_ENREF_10)). | MS |
| 20 | 58-75 | During the 18-yr reign of Emperor Ming, the Eastern Han Dynasty entered a period of social stability and economic development ([Zhu and Shi, 1995](#_ENREF_22)). | RMP |
| 21 | 58-68 | The positive measures of developing production began to reap benefits in the middle of Emperor Ming’s reign: “a bumper harvest in agriculture in the 9th yr of Yongping (AD 66)” ([Zhu and Shi, 1995](#_ENREF_22)). | MS |
| 22 | 69-75 | At the end of Emperor Ming’s reign, the social economy of the Eastern Han Dynasty peaked prosperously, but the economic rally did not return to its peak level in the Western Han Dynasty ([Zhu and Shi, 1995](#_ENREF_22)). | MS |
| 23 | 69-69 | In the 12th yr of the Yongping Age, “the country is peaceful and stable, there is no corvée, the yearly harvest allows peasants to live in wealth; the price of millet is only 30 qian(penny) per hu (1 hu = 100 litre), and horses and cattle are scattered across the fields”; the economy was prosperous ([Tian and Qi, 1998](#_ENREF_14)). | MS |
| 24 | 76-88 | The national economy during Emperor Zhang displayed prosperity but failed to reach the height of the Western Han Dynasty ([Shi and Hu, 1994](#_ENREF_10)). | MS |
| 25 | 76-88 | The periods of Emperors Zhang and He were the most prosperous in the history of the Eastern Han Empire but failed to reach comparable levels to that of the early years of Emperor Wu of the Western Han Dynasty ([Zhao, 2002](#_ENREF_18)). | MS |
| 26 | 76-88 | A scene of economic prosperity and peace ([Fu, 1981-1989](#_ENREF_4)). | MS |
| 27 | 89-105 | The economy of Emperor He was still reluctantly maintaining prosperity and peace ([Zhu and Shi, 1995](#_ENREF_22)). | MS |
| 28 | 89-105 | The periods of Emperor Zhang and He were the most prosperous in the history of the Eastern Han Empire but failed to reach comparable levels to that of the early years of Emperor Wu of the Western Han Dynasty ([Zhao, 2002](#_ENREF_18)). | MS |
| 29 | 89-105 | During the reign of Emperor He, the national economy ceased further development and began to gradually decline after Emperor He ([Zhu and Shi, 1995](#_ENREF_22)). | RMP |
| 30 | 89-105 | Since Emperor He, the development of the national economy gradually slowed, exhibiting a declining trend ([Shi and Hu, 1994](#_ENREF_10)). | RMP |
| 31 | 89-105 | The prosperous economy began to decline after Emperor He ([Fu, 1981-1989](#_ENREF_4)). | RMP |

**5. Trend-controlling series**

The trend-controlling series is a controlling series consisting of levels and trends without a fixed time resolution. Levels refers to the controlling points at which the economic level is relatively easy to grade or breakpoints with obvious economic transitions. For each dynasty, except for some other apparent turning periods, material is generally the most abundant in periods of economic collapse and prosperity (including climax), when the entry levels and intervals can thus be determined most easily. The higher-resolution descriptions of groups MS and RMP are used to evaluate the economic level of key turning-point years, and a total of 109 turning points (69 for the unified period, 20 each for the north and south in the period featuring two major divisions) are ultimately determined, as shown in Figure 1(a). The trend is directly determined by the connection between levels, mainly reflecting the macro-economic tendency conveyed by the descriptions of group RMP with relatively lower resolution (for instance, intervals greater than 30 yr).

