The impact of oil prices on CO2 emissions in China: A Wavelet coherence approach

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Abstract

This paper observes the possible co-movements of oil price and CO2 emissions in China by following wavelet coherence and wavelet partial coherence analyses to be able to depict short-run and long-run co-movements at both low and high frequencies. To this end, this research might provide the current literature with the output of potential short run and long run, structural, changes in CO2 emissions upon a shock (a change) in oil prices in China together with the control variables of World oil prices, fossil energy consumption, and renewables consumption, and, urban population in China.

Therefore, this research aims at determining wavelet coherencies between the variables and phase differences to exhibit the leading variable in potential co-movements.

By following the time domain and frequency domain analyses of this research, one may claim that the oil prices in China has considerable negative impact on CO2 emissions at high frequencies for the periods 1960-2014 and 1971-2014 in China. Besides, one may underline as well other important output of the research exploring that the urban population and CO2 emissions have positive associations, move together for the period 1960-2014 in China. Eventually, this paper might suggest that authorities follow demand side management policies considering energy demand behavior at both shorter cycles and longer cycles to diminish the CO2 emissions in China.

Keywords: Wavelet coherence, wavelet partial coherence, oil price, CO2 emissions, urbanization, China

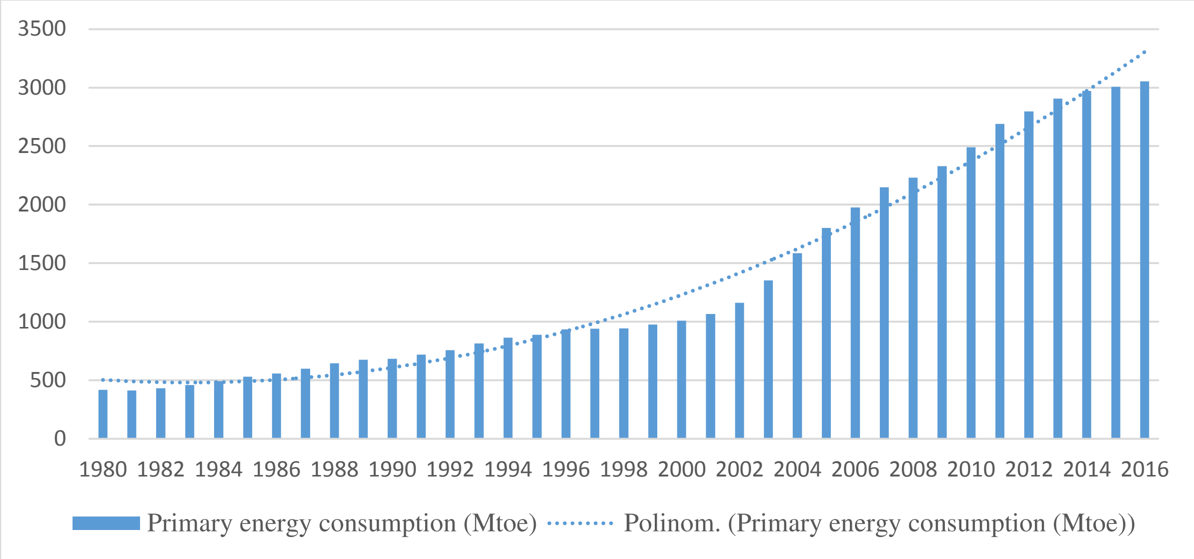
JEL: C1, Q3, Q4, Q5

1. Introduction

China has been in a process of rapid economic development with openness and reform policies that began since the end of the 1970s. The country transitions from a central planning economy to a market economy. China has moved from an autocratic economic structure to a growth policy based on exports by utilizing the low-wage labor force (Kei, 2000). During this 40-year period, the Chinese economy continues to grow rapidly. The country experiences industrialization, urbanization, physical infrastructure, institutional structure, lifestyle, technology and motorization developments (Ma et al. 2012; Zhang et al. 2017). China has become one of the major producers and exporters in the world today. Export earnings have accelerated new entrepreneurial activities, local infrastructure projects and foreign capital investments. For example, the "Made in China" label was very rare in developed countries' markets in the 1980s, but since the 1990s, it has become a widespread and dominant label on all world markets (Paltsev et al. 2012). Today, China is the second largest exporter, importer and economy of the world after the United States (Qi et al. 2014). Population is also increasing rapidly in connection with this development process. The population of China increased by 21% between 1990 and 2015 to 1.37 billion from 1.14 billion (see table 1). Energy consumption is shown as the most important leverage in China's performance in this brilliant economic development. Many researchers argue that there is a strong relationship between economic development, industrialization and urbanization and energy consumption in China (Dong et al. 2017; Bilgili et al. 2017a). The most important indicator of this argument is that China's total energy consumption rises to 417, 683, 1007 and 3052 Mtoe in 1980, 1990, 2000 and 2016, respectively. The Graph 1 depicts the dramatic rise in China's energy demand during the period 1980-2016. In addition, it is estimated that this increase in demand for energy will continue in the future.

China meets 90% of the energy demand from fossil sources. This energy structure has not changed much since the 1980s. While the share of the coal in total energy consumption was 71% in the 1980s, this share was 70% in 2002 (Guan et al. 2008). The share of coal in China's total energy consumption is now 67% (BP, 2017). In addition, the other important part of this demand is covered by other fossil resources such as oil (18%) and natural gas (5%). Industry sector is the most important actor of energy consumption with 51% share. Other important drivers of energy demand are residential, transportation and commercial - public sectors with and share of 16%, 15% and 4% respectively (IEA, 2017b). However, the most important point to be emphasized about China's energy structure is that it is the world's largest energy consumer country. According to the Global Energy trends (2017) report, China's share of global energy demand in 2016 is 23%. Moreover, China has not achieved efficiency in energy use compared to other major energy consuming countries such as the US and Japan. China's energy intensity is 3.4 times higher than the US and 9 times higher than Japan's (Guan et al. 2008). China clearly appears as a country with high energy intensity and a fossil energy dependency. China is the most important country responsible for the greenhouse gas emissions of the world as a natural consequence of the economic development process and energy structure. While the United States is the world's largest CO2 emitter country by 2007, the emissions leader since 2007 is China (Bilgili et al. 2016a). China alone is responsible for 28% of global CO2 emissions. China has particularly diverged from other countries between 1990 and 2015, and CO2 emissions have increased very rapidly by about 331%. This emission increase is not only at the total level. The amount of emissions per capita has also risen dramatically (see Table 1).

Graph 1: The bar and line graph on China's energy consumption trend (1980-2016)



Source: BP Statistical Review of World Energy, 2017.

Table 1: Carbon dioxide emissions, GDP and Population in China (1990-2015)

Indicators (unit)	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**90-15 (%change)**
CO2 fuel combustion (MtCO2)	2109.2	2923.6	3127.1	5399.0	7748.6	9084.6	%331
Share of World CO2 from fuel combustion (%)	10	14	14	20	25	28	
GDP (billion 2010 USD)	933.7	1613.8	2390.5	3758.5	6329.3	9174.1	883%
Population (millions)	1140.9	1211.0	1269.3	1310.5	1344.7	1378.5	21%
CO2 / population (CO2 per capita)	1.9	2.4	2.5	4.1	5.8	6.6	256%

Source: IEA, 2017a.

The world of science considers greenhouse gases such as carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and hydrofluorocarbons (HFCs), which are emitted from fossil energy use, as a fundamental source of various environmental problems such as global warming, climate change, local air pollution and acid rain. But the most dangerous of these pollutants is CO2 gas since the share of CO2 in total greenhouse gases is about 60%. Moreover, it is the fastest growing gas since the Industrial Revolution (Bilgili et al. 2016a). For this reason, China's environmental and energy policies directly affect CO2 emissions and global environmental problems. On the other hand, energy consumption has critical importance in maintaining China's current economic performance. As a result, researchers and policy makers have been concentrated on the following two issues: (a) What are China's efforts to reduce CO2 emissions? (b) What are the driving forces of China's CO2 emissions and energy consumption? In this context, we exhibit the relationship between oil prices and CO2 emissions. The purpose of our study is to investigate the effect of oil price movements on CO2 emissions of the China through time series and frequency analysis. The importance and literary contribution of this study is twofold. First, oil and the future are an important debate in the context of China's energy security and environmental policies. Oil meets a significant portion of China's energy demand. In particular, it is argued that the rising demand in the automotive sector and the developments in transportation will continue to increase the demand for oil in future periods (Ma et al. 2012). The results of this study are expected to give a light to these discussions.

Secondly, there has been a global expectation that oil prices will be low in the recent periods and these low prices will continue for a long time. As known, there has been an important event arising in energy sector that is a rapid fall in crude oil prices from 2014 to 2015. Brent crude oil price reaches its lowest level, less than $40 per barrel, since 2008. This fall in oil prices does not seem to be transitory as International Monetary Fund re-elected director Christine Lagarde predicts that crude oil prices will probably stay low for longer than expected because even the energy security concerns due to Syrian conflict and political controversies in the Middle East could not put pressure on the prices since 2014 (Bloomberg 2016). Unfortunately this decline in oil prices may give rise to substitute oil to natural gas in heating of buildings, change the energy mix in manufacturing sector through fossil fuels and the consumer preferences while choosing the electricity appliances or vehicles, or miles travelled (Yang and Timmermans 2012; Zhang et al. 2014; Pereira and Pereira 201; Wang 2015; Wang and Li 2016). McCollum et al (2016) analyze how the future oil prices uncertainties affect the energy sector and economy worldwide by simulating through an integrated assessment model (MESSAGE). They find that long-standing high or low oil prices could alter the energy mix dynamics of countries in energy production: low oil prices are expected to weaken carbon mitigation initiatives on the contrary high oil prices support them.

Besides any permanent decrease in fossil fuel prices may affect the renewable energy investment decisions negatively (Wang, 2015; Wang and Li 2016). The low level of crude oil prices together with commodity prices is expected to improve overall income in the economy, which would increase energy demand (World Bank, 2015). Both substitution and income effects of the fall in oil prices can be seen as a risk for China to reduce CO2 emissions. This paper is to investigate whether this downfall in oil prices is a threat for the China's reduction of CO2 in the short and long run, while high oil price argument was often treated as an opportunity. The results of this study contribute to the design of China's energy and environmental policies by policy makers.

The rest of the paper is as follows:
(1) Section 2 reviews the literature. (2) Section 3 introduces the wavelet methodology and the data. (3) Section 4 presents empirical results of wavelet coherency and phase analysis. (4) Section 5 provides conclusions and some policy recommendations.

