Title

A Spectral Analysis of World GDP Dynamics: Kondratieff Waves, Kuznets Swings, Juglar and Kitchin Cycles in Global Economic Development, and the 2008–2009 Economic Crisis

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Introduction

A Russian economist writing in the 1920s, Nikolai Kondratieff observed that the historical record of some economic indicators then available to him appeared to indicate a cyclic regularity of phases of gradual increases in values of respective indicators followed by phases of decline (Kondratieff 1922: Chapter 5; 1925, 1926, 1935, 2002); the period of these apparent oscillations seemed to him to be around 50 years. This pattern was found by him with respect to such indicators as prices, interest rates, foreign trade, coal and pig iron production (as well as some other production indicators) for some major Western economies (first of all England, France, and the United States), whereas the long waves in pig iron and coal production were claimed to be detected since the 1870s for the world level as well[1].

Among important Kondratieff predecessors one should mention J. van Gelderen (1913), M. A. Buniatian (1915), and S. de Wolff (1924) (see, *e.g.*, Tinbergen 1981). One can also mention William Henry Beveridge (better known, perhaps, as Lord Beveridge, the author of the so-called Beveridge Report on Social Insurance and Allied Services of 1942 that served after the 2nd World War as the basis for the British Welfare State, especially the National Health Service), who discovered a number of cycles in the long-term dynamics of wheat prices, whereas one of those cycles turned to have an average periodicity of 54 years (Beveridge 1921, 1922). Note that the results of none of the above mentioned scientists were known to Kondratieff at the time of his discovery of long waves (see, *e.g.*, Kondratieff 1935: 115, note 1).

Kondratieff himself identified the following long waves and their phases (see Table 1):

[1] Note that as regards the production indices, during decline/downswing phases we are dealing with the slowdown of production growth rather than with actual production declines that rarely last longer than 1–2 years, whereas during the upswing phase we are dealing with a general acceleration of the production growth rates in comparison with the preceding downswing/slowdown period – see, *e.g.*, Modelski and Thompson 1996; Thompson 2000: 11; Rennstich 2002: 155; Modelski 2006: 295, who prefer quite logically to designate "decline/ downswing" phases as "phases of take-off" (or innovation), whereas the upswing phases are denoted by them as "high growth phases", *e.g.*, Thompson 2000: 11; Rennstich 2002: 155; Modelski 2001: 76; 2006: 295.

Table 1. Long Waves and Their Phases Identified by Kondratieff

Long wave number	*Long wave phase*	*Dates of the beginning*	*Dates of the end*
One	A: upswing	"The end of the 1780s or beginning of the 1790s"	1810–1817
	B: downswing	1810–1817	1844–1851
Two	A: upswing	1844–1851	1870–1875
	B: downswing	1870–1875	1890–1896
Three	A: upswing	1890–1896	1914–1920
	B: downswing	1914–1920	

The subsequent students of Kondratieff cycles identified additionally the following long-waves in the post-World War 1 period (see Table 2):

Table 2. "Post-Kondratieff" Long Waves and Their Phases

Long wave number	*Long wave phase*	*Dates of the beginning*	*Dates of the end*
Three	A: upswing	1890–1896	1914–1920
	B: downswing	From 1914 to 1928/29	1939–1950
Four	A: upswing	1939–1950	1968–1974
	B: downswing	1968–1974	1984–1991
Five	A: upswing	1984–1991	2008–2010?
	B: downswing	2008–2010?	?

Sources: Mandel 1980; Dickson 1983; Van Duijn 1983: 155; Wallerstein 1984; Goldstein 1988: 67; Modelski, Thompson 1996; Bobrovnikov 2004: 47; Pantin, Lapkin 2006: 283–285, 315; Ayres 2006; Linstone 2006: Fig. 1; Tausch 2006: 101–104; Thompson 2007: Table 5. Jourdon 2008: 1040–1043. The last date is suggested by the authors of the present paper. It was also suggested earlier by Lynch 2004; Pantin, Lapkin 2006: 315; see also Akaev 2009.

A considerable number of explanations for the observed Kondratieff wave (or just K-wave [Modelski, Thompson 1996; Modelski 2001]) patterns have been proposed. As at the initial stage of K-wave research the respective pattern was detected in the most secure way with respect to price indices (see below), most explanations proposed during this period were monetary, or monetary-related. For example, K-waves were connected with the inflation shocks caused by major wars (*e.g.*, Åkerman 1932; Bernstein 1940; Silberling 1943, *etc.*). Note that in recent decades such explanations went out of fashion, as the K-wave pattern ceased to be traced in the price indices after the 2nd World War (*e.g.*, Goldstein 1978: 75; Bobrovnikov 2004: 54).

Kondratieff himself accounted for the K-wave dynamics first of all on the basis of capital investment dynamics (Kondratieff 1928, 1984, 2002: 387–397). This line was further developed by Jay W. Forrester and his colleagues (see, *e.g.*, Forrester 1978, 1981, 1985; Senge 1982 *etc.*), as well as by A. Van der Zwan (1980), Hans Glisman, Horst Rodemer, and Frank Wolter (1983) *etc.*

However, in the recent decades the most popular explanation of K-wave dynamics was the one connecting them with the waves of technological innovations.

Already Kondratieff noticed that "during the recession of the long waves, an especially large number of important discoveries and inventions in the technique of production and communication are made, which, however, are usually applied on a large scale only at the beginning of the next long upswing" (Kondratieff 1935: 111, see also, *e.g.*, 2002: 370–374).

This direction of reasoning was used by Schumpeter (1939) to develop a rather influential "cluster-of-innovation" version of K-waves' theory, according to which Kondratieff cycles were predicated primarily on discontinuous rates of innovation (for more recent developments of the Schumpeterian version of K-wave theory see, *e.g.* Mensch 1979; Dickson 1983; Freeman 1987; Tylecote 1992; Glazyev 1993; Maevskiy 1997; Modelski, Thompson 1996; Modelski 2001, 2006; Yakovets 2001; Ayres 2006; Dator 2006; Hirooka 2006; Papenhausen 2008; for the most recent presentation of empirical evidence in support of Schumpeter's cluster-of-innovation hypothesis see Kleinknecht, van der Panne 2006). Within this approach every Kondratieff wave is associated with a certain leading sector (or leading sectors), technological system or technological style. For example the third Kondratieff wave is sometimes characterized as "the age of steel, electricity, and heavy engineering[2]. The fourth wave takes in the age of oil, the automobile and mass production[3]. Finally, the current fifth wave is described as the age of information and telecommunications[4]" (Papenhausen 2008: 789); whereas the forthcoming sixth wave is sometimes supposed to be connected first of all with nano- and biotechnologies (*e.g.*, Lynch 2004; Dator 2006).

There were also a number of attempts to combine capital investment and innovation theories of K-waves (*e.g.*, Rostow 1975, 1978; Van Duijn 1979, 1981, 1983; Akaev 2009 *etc.*). Of special interest is the Devezas – Corredine model

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[2] Or, *e.g.*, "steel, chemicals, and electric power" according to Modelski and Thompson 1996; see also Thompson 2000: 11 and Rennstich 2002: 155.

[3] Or, *e.g.*, "motor vehicles, aviation, and electronics" according to Modelski and Thompson 1996; see also Thompson 2000: 11 and Rennstich 2002: 155.

[4] Or, *e.g.*, "ICT and networking" according to Modelski and Thompson 1996; see also Thompson 2000: 11 and Rennstich 2002: 155.

based on biological determinants (generations and learning rate) and information theory that explains (for the first time) the characteristic period (50–60 years) of Kondratieff cycles (Devezas, Corredine 2001, 2002; see also Devezas, Linstone, Santos 2005).

Note that many social scientists consider Kondratieff waves as a very important component of the modern world-system dynamics. As has been phrased by one of the most important K-wave students, "long waves of economic growth possess a very strong claim to major significance in the social processes of the world system. Long waves of technological change, roughly 40–60 years in duration, help shape many important processes… They have become increasingly influential over the past thousand years. K-waves have become especially critical to an understanding of economic growth, wars, and systemic leadership... But they also appear to be important to other processes such as domestic political change, culture, and generational change. This list may not exhaust the significance of Kondratieff waves but it should help establish an argument for the importance of long waves to the world's set of social processes" (Thompson 2007).

Against this background it appears rather significant that the evidence on the very presence of the Kondratieff waves in the world dynamics remains rather controversial.

The presence of K-waves in price dynamics (at least till the 2nd World War) has found a very wide empirical support (see, *e.g.*, Gordon 1978: 24; Van Ewijk 1981; Cleary, Hobbs 1983 *etc.*). However, as has been mentioned above, the K-wave pattern ceased to be traced in the price indices after the 2nd World War (*e.g.*, Goldstein 1988: 75; Bobrovnikov 2004: 54).

As regards long waves in production dynamics, here we shall restrict ourselves to the analysis of the evidence on the presence of K-waves in the world production indices only. Note that as Kondratieff waves tend to be considered as an important component of the world-system social and economic dynamics, one would expect to detect them with respect to the major world macroeconomic indicators, and first of all with respect to the world GDP dynamics (Chase-Dunn, Grimes 1995: 405–411). Until now, however, the attempts to detect them in the world GDP (or similar indicators') dynamics record have brought rather controversial results.

As has been mentioned above, Kondratieff himself claimed to have detected long waves in the dynamics of world production of coal and pig iron (*e.g.*, 1935: 109–110). However, his evidence on the presence of long waves in these series (as well as in all the production dynamics series on national levels) was criticized most sharply:

> "Foremost among the methodological criticisms have been those directed against Kondratieff's use of trend curves. Kondratieff's method is first to fit a long-term trend to a series and then to use moving averages to bring out long waves in the residuals (the fluctuations around the trend curve). But 'when he eliminated the trend, Kondratieff failed to formulate clearly what the trend stands for' (Garvy 1943: 209). The equations Kondratieff uses for these long-term trend curves… include rather elaborate (often cubic) functions[5]. This casts doubt on the theoretical meaning and parsimony of the resulting long waves, which cannot be seen as simple variations in production growth rates" (Goldstein 1988: 82; see also, *e.g.*, Barr 1979: 704; Eklund 1980: 398–399, *etc.*).

Later, however, quite a few scientists presented new evidence supporting the presence of long waves in the dynamics of the world economic indicators. For example, Mandel (1975: 141; 1980: 3) demonstrated that, in a full accordance with Kondratieff's theory, during Phases A of K-cycles the annual compound growth rates in world trade were on average significantly higher than within adjacent Phases B during the period between 1820 and 1967. Similar results were arrived at by David M. Gordon (1978: 24) with respect to the world per capita production for 1865–1938 on the basis of the world production data from Dupriez (1947, 2: 567), by Thomas Kuczynski (1982: 28) with respect to the world industrial dynamics (for 1830–1980) and for the average growth rates of the world economy (1978:86) for 1850–1977; similar results were obtained by Joshua Goldstein (1988: 211–217).

Of special interest are the works by Marchetti and his co-workers at the International Institute for Advanced System Analysis who have shown extensively the evidence of K-waves using physical indicators, as for instance energy consumption, transportation systems dynamics, *etc.* (Marchetti 1980, 1986, 1988 *etc.*).

Note also that Arno Tausch claims to have detected K-waves in the world industrial production growth rates dynamics using polynomial regression methods (Tausch 2006a: 167–190). However, empirical tests produced by a few other scholars failed to support the hypothesis of the K-waves' presence in the world production dynamics (see *e.g.*, Van der Zwan 1980: 192–197; Chase-Dunn, Grimes 1995: 407–409, reporting results of Peter Grimes' research).

There were a few attempts to apply spectral analysis in order to detect the presence of K-waves in the world production dynamics. Thomas Kuczynski (1978) applied spectral analysis in order to detect K-waves in world agricultural production, total exports, inventions, innovations, industrial production, and total production for the period between 1850 and 1976. Though Kuszynski suggests

[5] For example for the trend of English lead production the function used by Kondratieff looks as follows: y = 10^(0.0278 – 0.0166x – 0.00012x^2).

that his results "seem to corroborate" the K-wave hypothesis, he himself does not find this support decisive and admits that "we cannot exclude the possibility that the 60-year-cycle… is a random cycle" (1978: 81–82); note that Kuszynski did not make any formal test of statistical significance of the K-waves tentatively identified by his spectral analysis. K-waves were also claimed to have been found with spectral analysis by Rainer Metz (1992) both in GDP production series on eight European countries (for the 1850–1979 period) and in the world production index developed by Hans Bieshaar and Alfred Kleinknecht (1984) for 1780–1979; however, later he renounced those findings (Metz 1998, 2006).

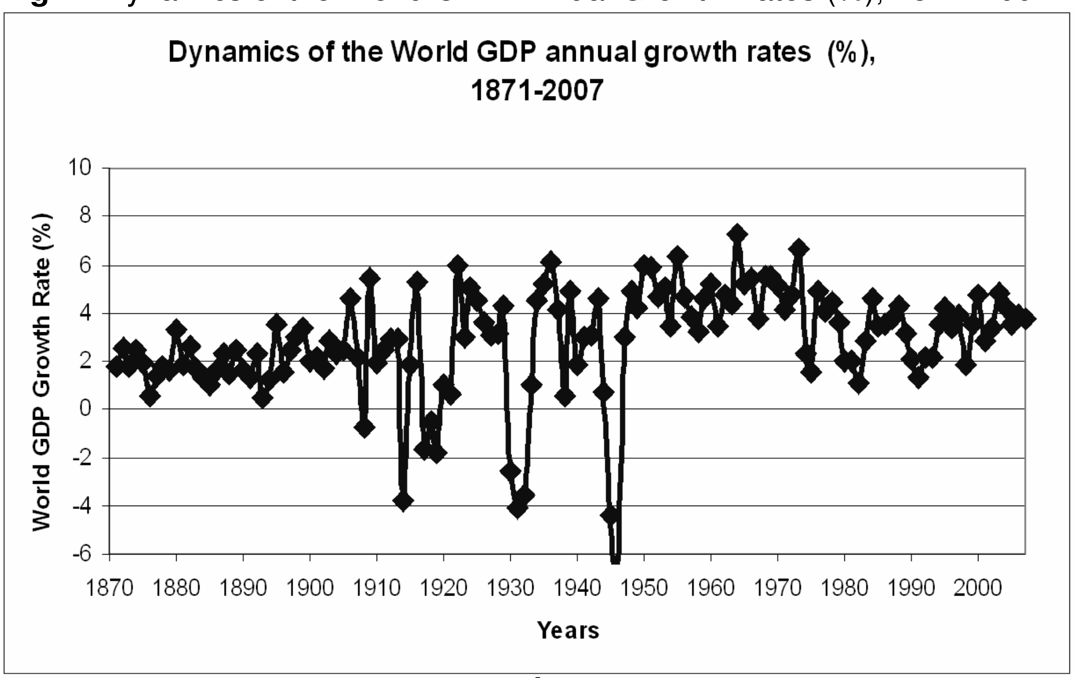
Note also that a few scientists have failed to detect through a spectral analysis K-waves in production series on national levels of quite a few countries (*e.g.*, Van Ewijk 1982; Metz 1998, 2006; Diebolt, Doliger 2006, 2008).

Spectral analysis

Against this background we have found it appropriate to check the presence of K-waves in the world GDP dynamics using the most recent datasets on GDP growth rates' dynamics covering the period between 1870 and 2007 (Maddison 1995, 2001, 2003, 2009; World Bank 2009*a*; for more detail see Appendix 2).