Using the period from the late Western Han Dynasty to the early stage of the Eastern Han Dynasty as an example, as shown in Table 2, entries of No. 3 and 4 reveal the general economic state of the Eastern Han Dynasty on a nearly 200-yr scale, based on which the economic level of the Eastern Han Dynasty can be roughly determined as being between 1 to 4 (the highest level for the Western Han Dynasty is 5). Entries No. 5 to 8 are records with an approximately 60-yr resolution, showing an upward trend of economic recovery and development of the early Eastern Han Dynasty. According to entries No. 1, 2, 11, 12, and 13, with a 10-yr resolution, the level from the end of the Western Han Dynasty to the beginning of the Eastern Han Dynasty (AD 17-36) is ranked as 1, while an economic level of 4 is assigned to the period from the end of Emperor Ming (AD 69-75) based on entry No. 22. Finally, level 1 is determined as the year AD 17 and AD 36, respectively, and level 4 as the year AD 75, their connections are on behalf of the economic growth process reflected by the two 60-yr-resolution entries.

One of the main issues involving the judgements above is determining the year of the turning point, as most of the descriptions describe the economic situations over a period of time instead of a single year. Moreover, description of the beginning and ending time for the entries is relatively vague, as observed above. Even when a specific year is given for an economic situation, it is often actually expressing the situation of a period (e.g. entry No. 3 in Table 2). Therefore, the following principles are introduced to help determine the year of the turning point:

1. The definite-year first principle, in which the definite year expressed in the economic descriptions is used as the transition year. For example, the 12th yr of Jianwu (AD 36) is chosen as the year of turning point between the descriptions “after the middle of Emperor Guangwu’s reign” and “After the reunification of the country (12th yr of Jianwu)” (Table 2, No. 15 and 16).
2. The end/midpoint alterative principle, in which the endpoint or midpoint of an economic level over a period that is relatively explicitly and easily judged is used when a definite year of economic transition is absent. For instance, according to “since the reign of Emperor Suiyang, the upward economic trends during the years of Kai Huang suddenly reversed, and the social economy was caught in a comprehensive collapse” ([Fu, 1981-1989](#_ENREF_4)), this element can be categorised as level 1 during the reign of Emperor Suiyang (AD 604-618), where the midyear of AD 611 is selected as the turning point for level 1. Whether the endpoint or midpoint is selected largely depends on a comprehensive tradeoff between the given stage and the previous and later stages. In this example, the year AD 604 has been chosen as the turning point for level 5 (AD 589-604), whereas AD 618 is rather distant from the starting point of the collapse and is therefore not suitable as a turning point. Thus, the midpoint between AD 604 and AD 618 is adopted instead.
3. The major opinions principle, in which the breakpoint used by the majority of historians is used when the years cited by different economic historian conflict. For example, most records agree that the economy of Emperor He (AD 88-105) was prosperous, except for entry No. 30, which indicates that the economy of that period began to decline (Table 2, No. 27-31). Thus, the year of AD 105 is selected as the turning point from prosperity to depression.
4. The medium principle, in which the middle value is used when the proportions of entries with each conflicting report are similar.
5. The aid of historical events principle, in which the year of major historical events is selected as the turning point, such as the end of a war or the beginning of tax reform. For instance, there is lack of a definite year for when the economy began to decline due to the frequent wars during the reign of Emperor Wu of the Western Han Dynasty. It is known that the year 119 BC is an important starting time for large-scale tax reform during the period of Emperor Wu in the Western Han Dynasty ([Li, 1991](#_ENREF_5)). Therefore, 119 BC is selected as the turning point from prosperity to the verge of collapse at the end of Emperor Wu’s reign.

The judgement of each level is referenced to the standard in Table 1. When the descriptions of different economic historians are in conflict, the judgement of economic level is based on the views of the majority. For instance, three of the four entries (each entry representing one expert’s view) insist that the economy in the late years of Emperor Kangxi (approximately AD 1700-1722) was only preliminarily prosperous and could not be compared with the climax of the Ming Dynasty. Considering that the majority of records agree with a description of preliminary prosperity, level 4 is used to describe the period for AD 1700-1722, and the year AD 1710 is selected as the turning point. In contrast, if the number of records supporting each conflicting report is similar, the economic level will be graded by comparison between the given time period and those before and after based on descriptions with lower resolution or using the average value, as discussed in the following.

