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The International Trade Network: weighted network analysis and modelling

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Abstract. Tools of the theory of critical phenomena, namely the scaling analysis and universality, are argued to be applicable to large complex web-like network structures. Using a detailed analysis of the real data of the International Trade Network we argue that the scaled link weight distribution has an approximate log-normal distribution which remains robust over a period of 53 years. Another universal feature is observed in the power-law growth of the trade strength with gross domestic product, the exponent being similar for all countries. Using the 'rich-club' coefficient measure of the weighted networks it has been shown that the size of the rich-club controlling half of the world's trade is actually shrinking. While the gravity law is known to describe well the social interactions in the static networks of population migration, international trade, etc, here for the first time we studied a non-conservative dynamical model based on the gravity law which excellently reproduced many empirical features of the ITN.

Keywords: critical exponents and amplitudes (experiment), network dynamics, random graphs, networks

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Are those large real or man-made networks with complicated and heterogeneous connections scale-invariant and obey the well-known scaling analysis and universality concepts of Statistical Physics? In recent years, extensive research effort have been devoted to analysing the structure, function and dynamics of complex networks relevant to multidisciplinary fields of science [1]–[3]. Indeed scale-free networks reflect such scale invariance in the link–node structures of electronic communication networks like the Internet, World Wide Web, protein interaction networks and even in research collaboration networks. More recently it has been observed that the strengths of links of the networks, called weights in graph theory, also have very interesting properties and can shed much light into the understanding of the details of the network [4]–[8]. Lately it has been proposed that the International Trade Network (ITN), i.e. the system of mutual trading between different countries in the world, can also be viewed as an interesting example of real-world network [9]–[15].

In this paper we study the ITN as an excellent example of the weighted networks obeying the scale-invariance and universality properties where the extent of trade between a pair of countries can be treated as the link weight [16, 17]. It is observed that the suitably scaled link weight distribution over many years can be approximated well by a log-normal law. The nodal strength measuring the total volume of trade of a country is seen to depend nonlinearly on the country's gross domestic product with a robust exponent. Many features observed in the analysis can be explained with a simple dynamical model, which has the well-known gravity model of international trade as its starting point [18].

In the ITN, a node depicts a country and an undirected link exists between any pair of nodes if the trade volume between the corresponding countries is non-zero. Both the number of nodes N and the number of links L in the ITN show annual variation and grow almost systematically over 53 years, e.g. in 1948 $N = 76$ and $L = 1494$ whereas in 2000 $N = 187$ and $L = 10\,252$. On the other hand the link density $L/[N(N-1)/2]$ is observed to remain roughly constant, with values around 0.52 for the same period. The annual trade data are expressed in millions of dollars (M\$) of imports and exports between countries i and j using four different quantities $\exp_{ij}$, $\exp_{ji}$, imp_{ij} and imp_{ji} [16, 17]. Due to differences in reporting procedures, there are usually small deviations between exports $\exp_{ij}$ from i to j and imports imp_{ji} to j from i. Therefore, we define the link weight w_{ij}, as a measure of the total trade volume between the two countries (in M\$), as follows:

$$w_{ij} = (\exp_{ij} + \exp_{ji} + \text{imp}_{ij} + \text{imp}_{ji})/2. \quad (1)$$

This quantity tends to average out the aforementioned discrepancies. The distribution of weights is observed to be broad, with the smallest non-zero trade volume being less than 1 M\$ and the largest of the order of 10^5 M\$. The number of links with very small weights is quite large, whereas only a few links with very large weights exist (figure 1). The tail of the distribution consists of links connecting very few high-income countries [19]. The average weight per link is observed to grow during the investigated period, from 15.54 M\$ in 1948 to 308.8 M\$ in 2000.

