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Author(s): Antoine Flahault, Séverine Deguen and Alain-Jacques Valleron
Source: *European Journal of Epidemiology*, Vol. 10, No. 4 (Aug., 1994), pp. 471-474
Published by: Springer
Stable URL: https://www.jstor.org/stable/3520982
Accessed: 19-04-2020 21:19 UTC

European Journal of Epidemiology 10: 471–474, 1994.

A mathematical model for the European spread of influenza

Antoine Flahault, Séverine Deguen & Alain-Jacques Valleron
B3E, Faculté de Médecine Saint-Antoine, Paris, France

Abstract. Following a study modelling the geographical spread of influenza in France, on the basis of population movements through the use of railroad data, we applied the same methodology on a European scale. We simulated an epidemic within a network of 9 European cities (Amsterdam, Berlin, Budapest, Copenhagen, London, Madrid, Milano, Paris, Stockholm), only taking into account regular between-cities air transport. Transportation data were obtained from the International Civil Aviation Organization (1991). The theoretical results show that the time lag for action is probably short (less than one month) after the first detection of an epidemic focus.

Key words: Epidemic forecasting, Influenza virus, Passenger air traffic

Introduction

A large amount of work on influenza modeling has been done over the past 30 years. In 1985, a Soviet-American team demonstrated that, on the basis of air travel, it was possible to reconstitute retrospectively the last (1968) Hong Kong pandemic through a worldwide network of 52 large cities [1]. A new strain of the virus (H3N2) had spread all over the world in less than two years, in a population entirely susceptible to it. From city to city, epidemiological stations of surveillance had noted that from the time the strain appeared, an epidemic wave followed. Much data was collected on morbidity and mortality, allowing the validation of these models. The underlying assumption was that air travel was the main route of international dispersion of the virus. In France, we used a similar methodology applied to the data collected through the Computer Network for Surveillance of Communicable Diseases (CNSCD) from 1984. Data on regular railroad traffic between the 22 metropolitan districts were used [2].

However, no tool was available for simulating and forecasting the spread of influenza in Europe, while European efforts can be organized to control an epidemic. Therefore we decided to work on a flexible European network, showing the preliminary results of an application to 9 cities (Amsterdam, Berlin, Budapest, Copenhagen, London, Madrid, Milano, Paris, Stockholm). Transportation data were obtained from the International Civil Aviation Organization (1991).

Material and methods

The model. The model involves a network of 9 cities in a discrete space domain. The time-domain is continuous. Within each city (index i), n_i is the population size. These n_i persons are classified in 4 groups, according to their status concerning infection with the influenza virus: $S_i\ (t)$ is the number of susceptible persons, $C_i\ (t)$ is the number of contagious persons incubating the virus without symptom of the disease, $I_i\ (t)$ is the number of ill persons, and $R_i\ (t)$ is the number of recovered persons. The spread of the virus involves two processes: First, the dynamic of contacts in a given city between susceptible and contagious persons; second, the passenger air traffic between cities which bring contagious persons from one place to another. In this model, we assumed that all persons except those with the illness may travel. The population size and the transportation fluxes are assumed constant during the simulation.

The model is a compartmental system of 9 × 4 differential equations. For each city, the system of differential equations is:

$$dS_i/dt = -a\ C_i\ S_i/n_i + \Omega(S_i),$$
$$dC_i/dt = a\ C_i\ S_i/n_i - b\ C_i + \Omega(C_i),$$
$$dI_i/dt = b\ C_i - d\ I_i,$$
$$dR_i/dt = d\ I_i + \Omega(R_i),$$

where $n_i = S_i + C_i + I_i + R_i$ and a has a dimension of a contact rate. The parameters $1/b$ and $1/d$ are, respectively, the mean length of incubation time and the mean length of illness.

A transport operator (Ω) which is applied to the variables $X_i (X_i = S_i,\ C_i$ or R_i), is defined as:

$$\Omega(X_i) = \sum_{j=1}^{9} (c_{ji}\, X_j/n_j - c_{ij}\, X_i/n_i),$$

where c_{ij} is the mean annual number of airline passengers travelling from city i to city j. We applied the model to a flexible network of cities, but this paper presents results on 9 European cities for which we collected data on regular airline traffic. These data are presented in Table 1.

Such a system allows the representation of the consequences of any hypothesis regarding the start of the epidemic, i.e. at different places, in one unique city or in several simultaneous locations.

