Global air transportation and the spread of infectious diseases

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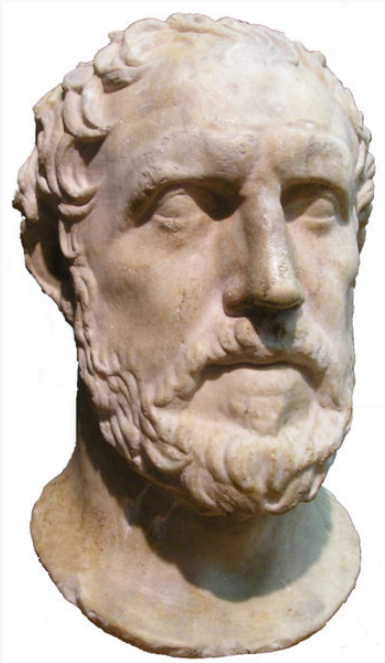
Diseases have been moving around for a while

It first began, it is said, in the parts of Ethiopia above Egypt, and thence descended into Egypt and Libya and into most of the [Persian] King's country. Suddenly falling upon Athens, it first attacked the population in Piraeus [..] and afterwards appeared in the upper city, when the deaths became much more frequent.

Thucydides (c. 460 BC - c. 395 BC)
History of the Peloponnesian War
(plague of Athens of 430 BC)



SARS epidemic of 2002-2003

Severe acute respiratory syndrome (SARS)

- appears (traced) in November 2002 in Guandong Province
- first reports (detected) in Asia in February 2003
- propagation to 27 countries in Asia, North and South America, Europe, in a matter of months
- 8098 infected in 28 countries, 774 deaths

36 cities imported SARS cases:

- 24 had direct nonstop flights from Hong Kong (HKG)
- 12 were 1 stop away from HKG

137 cases showed (Bio.D case investigation) to have crossed national boundaries while infected:

- 129 travelled by air

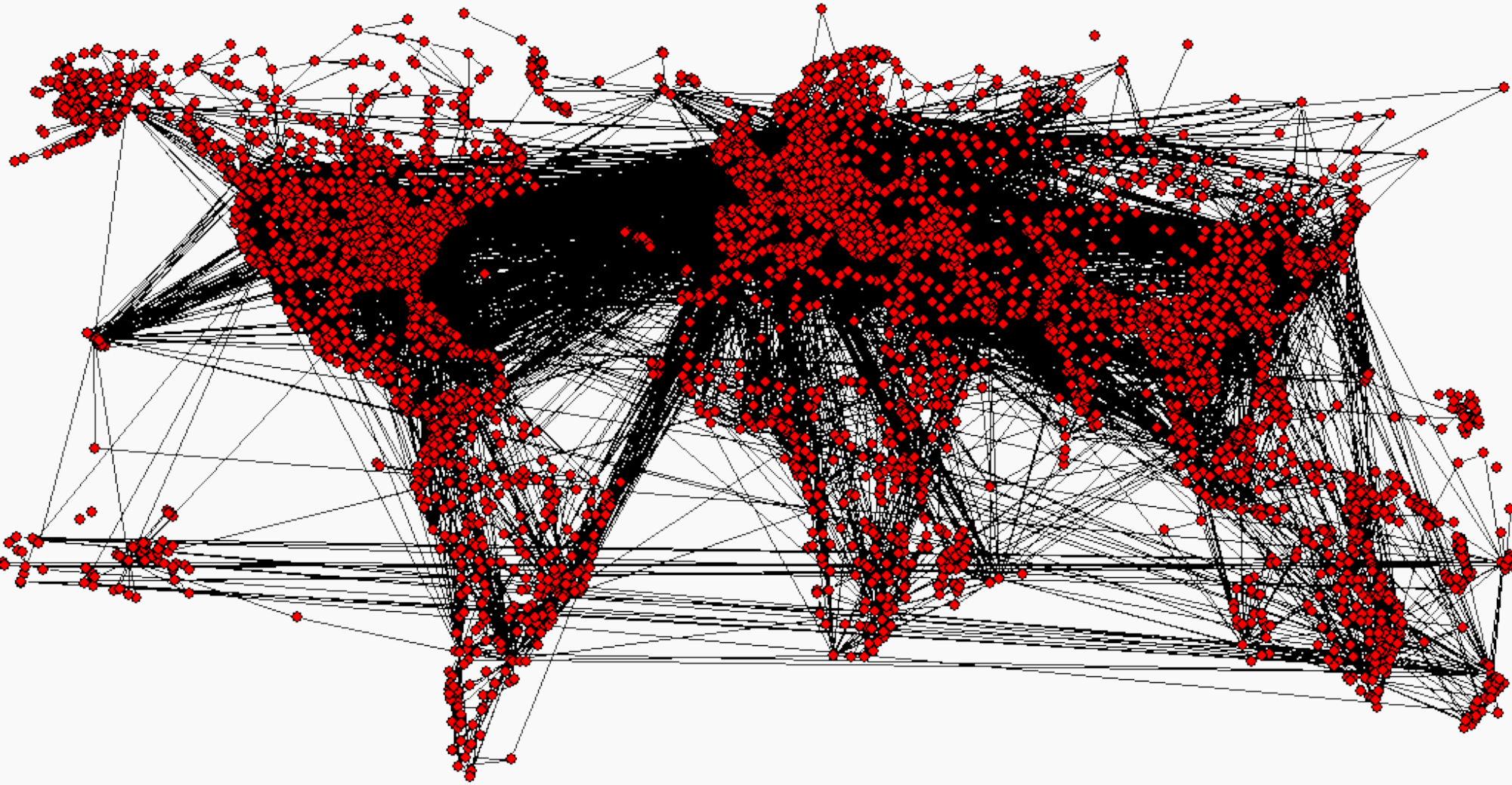
Principal data sources (for me) in Bio.Diaspora

OAG

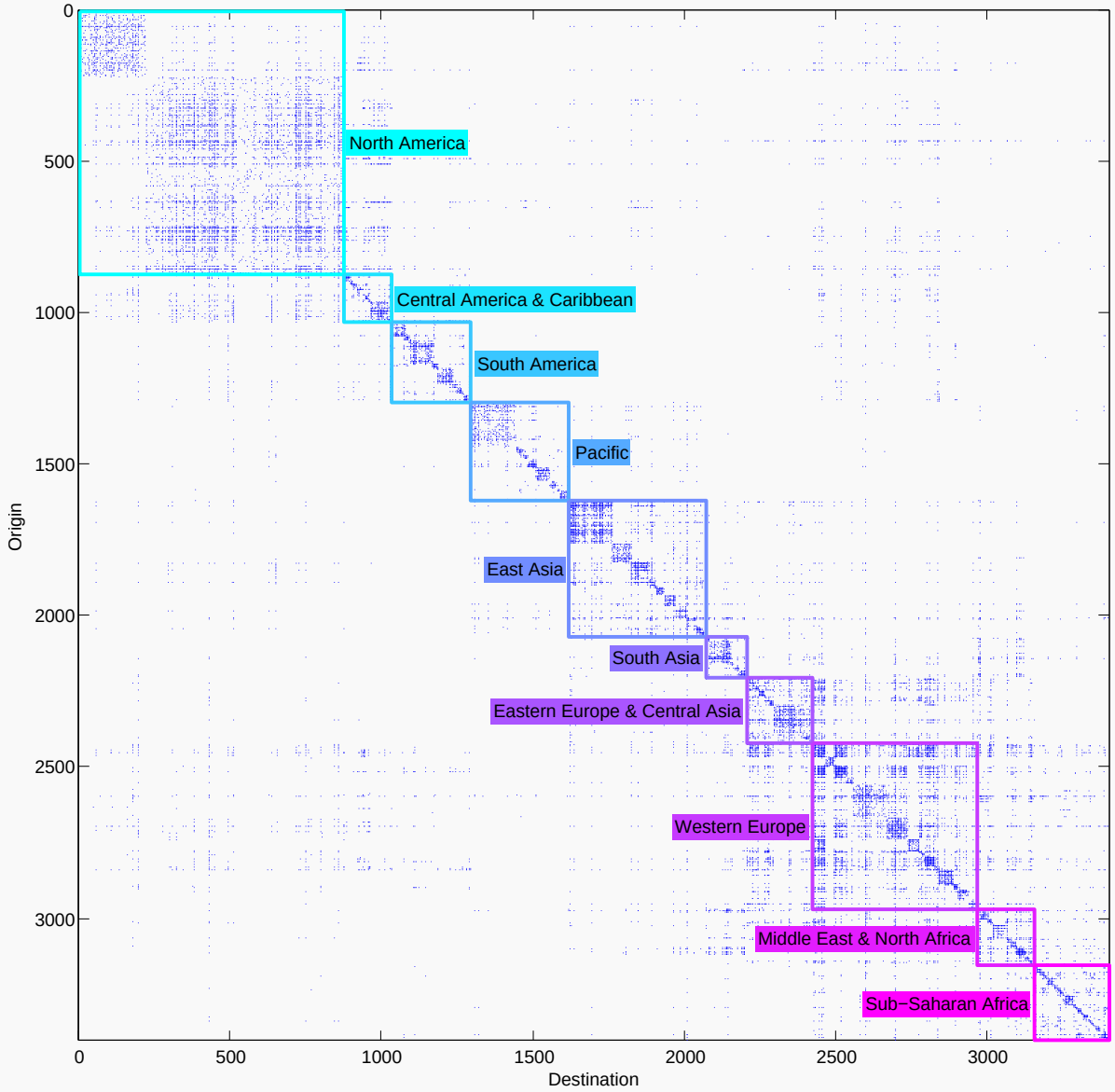
- Official Airline Guide
- All regular and chartered flights, 2000-2010 (2011 in pre-processing)
- **Potential** volume between airports
- 900 airline companies, upward of 3500 airports
- Granularity: minute
- 2008: 3,214,017,034 seats, 35,120 direct flights

IATA

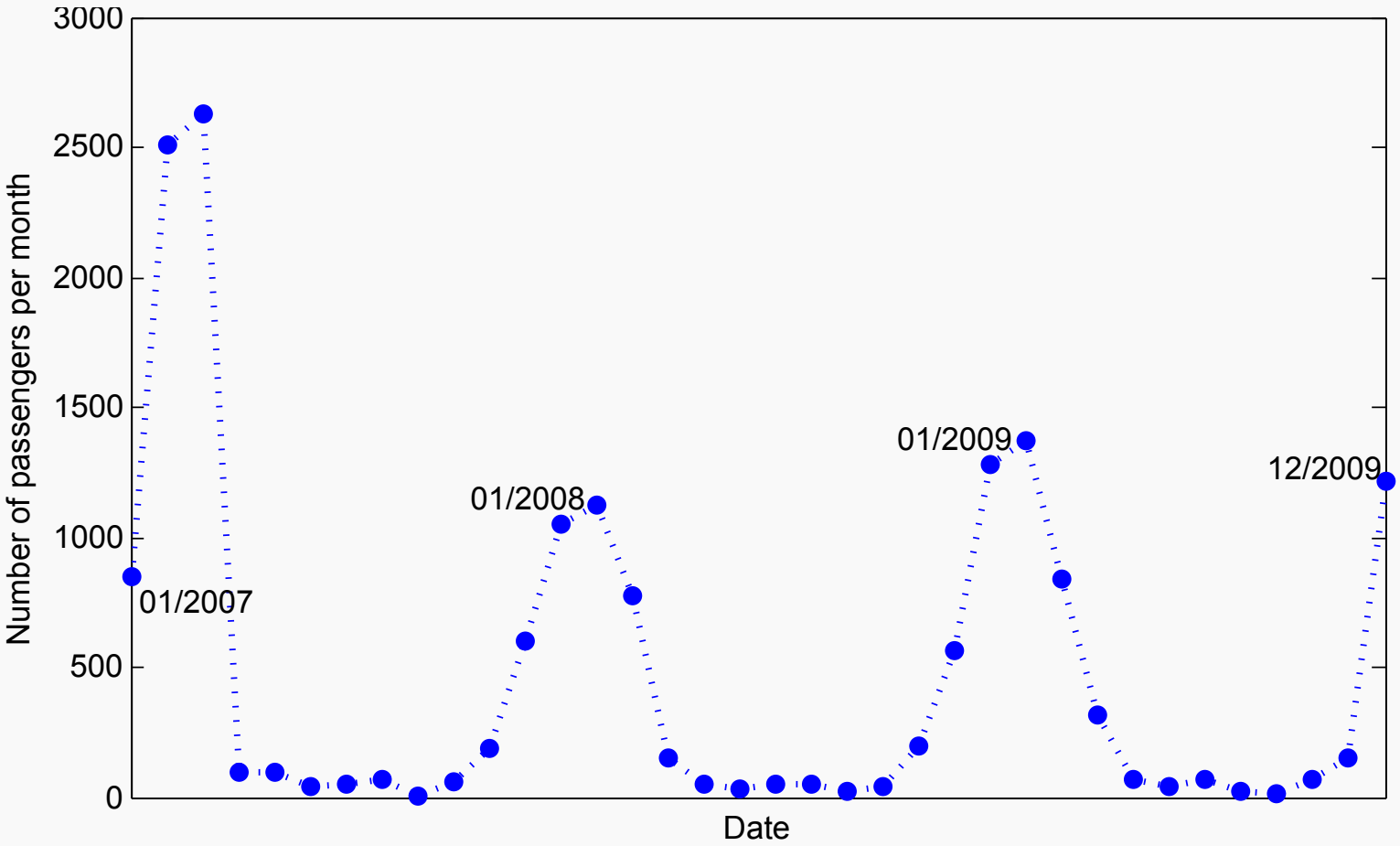
- International Air Transportation Association
- Almost all tickets emitted in 2007, 2008 and 2009
- **Effective** volume between origin and destination, including up to 5 intermediate stops
- Granularity: month
- 2007: 2,079,528,805; 2008: 2,063,435,724 trips (2,775,430 routes); 2009: 2,108,295,202 trips



Connection matrix, OAG 2008



Volumes along arcs change – YWG to CUN



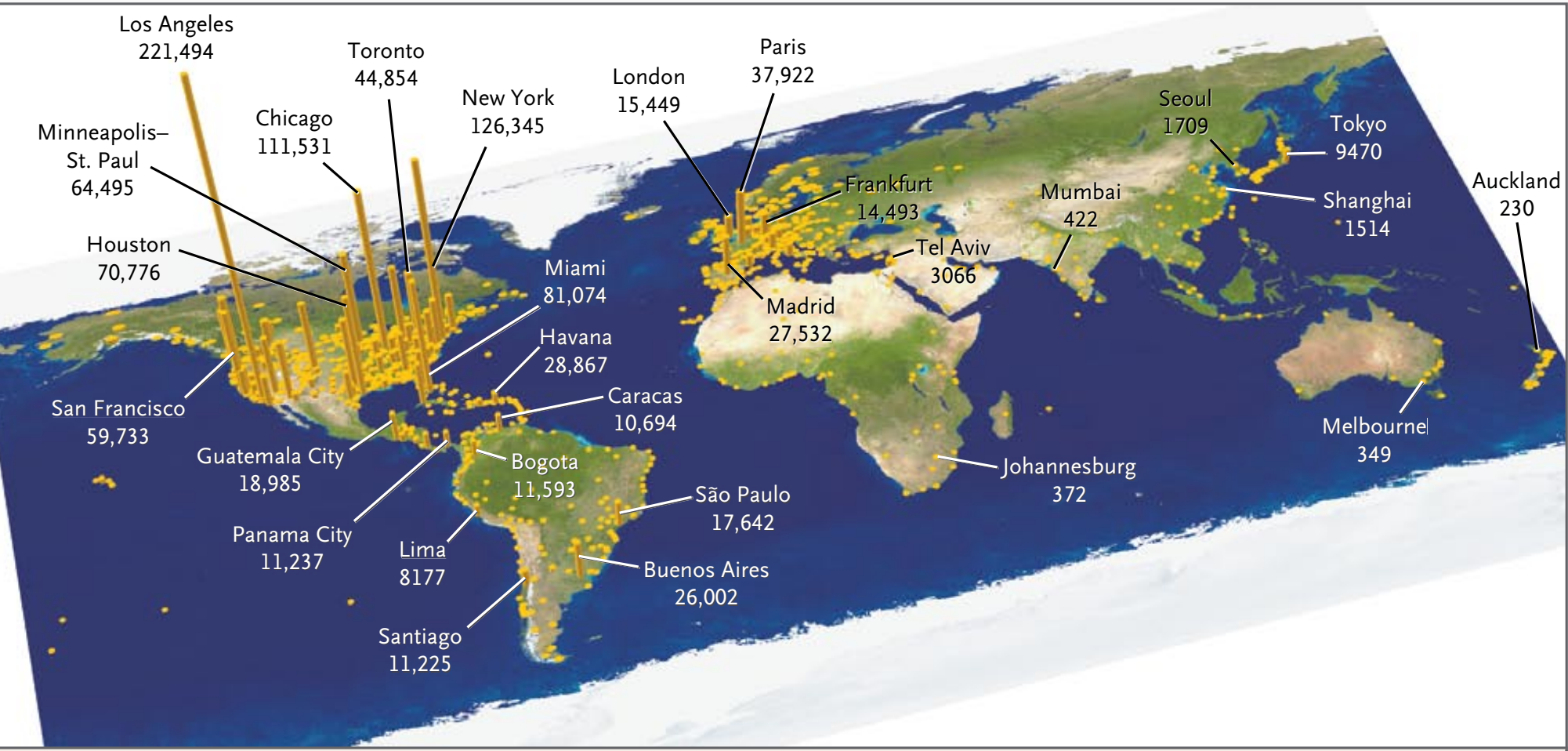


Figure 1. Destination Cities and Corresponding Volumes of International Passengers Arriving from Mexico between March 1 and April 30, 2008.