The probability density distribution of the link weights is defined as the probability $\text{Prob}(w)\,\mathrm{d}w$ that a randomly selected link has a weight between w and $w + \mathrm{d}w$. The probability decays systematically with increasing weight and has a long tail with considerable fluctuation. We note that inferring the form of a broad probability distribution based on a relatively small number of data points has its difficulties; in

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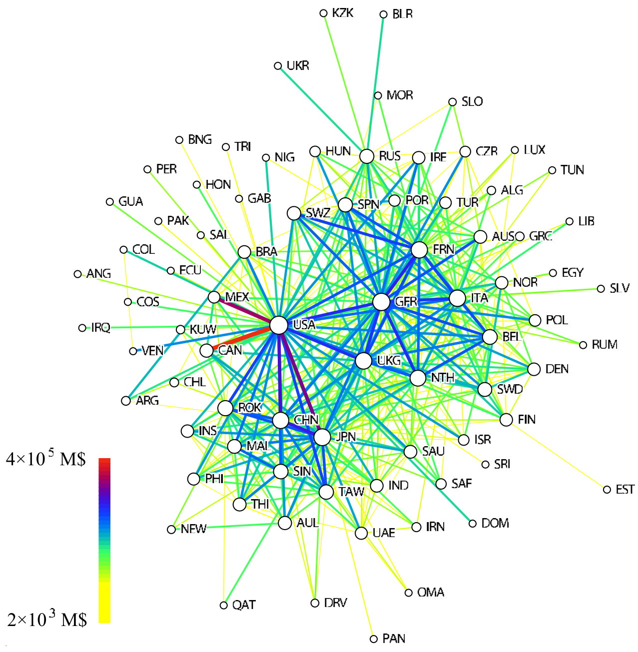

Figure 1. A subnetwork of the ITN for the year 2000, where only links with the highest 4% of weights and the associated nodes (countries) are included [20], yielding in total 80 nodes and 411 links. The node size is proportional to its strength and link colour to its weight. Link weights are defined as the volume of annual trade between two countries in M$.

the case of ITN, log–log plots of the distributions (not shown) display small intermediate linear regions which are (too) often interpreted as power laws. However, the tails of the distributions show clear curvature and much better fits to data are obtained by using a log-normal distribution of the form

$$\mathrm{Prob}(w) = \frac{1}{\sqrt{2\pi\sigma^2}}\frac{1}{w}\exp\left(-\frac{\ln^2(w/w_0)}{2\sigma^2}\right), \tag{2}$$

where the constants defined as $w_0 = \exp(\langle\ln(w)\rangle)$ and $\sigma = \{\langle(\ln(w))^2\rangle - \langle\ln(w)\rangle^2\}^{1/2}$ are observed to have different values for the weight distributions for different years. However, one can get a plot independent of w_0 and σ by drawing $-2\sigma^2\ln[\mathrm{Prob}\{\ln(w)\}\sqrt{2\pi\sigma^2}]$ as a function of $\ln(w/w_0)$, which gives a simple parabola $y = x^2$ for all years (note that $\mathrm{Prob}\{\ln(w)\}\,\mathrm{d}\{\ln(w)\} = \mathrm{Prob}(w)\,\mathrm{d}w$ implies $\mathrm{Prob}\{\ln(w)\} = w\mathrm{Prob}(w)$). In figure 2 we show such a plot, where the data has been aggregated for five-year periods to reduce noise, i.e. 1951–55, 1956–60, …, 1996–2000, each represented with its own symbol. It is clearly seen that the data points for each period fall close to the parabola $y = x^2$, displayed as a solid line. Therefore, we conclude that the annual weight distributions are reasonably well approximated by the log-normal distribution. This log-normal distribution of trade volumes has been discussed also in [12]. Note also that the trade imbalances have been reported to follow a log-normal distribution [13].

For weighted complex networks, the strength s_i of node i is defined as $s_i = \Sigma_j w_{ij}$ [4], which in the case of the ITN corresponds to the total volume of annual trade associated