Data collection. Estimations of the parameters (i.e. contact rate, incubation time, length of illness, fraction of susceptible individuals in the population) should be drawn from up-to-date observed data through optimization procedures, since these parameters may vary from one epidemic to another. Although efforts have been undertaken, as those promoted by EUROSENTINEL and EUROGROG, online data on morbidity are not yet available in Europe on the whole.

We are presenting theoretical results based upon real and recent data on air travel, assuming that an influenza epidemic had started in Amsterdam in a population where 25% are susceptible to the strain of the virus, with a contact rate of 8 persons per week, with an incubation time of 0.42 week, and a length of illness of 0.714 weeks. These values were drawn from our previous published work on an inflenza epidemic in France [2].

Results

Weekly maps. The space-time simulated spread of the influenza epidemic in the 9 European cities is shown on maps presented in Figures 1–3.

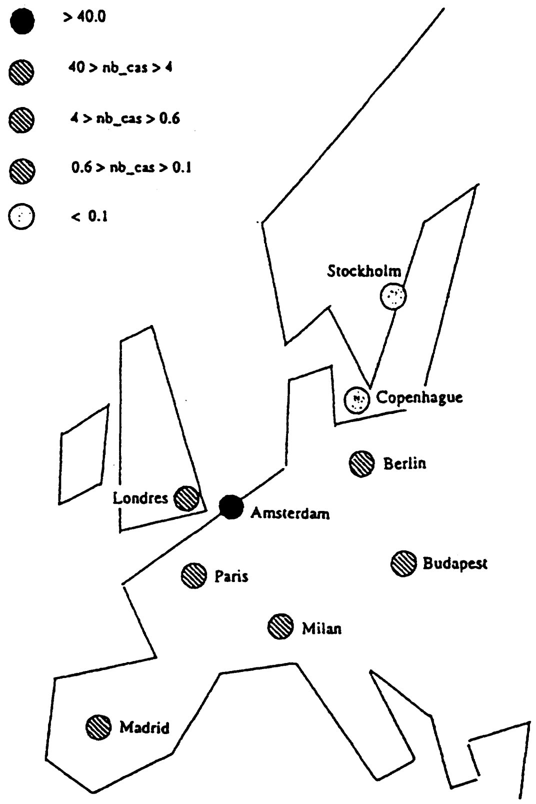

Figure 1. Simulated spread in nine European cities at week no. 1.

Table 1. The transportation matrix of c_{ij} (mean annual number of airline passengers between 9 cities in Europe)

	Ams	Ber	Bud	Cop	Lon	Mad	Mil	Par	Sto
Amsterdam n = 702444		31956	36309		804986	101399	126628	292172	
Berlin n = 3409737	32796				149052	10929	14047	89383	
Budapest n = 2016774	41125			38700	77537		15947		9448
Copenhague n = 900000	132826	15453	36818		275589	40184	62178	146629	327980
London n = 2349900	802349	146342	74385	267596		333766	286682	1591794	202461
Madrid n = 4935642	103842	11067		41092	304728		124758	322620	15638
Milan n = 1371008	127245	14446	15656	66128	277247	122582		328262	28332
Paris n = 2152430	300789		81224	159168	1533286	300982	344491		
Stockholm n = 674452	84514	10208	334241	199734	15300	23820	107196		

Source: From the International Civil Aviation Organization (1991).

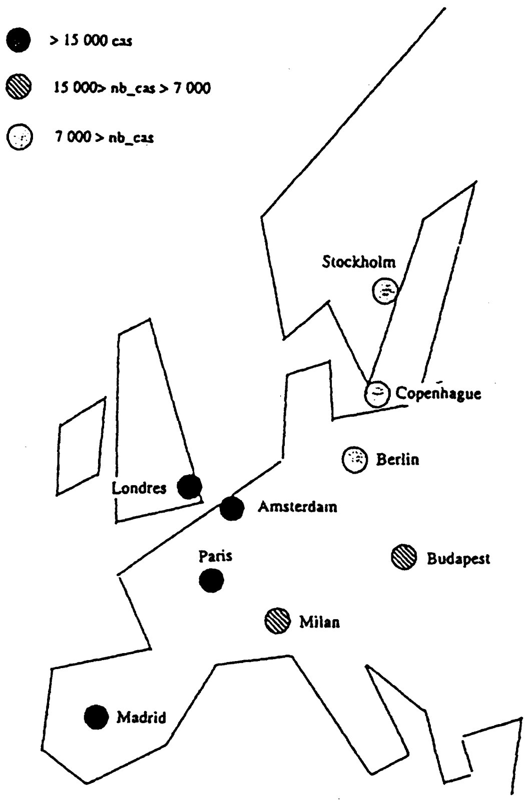

Figure 2. Simulated spread in nine European cities at week no. 9.

