Using index numbers for deflation in environmental accounting

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ONLINE APPENDIX

A.0. Data for replication

The emissions and marginal damage data used in this analysis for the years 1999, 2002, 2005, 2008 are available for free download at the author's website: https://sites.google.com/site/nickmullershomepage/. Proceed to the AP2 model page where the data are available as excel spreadsheets.

A.1. Marginal damage maps

Figure 3 displays the map of percentage changes for $PM_{2.5}$ shadow prices between 1999 and 2008. Most areas in the central US exhibit a reduction in the per ton impact of $PM_{2.5}$ of between 10 and 30 per cent. Large metropolitan areas in the southeast show *increases* in the shadow price of greater than 10 per cent. Cities and associated counties in Texas and Florida especially show marked increases in $PM_{2.5}$ damages per ton. Counties along the coast in the northeast also have increasing $PM_{2.5}$ marginal damages between 1999 and 2008. Most counties west of the Rocky Mountains show increases between 1999 and 2008. For many of these locations, populations in these areas have grown which drives up exposure and damage per ton.

Figure 4 indicates that the change in marginal damages for SO_2 between 1999 and 2008 exhibits an altogether different pattern. West of 100^o longitude nearly every county displays an increase in SO_2 damages of over 5 per cent; the Denver, Seattle, and Salt Lake City metropolitan areas experience increases in excess of 50 per cent. In the central US, many counties show small increases (less than 10 per cent). However, east of the Mississippi River there is a north-south oriented band of counties in which damages increase by greater than 10 per cent. Around the large cities of the east coast, damages increase by between 10 per cent and 50 per cent. In contrast, there are two large areas (one in New England, and one in the Appalachian Mountains) where SO_2 marginal damages decrease).

Figure 5 reflects what the prices indices reported: marginal damages for NO_x increase significantly in most parts of the US. In the western US, most counties show an increase in NO_x damages of between 10 and 50 per cent. Most of the coastal regions of the west show significantly larger increases. The Los Angeles area shows a decrease of more than 10 per cent in absolute value. In the central US changes in NO_x marginal damages generally range between +10 per cent and -10 per cent. In the east, most counties show an increase of between 10 per cent and 50 per cent. Within this region, the areas that stand out as having much larger increases include an area extending from roughly Ohio up through New England. In addition, a group of counties in South Carolina, Georgia, and Alabama and the Gulf coast also show increase in damages per ton of NO_x that are greater than 50 per cent. It is important to consider that NO_x emissions react with other pollutants to form both O_3 and $PM_{2.5}$. Thus, changes in emissions of VOC, NH_3, SO_2, and NO_x all have an effect on the magnitude of NO_x damage per ton. For example, SO_2 and NO_x emissions have decreased by regulatory mandate over the 1999 to 2008 time period. All else equal this means that more suspended ammonia is effectively free to react with a marginal ton of NO_x, increasing the marginal effect of an additional ton.

Figure 6 is congruent with the large, significant decrease in NH_3 marginal damages reported in the tables 1 and 2. Throughout most of the US, incremental NH_3 emissions cause less harm in 2008 than in 1999. The areas in the Carolinas, and in South Texas are correlated with the *change in* NO_x marginal damages shown in figure 3. The likely mechanism behind this association is the interaction between ambient NO_x, SO_2, and NH_3 in the formation of $PM_{2.5}$. Figure 7 displays the per cent change in VOC marginal damages. Most of the country shows decreases of between 0 and 50 per cent in the shadow price for VOC. Large metropolitan areas in the southeast and in the interior west show increases.

A.2. Relation of the paper to the literature

This analysis relates to several areas in the economics literature. The paper is clearly related to the literature on augmented accounting (NAS NRC, 1999; Nordhaus, 2006; Abraham and Mackie, 2006; Muller *et al*., 2011). The analysis connects to the papers on sustainability accounting in that it measures pollution damage across time (Arrow *et al*., 2012; Dasgupta and Maler, 2000; Smulders, 2012). More specifically, the current paper builds on the treatment of prices set forth in this literature.

