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THE INCLUSIVE COST OF PANDEMIC INFLUENZA RISK

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ABSTRACT

Estimates of the long-term annual cost of global warming lie in the range of 0.2-2% of global income. This high cost has generated widespread political concern and commitment as manifested in the Paris agreements of December, 2015. Analyses in this paper suggest that the expected annual cost of pandemic influenza falls in the same range as does that of climate change although toward the low end. In any given year a small likelihood exists that the world will again suffer a very severe flu pandemic akin to the one of 1918. Even a moderately severe pandemic, of which at least 6 have occurred since 1700, could lead to 2 million or more excess deaths. World Bank and other work has assessed the probable income loss from a severe pandemic at 4-5% of global GNI. The economics literature points to a very high intrinsic value of mortality risk, a value that GNI fails to capture. In this paper we use findings from that literature to generate an estimate of pandemic cost that is inclusive of both income loss and the cost of elevated mortality. We present results on an expected annual basis using reasonable (although highly uncertain) estimates of the annual probabilities of pandemics in two bands of severity. We find:

1. Expected pandemic deaths exceed 700,000 per year worldwide with an associated annual mortality cost of estimated at \$490 billion. We use published figures to estimate expected income loss at \$80 billion per year and hence the inclusive cost to be \$570 billion per year or 0.7% of global income (range: 0.4-1.0%).
2. For moderately severe pandemics about 40% of inclusive cost results from income loss. For severe pandemics this fraction declines to 12%: the intrinsic cost of elevated mortality becomes completely dominant.
3. The estimates of mortality cost as a % of GNI range from around 1.6% in lower-middle income countries down to 0.3% in high-income countries, mostly as a result of much higher pandemic death rates in lower-income environments.
4. The distribution of pandemic severity has an exceptionally fat tail: about 95% of the expected cost results from pandemics that would be expected to kill over 7 million people worldwide.

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The Inclusive Cost of Pandemic Influenza Risk

The recent Ebola outbreak in Guinea, Liberia and Sierra Leone reminded the world that enormous economic and human costs result from the uncontrolled spread of deadly infection. Less noticed was that a pandemic with characteristics similar to that of influenza in 1918 would have killed about 10 times as many people in those three countries as did Ebola. Worldwide the death total from such a pandemic would be on the order of 2500 times higher than WHO's estimate of a little over 11,300 Ebola deaths through the end of the epidemic on March 17, 2016 (World Health Organization, 2016).

One important dimension of the cost of a pandemic lies in its impact on income. Premature deaths reduce the labor force; illness leads to absenteeism and reduced productivity; resources flow to treatment and control measures; and individual and social measures to reduce disease spread can seriously disrupt economic activity. The World Bank has generated estimates of these costs (Burns, Mensbrugge, and Timmer 2008; Jonas 2013). The World Bank studies found, among other things, that a 1918-severity pandemic might reduce global GDP by about 5% and that the disruptive effects of avoiding infection would account for about 60% of that total. McKibben and Sidorenko (2006) examined consequences of a range of pandemic severities including an 'ultra' scenario (toward the upper end of the range of estimates for severity in 1918). They concluded this extreme scenario would lead to income losses of over 12% of GNI worldwide and over 50% in some developing countries.

The second major dimension of pandemic cost lies in the intrinsic value of lives prematurely lost and of illness suffered. Efforts to measure the costs of premature mortality and illness remain imperfect but, that said, extensive empirical findings do appear in the economics

literature, particularly for the costs of premature mortality (Viscusi, 2014; Hammitt and Robinson, 2011; Lindhjem, Navrud and Braathen, 2010). While valuation of mortality change appears most frequently in the environmental economics literature (see, for example, OECD 2014), the report of *The Lancet* Commission on Investing in Health – *Global Health 2035* – systematically applied these methods to understanding of global health (Jamison, Summers et al. 2013). Our purpose in this paper is to estimate the magnitude of this second dimension of pandemic cost using standard methods. As large as the direct impact of a pandemic on income appears to be, we conclude that this second, intrinsic, dimension of cost far exceeds the cost of lost income. The *inclusive* cost of a pandemic is the sum of its adverse impact on income and of the intrinsic cost of premature mortality and illness.