nH1N1 influenza of 2009

In March and April 2008 (used as surrogate for 2009 data),

- 2.35 million passengers flew from MX to 1018 cities in 164 countries
- 80.7% flew to US and Canada, 8.8% South and Central America, 8.7% Europe
- of 20 countries with highest volumes of passengers arriving from MX, 16 had confirmed importations from MX on 5/25
- ROC curve of relationship between international air-traffic flows and H1N1 importation: countries receiving more than 1400 passengers from MX at significantly elevated risk for importation
- Use this passenger threshold: international air-traffic volume alone was more than 92% sensitive and more than 92% specific in predicting importation, with an area under the ROC curve of 0.97

Khan et al, New England J. Med., July 9, 2009

Trips out of CVJ – March & April 2009

mth	destinationCity	conn1City	paxTotal
3	CJS	MTY	90
4	CJS	MTY	54
3	CUN	MTY	56
4	CUN	MTY	26
3	CUU	MTY	32
4	CUU	MTY	28
3	LAP	MTY	58
4	LAP	MTY	51
3	MID	MTY	31
3	MTY		1274
4	MTY		548
3	TIJ	MTY	117
4	TIJ	MTY	51

Revision of the results

- Originally worked with 2007-2008 data as proxy for 2009
- PHAC contract to study the situation during the pandemic crisis using 2009 data

$\Rightarrow$ Report to PHAC, where we address the problem through 5 questions

Impact on MX

Question 1.

Did awareness of the H1N1 threat precipitate a rapid departure of travellers out of Mexico? If so, could this have accelerated importation and evolution of the H1N1 epidemic in Canada?

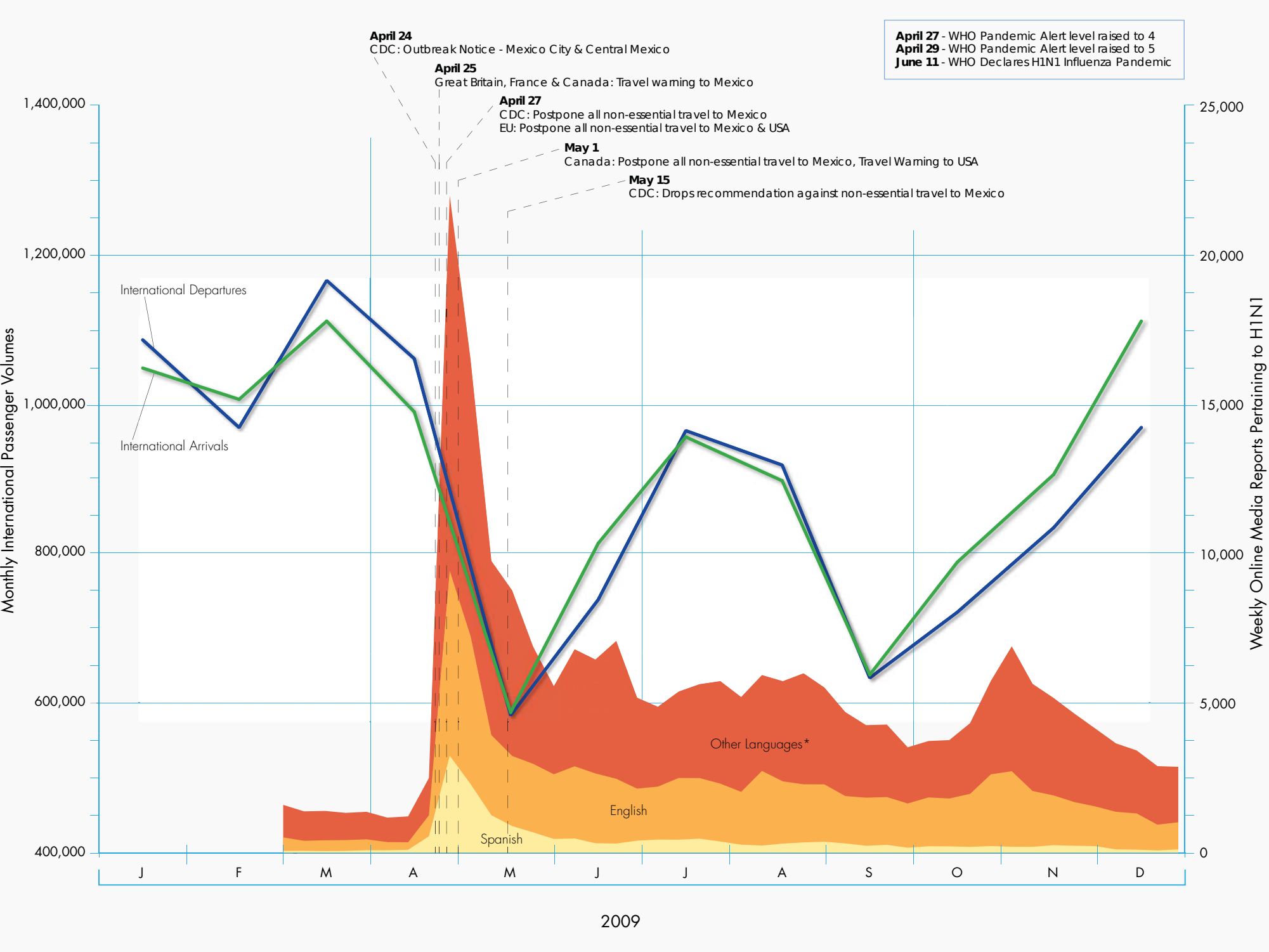
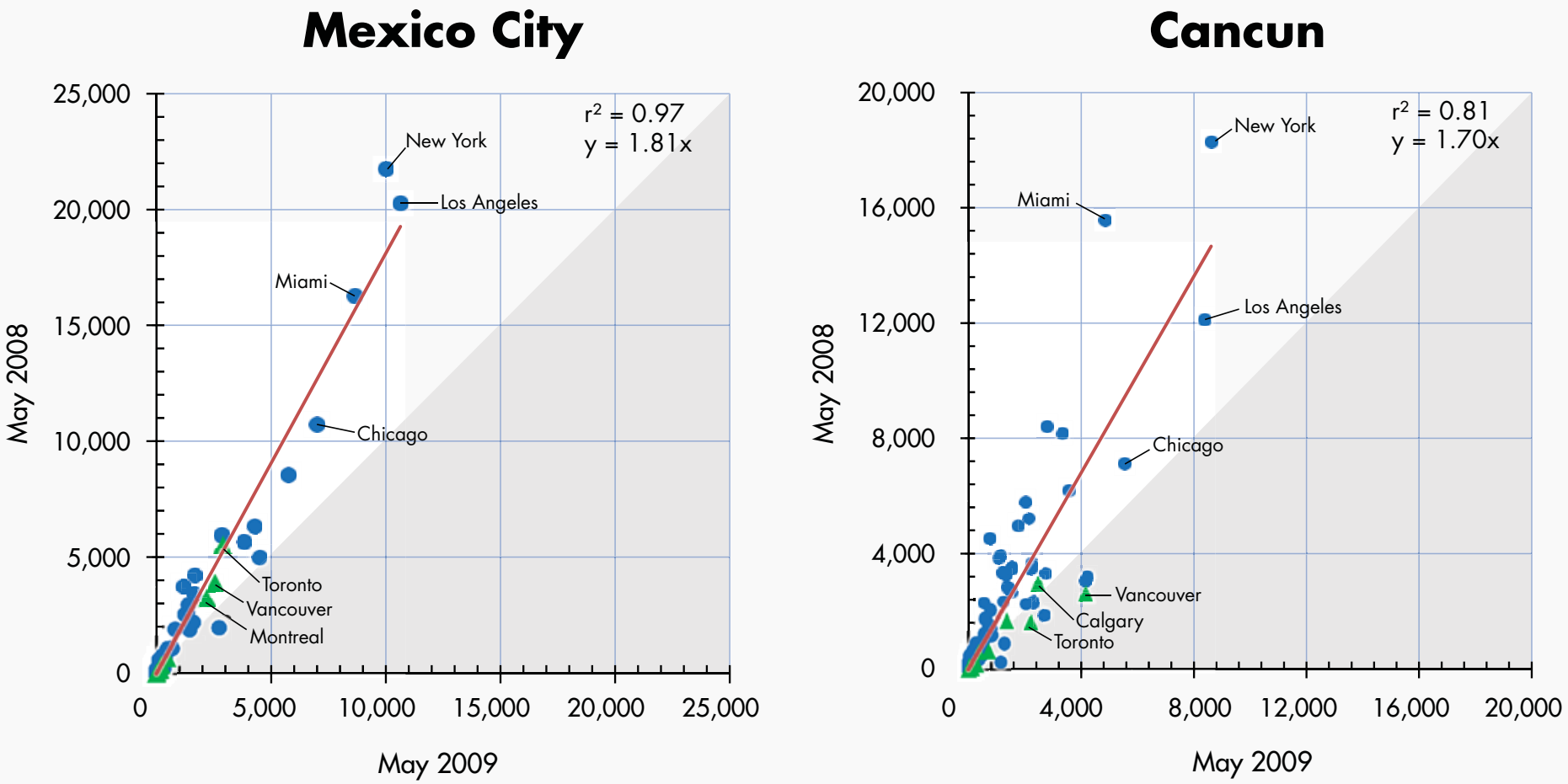
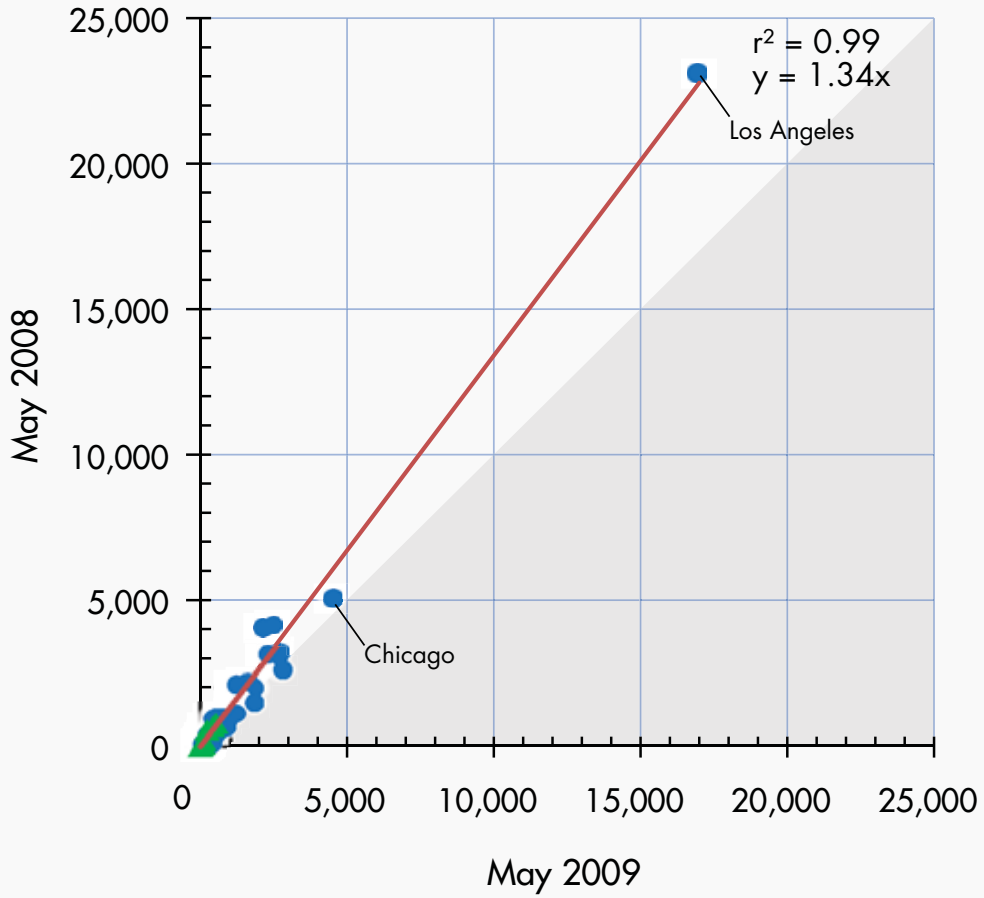

April 24
CDC: Outbreak Notice - Mexico City & Central Mexico
April 25
Great Britain, France & Canada: Travel warning to Mexico
April 27
CDC: Postpone all non-essential travel to Mexico
EU: Postpone all non-essential travel to Mexico & USA
May 1
Canada: Postpone all non-essential travel to Mexico, Travel Warning to USA
May 15
CDC: Drops recommendation against non-essential travel to Mexico
April 27 - WHO Pandemic Alert level raised to 4
April 29 - WHO Pandemic Alert level raised to 5
June 11 - WHO Declares H1N1 Influenza Pandemic
1,400,000
1,200,000
1,000,000
800,000
600,000
400,000
25,000
20,000
15,000
10,000
5,000
0
Monthly International Passenger Volumes
Weekly Online Media Reports Pertaining to H1N1
International Departures
International Arrivals
Other Languages*
English
Spanish
J
F
M
A
M
J
J
A
S
O
N
D
2009

Exhibit 2: International Passenger Departures from Six Leading Mexican Cities into Cities in Canada and the United States, May 2008 & May 2009