**6. Decadal Series**

The trend-controlling series conveyed by the low-resolution descriptions indicates the general tendency of economic development. The next step is to further refine the time resolution of the series, which is achieved by integrating economic descriptions with multi-time resolutions to judge the economic level using higher-resolution descriptions controlled by the series with lower resolution.

According to the vocabulary groups and their priority order, the MS (highest priority) will be used as the main basis for evaluating the level of the entry. When MS data are unavailable or insufficient to grade a level, the RMP will be used to determine the entry level, and so on. As mentioned above, entries on economic collapse and prosperity (and climax) are much more abundant, and their levels are thus easier to identify than entries during average conditions and depression, which are fewer and more difficult to classify. Therefore, this study will give precedence to classifying the more definite levels, such as collapse and climax, followed by the periods in other levels. For each interval’s grade judgment, conflicts among multiple records in the same interval might occur due to truly different views by the authors or to different writing styles/habits. To handle this problem, we proposed several principles. If all of the records in one interval indicated the same economic grade, the grade was ranked according to the criterion in Table 1. If different records indicated the same type of either depression (1-3) or prosperity (3-5) but with different grades, then the level was graded based on the grade of the majority of the records. In the cases with equal frequency, comparison records in the RMP group were given priority for the grade rating, i.e., grade 5 was given priority over grade 4, while grade 4 was given priority over grade3; similarly, grade 1 was given priority over grade 2, while grade 2 was given priority over grade 3. If different records indicated different economic phases (e.g., collapse and prosperity), then the grade was rated according to the predominant level of the majority of the records or a compromising grade was selected.

Using the early Eastern Han Dynasty as an example again, the trend-controlling series shows that the economic development of the early Eastern Han Dynasty (AD 25-88) exhibited an increasing trend from level 1 to 4. As shown in Table 2, the 30-yr state records of No. 9, 19, 24, and 30 divided the economic development of the early Eastern Han Dynasty into two sections: the period before Emperor Guangwu (AD 25-57), with an economic level less than or equal to 2, and the reigns of Emperors Zhang and Ming (AD 58-88), with an economic level of at least 3. If none of the three groups with higher-resolution entries were available, the economic level of the early Eastern Han Dynasty could only be determined with a resolution of 30 yr: 1 for the period of AD 25-57 and 4 for the period of AD 58-88. Fortunately, both periods are described by entries with a resolution higher than 30 yr, and the entry type that is ultimately used to determine the economic level is determined based on priority. According to state entries (MS) No. 11 and 12 (Table 2), the level of AD 25-36 is 1. From AD 37-57, there are no state records, but the RMP entries can be used to classify this decade as level 2. Likewise, there are two 20-yr MP and RMP entries (Table 2, No. 19 and 20, respectively) during the reign of Emperor Ming (AD 58-75), which is divided into two periods with approximately 10-yr MS entries by No. 21 and 22 in Table 2. The difference in the economic state between the two periods was obvious. Based on the dividing year of AD 69 (No. 23 in Table 2), it is easier to judge the level of AD 69-75 as 4 and that of AD 58-68 as 3.

Finally, the economic level of each decade is calculated. According to the previous analysis, a total of 148 intervals’ (24 during the periods AD 317-589 and AD 1127-1279 and 124 during the period 221 BC-AD 1911, see below and Fig. 1) grades can be determined. The proportions of interval grades that were primarily ranked according to evidence from the MS, RMP, and LFS groups accounted for 68.2% (101), 18.2% (27), and 13.6% (20), respectively, of the data. The number of grades with interval lengths of 1-10, 21-30, 31-40, 41-50, and 51-60 yr were 43 (29.1% of the total 148), 57 (38.5%), 34 (23%), 7 (4.7%), 6 (4.1%), and 1 (0.6%), respectively. The economic grades of the 148 intervals are resampled by calculating the weighted mean (the temporal proportion of each economic level within a decade is used as the weighting coefficient) as the final economic level for a given decade (e.g., AD 1-10). When a decade was only represented by a single grade, this grade was used as the decadal economic level.