2. Literature review

There are numerous studies in the literature that examine energy consumption, economic growth and environmental relations (Ozturk, 2010; Omri, 2014; Bilgili et al. 2016b, Bilgili et al. 2017b). However, few studies have focused on the relationship between oil consumption/ oil prices and environmental quality (Maji et al., 2017). For this reason, we evaluate the studies that examine the relationship between oil and CO2 emissions. Firstly, De bruyn et al. (1999) investigate the relationship between economic growth, oil prices and greenhouse gas emissions in the Netherlands, UK, USA and Germany during the period 1960-1993 through empirical methods. The results indicate that the increase in oil prices in the US is a negative effect on CO2 emissions. There is no significant relationship between oil price and CO2 emissions for the other countries. Lindmark (2002) examines the relationship between CO2 emissions, technology, economic growth and fuel prices in Sweden in the period 1870-1997.

The results show that the increase in fuel prices is a mitigating effect on CO2 emissions. He and Richard (2010) explore the impact of economic growth, industrialization, trade and oil prices on CO2 emissions in Canada from 1948-2004. The study suggests that the increase in oil prices is a mitigating effect of CO2 emissions. Payne (2012) analyses the effect of oil prices on CO2 emissions in the US during the years between 1949 and 2009. The results imply a long-run significant negative impact of oil price on CO2 emissions in the US. Hammoudeh et al. (2014); Wang and Li (2016); Zhang and Zhang (2016); McCollum et al (2016) and Maji et al. (2017) show that the increase in oil prices is a mitigating effect of CO2 emissions by reaching similar results (see Table 2).

Contrary to expectations, some studies in the literature reveal that the increase (decrease) in oil prices is a positive (negative) effect on CO2 emissions, while some other studies show that there is no significant relationship between oil prices and CO2. Sadorsky (2009) investigates the impact of oil price, CO2 emissions and economic growth on renewable energy in G-7 countries between 1980 and 2005. Empirical findings indicate that economic growth and increases in CO2 emissions have a strong influence on the increase in renewable energy consumption. However, the impact of rising oil prices on renewable energy consumption is weak. Salim and Rafiq (2012) examine the relationship between economic growth, oil prices, renewable energy and CO2 emissions in the developing countries for the period 1980-2006.

The empirical findings indicate that oil prices are not a significant influence on renewable energy and CO2 emissions. Zhang and Zhang (2016) examine the effect of oil prices on CO2 allowance prices in China with the daily data for the period 2013-2015. The results of the study indicate that oil prices are a positive influence on CO2 emissions allowance price. Nwani (2017) estimates the relationship between oil prices, energy consumption and CO2 emissions in Ecuador from the period 1971-2013 through an autoregressive distributed lag (ARDL) approach. Estimation findings show that the increase in oil prices is an increasing effect on CO2 emissions. Blazquez et al. (2017) investigate the impact of oil price shocks on the CO2 emissions from Spain for the period 1969-2003. The study shows that oil price shocks are not a significant effect on CO2 emissions.

Finally, the literature investigating the relationship between oil consumption and CO2 emissions is evaluated. Lim et al. (2014) examine the causality relationship between oil consumption, economic growth and CO2 emissions in the Philippines during the period 1965-2012. Causality test results show that there is a bi-directional relationship between oil consumption and both CO2 emissions and economic growth. This result indicates that there is a feedback relationship between oil price and CO2 emissions. Alam and Paramati (2015) estimate the impact of economic growth, oil consumption, financial development, industrialization and trade openness on CO2 emissions in developing countries that consumed major oil in the period 1980-2012. Estimation results confirm that oil consumption and economic growth have a significant impact on CO2 emissions. Saboori et al. (2017) analyze the relationship between oil consumption, economic growth and CO2 emissions in China, Japan and South Korea from 1980 to 2013. Empirical findings are as follows: (1) It is revealed that petroleum consumption in China is an important cause of economic growth and

CO2 emissions. (2) Oil consumption in Japan is an important reason for economic growth. However, there is no causality relationship between petroleum consumption and CO2 emissions. (3) Oil consumption in South Korea is an important cause of economic growth and CO2 emissions. Moreover, this relationship is bidirectional, and economic growth and CO2 emissions also affect oil consumption.

Table 2 summarizes the literature findings. Researches often use time series and panel data analysis methods. In general, there is no extensive literature on this area. There are very few empirical studies on China. The general tendency of the findings is that the increase in oil prices and the decrease in oil consumption is a mitigating effect of CO2 emissions. The findings of the research differ according to country, period and method. Finally, further research is needed in the literature.

Table 2: Summary of empirical literature on oil price/ oil consumption and CO2 emissions

Author(s)	Country	Period	Methodology	Conclusion
De bruyn et al. (1999)	Netherlands, UK, USA and Germany	1960-1993	Panel data analysis	Increase (decrease) in oil prices reduce (increase) CO2 emissions
Lindmark (2002)	Sweden	1870-1997	Time series analysis	Increase (decrease) in oil prices reduce (increase) CO2 emissions
Sadorsky (2009)	G7 countries	1980-2005	Panel data analysis	The impact of oil prices on renewable energy consumption and hence on CO2 emissions is weak.
He and Richard (2010)	Canada	1948-2004	Time series analysis	Increase (decrease) in oil prices reduce (increase) CO2 emissions
Payne (2012)	USA	1949-2009	Time series analysis	Increase (decrease) in oil prices reduce (increase) CO2 emissions
Salim and Rafiq (2012)	Developing countries	1980-2006	Panel data analysis	Oil prices are not a significant influence on renewable energy and CO2 emissions.
Hammoudeh et al. (2014)	USA	2006-2013 (monthly)	Time series analysis	Increase (decrease) in oil prices reduce (increase) CO2 emissions allowance price.
Lim et al. (2014)	Philippines	1965-2012	Time series analysis	Increase (decrease) in oil consumption increase (decrease) CO2 emissions.
Alam and Paramati	Developing	1980-2012	Panel data	Increase (decrease) in oil

(2015)	countries		analysis	consumption increase (decrease) CO2 emissions.
Wang and Li (2016)	OECD	no period	SWOT analysis	Increase (decrease) in oil prices reduce (increase) carbon intensity
Zhang and Zhang (2016)	China	2013-2015 (daily)	Time series analysis	Increase (decrease) in oil prices increase (decrease) CO2 emissions allowance price.
McCollum et al (2016)	Worldwide	no period (simulation)	Integrated Assessment Model	Low oil prices weaken carbon mitigation initiatives.
Blazquez et al. (2017)	Spain	1969-2003	Dynamic Stochastic General Equilibrium (DSGE) model and time series analysis	Oil price shocks are not a significant effect on CO2 emissions
Saboori et al. (2017)	China, Japan and South Korea	1980-2013	Time series analysis	Increase (decrease) in oil consumption increase (decrease) CO2 emissions (for China and South Korea). No causality relationship between petroleum consumption and CO2 emissions (for Japan).
Nwani (2017)	Ecuador	1971-2013	Time series analysis	Increase (decrease) in oil prices increase (decrease) CO2 emissions.
Maji et al. (2017)	Malaysia	1983-2014	Time series analysis	Increase (decrease) in oil prices reduce (increase) CO2 emissions
Kumar and Managi (2009)	80 countries	1971-2000	Directional Output Distance Function Estimation	Increase in oil prices induces technological progress in ren energy
Yang and Timmermans (2012)	Netherlands	Survey	Pseudo-Panel Survey Methodology	The effect of rise in oil prices on carbon emissions is ambiguous.

Oil prices may affect carbon emissions through three channels; first falling oil prices would increase carbon intensity in manufacturing sector by altering energy mix and efficiency in production (Zhang, 2014). In addition to firms, the vehicle preferences of US consumers have been shifting from hybrid to less fuel-efficient Sport Utility Vehicles (SUV's) due to falling oil prices, which also increase concerns over energy-saving, efficiency and renewable energy investments (Wang, 2015; Wang and Li 2016). As renewable energy sources are considered as the most likely substitute of oil and its derivations (Sadorsky, 2009; Aspergis and Payne, 2014), any change in oil price may directly affect the demand for renewables. Winchester and Ledvina (2017) supports this result by constructing a dynamic stochastic general equilibrium model in which the energy production mix is simulated under alternative fossil price scenarios. They conclude that higher fossil fuel prices could boost biofuel production in the long-run, therefore less GHG emission. Besides the negative effect of low oil prices on some renewable is expected to be very limited in short-run, since especially the purchase contracts of wind and solar photovoltaic energy cannot be revised easily (Wang and Li, 2016).

As the second point, falling oil prices would have a stimulating economic growth effect which has a positive effect on carbon emissions (Canadell et al, 2007; Wang, 2010; de Bruyn et al, 1998; Pereira and Pereira, 2014). However Hamilton (2003) shows that there is a clear evidence of non-linear relation between oil price change and economic growth during post-war period in the US indicating that the oil price increases are expected to be much more important than oil price decreases. Lastly it would increase the carbon reduction costs with a rising marginal cost of emission reducing tax (Wang and Li, 2016). Thus the environmental concerns over falling oil prices seem to become a reality in the US.

This paper employs wavelet coherence analysis so as to find out the local correlation between the Chinese CO2 emissions and the real price of imported oil since the first oil shock appeared in 1974. Then, section 3 introduces the wavelet methodology and the data. While Section 4 presents empirical results of wavelet coherency and phase analysis, finally section 5 concludes.

3. Wavelet Methodology

Spectral analysis of economic time series consists of time and frequency dimensions. Fourier analysis finds out that any periodic and some non-periodic functions can be shown as a function of sines and cosines[1]. Fourier transformation (FT) of a signal or a function yields decomposition of time series into frequency domain in which it becomes easier to investigate

[1] If $f(x)$ is a non-periodic function, its Fourier Transform $F(x): \mathbb{R} \rightarrow \mathbb{C}$ returns a complex-valued function, which has complex weights for different frequency contributions under integral as a similar way to the coefficients in the periodic functions' case.

predominant business cycles (Merrill et al, 2008) and seasonal characteristics (Wen, 2002). Nevertheless, FT does not give information about when various frequencies appear in time horizon, namely it is lack of time information. A frequency spectrum measures current oscillations in a signal or a function lacking of transition type (gradual or abrupt) among periods and jumps or structural changes. Given a signal or a function $h(t)$, equation 1 shows FT of it as below,

(1)[2] $$H(\kappa) = \int_{-\infty}^{\infty} h(t) e^{-i2\pi\kappa t} dt = \int_{-\infty}^{\infty} h(t)[cos(2\pi\kappa t) - i\, sin(2\,\pi\kappa t)]dt\ ,$$

where $H(\kappa)$ represents the FT of function $h(t)$, hence, is a function of frequency κ and $i = \sqrt{-1}$ is the complex or imaginary number. Aguiar-Conraria (2013) states that Fourier techniques are applicable only with stable statistical properties and that, however most of economic time series follow unstable statistical properties such as time-varying moments of distribution (non-stationary), strong time trends and complexity.