Our paper assesses the *expected* annual cost of a pandemic with risk r (expressed as the annual probability of a pandemic in %) and severity s (expressed as the fraction of the world population that dies from the pandemic). It uses the historical and modelling literatures to generate expected values of r and s , and uses those values to generate estimates of mortality and its associated costs.

Pandemics: history, risk, severity

Papers in the literature define pandemic severity in different ways hence it is important to specify the definitions we use in this paper. For simplicity we define severity in terms only of mortality although in practice differing case fatality rates lead to different numbers of severe cases for any given level of mortality. *Global Health 2035* introduced the term ‘standardized mortality unit’ (SMU) to convey mortality rates that are small. The SMU is 10^{-4} and hence, for example, the pandemic of 1957-58 would be characterized as having a global death rate of 3 SMU rather than 0.03%. In the world’s 2015 population of 7.35 billion, 1 SMU corresponds to

735,000 deaths. Seasonal influenza causes about 250-500,000 deaths per year (WHO, 2014). We define *severe* pandemics as having mortality rates of 10 SMUs or greater, and *moderately severe* pandemics as having a severity less than 10.

The historical record suggests that the 1918 influenza was an outlier among outliers, with unusual circumstances including the co-occurrence of World War I. No other influenza pandemic on record had such devastatingly high mortality rates, with estimates ranging from 20 million to 50 million (or more) excess deaths over the period 1918-20, but concentrated in 1918. (20 million deaths would comprise 1.1% of the world's 1918 population.) In addition to the severe pandemic of 1918 the sparse record suggests that there have been about 12-17 other pandemics since 1700. Of these we identify six as having substantial excess mortality, with mortality rates in the range of 3-8 SMU (Table 1). While the world may be expected to experience moderately severe to severe pandemics several times each century, there is consensus among influenza experts that an event on the very severe scale of the 1918 pandemic may be plausible but remains historically and biologically unpredictable (Taubenberger, Morens, and Fauci, 2007). A modelling exercise for the insurance industry concluded that the 'return period' would be 100-200 years for a 1918-type pandemic, but acknowledged major uncertainty (Madhav, 2013). While a biological replica of the 1918 flu would no doubt result in lower mortality rates than occurred in 1918 (Madhav, 2013), both that study and other analysts point to the possibility that exceptionally transmissible and virulent viruses could lead to global death rates substantially higher than in 1918 (see McKibben and Sidorenko, 2006, or Osterholm, 2005).

India suffered a disproportionate share of global pandemic mortality in 1918 (Davis, 1951). In general, lower income parts of the world suffered more in 1918. Morens and Fauci (2007) and Madhav (2013) argue, very plausibly, that a modern epidemic would likewise

Table 1. Worldwide mortality from selected influenza pandemics, 1700-2000^a

Year	Estimated worldwide pandemic-related deaths (millions)	Estimated world population (millions)	Severity, <i>s</i> (fraction of world population killed, measured in SMUs)^b
1729 ^c	0.4	720	6
1781-82 ^c	0.7	920	8
1830-33 ^c	0.8	1150	7
1898-1900 ^c	1.2	1630	7
1918-20 ^{c,d}	20-50	1830	110-270
1957-58 ^c	1	2860	3
1968-69 ^{c,e}	1-2	3540	3-6

^a For pandemics to include in this table we chose those in the period from 1700 to the present whose severity we could ascertain from the literature. Morens and Fauci (2007, figure 4) and Morens and Taubenberger (2011) identify 12-17 pandemics in the period from 1700 but many of those resulted in substantially lower mortality than for those in this table (or had mortality levels we could not ascertain).

^b The standardized mortality unit (SMU) represents a 10^{-4} mortality risk and is used to represent small numbers as integers. For example the 1729 pandemic led to an elevation in mortality of 0.06% of the world's population which is more conveniently expressed as 6 SMUs. In the world's 2015 population 1 SMU corresponds to 735,000 deaths.

^c Potter (2001).