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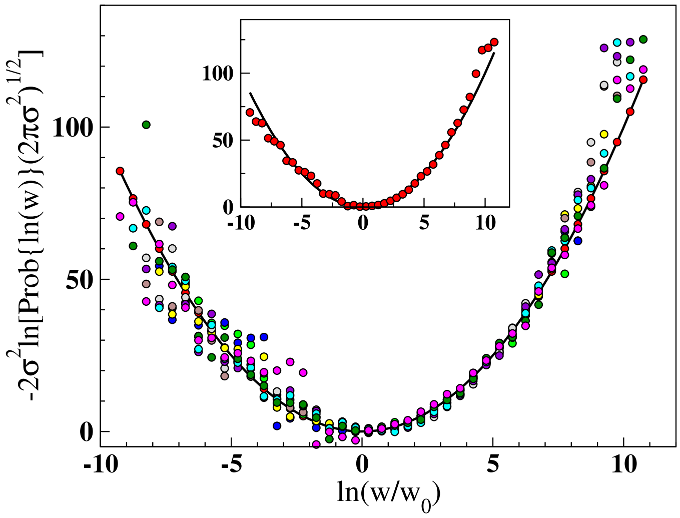

Figure 2. The probability distribution of link weights of the ITN. This plot displays $-2\sigma^2 \ln[\mathrm{Prob}\{\ln(w)\}\sqrt{2\pi\sigma^2}]$ as a function of $\ln(w/w_0)$. The data points scatter around the parabola $y = x^2$ (solid line), which implies a log-normal probability distribution (see text). Different symbols depict empirical distributions where the data have been aggregated over five-year periods. The inset shows the distribution of all link weights over the time span of 50 years from 1951 to 2000.

with a node. Intuitively, one can expect that in general the strengths of high-GDP countries are higher than those of the low-GDP countries. To see this in a quantitative fashion, we have utilized an elastic constant γ to measure how changes in strength respond to changes in GDP (we have used total gross domestic product of the country and not the GDP per capita without taking into account inflation). Hence, we define γ as: $(\mathrm{d}s/s)/(\mathrm{d}G/G) = \gamma$, which results in a power-law relationship $s_i \propto G_i^{\gamma}$. In figure 3 we plot the strengths s_i versus GDP G_i for 22 different countries, representing a good mix of economic strengths, i.e. 10 high, 5 middle and 7 low income countries. It is observed that the strength of each country grows nonlinearly with its GDP with approximately the same slope. In the inset of this figure we show the probability distribution of γ values for 168 different countries. The distribution has a long tail and the γ values of 12 countries are found to be larger than 2. A detailed inspection reveals that the majority of these 12 countries are those originating after the Soviet Union, Yugoslavia and Czechoslovakia were fragmented. An overall average of the growth exponents has been estimated to be $\gamma = 1.26$, which comes down to 1.06 if these 12 countries are not considered for the averaging. The peak value of the distribution occurs very close to $\gamma = 1$. Interestingly, Irwin [21] has observed earlier that the total world export volume varies as a function of the total world real GDP to the power of 1.16, along with other factors. In comparison, however, our observation reveals a more detailed picture, indicating that the total trade volumes of individual countries are also approximately power laws as a function of their individual GDPs, with exponents close to this value.

Non-trivial correlations among the nodes of different real-world networks have been observed. For an unweighted network this means that large degree nodes are connected

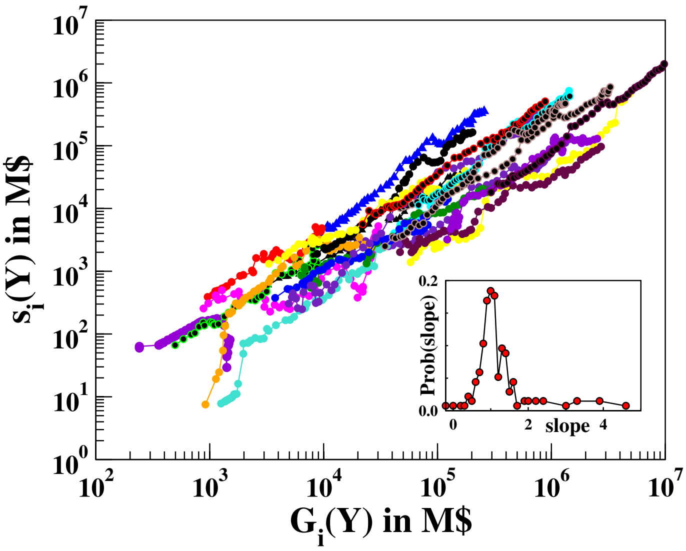

Figure 3. The dependence of strength $s_i(Y)$ of country i measuring its total volume of trade on its GDP $G_i(Y)$ in year Y, plotted for each country (colour coded) over the 53 year span from 1948 to 2000. The general trend corresponds to a nonlinear growth with an average exponent of around 1.2. The inset shows the distribution of exponents associated with individual countries.