At the first stage of this research we performed a spectral analysis of the initial series of rates of the world annual GDP growth rates presented in Fig. 1:

Fig. 1. Dynamics of the World GDP Annual Growth Rates (%), 1871–2007



It is easy to see that the turbulent 2nd – 4th decades of the 20th century are characterized by enormous magnitude of fluctuations of the world GDP growth rates (not observed either in the previous or subsequent periods). On the one hand, the lowest (for 1871–2007) figures of the world GDP annual rates of change are observed just in these decades (during the Great Depression, World Wars 1 and 2 as well as immediately after the end of those wars). On the other hand, during the mid-20s and mid-30s booms the world GDP annual growth rates achieved historical maximums (they were only exceeded during the K-wave 4 Phase A, in the 1950s and 1960s, and were generally higher than during both the pre-World War 1 and recent [1990s and 2000s] upswings).[6] This, of course, complicates the detection of the long-wave pattern for 1914–1946.

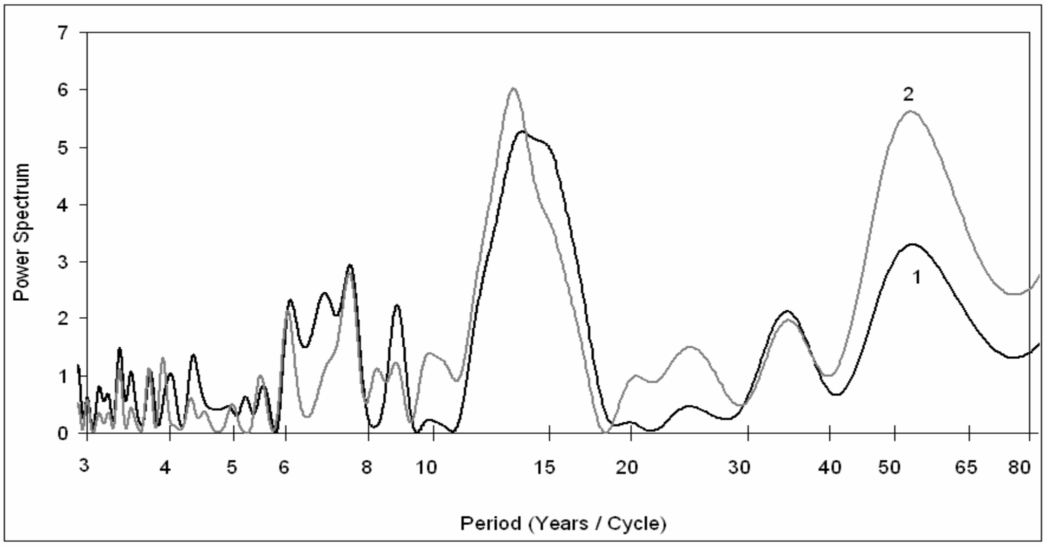
Because of this, following Rainer Metz (1992) we also have investigated the corrected series of the annual GDP growth rates with excluded periods of the world wars and first post-war years (1914–1919, 1939–1946). In order to retain intact postwar values of GDP, the actual values of GDP growth rates were replaced with geometric means; thus for the 1914–1919 period $r_{WW1} = ((GDP_{1919} - GDP_{1913})^{1/6} - 1)*100\% = -0.145\%$ and for the 1939–1946 period $r_{WW2} = ((GDP_{1946} - GDP_{1939})^{1/7} - 1)*100\% = 0.745\%$.

Hence, below Fig. 2A shows the power spectra of these GDP growth rates with the initial series (1) and the series with values for the world war periods replaced with geometric means (2); Fig. 2B shows the power spectra of these GDP growth rates with the series with values for the whole 1914–1946 period replaced with geometric means (1), and with an average of distribution (2); whereas Fig. 2C and Fig. 2D show the reduced spectra for the four series in Fig. 2A and Fig. 2B, using the methods of Appendix 1:

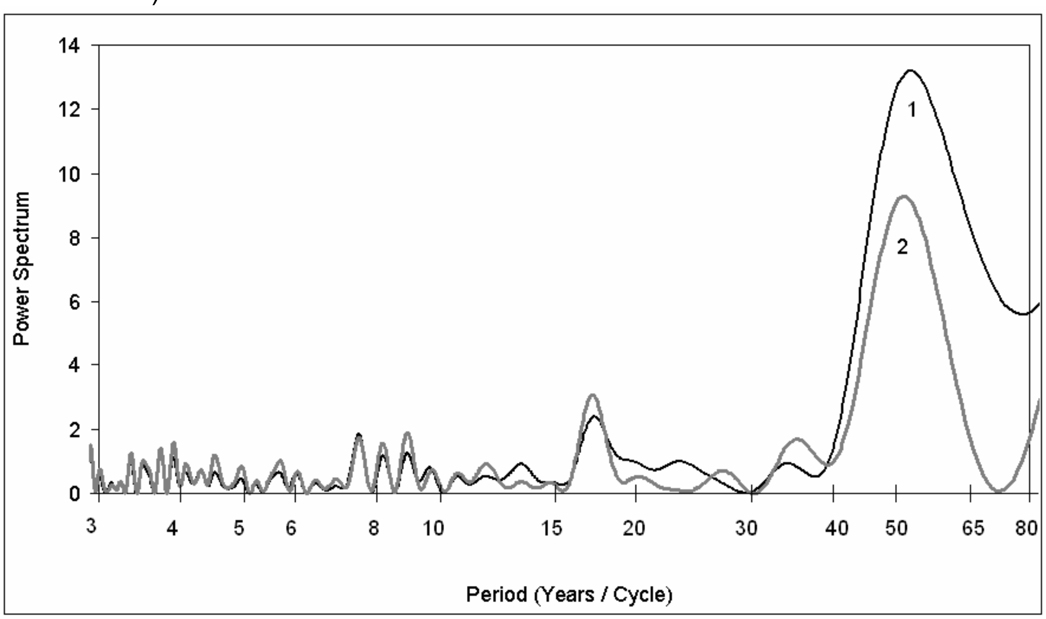
[6] For mathematical models describing general trends of the world GDP dynamics see, *e.g.*, Korotayev, Malkov, Khaltourina 2006a, 2006b; Korotayev, Khaltourina 2006; Korotayev 2007.

Fig 2. Power Spectra

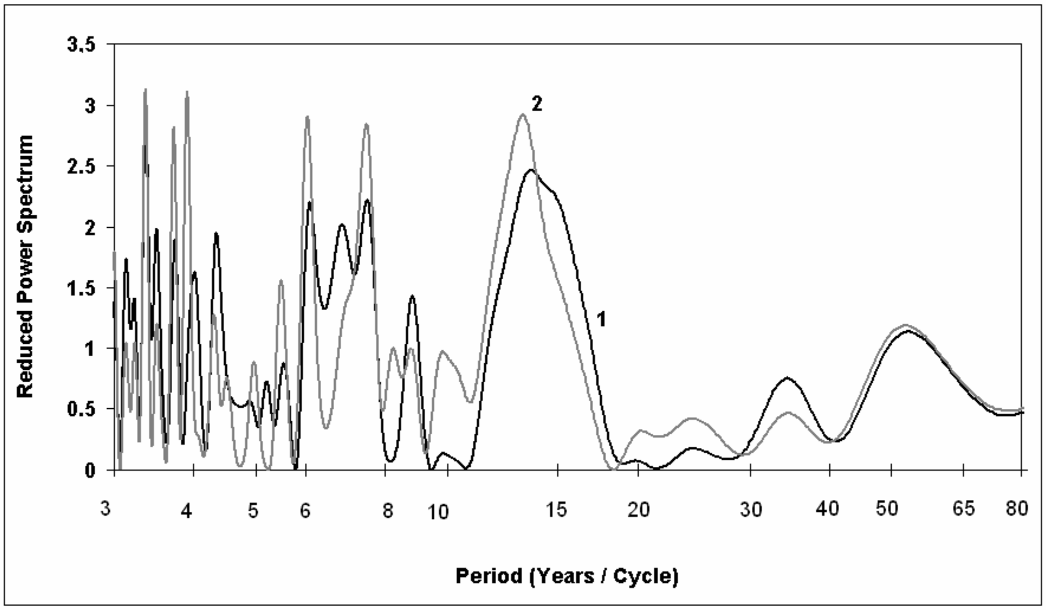
A. Power spectra of the initial series (1) and the series with corrected values for the world war periods (2)



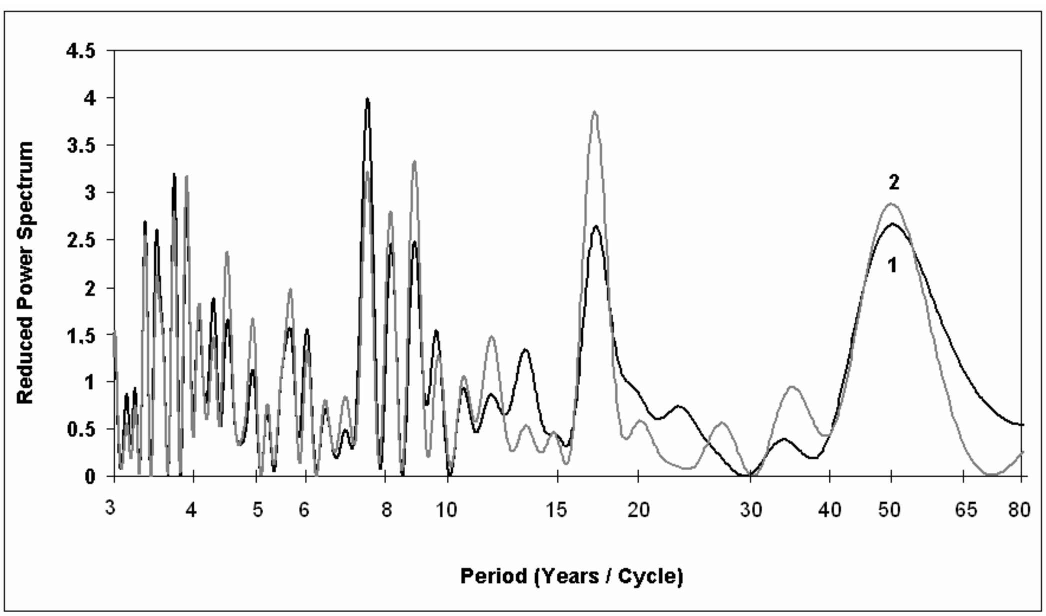
B. Power spectra for series with excluded values for 1914–1946 (1 – replacement with geometric means, 2 – replacement with an average of distribution)



C. Reduced spectra for spectra 1 and 2 of Fig. 2A, excluding the autocorrelation



D. Reduced spectra for spectra 1 and 2 of Fig. 2B (with excluded values for 1914–1946)



As is easily seen in Fig. 2A in both spectra one can detect distinctly the Kondratieff cycle (its period equals approximately 52–53 years), however, the cycle with a period of 13–15 years is detected even more distinctly. In the study by Claude Diebolt and Cédric Doliger (2006, 2008) this wave is tentatively identified with Kuznets "swings".[7] However, these are approximately such periods of time that separate World War I from the Great Depression or the Great Depression and World War II, with which the largest variations in Fig. 1 are connected (the replacement of actual values with geometric means does not eliminate collapses; it only makes them less salient and more stretched in time). That is why the second possible source of such cycles can be identified with the huge variations of the world GDP in the years of world wars and interwar years. Note that, in addition to Kuznets swings, our spectral analysis also detects a rather salient presence of economic cycles with periods of 6–8 and 3–4 years that can be tentatively identified with, respectively, Juglar and Kitchin cycles. Those cycles will be discussed in more detail in the next section.

Kondratieff waves, Kuznets swings, Juglar and Kitchin cycles

The **Kitchin** cycles (with a period between 40 and 59 months) are believed to be manifested in the fluctuations of enterprises' inventories. "The logic of this cycle can be described in a rather neat way through neoclassical laws of market equilibrium and is accounted for by time lags in information movements affecting the decision making of commercial firms. As is well known, in particular, firms react to the improvement of commercial situation through the increase in output through the full employment of the extent fixed capital assets. As a result, within a certain period of time (ranging between a few months and two years) the market gets 'flooded' with commodities whose quantity becomes gradually excessive. The demand declines, prices drop, the produced commodities get accumulated in inventories, which informs entrepreneurs of the necessity to reduce output. However, this process takes some time" (Rumyantseva 2003: 23–24). It takes some time for the information that the supply exceeds significantly the demand to get to the businessmen. Further it takes entrepreneurs some time to check this information and to make the decision to reduce production, some time is also necessary to materialize this decision (these are the time lags that generate the Kitchin cycles). Another relevant time lag is the lag between the materialization of the above mentioned decision (causing the capital assets to work well below the level of their full employment) and the decrease of the excessive amounts of

[7] Estimates of the length of Kuznet cycles will vary: here, 13–15 years but we note below estimates by others of 15–25 and later give our own estimate of 17–18 which agrees rather well with the original Kuznets' estimate.

commodities accumulated in inventories. Yet, after this decrease takes place one can observe the conditions for a new phase of growth of demand, prices, output, *etc.* (Kitchin 1923; Van Duijn 1983: 9; Rumyantseva 2003: 23–24).

The best known economic cycles (with a period ranging from 7 to 11 years) that are typical for modern industrial and postindustrial economies (known also as *business cycles*) are named after the French economist Clement **Juglar** who was one of the first to discover and describe those cycles (Juglar 1862; Grinin, Korotayev 2010; Grinin, Korotayev, Malkov 2010). "One should take into consideration the point that within the *business cycle* (with a period between 7 and 11 years) one can observe the investment into fixed capital (including the renovation of production machinery) and not just changes in the level of employment of the fixed capital. Thus, the Kitchin cycles are generated first of all by the market information asymmetries" (Rumyantseva 2003: 24), whereas with respect to the Juglar cycle "the first place is occupied by the investment and innovation aspects" (Rumyantseva 2003: 24). This adds one more time lag. Indeed, during the early years of the upswing phase of Juglar cycles the excess of demand over supply is so great that it cannot be met just by the full employment of the extent fixed capital, which makes it necessary to create new capital assets through increasing investments. The decline of demand affects output with some time lag even when the output growth was achieved through the increase in the employment of extent capital assets. However, the time lag will be significantly greater when the output growth is achieved through the investment in the fixed capital – it is much more difficult to stop the construction of a half-built factory than to decrease the production in an extent factory (on the other hand, it is much faster to increase the output through the increase in capacity utilization in an extent factory [especially, when, say, half of those capacities are not used] than to achieve this through a construction of a new factory). Correspondingly, the period of Juglar cycles is significantly longer than the one of Kitchin cycles (see Grinin, Korotayev, Malkov 2010 for more detail).

One more type of economic cycles (its period is identified by various students in the range between 15 and 25 years) is named after Nobel laureate Simon Kuznets who first discovered and described them (Kuznets 1930; Abramovitz 1961) and are known as **Kuznets swings** (see, *e.g.*, Abramovitz 1961: 226; Solomou 1989; Diebolt, Doliger 2006, 2008). Kuznets himself first connected these cycles with demographic processes, in particular with immigrant inflows/outflows and the changes in construction intensity that they caused, that is why he denoted them as "demographic" or "building" cycles/swings. However, there is a number of more general models of Kuznets swings. For example, Forrester suggested to connect Kuznets swings with major investments in fixed capital, whereas he accounted for the Kondratieff waves through the economic and physical connections between the capital producing and capital consuming sectors (Forrester 1977: 114; Rumyantseva 2003: 34–35). Note also the interpretation of Kuznets swings as *infrastructural investment cycles* (*e.g.*, Shiode *et al*. 2004: 355).

Note that a number of influential economists deny the presence of any economic cycles altogether (the title of the respective section in a classical *Principles of Economics* textbook by N. Gregory Mankiw[8] – "Economic Fluctuations Are Irregular and Unpredictable" [Mankiw 2008: 740] is rather telling in this respect; see also, *e.g.*, Zarnowitz 1985: 544–568). Hence, one of the aims of our spectral analysis was to check the presence in the world GDP dynamics time series of not only Kondratieff, but also Kuznets, Juglar, and Kitchin cycles.

