NEWS & VIEWS

COMPLEX SYSTEMS

Spotlight on mobility

The complexity in patterns of human mobility, migration and communication has been difficult to unpack. Researchers have now come up with a simple theory that captures the intricacy of such phenomena. **SEE LETTER P.96**

DIRK BROCKMANN

Humans are mobile, interacting animals. In this respect, we are no different from most of our fellow species: single-cell, slime-mould amoebas crawl up a chemical signal gradient to aggregate into a multicellular organism; mice seek breadcrumbs to deliver to their litters; and blue whales travel thousands of kilometres to find a mate. Most of what humans do is driven by our interactions and mobility — society doesn't work without it. Children take the bus to school and interact with their peers, employees commute to their workplaces to collaborate with their colleagues, students leave home to attend a college and subsequently seek a job in a distant city. Our movement patterns shape the structure of urban areas and the connectivity of our transportation and trade networks.

The complexity of human mobility, migration and communication patterns may suggest that no simple theory can capture these phenomena. But on page 96 of this issue, Simini *et al.*[1] propose a simple model that agrees with observations remarkably well.

With the emergence of pervasive data on human interactions and mobility, the past couple of years have witnessed a proliferation of empirical studies on these topics[2–5]. Social-network sites, location-aware devices, mobile and smart phones, e-mail communication and related technologies have generated an immense body of large-scale data sets. Numerous papers have been published reporting statistical properties, peculiarities and surprisingly simple regularities, power laws and scaling laws for human mobility. But the great mystery remains: why do we observe what we observe?

Researchers have proposed both phenomenological and ad hoc models to account for mobility data (Fig. 1). More often than not, they have had limited success. Although many of the studies are interesting, they lack the heartbeat of a solid and plausible theoretical foundation that can describe observed patterns without — or, at least, with little — parameter tuning. More importantly, there are no theories that can explain the observed patterns on the basis of fundamental principles.

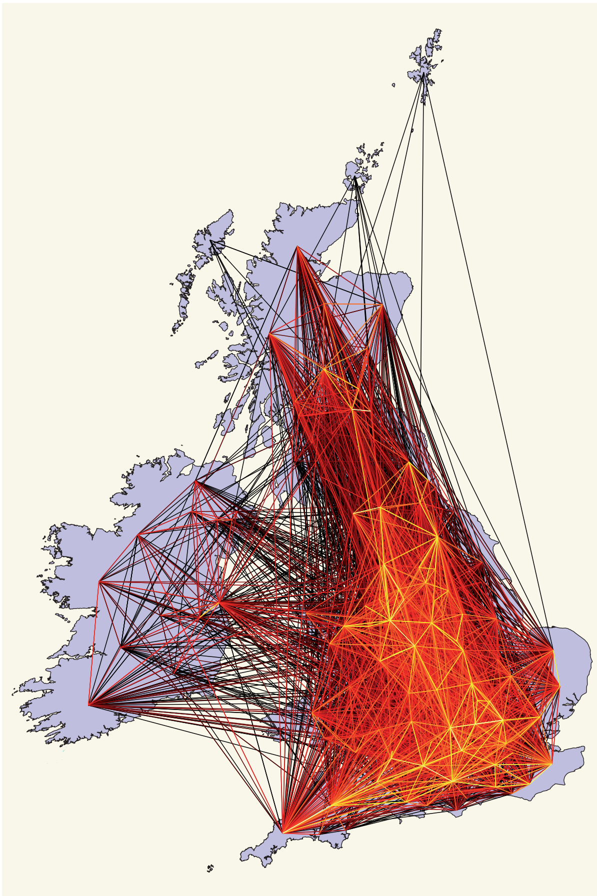

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Figure 1 | Human-mobility pattern in the United Kingdom and Ireland. Simini and colleagues' model[1] for human mobility and migration could explain complex patterns such as that seen here[6]. Each line represents mobility flux, the estimated amount of traffic between counties per unit time. Bright lines indicate strong flux, and darker lines denote weaker flux. This network was derived from proxy data for human mobility integrated over a period of 3 years.

Lacking a sound theory, many researchers performing empirical studies on human mobility and communication have tried to fit their data to what has been termed the gravity law of transportation. This traditional phenomenological model draws on an analogy to the force of gravity between two objects. It relies on the intuitive notion that the amount of traffic, T_{ij}, between two cities, i and j, increases with some power of their population size, m_i and m_j, and decreases with some power of the distance between them, d_{ij}, as: $T_{ij} \approx m_i^{\alpha} \times m_j^{\beta}/d_{ij}^{\gamma}$. But the model typically has three unknown parameters (the exponents α, β and γ in the equation), and almost every study that fits the gravity model to data obtains different best-fit values. Most crucially, the gravity law does not emerge from testable underlying hypotheses.

Simini and colleagues[1] change this situation. They propose a 'radiation model' for human mobility and migration. This model is based on two simple and plausible assumptions: humans do not enjoy moving, and they take the nearest opportunity that improves their circumstances. In other words, individuals move to a new location only because it is the closest location that offers, say, a better job. Therefore, Simini *et al.* assume that a person's geographical spotlight, centred at their current location, increases until a better place is identified, but no farther. The crucial assumption in the radiation model is that individuals do not necessarily seek the best opportunity, but rather their priority is to pick the closest destination.

By assuming that the number of opportunities offered at a location is proportional to the population size of that location, and that each opportunity has a random quality score, the researchers[1] were able to compute the expected flux of individuals between two locations, making the spatial distribution of the population the only input to their theory. The authors then compared the theory's predictions with multiple data sets ranging from daily-commute traffic to long-term migration patterns, mobile-phone mobility and communication patterns. They find that this theory substantially outperforms the gravity model.