among themselves, forming a club. More precisely, such a club consists of a subset of n_k nodes whose degree values are at least k. A rich-club coefficient (RCC) is measured as $\phi(k) = 2E_k/[n_k(n_k - 1)]$, where E_k is the number of links actually existing in the club and $[n_k(n_k - 1)]/2$ is the total number of node pairs in the club [22]. A high value of $\phi(k)$ implies that members are indeed tightly connected. However, it has been realized that only this definition is not enough, since with this measure even uncorrelated random graphs show some rich-club effect as well [22]. It is suggested that one needs to define a 'null model' or the maximally random network (MRN) keeping the nodal degree values $\{k_i\}$ preserved, measure the corresponding RCC $\phi_{\rm ran}(k)$ and observe the variation of the ratio $\rho(k) = \phi(k)/\phi_{\rm ran}(k)$. We have executed the same analysis for the ITN for the year 2000 and generated the MRN using the pairwise linked exchange method [22]. However, it is observed that the variations of $\phi(k)$ and $\phi_{\rm ran}(k)$ with k are nearly the same and consequently $\rho(k)$ is nearly equal to unity for the whole range of degree values.

Next we studied the rich-club effect of the same ITN but now considering it as a weighted network. The rich-club is now defined as the subset of nodes whose strengths are at least s controlling a major share of the world's trade dynamics. The RCC of the weighted network is defined as

$$R_w(s) = 2\Sigma_{i,j} w_{ij}/[n_s(n_s - 1)]. \tag{3}$$

The corresponding maximally random weighted network (MRWN) has been generated keeping both the nodal degrees $\{k_i\}$ as well as the nodal strength values $\{s_i\}$ preserved.

To generate the MRWN from the MRN of the ITN of the year 2000 described above a self-consistent iteration procedure is used to obtain the link weight distribution consistent with the nodal strength list $\{s_i\}$. We start assigning arbitrary random numbers as the

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weights w_{ij} to all links maintaining that the weight matrix is always symmetric, i.e. $w_{ij} = w_{ji}$. For an arbitrary node i the difference $\delta_i = s_i - \Sigma_j w_{ij}$ is calculated. Weights of all k_i links meeting at the node i are then updated as

$$w_{ij} \to w_{ij} + \delta_i \left(w_{ij} / \Sigma_j w_{ij} \right), \tag{4}$$

to balance s_i and $\Sigma_j w_{ij}$. By repeated iterations the link weights quickly convergence and attain consistency with nodal strengths $\{s_i\}$. It is checked that the $\langle s_i s_j \rangle \sim w_{ij}$ relation is well satisfied for this MRWN.

In figure 4(a) we plot both $R_w(s)$ for the ITN and $R_w^{\text{ran}}(s)$ for the MRWN with the scaled nodal strength s/s_{max}. The two measures are found to be nearly the same, growing like $s^{0.85}$ for large s values and their ratio $\rho_{\text{ran}}(s)$ is nearly equal to 1, except for a few values of s near s_{max} (figure 4(b)).

To explain this we observe that only 15% of the elements of the adjacency matrices of the ITN and the MRN are different. Therefore a typical node of the ITN retains the links to most of its neighbors even after maximal randomization. This is because of the high value of the link density (59%) of the ITN for the year 2000. As a result $\rho_{\text{ran}}(k)$ as well as $\rho_{\text{ran}}(s)$ are nearly equal to unity. This implies that the pairwise link connections and the associated link weights of the original ITN are very close to those of the corresponding MRWN. In fact, one can say that the original ITN is a typical member of the different random configurations of the MRWN when the $\{k_i\}$ as well as $\{s_i\}$ sets of the ITN are preserved. These results on the randomized unweighted ensemble confirms the results in [10] when compared with randomized networks with fixed degree sequence as in [14].