In order to check the source of cycles with the period of 13–15 years (which looked too short for a Kuznets swing) and to eliminate entirely large variations of world GDP growth in the years of world wars and interwar years at the next stage of our research we have replaced all the values for the period between 1914 and 1946 with geometric means (1.5% per year). The second version of series correction was even more radical – the values for years between 1914 and 1946 were replaced by the mean value (3.2%) for the whole period under study (1871–2007), that is, those values were actually excluded from the spectral analysis. The results of respective analyses are presented in Fig. 2B.

As can be easily seen, within spectra of corrected series the Kondratieff cycle clearly dominates; however, the cycle with a period of 17–18 years is also rather salient (it can be identified tentatively with the third harmonic of the Kondratieff cycle[9]). The second peak (that could be seen so saliently in the previous figure) has entirely disappeared, which indicates rather clearly its origins. However, notwithstanding impressive sizes of peaks in our figures of the respective spectrum part, the portion of total variation accounted for by the Kondratieff cycle is not so large, it equals approximately 20% together with the 17-year cycle. A somewhat larger portion (about 25%) is accounted for by the acceleration of the relative growth rates within the period under study, whereas the Juglar cycles only account for 3-4% of total variation. All these estimates naturally refer to cycles with omitted world war and interwar years. In the initial series (see Fig. 2A, curve 1) the Kondratieff cycle controls about 5% of total variation, whereas in the series with corrected values for the world war years (Fig. 2A, curve 2) it does not account for more than 8%.

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[8] Who, incidentally, from 2003 to 2005 was the chairman of President Bush's Council of Economic Advisors.

[9] Let us recollect that the second (third, fourth, *etc.*) harmonic of a periodic wave can be defined as a higher frequency of that wave, i.e., multiplied by two, three, four, *etc.* Respectively, their periods will be two, three, four *etc.* times shorter than the period of the main wave.

To estimate the statistical significance of the detected cycles we have applied our own methodology described in Appendix 1. According to the proposed methodology, the initial spectra were transformed into reduced spectra, excluding the autocorrelation influence. Fig. 2C presents reduced spectra for spectra 1 and 2 of Fig. 2A, whereas Fig. 2D presents reduced spectra for spectra 1 and 2 of Fig. 2B.

As can be seen in Fig. 2C, both for the initial series and for the series in which the values observed in the world war years are replaced with geometric means, the Kondratieff cycle turns out to be statistically insignificant. What is more, the peak values are close to one, that is, the Kondratieff wave amplitude almost does not stand out of the series of amplitudes of the reduced spectrum of power. Fig. 2C seems to indicate quite clearly the causes of why many authors failed to detect Kondratieff waves in the world GDP dynamics, as for both series the greatest significance is possessed by the 13–14 year cycle discussed above, as well as by Juglar (6–8 year) and (3–4 year [Kitchin?]) cycles.

We can see quite a different picture in Fig. 2D. The first harmonic of Kondratieff cycle has statistical significance of about 6–7%, which definitely brings it out of the general amplitude series of the reduced spectrum; yet, it does not make it possible to maintain with real confidence the presence of a periodical component with the period of 52±0.5 years.

The tripled period of the next peak on spectrum (17.2–17.3 * 3 = 51.6–51.9 years) coincides with a very high accuracy (with the deviation of no more than 1%) with the Kondratieff wave period, which makes it possible to consider this wave as the third harmonic[10] of the Kondratieff waves. An alternative explanation that connects this harmonic with Kuznets swings implies, firstly, the high regularity of those cycles, and, secondly, their tight connection with Kondratieff cycles – precisely three Kuznets swings per one Kondratieff wave. With these assumptions Kuznets swings loose their independent meaning and the difference between the alternatives becomes purely nominal. Note that this is quite congruent with Berry's discussion of two growth cycles of Kuznets type embedded in each Kondratieff wave, and, especially, his observation that "economic growth accelerates and decelerates between the Kondratiev peaks and troughs with the 25-to-30 year periodicity suggested by Simon Kuznets" (Berry 1991: 76). Note, however, that though our spectral analysis has confirmed a rather tight connection between Kondratieff waves and Kuznets swings, it suggests three rather than two Kuznets swings per a K-wave identifying Kuznets swings as the third harmonic of the K-wave. Incidentally, the respective period (17–18 years) is

[10] Let us mention again that the second (third, fourth, *etc.*) harmonic of a periodic wave can be defined as a higher frequency of that wave, *i.e.*, multiplied by two, three, four, *etc.* Respectively, their periods will be two, three, four *etc.* times shorter than the period of the main wave (= the first harmonic).

quite congruent with the one initially discovered by Kuznets (cf., *e.g.*, Abramovitz 1961). Note also that our analysis (see Fig. 3 below) indicates that the interaction of the first and third harmonics of the K-wave produces just its rather peculiar shape revealed by Berry (1991).

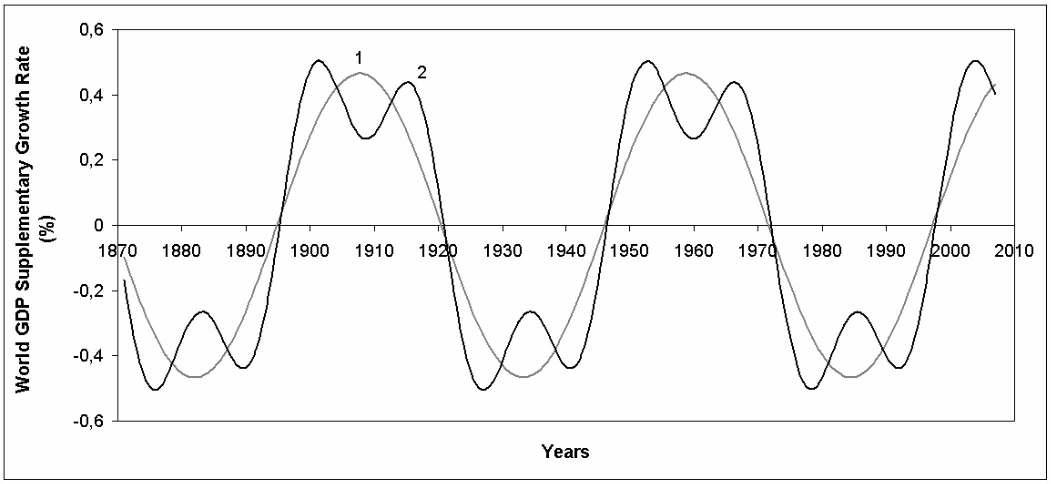
Thus, assuming a tight connection between the harmonics in question, we can estimate their combined significance; the arrived values turn out to be in the range between 4 and 5 per cent. These numbers ($0.04 < p < 0.05$) are the ones that characterize the degree of our confidence that we have managed to detect K-waves with spectral analysis on the basis of series of observations that cover a period that does not exceed the length of three cycles. Note that such a level of statistical significance is generally regarded to be sufficient to consider a hypothesis as having been supported by an empirical test. Thus, we have some grounds to maintain that our spectral analysis has supported the hypothesis of the presence of Kondratieff waves in the world GDP dynamics.

In addition, the reduced spectra analysis indicates a rather high (2–3%) significance of Juglar cycles and increases a little their length in comparison with the initial series spectrum (7–9 years, as compared to 6–8 years). Kitchin cycles have approximately the same (and rather high, 2–3%) significance as Juglar cycles for Fig. 3C, but this significance is substantially lower for Fig. 3D; this seems to indicate that those cycles were especially pronounced in the period between the two world wars.

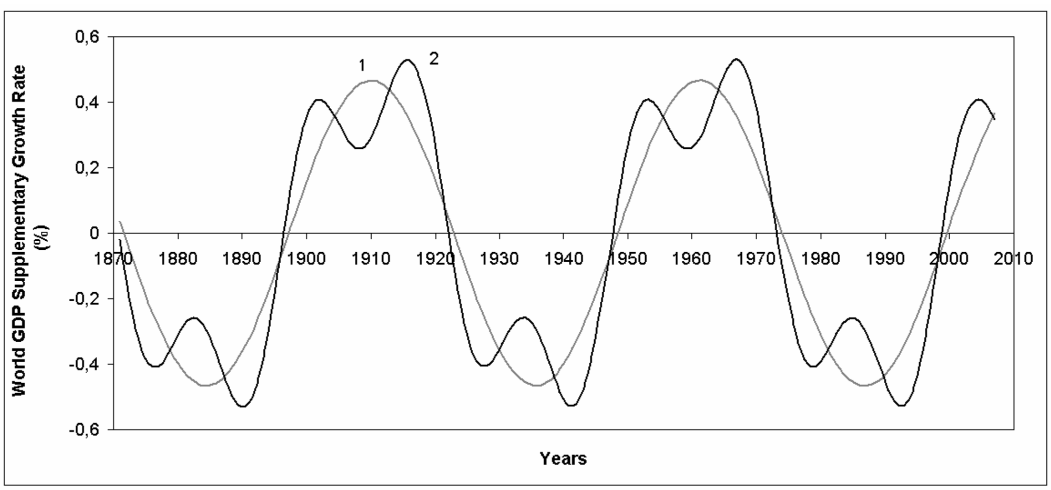
It is rather telling to consider the form of K-waves detected by spectral analysis. Fig. 3 (A and B) represents the first harmonic (curve 1) and the sum of the first and the third harmonics (curve 2) respectively for the replacement of the world war and interwar values with the geometric means and the average of distribution. As can be easily seen, this picture has a considerable similarity with a well known idealized scheme of the U.S. whole-sale price oscillations in course of Kondratieff waves (see Fig. 3C):

Fig. 3. K-Wave Pattern Revealed by Spectral Analysis

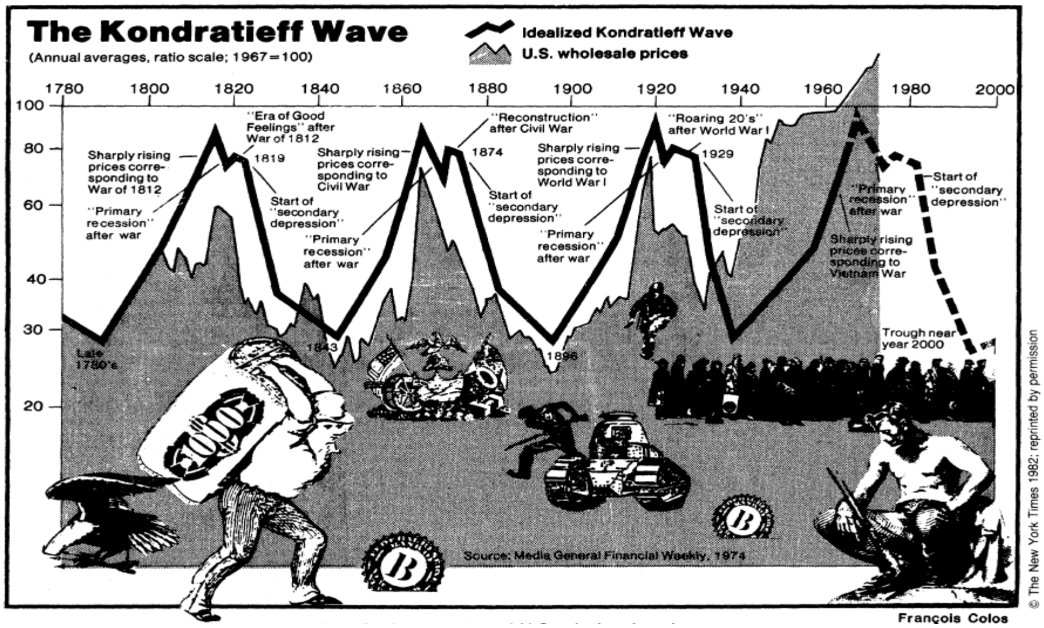
A. The first harmonic (curve 1) and the sum of the first and the third harmonics (curve 2) with the world war and interwar values replaced with the geometric means



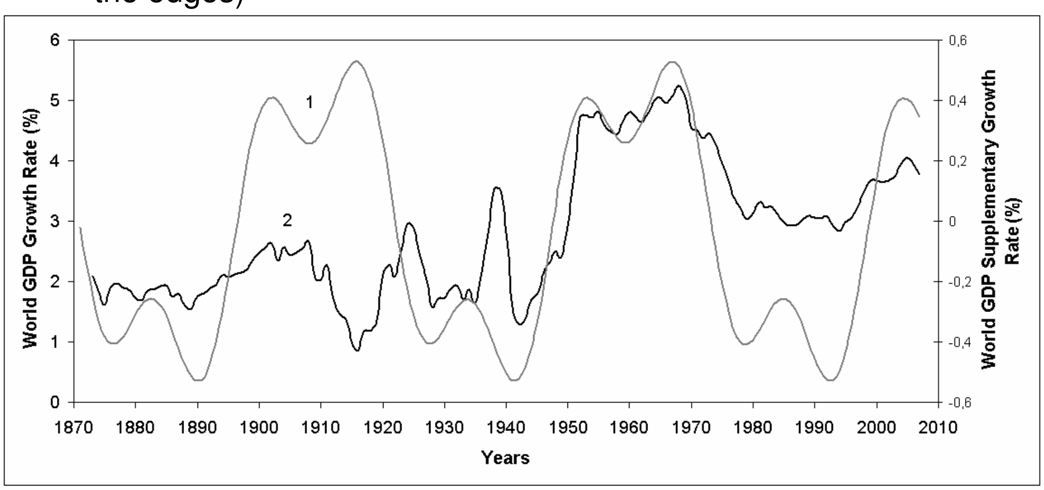
B. The first harmonic (curve 1) and the sum of the first and the third harmonics (curve 2) with the world war and interwar values replaced with the average of distribution



C. Kondratieff waves and U.S. wholesale prices (Dickson 1983: 935)



D. Comparison between the constructed K-wave (curve 1) and the smoothed series of the world GDP growth rates (moving 11-year average for the main part of the series and by smaller intervals at the edges)



Note: "World GDP supplementary growth rate" denotes the change in the world GDP growth rate in connection with Kondratieff cycle. The spectral analysis makes it possible to reveal an idealized (harmonic) K-wave from the observation series, or, in other words, a series of increments (or decreases) of the annual world GDP growth rates that are accounted for by Kondratieff waves. As we see the value of this difference oscillates in the range –0.5-to-+0.5%, which constitutes about 1/6 of the average world GDP growth rate in the period in question.

Comparison of these figures indicates not only a certain similarity, but also significant differences. The differences between oscillations of prices and oscillations of additional (cyclical) value of the world annual GDP growth include

- 1) a phase displacement – the double peak of prices is situated at the beginning of downswing, whereas the double peak of the GDP growth is situated within the upswing;
- 2) significant differences of the peak width – the double peak of prices does not cover more than 15–20% of the cycle length, whereas the double peak of the world GDP growth covers half of the cycle length.

However, notwithstanding these differences, the similarity is still rather significant and deserves a more attentive study.

There is some evidence that the pattern of the K-wave influence on the world GDP dynamics depicted by Fig. 3B has something to do with reality. As the comparison between the wave constructed in Fig. 3B and the smoothed series of the world GDP growth rates (Fig. 3D) demonstrates, there is a clear correspondence between them for the post-war years, whereas it is less clear (but still quite detectable) for the period prior to the 1st World War. Really significant deviations from this pattern are only observed for the world-war and inter-war years (that were virtually excluded from the spectral analysis). However, if we suppose that the 1st World War moved to the 1920s the second part of the upswing phase of the 3rd K-wave, whereas in the 1930s and 1940s the return to the original "phase timetable" took place, then the deviation from the pattern in question observed in those years can be also interpreted. The discussion of the reasons why the 2nd World War (in contrast to the 1st one) did not disturb the phase timetable, but rather contributed to its restoration goes out of the scope of the present article.