A connection between the literature on index numbers and the current paper lies in the choice of index number formulae (Diewert, 1983, 1998; Shapiro and Wilcox, 1997). It is well known that both Laspeyres and Paasche indices suffer from substitution bias stemming from the correlation between prices and quantities (Allen *et al*., 1963). Whether or not marginal damages and emission quantities are correlated and how this affects the Laspeyres and Paasche indices is not the main focus of this analysis. However, recognizing that these index numbers are sensitive to such correlations motivates the estimation in this paper of both the Tornquist and Fisher indices. The paper is also tangentially related to a literature on superlative price index forms (Diewert, 1993) and differences among various forms (Dumagan, 2002).

The present paper is indirectly related to research on augmented price indices (Pollack, 1981; Nordhaus, 1999; Banzhaf, 2006). The analysis builds on the literature that uses integrated assessment to calculate the marginal damage of air pollution emissions. Prior papers in this field include the work of Muller and Mendelsohn (2007, 2009), Fann *et al*. (2009); Mauzerall *et al*.

(2004); Muller *et al*. (2011). Related work by federal agencies include: USEPA (1999, 2010). To the author's knowledge, this is the first paper to estimate marginal damages in multiple time periods for a large number of individual sources.

A.3. Index numbers

The literature focusing on index numbers suggests that there is no clear choice of functional form. A number of different tests (e.g., axiomatic, theoretical) are proposed in order to evaluate different index forms (Diewert, 1993). This literature points towards superlative index forms as being preferred. As such the paper computes two superlative forms: Fisher and Tornquist indices. Computing these indices requires the estimation of Paasche and Laspeyres indices. Each form is shown below.

The Paasche price index (P_{PS}) for pollutant (s) is computed according to the formula in (1).

$$P_{PS} = \frac{\sum_{i=1}^{N} p_{sit} q_{sit}}{\sum_{i=1}^{N} p_{si0} q_{sit}} \qquad (1)$$

where p_{sit} = marginal damage (\$/ton) for pollutant (s), emitted in location (i), time (t) and q_{sit} = emission tonnage for pollutant (s), location (i), time (t).

The Laspeyres price index (P_{LS}) for pollution species (s) is computed according to the formula displayed in (2).

$$P_{LS} = \frac{\sum_{i=1}^{N} p_{sit} q_{si0}}{\sum_{i=1}^{N} p_{si0} q_{si0}} \qquad (2)$$

where q_{sit0} = emission tonnage for pollution species (s), location (i), time (t=0).

The Fisher index (P_{FS}) for pollution species (s) is calculated using the formula shown in (3).

$$P_{FS} = \sqrt{P_{PS} P_{LS}} \tag{3}$$

The Tornquist price index (P_{TS}) assumes the following form:

$$P_{TS} = \prod_{i=1}^{N} \left(\frac{p_{sit}}{p_{si0}} \right)^{s_i} \tag{4}$$

where $s_n = \frac{1}{2} \left(\frac{p_{sit} q_{sit}}{\sum_{i=1}^{N} (p_{sit} q_{sit})} + \frac{p_{si0} q_{si0}}{\sum_{i=1}^{N} (p_{si0} q_{si0})} \right)$.

In addition to bilateral indices computed for each pair of years in the analysis, chain-type indices spanning 1999 to 2008 are tabulated for each form. The analysis also computes quantity indices for each form. This facilitates the real and nominal *GED* calculations[1].

A.4. Methods for valuation of external costs from fossil fuels

In order to demonstrate how the marginal damages estimated in this paper might be applied in a context that is relevant to environmental accounting, the analysis tabulates the marginal external cost (MEC) for oil, natural gas, and coal in the US for 1999, 2002, 2005, and 2008. The MEC estimates are then compared to market prices for each fuel. To accomplish this, data are gathered on market prices for each fuel type, and air pollution emission rates associated with recovery (extraction) and delivery to power generators. Coal price information is provided by US DOE

[1] In order to compute standard errors for the index numbers, a bootstrap procedure is executed that entails 1,000 iterations. Drawing a bootstrap sample of emissions and marginal damages from the "population" of nearly 10,000 sources, the index numbers are computed and stored. This algorithm repeated 1,000 times and the resulting means and standard errors are reported in the empirical results section.

