The complex network of global cargo ship movements

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Objective

Based on the network of cargo ship movements, calculate likely invasion routes of alien marine species.

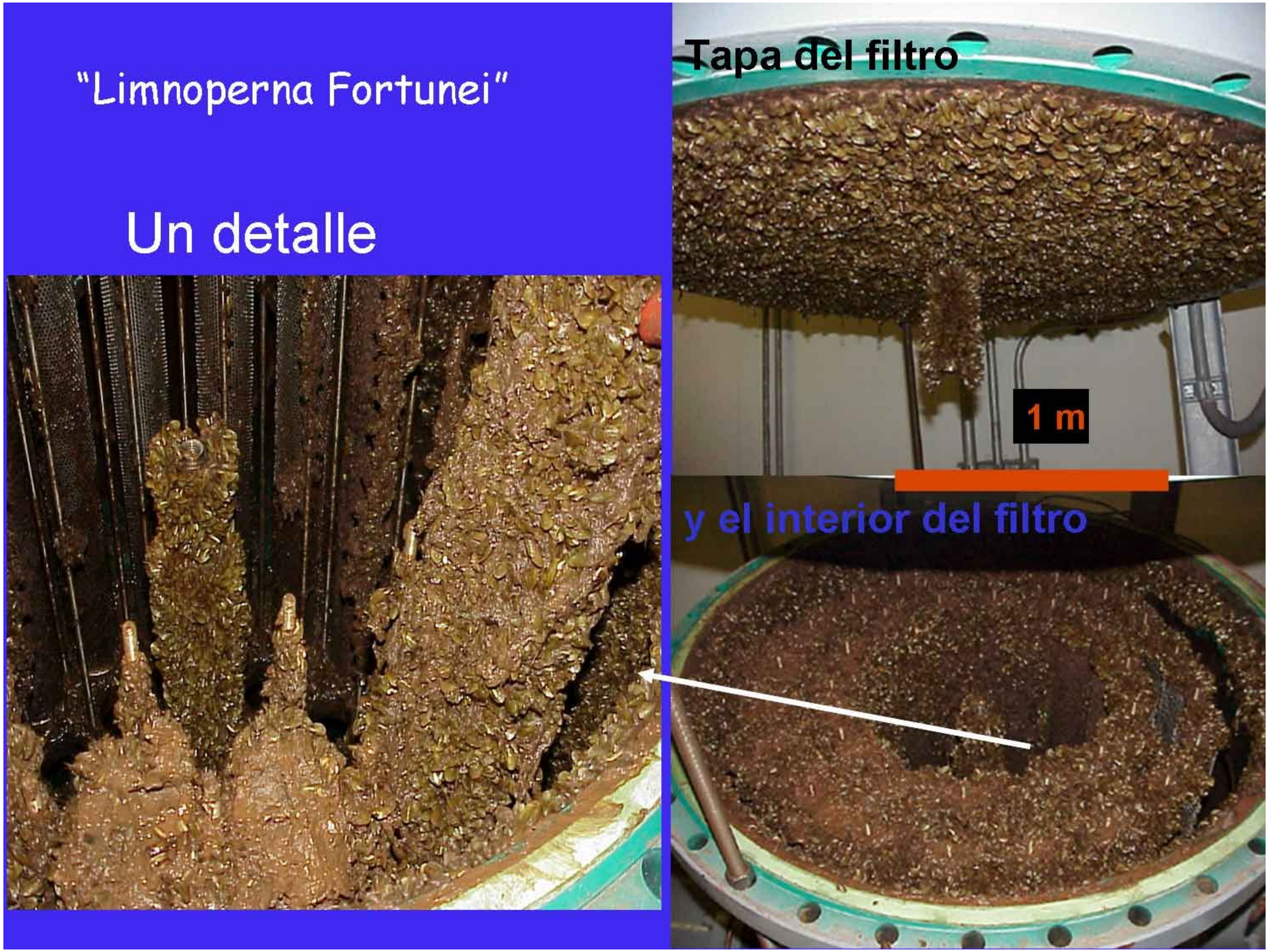
Examples of invasive species

Zebra mussel (*Dreissena polymorpha*): native to the Black and Caspian Sea, invasive in the Great Lakes of North America.

Shopping cart left for a few months in a mussel-infested lake.

Examples of invasive species

Golden mussel (*Limnoperna fortunei*): introduced into Argentina from South East Asia in 1991, within a decade spread to four other South American countries.



Filter at a hydro-electric plant.

Examples of invasive species

Shore crab (*Carcinus maenas*):
indigenous to Western Europe;
invasive in North and South America, Australia, South Africa.

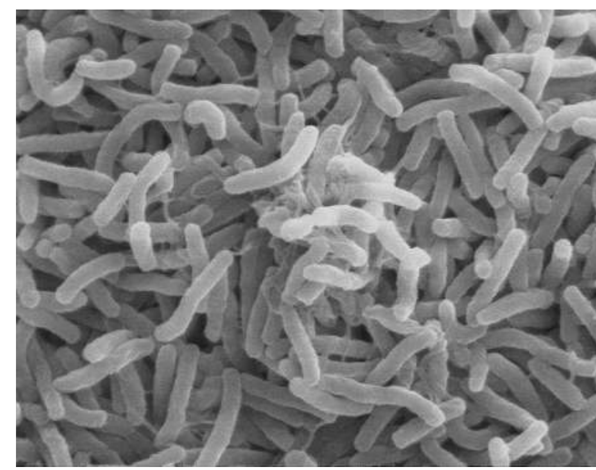
Warty comb jelly (*Mnemiopsis leidyi*):
indigenous to USA and West Indies;
invasive in Europe.

Northern Pacific seastar (*Asterias amurensis*):
indigenous to Northeast Asia;
invasive in Australia.

Examples of invasive species

Round goby (*Neogobius melanostomus*):
indigenous to Europe;
invasive in North America.

Cholera (*Vibrio cholerae*):
1991 outbreak in South America,
apparently initiated when a ship
discharged ballast water.



brief communications

Global spread of microorganisms by ships

Ballast water discharged from vessels harbours a cocktail of potential pathogens.

Why do cargo ships increase the risk of bio-invasion?

Two main pathways:

Ballast water:
added when ship is empty
to improve stability.

Hull fouling:
organisms attach themselves
to the hull during a voyage.

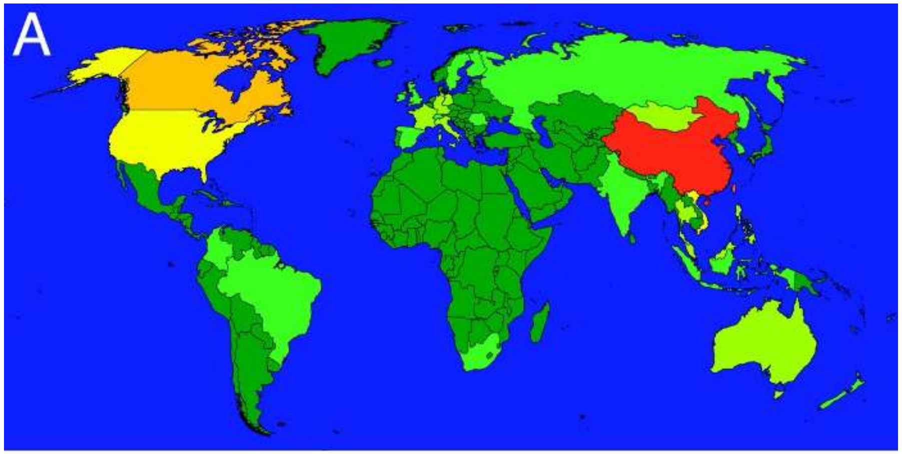
Economic damage (in US$) estimated to be in the billions.