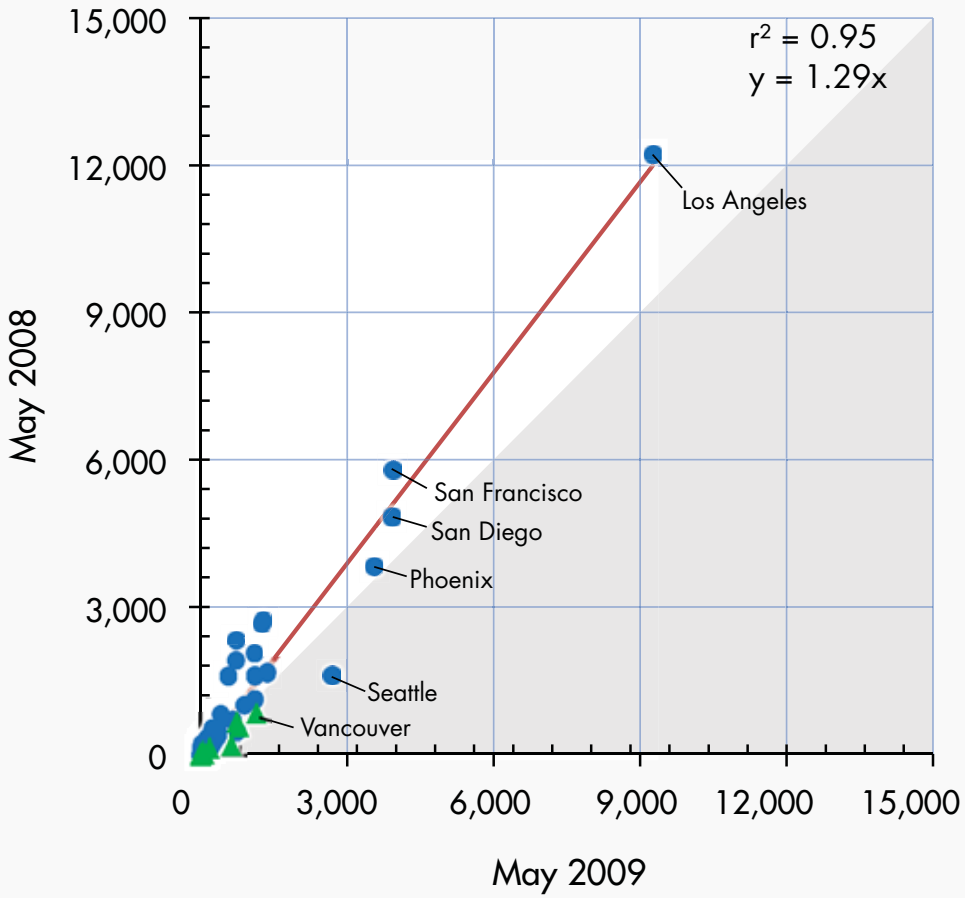


Data Source: International Air Transport Association (IATA)

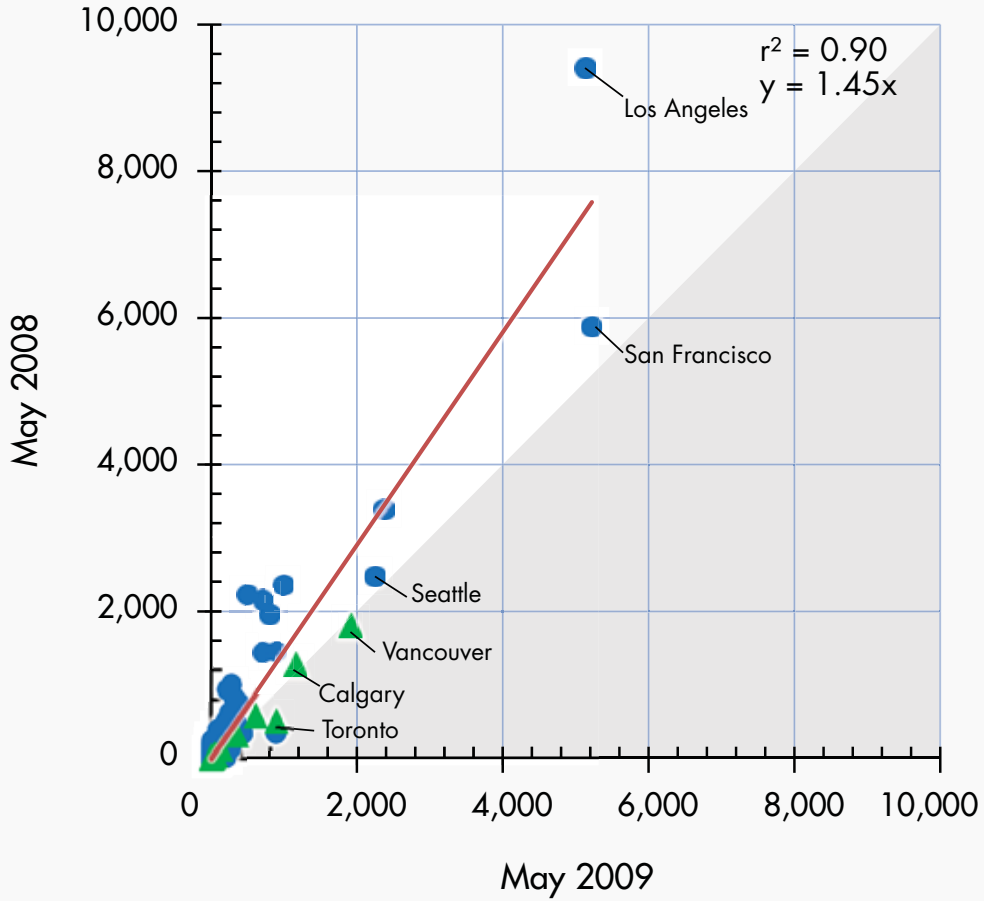
Guadalajara



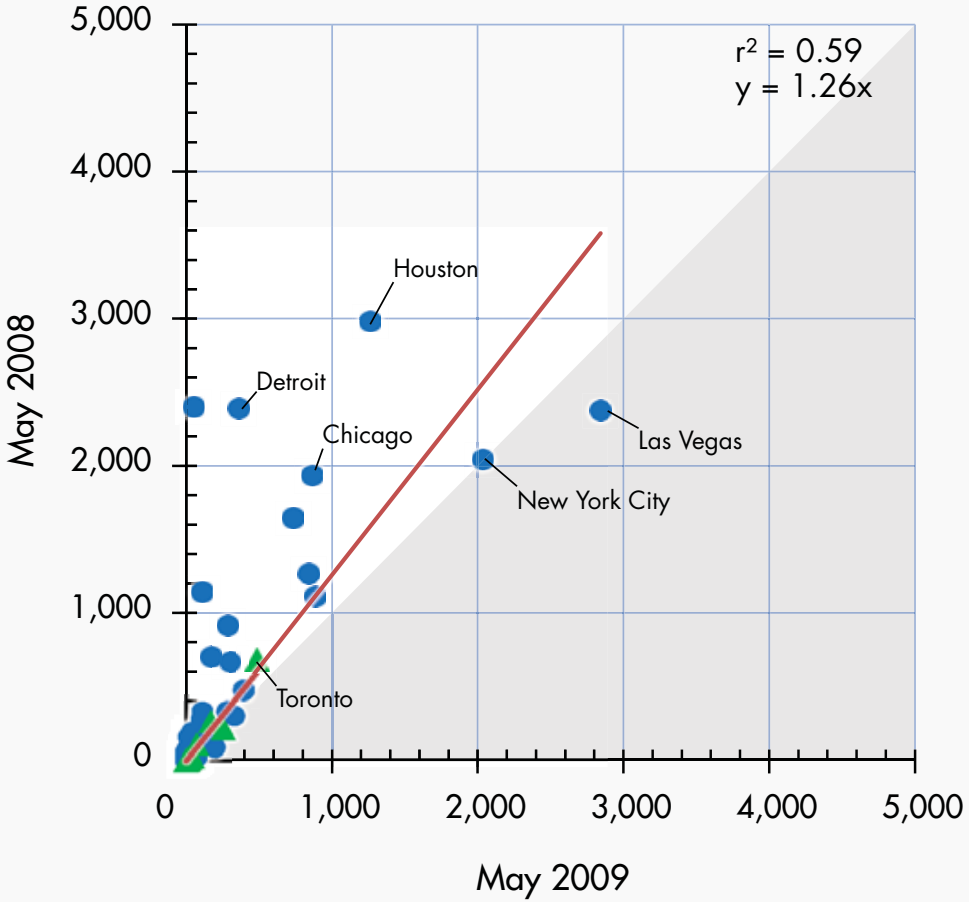
Cabo San Lucas



Puerto Vallarta



Monterrey



- Volume MX into CA in May 2008 $>$ volume in May 2009 [but recall: economic crisis]
- More marked for resorts (CUN, PVR, SJD) than economic centres (MEX, GDL, MTY)
- But no semblance of exodus of Canadian travellers

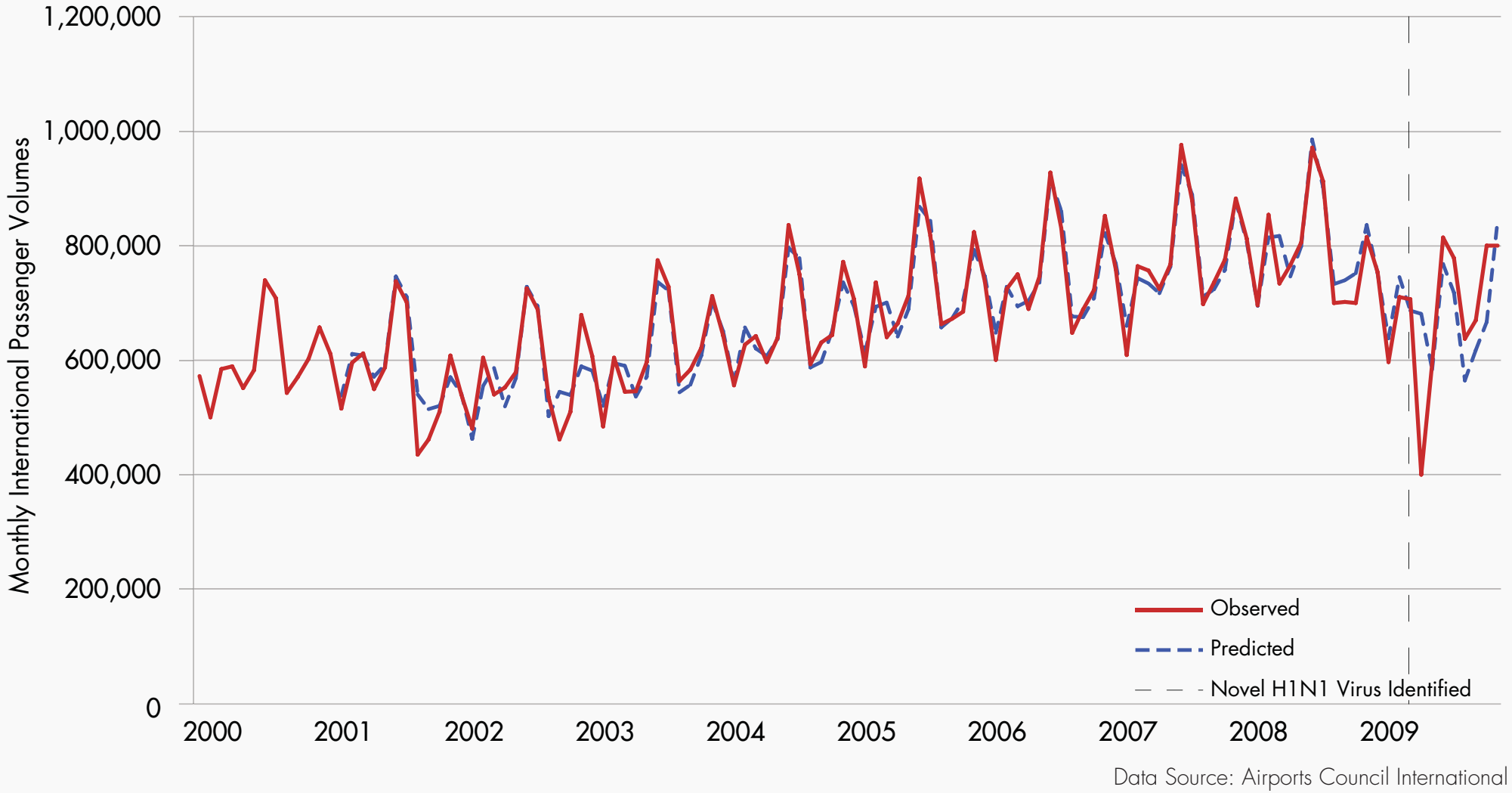
Global effect

Question 2.

What impact did the H1N1 pandemic have on international air travel to and from Mexico? Was international air travel to and from the United States and Canada also disrupted, and if so in what way?

Exhibit 4: International Passenger Arrivals plus Departures in Mexico City, 2000-2009 (Juárez International Airport)

A Comparison of Observed versus Predicted Traffic Flows



Data Source: Airports Council International

Deviation between Observed and Predicted Flows of International Passenger Traffic in Mexico City, 2001-2009

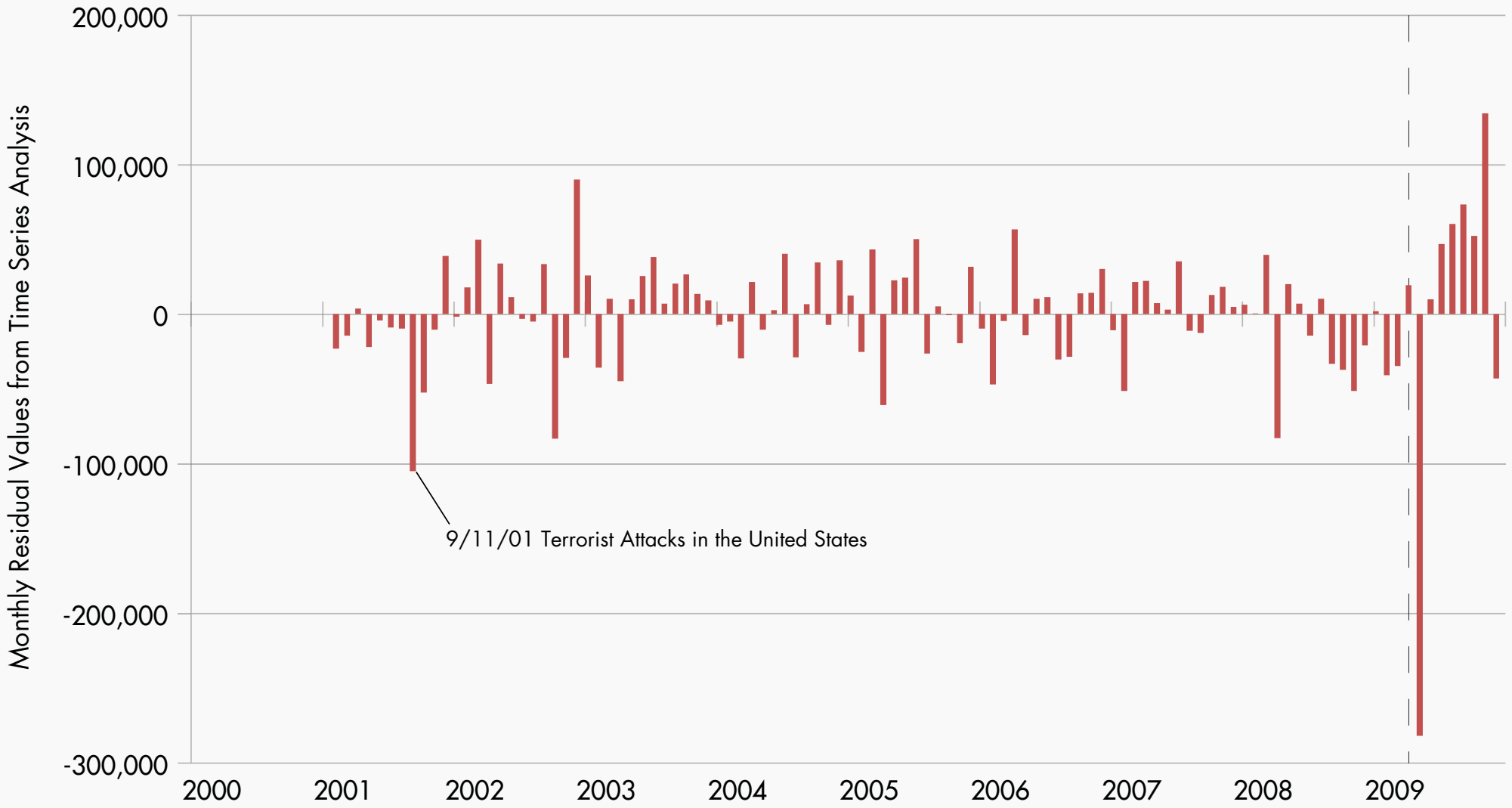
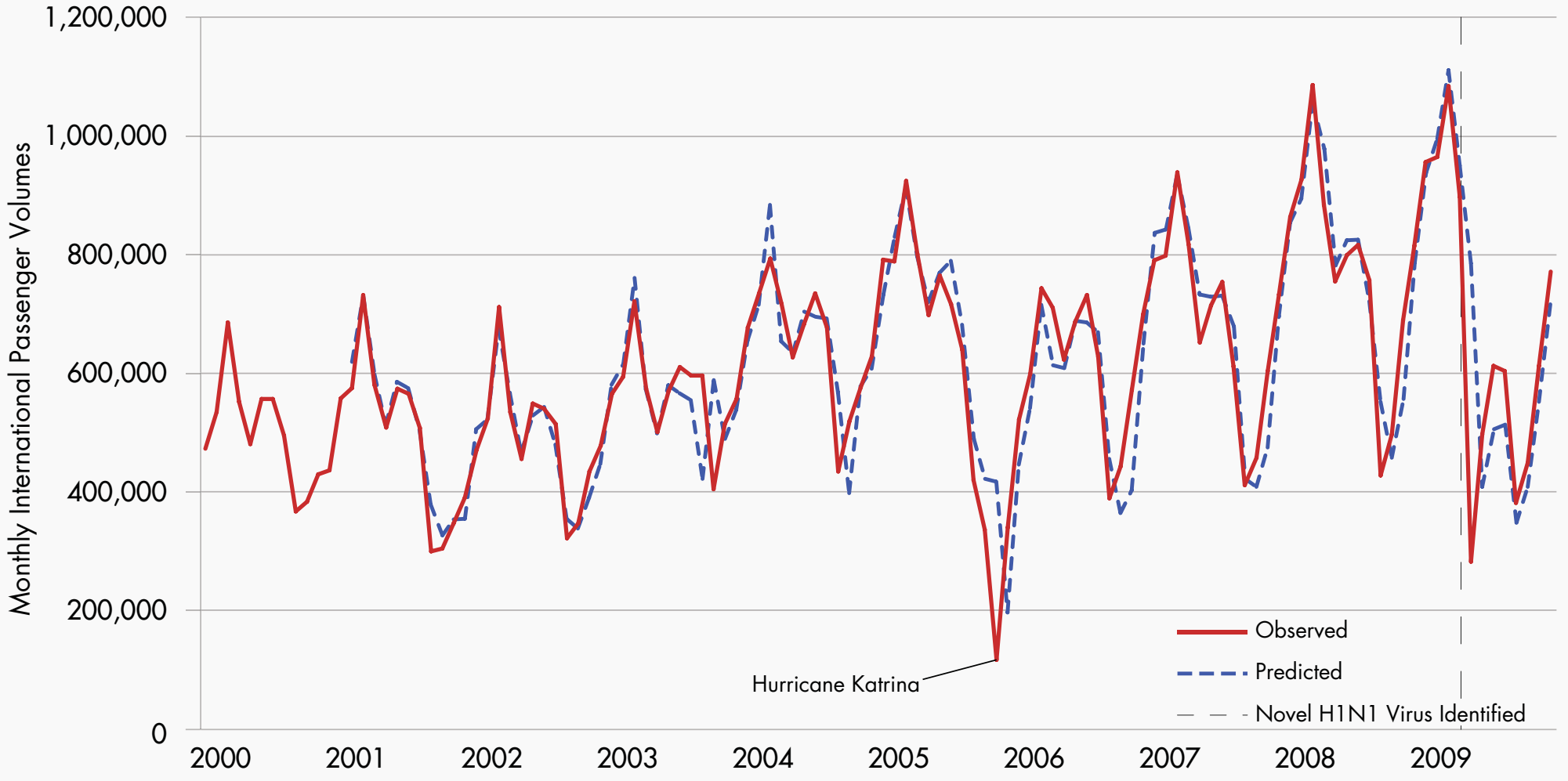