(USDOE, 1999; 2002; 2005; 2008). Natural gas prices are provided by USDOE (2013b) and oil prices are found at USDOE (2013a).

Air pollution emission rates are provided by the GREET life-cycle analysis model (Burnham *et al*., 2006). GREET provides estimates of emissions associated with extraction and use of coal, oil, and natural gas expressed in mass-per unit energy (grams/mmbtu, e.g.). Except for NH_3, GREET provides emission estimates for each of the pollutants covered in the current paper. These are converted to physical units in which prices are expressed (tons for coal, barrels for oil, and cubic feet for natural gas). The marginal damage estimates are converted from dollars per ton to dollars per gram. Using these conversions the marginal external cost per marketable unit is estimated for each fuel: external cost per barrel of oil, ton of coal, and cubic foot of natural gas.

The GREET model reports emission rates for various stages in each fuel's life cycle. GREET reports emission rates for extraction of each fuel and emission rates for delivery of the fuels for a series of end uses. The empirical analysis in this paper computes the MEC at two stages in the life cycle of oil, natural gas, and coal: extraction and delivery for electric power generation. Because GREET reports one emission rate per pollutant at each stage, the national average marginal damage for each pollutant is employed in this application (these values are reported in table 1).

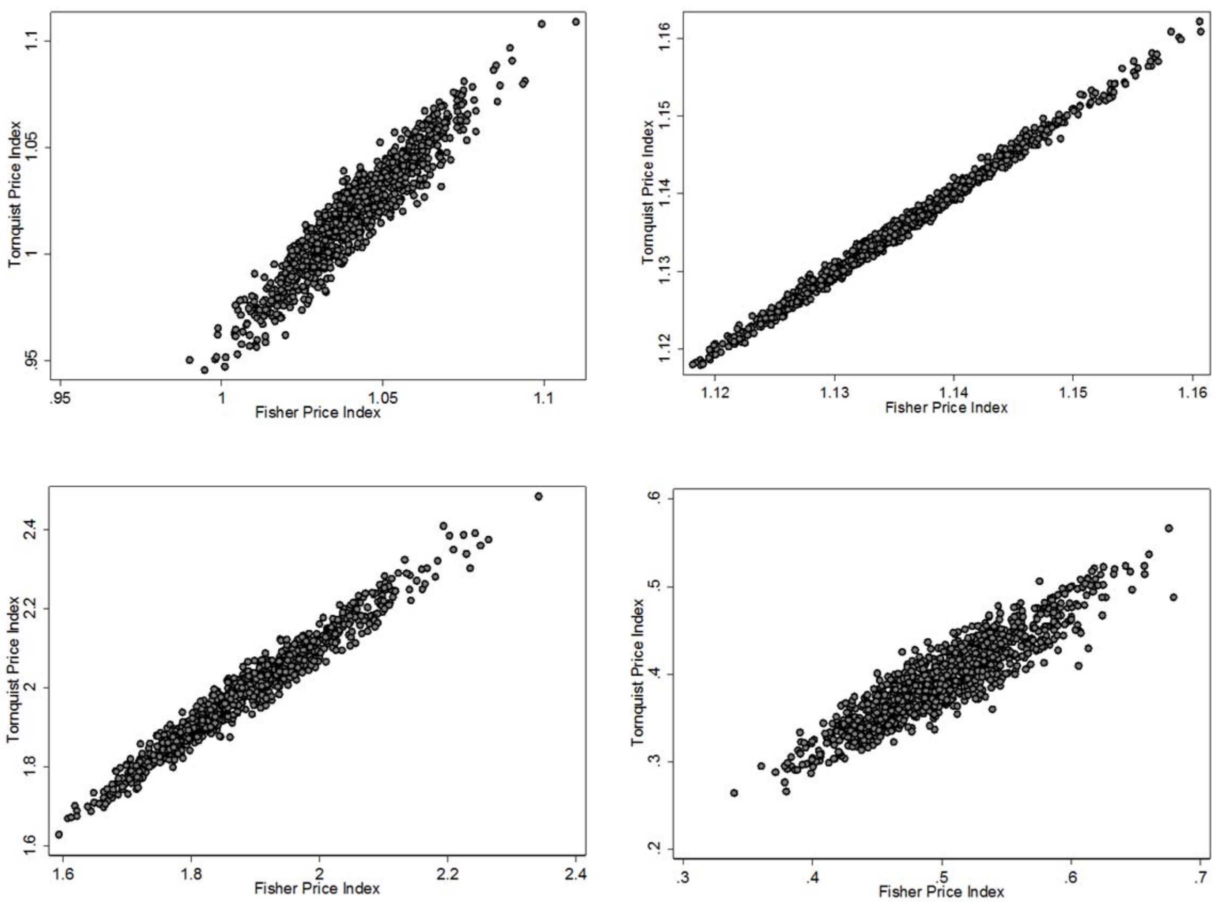

Figure 1. *Comparison of Fisher and Tornquist Price Indices (Top left: Multi-pollutant index, top right: SO_2, bottom left: NO_x, bottom right: NH_3)*