Analogy with epidemic spread in the airline network

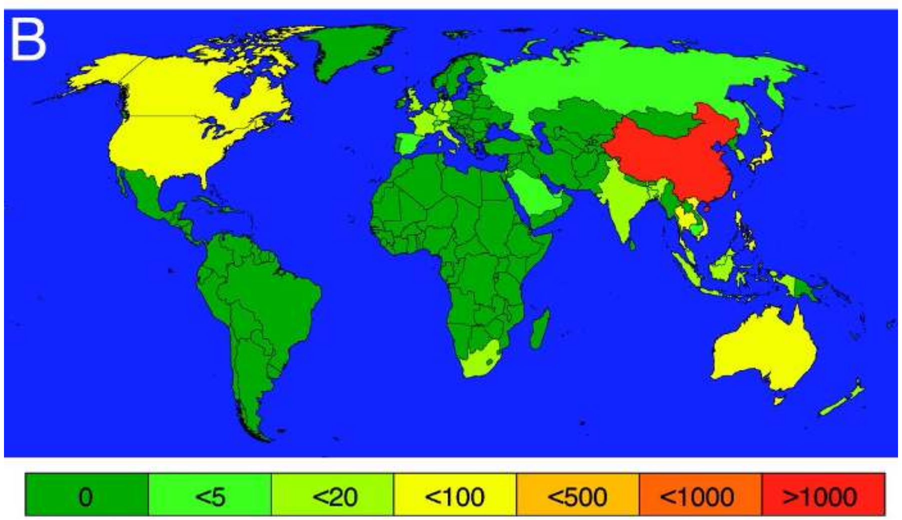
Two studies (2004 and 2005)* used the global airline network to "postdict" the 2003 SARS cases.

*Hufnagel, Brockmann, Geisel (2004) and Colizza, Barrat, Barthelemy, Vespignani (2005), both PNAS

SARS prediction



Observed cases on 30 May, 2003.



Simulation results.

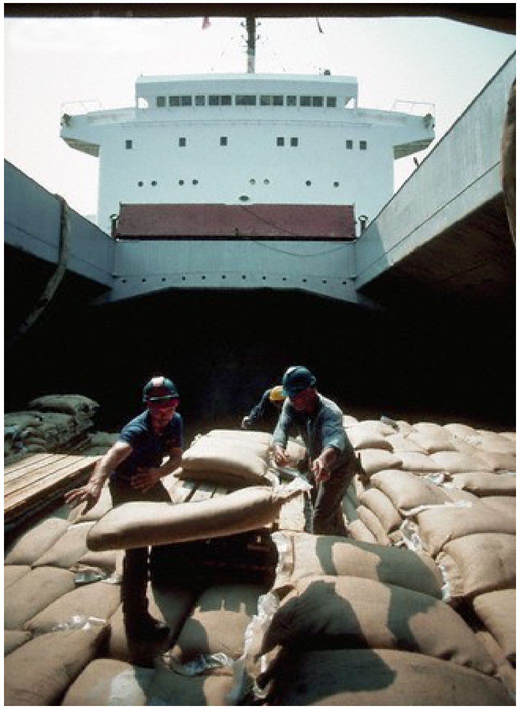
→ Surprisingly simple epidemiological models give good correlation between theory and data.

Can we similarly predict patterns of bio-invasion from the global cargo ship network?

And if not, are there other lessons we can learn?

Cargo ships – engines of the global economy

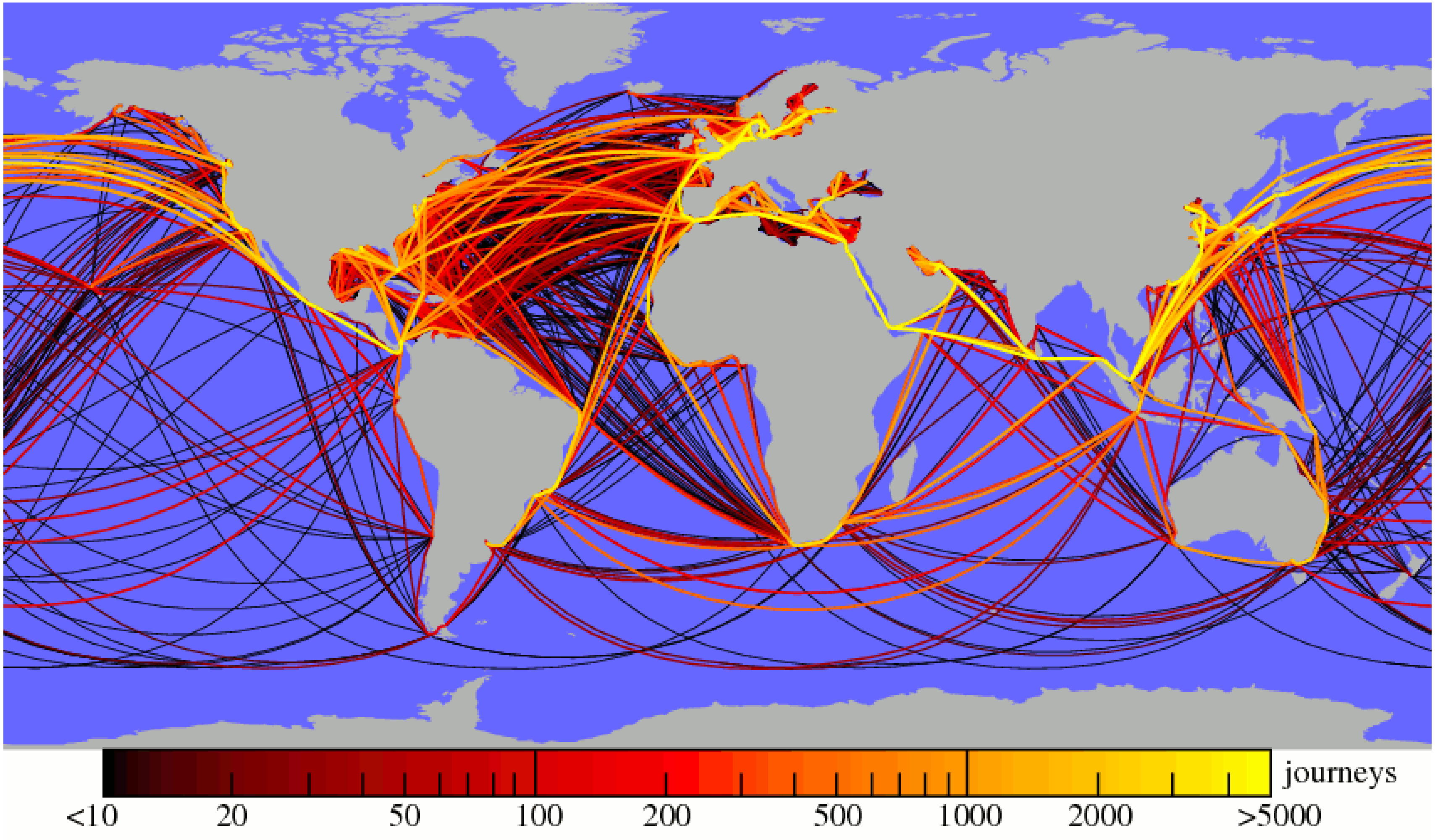
90 % of world trade hauled by ships.
7.4 billion tons of goods loaded at the world's ports (2006).
Trade volume: > 30 trillion ton-miles.
Until recently, growth rates of ~5% annually.