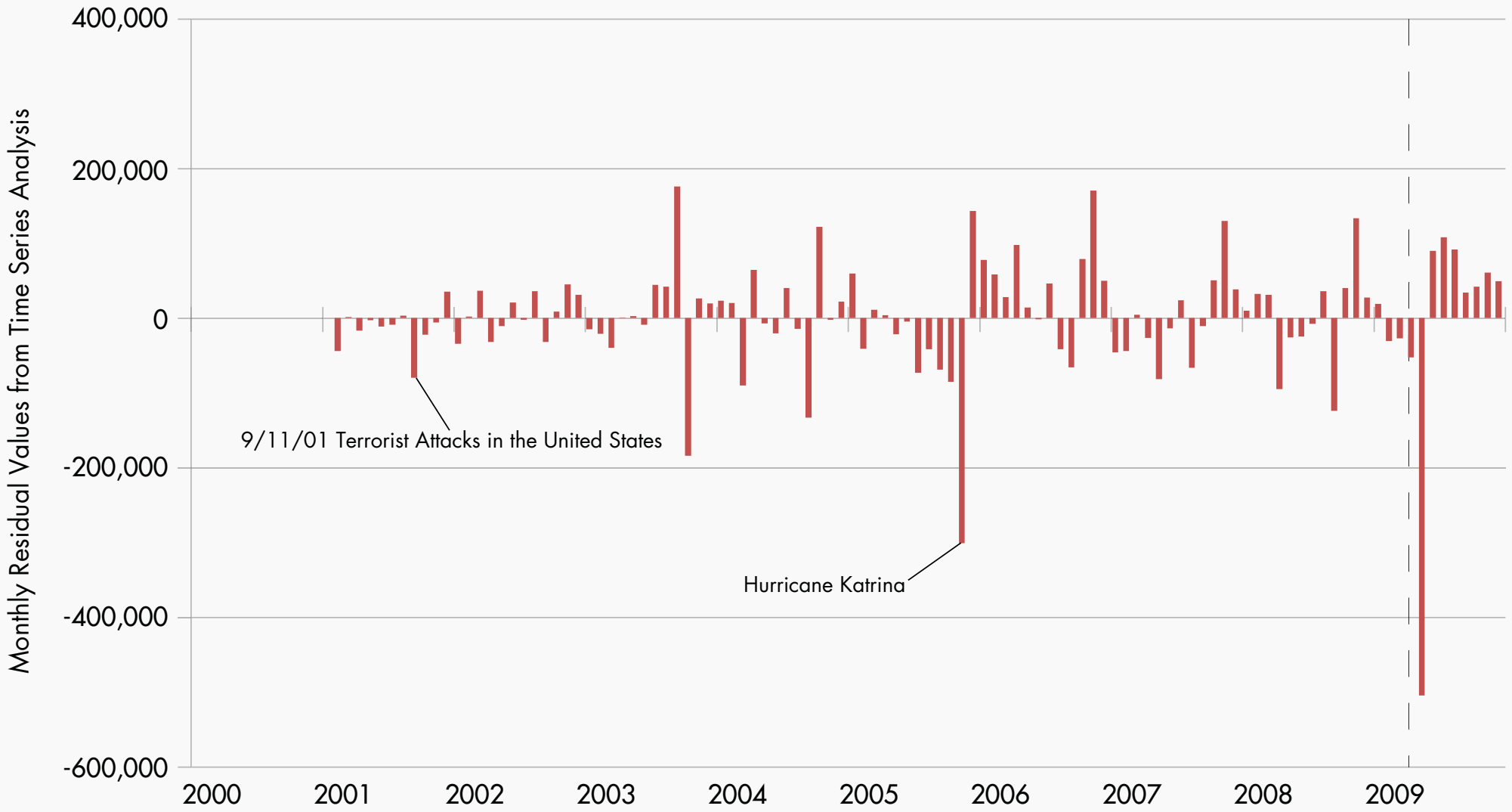
Exhibit 5: International Passenger Arrivals plus Departures in Cancun, 2000-2009

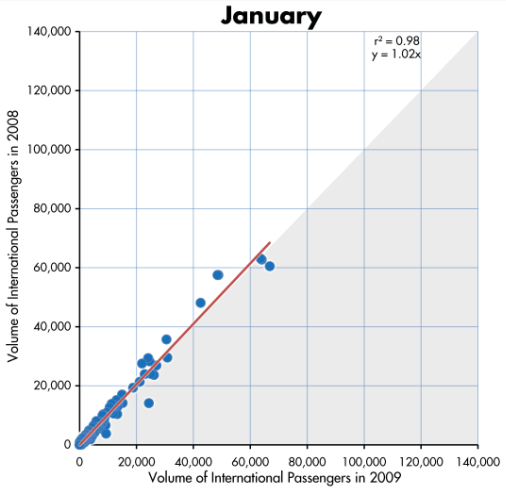
A Comparison of Observed versus Predicted Traffic Flows

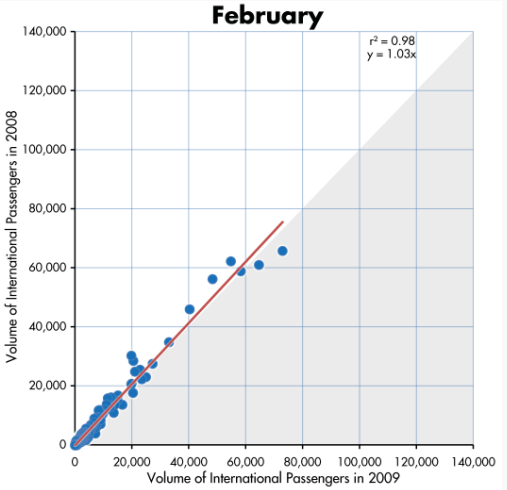


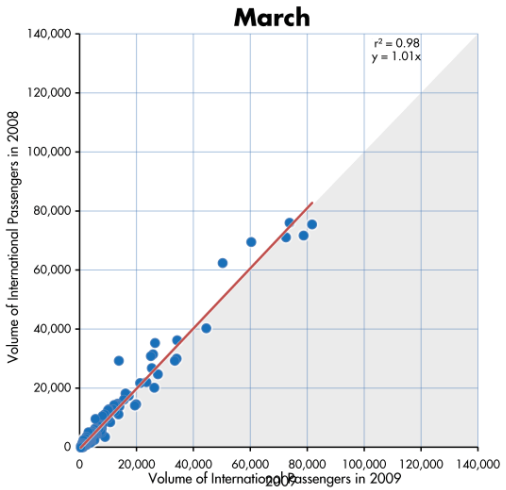
Data Source: Airports Council International

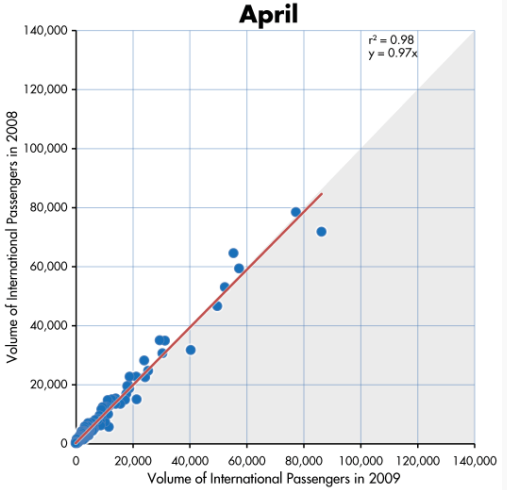
Deviation between Observed and Predicted Flows of International Passenger Traffic in Cancun, 2001-2009

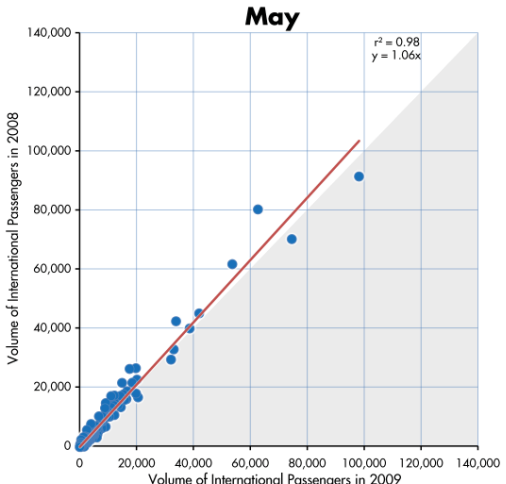


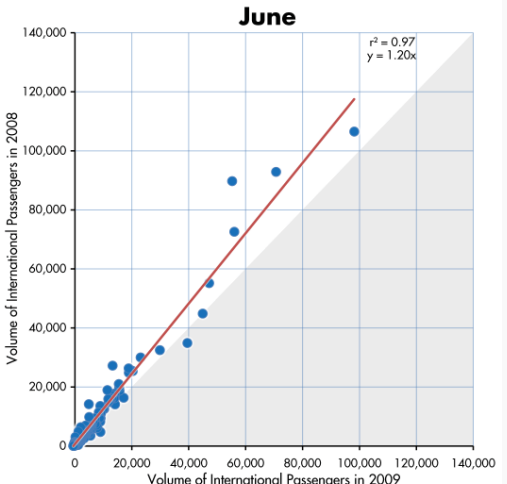

January
r² = 0.98
y = 1.02x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000

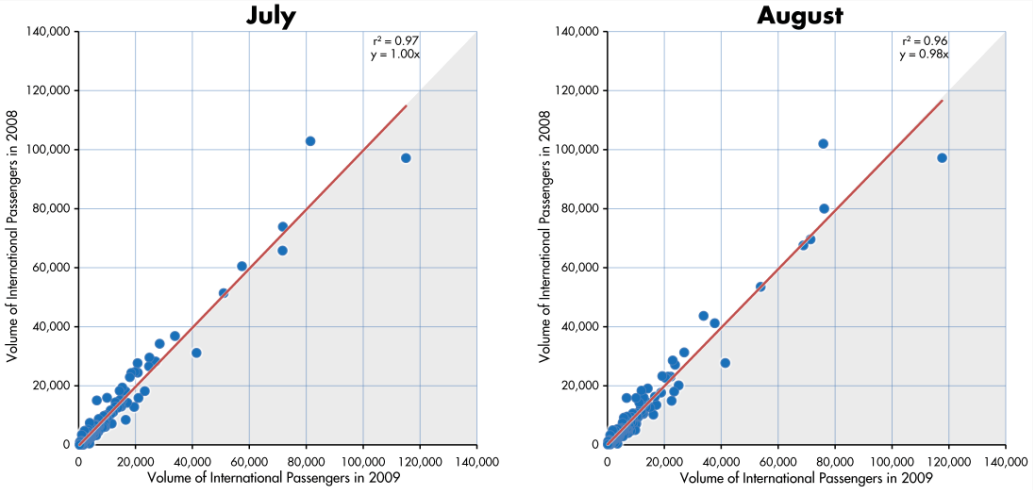

February
r² = 0.98
y = 1.03x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000


March
r² = 0.98
y = 1.01x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000

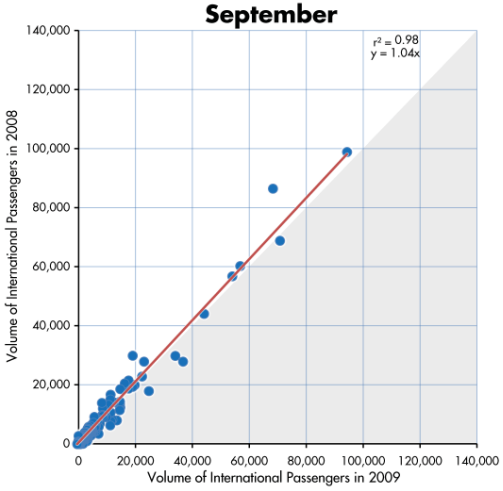

April
r² = 0.98
y = 0.97x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000