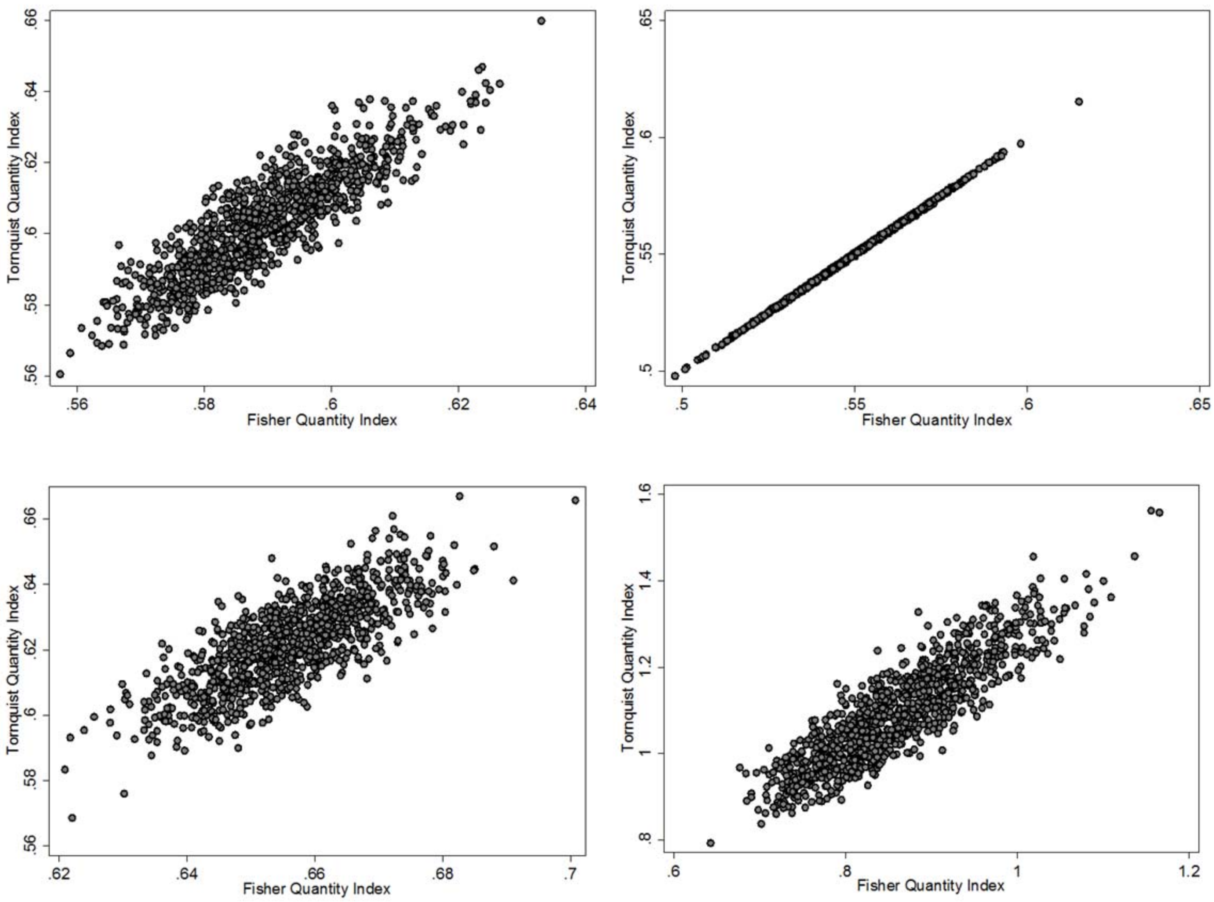

Figure 2: *Comparison of Fisher and Tornquist Quantity Indices (Top left: Multi-pollutant index, top right: SO_2, bottom left: NO_x, bottom right: NH_3)*