In addition to frequency analysis, wavelet methods consider time series in both time and frequency domain at the same time. Wavelet analysis evaluates how cycles, trends or seasonality extracted from the transformation of a time series change over time. Gencay et al. (2001) suggests wavelet transformation as a best device for analyzing non-stationary time series due to the favor of scaling tool; wavelet transformation may focus on wide range of frequencies, which provides the ability to capture events that are local in time. That is why wavelet methodology has become popular in economics and finance literature including those of Gencay et al. (2001, 2005), Crowley (2007), Kim and In (2007), Aguiar-Conraria et al. (2011), Vacha and Barunik (2012) and Khalfaoui et al. (2015). A wavelet function can be written as below,

(2) $$\phi_{(s,v)}(t) = \frac{1}{\sqrt{s}} \phi\left(\frac{t-v}{s}\right), \qquad v \in \mathbb{R}\ and\ s \in \mathbb{R}^{+}\ .$$

The mother wavelet $\phi(.)$ is scaled by s and located by v in order to obtain a wavelet daughter $\phi_{(s,v)}(t)$ which is a square differentiable function of time, $\phi(.) \in L^2(\mathbb{R})$[3]. Parameter v is the location or translation parameter that shows where the wavelet centered or

[2] There is an alternative representation of Fourier transformation analogous (identical) to Equation1. Since sines and cosines are 2π-periodic functions, $w = 2\pi\kappa$ denotes radian frequency: $H(w) = \int_{-\infty}^{\infty} h(t)e^{-iwt}dt = \int_{-\infty}^{\infty} h(t)[\cos(wt) - i\sin(wt)]dt$

[3] If a wavelet is square integrable $\phi(t) \in L^2(\mathbb{R})$, then it must satisfy $\int_{-\infty}^{\infty} \emptyset(t)^2 dt < \infty$.

located in time. Parameter s is scale or dilation parameter that compresses or enlarges wavelet to detect cycles or trends in different frequencies. For instance, an increasing scaling s generates long wavelets, which capture long-run (low frequency) properties of time series whereas a decreasing s compresses it to measure short-run (high frequency) dynamics. Thus there is an inverse relation between scale and frequency.

The continuous wavelet transformation (CWT) of a considered time series $h(t) \in L^2(\mathbb{R})$ with respect to wavelet $\phi_{(s,v)}(t)$ is defined as:

(3) $$W_h(s,v) = \int_{-\infty}^{\infty} h(t) \frac{1}{\sqrt{s}} \overline{\phi\left(\frac{t-v}{s}\right)} dt\,, \qquad v \in \mathbb{R}\; and\; s > 0\;,$$

where $W_h(s,v)$ represents CWT and the bar over the mother wavelet function denotes complex conjugation.[4]

In addition to square differentiability, any mother wavelet should satisfy admissibility condition which provides recovery of function $h(t)$ from its wavelet transformation. The admissibility condition is defined as,

(4) $$C_{\emptyset} = \int_0^{\infty} \frac{|\Phi(\kappa)|^2}{\kappa} d\kappa < \infty\,,$$

where $C_{\emptyset}$ is the admissibility constant and $\Phi(\kappa)$ is the FT of wavelet $\phi(t)$. This condition implies that the wavelet does not have any zero frequency components, $\Phi(0) = \int_{-\infty}^{\infty} \emptyset(t)dt = 0,$ thus it must have negative and positive oscillations that cancel out each other namely it has zero mean. Furthermore the wavelet is generally normalized to have unit energy, $\int_{-\infty}^{\infty} |\emptyset(t)|^2 dt = 1$, which provides the comparison of the wavelet transforms at each scale s and the transforms of other time series (Torrence and Compo 1998).

There are so many types of wavelet functions with different characteristics such as Haar, Daubechies, Mexican hat, Cauchy, Coiflets and Morlet, etc. Since wavelet transformation merges information coming from signal $h(t)$ and wavelet $\emptyset(t)$, it is crucial to choose most appropriate wavelet which fits best with the data. Aguiar-Conraria et al. (2008) suggests choosing a complex wavelet as it presents a complex transformation, which has information on both amplitude (from mid-cycle phase of the period to the peak point or through the point)

[4] The conjugate of a complex number, $c + di$, is simply $c - di$. If the value is real rather than complex, its conjugate is itself. In economic applications complex wavelets are popular, thus the conjugation becomes important.

and phase (horizontal angle of the wave). The phase differences become important while analyzing the position of variables in cycles.

In the analysis, we prefer to use complex Morlet wavelet, first introduced by Morlet et al. (1984), can be defined as:

$$(5) \qquad \emptyset_\gamma(t) = \frac{1}{\pi^{1/4}}\left(e^{i\gamma t} - e^{\frac{-\gamma^2}{2}}\right)e^{\frac{-t^2}{2}},$$

where parameter γ denotes the central frequency parameter of Morlet wavelet $\emptyset_\gamma(t)$. In equation 5, if the location parameter is set $\gamma > 5$ as the value of term $e^{-\gamma^2/2}$ becomes negligibly small. This yields a simplified version of Morlet wavelet function as below,

$$(6) \qquad \emptyset_\gamma(t) = \frac{1}{\pi^{1/4}} e^{i\gamma t} e^{\frac{-t^2}{2}} .$$

Economic and financial applications often set $\gamma = 6$, since it provides a parameter choice conversion between scale and frequency thus Morlet wavelet might be considered as function of frequency as well-see for further discussions about the use of complex Morlet wavelets for economic applications Aguiar-Conraria et al. (2013), Madaleno and Pinho (2014), Aguiar-Conraria et al. (2008), Rua and Nunes (2009), Crowley (2005), Percival and Walden (2000).

The admissibility condition of wavelets, introduced in equation 4, is a sufficient condition for time series to return back to its original form from their wavelet decomposition. Admissibility condition ensures to get $W_h(s, v)$ CWT from time series $h(t)$, and go from wavelet transformation to $h(t)$ as a new representation below,

$$(7) \; h(t) = \frac{1}{C_\emptyset}\int_0^\infty \left[\int_{-\infty}^\infty W_h(s, v)\, \phi_{(s,v)}(t) dv\right]\frac{ds}{s^2}, \qquad v \in \mathbb{R} \; and \; s > 0 .$$

CWT should maintain energy of time series $h(t)$, by applying unit energy property of wavelets. The energy of $h(t)$ preserved by its wavelet transformation, $||h||^2$ can be written as,

$$(8) \; ||h||^2 = \frac{1}{C_\emptyset}\int_0^\infty \left[\int_{-\infty}^\infty |W_h(s, v)|^2 \, dv\right]\frac{ds}{s^2}, \qquad v \in \mathbb{R} \; and \; s > 0 \qquad ,$$

where $|W_h(s,v)|^2$ shows wavelet power spectrum which shows the distribution energy of the time series $h(t)$ in both frequency and time space. In addition to analysis of a single time series, wavelet analysis can be applied for the analysis of time-frequency interactions between two time series such as cross wavelet power, wavelet coherency and phase differences. While the wavelet power spectrum depicts the variance of a single time series, the cross wavelet power of time series measures the local covariance between two time series at each time and frequency. The cross wavelet power of two time series, $W_{xy}(s,v)$ can be stated as first introduced by Hugdins (1993) as,

(9) $$W_{xy}(s,v) = W_x(s,v)\overline{W_y(s,v)} \quad ,$$

where $W_x(s,v)$ and $W_y(s,v)$ are the continuous wavelet transforms of time series $x(t)$ and $y(t)$ respectively, s is scale and v is location parameter as same as continuous wavelet transformation formula in equation 3. While cross wavelet transform shows regions where two time series show high common power, the wavelet coherency works like a traditional correlation coefficient which depicts where two time series move together but do not necessarily have high common power. Following Conraria (2013), wavelet coherency between $x(t)$ and $y(t)$ R_{xy} can be defined as:

(10) $$R_{xy}(s,v) = \frac{|S(W_{xy}(s,v))|}{\sqrt{S(W_x(s,v))S(W_y(s,v))}} \quad ,$$

where R_{xy} shows local correlation parameter which ranges from zero (no coherency) to 1 (strong coherency) in time and frequency space. Besides S denotes smoothing parameter which is necessary otherwise coherency would be equal to 1 for all scales and times (Liu 1994)[5].

The phase difference defines phase relationships between two time series for instance lead-lag relation or whether they are negatively or positively correlated. The phase difference $\varphi_{x,y}$ between time series $x(t)$ and $y(t)$ can be written as:

[5] Grinsted et al. (2004) provides an example of a derived smoothing parameter of the cross wavelet coherency generated from complex Morlet wavelet transformation.

$$\varphi_{x,y} = tan^{-1}\left(\frac{\Im\left(W_{xy}(s,v)\right)}{\Re\left(W_{xy}(s,v)\right)}\right), \quad \text{with } \varphi_{x,y} \in [-\pi, \pi] \tag{11}$$

where, for a given a complex wavelet transformation $\Im\left(W_{xy}\right)$ and $\Re\left(W_{xy}\right)$ denote, imaginary and real part of wavelet transformation respectively. A phase difference of zero indicates that the time series move together at specified frequency. If $\varphi_{x,y} \in \left(0, \frac{\pi}{2}\right)$ then the series move in phase, where $y(t)$ leads $x(t)$. if $\varphi_{x,y} \in \left(-\frac{\pi}{2}, 0\right)$ then the series move again in phase however now $x(t)$ leads $y(t)$. A phase difference of π or $-\pi$ implies an anti-phase relation namely negative correlation. If $\varphi_{x,y} \in \left(-\pi, -\frac{\pi}{2}\right)$ then the series move out of phase, where $y(t)$ leads and if $\varphi_{x,y} \in \left(\frac{\pi}{2}, \pi\right)$ then the series move again out of phase where $x(t)$ leads.

4. The results of wavelet coherency and partial wavelet coherency analyses

Through wavelet coherency and partial wavelet coherency analyses, we aim at observing the potential possible short run and long run co-movements between oil prices and CO2 emissions at different frequencies in China. As we analyze the data for oil prices and emissions', we also employ other relevant data for as control variables such as World oil prices, fossil fuel energy production, renewable energy production, population, and urban population to follow well identified models. The full descriptions, relevant codes and available periods of the data are given in Appendix in Table A.1

The wavelet coherence and partial wavelet coherence estimations are presented by the Figures 1, 2a, 3a, 4a and 5a and in each figure, the black curve (contour) exhibits the 5% significance level of the wavelet coherence output through an ARMA (1, 1) representation. AR (1) and MA (1) terms of the ARMA model denote the autoregressive with one lag and moving average with one lag, respectively. The color code bars next to the figures reveals the range from weak coherency (blue) to strong coherency (red) between the variables. The color code, therefore, depicts the range from possible weakest coherence (dark blue) and to strongest coherence (dark red). The dark blue and dark red, thereby, refer to low energy of association and high energy of association between the variables, respectively. Then, one may consider the energy of association the power of correlation ranging from 0.05 to 0.95.

The Figure 1.a depicts wavelet coherency between real oil price and total CO2 emissions for the period 1960-2014 in China by considering simultaneously (a) the time series observations, and, (ii) frequencies ranging from 1 to 8 years.