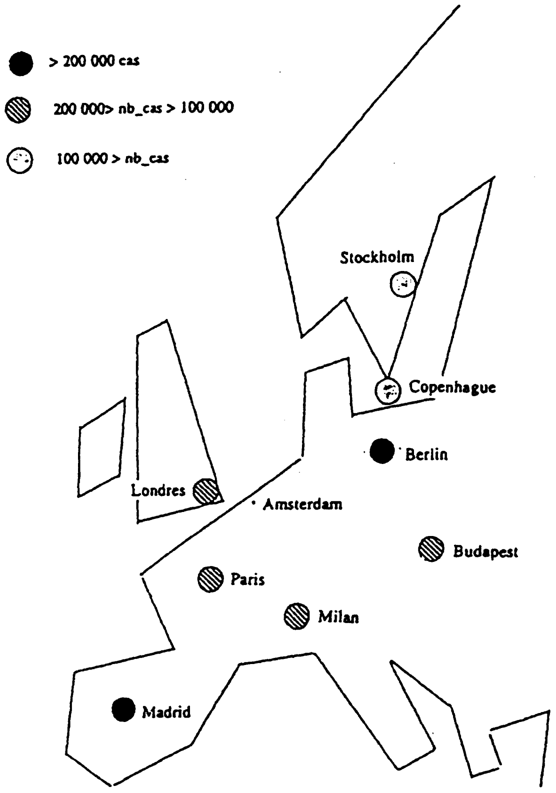

Figure 3. Simulated spread in nine European cities at week no. 16.