^d Beveridge (1991); Ghendon (1994); Johnson and Mueller (2002).

^e Hampson and Mackenzie (2006).

disproportionally affect poor countries. That said, China's mortality rate in 1918 was low, probably because of lower case fatality rates rather than lower incidence (Cheng and Leung 2007). This points to the possibility of great within income group heterogeneity in a modern pandemic.

Our intention in this paper is not to provide a new review of the literature on mortality in previous pandemics but rather to select plausible values from that literature to define our reference cases while emphasizing, with Taubenberger and colleagues, the uncertainty inherent both in the history and in projections to be drawn from it. In light of this literature (and its attendant uncertainty) we develop and report results for two representative levels of severity. Table 2 defines the severity levels we use and indicates the levels of annual risk assigned to them. Box 1 provides the background to the calculation of expected severity that Table 2 summarizes.

Methods

The effort proceeds in two steps. First, information on pandemic severity is used to generate increases in age-specific death rates for the world and for each of the World Bank's four income groups of countries. Second, the literature on valuation of changes in mortality rates is used to generate estimates of the age-specific costs of mortality increase, and hence of the total cost.

We begin by estimating the change in a population's age-specific mortality rate for the two severity reference cases. Estimates of the age-specific excess mortality rates of different populations from the 1918 pandemic are consistent in their shape by having a unique inverted-*U* shaped distribution, whereby adults aged 15 to 60 experienced elevated rates compared to the elderly (Murray et al., 2006; Luk, Gross, and Thompson, 2001). We thus used the specific U.S. data for age distribution of excess deaths to generate age distributions for the world, adjusting

Table 2: Worldwide pandemic risk – two representative scenarios, 2015

	Moderately severe pandemic (< 10 SMU)^b	Severe pandemic (≥ 10 SMU)^a	Any pandemic
1. Annual probability, r^b	2%	1.6%	3.6%
2. Return time, $1/r$	50 years	63 years	28 years
3. Average severity (SMU)^c	2.5	58	27
3. Expected severity, s^d	0.05 SMU	0.93 SMU	0.98 SMU

^a See footnote b, Table 1.

^b These severity states are mutually exclusive. Hence the annual probability of any pandemic is $[1 - (1-0.2)(1-0.016)] = 3.6\%$.

^c The ‘average severity’ of a pandemic in a given severity range is the expected value of severity given that a pandemic did in fact occur in that range – e.g. 2.5 SMUs is the expected severity given that a pandemic of severity $s < 10$ SMUs has occurred.

^d ‘Expected severity’ is average severity times probability of occurrence [= row (3) x row (1)].

Box 1: Estimating Pandemic Severity and Risk

Following usage in the insurance industry we define risk, $r(s)$, in terms of ‘exceedance probability’, the annual probability of a pandemic having a severity *exceeding* s . Again following insurance industry usage, the ‘return time’ for s is the expected number of years before there will be a pandemic of at least severity s . If $t(s)$ is the return time then $t(s) = r(s)^{-1}$. For example, if the annual probability of a pandemic of severity at least s is 1% then its return time will be 100 years.

If we had access to a function $r(s)$ showing exceedance probability as a function of severity our analysis could proceed using the expected value of severity of all pandemics. As $r(s)$ is the complementary cumulative of the density for s , we would have:

Box equation 1.1:
$$\text{expected value of } s = \int_0^{\infty} r(s) \, ds.$$

Modelled estimates of the function $r(s)$ are not (publicly) available so we approximate in two steps. We label pandemics with global $s \geq 10$ SMUs as ‘severe’. (As defined in the text, 1 SMU corresponds to a 10^{-4} mortality risk.) We label pandemics with global $s < 10$ as moderately severe and, for the first step in our assessment of expected severity, we use recent history as a straightforward guide to frequency and severity of moderately severe pandemics. In particular we assume two such pandemics per century in this severity range and that the average severity is 2.5 SMUs globally. The *expected* annual severity of moderately severe pandemics is then, $0.02 \times 2.5 = 0.05$ SMU, corresponding to expected annual deaths of a little over 35,000 worldwide.