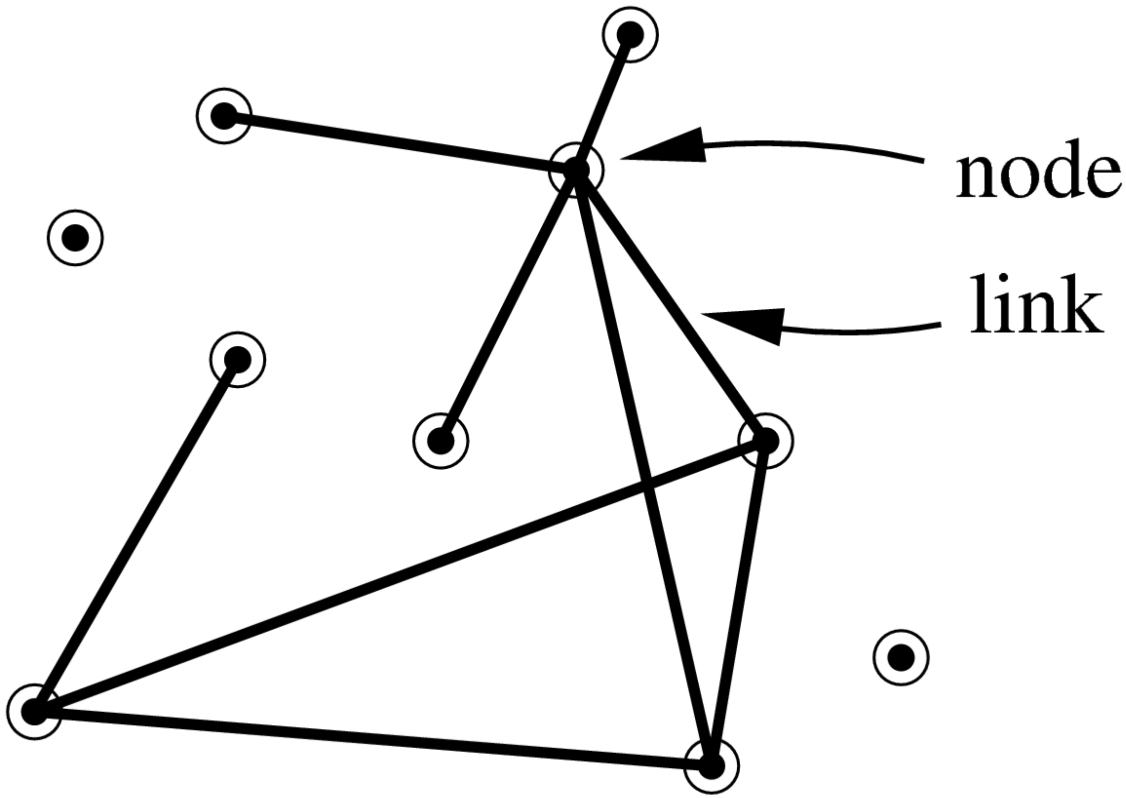
Emma Maersk, the world's largest container ship. 400m long, can carry 11,000 containers.

Data

Ships equipped with Automatic Identification System (AIS).
Ports record ship ID upon arrival and departure.
In our study: 16,363 ships (larger than 10,000 GT)
951 ports, 490,517 nonstop journeys in 2007.



Some network jargon



Degree: Number of links adjacent to a node.

Path length: Minimum number of links separating two nodes.

Clustering: Statistically significant tendency of links to form triangles, i.e., if A→B and B→C, then A→C.

The global network of cargo ships

Nodes: ports.

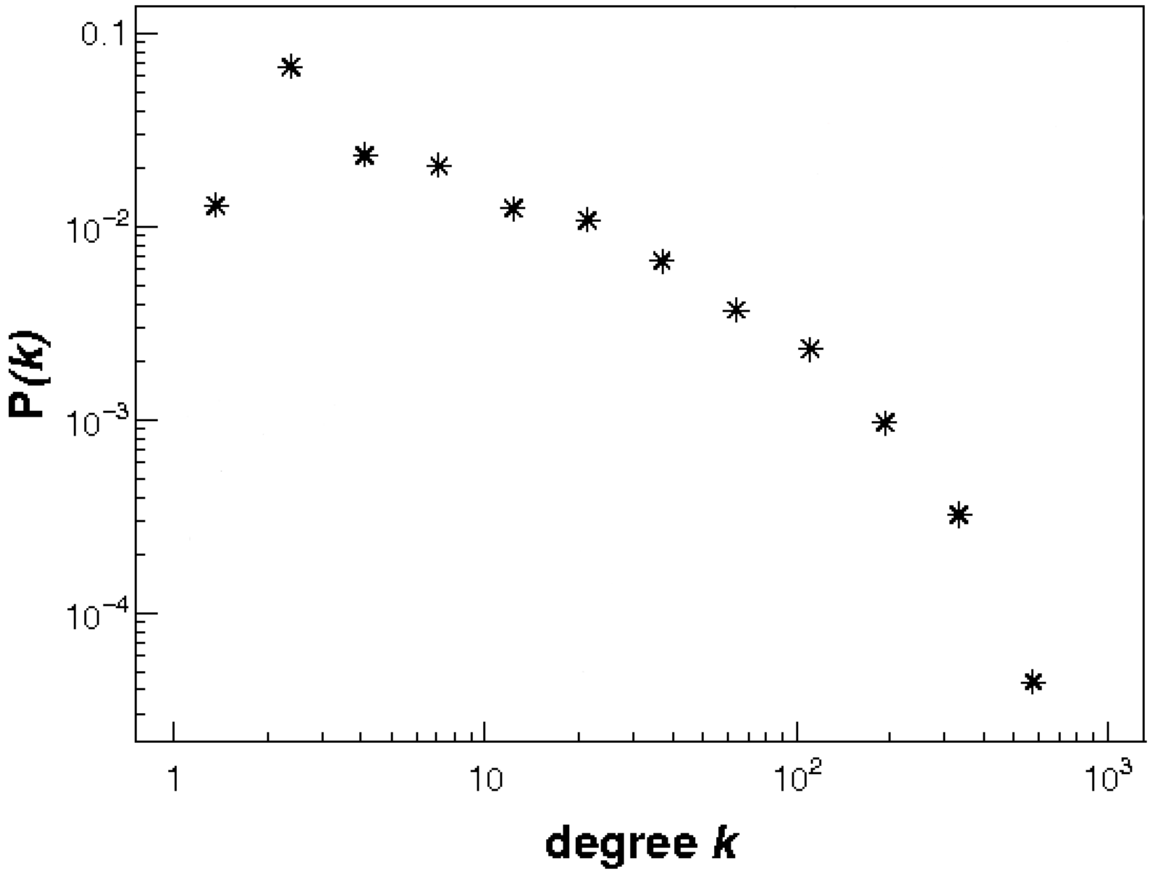
Links: nonstop journeys.