Figure 1.a reveals, then, some weak and strong coherencies between oil price and total CO2 emissions at high frequency periods (1-1.5 year frequency) for the periods 1960-1970 and 1977-2014. When the control variable of World oil price is added into the model, the wavelet coherencies become more explicit as depicted by in Figure 2.a. The wavelet partial coherency given in Figure 2.a explores additionally the strong co-movements between oil price and CO2 emissions at 2-year, 4-year and 5-8-year frequencies. The figure 2a exhibits well stronger coherencies between the variables at higher periods (lower frequencies).

Following the Figure 2a, the Figures 2b and 2c show the phase differences at 1-2-year and 2-4-year frequencies as the Figures 2d, 2e exhibit the phase differences within 1-3 frequency bands. At 1-2 frequency band, the oil prices, as leading variable for the periods, 1982, 1987-1994, 1997-1999, 2005-2014, decreases CO2 emissions in China. One of the plausible reasons of this output might be a possible switch from fossil fuel to renewables due to increase in the ratio of oil price in China to the oil price of in the World.

Figure 1.a: Wavelet coherency (Oil price, CO2 total), 1960-2014

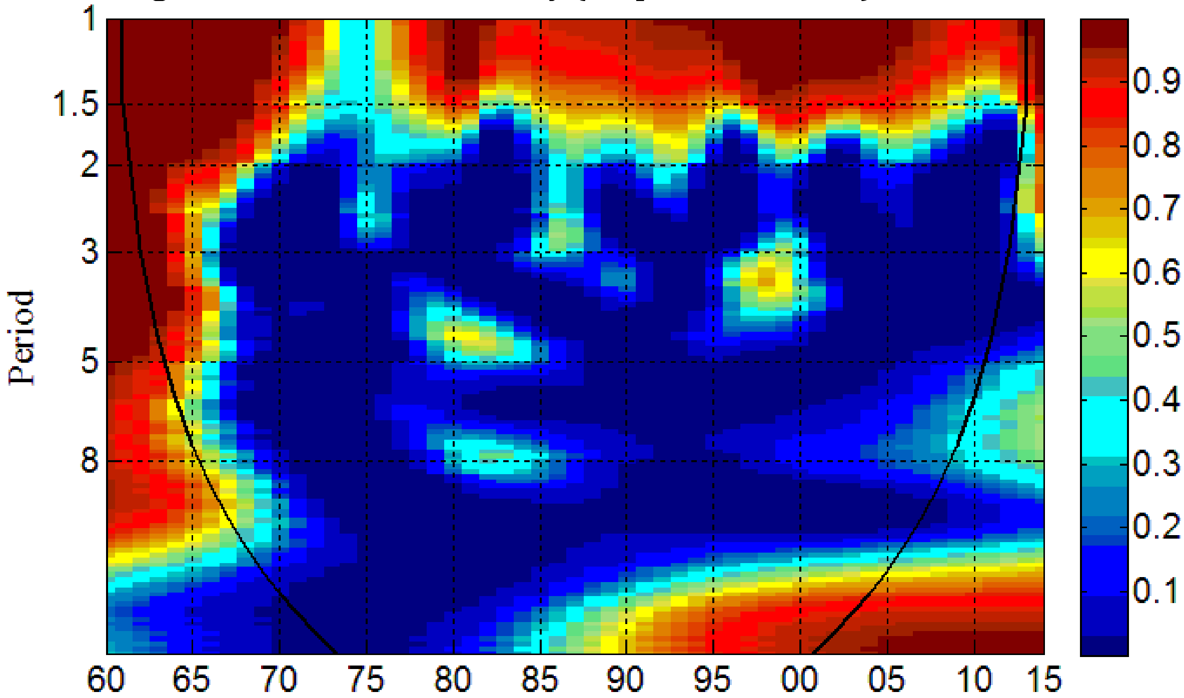
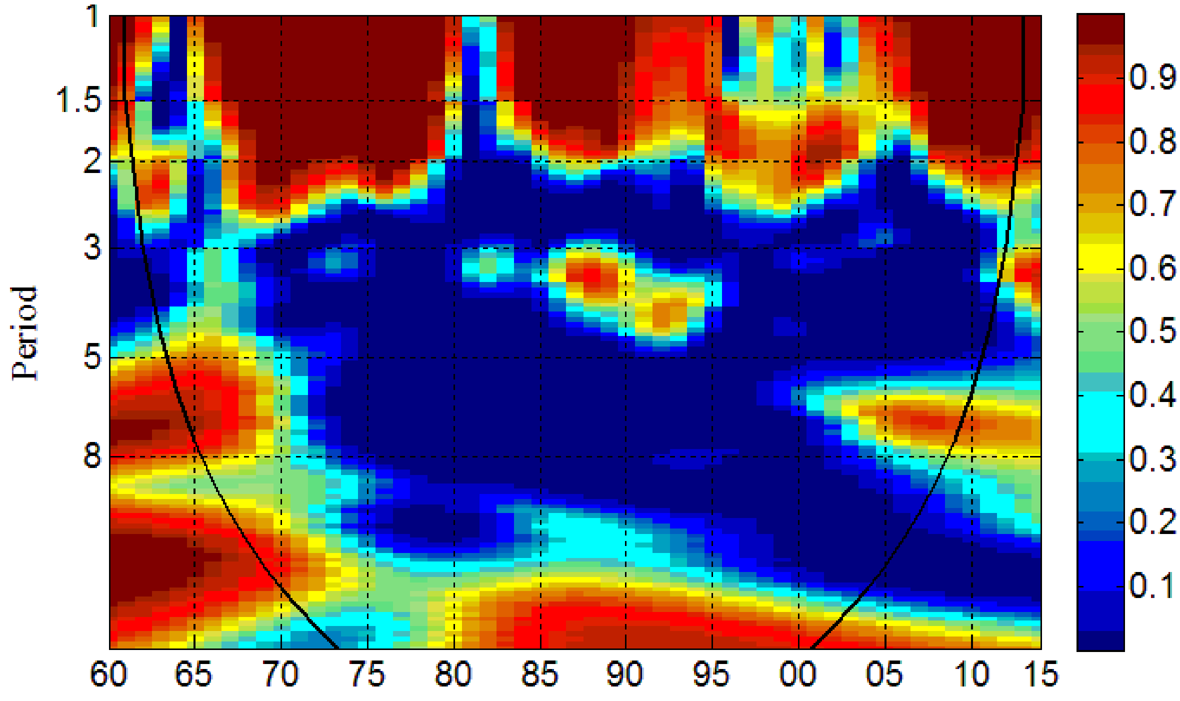


Figure 2.a: Wavelet partial coherency (Oil price, CO2 total|| World oil price), 1960-2014



This decline in emissions, due to increase in oil prices, appears in the years of 2009-2014 at 2-4-frequency band, 1-3-frequency band (Figure 2d) and 3-8-year frequency band (Figure 2e).

Figure 2.b: 1~ 2 frequency band, 1960-2014

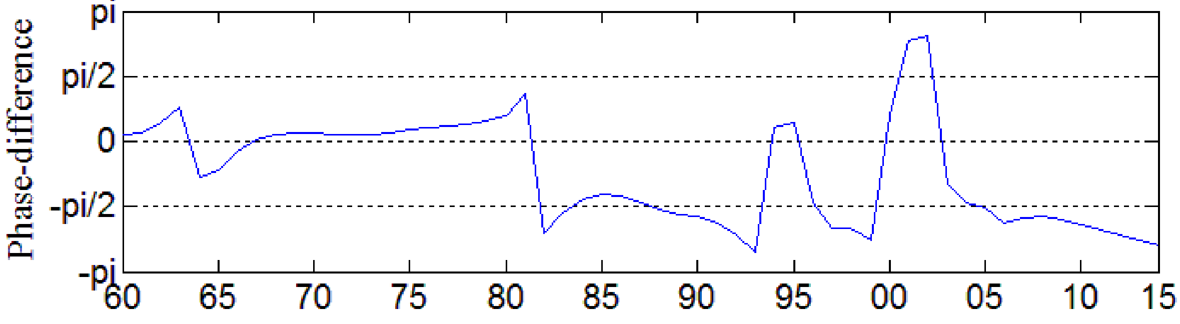


Figure 2.c: 2~ 4 frequency band, 1960-2014

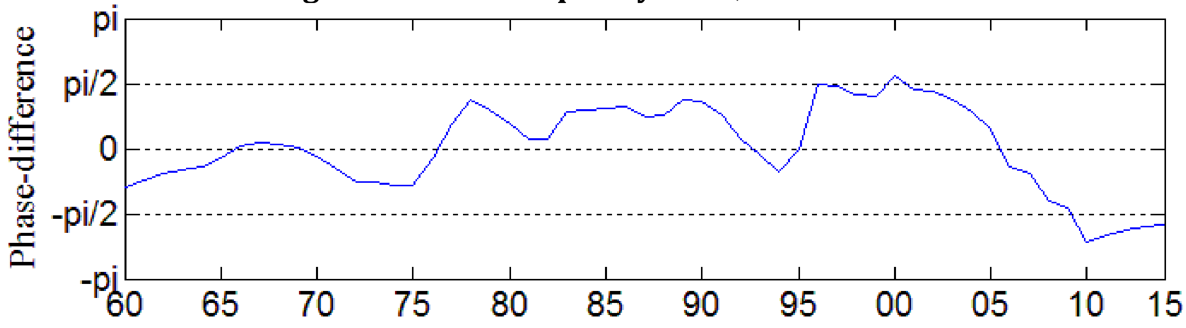


Figure 2.d: 1~ 3 frequency band, 1960-2014

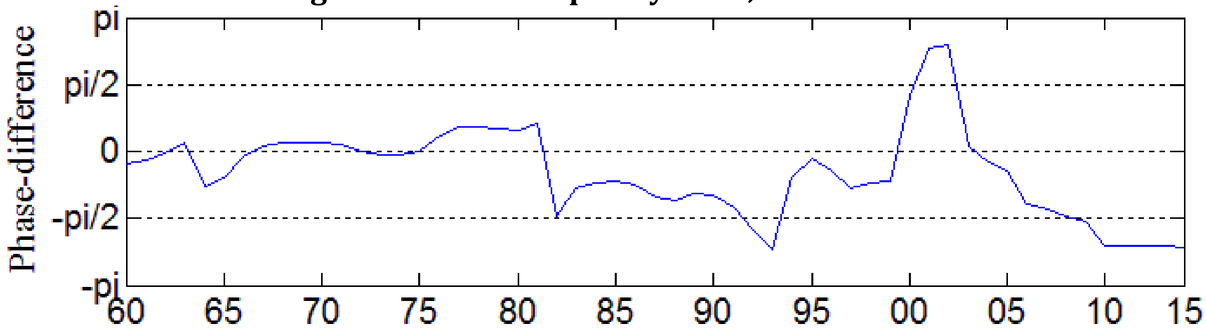
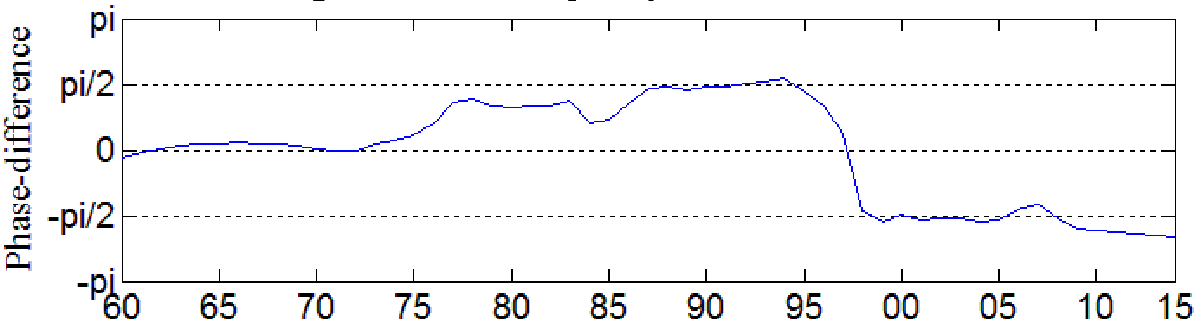


Figure 2.e: 3~ 8 frequency band, 1960-2014



The decrease in CO2 emissions at 3-8 year frequency band, however, seems to be significant just for the period 2004-2010 (Figure 2a).