**7. Weighting between the north and south**

For the major disunified periods, separate series are reconstructed for the north and south and then weighted spatially to generate a series for the empire-wide economy.

Beginning in the Qin and Han Dynasties, historical China experienced three major division periods: from the Three Kingdoms to the Sui Dynasty (approximately AD 220-589), the Five Dynasties and Ten Kingdoms (approximately AD 907-960), and the Southern Song Dynasty (approximately AD 1127-1279), when economic development appeared split between the north and south. During the period of AD 220-589, the Western Jin witnessed a short reunification during AD 280-317. From the starting of the Three Kingdoms to the early Western Jin (AD 220-279), the north was still the economic centre of the country, and its economy changed more dramatically than that of the two southern regimes, which had very weak economic power and was still in the phase of exploitation. Thus, the northern economic development of the Cao Wei and early Western Jin Dynasty (AD 221-280) is considered to be representative of the empire-wide macro economy. From the end of the Western Jin Dynasty to the reunification of the Sui Dynasty (AD 321-590), the south-north population ratio of 1:2 (4,816,685 people in the South and 10,367,032 people in the North) in the first year (AD 280) of the Taikang Age ([Cheng, 2004](#_ENREF_2); [Liang, 2008](#_ENREF_6)) is used as the weighting coefficient to average the economic levels between the south and north. Because the period of the Five Dynasties and Ten Kingdoms (AD 907-960) was relatively short and economic regions were decentralised, the national economic level is judged against the average conditions of different economic regions.

For the last division period of AD 1127 to 1279, the south-north population ratio generally remained in the range of 0.4 to 0.6 during the times around the Southern Song and the Jin (AD 1127-1234) ([Liang, 2008](#_ENREF_6)). However, many studies on the transformation of the ancient Chinese economic centre have shown that that economic centre finished shifting from the north to the south in the Southern Song Dynasty ([Cheng, 2004](#_ENREF_2)). During the early confrontation period between the Song and Jin (approximately AD 1141-1205), the number of households in the south was more than that in the north, but the population (kou, a unit of measure for population size) in the south was less than that in the north (in the 14th yr of the Chun Xi Age in the Southern Song in the south, the number of households and population were 12,376,522 and 24,311,789, respectively; in the 27th yr of the Dading Age of Emperor Shizong in the north, the corresponding numbers were 6,789,449 and 44,705,086, respectively) ([Liang, 2008](#_ENREF_6)). [Zheng (2003](#_ENREF_20)) believed that the actual population for the Southern Song Dynasty should not be less than that of the northern region of the Northern Song Dynasty. As a compromise, this article uses 1:1 as the weighting coefficient to average the economic levels between the south and north. The weighted calculations are rounded to an integer to generate the empire-wide macroeconomic volatility series (Fig. 1 (c)).



**Figure 1.** Reconstruction of the economic series for 220 BC-AD 1910 in China. (a) Trend-controlling economic series reconstructed from the economic grades of key turning points (no fixed time resolution), in which, when there is a red line, the red and black solid lines represent the series of the south and north, respectively; (b) 10-yr-resolution economic series, in which, when there is a red line, the red and black solid lines represent the 10-yr-resolution series of the south and north, respectively; (c) 10-yr-resolution economic series spatially weighted between the north and south. Economic level 5-1 represent the relative phases of economic state identified from the word’s semantics; 5: Climax; 4: prosperity; 3: average condition; 2: depression; and 1: collapse. Dynastic periods are defined by following [Mao (2002](#_ENREF_7)) as: Qin (221-206 BC); W. Han ( 206 BC-AD 25); E. Han (AD 25-220); Three Kingdoms (AD 220-280); W. Jin (AD 265-317); E. Jin (AD 317-420); Sixteen Kingdoms (AD 304-420); N. Dynasty and S. Dynasty (AD 420-581); Sui (AD 581-618); Tang (AD 618-907); Five Dynasties and Ten Kingdoms (AD 907-979); N. Song (AD 960-1127); S. Song (AD 1127-1279); Jin (AD 1127-1234), Yuan (AD 1234-1368); Ming (AD 1368-1644); and Qing (AD 1644-1911).