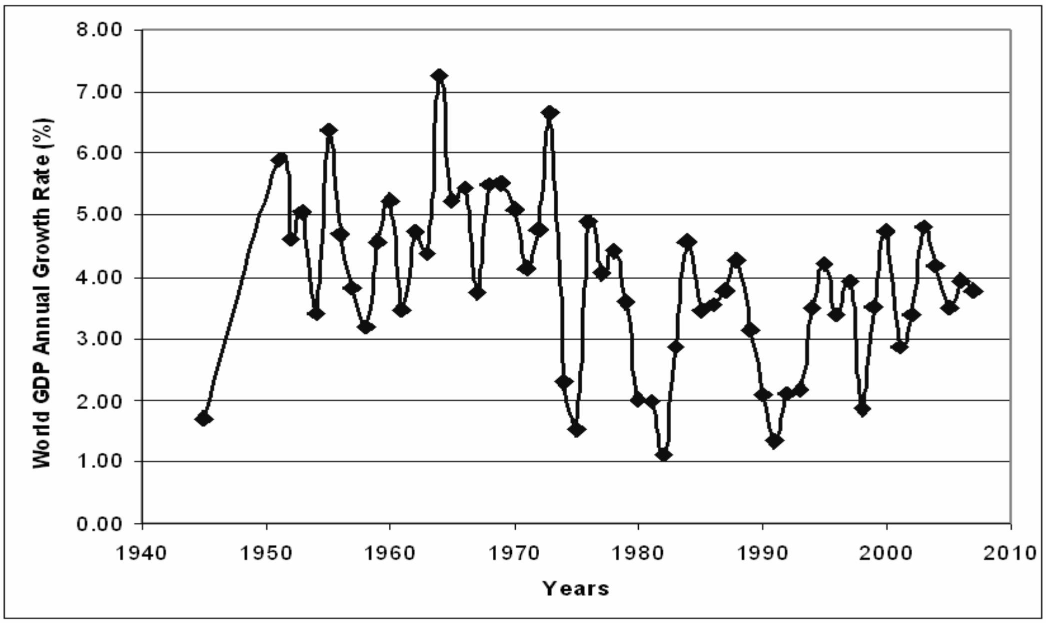
Kondratieff waves in post-World War II GDP data

Note that the Kondratieff-wave component can be seen quite clearly in the post World War II dynamics of the world GDP growth rates even directly, without the application of any special statistical techniques[11] (see Fig. 4A). However, the Kondratieff wave component becomes especially visible if a LOWESS (= *LOcally WEighted Scatterplot Smoothing*) line is fitted (see Fig. 4B):

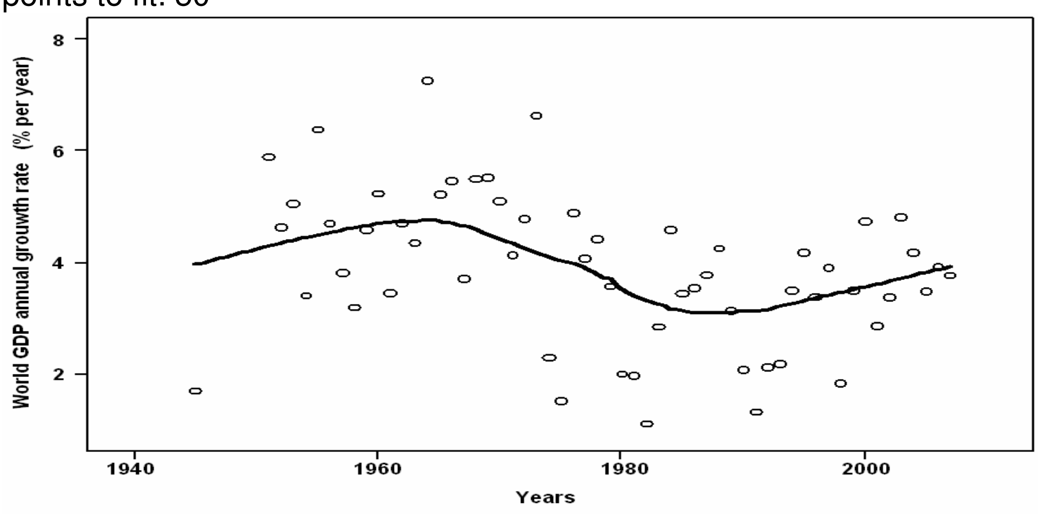
[11] Note that for recent decades K-waves (as well as Juglar cycles) are also quite visible in the world dynamics of such important macroeconomic variables as the world gross fixed capital formation (as % of GDP) and the investment effectiveness (it indicates how much dollars of the world GDP growth is achieved with one dollar of investments) – see Appendix 3, Figs. S1 and S2. Note that the dynamics of both variables is rather tightly connected with the world GDP dynamics. Actually the world GDP dynamics is determined to a considerable extent by the dynamics of those two variables.

Fig. 4. Dynamics of the Annual World GDP Growth Rates (%), 1945–2007; 1945 point corresponds to the average annual growth rate in the 1940s

A. Initial series: Maddison/World Bank empirical estimates. 1945 point corresponds to the average annual growth rate in the 1940s



B. Maddison/World Bank empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. Kernel: Triweight. % of points to fit: 50



As can be seen, Fig. 4 indicates:

1) that the Kondratieff-wave pattern can be detected up to the present in a surprisingly intact form – though, possibly, with a certain shortening of its period, suggested by a few authors (see, *e.g.*, van der Zwan 1980; Bobrovnikov 2004; Tausch 2006*a*; Pantin, Lapkin 2006), due to which K-wave period might have become by now closer to 45 years;

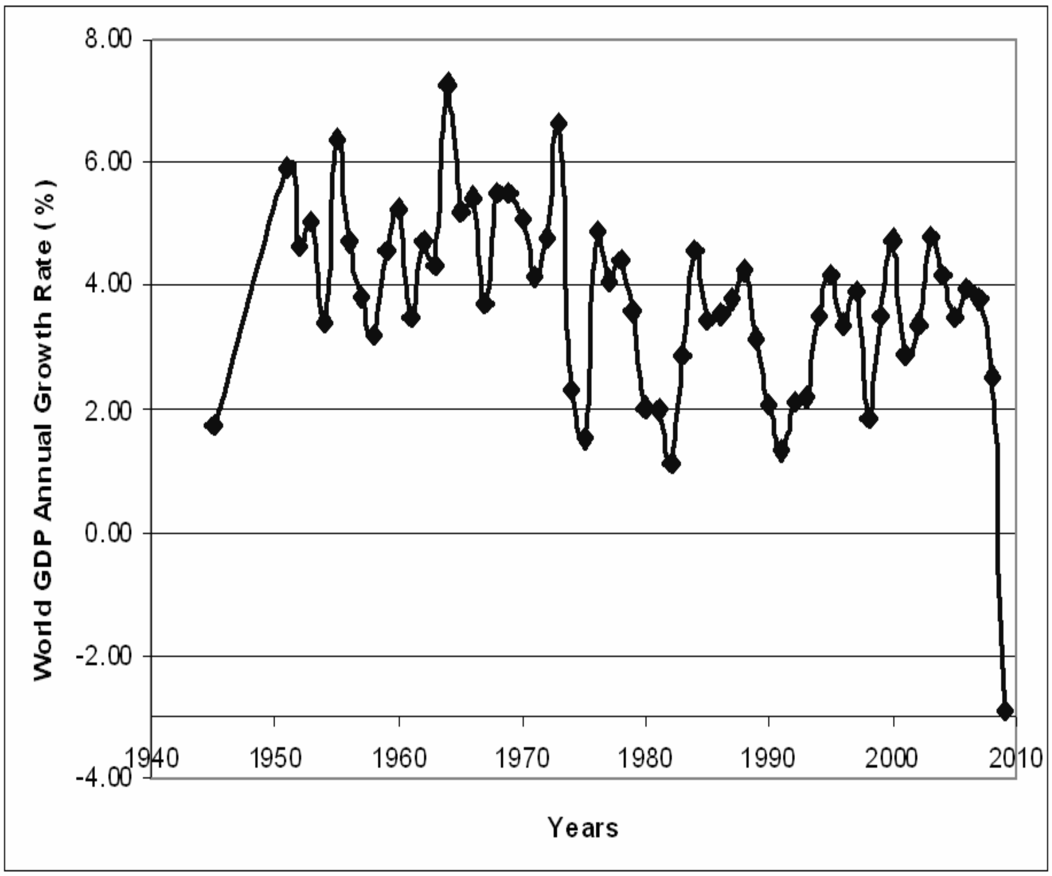
2) that the present world financial-economic crisis might indeed mark an early beginning of a new Kondratieff Phase B (downswing);

3) that the present Kondratieff-wave Phase B might have started somehow prematurely (by 3–5 years) – we believe to a considerable degree due to subjective mistakes of some important political economic actors (and, first of all, G. Bush's administration).

Note, however, that Fig. 3B (curve 2) above can be also interpreted in a more optimistic way, suggesting that the current world economic crisis might mark not the beginning of the downswing phase of the 5th Kondratieff wave, but it may be interpreted as a temporary depression between two peaks of the upswing (whereas Fig. 3B [curve 2] suggests that the next peak might even exceed the previous one). By extrapolating curves 2 in Fig. 3 (A and B) we arrive at a forecast that the new upswing will start in 2011–2012 (or perhaps has already begun) and will reach its maximum in 2018–2020. Note, however, that the third harmonic phase is rather unstable and changes significantly with minor variations of the analyzed series. The source of the possible resumption of fast growth of the world economy is not clear either. There are sufficient indicators that the current "age of information and telecommunications" is about to exhaust its reserves of fast growth, whereas it is difficult to see new products and technologies that would be able within 2–3 years to stop the downswing and to give a new impulse to the world economy. The most probable realistic scenario of the resumption of the fast world GDP growth is connected with the fast decrease in the inequality between the World System core and periphery through the acceleration of the diffusion of the extant high technologies to the populous countries of the World System periphery and especially semiperiphery. On the other hand, this scenario (notwithstanding all its social attractiveness) is rather dangerous from the environmental point of view. Some hopes may be connected with the start of mass production of electrical and hybrid automobiles that is planned for 2010–2011 by most major car producers. If this line of transformation of the industrial world continues, we shall see for the first time such an economic growth that is based not on the maximization of the personal utility function, but on the maximization of moral satisfaction with the behavior that is right from the ecological (energy, moral value, *etc.*) point of view.

On the other hand, there also seems to be some evidence supporting the first interpretation (based on the assumption that the current world financial-economic crisis marks the beginning of the downswing phase of the 5th Kondratieff wave). Indeed, consider the post-World War II dynamics of the world GDP growth rates taking into account the last two years, 2008 and 2009 (using the World Bank early estimates for 2009) (see Fig. 5):

Fig. 5. Dynamics of the Annual World GDP Growth Rates (%), 1945–2009



Sources: World Bank 2008[12], 2009*a*[13], 2009*c*[14]; Maddison 2009[15].

As we see, according to its magnitude the current financial-economic crisis does not appear to resemble a usual crisis marking the end of a Juglar cycle amidst an upswing (or even downswing) phase of a Kondratieff cycle (which one would

[12] World GDP growth rate estimate for 2008.
[13] World GDP growth rate estimate for 2003–2007.
[14] World GDP growth rate forecast for 2009.
[15] World GDP growth rate estimate for 1940–2003.

expect with the second interpretation); it rather resembles particularly deep crises (similar to the ones of 1973–1974, 1929–1933, mid 1870s or mid 1820s) that are found just at the border of phases A and B of the K-waves (note that the Great Depression crisis of 1929–1933 was even more extreme than that of 2009 shown in Fig. 5, see, *e.g.*, Grinin, Korotayev 2010).

At the moment it does not seem to be possible to decide finally which of those two interpretations is true.

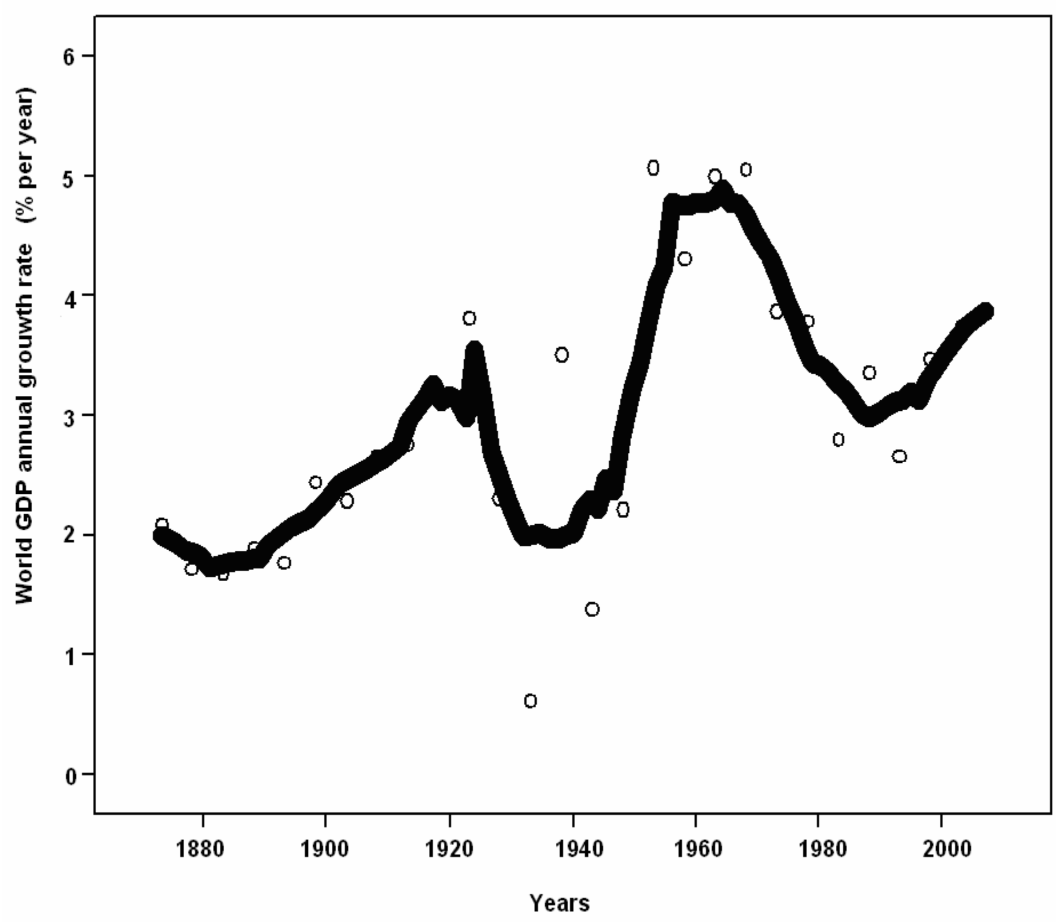
Kondratieff waves in pre-1945/50 world GDP data

As can be seen above in Fig. 1, for the 1870–1945/50 period the K-wave pattern is not as easily visible as after 1945/50. It is easy to see in this figure that the turbulent 2nd, 3rd and 4th decades of the 20th century are characterized by enormous magnitude of fluctuations of the world GDP growth rates (not observed either in the previous or subsequent periods). On the one hand, the lowest (for 1871–2007) figures of the world GDP annual rates of change are observed just in these decades (during the Great Depression, World Wars 1 and 2 as well as immediately after the end of those wars). On the other hand, during the mid-20s and mid-30s booms the world GDP annual growth rates achieved historical maximums (they were only exceeded during the K-wave 4 Phase A, in the 1950s and 1960s, and were generally higher than during both the pre-World War 1 and recent [1990s and 2000s] upswings). This, of course, complicates the detection of the long-wave pattern during those decades.