The immediate result from the outputs from Figure 2a to Figure 2e is that the strong and significant negative impact of oil price on CO2 emissions appears more considerable at higher frequencies (1-2-year cycles). Within 1-2 year cycles, there also exist positive-co movements between variables, as oil price leads, from 1967 to 1982 and in 1995.

As we launched the same wavelet coherence and wavelet partial coherence estimations by employing per capita CO2 emissions instead of total CO2 emissions, we observed that the main output has not changed. We do not plot here the relevant figures but exhibit them in Appendix section.

We added additionally the fossil fuel energy consumption (% of total energy) as control variable into the model and we have observed that the short-term-cycle (1-2-year frequency) co-movements of the variables become stronger than the co-movements of the variables given by Figure 2a (without control variable of fuel oil consumption) for the period 1995-2014. Besides, the Figure 3.a yields strong coherencies at 8-year frequency during 2004-2010. Since the available data points of fossil fuel consumption cover the period 1971-2014, as is given in Table A.1 in Appendix, the wavelet model has been adjusted from period 1960-2014 to period 1971-2014.

Figure 3.a: Wavelet partial coherency (Oil price, CO2 total || World oil price, Fossil fuel), 1971-2014

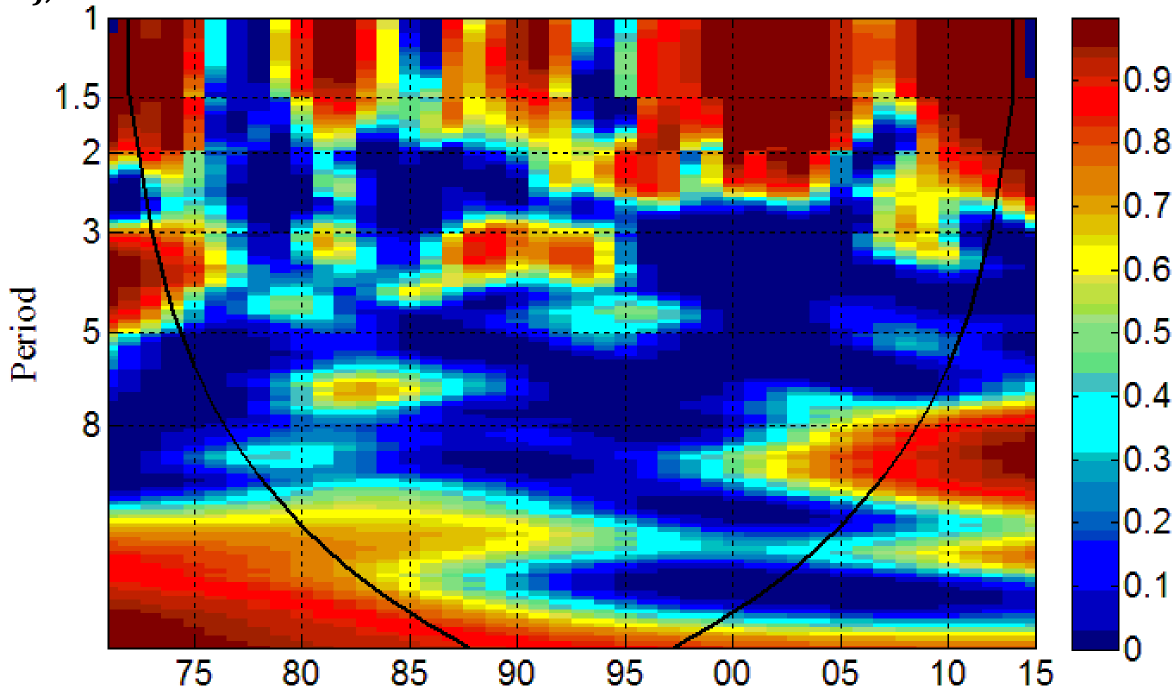


Figure 3.b: 1~ 2 frequency band, 1971-2014

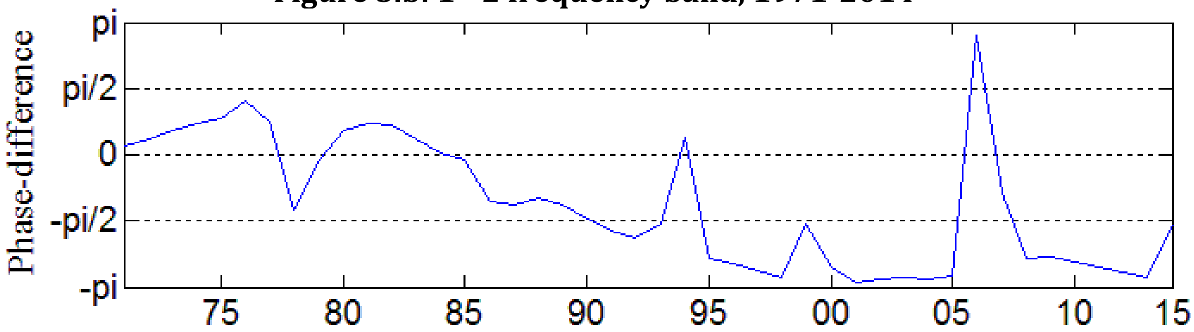


Figure 3.c: 2~ 4 frequency band, 1971-2014

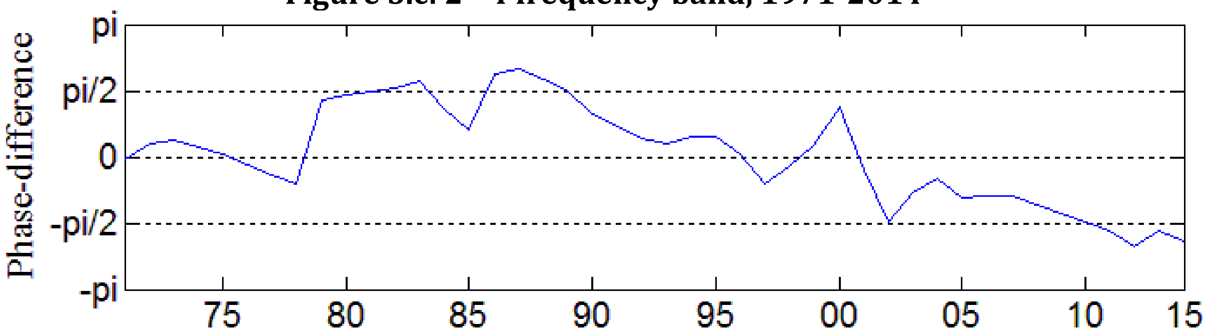


Figure 3.d: 1~ 3 frequency band, 1971-2014

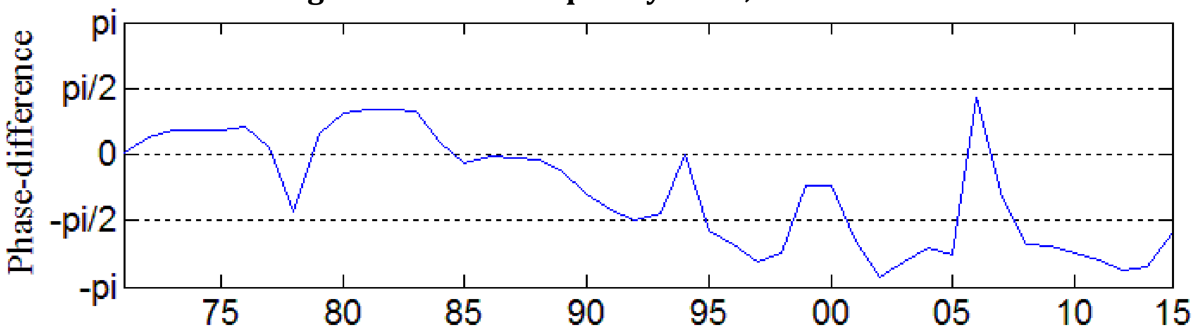
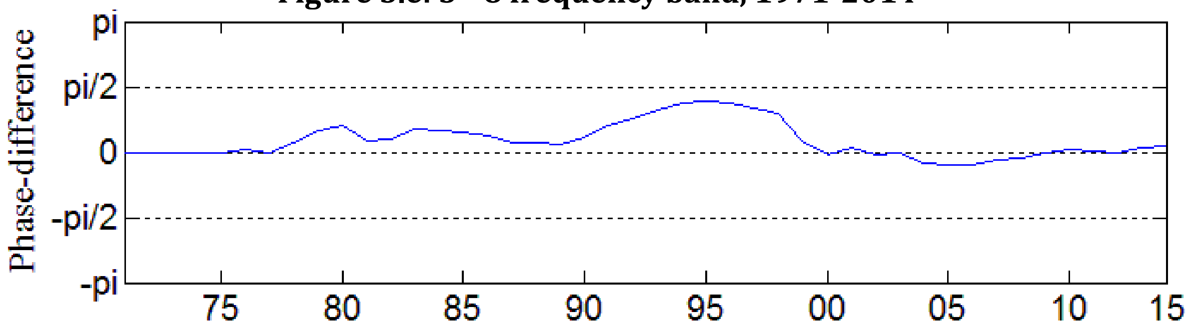
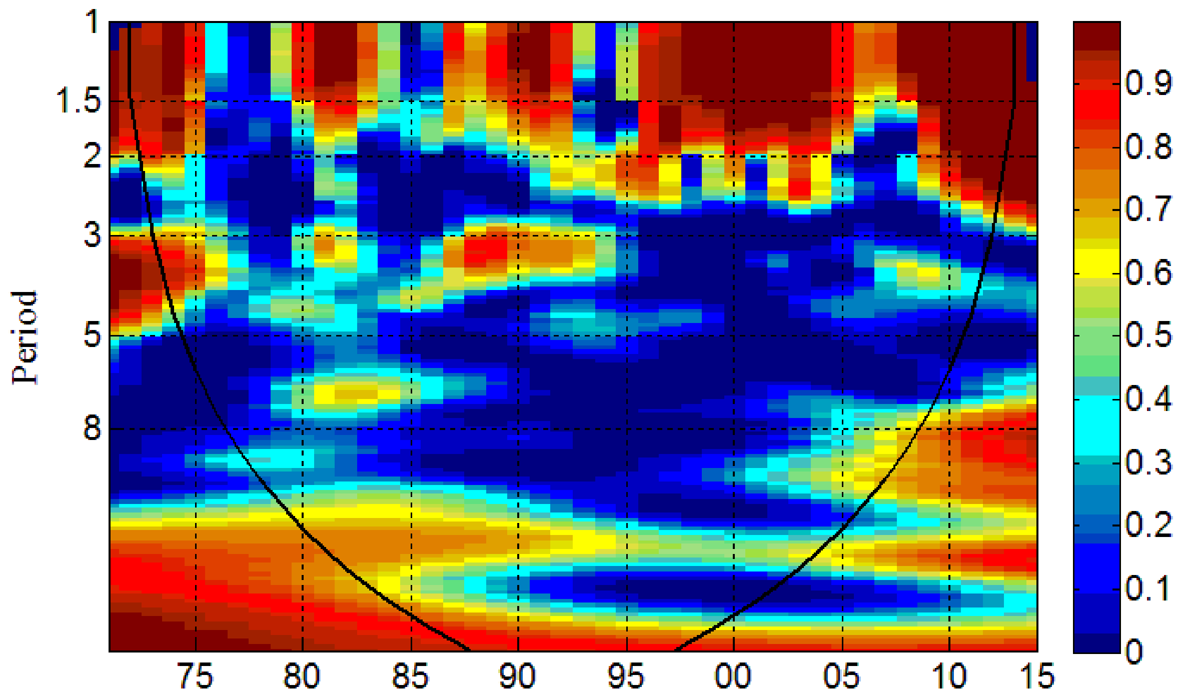