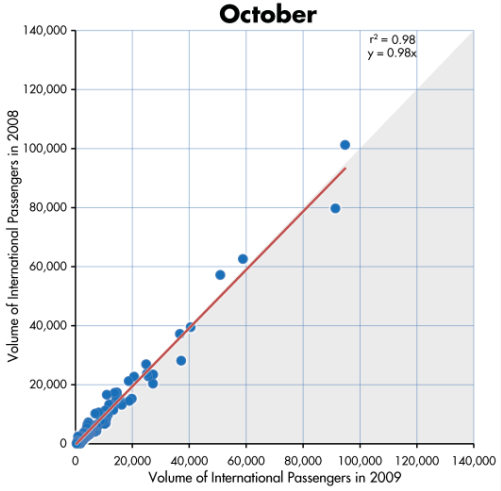

May
r² = 0.98
y = 1.06x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000

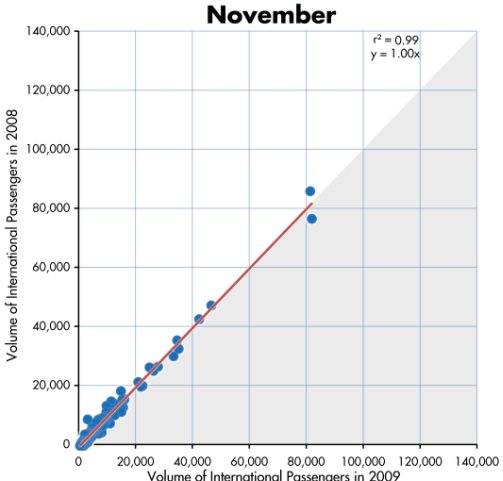

June
r² = 0.97
y = 1.20x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000


July
r² = 0.97
y = 1.00x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000

August
r² = 0.96
y = 0.98x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000


September
r² = 0.98
y = 1.04x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000


October
r² = 0.98
y = 0.98x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000


November
r² = 0.99
y = 1.00x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000

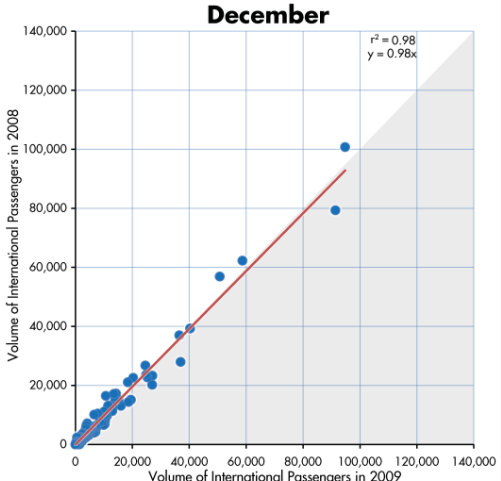
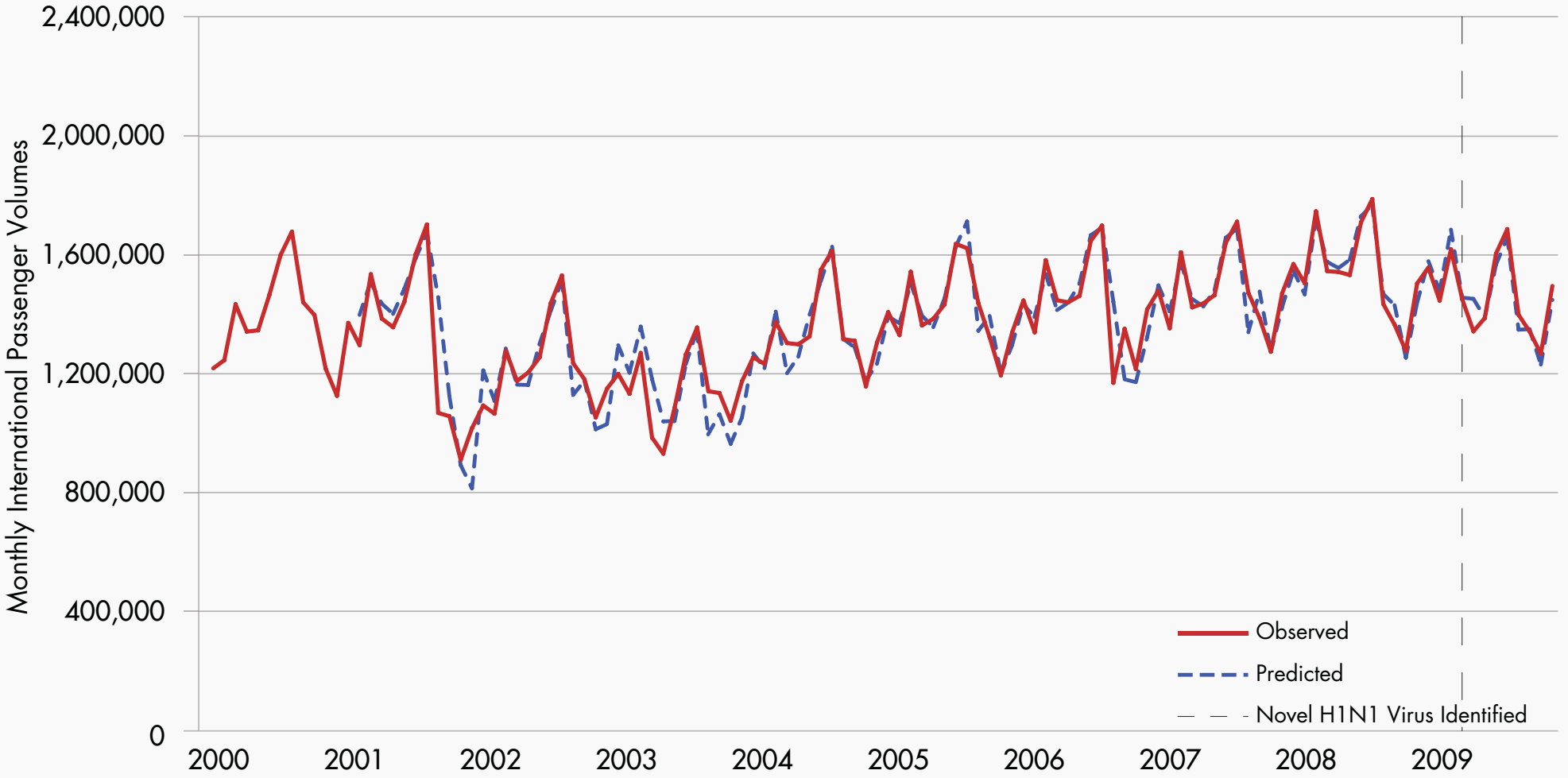

December
r² = 0.98
y = 0.98x
Volume of International Passengers in 2008
Volume of International Passengers in 2009
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000

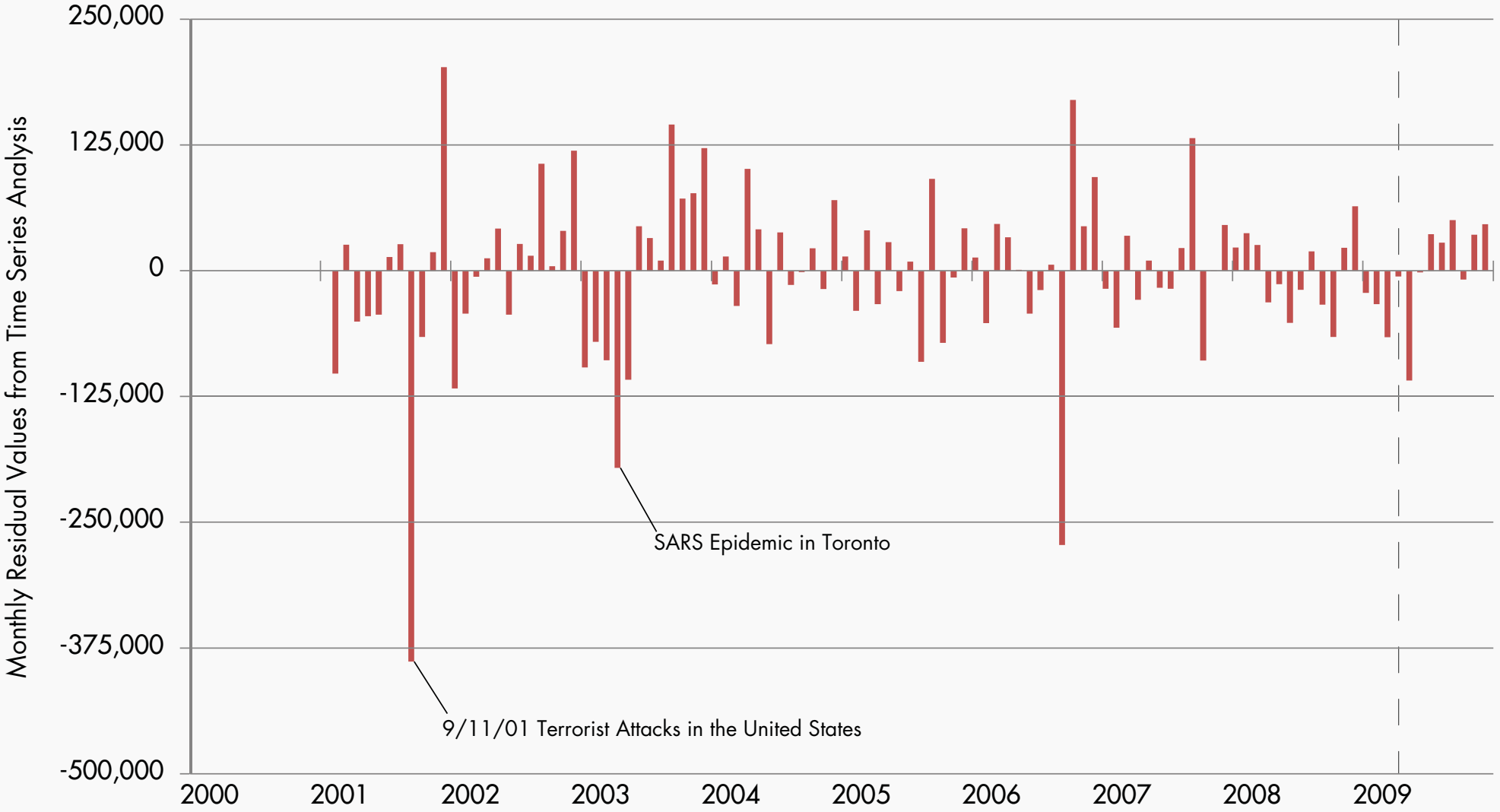
Exhibit 12: International Passenger Arrivals plus Departures in Toronto, 2000-2009 (Pearson International Airport)

A Comparison of Observed versus Predicted Traffic Flows



Data Source: Airports Council International

Deviation between Observed and Predicted Flows of International Passenger Traffic in Toronto, 2001-2009



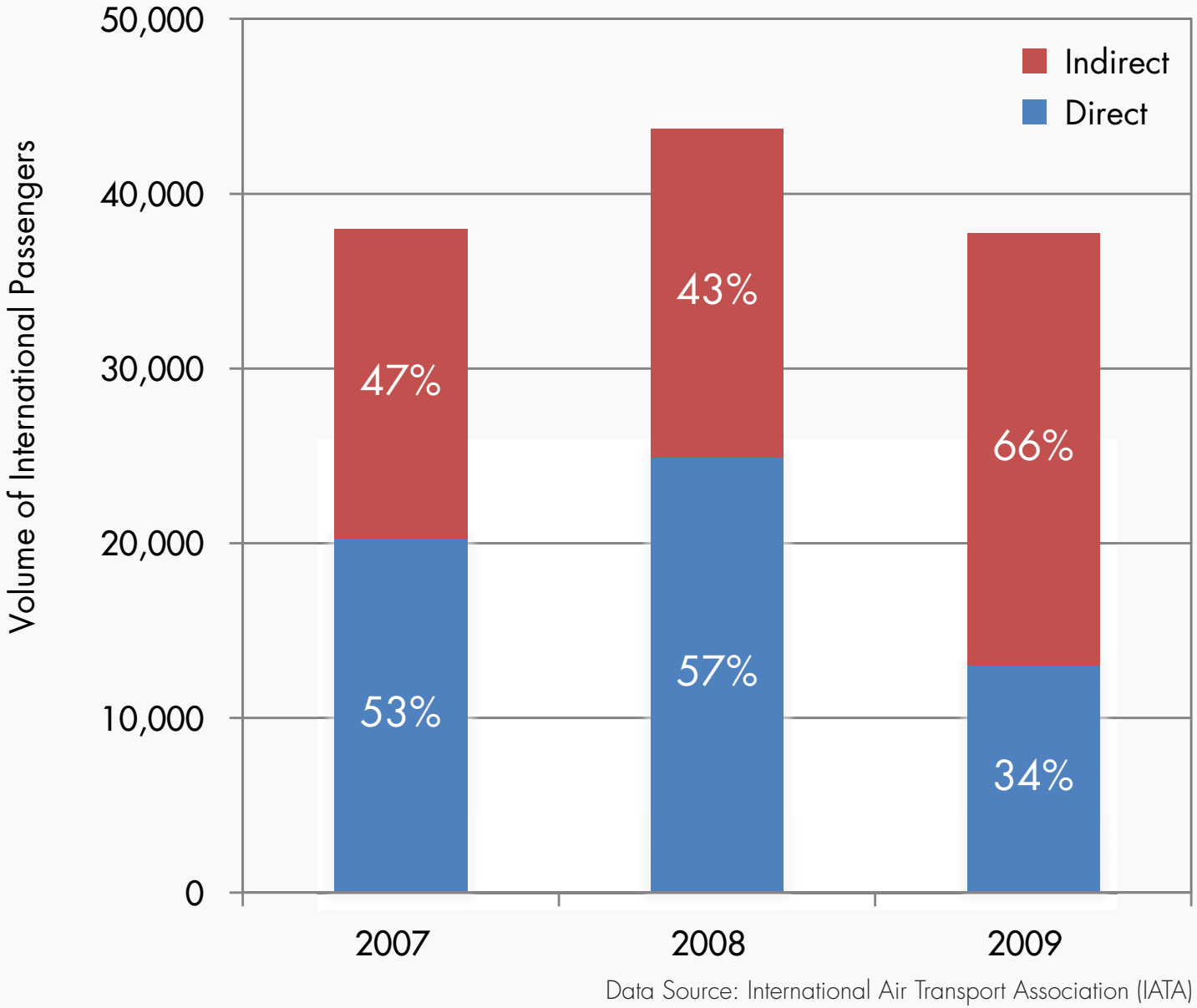
- Estimated deficit of more than 1 million travellers to and from MX in May 2009
- 17 commercial airports in Canada were receiving international passengers from Mexico in the month of May 2009 (5 of them accounting for $> 95\%$)
- Only modest decline in CA except YEA

Effect of travel restrictions

Question 3.