Actually, this pattern is somehow better visible in the diagrams for 5-year moving average, and, especially, for simple 5-year averages (see Appendix 3, Figs. S3 and S4). The application of the LOWESS technique reveals a certain K-wave pattern in the pre-1950 series (see Appendix 3, Fig. S5). In fact, the LOWESS technique reveals quite clearly the K-wave pattern prior to World War 1 (in the period corresponding to Phase B of the 2nd Kondratieff wave and major part of Phase A of the 3rd wave) (see Appendix 3, Fig. S6). However, the 3rd K-wave (apparently strongly deformed by World War 1) looks much less neat (see Appendix 3, Fig. S7). The main problem is presented by Phase B of the 3rd Kondratieff cycle – as it remains unclear as to the timing of its start (1914, or mid 1920s?). Our analysis does not make it possible to choose finally between two options – either K3 Phase B started in 1914 and was interrupted by the mid 1920s boom; or K3 Phase A continued till the mid 1920s having been interrupted by the WW1 bust.

However, the LOWESS technique produces an especially neat K-wave pattern with the second assumption – that is, we get it when we omit the WW1 influence (see Fig. 6):

Fig. 6. World GDP annual growth rate dynamics, **5-year averages**: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. **1870–2007, omitting World War 1 influence**



Note: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. Kernel: Triweight. % of points to fit: 20.

This figure reveals rather distinctly double peaks of the upswings. With a stronger smoothing (see Appendix 3, Fig. S8) the form of the peaks becomes smoother, whereas the waves themselves become more distinct.

Hence, it looks a bit more likely that K3 Phase A lasted till the mid 1920s (having been interrupted by WW1). Incidentally, if we take the WW1 influence years (1914–1921) out, we arrive at a quite reasonable K3 Phase A length – 26 years (1/2 of a full K-cycle of 52 years), even if we take 1929 as the end of this phase:

$$1929 - 1895 = 34$$
$$34 - 8 = 26$$

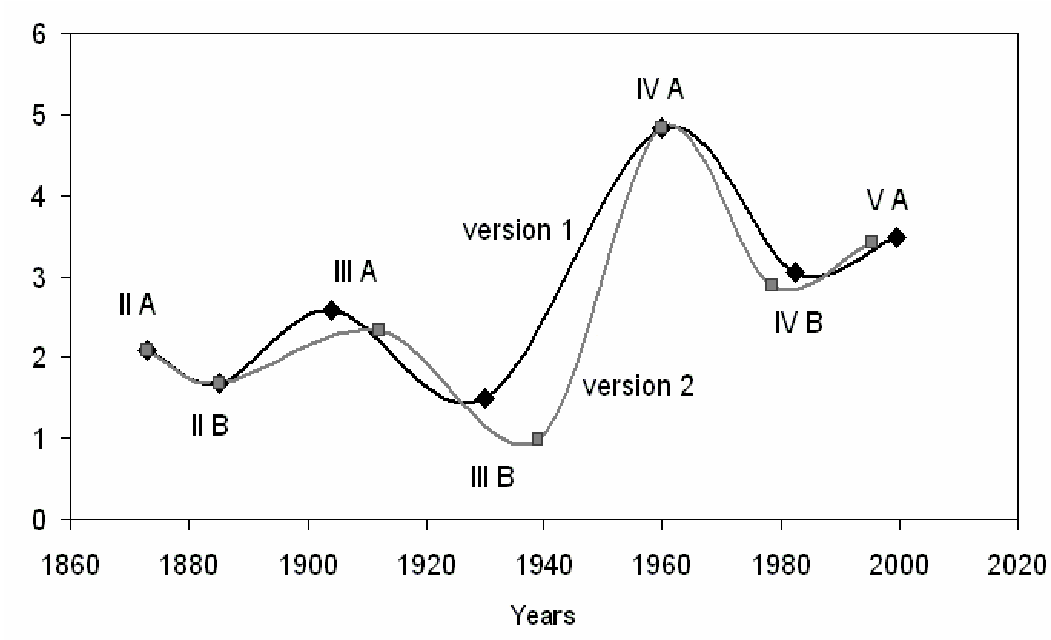
Note that with the first assumption (K3 Phase B started in 1914 and was interrupted by the mid 1920s boom) we would have an excessive length of K3 Phase B – 32 years (that would, however, become quite normal, if we take out the mid 1920s boom years).

Yet, it seems necessary to stress that we find overall additional support for the Kondratieff pattern in the world GDP dynamics data for the 1870–1950 period. First of all, this is manifested by the fact that both Phases A of this period have relatively high rates of the world GDP growth, whereas both Phases B are characterized by relatively low rates. Note that this holds true without taking out either the World War 1, or the 1920s boom influence, and irrespective of whatever datings for the beginnings and ends of the relevant phases we choose (see Table 3 and Fig. 7):

Table 3. Average annual World GDP growth rates (%) during phases A and B of Kondratieff waves, 1871–2007

Kondratieff wave number	*Phase*	*Years*		*Average annual World GDP growth rates (%) during respective phase*	
		Version 1	*Version 2*	*Version 1*	*Version 2*
II	End of Phase A	1871–1875	1871–1875	2.09	2.09
II	B	1876–1894	1876–1894	1.68	1.68
III	A	1895–1913	1895–1929	2.57	2.34
III	B	1914–1946	1930–1946	1.50	0.98
IV	A	1947–1973	1947–1973	4.84	4.84
IV	B	1974–1991	1974–1983	3.05	2.88
V	A	1992–2007	1984–2007	3.49	3.42

Fig. 7. Average annual World GDP growth rates (%) during phases A and B of Kondratieff waves, 1871–2007



With different dates for beginnings and ends of various phases we have somehow different shapes of long waves, but the overall Kondratieff wave pattern remains intact. Note that the difference between the two versions can be partly regarded as a continuation of controversy between two approaches ("the K-wave period is approximately constant in the last centuries" *vs.* "the period of K-waves becomes shorter and shorter"[16]). The first approach correlates better with the results of the spectral analysis that have been presented above and the optimistic forecast, whereas the second approach correlates better with the interpretation of the current crisis with the beginning of the downswing phase of the 5th K-wave.

Kondratieff waves in pre-1870 world GDP dynamics

There are certain grounds to doubt that Kondratieff waves can be traced in the world GDP dynamics for the pre-1870 period (though for this period they appear to be detected for the GDP dynamics of the West).

Note that for the period between 1700 and 1870 Maddison provides world GDP estimate for one year only – for 1820. What is more, for the period before 1870 Maddison does not provide annual (or even per decade) estimates for many

[16] See, *e.g.*, van der Zwan 1980; Bobrovnikov 2004; Tausch 2006*a*; Pantin, Lapkin 2006.

major economies, which makes it virtually impossible for this period to reconstruct the world GDP annual (or even per decade) growth rates. However, it appears possible to reconstruct a world GDP estimate for 1850, as for this year Maddison does provide his estimates for all the major economies. Thus, it appears possible to estimate the world GDP average annual growth rates for 1820–1850 (that is the period that more or less coincides with K1 Phase B) and for 1850–1870/1875 (that is K2 Phase A), and, consequently, to make a preliminary test whether the Kondratieff wave pattern can be observed for the 1820–1870 period.

The results look as follows:

Table 4. Average annual World GDP growth rates (%) during phases A and B of Kondratieff waves, 1820–1894

Kondratieff wave number	*Phase*	*Years*		*Average annual World GDP growth rates (%) during respective phase*		*Average annual World GDP growth rate predicted by Kondratieff wave pattern*	*Observed*
		Version 1	*Version 2*	*Version 1*	*Version 2*		
I	B	1820–1850	1820–1850	0.88	0.88		
II	A	1851–1875	1851–1870	1.26	1.05	to be significantly higher than during the subsequent phase	significantly lower than during the subsequent phase
II	B	1876–1894	1871–1894	1.68	1.76	to be significantly lower than during the subsequent phase	significantly higher than during the subsequent phase

Thus, whatever datings of the end of K2 Phase A we choose, we observe a rather strong deviation from the K-wave pattern. Indeed, according to this pattern one would expect that in the 1850–1870/5 period (corresponding to Phase A of the 2nd Kondratieff wave) the World GDP average annual growth rate should be higher than in the subsequent period (corresponding to Phase B of this K-wave). However, the actual situation turns out to be squarely opposite – in 1870/75–1894 the World GDP average annual growth rate was significantly higher than in 1850–1870/75.

Note, however, that the K-wave pattern still seems to be observed for this period with respect to the GDP dynamics of the West[17] (see Table 5 and Fig. 8):

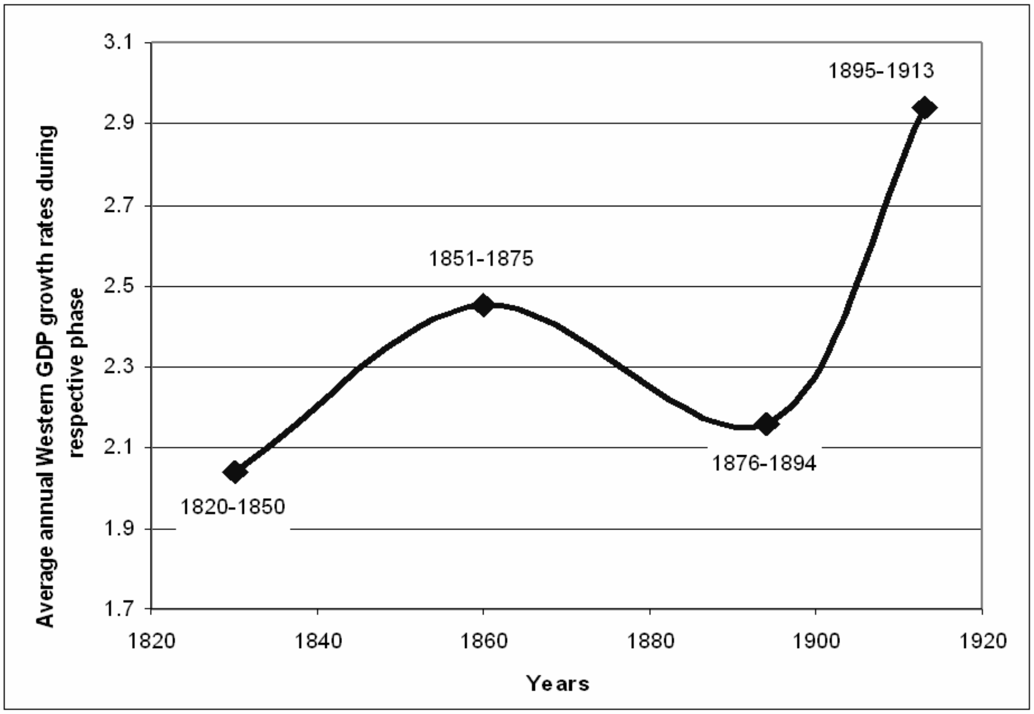
Table 5. Average annual World GDP growth rates (%) of the West during phases A and B of Kondratieff waves, 1820–1894

Kondratieff wave number	*Phase*	*Years*	*Average annual World GDP growth rates (%) during respective phase*	*Average annual World GDP growth rate predicted by Kondratieff wave pattern*	*Observed*
I	B	1820–1850	2.04	to be significantly lower than during the subsequent phase	significantly lower than during the subsequent phase
II	A	1851–1875	2.45	to be significantly higher than during the subsequent phase	significantly higher than during the subsequent phase
II	B	1876–1894	2.16	to be significantly lower than during the subsequent phase	significantly lower than during the subsequent phase
III	A	1895–1913	2.94	to be significantly higher than during the previous phase	significantly higher than during the previous phase

NOTE: Data are for 12 major West European countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Sweden, Switzerland, United Kingdom) and 4 "Western offshoots" (United States, Canada, Australia, New Zealand).

[17] What is more, this pattern appears to be observed in the socio-economic dynamics of the European-centered world-system for a few centuries prior to 1820, approximately since the late 15th century (see, *e.g.*, Beveridge 1921, 1922; Goldstein 1988; Jourdon 2008; Modelski 2006; Modelski, Thompson 1996; Pantin, Lapkin 2006; Thompson 1988, 2007).

Fig. 8. Average annual World GDP growth rates (%) of the West during phases A and B of Kondratieff waves, 1820–1913



We believe that the point that K-wave pattern can be traced in the GDP dynamics of the West for the pre-1870 period and that it is not found for the world GDP dynamics is not coincidental, and cannot be accounted for just by the unreliability of the world GDP estimates for this period. In fact, it is not surprising that the Western GDP growth rates were generally higher in 1851–1875 than in 1876–1894, and the world ones were not. The proximate explanation is very simple. The world GDP growth rates in 1851–1875 were relatively low (in comparison to 1876–1894) mostly due to the enormous economic decline observed in China in 1852–1870 due to social-demographic collapse in connection with the Taiping Rebellion and accompanying events of additional episodes of internal warfare, famines, epidemics and so on (Iljushechkin 1967; Perkins 1969: 204; Larin 1986; Kuhn 1978; Liu 1978; Nepomnin 2005 *etc.*) that resulted, for example, in the human death toll as high as 118 million human lives (Huang 2002: 528). Note that in the mid 19th century China was still a major world economic player, and the Chinese decline of that time affected the world GDP dynamics in a rather significant way. According to Maddison's estimates, in 1850 the Chinese GDP was about 247 billion international dollars (1990, PPP), as compared with about 63 billion in Great Britain, or 43 billion in the USA. By 1870, according to Maddison, it declined to less than $190 billion, which compensated up to a very high degree the acceleration of economic growth observed in the same years in the West (actually, Maddison appears to underestimate the magnitude of the Chinese economic decline in this period, so the actual influence of the Chinese 1852–1870 sociodemographic collapse might have been even much more significant). K2 Phase A in the Western GDP dynamics started to be felt on the world level only in the very end of this phase, in 1871–1875, after the end of the collapse period in China and the beginning of the recovery growth in this country.

In more general terms, it seems possible to maintain that in the pre-1870 epoch the Modern World System was not sufficiently integrated, and the World System core was not sufficiently strong yet[18] – that is why the rhythm of the Western core's development was not quite felt on the world level. Only in the subsequent era the World System reaches such a level of integration and its core acquires such strength that it appears possible to trace quite securely Kondratieff waves in the World GDP dynamics.[19]

Main conclusions

Our research suggests the following main conclusions:

1) Our spectral analysis has detected the presence of Kondratieff waves (their period equals approximately 52–53 years) in the world GDP dynamics for the 1870–2007 period. To estimate the statistical significance of the detected cycles we have applied our own methodology described in Appendix 1. The significance of K-waves in the analyzed data has turned out to be in the range between 4 and 5 per cent. These numbers ($0.04 < p < 0.05$) are the ones that characterize the degree of our confidence that we have managed to detect K-waves with spectral analysis on the basis of series of observations that cover a period that does not exceed the length of three cycles. Note that such a level of statistical significance is generally regarded to be sufficient to consider a

[18] On the general trend toward the increasing integration of the World System see, *e.g.*, Korotayev 2007.

[19] The phenomenon that K-waves can be traced in the Western economic dynamics earlier than at the world level has already been noticed by Reuveny and Thompson (2008) who provide the following explanation: if one takes the position that the core driver of K-waves is intermittent radical technological growth primarily originating in the system leader's lead economy, one would not expect world GDP to mirror k-wave shapes as well as the patterned fluctuations that are found in the lead economy and that world GDP might correspond more closely to the lead economy's fluctuations over time as the lead economy evolves into a more predominant central motor for the world economy. They also argue that to the extent that technology drives long-term economic growth, the main problem (certainly not the only problem) in diffusing economic growth throughout the system is that the technology spreads unevenly. Most of it stayed in the already affluent North and the rest fell farther behind the technological frontier. Up until recently very little trickled down to the global South (Reuveny, Thompson 2001, 2004, 2008, 2009). Our findings also seem congruent with this interpretation.

hypothesis as having been supported by an empirical test. Thus, we have some grounds to maintain that our spectral analysis has supported the hypothesis of the presence of Kondratieff waves in the world GDP dynamics.