We turn next to Box equation 1.1 to estimate the contributions to expected severity from pandemic severity greater than 10 SMUs worldwide (or 4 SMUs in the U.S.). Let $s^*(x)$ be the contribution of pandemic severity greater than x to expected pandemic severity. Information available from AIR (2016) allows calibration of $r(s)$ for the U.S. with $s \geq 4$:

$$s^*(4) = \int_4^{\infty} r(s) \, ds.$$

[Available data allow us to calibrate only an exceedance probability function, $r(s)$, for the U.S. Hence we start with that and translate to world values from severity ratios available in Madhav (2013).] The calibration points to a very ‘fat-tailed’ distribution. The hyperbolic family of complementary cumulative distributions provides natural candidates for $r(s)$ and we parameterize the hyperbolic in terms of its expectation and the fatness of its tail (see Jamison and Jamison 2011, Table 2, in the formally identical context of discounting). Thus

Box equation 1.2:
$$r(s) = [1 + m(1 - f)s]^{-[1 + 1/(1 - f)]},$$

where $1/m$ is the expected value of s , and f indicates the fatness of the tail (smaller values imply a fatter tail). Our calibration yields a value of m of 1.8 and of $f = -2$. Hence $s^*(0) = 1 / 1.8 = 0.56$. $s^*(4)$ is thus given by:

$$s^*(4) = 0.56 - \int_0^4 (1 + 3ms)^{-1.33} ds ,$$

and the integral can be approximated to be 0.38. (For small values of s , Box equation 1.2 substantially overestimates r when the equation for $r(s)$ has been calibrated to fit larger values of s . Thus the need for this two-step procedure.) Hence $s^*(4) = 0.56 - 0.38 = 0.18$, which is the contribution to expected severity in the U.S. of severity levels ≥ 4 . We infer global severity from U.S. severity using the approach described in the main text.

Madhav (2013), using the AIR model, estimates that a 1918-type pandemic would kill 21 to 33 million people in today's world. She reports a mid-range severity for the U.S. of such a pandemic of 8.8 SMU with a return time of 100-200 years. Box equation 1.2 predicts that the return time for a pandemic of at least that severity is about 175 years.

It is worth commenting that our calibrated value of -2 for f , the tail fatness parameter in box equation 1.2, implies that the distribution of exceedance probabilities is very fat tailed indeed. An exponential distribution for $r(s)$ could be considered to be neither fat nor thin tailed. Calibrating an exponential as we did for the hyperbolic – so that the contribution to expected severity of severity ≥ 4 is equal to 0.18 – gives $r(s) = e^{-0.57s}$, and a return time for a 1918-type pandemic of 150 years – quite close to the 175 years of box equation 1.2. But for $s = 4$ in the U.S. (over 7 million deaths worldwide) the exponential gives an unrealistic return time of only 10 years whereas box equation 1.2 gives 63 years. AIR (2016) estimates that an extreme pandemic with $s = 30$ in the U.S. (and perhaps 100 million deaths worldwide) has a return time of 1000 years and box equation 1.2 gives 875 years. The exponential gives 27 million years.

We hardly need reiterate the uncertainty surrounding the numbers we use to reflect the likelihood of pandemics of varying levels of severity. That said, our numbers represent conservative choices that are broadly consistent with historical experience and modelling parameters. [Substantially greater severities and likelihoods have been discussed – both by Madhav (2013) and elsewhere in the literature (McKibben and Sidorenko, 2006; Osterholm, 2005; DeBruin, et al, 2006).] As Morens and Taubenberger have put it (2011, p. 277): “With human influenza the only certain thing seems to be uncertainty.” We would slightly modify that to assert the virtual certainty that, sooner or later, the world will again suffer a severe pandemic.

for greater absolute increases elsewhere. The fatality rate among young adults, although high in the 1918 pandemic influenza, was low relatively in the 1957 and 1968 epidemics – (Simonsen et al, 1998). We also use an alternative and more typical distribution of excess mortality where young children and the elderly are disproportionately affected as well as a combination of the two resulting from assuming the same proportional increase in mortality for all age groups. Our final calculations are based on the assumption that moderately severe pandemics will have age distributions like those of 1957 and 1968 whereas severe pandemics will have age distributions of death like that of 1918.