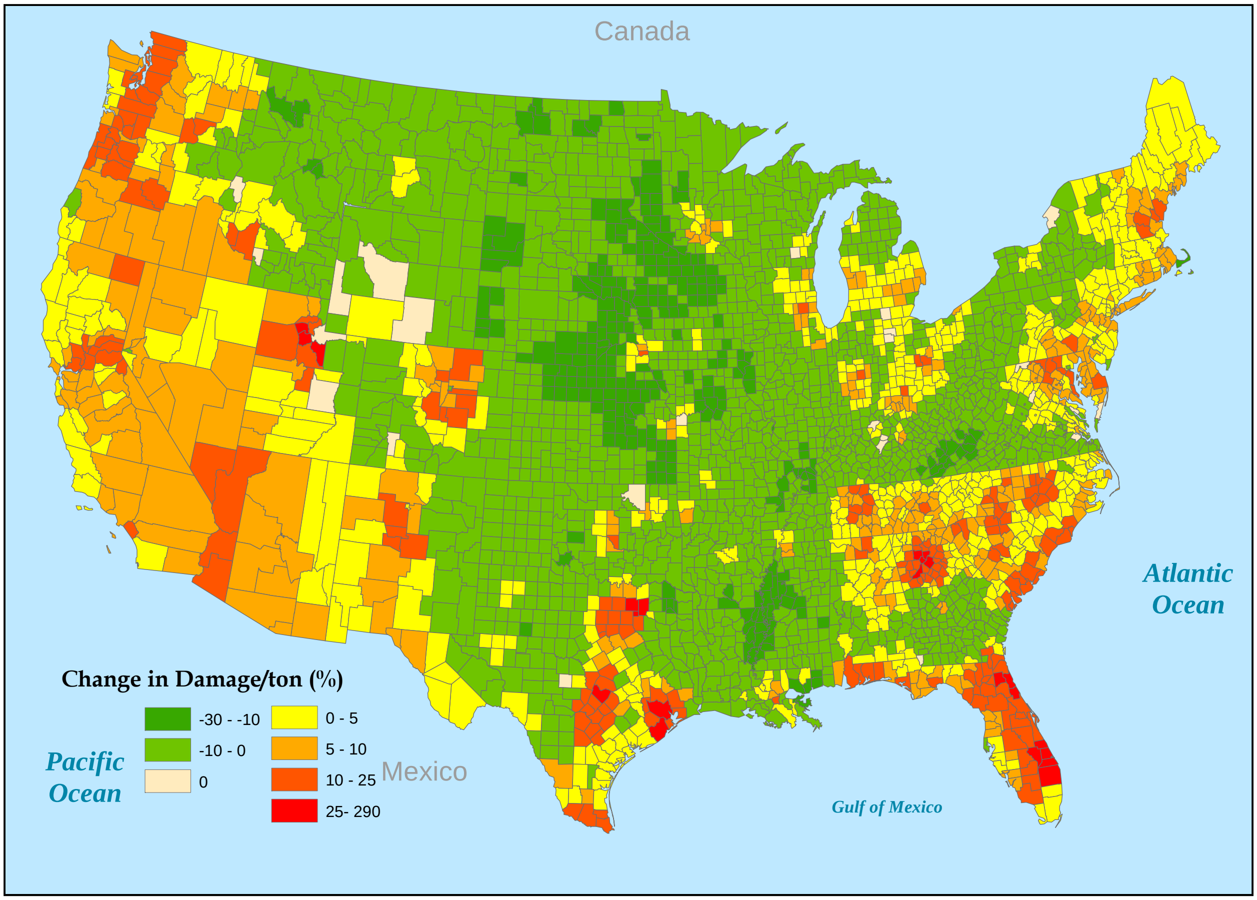

Figure 3: *Per cent change in $PM_{2.5}$ marginal damages: ground level emissions 1999 - 2008*