Zhou and Mondragón [23] observed a very similar behaviour for the Internet statistics. Following them we conclude that rich nodes in the original ITN and in its corresponding MRN and MRWN are tightly connected and the similarity of the rich-club connectivity in the ITN structure (with and without weights) does not imply that ITN lacks a rich-club structure.

In fact, the presence of the rich-club effect is evident even if we simply analyse the variation of the fraction $f_w(s)$ of the total volume of trade taking place among the members of the club. This is depicted in figure 4(c) which shows that $f_w(s)$ remains close to unity until high values of s/s_{max}, then decreases gradually to 1/2 at $s/s_{\text{max}} \approx 0.11$, and finally drops sharply. Very interestingly we also observe that the size of the rich club containing 50% of the total volume of annual trade shrinks almost systematically from 19% in 1948 to 8% in 2000.

The very heterogeneous distribution of trade volumes in the ITN is also reflected in the average pair correlation function $\langle s_i s_j \rangle$ of nodal strengths and in its power-law dependence on the link weights w_{ij}. Links with high weights $w_{ij} \sim w_{\text{max}}$ obviously must connect pairs of nodes of high strength, and for them $\langle s_i s_j \rangle \sim s_{\text{max}}^2$. On the other hand, for links of weights around unity, $\langle s_i s_j \rangle \sim s_{\text{max}}$. Assuming that w_{max} itself is of the order of s_{max}, we find an upper bound for the exponent $\nu = 1$ describing the variation of $\langle s_i s_j \rangle \sim w_{ij}^{\nu}$. Our analysis of the ITN yields, however, a somewhat smaller value of ν, being between 0.65 and 0.90 for different financial years between 1948 and 2000. The dependence of the weight distribution on the underlying topological structure of the ITN is studied by measuring the average strength of a node as a function of its degree, which turns out to exhibit a strong degree of nonlinearity: $\langle s(k) \rangle \propto k^{\mu}$, where μ varies between 3.4 and 3.7 for the same period.