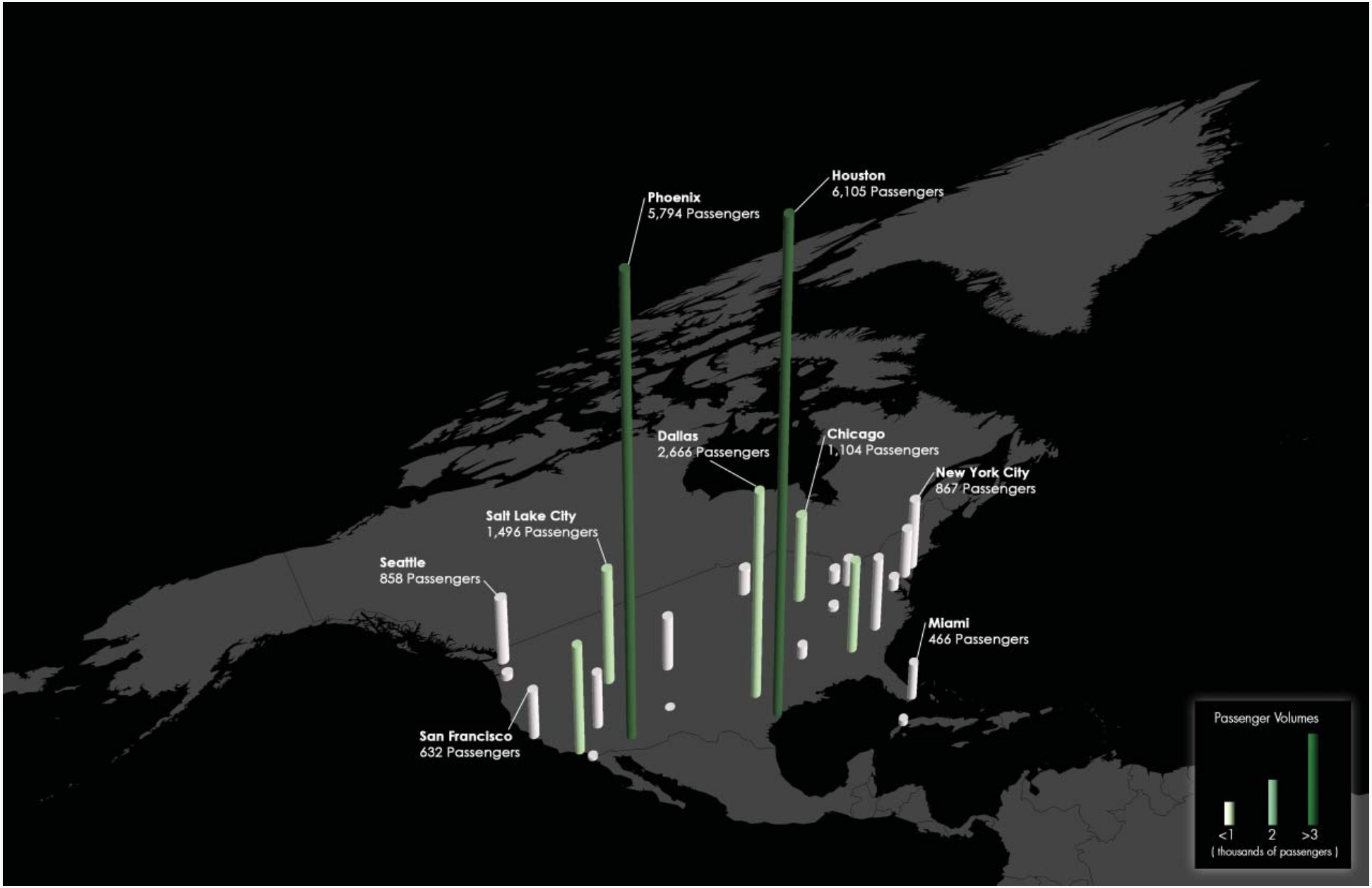
Some airlines temporarily cancelled international flights between Mexico and Canada during the early stages of the H1N1 pandemic. Did this interruption in air travel hinder population mobility between the two countries and if so, could it have delayed the spread of H1N1? Or did travellers simply bypass these cancelled flight routes to reach their intended destinations?

Exhibit 17: Travel Routes used by International Passengers Departing Mexico for Final Destinations in Canada, May 2007, 2008 & 2009



Data Source: International Air Transport Association (IATA)

Exhibit 18: Leading Cities for Connecting Flights by International Passengers Travelling from Mexico to Canada, May 2009



Data Source: International Air Transport Association (IATA)

Effect of border screening

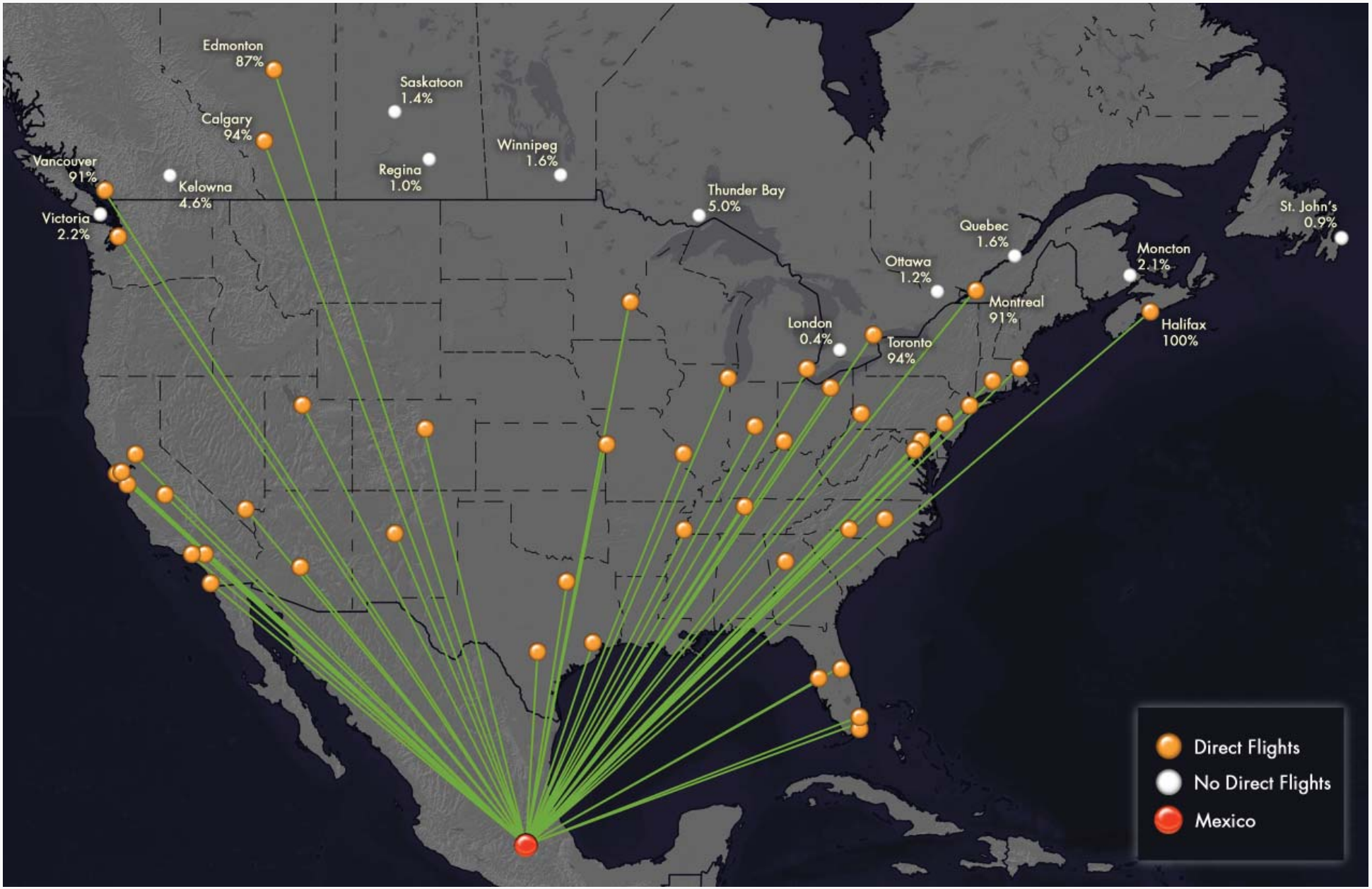
Question 4.

During infectious disease emergencies, public health decision-makers often face pressure to implement airport-based screening measures such as infrared thermography scanning to prevent disease importation. How efficient or inefficient would these measures have been if they were implemented in Canada during the early stages of the H1N1 epidemic?

For this, we use the **maximum potential efficiency** of airport-based entry screening of travellers arriving in Canadian cities, defined as proportion of travellers arriving into Canadian airports who originated their trip from an H1N1 affected area

- Max. potential efficiency of entry screening travellers arriving in Canadian cities without direct flight connections with Mexico extremely limited (max. efficiency $< 5\%$) [all international arriving travellers must be screened regardless of their geographic point of origin]
- By contrast, maximum potential efficiency of entry screening travellers significantly increases if specific flights originating from within Mexico are targeted (max. efficiency $> 85\%$)
- However that these values do not take into consideration the prevalence of H1N1 infection in the travelling population. If the prevalence of H1N1 infection in travellers is sufficiently low (or if the prevalence of other febrile illnesses in travellers is high), even targeted entry screening of travellers from affected areas could become inefficient

Exhibit 20: Flight Pathways from Mexico into Canadian and U.S. Cities and the Potential Efficiency of Entry Screening, May 2009



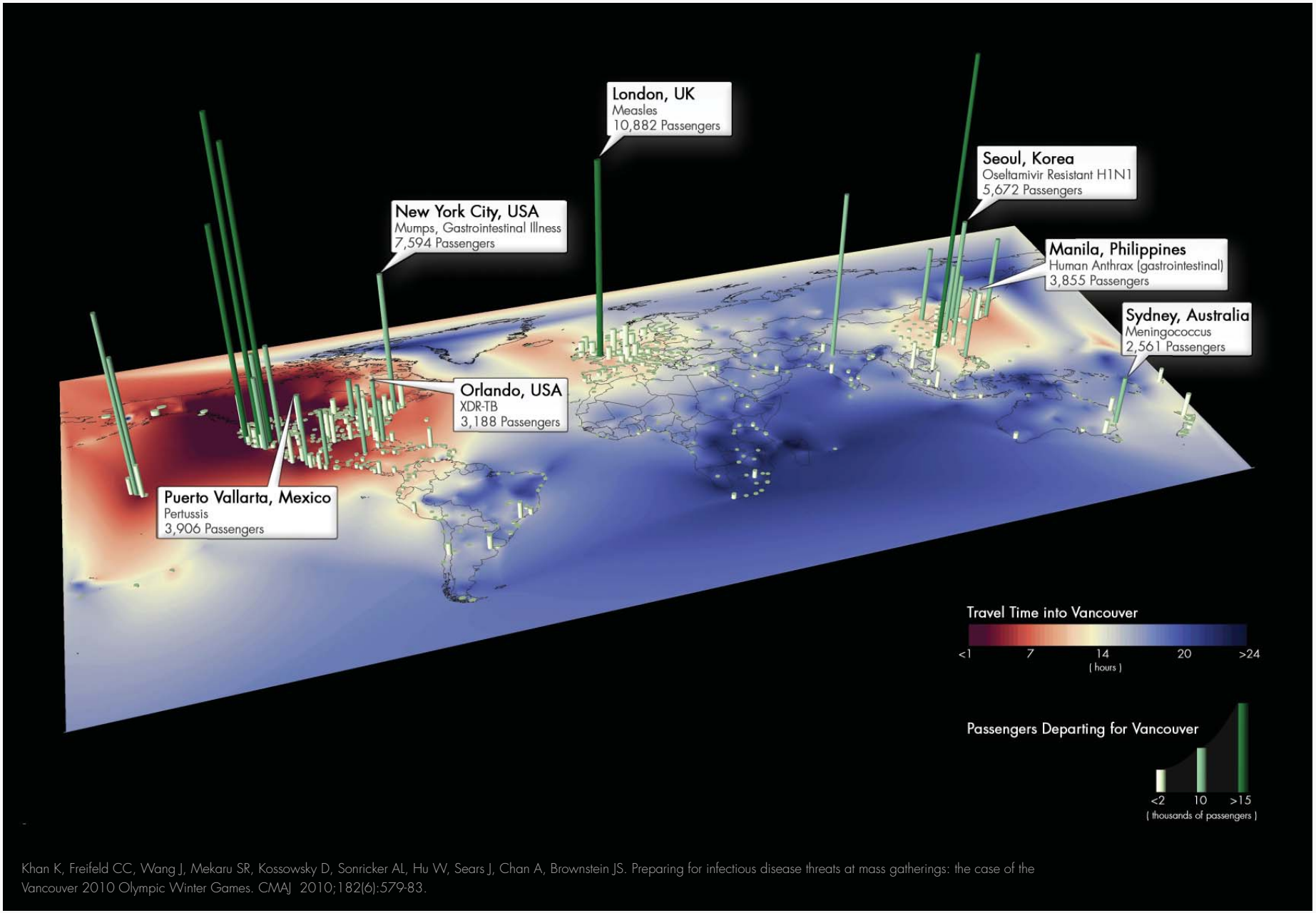
Data Source: International Air Transport Association (IATA), and the Official Airline Guide

Interactions with mass gatherings

Question 5.

Well into the course of the H1N1 pandemic, Canada hosted the 2010 Winter Olympic Games in Vancouver. While mass gatherings have been known to attract, amplify, and subsequently disseminate infectious diseases around the world, this was not observed with H1N1 during the Olympic Games. However, could knowledge of global air traffic patterns help mitigate infectious disease risks associated with future mass gatherings?

Exhibit 22: Potential Infectious Disease Threats to Vancouver during the 2010 Winter Olympic Games in Vancouver



Khan K, Freifeld CC, Wang J, Mekaru SR, Kossowsky D, Sonricker AL, Hu W, Sears J, Chan A, Brownstein JS. Preparing for infectious disease threats at mass gatherings: the case of the Vancouver 2010 Olympic Winter Games. CMAJ 2010;182(6):579-83.

Data Sources: HealthMap Project, International Air Transport Association (IATA), and the Official Airline Guide

Simulations on the network

Requirements

- Use minimal number of parameters
- Account for variability
- Parametrize travel using flight/trip information data
- Be able to parametrize with available data (if real event)

So

- Metapopulation framework
- Continuous time Markov chain
- Minimalistic model (to begin with): EI model

We have seen several metapopulation models, so I will spare you the details

Who uses that airport anyway?

We need the **catchment area** of each airport

Definition 1

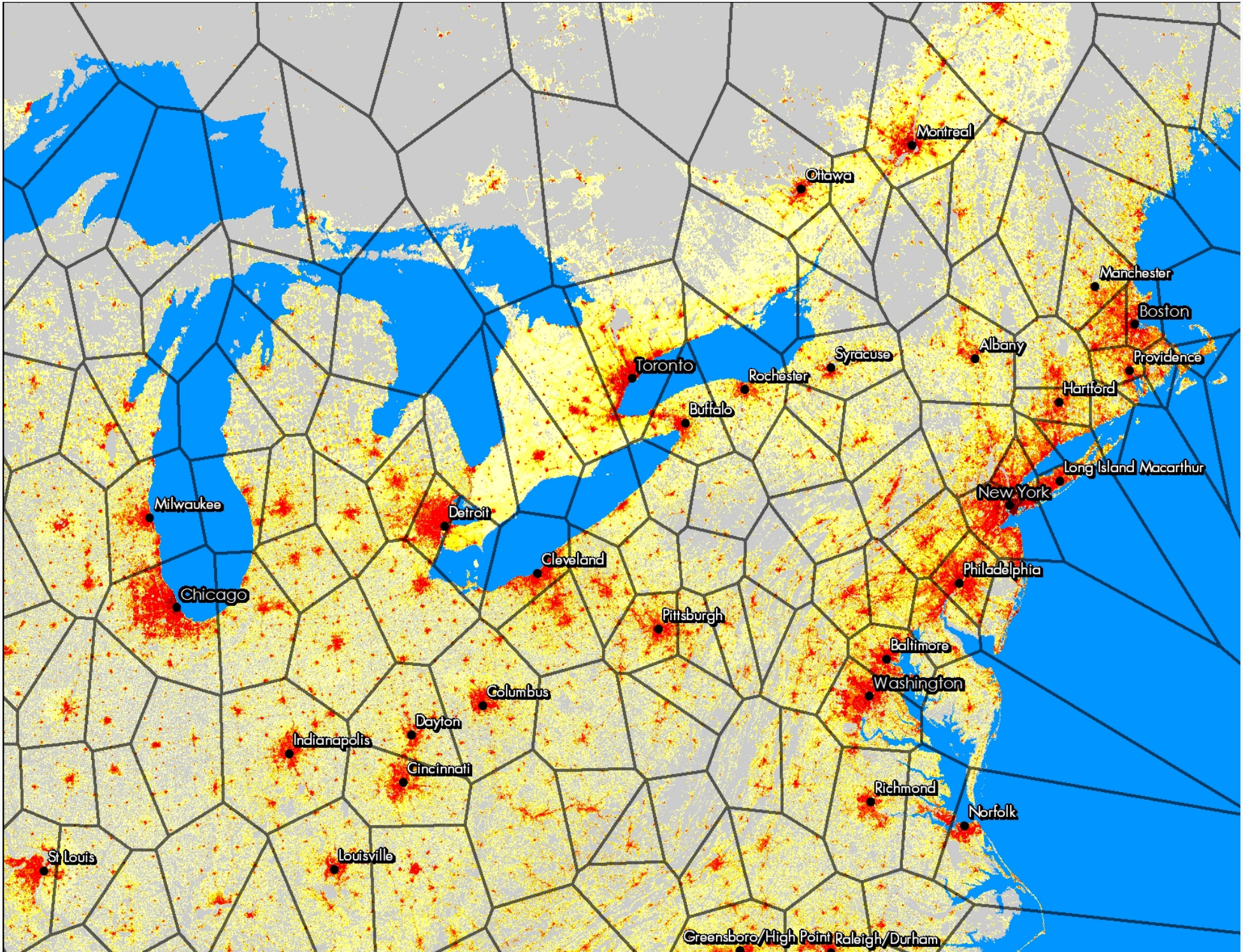
Let $\mathcal{P}$ be a finite set of points in Euclidean space, the "sources".
For each pair of points $P, Q \in \mathcal{P}$, define