2) In addition, the reduced spectra analysis has indicated a rather high (2–3%) significance of Juglar cycles (with a period of 7–9 years), as well as the one of Kitchin cycles (with a period of 3–4 years). Thus our spectral analysis has also supported the hypothesis of the presence of Juglar and Kitchin in the world GDP dynamics. On the other hand, our analysis suggests that the Kuznets swing should be regarded as the third harmonic of the Kondratieff wave rather than as a separate independent cycle.
3) Our research suggests two interpretations of the current global economic crisis. On the one hand, our spectral analysis suggests rather optimistically that the current world economic crisis might mark not the beginning of the downswing phase of the 5th Kondratieff wave, but it may be interpreted as a temporary depression between two peaks of the upswing (whereas Fig. 3B suggests that the next peak might even exceed the previous one but only postpone the downswing). By extrapolating curves 2 in Fig. 3 (A and B) we arrive at a forecast that the new upswing will start in 2011–2012 and will reach its maximum in 2018–2020.
4) On the other hand, there also seems to be some evidence supporting another interpretation based on the assumption that the current world financial-economic crisis marks the beginning of the downswing phase of the 5th Kondratieff wave. Indeed, according to its magnitude the current financial-economic crisis does not appear to resemble a usual crisis marking the end of a Juglar cycle amidst an upswing (or even downswing) phase of a Kondratieff cycle (which one would expect with the second interpretation); it rather resembles particularly deep crises (similar to the ones of 1973–1974, 1929–1933, mid 1870s or mid 1820s) that are found just at the border of phases A and B of the K-waves. At the moment it does not seem to be possible to decide finally which of those two interpretations is true.
5) It does not appear possible to detect Kondratieff waves in the world GDP dynamics for the pre-1870 period, though for this period they appear to be detected for the GDP dynamics of the West[20].
6) This suggests that in the pre-1870 epoch the Modern World System was not sufficiently integrated, and the World System core was not sufficiently strong yet – that is why the rhythm of the Western core's development was not quite felt on the world level. Only in the subsequent era the World System reaches

[20] Note, however, that Modelski and Thompson (as well as Pantin and Lapkin) appear to have found K-waves in the World System dynamics for the whole of the 2nd millennium CE using some indicators other than GDP (see, *e.g.*, Modelski, Thompson 1996; Modelski, Thompson 1996; Modelski 2006; Thompson 2000, 2007; Pantin, Lapkin 2006).

such a level of integration and its core acquires such strength that it appears possible to trace quite securely Kondratieff waves in the World GDP dynamics.

We believe that our analysis may pave the way to a number of new directions of scientific research in social sciences.

Firstly, the development of a more precise method for the estimation of the statistical significance of various cycles in autocorrelated series opens perspectives for the expansion of studies of recurrent social, political, economic, and cultural phenomena. The first application of an early version of this method made it possible to detect 300-year cycles in the political history of South Asia (Wilkinson, Tsirel 2005), whereas the current analysis has let us achieve a deeper understanding of the cyclical processes in the world economy of the last centuries. We hope that the method described in the present article will create a number of other possibilities for future research.

Secondly, a more rigorous detection of cycles creates new prospects for the study of their causes and regularities of their reproduction. We hope that with respect to K-waves the future research will be able to shed a new light on their connection with the two-generation-cycles, as well as on the reasons why two world wars produced so different influence on the Kondratieff cycle dynamics.

Thirdly, the knowledge of cyclical dynamics creates possibilities for the elaboration of a new generation of mathematical models of the World System evolution (see Tsirel 2004; Korotayev 2005, 2007; Korotayev, Malkov, Khaltourina 2006*a*, 2006*b*; Korotayev, Khaltourina 2006, *etc.* for more detail) and, consequently, for the development of more precise forecasts of future global dynamics.

APPENDIX 1: Methods

We have used standard methods of spectral analysis to detect periodical components in time series. The most important stage was constituted by the estimation of significance of detected periodic trends.

The classical methods of the estimation of significance of components of unsmoothed spectrum imply an uncorrelated random process (white noise) as the null hypothesis. For such a case methods of significance estimation are well known (Schuster 1898; Fisher 1929; Priestley 1981). We deal with a much more complex situation if the null hypothesis (~ null/zero process) implies correlations between subsequent values, where we have to detect periodical components from a spectrum, within which amplitudes depend on frequency. Such processes are often denoted as red noise (unfortunately, different authors use the "red noise" notion to designate different processes – any correlated processes, first-order autoregressive processes [AR1], or combinations of correlated and uncorrelated processes). In contrast to the white noise, we lack established methods to estimate the statistical significance of the spectrum maxima.

The estimation of significance of periodical components of arbitrary unsmoothed spectrum may be performed in three ways. The first way implies the application of Monte Carlo method to model the null process (Timmer, Konig 1995, Benlloch *et al.* 2001). The deficiencies of such an approach are produced by the laboriousness of calculations and the absence of the unification of the null process description, which leads to the differences of estimates, arrived at by different scientists.

The second method implies the isolation of a certain neighborhood of the tested component in the spectrum and the significance estimation is performed in comparison with components belonging to this neighborhood (see, *e.g.*, Lukk 1991). The main virtue of this approach lies in the independence from the spectrum form, and, consequently from the hypotheses regarding the process character. However, we believe that this approach can only be used as a last resort, as in addition to this virtue it has serious deficiencies. Note the two most important of them. The first is the arbitrariness as regards the selection of the neighborhood size. For the estimation of the component mean Gar'kavyj (2000) recommends to take 10–25 frequencies from each side of the tested frequency, but he does not suggest any clear basis for the selection of the frequency diapasons of this size. What is more, there are no recommendations as regards the selection of concrete size of the neighborhood, whereas the arbitrariness with the selection of the neighborhood size leads to the arbitrariness with the significance estimations. The second deficiency lies in the point that if a clear trend is observed in a spectrum (the mean amplitude changes significantly with the frequency), then the selection of any diapason (except the most narrow and, hence, the least representative) leads to the drift of estimates.

Thus, the most correct approaches are the ones that use some null hypothesis as regard the character of the process in question and its spectrum (Vaughan 2005; Schulz, Mudelsee 2002; Timashev 1997; Timashev, Polyakov 2007). The main problem lies in the point that we do not often know in advance the type of the random process, and, hence, we have to formulate the null hypothesis (aperiodic process) on the basis of the experimental data themselves, whereas a wrong selection of the null hypothesis may lead to gross errors as regards the estimation of statistical significance of certain periodic components.

The method proposed below is based on the approaches developed by the above-mentioned group of scientists. It is based on the assumption that a broad class of aperiodic natural, technical, and social processes may be represented as sums of random process with stationary increments of different orders: $f(x) = a_0(x)$

$+ a_1(x) + a_2(x) + ...$, where $a_i(x)$ is a process whose i's increments are stationary. Practically, with usual lengths of time series (hundreds to a few thousand points) processes $a_2(x)$, $a_3(x)$,... are estimated as a trend; this is also relevant for some small part of process $a_1(x)$. The second assumption lies in the point that (with sufficiently large intervals between points and with the absence of periodical reference components) $a_0(x)$ is a sequence of independent, or almost independent values, whereas $a_1(x)$ is a process with independent or almost independent increments for an exponential (or close to it) function. Then for all the frequencies (except the lowest ones) the spectral density can be represented as follows:

$$f(\omega) \approx a + b\ \alpha/(\alpha^2 + \omega^2), \tag{A1}$$

whereas its components obey the $\chi_2^{\ 2}/2$ (exponential) distribution. Respectively, the estimation of significance of periodic components can be reduced to the calculation of the maximum likelihood estimates for coefficients a, b and α.

Compare equation (A1) with equations proposed in earlier studies of this school of research. The simplest method (Vaughan 2005) employs (the symbols are ours throughout) the following equation:

$$f(\omega) \approx a + b\ /\omega^n, \tag{A2}$$

that assumes an arbitrary exponent, but that does not take into account either the finiteness of the correlation distance ($\alpha > 0$), or the presence of the white noise in the spectrum.

In contrast, Timashev (1997, 2007) proposes very complex equations that assume both an arbitrary exponent (and, hence, processes with non-exponential correlation function – for example, the turbulence [n] according to Kolmogorov's theory equals 5/3), and the presence of the white noise, as well as the finiteness of the correlation distance:

$$f(\omega) \approx a + b\ \alpha^k/(\alpha^n + \omega^n)\ . \tag{A3}$$

However, we believe that the introduction of an additional parameter n (the value of k does not appear to affect the approximation) is not justified for the majority of real processes; yet, it complicates the computations and decreases the computational stability. In addition to this, as a result of the increase in the parameters' number we may miss some spectrum characteristics that could be of interest for us. On the other hand, for some processes the use of the more complex equation (A3) may be quite justified.

The process description that is the closest to (A1) is used by Schulz and Mudelsee (2002), however it is not expressed explicitly, but is arrived at through the corrections of the second term in equation (A1), whereas in order to estimate the significance of deviations from the null hypothesis they use not a deterministic algorithm, but the Monte Carlo method.

Computation stages

I. The first stage consists of the test whether the spectrum should be reduced to the white noise, or is already close to the white noise.

It is the easiest to test this through the calculation of the correlation coefficient r between frequency ω_k (or its number k – it is clear that this choice does not affect the result) and the components of the amplitude spectrum $A_k = \sqrt{I_k}$. In order to avoid the recognition of the spectrum variations as the evidence for the correlatedness of the process one should use a high critical value of significance level: $p = 0.01$. The estimation of statistical significance of the correlation coefficient is performed either through Student's t-test, or through the Fisher transform.

The test may result in three situations:

1) $r < 0$ – this implies that the process differs significantly from the white noise, and one should use the main set of methods (see below, stage II).
2) $r = 0$ – the null hypothesis is the white noise (the averages of distribution of all I_k are equal), then move to stage III.
3) $r > 0$ – the high-frequency oscillations are more intensive than the low-frequency ones. An example of such cases could be the study of the influence of the solar activity on the productivity of apple-trees; in such cases one could apply the methodology proposed by Lukk (1991) – to choose some neighborhood of the 11-year period in the spectrum and to conduct the comparison within this neighborhood.

II. The main stage – the reduction of spectrum to the white noise spectrum. For this purpose we approximate the spectrum with equation (A1).

As I_k values are distributed not according to normal law, but according to exponential law, we should use not the least-squares procedure, but the method of maximum likelihood.

Construct likelihood function:

$$l = \prod_{k=1}^{N} \left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2} \right)^{-1} \prod_{k=1}^{N} \exp\left(-\left[a + \frac{b\alpha}{\alpha^2 + \omega_k^2} \right]^{-1} I_k \right), \tag{A4}$$

then the log-likelihood function will look as follows:

$$L = \sum_{k=1}^{N} \ln\left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2} \right) + \sum_{k=1}^{N} \left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2} \right)^{-1} I_k \ . \tag{A5}$$

For the minimization of L (L has the opposite sign, hence, we should find its minimum, not maximum) we can use direct methods, for example, the alternating-variable descent method; however, the methods involving partial derivative computations are more effective here:

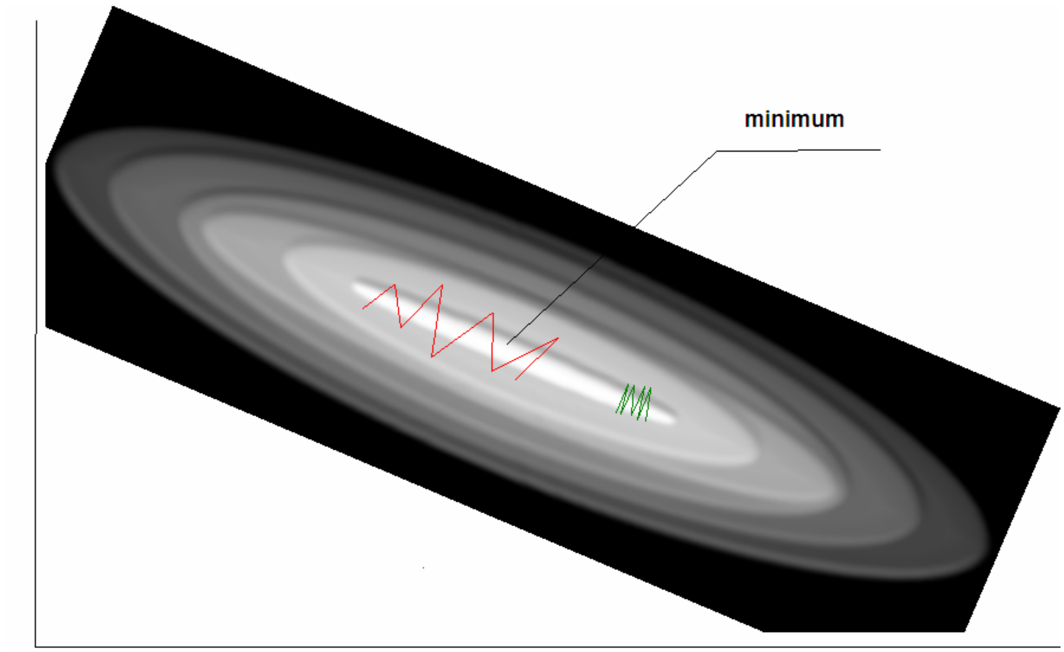
$$\frac{\partial L}{\partial a} = \sum_{k=1}^{N} \frac{I_k - \left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2}\right)}{\left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2}\right)^2} = 0$$

$$\frac{\partial L}{\partial b} = \sum_{k=1}^{N} \frac{\alpha}{\alpha^2 + \omega_k^2} \frac{I_k - \left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2}\right)}{\left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2}\right)^2} = 0 \quad . \tag{A6}$$

$$\frac{\partial L}{\partial \alpha} = \sum_{k=1}^{N} \frac{\omega_k^2 - \alpha^2}{\left(\alpha^2 + \omega_k^2\right)^2} \frac{I_k - \left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2}\right)}{\left(a + \frac{b\alpha}{\alpha^2 + \omega_k^2}\right)^2} = 0$$

The main problem lies here in the point that we are dealing with a task of a ravine type (that is, the area of search has a sort of ravine surface), as we are dealing with a narrow and long area, where the L function changes insignificantly with a large change in coefficients. Fig. M1 demonstrates an example of two fitted coefficients. In such cases the minimum search algorithms either skip it (red line), or move to it very slowly (green curve), or stop in a wrong point.

Fig. M1. An example of the solution search at a ravine surface.



It is very important to find correctly the starting point. To solve this problem the following method is proposed – to take a few values of I_k at the spectrum beginning (3 or 5 points, to increase the confidence) and to find the mean that will clearly be about b/α. Then take a few points in the middle of the spectrum, find the mean (it will equal approximately $\frac{(b/\alpha)\cdot\alpha^2}{\alpha^2+\omega_{N/2}^2}$); this will allow us to find α^2, α and b. Finally, take a few points at the very end, put in equation (A1) the obtained values α and b, and find a. If $a \le 0$, then consider $a = 0$; if $a << b/\alpha$, then take value a as the starting one. If the value of a turns out to be close to the value of b/α or even exceeds it, then make one more iteration. For this purpose subtract a from every I_k and repeat the computations; take new values $\alpha^{(1)}$ and $b^{(1)}$, as well as $a + a^{(1)}$ as starting ones.

These operations may be performed with a different number of points (while making computations, it is useful to discard those I_k values that deviate strongly from the neighboring ones) with the comparison of the values of L. Choose the set of values of a, α and b that has the minimum value of L as the starting one.

III. The estimation of statistical significance. The method of this estimation depends significantly on what we compare: the maximums in the spectrum, or frequencies selected in advance.