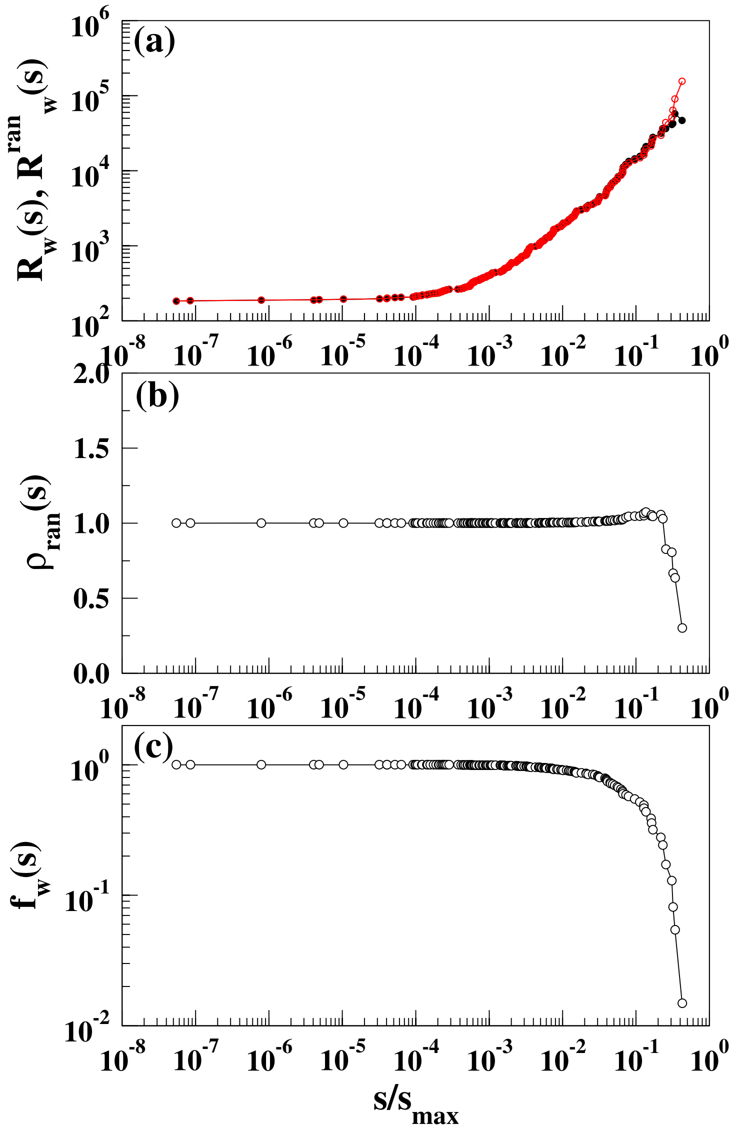

Figure 4. (a) The weighted rich-club coefficients $R_w(s)$ (black) and $R_w^{\mathrm{ran}}(s)$ (red) for the ITN of the year 2000. (b) The ratio $\rho_{\mathrm{ran}}(s)$ of these two coefficients is nearly equal to unity over the whole range of variation and (c) $f_w(s)$ of the international trade volume among the rich-club members having strengths s and above.

We now develop a dynamical model based on the well-established gravity model [18] used in social and economic sciences to describe the flow of social interaction between two economic centres i and j as a function of their economic sizes m_i, m_j and distance ℓ_{ij}: $F_{ij} = Gm_im_j/\ell_{ij}^2$. This equation has been generalized to the parametric form [24]

$$F_{ij} = m_i^{\alpha}\left(\frac{m_j^{\beta}}{\ell_{ij}^{\theta}}\bigg/\Sigma_{k\neq i}\frac{m_k^{\beta}}{\ell_{ik}^{\theta}}\right), \tag{5}$$

where the exponents α and β usually range between 0.7 and 1.1 whereas θ is observed to be around 0.6 [24].

In our model, we assume a unit square to represent the world and N points distributed at random positions representing the capital cities of different countries. Initially the GDP values m_i $(i = 1, N)$ are randomly assigned with uniform probability such that the total GDP is unity: $\Sigma_{i=1,N} m_i = 1$. Then we let the dynamics start, which is essentially a series of pairwise interactions. There are different pairwise wealth exchange models studied in the literature which calculate the distribution of wealth in a society [25]. A pair of countries (i, j) is randomly selected $(1 \leq i, j \leq N)$ for a transaction and time t is measured as the number of such transactions. In a transaction the selected countries invest the amounts F_{ij} and F_{ji} calculated using equation (5). Then the total amount of investment $\tilde{F}_{ij} = F_{ij} + F_{ji}$ is randomly shared between the two countries as a result of this transaction, as follows:

$$m_i = m_i - F_{ij} + \epsilon \tilde{F}_{ij} + \Delta_i, \tag{6}$$

$$m_j = m_j - F_{ji} + (1 - \epsilon)\tilde{F}_{ij} + \Delta_j. \tag{7}$$

Here ϵ is a random fraction freshly drawn for every transaction. The random sharing of $\tilde{F}_{ij}$ is justified by the fact that, while the gravity law describes the average interaction in terms of the strengths and distances of separation, the actual amount of trade depends on other factors, many of them political. In this idealized model countries are not allowed to make debts, which in turn makes the dynamics non-conservative through the parameters Δ_i and Δ_j. It holds for these parameters that $\Delta_i = 0$ if $F_{ij} < m_i$ and $\Delta_j = 0$ if $F_{ji} < m_j$. However, if for some transaction $F_{ij} > m_i$ or $F_{ji} > m_j$ then we add $\Delta_i = F_{ij} - m_i$ or $\Delta_j = F_{ji} - m_j$ such that after the transaction, the GDP balance does not become negative. Also after the transaction the individual GDPs are rescaled $m_i \to m_i/\Sigma_j m_j$ for the total GDP to remain unity. It is observed that a large number of pairwise transactions leads to a stationary state where $\langle m^2 \rangle$ fluctuates with time around a steady mean value. Any time after reaching the stationary state, the dynamics is used to construct a model ITN such that links are established between countries i and j whenever there is a transaction between them. We let the dynamics run until a pre-assigned link density (typically 0.3–0.5) has been reached. For example, to generate a network corresponding to the ITN of the year 2000, we take $N = 187$ and continue the exchange dynamics until $L = 10\,252$ distinct links are dropped, corresponding to the link density 0.59. The weight of a link is then defined as the total amount of investment between pairs of countries in all transactions.