Next, using the UN's current "World Population Prospects" (United Nations, 2015) age distributions of populations and life tables, we calculated excess deaths and the estimated reduction in life expectancy using these age-specific mortality rates (Preston, Heuveline, and Guillot, 2000). Table 3 shows the results for our severity categories. Our *expected* annual pandemic death total, across both severities is 720,000 (or about 1.2% of the number of actually occurring deaths). A consequence of this expected increase would be that life expectancy at birth would decrease – by about 0.3-0.4 years in low and lower-middle income countries.

Next we place dollar values on the changes in mortality rates. Our specific calculations followed the methods used in *Global Health 2035* (Jamison, Summers et al., 2013; Appendix 3), but with a slight change in some numbers. In particular, we used values of ν of 0.7, 1.0, 1.3 and 1.6% of income per capita per SMU of mortality increase, i.e. per 1/10,000 increase in mortality risk for one year for countries in each of the World Bank's four income groups of countries. (0.7% was used for low-income; 1.0% for lower-middle; 1.3% for upper-middle; and 1.6% for high-income.) In calculating the value of change in mortality at age a we used as a reference the literature's value as a fraction of gross national income per capita for 35 year

Table 3: Expected deaths from pandemic risk, by country income group, 2015^a

	Income level ^b				World
	Low	Lower-middle	Upper-middle	High	
1. Population (millions)	640	2900	2400	1400	7350
2. Moderately severe pandemics					
2.1 Relative pandemic severity ^c	4	3	2	1	-
2.2 <i>Expected</i> annual pandemic-related mortality rate, in SMU	0.08	0.06	0.04	0.02	0.05
2.3 <i>Expected</i> excess deaths per year [= (1) x (2.2)]	5100	18,000	9600	2800	37,000
3. Severe pandemics (all severities combined)					
3.1 Relative pandemic severity ^c	10	7	4	1	-
3.2 <i>Expected</i> annual pandemic-related mortality rate, in SMU	1.8	1.26	0.72	0.18	0.93
3.3 <i>Expected</i> excess deaths per year [= (1) x (3.2)]	120,000	370,000	170,000	25,000	680,000
4. <i>Expected</i> totals					
4.1 <i>Expected</i> mortality rate in SMU ^b	1.88	1.32	0.76	0.2	0.98
4.2 <i>Expected</i> excess deaths per year [= (2.3) + (3.3)]	120,000	390,000	180,000	28,000	720,000 (430,000-1,000,000) ^a

Footnotes on next page.

Footnotes, table 3

^a Very substantial uncertainty adheres to all numbers in rows 2-4 of this table. We judge that $\pm 40\%$ reasonably reflects this uncertainty. AIR's (Madhav, 2013) mortality estimates for a 1918-type pandemic occurring today are given $\pm 22\%$ and we have amplified that somewhat. Rather than tediously report a $\pm 40\%$ range, this table reports only our point estimates except for our estimate of total annual expected deaths where we state the range.

^b We use the World Bank's income level classification of countries (World Bank, 2015).

^c 'Relative severity' indicates severity in each income group relative to the high-income group. This ratio is assumed to be different for each level of severity. Our estimates for severe pandemics come from AIR (Madhav, 2013, Figure 3). AIR estimates a narrow range of mortality rates across high income countries (6-11 SMUs) for their model of a 1918 type pandemic, and the relative severities we indicate are consistent with the HIC rates and AIR's estimate of 21 to 33 million deaths globally in such a pandemic. Evidence for the moderate pandemics of 1957-58 and 1968-69 suggest a more compressed range for these less severe pandemics, and our relative severity numbers in row 2.1 reflect this.

olds. This amount was adjusted up or down for ages other than 35 in proportion to the ratio of life expectancies at those ages to life expectancy at age 35. Hence for a given value of overall mortality the mortality cost will depend on which of the age distributions of excess pandemic mortality described above is assumed. (Important strands of the benefit-cost literature choose not to adjust the value of mortality risk for age. We have repeated our calculations to test the sensitivity of our results to this alternative assumption and found a change of only about 5% in our headline number.)