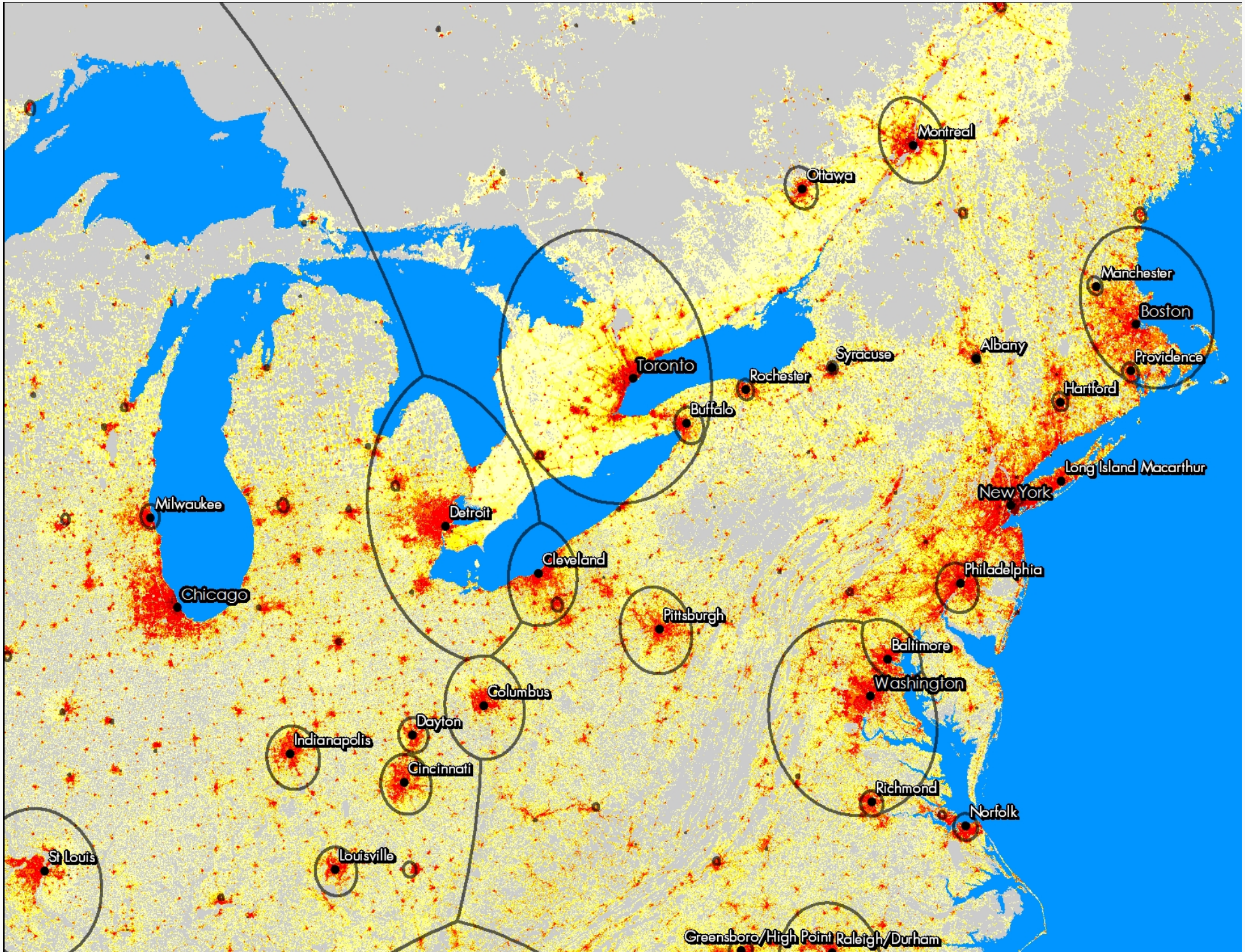
$$H_{PQ} = \left\{ X : \frac{|X - P|}{\sigma(P)} \leq \frac{|X - Q|}{\sigma(Q)} \right\}$$

where $\sigma(P) > 0$, and

$$K_{PQ} := H_{PQ} \cap H_{QP} = \left\{ X : \frac{|X - P|}{\sigma(P)} = \frac{|X - Q|}{\sigma(Q)} \right\}$$

For each $P \in \mathcal{P}$, let $R_p = \bigcap_{Q \neq P} H_{PQ}$ and $R = \{R_P, P \in \mathcal{P}\}$.
$R(\mathcal{P})$ is the **Dirichlet tessellation** of the plane


Montreal
Ottawa
Manchester
Boston
Albany
Syracuse
Providence
Toronto
Rochester
Hartford
Buffalo
Long Island Macarthur
New York
Milwaukee
Detroit
Cleveland
Philadelphia
Chicago
Pittsburgh
Baltimore
Washington
Columbus
Dayton
Indianapolis
Cincinnati
Richmond
Norfolk
St Louis
Louisville
Greensboro/High Point Raleigh/Durham


Montreal
Ottawa
Manchester
Boston
Albany
Syracuse
Providence
Toronto
Rochester
Hartford
Buffalo
Long Island Macarthur
New York
Milwaukee
Detroit
Cleveland
Philadelphia
Chicago
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Cincinnati
Richmond
Norfolk
St Louis
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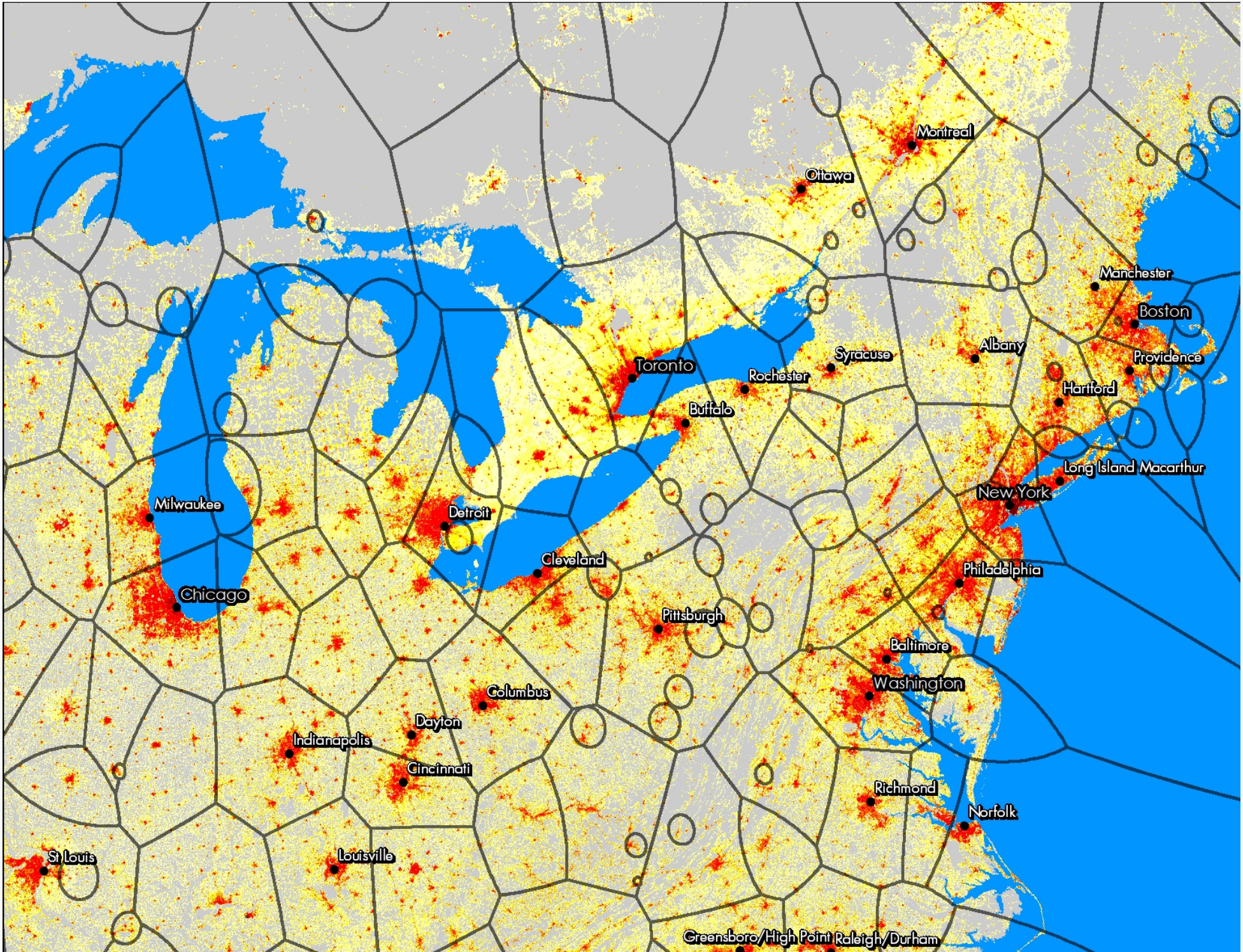
Greensboro/High Point Raleigh/Durham


Montreal
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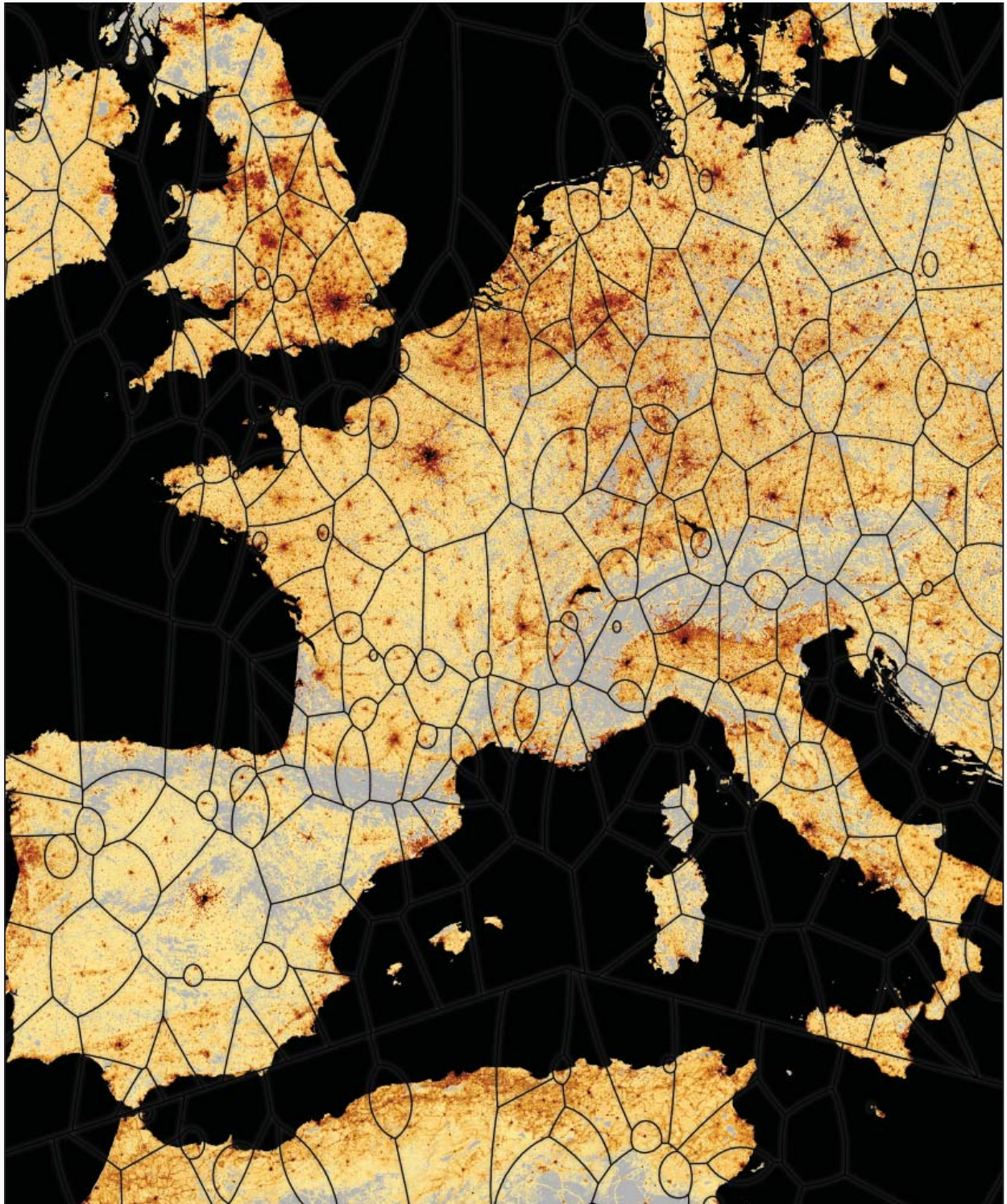
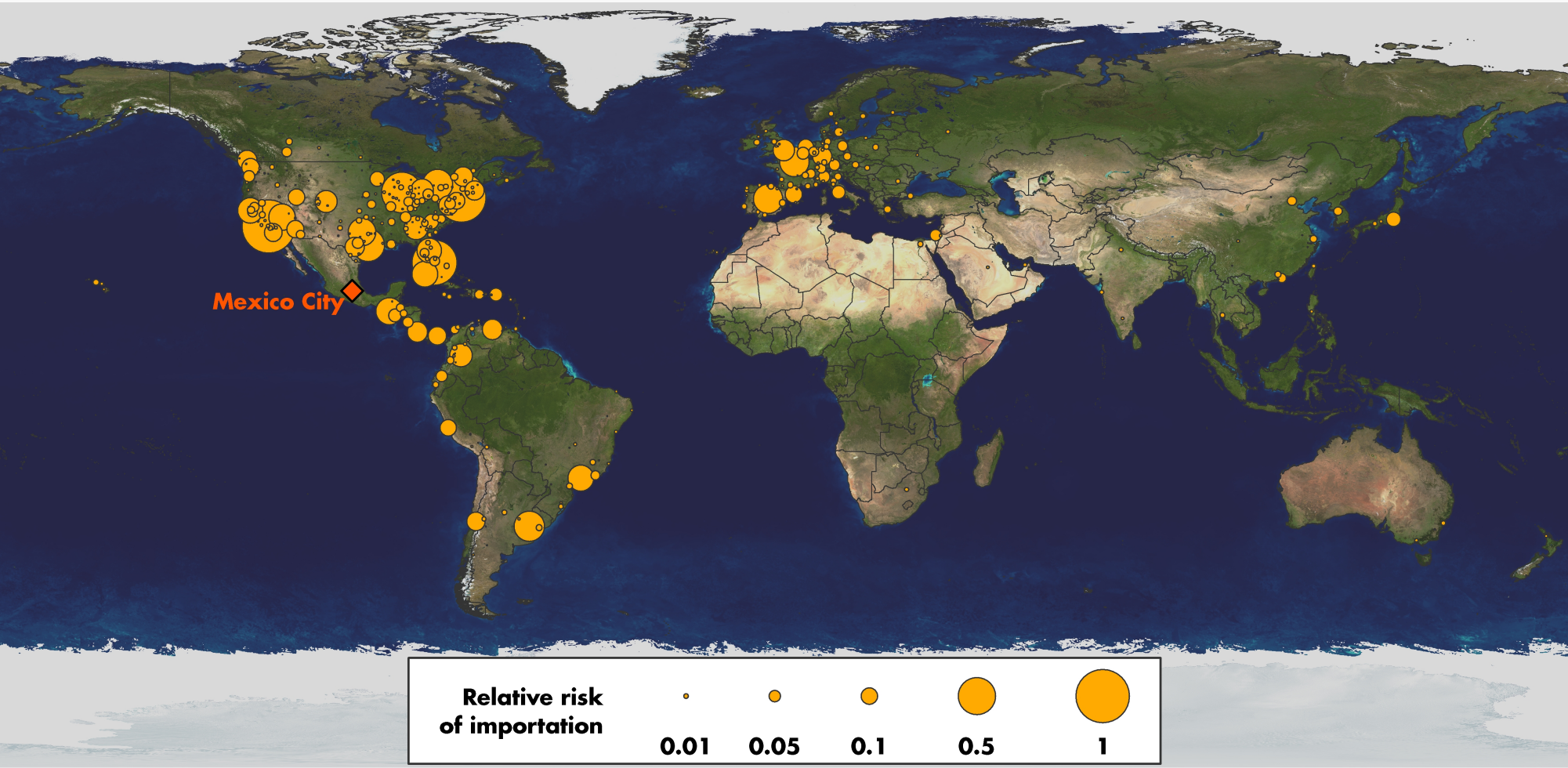