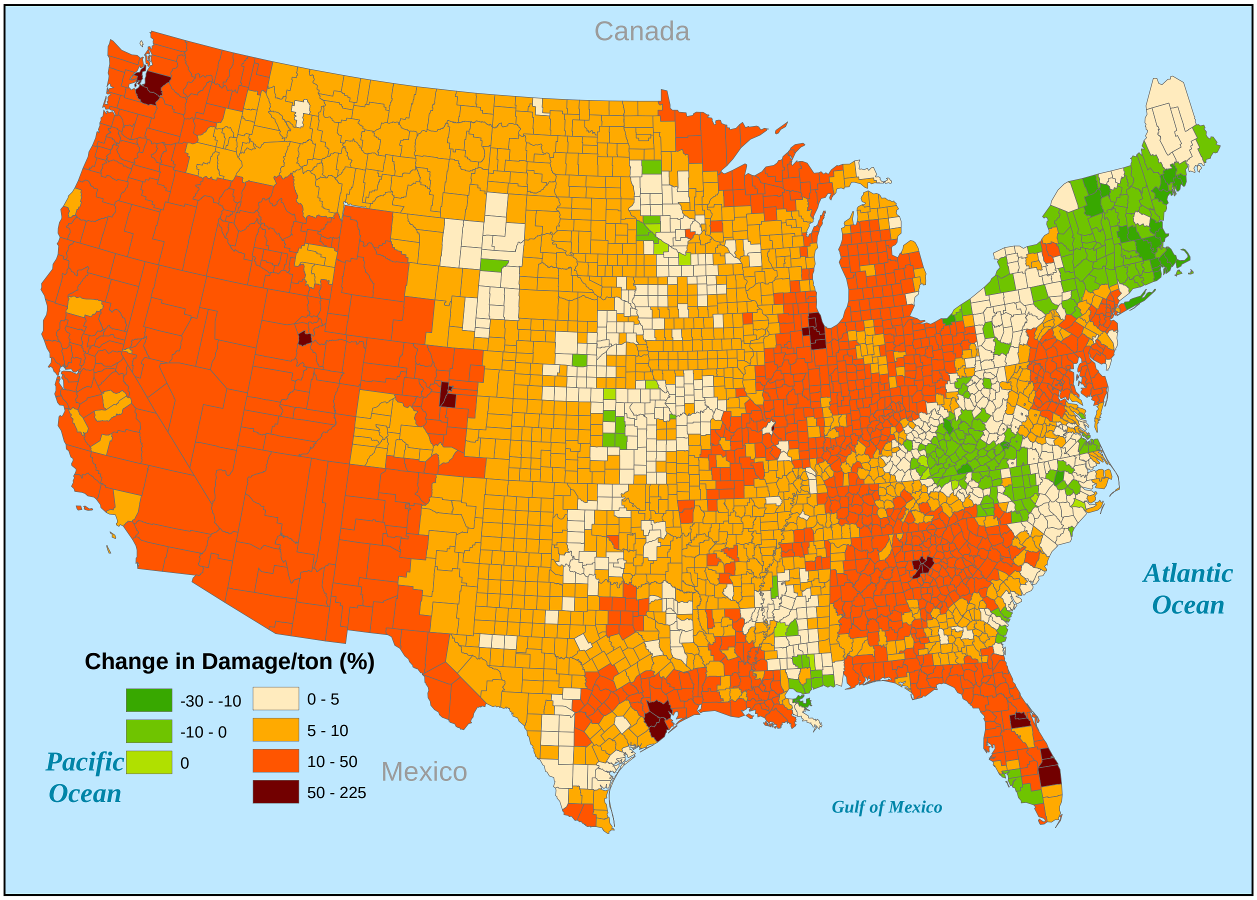

Figure 4: *Per cent change in SO_2 marginal damages: ground level emissions 1999-2008*