Results

Table 4 shows the results of our calculation of the intrinsic cost of pandemic risk using values of ν of 0.7-1.6% of GNI per SMU, depending on income category. We stress again that these are expected annual values of loss associated with the indicated risks of pandemics in the severity ranges we have chosen. Expected costs of an actual severe pandemic would be about 60 times as large. The World Bank likewise expresses income loss figures as expected annual values but uses different values for annual pandemic risk. Table 4 shows our estimate of the expected annual loss for the world as a whole from the intrinsic cost of pandemic risk to be -0.6% of global income or about \$490 billion per year. Loss varies by income group, from a little over 0.3% in high-income countries to 1.6% in lower-middle income countries.

To obtain an estimate of inclusive annual pandemic costs, we add an estimate of expected income losses. We have previously referred to estimates in the literature of the income loss from pandemics of differing levels of severity (McKibben and Sidorenko, 2006; Burns, Mensbrugge and Timmer, 2008; and Jonas, 2013). Our severity categories differ from theirs so it is difficult to use directly their estimates of income loss. That said we feel values of 1% of global income as the income loss from a moderately severe pandemic, as we define it, and 4% of global income for a severe pandemic would be consistent with the estimates

**Table 4: Mortality costs of pandemic risk, by country income group, 2015
(age-dependent VSMU)**

	Income level ^a				
	Low	Lower-middle	Upper-middle	High	World
1. Economic parameters					
1.1 Income, Y (trillions of 2013 \$)	0.7	6	20	54	80
1.2 Per person income, y (2013 \$)	780	2300	8200	41,000	11,000
1.3 ν^b	0.7%	1.0%	1.3%	1.6%	-
2. Pandemic costs ^c					
2.1 <i>Expected</i> annual mortality cost, C (billions of 2013 \$) ^d	-7	-100	-200	-180	-490 (-290 to -690)
2.2 Annual mortality cost, c [as a % of income = (2.1) \div (1.1)]	-1.1%	-1.6%	-1%	-0.34%	-0.62% (-0.37 to -0.87%)

^a We use the World Bank's income data and income level classification of countries (World Bank, 2015).

^b We use ' ν ' to denote the value of a 1 in 10,000 risk of death, expressed as a % of per capita GNI. The dominant position in the literature is that lower income countries should have lower values for ν (Hammit and Robinson, 2011). The literature provides only weak quantitative guidance on how ν should vary with y , if at all, and the numbers we have chosen should be viewed as reasonable assumptions within the spirit of the literature.

^c Very substantial uncertainty adheres to these cost estimates (footnote a, Table 3). We judge $\pm 40\%$ to reasonably reflect this uncertainty but report that range only for our estimates of worldwide costs.

^d For any given value of s , our calculation of the intrinsic cost of a pandemic depends on the age distribution of deaths from the pandemic, and the calculations reported here use different age distributions for pandemics of different severities. In particular for moderately severe pandemics we assume an older age distribution of deaths, typical of such pandemics. For severe pandemics we assume the younger age distribution of deaths that characterized the 1918 pandemic.

provided by these authors. Using our estimates of the annual probabilities of such pandemics (Table 2) we get expected annual income losses globally of \$16 billion for moderately severe pandemics and of \$64 billion for severe pandemics for a cost of about \$80 billion per year. Table 4 shows an expected annual mortality cost for pandemics of \$490 billion of which 95% is from severe pandemics. This suggests that income losses are only a small fraction of inclusive costs (about 12%) for severe pandemics but a much larger 40% of inclusive costs for moderately severe pandemics. The expected annual inclusive cost of pandemics is the sum of the income loss and the mortality cost or about \$570 billion per year. This represents slightly over 0.7% of global income with a range of perhaps 0.4-1.0% (Table 4).

Discussion

Expected annual pandemic costs appear substantial. This discussion section provides some comparative perspective, assesses sensitivity to key assumptions and discusses limitations to this study.