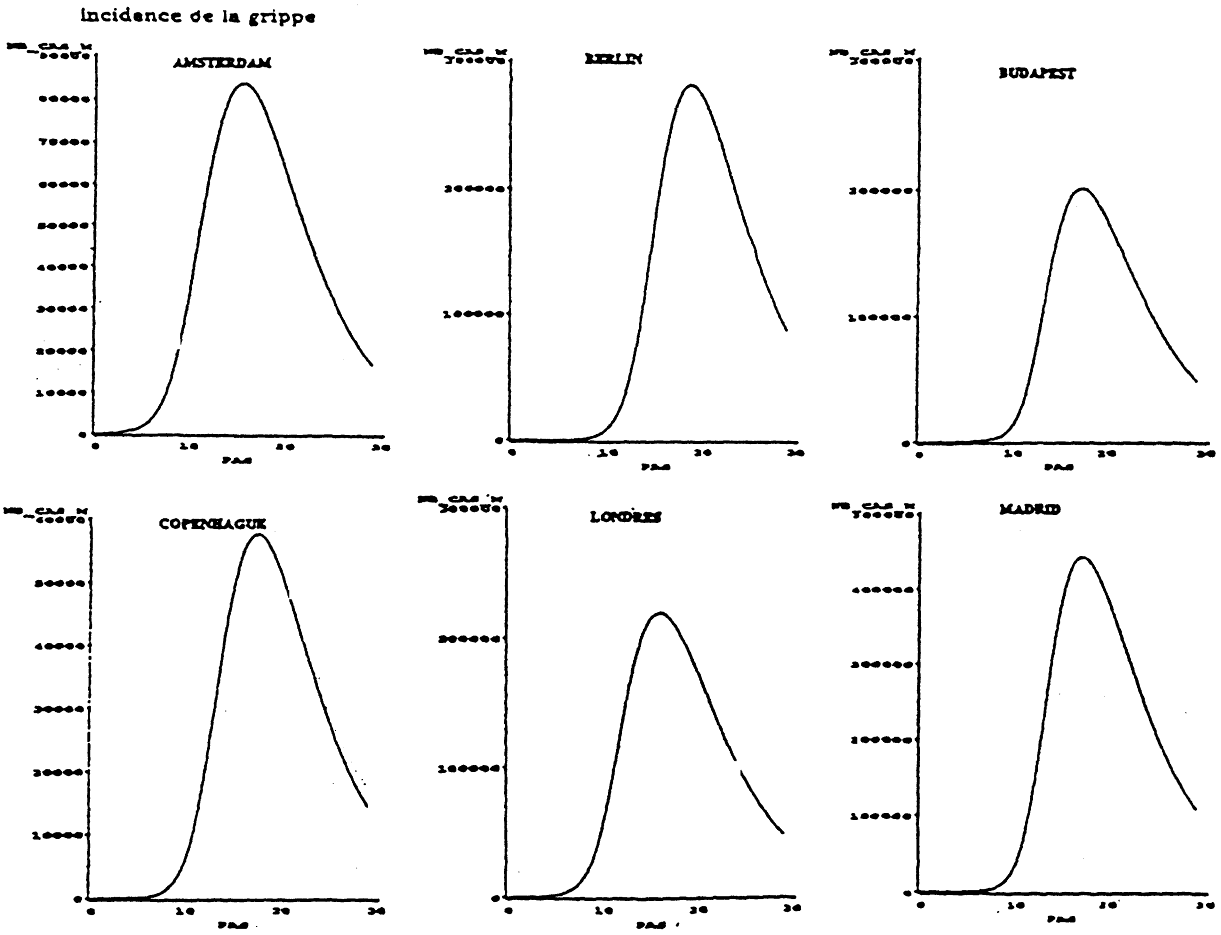

Figure 4. Simulated epidemic curves (i.e. number of new cases of influenza) in Amsterdam, Berlin, Budapest, Copenhagen, London, Madrid, from week no. 0 to week no. 30.

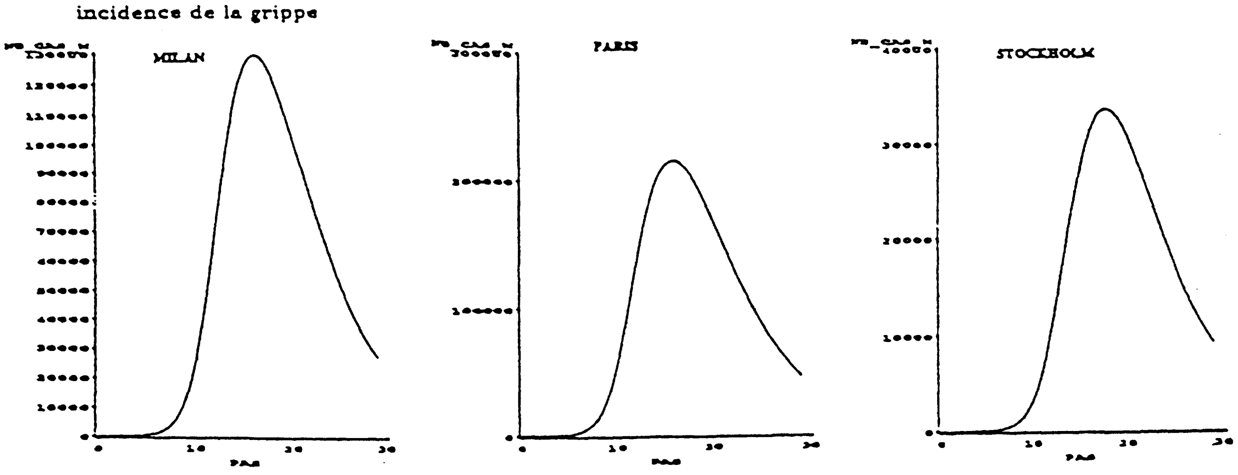

Figure 5. Simulated epidemic curves (i.e. number of new cases of influenza) in Milano, Paris, Stockholm, from week no. 0 to week no. 30.

City charts. Nine 'city charts', giving the simulated size of the epidemic and the time of its peak, are shown in Figures 4–5. The epidemic waves have a similar shape in all cities with differences in magnitude (different scales are used), and in the time of the peak. In Amsterdam (i.e. the starting place) the peak is reached during the 16th week, in London, Milano and Paris, during the 17th week, in Budapest, Copenhagen and Madrid, during the 18th, and in Berlin and Stockholm during the 19th. Therefore, an influenza epidemic would spread over these 9 European cities within a month. These theoretical results show that the time lag for action is probably short after the first detection of an epidemic focus, and this is only taking into account regular, between-cities air transport.

Conclusions

We have presented the preliminary results produced by a tool which is potentially useful for 1) restoring the dynamic of influenza epidemics in Europe, 2) forecasting the epidemic trends, 3) assessing the role of air transport in the spread of influenza in Europe, and 4) simulating public health policies, such as immunization.

This work outlines the need for European harmonization in data collection on the epidemiology of influenza. An online computer system, using a methodology similar to these of the Computer Network for Surveillance of Communicable Diseases, would provide data necessary for more rapid action.

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Address for correspondence: Antoine Flahault, B3E,
Faculté de Médecine Saint-Antoine, 27 rue Chaligny,
F-75571 Paris, Cedex 12, France
Phone: 33-1-4473 8430; Fax: 33-1-4473 8462