Figure 3.e: 3~ 8 frequency band, 1971-2014



The Figure 3.a, eventually, indicates the strong coherencies between oil price and CO2 emissions with the control variables of World oil price and fossil fuel consumption. The Figures 3b-3e reveal the phase differences underlying the fact that the negative significant impact of oil price on CO2 emissions in China become more apparent in short cycles (high frequencies). The Chinese oil prices influence the CO2 emissions negatively during 1995-2005 and 2007-2014 according to Figure 3b depicting phase differences at 1~ 2 frequency band. The Figure 3.e, on the other hand, indicates that there exist positive co-movements between oil price and emissions from 1977 to 2000 as oil price is leading. One might, however, not consider this output significant, since there is no strong association between oil price and the emissions for the period 1975-2003 at 3~ 8 frequency band as is indicated in Figure 3.a.

Figure 4.a: Wavelet partial coherency (Oil price, CO2 total || World oil price, Renewables), 1971-2014



The output of Figure 4.a confirms the output of Figure 3.a. Although Figure 4.a and Figure 3.a look like similar, with thorough investigation, one may depict that the explanatory power of fuel oil consumption at 2.5-year frequency and 8-year frequency (Figure 3.a) is slightly greater than that of renewables consumption at same frequencies (Figure 4.a). The main interpretation, however, about the short run and long run causality from oil price to carbon emissions has not changed. The real oil price changes affect the CO2 emissions reversely at higher frequencies and do not influence much the emissions significantly at higher periods (lower frequencies) in China.

Figures 4b, 4c, 4d and 4e plot the partial phase differences obtained from wavelet partial coherence analyses to observe the co-movements of the variables at the same or opposite direction(s) and yield that oil price leads CO2 emissions and increase in oil price diminishes the emissions at 1-2-year frequency between 1995 and 2005 between 2007 and 2014 and at 1-3-year frequency during 1995 and 2005 and 2007-2010.

The negative effect of oil price on emissions emerges at longer time horizon with higher frequencies as its influence on carbon emissions gets weak in higher time periods (low frequencies).

Figure 4.b: 1~ 2 frequency band, 1971-2014

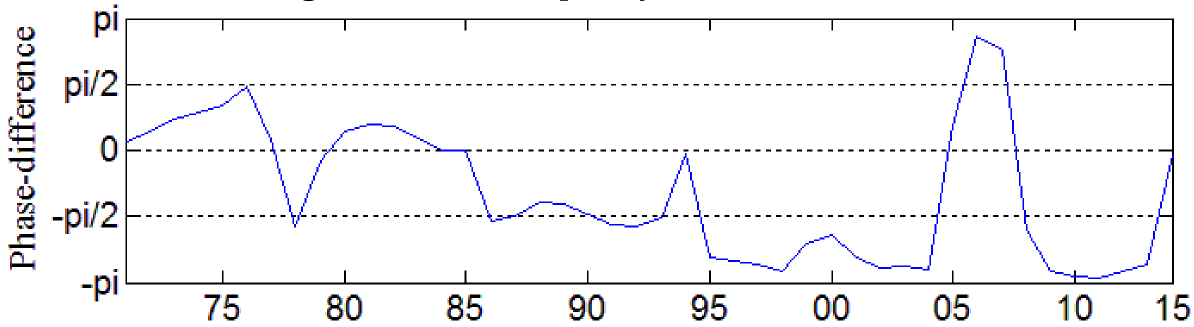


Figure 4.c: 2~ 4 frequency band, 1971-2014

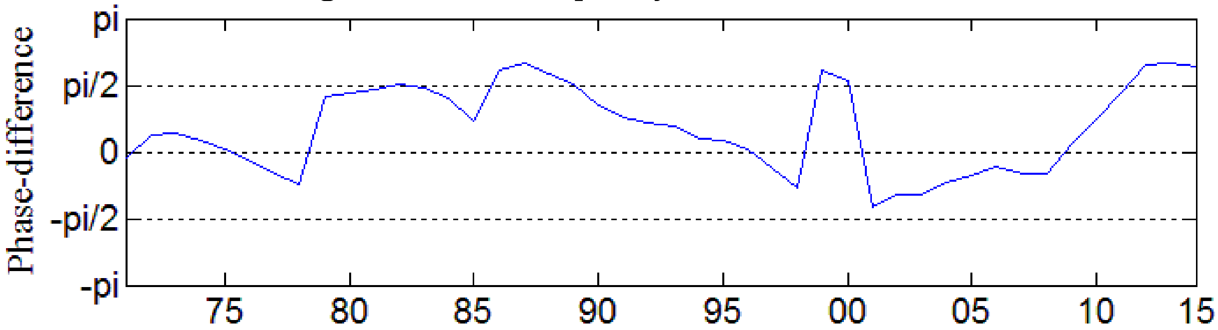


Figure 4.d: 1~ 3 frequency band, 1971-2014

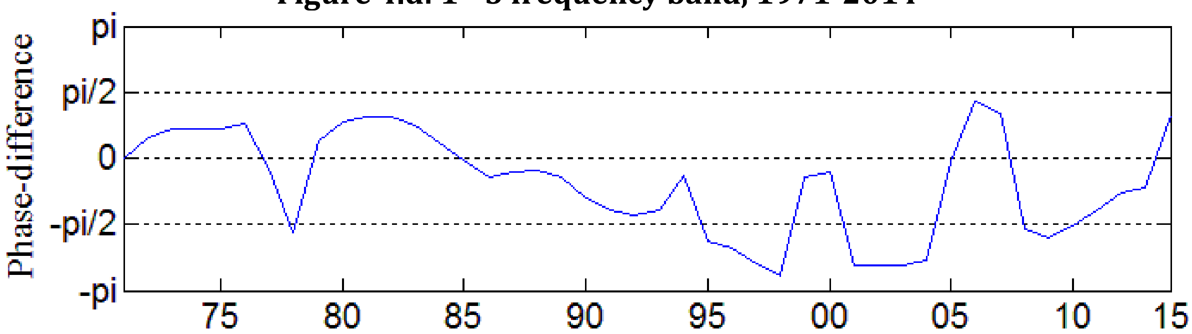
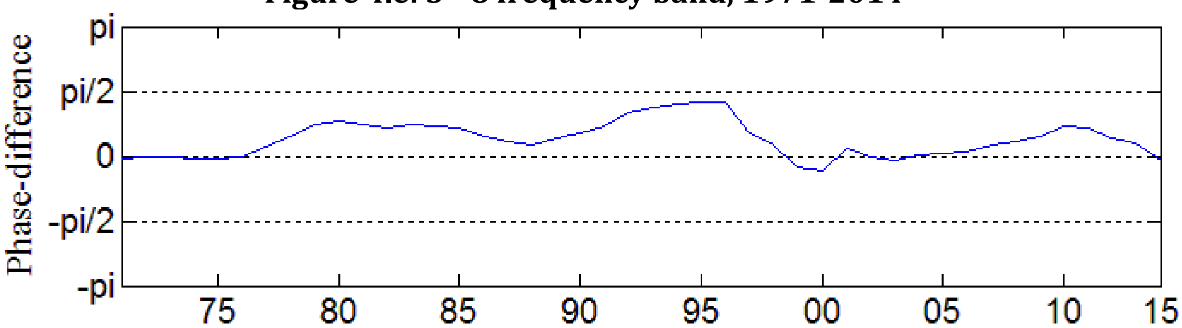
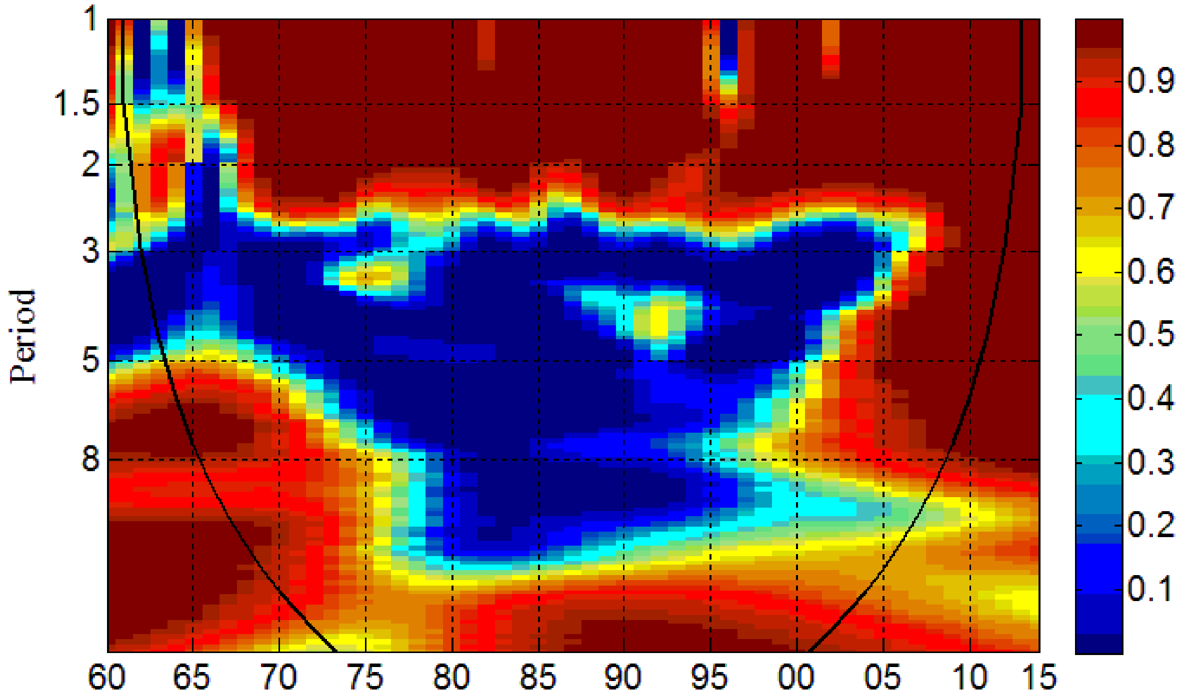


Figure 4.e: 3~ 8 frequency band, 1971-2014



Due to this weak coherency between oil price and CO2 emissions at 3-8-year cycles, we estimated a new model in which we can observe the possible co-movements of urban population and CO_2 emissions in China with the control variable of World oil price for the period 1960-2014.