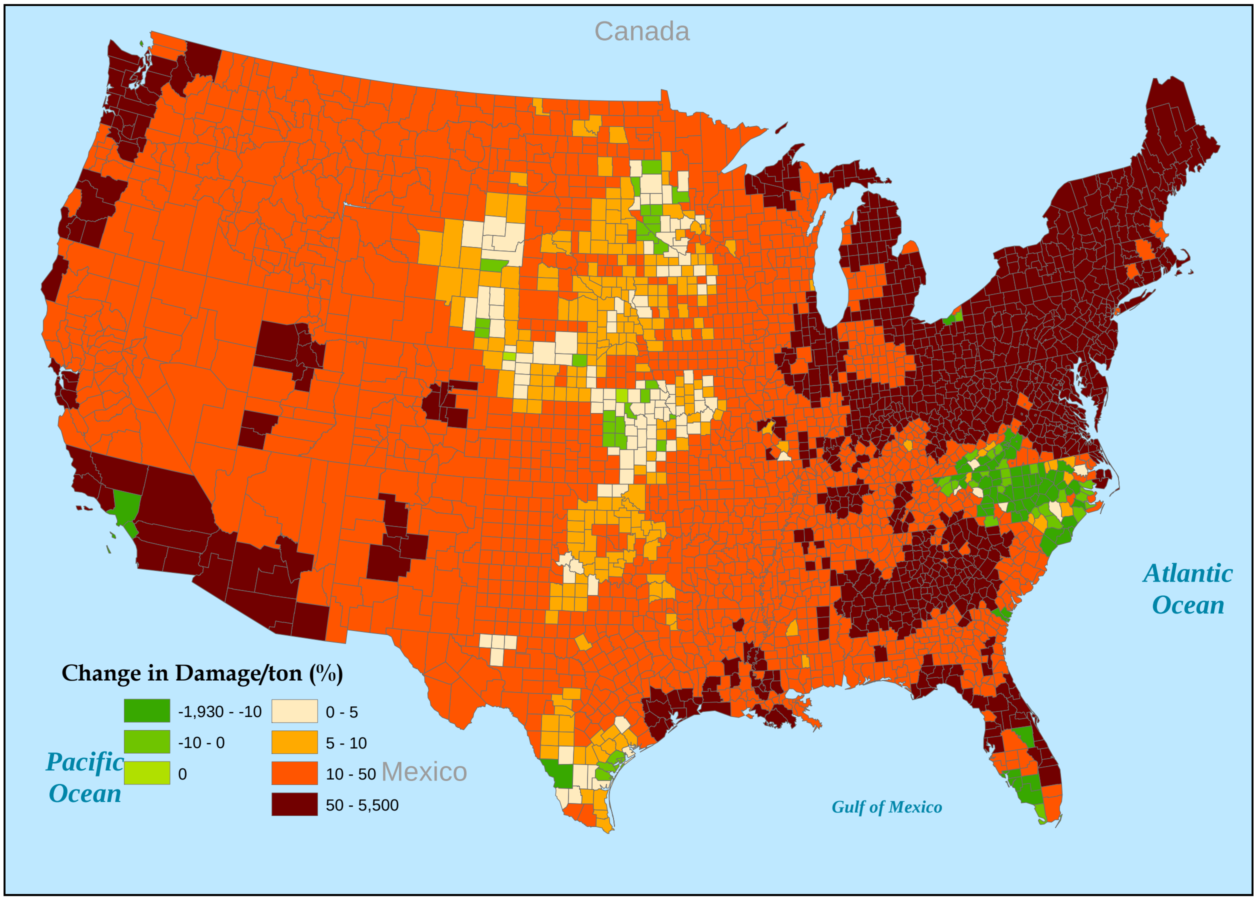

Figure 5: *Per cent change in NO_x marginal damages: ground level emissions 1999-2008*