Interestingly, their theory reduces to a specific type of gravity model when a homogeneous distribution of the populations (and thus opportunities) is assumed. This could explain why the gravity-theory analogy has been so persistent in mobility research, and also indicates that it is equivalent to an idealized scenario, one hardly ever encountered in real-life settings.

The radiation model may provide a route to further exploration. It could be useful for researchers interested in understanding processes mediated by human mobility, such as the introduction of animals and plants into a new habitat and the spread of human infectious diseases[2]. Until now, computational models in these areas relied on direct data implementation and gravity models to fill gaps in incomplete mobility data sets.

A pertinent question for future work is why some societies are more mobile than others. A comparative analysis between the United States and European countries would be a promising starting point for addressing this issue. ■

Dirk Brockmann *is at the Northwestern Institute on Complex Systems, and in the Department of Engineering Sciences and Applied Mathematics, Northwestern University, Evanston, Illinois 60208-3125, USA.*
e-mail: brockmann@northwestern.edu

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CLIMATE CHANGE

A tale of two hemispheres

A reconstruction of temperature from proxy records shows that the rise in global mean temperature closely resembled, but slightly lagged, the rise in carbon dioxide concentration during the last period of deglaciation. **See Article p.49**

ERIC W. WOLFF

Between about 19,000 and 10,000 years ago, Earth emerged from the last glacial period. The whole globe warmed, ice sheets retreated from Northern Hemisphere continents and atmospheric composition changed significantly. Many theories try to explain what triggered and sustained this transformation (known as the glacial termination), but crucial evidence to validate them is lacking. On page 49 of this issue, Shakun *et al.*[1] use a global reconstruction of temperature to show that the transition from the glacial period to the current interglacial consisted of an antiphased temperature response of Earth's two hemispheres, superimposed on a globally coherent warming. Ocean-circulation changes, controlling the contrasting response in each hemisphere, seem to have been crucial to the glacial termination.

The centrepiece of Shakun and colleagues' study[1] is a reconstruction — using 80 marine, terrestrial and ice-core proxy records — of the latitudinal temperature pattern and global mean temperature throughout the termination. This is a major achievement: the difficulties of synchronizing the records and of ensuring that they are sufficiently representative of the whole planet, are considerable. Global mean temperature rose in two main steps, closely mirroring the rise in atmospheric carbon dioxide measured[2] in Antarctic ice cores (see Fig. 2 of the paper[1]). And in contrast to Antarctic temperature[2], global mean temperature lagged carbon dioxide rise by 460±340 years during the termination.

As anticipated from comparisons of Antarctic with Greenland temperatures[3], the Northern and Southern Hemispheres show different patterns of temperature change (see Fig. 4 of the paper[1]). The authors[1] quantify this difference by subtracting the mean temperature of the Southern Hemisphere from that of the Northern. This gives a W-shaped profile that is remarkably similar in timing and shape to a geochemical record[4] that is considered to be a proxy for the strength of the Atlantic meridional overturning circulation (AMOC). The AMOC is the branch of ocean circulation in the Atlantic that takes warm surface waters northwards, balanced by the flow of cold deep water southwards. The strength of this circulation has a considerable impact on the transfer of heat between the hemispheres.

Some studies have proposed[5,6] that changes in ocean heat transport are an essential part of glacial termination. Shakun *et al.*[1] combine their data with simulations based on an ocean–atmosphere general circulation model to present a plausible sequence of events from about 19,000 years ago onwards. They propose that a reduction in the AMOC (induced in the model by introducing fresh water into the North Atlantic) led to Southern Hemisphere warming, and a net cooling in the Northern Hemisphere. Carbon dioxide concentration began to rise soon afterwards, probably owing to degassing from the deep Southern Ocean; although quite well documented, the exact combination of mechanisms for this rise remains a subject of debate. Both hemispheres then warmed together, largely in response to the rise in carbon dioxide, but with further oscillations in the hemispheric contrast as the strength of the AMOC varied. The model reproduces well both the magnitude and the pattern of global and hemispheric change, with carbon dioxide and changing AMOC as crucial components.

The success of the model used by Shakun and colleagues in reproducing the data is encouraging. But one caveat is that the magnitude of fresh water injected into the Atlantic Ocean in the model was tuned to produce the inferred strength of the AMOC and the magnitude of interhemispheric climate response; the result does not imply that the ocean circulation in the model has the correct sensitivity to the volume of freshwater input[7].

Shakun and colleagues' work does provide a firm data-driven basis for a plausible chain of events for most of the last termination. But what drove the reduction in the AMOC 19,000 years ago? The authors[1] point out that there was a significant rise in temperature between 21,500 and 19,000 years ago in the northernmost latitude band (60–90° N). They propose that this may have resulted from a rise in summer insolation (incoming solar energy) at high northern latitudes, driven by well-known cycles in Earth's orbit around the Sun. They argue that this rise could have caused an initial ice-sheet melt that drove the subsequent reduction in the AMOC.

However, this proposal needs to be treated with caution. First, there are few temperature records in this latitude band: the warming is seen clearly only in Greenland ice cores. Second, there is at least one comparable rise in temperature in the Greenland records, between about 62,000 and 60,000 years ago, which did not result in a termination. Finally, although it is true that northern summer insolation increased from 21,500 to 19,000 years ago, its absolute magnitude remained lower than at any time between 65,000 and 30,000 years ago. It is not clear why an increase in insolation from a low value initiated termination whereas a continuous period of higher insolation did not.

In short, another ingredient is needed to