Figure 5.a: Wavelet partial coherency (urban pop, CO2 total|| World oil price), 1960-2014



The Figure 5.a reveals the results that the urban population and CO_2 emissions have strong coherencies at both high and low frequencies. The energy demand by representative individual living urban areas in general tends to increase by following the average luxury life style and, hence brings about an immediate issue of potential increase in CO_2 emission as indicated by Sugihara and Tsuji (2008). Liu et al (2016) on the other hand underline the fact that the urban energy consumption, for instance, of Beijing in China, has been improved by decreasing the proportion of coal consumption and by increasing the proportion of natural gas consumption and other clean energies rose (Liu et al., 2016). The Figures 5.b and 5.c indicate that the urban population and CO_2 emissions tend to move together at same direction (positive correlation) at 1~ 3 frequency band and 3~ 8 frequency band during 1960-2014.

Figure 5.b: 1~ 3 frequency band, 1960-2014

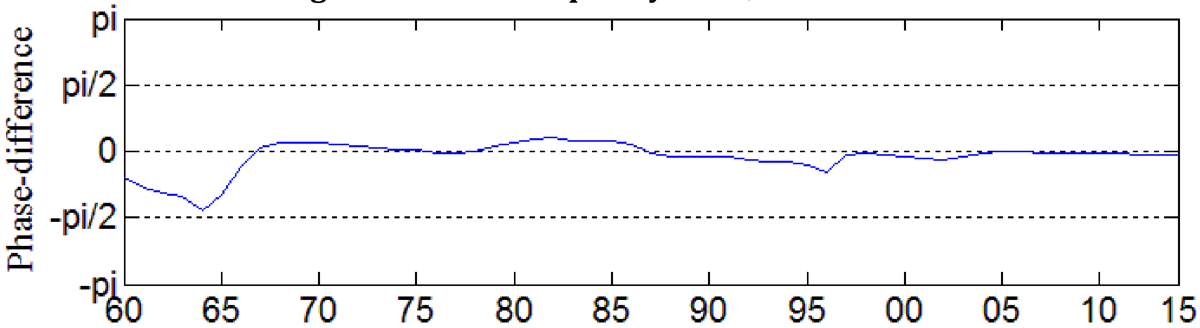
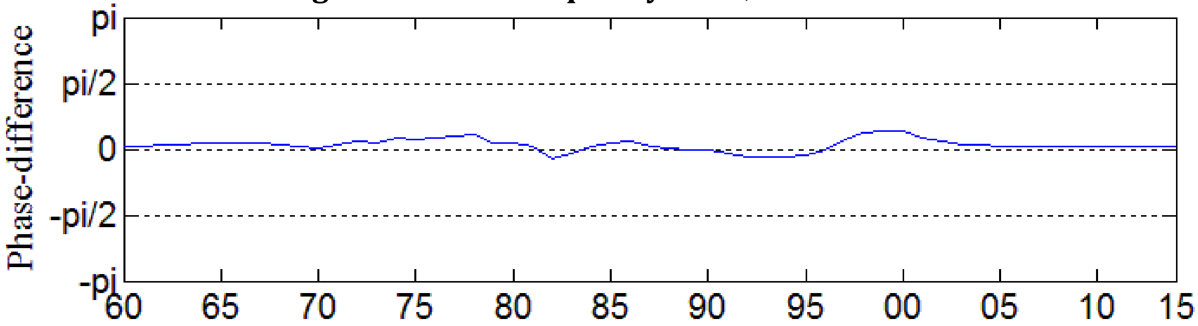


Figure 5.c: 3~ 8 frequency band, 1960-2014



This section of estimation output, hence, reveals two highlights. Firstly, the relative increase in oil price in China, in comparison with the World oil price, is an important factor that affects CO2 emissions negatively at shorter cycles (higher frequencies), secondly, the co-movements between urban population and emissions explore that they have positive correlation and move together.

The future possible researches on the determinants of CO2 emissions in China might need to consider other potential variables, such as clean energy prices, urbanization, ruralization, energy efficiency in urban and rural areas, awareness (schooling, media, researches, health expenditures due to environmental pollution etc.), as well as the oil price in China, World oil price, fossil energy consumption and renewables consumption in China.

5- Results, discussion and potential possible policy proposals

The estimation output of this paper yields two highlights. Firstly, the relative increase in oil price in China, in comparison with the World oil price, is an important factor that affects CO2 emissions negatively at shorter cycles (higher frequencies), secondly, the co-movements between urban population and emissions explore that they have positive correlation and move together.

By following the time domain and frequency domain analyses of this research, one may claim that the oil prices in China has considerable negative impact on CO2 emissions at high frequencies for the periods 1960-2014 and 1971-2014 in China. Besides, one may underline as well other important output of the research exploring that the urban population and CO2 emissions have positive associations, move together for the period 1960-2014 in China. Eventually, this paper might suggest that authorities follow demand side management policies considering energy demand behavior at both shorter cycles and longer cycles to diminish the CO2 emissions in China.

China accounts for the %80 of the global CO2 emissions increase since 2008 (Liu et al., 2013). As the largest energy-related carbon emitter country of the world, with a % 24 share of global GHG emissions, China's energy policies have a prominent role for achieving worldwide carbon emission targets (EPA 2016-b). By the ratification of Paris Agreement in 2015 adopted under the United Nations Framework Convention on Climate Change (UNFCCC), China pledges to reach its carbon emission peak until 2030, or earlier if possible, to drop carbon intensity of income by at least % 60 below 2005 levels by 2030 (according to Copenhagen Accord in 2009, China commits to reduce carbon intensity by %40 below 2005 levels by 2020) and increase the share of non-fossil energy sources to %20 in the total energy supply.

China has been implementing a series of minimum energy performance standards (MEPS), compulsory and voluntary energy labeling programs, carbon taxes for vehicles and introducing new strategic actions plans for energy development for over 25 years[6]. China imposes different tax rates for vehicles proportional to the size of vehicle engines since 1994. In 2008, this tax has been decreased to %1 in favor of engines of 1.0L and less and increased to between %25-%40 disfavor of cars with higher size engines. Besides Chinese government had differentiated energy prices for high energy-consuming industries for a limited time interval from 2004 to 2012 (Hu et al., 2012).

[6] For further information, please refer to IEA's policies and measures database and the following link. http://www.iea.org/policiesandmeasures/energyefficiency/?country=China

China improves its socio-economic targets with energy efficiency, transformation in energy mix, expansion on clean energy investments and more control on enterprises' energy consumption levels in the last 4 five-year plans on National Economic and Social Development. Although 10th five-year plan (2001-2005) established some objectives for renewable energy production by introducing income tax reductions and VAT exemptions for renewable energy projects, it did not set any future environmental or energy intensity target (IEA, 2017-a).

However 11th five-year plan (2006-2010) has revealed a target of reducing the energy intensity by an average of %4 per year, which is equivalent to %20 below 2005 levels compared to 2010 levels. Besides this plan has targeted to construct new wind farms with a total 100 Megawatts (MW) capacity and withdraw of old-fashioned inefficient and small coal-fired plants from energy production market (IEA, 2017-b). As a result of this action, the carbon emissions from Chinese electricity sector reached at its most likely peak, which is %40 of China's total GHG emissions in 2014, by falling use of coal (Fergus and Stern, 2015).

12th five-year economic development plan (2011-2015) highlights green development, environmental protection and energy conservation by incorporating required energy targets aiming to increase non-fossil energy consumption share to %11.4 of total primary energy consumption, reducing energy intensity by %16 and carbon intensity (CO2 emission per unit of income) by %15, by 2015 (IEA, 2017-c). Like the preceding development plan does, this plan also contains particular targets for improvement of renewable energy production by constructing additional capacities to hydro and wind power plants together with supporting research and development of clean and efficient energy production technologies. 13th and the last five-year economic development plan emphasizes on the regulation of top carbon emitting enterprises of China, and encourages those operate with efficient energy management and monitoring systems. According to this plan, China confirms that its total energy consumption will not exceed 3.375 billion metric tones of oil equivalent (or below 5 billion metric tones of coal equivalent)[7] (NDRC, 2016).

[7] 1 metric tones of coal equivalent = 0.675 metric tones of oil equivalent. China mostly converts its energy statistics into metrics tones of standard coal.

As a conclusion, until the 11th five-year plan (2006), China's energy efficiency targets were not presented and renewable energy policies were negligible and just the efficiency labeling standards and vehicle-carbon taxes were set (Halding et al., 2009). After 2006, energy efficiency targets (reduction of %20 and %16 by 2010 and 2015, respectively), investment subsidies on renewable energy technologies and minimum renewable energy production share target (at least %11.4 of total primary energy consumption by 2015) have given acceleration to the clean energy markets' expansion. Although coal consumption has predominantly the highest share in China's energy mix and is expected to remain for the near future (IEA, 2016), China successively reduces the carbon intensity of GDP by improving energy efficiency and diminishing use of coal in energy mix (Jotzo and Teng, 2014). Although China's energy-related emissions is growing (Boyd, 2012), China's abatement efforts improve fortunately the success probability of the world to achieve the 2°C climate target (Garnaut, 2014).