Comparators: It is worth comparing the inclusive cost of pandemic risk with the estimated costs of global warming. As with pandemic risk, much uncertainty is attached both to the magnitude of future global warming and to what its costs will be (or even whether costs should be modelled as affecting the level or the growth rate of income – Moore and Diaz, 2015). In contrast to the very modest number of studies of potential pandemic cost, Tol (2013) points to literally hundreds of studies on the cost of climate change, although Pizer et al (2014) point to the weakness of the key part of the literature that deals with the ‘social cost of carbon’ or SCC. Global CO₂ emissions were on the order of 36,000 million tons in 2013, containing 6,200 million tons of carbon (“Emissions | Global Carbon Atlas” 2015). Estimates of the social cost of carbon vary widely. But if the SCC were around \$120 per ton then the cost of CO₂ emissions in 2013 would be about 1% of world income. \$120 per ton, although high, is well

within the range of available estimates (Nordhaus, 2010; Tol, 2013). To the cost of carbon in CO₂ must be added its cost in methane, which Smith et al (2013) estimate to be substantial. The synthesis of the 2014 report of the Intergovernmental Panel on Climate Change provides the following assessment of a now-extensive literature: "...the existing incomplete estimates of global economic losses for warming of 2.5°C above pre-industrial levels are 0.2 to 2.0% of income..." (IPCC, 2015). Our expected annual inclusive cost of pandemic risk (at 0.7% of global income) lies about 25% of the way up from the low end of the range of the IPCC's estimated range for global warming.

While most studies of the cost of global warming fail to include the intrinsic cost of increased mortality risk, the effect of doing so may be modest. The IPCC report (2014) anticipates that there will be increased risks, with very high confidence, of ill health due to heat waves and fires, of undernutrition from diminished food production in poor regions, and of increased food- and water-borne diseases and some vector-borne and infectious diseases. Modest reductions in cold-related mortality and morbidity will be offset by the magnitude and severity of the aforementioned increased risks. Although the IPCC presents scenarios of health risks, the aggregate impact of climate change to mortality was not summarized. But the gradual nature of warming allows time for (costly) adaptations that could be expected to reduce the mortality consequences. A recent paper points to potentially important mortality gains in the U.S. from keeping U.S. emissions consistent with global warming of 2°C (Shindell et al, 2016). These benefits appear to flow almost entirely from reduced pollution rather than slower atmospheric warming. Most health costs of climate change are, then, likely to be included in the income cost of adaption rather than being additional to it.

Another useful comparator for pandemic risk lies in deaths from selected alternative causes. The expected annual number of pandemic flu deaths for 2015 in our reference cases is

720,000 (Table 3). To this might reasonably be added 300,000 deaths per year from seasonal flu (WHO, 2014) for a total of over one million. By comparison, *GH2035* (Appendix Table A1.9a), using WHO data, reported the following for 2011:

TB	0.98 million deaths
HIV/AIDS	1.6 million deaths
Maternal	0.28 million deaths
Cancers	7.9 million deaths
Ischaemic heart disease	7.0 million deaths
Stroke	6.2 million deaths

It is clear that the expected annual number of pandemic flu deaths is large on the scale of killers with high salience in low-income countries although much smaller than the major global killers of cancer and cardiovascular disease.

We are aware of one other study that estimates disease cost using valuation of estimated mortality. Watkins and Daskalakis (2015) found very high burdens from rheumatic heart disease using methods closely related to ours. Far more studies assess the burden of specific environmental risk factors (OECD, 2014).

Sensitivity to assumptions: The methods used to value mortality risk have limitations. The valuation of health risks – including fatalities, illness, and injuries – is inherently difficult because money is often an ineffective substitute for dimensions of human well-being. In practice, however, these estimates are obtained from *ex post* observations of the labor market and reflect how people in fact differentially value and trade-off very small fatality risks for income. Substantial variation exists both in the estimated value of a small mortality risk at a given age in the U.S. and in how the valuation (v) should vary across ages and countries (see Lindhjem,

Navrud and Braathen, 2010, and Hammitt and Robinson, 2011). And, as we have made clear throughout, the estimates we use for pandemic risk, r , and severity, s , remain subject to inherent uncertainty.