A) When we deal with the frequencies selected in advance (for example, we check the presence of a one-year period). Using equation (A1) calculate the average of distribution $\boldsymbol{I_k}$ for the given frequency and the ratio of the obtained amplitude to it $x = I_k / \boldsymbol{I_k}$. Here we can use Schuster's (1898) equation:

$$p = e^{-x} \tag{A7}$$

to calculate the significance of deviation p, compare it with the threshold value p_0 and find whether the presence of periodicity with frequency ω_k is statistically significant. Strictly speaking, one would be supposed to make the computations with Fisher's (1929) formula:

$$p = (1 - x/N)^{N-1}, \tag{A8}$$

as we use an estimate of $\boldsymbol{I_k}$, and not its precisely known value. However, the application of this formula only makes sense with small N, or with high threshold significance level (see Table M1):

Table M1. Critical values of x

Threshold significance levels p_0, %	Values of x according to Fisher's formula with different values of N			Values of x according to Schuster's equation ($N = \infty$)
	16	32	64	
5	2.9	2.95	2.95	3.0
3	3.3	3.4	3.45	3.5
1	4.2	4.4	4.5	4.6
0.5	4.75	5.0	5.15	5.3

It is necessary to pay attention to the point that with the frequency selected in advance critical values of x are relatively small; for example, with p_0 = 1%, it is necessary that the square of amplitude I_k would exceed the mean just 4.6 times only. These calculations may be transmitted to the amplitude spectra with the help of the following equation:

$$x_A = A_k / \boldsymbol{A_k} = 2\sqrt{x_I / \pi}\,, \tag{A9}$$

where $\boldsymbol{A_k}$ is a mean value of A_k in the amplitude spectrum. For example, for p_0 = 1% it is necessary to have the excess of the mean amplitude in the spectrum 2.42 times.

B) When we deal with the maximum value in a spectrum. The test is performed using Walker's (1914) equation:

$$p = 1 - \left(1 - \exp(-x)\right)^N . \quad \text{(A10)}$$

For the maximum value in periodogram much higher values are necessary than for frequencies selected in advance (see an example in Table M2):

Table M2. Critical values of x_I and x_A with p_0 = 1%

N	2	4	8	16	32	64	128	256
x_I	5.3	6.0	6.7	7.35	8.05	8.75	9.45	10.15
x_A	2.6	2.75	2.9	3.05	3.2	3.35	3.45	3.6

With small values of N a more precise result can be obtained with Fisher's (1929) formula:

$$p = \sum_{j=1}^{\left[\frac{N}{x}\right]} (-1)^{j-1} C_N^{j-1} \left(1 - jx/N\right)^{N-1} , \quad \text{(A11)}$$

where square brackets over the summation sign denote an integer part of the respective number. Within the above described algorithm, in equations (A10) and (A11) N equals the total number of frequencies in a spectrum; with the selection of a certain neighborhood, N is the number of frequencies in this neighborhood.

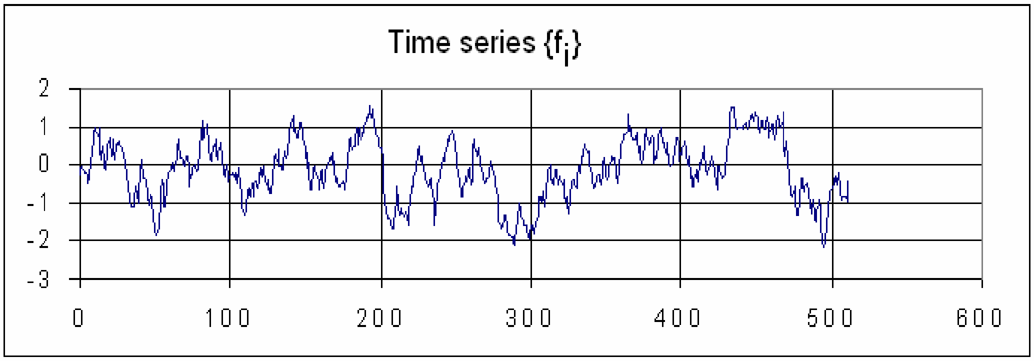
A more complex problem is constituted by the estimation of the statistical significance of I_k that is smaller than the maximum. There are a number of algorithms that differ substantially from each other. It appears reasonable to use the not very rigorous but simple Whittle's (1952) algorithm. This algorithm implies that after the test of the maximum value of I_k (if it passed the test), the number of frequencies is reduced by one, and the whole computation is conducted anew. A certain difficulty may lie here in the point that if the maximum I_k is very high, then it turns out to be necessary to make a new approximation of the spectrum and to compute all the $\boldsymbol{I_k}$ anew.

As an example consider a random process (Fig. M2) that is close to a process with uncorrelated increments:

$$f_i = 0.9\, f_{i-1} + R(-0.5, 0.5) + 0.1\, (f_{i-1} - f_{i-2}) = f_{i-1} + R(-0.5, 0.5) - 0.1\, f_{i-2} \quad \text{(A12)}$$

where R(-0.5, 0.5) is an evenly distributed random number in the diapason (-0.5, 0.5):

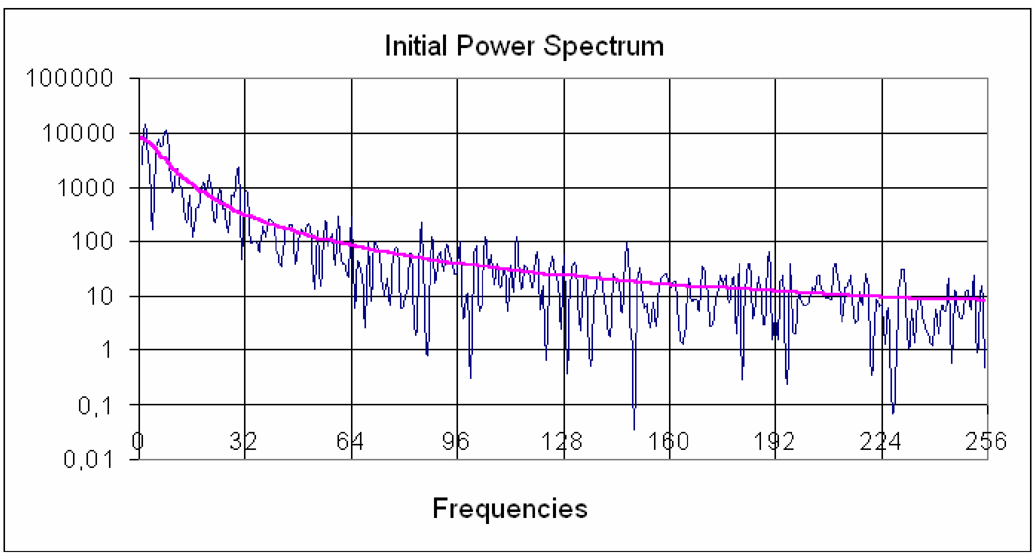
Fig. M2. An Example of Process



In this case the spectral density (Fig. M3) may be approximated with the following equation:

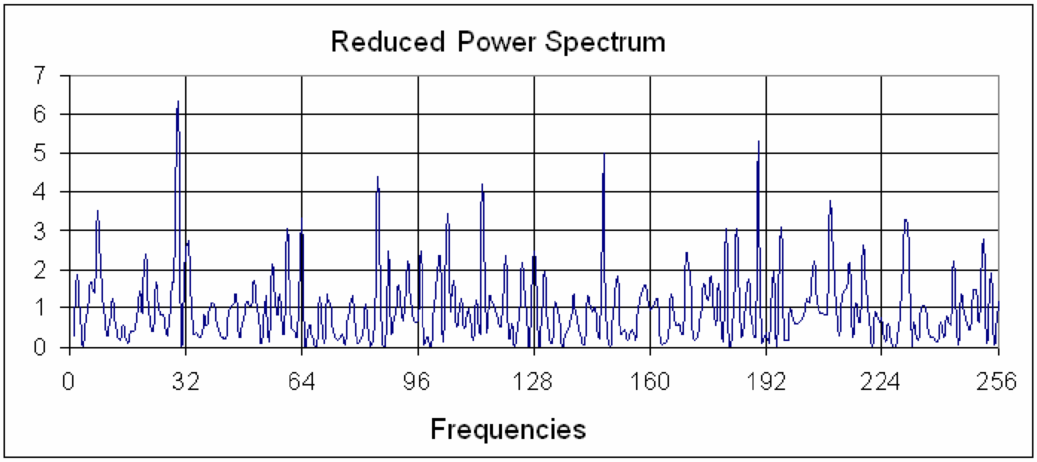
$$f(\omega) \approx a + b \cdot \alpha/(\alpha^2 + \omega^2) \approx 3.022 + 327.2 \cdot 0.03887/(0.03887^2 + \omega^2) \quad \text{(A13)}$$

Fig. M3. Initial Power Spectrum



For the detection of periodic components we shall consider the reduced power spectrum $x = I_k / \boldsymbol{I_k}$. (Fig. M4), that is the ratio of actual values of I_k to the approximation $f(\omega)$.

Fig. M4. Reduced Power Spectrum



In the reduced spectrum the most likely candidate for the periodicity is the 30^{th} component; however, its statistical significance is only 35%. Yet, if it had been proposed in advance that we should expect a cycle with such a frequency, then the respective hypothesis would have been supported at 0.17% level (p = 0.0017).

APPENDIX 2: Empirical Evidence on the Word GDP Dynamics

We have used Maddison's (2009) database as the main source of empirical estimates of the world GDP dynamics. The main problem was constituted here by the fact that Maddison provides yearly empirical estimates for the period after 1950, whereas for the 1870–1950 period he only provides world GDP estimates for the following years: 1870, 1900, 1913, 1940, and 1950.

However, *for the 1940–1950 period* the situation is not really problematic. Indeed, for this period Maddison provides annual GDP estimates for the following groups of countries: Western Europe, Western Offshoots (*i.e.*, Australia, New Zealand, Canada, and the USA), 8 major Latin American countries (Argentina, Brazil, Chile, Colombia, Mexico, Peru, Uruguay, Venezuela); he also provides empirical estimates for the following countries: USSR, India, Indonesia, Japan, Philippines, Korea, Taiwan, Malaysia, Sri Lanka, Turkey, Bulgaria, Hungary, Costa Rica, Cuba, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Paraguay). The only major country missing from this list seems to be China (though it has turned out to be possible to reconstruct the outline of its GDP dynamics on the basis of the available economic histories of this country). In general, in 1940 those countries produced 82.5% of all the world GDP, so even with an exponential interpolation for the rest of the countries the resulting error cannot be significant. Yet, as we shall see for the most important countries not covered by Maddison estimates (first of all China) a much more accurate interpolation is possible, whereas the remaining countries (mostly in Africa) did not experience in 1940–1950 any fluctuations comparable with the main GDP producers of this period, which were strongly affected by the Second World War, and the post-war recovery/reconversion.

For *the 1913–1940 period* Maddison provides annual estimates mostly for the same countries and regions. However, his dataset does not contain annual estimates for the following countries and years: Russia/USSR (1914–1927); Ireland and Greece (1914–1920); most small Latin American countries (most of the period). This is compensated rather significantly by the presence in Maddison's data of annual estimates of the Chinese GDP for the 1929–1938 period. In addition, for most of the period in question Maddison provides empirical estimates for most of the Eastern European countries not covered for the 1940–1950 period. As a result, for example, for 1938 we have approximately the same coverage of the world GDP production (82.42%) as we have for 1941 (82.46%). The reconstruction of the World GDP dynamics in the 1913–1940 period is further facilitated by a rather detailed coverage provided by Maddison for the year 1929. For this year Maddison provides his empirical estimates for all the European countries, "Western Offshoots", USSR, most of Latin American countries, almost all the Asian countries (with a major exception of West Asia, but still including Turkey). Thus, the major exceptions here are constituted by West Asia and Africa that were not major GDP producers of that time – in general, the countries covered by Maddison's dataset for the year 1929 produced in 1940 more than 92% of all the world GDP.

For *the period between 1900 and 1913*, in addition to countries for which the dataset lacks information for the more recent periods, it does not contain annual empirical estimates for Russia, China, Turkey, and all the small Latin American countries for the whole of this period; for Korea and Malaysia it does not provide data for a part of this period (1901–1910). As a result, for this period Maddison's dataset covers a smaller fraction of the world GDP dynamics than for the more recent periods but it still covers the predominant part of it – for example, the countries for which Maddison provides GDP estimates for the year 1901 produced 68% of all the world GDP in the year 1900.

For *the 1870–1900 period* Maddison's dataset lacks estimates for some large Latin American countries (and for all the smaller ones), as regards Asia, it only provides empirical estimates for Japan, Indonesia, and Sri Lanka for the whole period, and it does for India starting from 1884. However, even Maddison's data for 1871 still cover almost half of all the world GDP, whereas already for 1884 it covers almost two thirds of it (65.5%). The reconstruction of the World GDP dynamics in the 1870–1900 period is further facilitated by a rather detailed coverage provided by Maddison for the year 1890. For this year, in addition to the countries mentioned above, Maddison provides estimates on the

GDP of the following countries and groups of countries: small Western European countries, Eastern Europe, Argentina, Mexico, China (!), and Thailand. As a result, for this year his dataset covers about 85% of all the world GDP production.

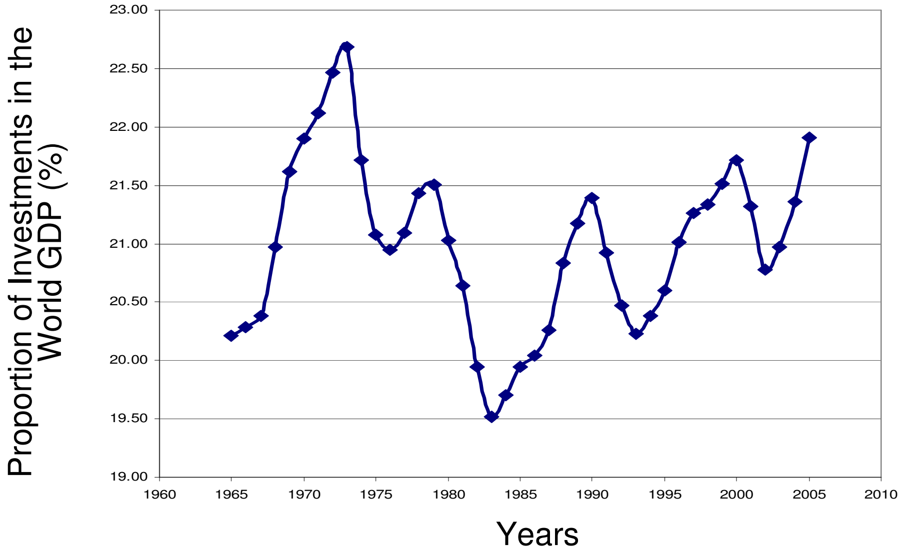
To sum up, for the 1870–1950 period Maddison provides world GDP estimates for 1870, 1900, 1913, 1940, 1950 that makes it possible to calculate directly the average world GDP growth rates for 1870–1900, 1900–1913, 1913–1940, and 1940–1950. In addition, his annual data cover more than 80% of all GDP production for the following years: 1890, 1930–1939, 1941–1949, whereas for the year 1929 Maddison's dataset covers more than 90% of all the world GDP production. Hence, we can reconstruct with a considerable degree of confidence dynamics of the world GDP growth rates for the 1929–1950 period, whereas we can be quite confident about average annual growth rates in the following periods: 1870–1890, 1890–1900, 1900–1913, 1913–1920, 1920–1929.

In addition, some interpolations can be done with a considerable degree of confidence. For example, as we know for most of the period in question the annual GDP estimates for all the major Latin American countries we can interpolate the annual growth rates for the rest of Latin America on this basis.