Small-world network:

average path length: $\langle l \rangle$=2.5.

high clustering coefficient: C=0.49.

Degree distribution heavy-tailed.

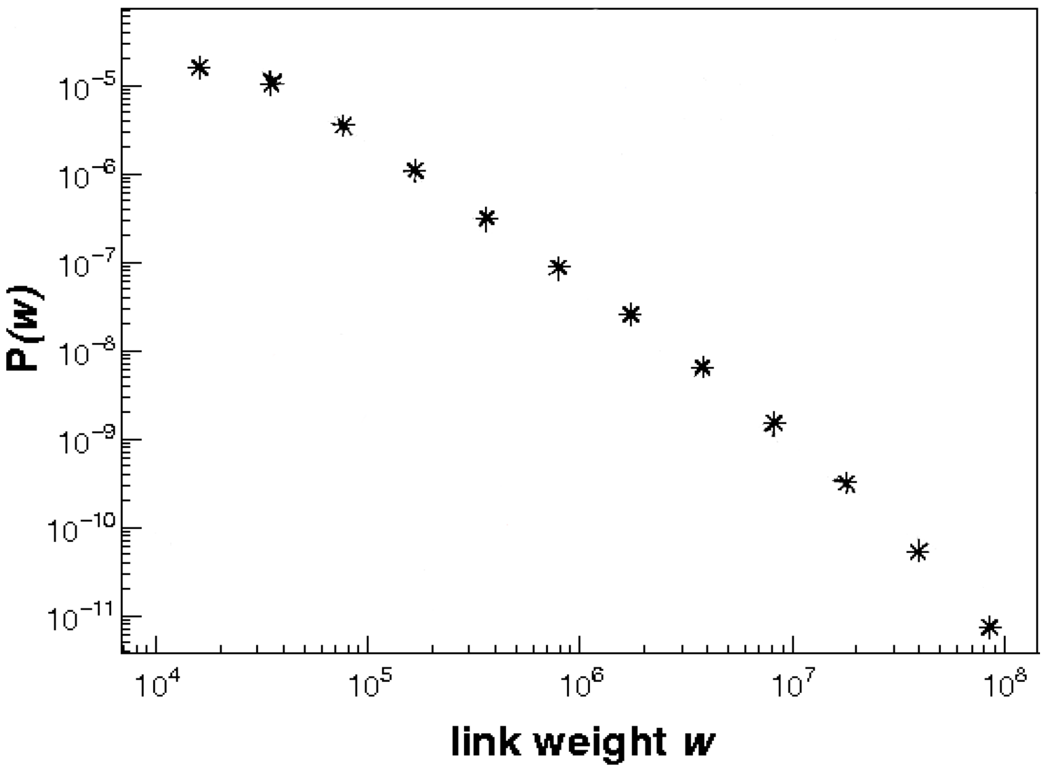


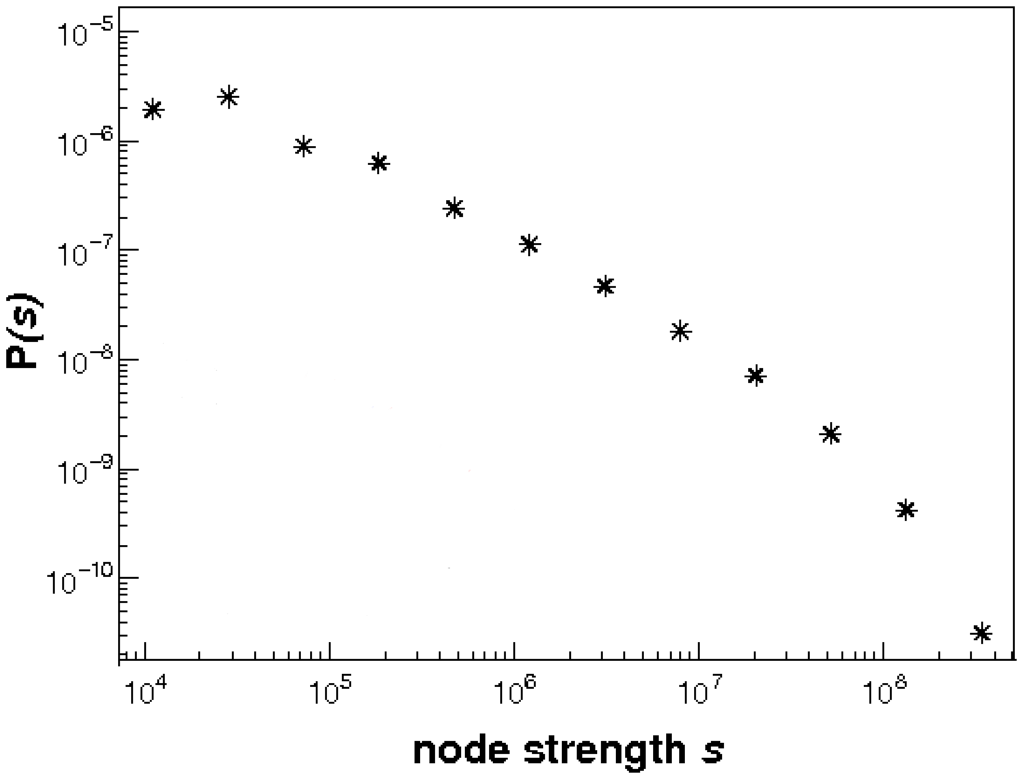
Year: 2007

Weighted network

Links are weighted by total Gross Tonnage (GT).
GT ~ ship's overall internal volume.

Nodes are weighted by “strength”.
Strength = all GT handled at a port.