One may extend the discussion about the environmental, demographical facts, natural endowments, targets, achievements, endogenous and exogenous dynamics, obstacles, and environmental quality targeted in China considering mainly the adverse effect of residential and industrial demand for fossil energy on environmental quality/CO2 emissions. The future possible researches on the determinants of CO2 emissions in China might, hence, need to consider other potential variables, such as clean energy prices, urbanization, ruralization, energy efficiency in urban and rural areas, awareness (schooling, media, researches, health expenditures due to environmental pollution etc.), as well as the oil price in China, World oil price, fossil energy consumption and renewables consumption in China.

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Appendix:

Table A.1: Variables, codes, available periods

Variable	Code	Available Period
CO2 emissions (kt)	EN.ATM.CO2E.KT	1960-2014
CO2 emissions (metric tons per capita)	EN.ATM.CO2E.PC	1960-2014
Oil Price in China in $ 2016	BP/CRUDE_OIL_PRICES	1960-2014
Oil Price in the World in $ 2016	BP/CRUDE_OIL_PRICES	1960-2014
Combustible renewables and waste (% of total energy)	EG.USE.CRNW.ZS	1971-2014
Fossil fuel energy consumption (% of total)	EG.USE.COMM.FO.ZS	1971-2014
Urban population (% of total)	SP.URB.TOTL.IN.ZS	1960-2014
Population, total	SP.POP.TOTL	1960-2014

Source: World Bank, World Bank Indicator, https://data.worldbank.org/country/china, January, 2018

Figure A.1.a: Wavelet coherency (Oil price, CO2 per capita), 1960-2014

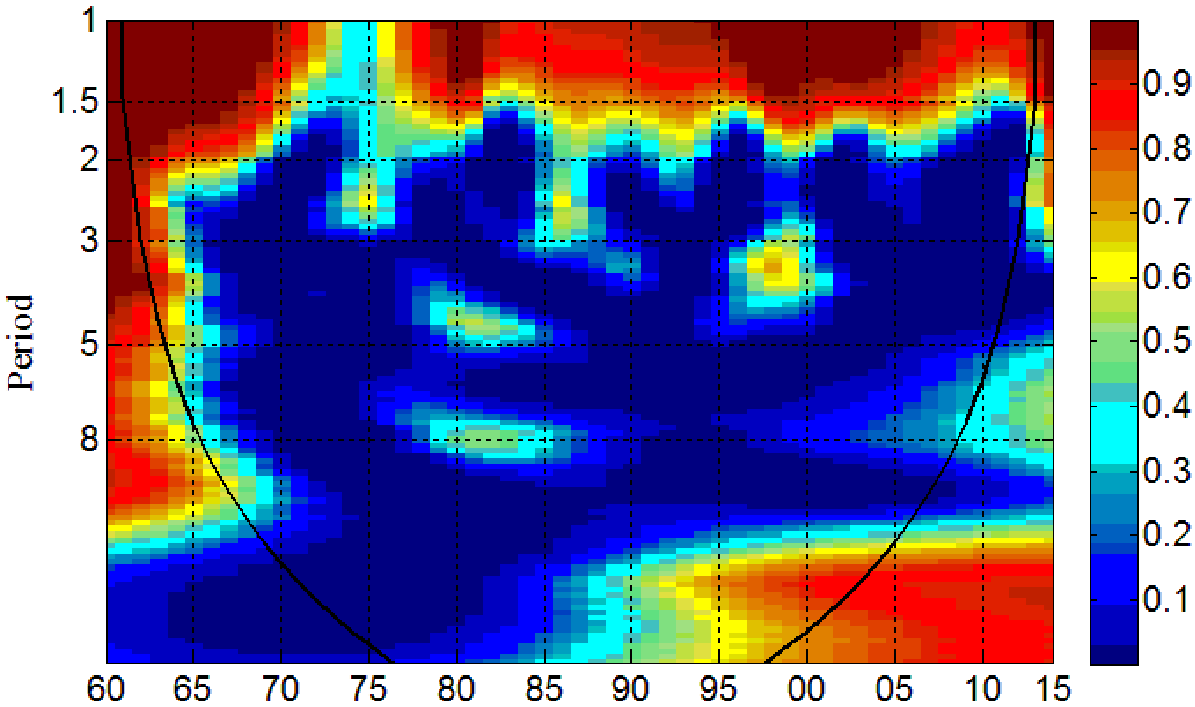

Figure A.1.b: 1~ 3 frequency band, 1960-2014

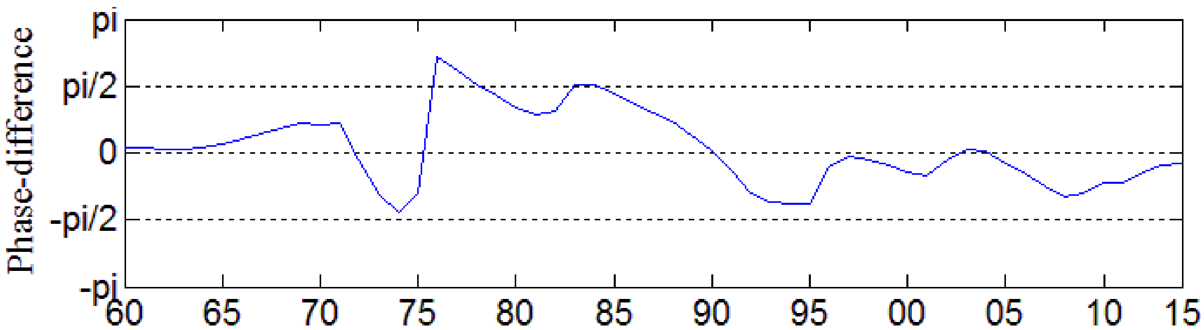

Figure A.1.c: 3~ 8 frequency band, 1960-2014

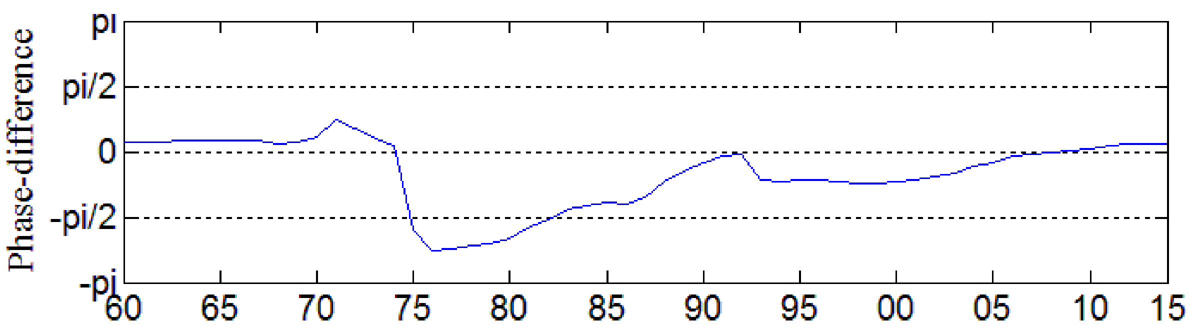

Figure A.2.a: Wavelet partial coherency (Oil price, CO2 per capita|| World oil price), 1960-2014

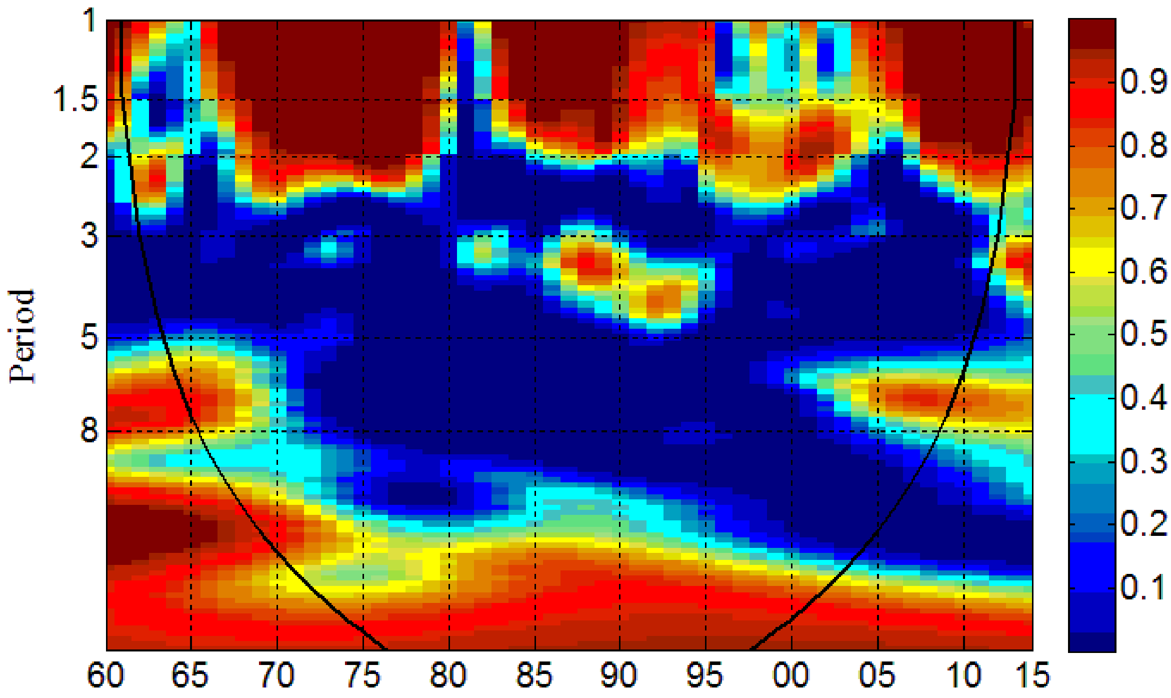

Figure A.2.b: 1~ 3 frequency band, 1960-2014

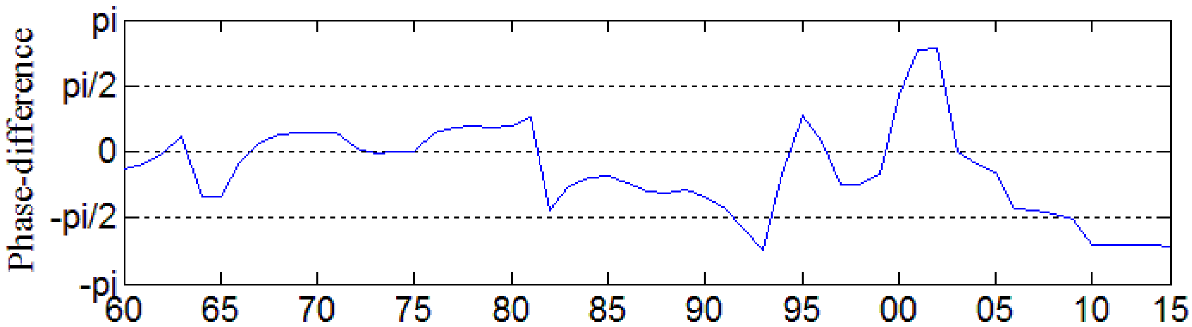

Figure A.2.c: 3~ 8 frequency band, 1960-2014