Note that the main source of the uncertainty of the world GDP dynamics for the period in question is constituted by the absence of GDP data on China for 1871–1889, 1891–1899, 1901–1912, 1914–1928, and 1939–1949; on Russia/USSR for 1871–1899, 1901–1912, and 1914–1927; on India for 1871–1883. Note that in 1870 the share of those three countries in the world GDP constituted 37% (whereas the total percentage of the world GDP not covered by Maddison's estimates was for 1871 just about 50%). Thus, if it is possible to reconstruct the GDP dynamics of those three countries in those periods for which we lack Maddison's estimates, then it is possible to reconstruct with a sufficient degree of confidence the overall world GDP dynamics for the period in question. Such a reconstruction has turned out to be possible, as for the periods in question we have a sufficient amount of economic histories of the respective countries, including data on all the major crop failures that (in addition to major political upheavals) were the main sources of GDP fluctuation in those countries that were still predominantly agrarian in the period in question (Rastiannikov, Deriugina 2009; Feuerwerker 1980, 1983; Perkins 1969; Rawski 1989; Samohin 2001: 108–234; Bobovich 1995; Davydov 2003; Guseinov 1999; Nove 1991; Gregory 1983, 2003; Nefedov 2005; Habib 2006; Kumar, Desai 1983; Tomlinson 1996; Roy 2002).

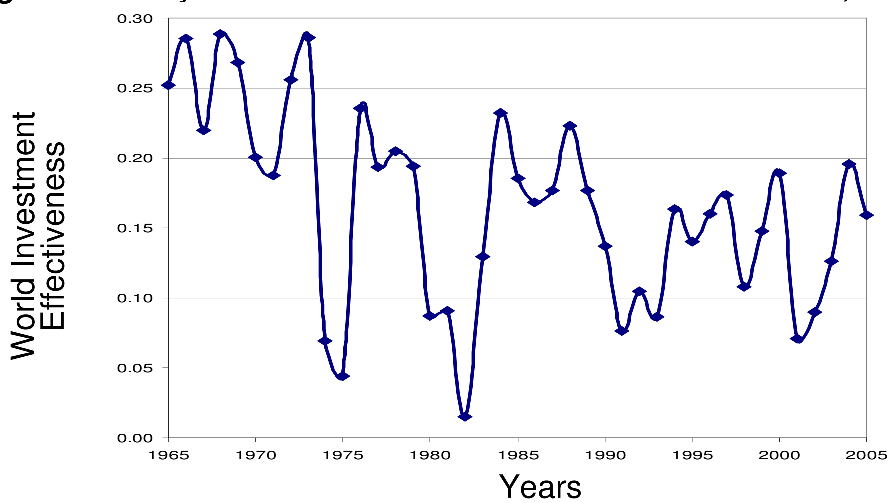
APPENDIX 3: Supplementary Figures

Fig. S1. Dynamics of Proportion of Investments in the World GDP (%), 1965–2005



Source: World Bank 2009*a*[21].

Fig. S2. Dynamics of the World Investment Effectiveness, 1965–2005



Source: World Bank 2009*a*[22]. *Note*: This variable indicates how much dollars of the world GDP growth is achieved with one dollar of investments.

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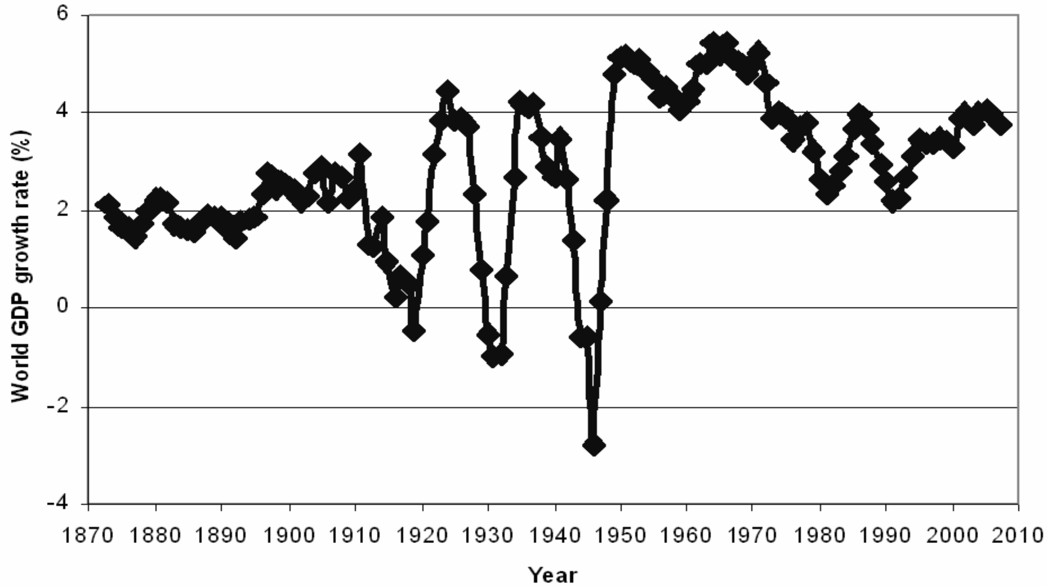
[21] Dynamics of this variable has been calculated by Yustislav Bozhevolnov (Moscow State University, Department of Physics) with the World Bank database through dividing of the world gross fixed capital formation indicator (in constant international 2000 dollars) for a given year by the world GDP (in constant international 2000 dollars) for the same year.

[22] Dynamics of this variable has been calculated by Yustislav Bozhevolnov.

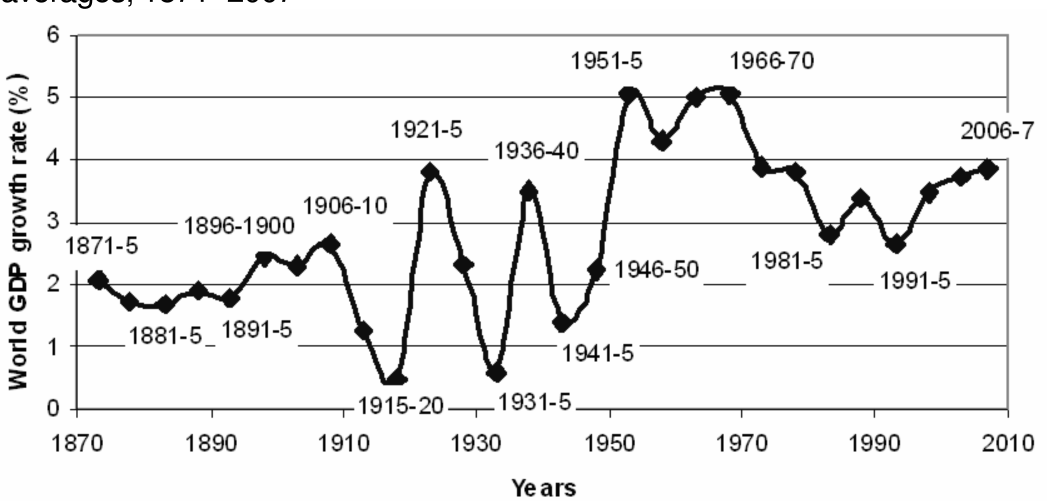
Fig. S3. Dynamics of the World GDP annual growth rates (%), moving 5-year averages, 1871–2007



Sources: World Bank 2009*a*; Maddison 2009.

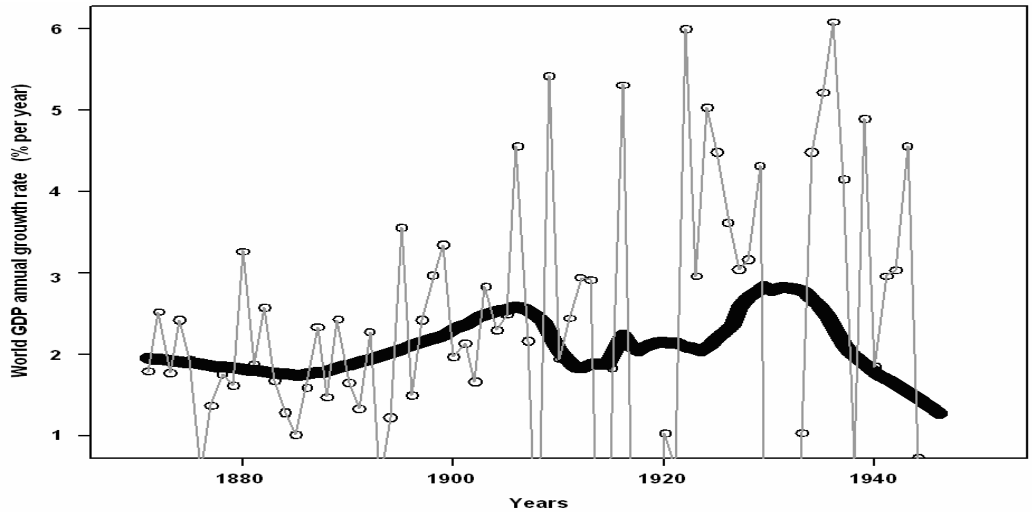
Note: 1873 point corresponds to the average annual growth rate in 1871–1875, 1874 to 1872–1876, 1875 to 1873–1877… 2005 to 2003–2007; 2006 and 2007 points correspond to the annual growth rates in years 2006 and 2007 respectively.

Fig. S4. Dynamics of the World GDP annual growth rates (%), 5-year averages, 1871–2007



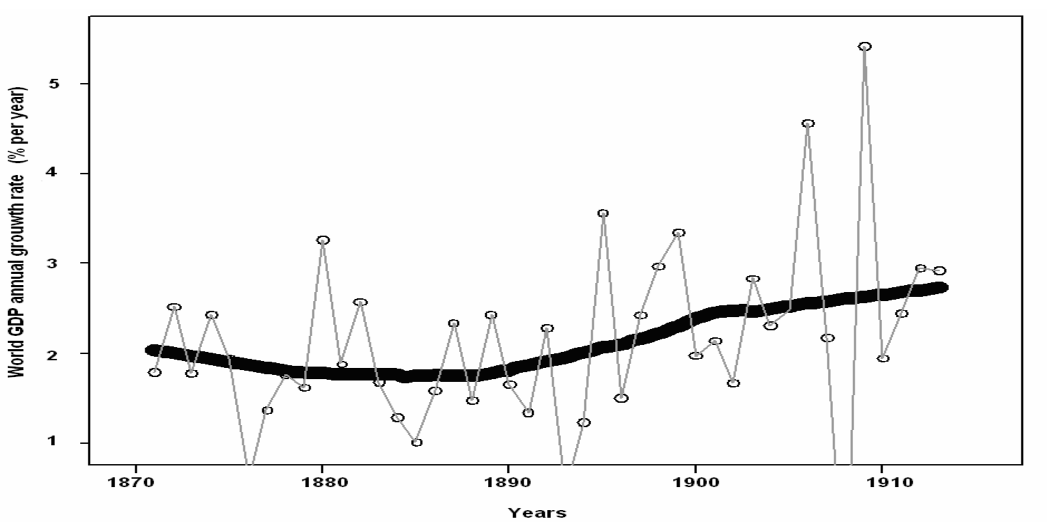
Sources: World Bank 2009*a*; Maddison 2009.

Fig. S5. World GDP annual growth rate dynamics (1870-1946): Maddison empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line



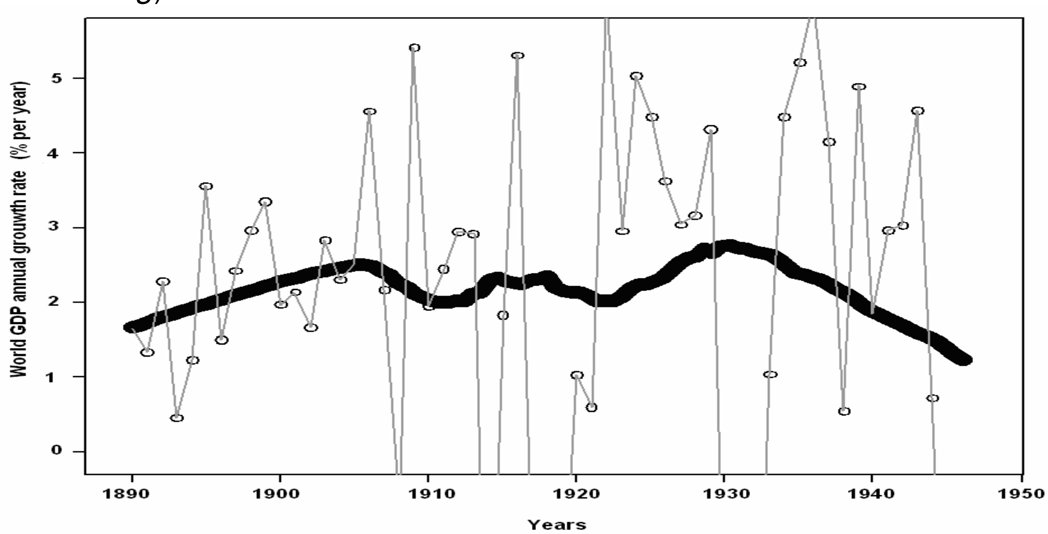
Note: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. Kernel: Triweight. % of points to fit: 40.

Fig. S6. World GDP annual growth rate dynamics: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. Phase B (Downswing) of the 2nd Kondratieff Wave and Phase A (Upswing) of the 3rd Wave, 1871–1913



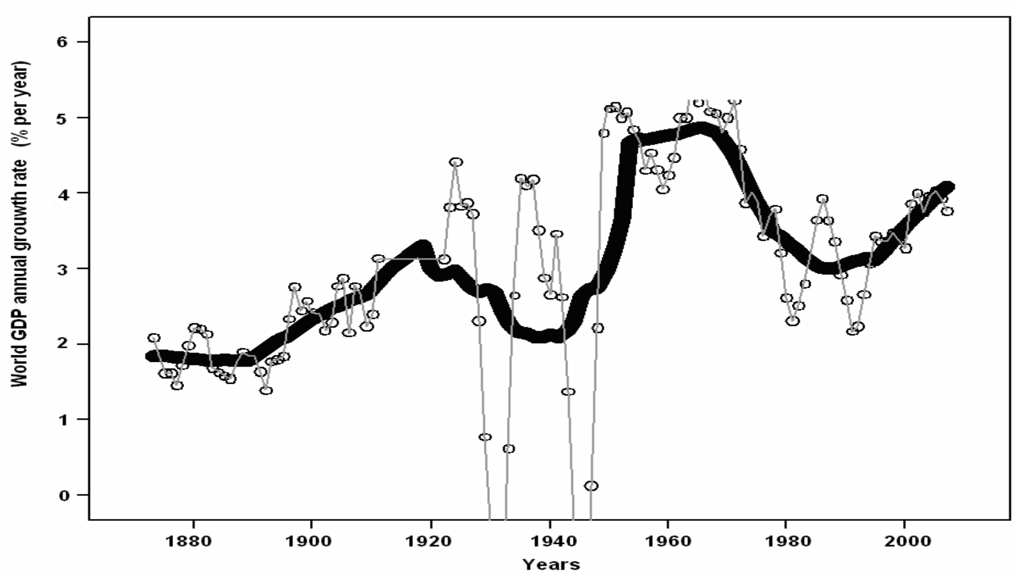
Note: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. Kernel: Triweight. % of points to fit: 50.

Fig. S7. World GDP annual growth rate dynamics: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. The 3rd Kondratieff Wave



Note: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. Kernel: Triweight. % of points to fit: 60.

Fig. S8. World GDP annual growth rate dynamics, 5-year moving average: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. 1870–2007, omitting World War 1 influence



Note: Maddison-based empirical estimates with fitted LOWESS (=*LOcally WEighted Scatterplot Smoothing*) line. Kernel: Triweight. % of points to fit: 20.

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