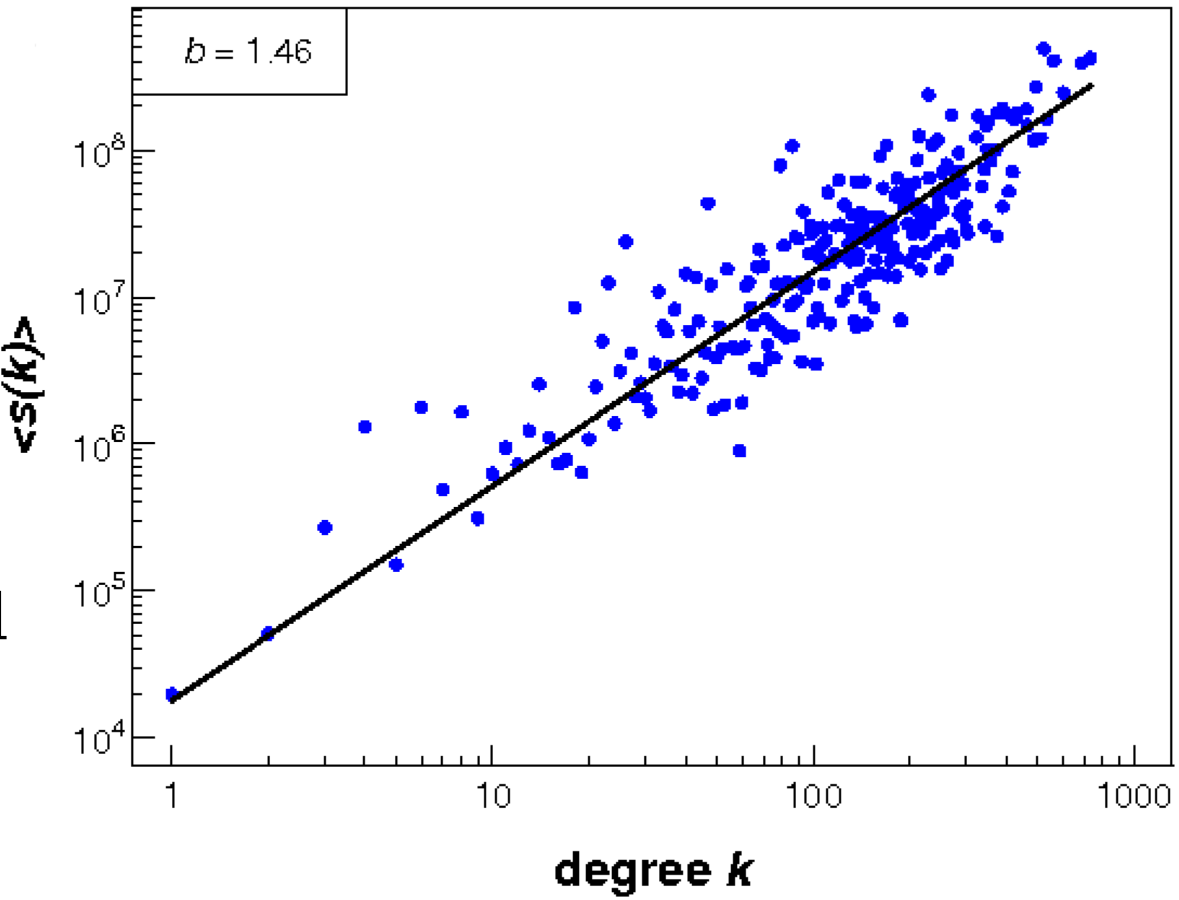


Scaling of degree and strength

Strengths and degrees follow the scaling law:

$\langle s(k) \rangle \propto k^{\,1.46 \pm 0.1}$

→ Links to highly connected ports have a disproportionately high weight.



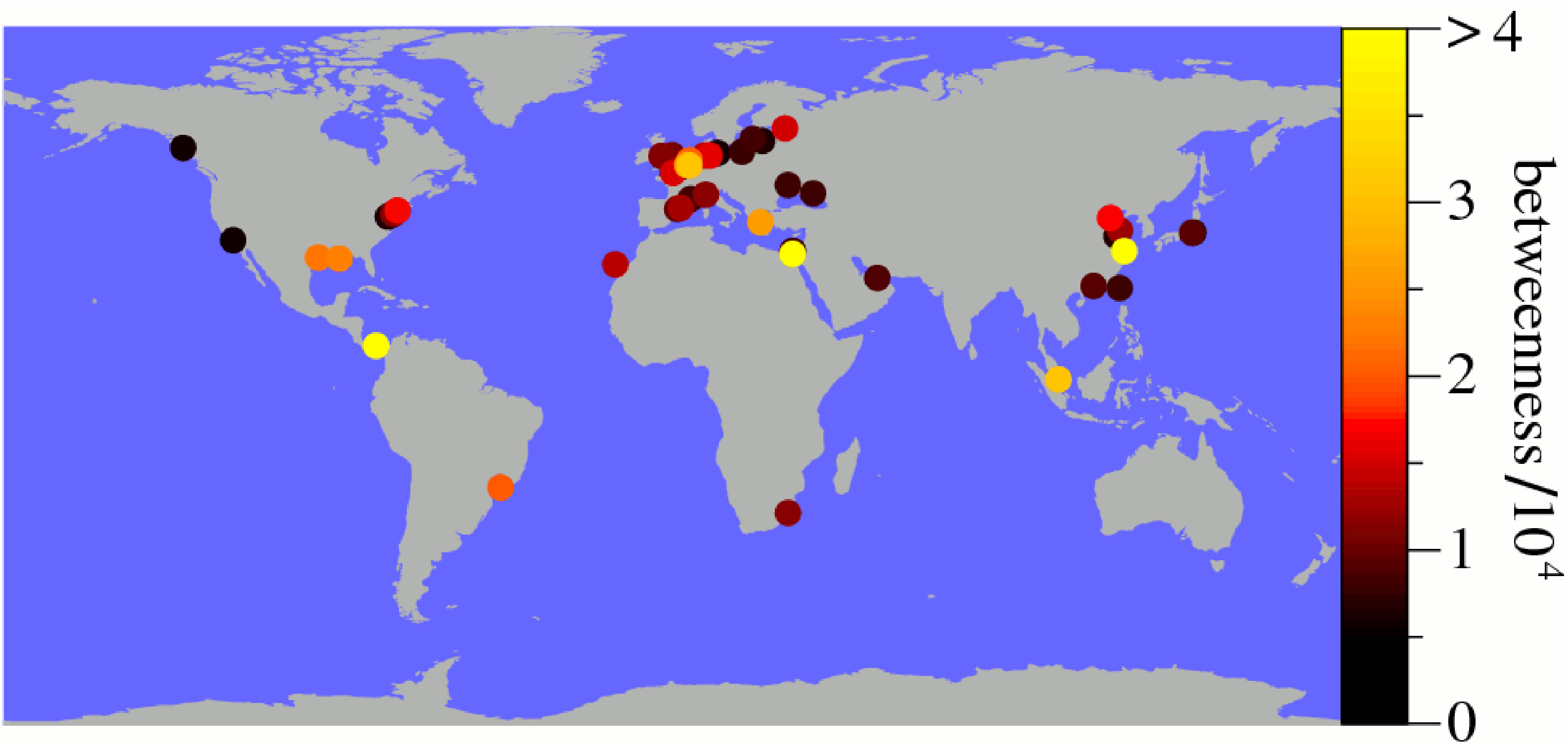
The same exponent had been observed for the airline network.

Universality?

The most central ports

Importance of a port?
"betweenness centrality" = number of shortest paths in the network through the node.