Mexico City
Relative risk of importation
0.01
0.05
0.1
0.5
1

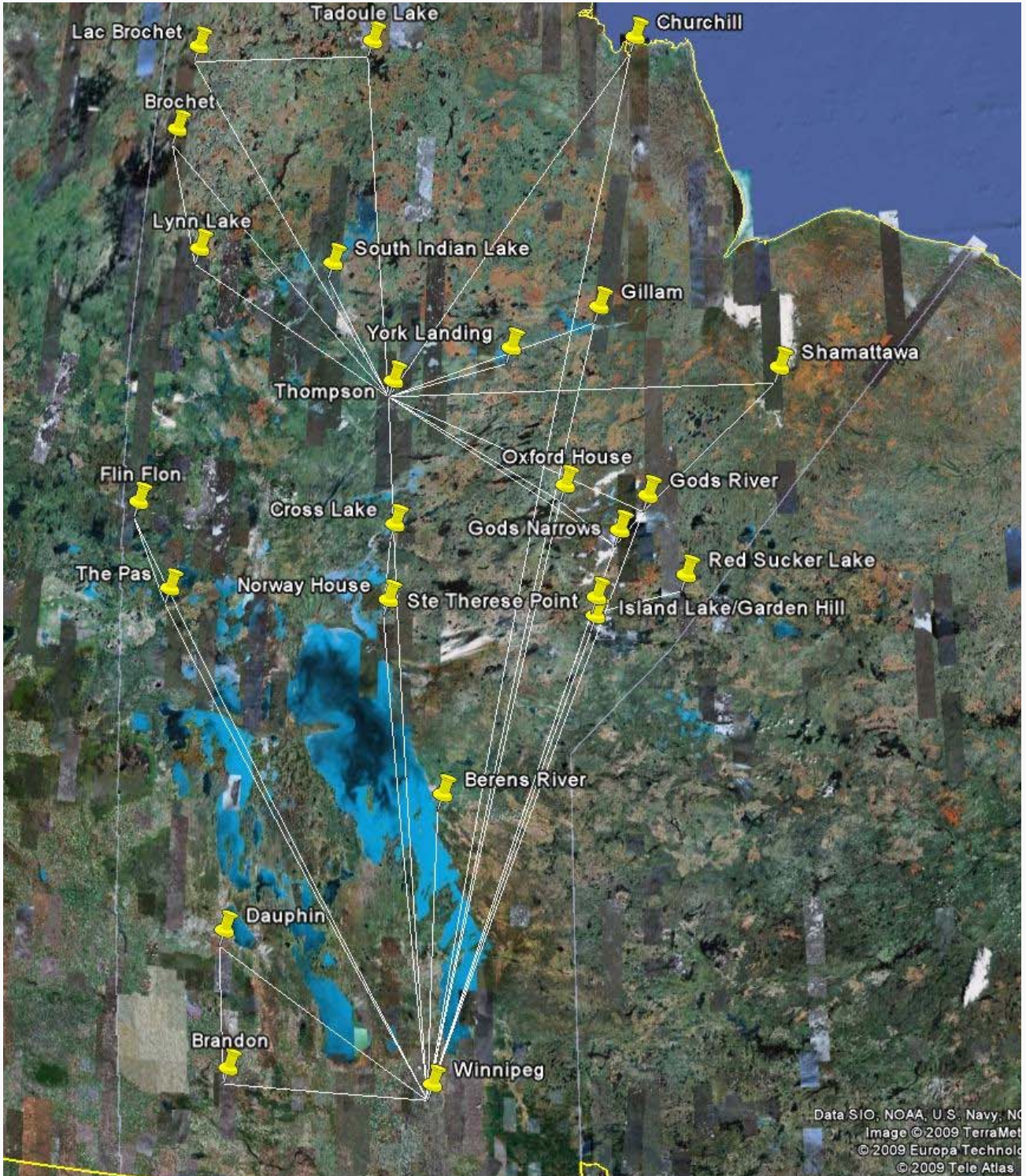
Work in progress/upcoming

Mathematics:

- More on the network
- Daily $m_{ij}(t)$ (by interpolation or regression)
- Effect of border screening
- ODE versions
- Propagation to isolated communities
- Effect of media coverage
- General theory of metapopulations

Bio.D:

- Link with real time surveillance (HealthMap)
- Development of a web platform (CDC)
- Integration of real time flight info


Tadoule Lake
Lac Brochet
Churchill
Brochet
Lynn Lake
South Indian Lake
Gillam
York Landing
Shamattawa
Thompson
Oxford House
Flin Flon
Gods River
Cross Lake
Gods Narrows
Red Sucker Lake
The Pas
Norway House
Ste Therese Point
Island Lake/Garden Hill
Berens River
Dauphin
Brandon
Winnipeg
Data SIO, NOAA, U.S. Navy, NG
Image © 2009 TerraMet
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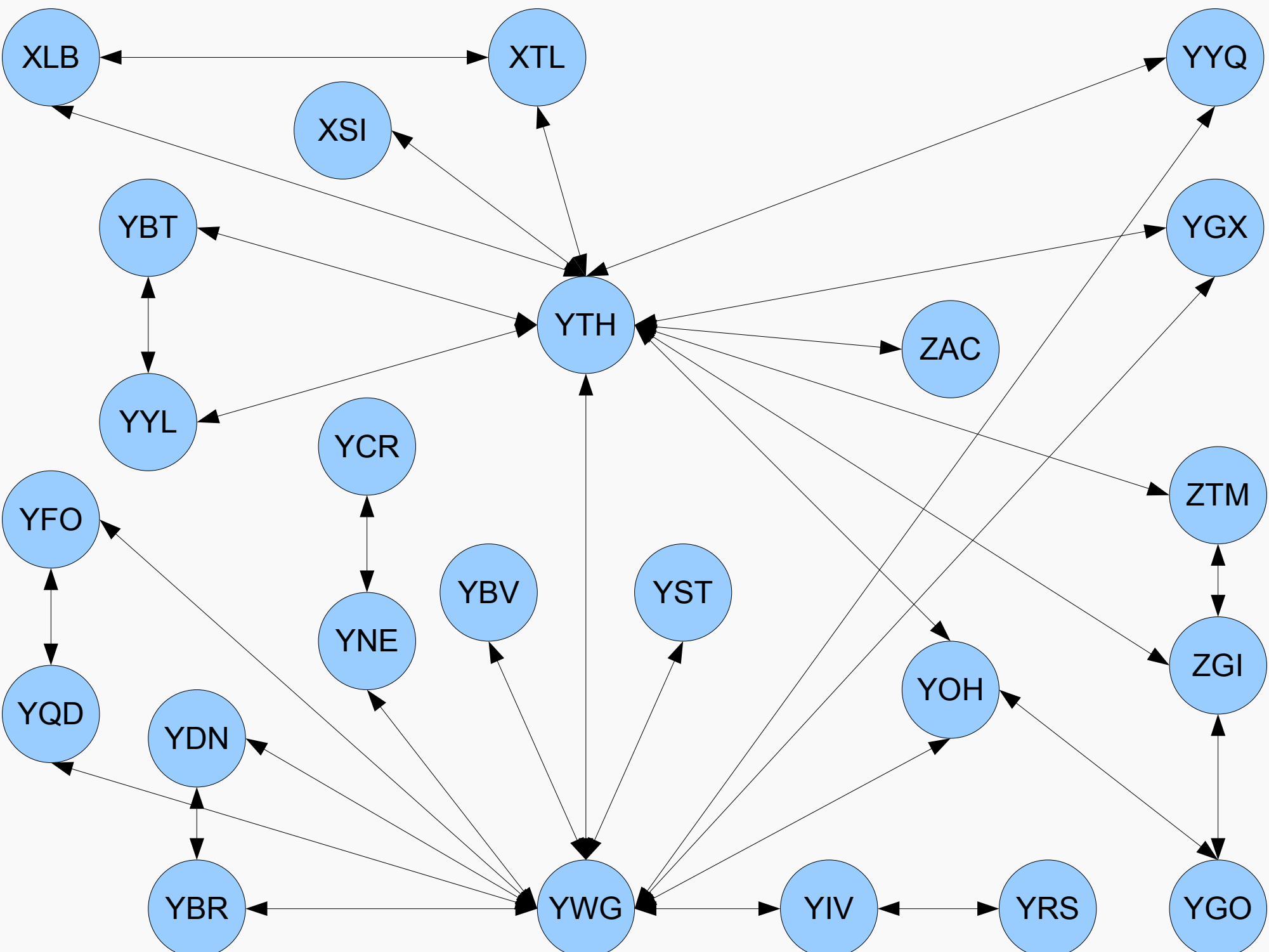

XLB
XTL
YYQ
XSI
YBT
YGX
YTH
ZAC
YYL
YCR
ZTM
YFO
YBV
YST
YNE
ZGI
YOH
YQD
YDN
YBR
YWG
YIV
YRS
YGO

NORTHERN MANITOBA

THIS AREA REDUCED IN SCALE
SCALE IN KILOMETERS
0 20 40 60 80 100

SEE ENLARGEMENT OF LYNN LAKE

SEE ENLARGEMENT OF FLIN FLON

SEE ENLARGEMENT OF THE PAS AND AREA

South Indian Lake
Leaf Rapids
Gillam
Thompson
Wabowden
Snow Lake
Cranberry Portage
Jenpeg
Norway House
Cormorant
Moose Lake
Brand Rapids
Easterville
The Pas
Lynn Lake
Flin Flon

5

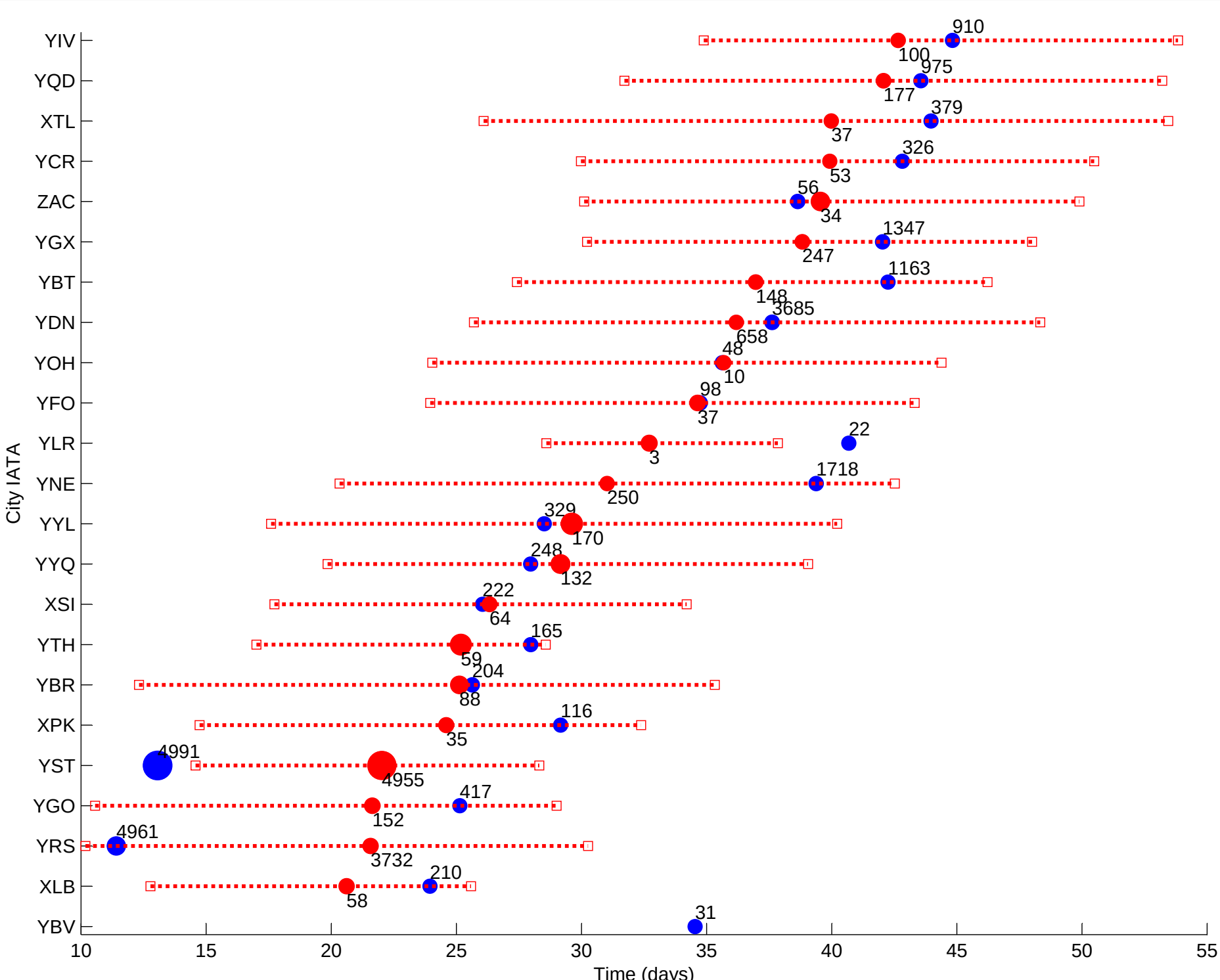
ENLARGEMENT OF FLIN FLON
(NOT TO SCALE)

ENLARGEMENT OF LYNN LAKE
(NOT TO SCALE)

ENLARGEMENT OF THE PAS AND AREA
(NOT TO SCALE)

Manitoba

Lac Brochet	XLB	604	isolated
South Indian Lake	XSI	857	
Tadoule Lake	XTL	671	isolated
Brochet	YBT	306	isolated
Cross Lake	YCR	406	
Gods Narrows	YGO	2500	isolated
Gillam	YGX	1209	
Island Lake/Garden Hill	YIV	1878	isolated
Leaf Rapids	YLR	539	
Norway House	YNE	4071	
Oxford House	YOH	1947	isolated
Red Sucker Lake	YRS	845	isolated
Ste Therese Point	YST	2632	isolated
Thompson	YTH	13446	
Lynn Lake	YYL	714	
York Landing	ZAC	416	
Gods River	ZGI	556	isolated
Shamattawa	ZTM	920	isolated
Churchill	YYQ	923	isolated


City IATA
YIV
YQD
XTL
YCR
ZAC
YGX
YBT
YDN
YOH
YFO
YLR
YNE
YYL
YYQ
XSI
YTH
YBR
XPK
YST
YGO
YRS
XLB
YBV
910
100
975
177
379
37
326
53
56
34
1347
247
1163
148
3685
658
48
10
98
37
22
3
1718
250
329
170
248
132
222
64
165
59
204
88
116
35
4991
4955
417
152
4961
3732
210
58
31
10
15
20
25
30
35
40
45
50
55
Time (days)

Thanks

Bio.Diaspora	Manitoba	Theory
Rose Eckhardt	Chris Bowman Seyed Moghadas	Arnaud Ducrot
Vivian Hu		Abderrahman Iggidr
Kamran Khan		Edwige Maleka
David Kossowsky		Liliana Menjivar
Michael Macdonald		Gauthier Sallet
Jennifer Sears		Chengjun Sun
Langhi Shen		P. van den Driessche
Graham Smith		Lindsay Wessel
Jun Wang		Pascal Zongo

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