For comparison the weight distribution of our model networks is analysed in the same way as the real ITN data, and it turns out that an excellent consistency with the simple parabola $y = x^2$ is observed for parameter values $\alpha = 1/2, \beta = 1, \theta = 1/2$, within a tolerance of 0.2 for all exponents, see figure 5. We also find that the GDP distribution is broad, showing a power-law-like behaviour for a short interval of m (with exponent $\sim$1.9) before finite size effects set in. This is to be compared with the real-world data where the GDP distribution of different countries has been argued to be consistent with the Pareto law [26]. Finally, as in the real ITN, the two-point strength correlation is seen to grow like $\langle s_i s_j \rangle \propto w_{ij}^{\nu}$ with $\nu \approx 0.98$ in the large weight limit, compared to the range of values 0.65–0.90 in the real ITN. In addition we find that the cumulative degree distribution is consistent with the results on the real ITN.

To summarize, we have shown that the weighted International Trade Network can be looked upon as an excellent example of a complex network obeying scale-invariance

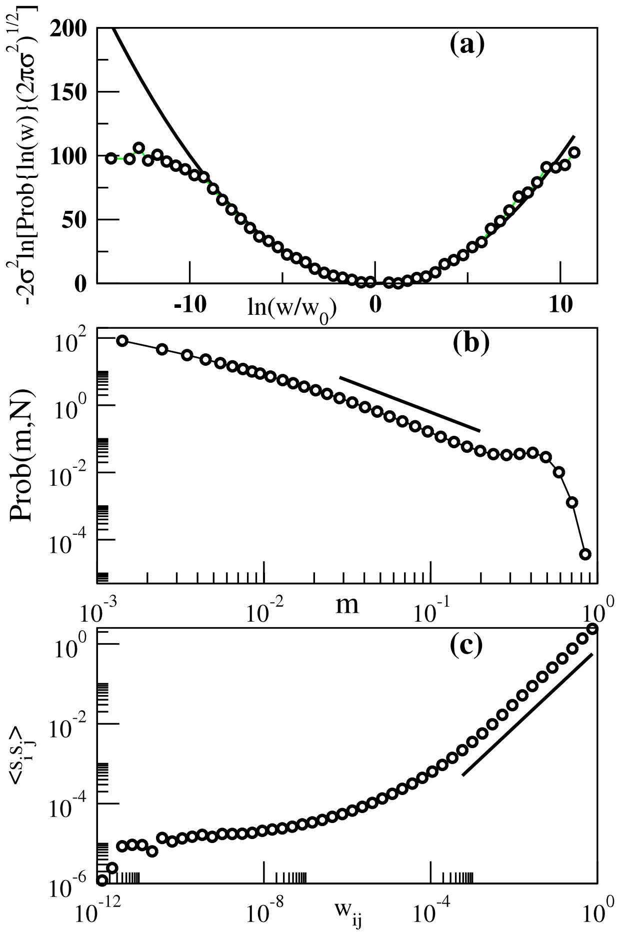

Figure 5. Model results: (a) scaled weight distribution fits well with the simple parabola $y = x^2$. (b) The GDPs of the individual countries have a broad distribution, which in the tail region seems to follow roughly a power-law behavior (shown as a line with exponent ∼1.92). (c) The strength correlation $\langle s_i s_j \rangle$ as a function of link weight is shown to grow approximately as $\langle s_i s_j \rangle \propto w_{ij}^{0.98}$.

and universality features. The scaled distributions of annual world trade volumes between countries collapse well to a log-normal distribution and it remains unchanged over a span of 53 years, implying robustness or universality. Secondly, the nodal strength measuring the total trade volume associated with a country grows nonlinearly with its GDP with a robust exponent. Also a large fraction of the global trade is controlled by a club of a few rich countries which shrinks in size as time goes on. Finally, the main features of the real-world ITN have been reproduced by using a simple non-conservative dynamical model starting from the well-known gravity model of social and economic sciences.

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