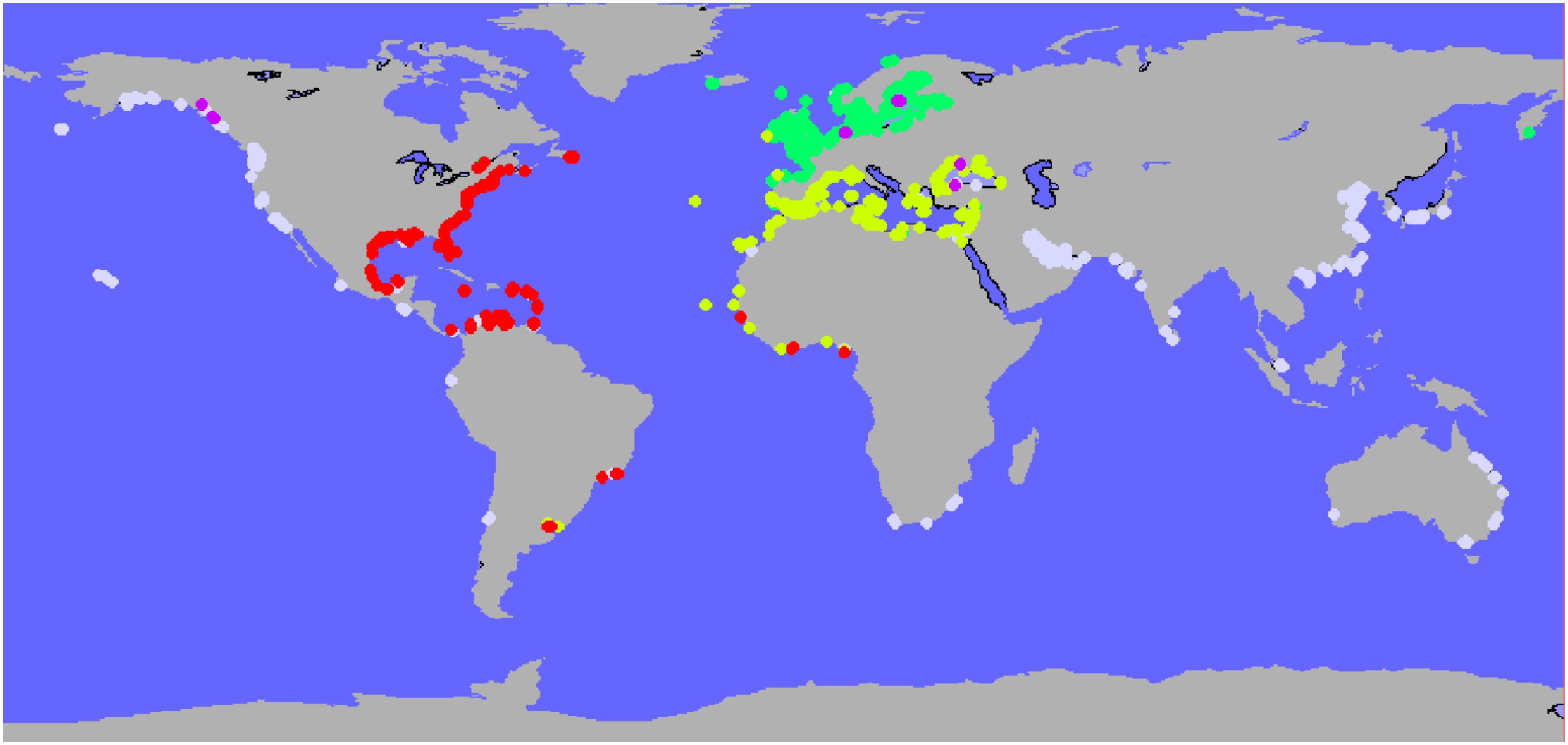
Top 50:



Top 5: (1) Panama Canal (2) Suez Canal
(3) Shanghai (4) Singapore (5) Antwerp

What role does geography play in the network?

Communities of ports:
Many links within the same community,
few links between different communities.



Most communities correspond to geographical regions.

Gravity model

"All things are related, but nearby things are more related than distant things" (Tobler 1970).

Hypothesis: Trips are more likely between nearby ports.

Distance.

$$F_{ij} = a_i \, b_j \, O_i \, I_j \, f(d_{ij}).$$

Flow from port *i* to *j*.

Total flow out of *i*.

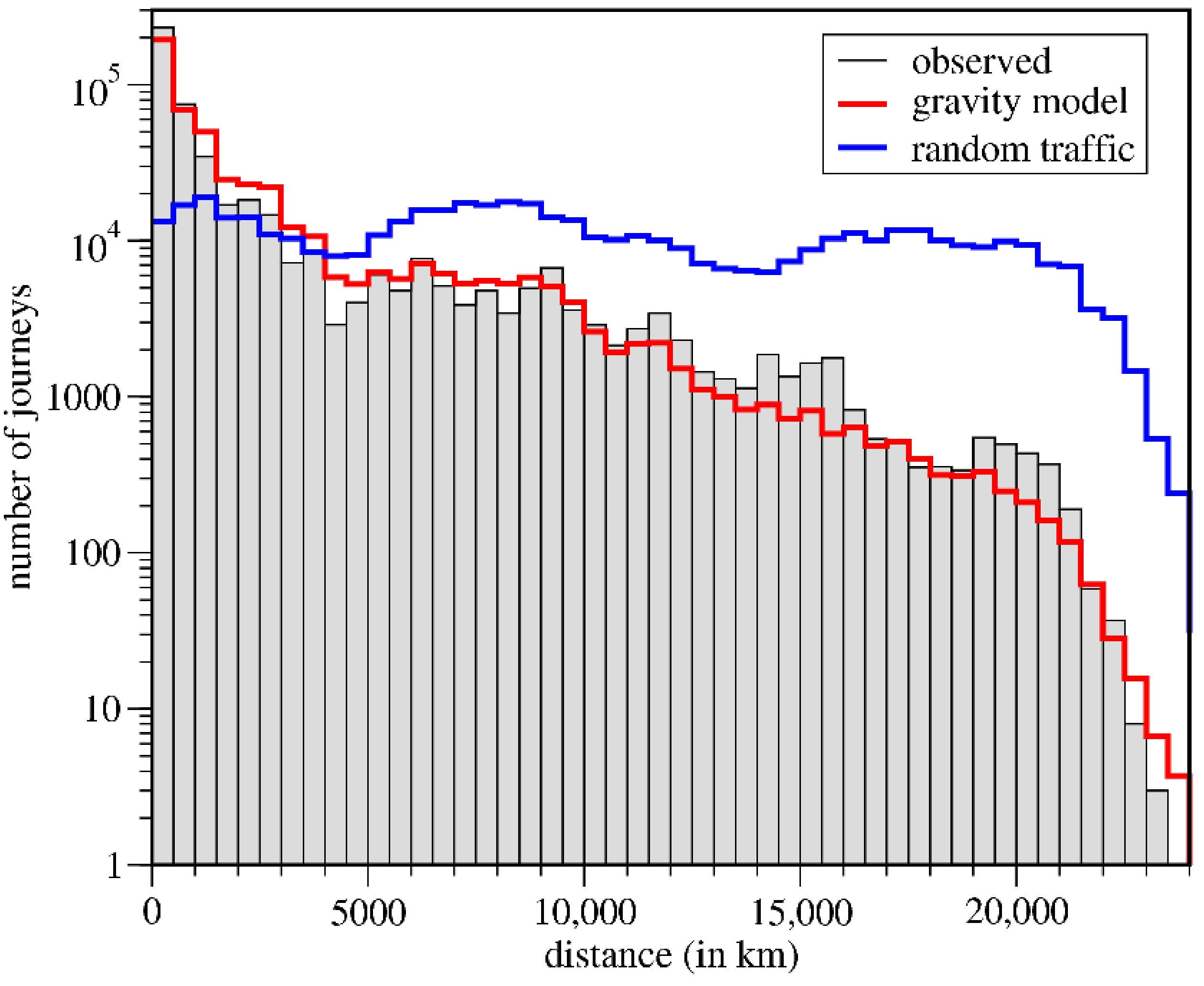
Total flow into *j*.