**8. Results and uncertainty**

Figure 1 (c) shows the final results of a 2130-yr-long series covering the periods from 220 BC to AD 1910, depicting the fluctuations of the empire-wide macro-economy with a 10-yr resolution. The proportion of level 1 to 5 is 10.3%, 24%, 28.6%, 22.5%, and 14.6%, respectively, which demonstrates an approximately normal distribution and indicates to some extent the reasonableness of the reconstruction. Because the economic level for most of the periods is evaluated by comparison between a given stage and the previous and later stages, the sequence mainly reflects the relative volatility of the economic situation.

The cyclical fluctuations of the macro economy over the past 2100 yr in China are obvious. Four main stages can be easily discerned. The relatively prosperous period during 220 BC-AD 150, with an average level of 3.2, was followed by a long-term economic downturn with an extremely low mean economic level of 2.3 during AD 151-610. A significant return to prosperity (with an average level of 3.5) was witnessed during AD 611-1230. This economic prosperity ended with a mild decline to an average level of only 3.1 from AD 1231 to AD 1910 but is still better than that of the period AD 151-610. Each main stage featured smaller stages and cycles spanning from approximately 100 to 200 yr.

To further analyse the reasonableness of the reconstruction, possible uncertainties are assessed in this section. As a result of efforts to ensure the credibility of the sources and feasibility for the reconstructed method, the factors that induce series error are mainly due to the availability of records and the degree of consistency in measuring the ancient economic level among different economic historians. We take two aspects, the quantity and quality of data (including time coverage, amount, and time resolution) and judging subjectivity, into accounts in the uncertainty assessment.

Based on the data, Figure 2 shows all periods covered by related materials and the differences in the quantity of records for each period. For the series for the whole nation and the north during the major division (220 BC-AD 1910), the number of entries for the periods of 120 BC-AD 10, AD 761-960, AD 1071-1120, AD 1191-1260, AD 1531-1640, and AD 1841-1910 is less than the average of 20, with approximately 14, 11, 12, 16, 14, 11, and 20 for each decade, respectively. For the series for the south in the division period (AD 321-590, AD 1131-1280), the number of entries is low during the period of AD 1131-1280, with an average of approximately 12. In terms of resolution, the entries with intervals of less than 35 yr account for nearly 70 percent of the totals, mainly distributed in the periods of the Han Dynasty (206 BC-AD 220), the Three Kingdoms to the middle of the Tang Dynasty (approximately AD 220-800), and the middle of the Northern Song Dynasty to the early Ming Dynasty (approximately AD 1100-1400). In particular, the intervals for records located at the turn of two dynasties are shorter than that of other times.

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**Figure 2.** Time coverage and number of entries for different time resolution. From fine to coarse, the lines represent total numbers of entries from 1 to 16. The red lines are the number of entries for the south during two major division periods (AD 317-589, and AD 1127-1279); green lines are the number of entries of semantic opposition records relative to the judged levels.