Hammitt and Robinson (2011) have assembled the evidence that the value of mortality risk as a percent of income in low-income countries may be less than for high-income countries. *GH2035* did not include this potential effect in its calculations. In this paper we do include adjustment for this, which leaves estimates of cost in high income countries unchanged but reduces our estimated cost for the world as a whole. As previously noted we assessed the sensitivity of our results to alternative assumptions on this point (and others) and concluded our main findings to be robust to the specific assumptions made.

Limitations: A key limitation of this study is that it used historical mortality estimates and modelled estimates from various sources to estimate excess pandemic mortality in 2015. While the AIR modelling efforts (Madhav, 2013) explicitly account for potentially increased risks associated with increased air travel and mobility of persons and goods, as well as increased urbanization, we lacked access to the full results of that study. Likewise while AIR attempted to account for decreased risks associated with increased incomes, schooling, and access to health-care services (including vaccination, antiviral medications, improved infection control, increased surveillance, and real-time communications), we could only indirectly use that information. Increased global temperature may reduce the case fatality rates of flu, but may also increase the transmissibility of the virus. Population level immunity against a particular influenza strain likely varies by region and by age distribution, although the extent of that variation is not known. In 1918 a few countries (e.g. China and Mexico) did not experience the typical inverted-U distribution of excess age-specific mortality from flu. In Mexico, for example, the elderly were

not spared from excess mortality as seen in the U.S., although its working-age population were hit as hard as other regions (Chowell et al. 2010). In China mortality rates were low at all ages. The characteristics of new pandemic viral strains depends on poorly understood patterns of immunity and the complex and poorly understood process of viral evolution and genetic reassortment in dynamic ecosystems (Morens, Folkers, and Fauci 2004).

An additional limitation of this study is that it does not include an estimated value of the intrinsic undesirability of nonfatal illness or of pandemic fear – significant characteristics of population response to SARS in Taiwan (Liu et al. 2005). The high media salience and associated fear may also lead populations to overreact to mild pandemics – increasing their cost beyond what might be considered optimal (Brahmbhatt and Dutta, 2008). The economics literature currently provides value estimates almost entirely for mortality risk, but when appropriate valuations of illness and fear become available our results may be shown to be underestimates for this reason.

Conclusions

World Bank studies estimate that around 5% of global income as the probable income loss from a 1918-severity pandemic. In this paper we estimate the intrinsic cost of the excess deaths from potential pandemics and add that to income loss to provide an estimate of the expected annual inclusive cost of a very severe pandemic. Our estimate of the expected number of pandemic deaths per year is 720,000 (subject to major uncertainty). The expected annual inclusive cost that results for the world is \$570 billion or 0.7% of global income. In comparison, the Intergovernmental Panel on Climate Change estimates the likely cost of global warming to fall in the range 0.2 to 2% of global income annually. Posner (2004) has argued that economics and the social sciences more generally pay far too little attention to potentially catastrophic events, although a literature is now beginning to emerge (Barro and Jin, 2011 and Pindyck and Wang, 2013). We find it natural to conclude that the academic and policy

attention provided to pandemic risk falls well short of a reasonably estimated comparison of that risk with its consequences. That said recent trends encourage. Japanese Prime Minister S. Abe, as he prepares to host the G-7 in 2016, has placed high priority on dealing with health crises (Abe, 2015). And a recent Commission, hosted for WHO and the World Bank by the U.S. National Academy of Medicine, points to practical and significant financial and organizational steps to improve pandemic preparedness and response (Sands, 2016).

It remains for other efforts to assess the costs and probable impact of investments to reduce the likelihood or probable severity of a pandemic. These investments potentially range from R&D toward a universal flu vaccine through pre-investment in manufacturing capacity for (or stockpiling of) drugs and vaccines to implementing global programs to immunize humans, swine and birds against seasonal flu. Important investments along these lines are indeed being made. It is our sense, however, that given this paper's cost estimates for pandemic risk the economic benefits of further investments are likely to substantially exceed their costs.

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