The coefficients a_i and b_j must be chosen such that the flows are self-consistent.

f is the "distance deterrence function":

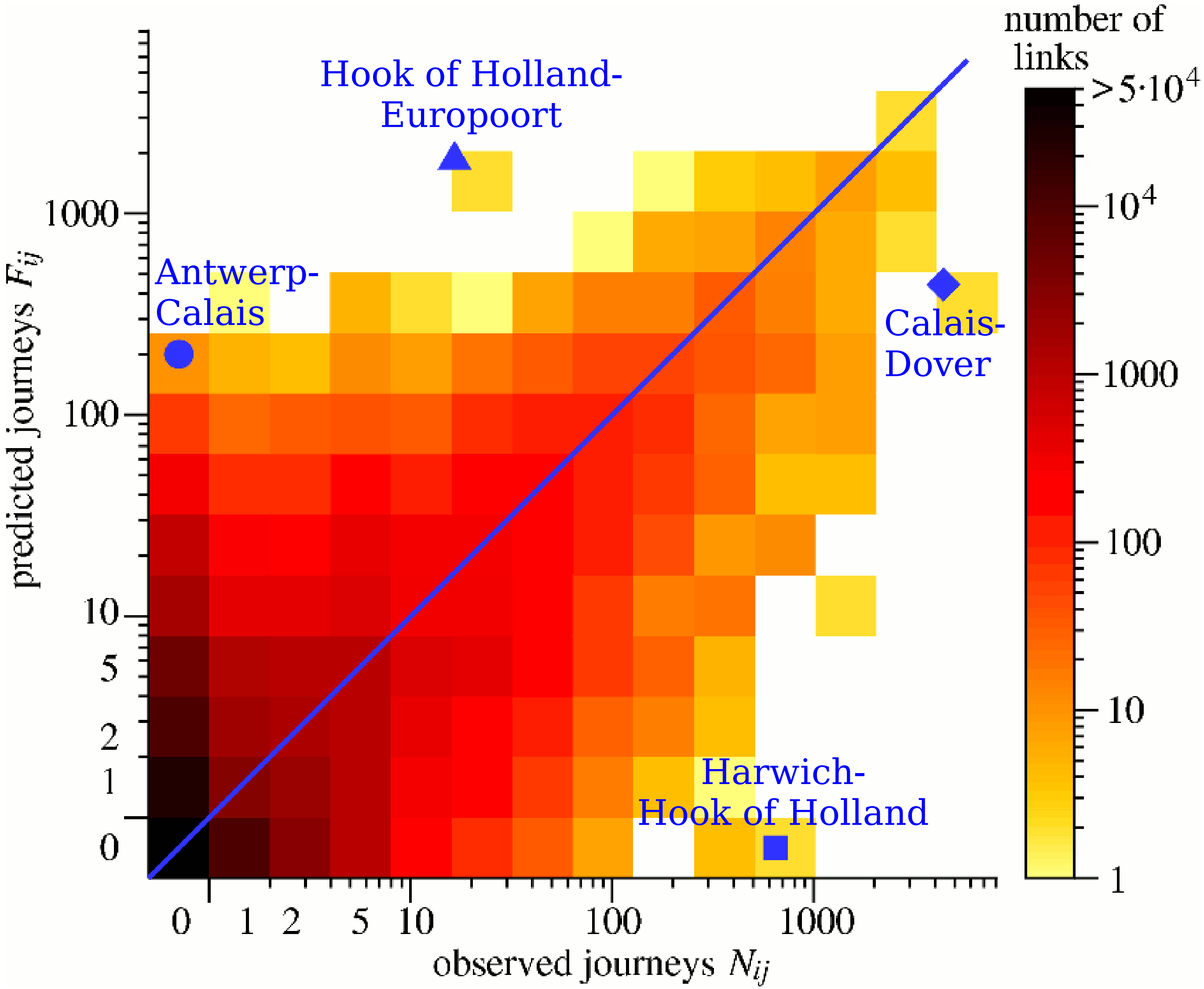
$f(d_{ij}) = d_{ij}^{\,-\beta} \exp(-d_{ij}/\kappa)$ with β=0.59, κ=4900 km.

Gravity model



The gravity model gives a reasonable fit to the distribution of distances traveled in the network, but ...

Gravity model



The correlation between the predicted and observed journeys in the network is only moderate (τ=0.433).

Metapopulation model of bio-invasion

Population dynamics on the nodes coupled by transportation on the links.

Population at port *i*.

$$\frac{dP_i}{dt} = \underbrace{rP_i(1-P_i)}_{\text{Logistic growth.}} + \underbrace{\sqrt{P_i}\xi(t)}_{\text{Demographic stochasticity.}} + \underbrace{\Omega(\mathbf{P})}_{\text{Transport operator.}}$$

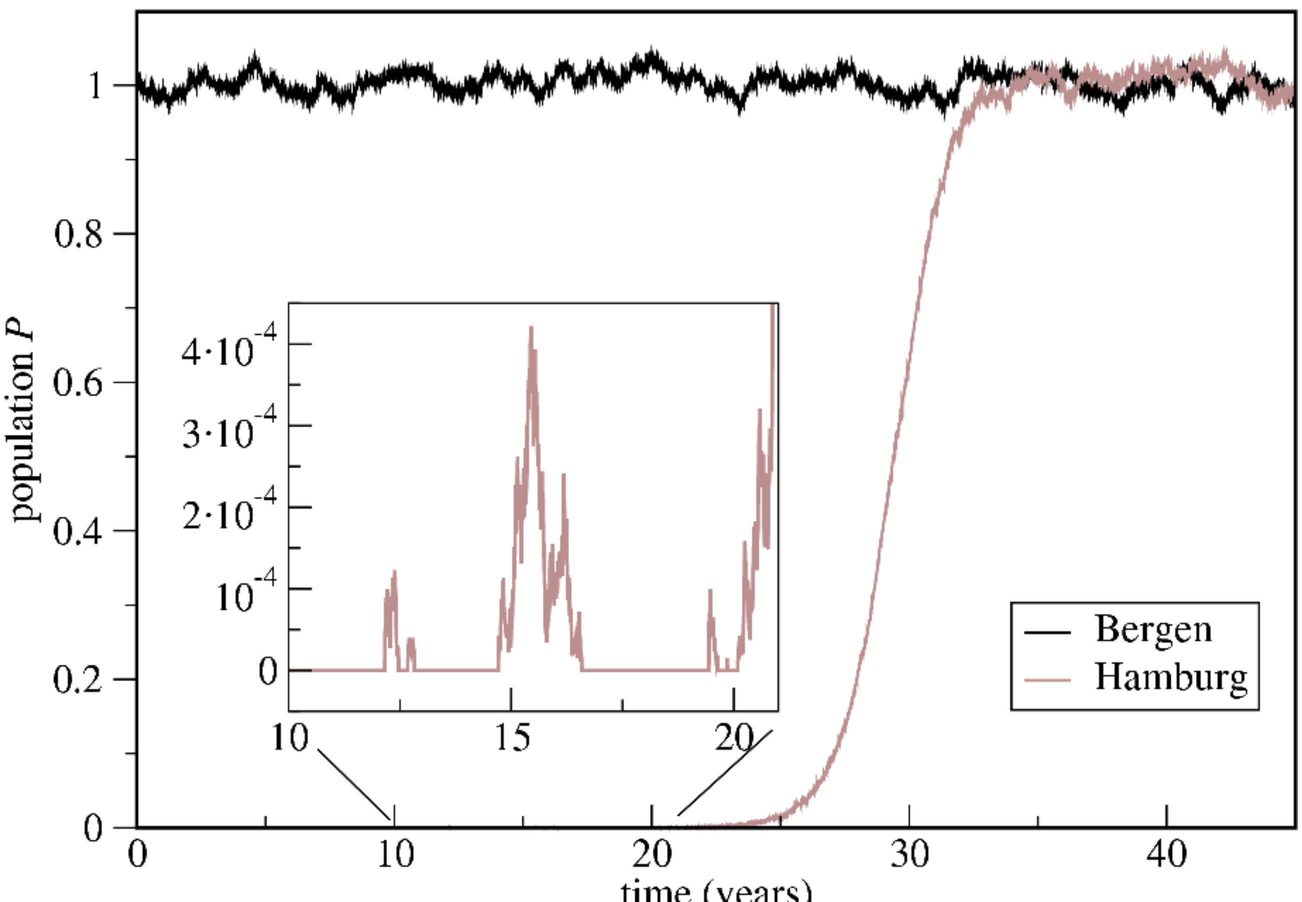
Transport operator Ω contains:

- Frequency of journeys from *i* to all other ports and vice versa.
- Probability of pumping organisms into ballast tank.
- Probability of surviving the journey.

Metapopulation model of bio-invasion

Initial condition:

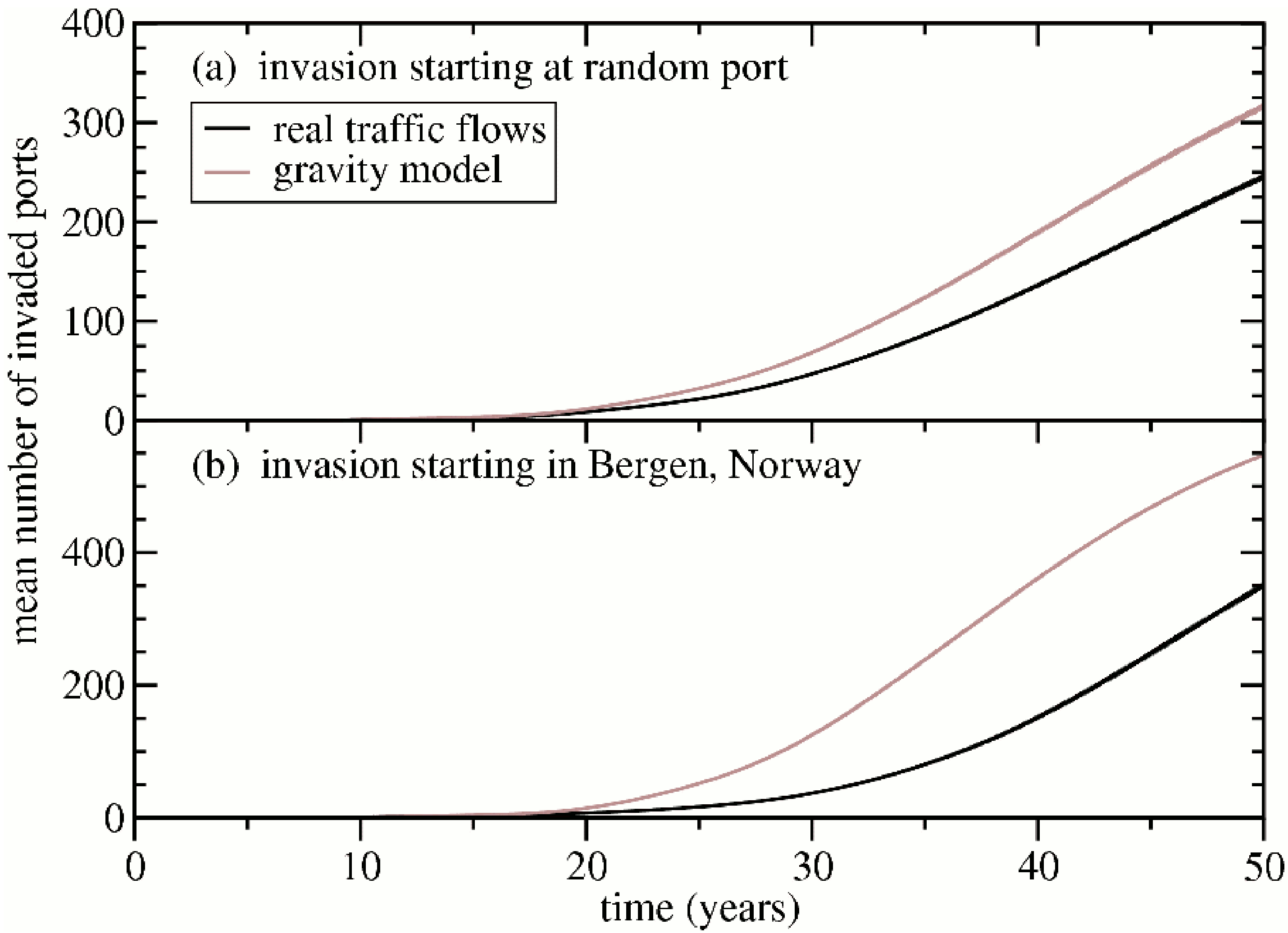
$$P_i = \begin{cases} \text{carrying capacity where species is endemic,} \\ 0 \text{ everywhere else.} \end{cases}$$



Parameters chosen to match previous estimates for average invasion probability.

Gravity model vs. real data

In general, the gravity model predicts a faster spreading rate than simulations on the empirical network.



How much ecology do we need for predicting bio-invasions?

Introduction:
How likely is it for an organism to enter the ballast tank?
Can the organism survive the journey?
Most die after a few days, a few become more abundant.

Establishment:
Can the organism cope with the physical conditions at the new habitat (e.g. temperature, salinity)?

Reproduction:
What is the rate of reproduction for a small population?
How will the ecosystem react to a new species?

→ “Ecological roulette” (Carlton & Geller 1993).

Summary

We use AIS records to construct the network of cargo ship movements in 2007.

Degrees and weights follow right-skewed distributions.

The gravity model can explain some general patterns of network flows, but is too crude for quantitative predictions.

Calculations of bioinvasion risks under way.

Kaluza, Kölzsch, Gastner & Blasius: The complex network of global cargo ship movements, J. Roy. Soc. Interface, doi:10.1098/rsif.2009.0495

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