Errors from subjective judgement refer to different views on the economic level and different meanings of vocabulary descriptions used by experts. The different views on the economic level can be attributed two aspects: the first is that scholars do don’t agree with each other; the second may be influenced by the expressions. Since judgment of the economic level is based on the statements of particular group, it is closely related with the writing style among different scholars. When some scholars are good at using kinds of vocabularies to describe the change of economic state, their statements will be more referred to facilitate the level judgement, and vice versa. Besides, instead of focusing on the general economic condition, some books are more interesting in the advance and retreat of economic productivity. In this case, we usually won’t turn to this kind of statement unless other state related descriptions are unavailable. In fact, when analysing the semantics of vocabulary, we find it is relatively more difficult to categorize descriptions since the Song Dynasty. Because the economy fluctuated less significantly than before and scholars focus on much more the development of specific economic sectors or regional economic development. This can be reflected obviously by the more green lines in Figure 2. Besides, the obviously conflicted records are mainly distributed during the late part of the dynasties, such as the late sections of the Western Han Dynasty, Eastern Han Dynasty, and Ming and Qing Dynasties, which indicates an increased possibility of errors in terms of assigning the levels for the later part of the dynasties.

Influences originating from the differences in vocabulary descriptions are eliminated to some extent by vocabulary grading in Table 1. Any other influencing factors may come from the use of the same vocabulary descriptions by different experts to express different opinions or vice versa. This study safely assumes that there is no fundamental semantic difference between similar vocabulary descriptions. For instance, it is difficult to believe that the term “prosperity” would be used to describe economic depression. Therefore, in the present study, the results are acceptable and believable as long as the deviation of the judged level from the actual level is not substantially different (for example, an actual level of 4 is not graded as 1 or 2) or if both the upper and lower deviation for the level are no more than one grade. It is estimated that proportion of such levels is at least 80%.

To summarise the above analysis, the levels of uncertainty for the economic series are lower before the mid-Tang Dynasty and higher for the other periods. Within a given dynasty, the errors in both the early and late stages of the dynasty are likely to be lower than those for other periods of the dynasty. Finally, in terms of grade, 1, 4, and 5 are subject to less error than the others.

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**Appendix**

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**Part B. Supporting figures and tables**

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**Figure 3.** Real part of Morlet wavelet spectrum using Continuous wavelet transformation for the 2130-yr long economic series in China. The decadal economic series is firstly extended 2-exponential length from 213 to 256 with method of symmetrical at both ends, and then removed the extension samples in the producing contour graphs. The economic fluctuation displays multiple dominant periodicities as 60, 100, 160-200, 250, 300, and 800 yr.

**Table 3** Augmented Dickey-Fuller (ADF) Unit Root Test for indexes

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Item | Exogenous | t-statistic | | | | Results |
| ADF\* | 1% level | 5% level | 10% level |
| economy | Constant | -4.902 | -3.461 | -2.875 | -2.574 | No unit root at 1% level |
| TempC.G | Constant | -5.287 | -3.463 | -2.876 | -2.575 | No unit root at 1% level |
| Prec.Z | Constant | -9.263 | -3.465 | -2.877 | -2.575 | No unit root at 1% level |

\*All Lag Lengths are 0. TempC.G and Prec.Z are temperature of entire China and precipitation of eastern China, respectively (see Table 1).



**Figure 4.** Comparison between economic series and climate indexes. A: Decadal economic series; B: temperature of entire China (Table 1, TempC.G); C: precipitation of eastern China (Table 1, Prec.Z). The colored lines represent the corresponding 3-point FFT low-pass filter series. The shaded boxes indicate the periods when economic fluctuation coincided well with the long-term precipitation change under a relatively dry climate. Arrows indicate an approximately 30 to 60-yr lagging of economy to temperature based on the 3-point FFT series.



**Figure 5.** Wavelet coherences between the decadal series. (A) Economic level and temperature of the whole of China (Table 1, TempC.G), during AD 1-1910; (B) economic level and precipitation of the eastern China (Table 1, Prec.Z), during AD 100-1910. The color codes for power values vary from dark blue (low values) to dark red (high values). The 5% significance level against red noise based on 1000 surrogate data set pairs is shown as a thick contour. Semitransparent cones indicate the regions influenced by edge effects. The arrows indicate the relative phase relationship (right: in-phase; left: out-of-phase).