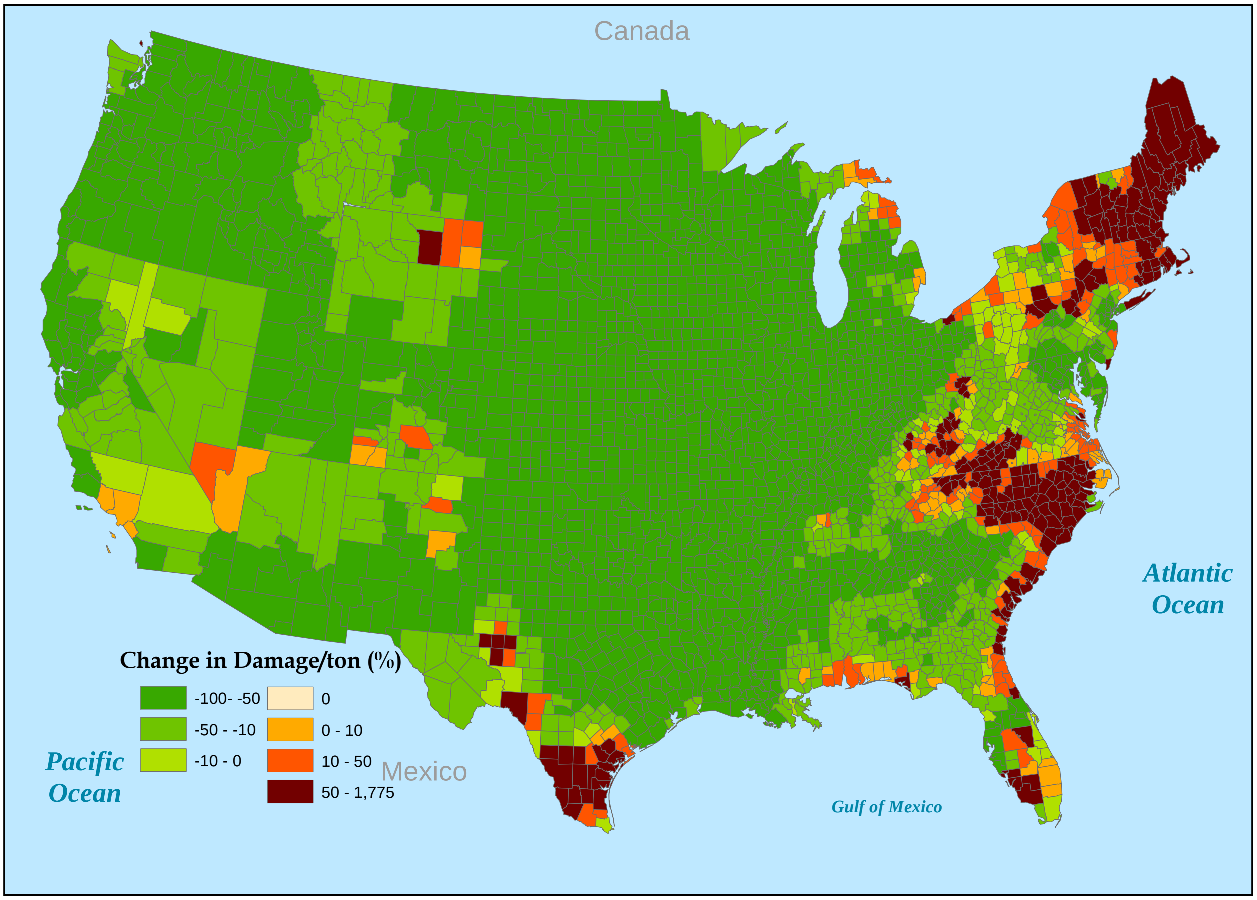

Figure 6: *Per cent change in NH_3 marginal damages: ground level emissions 1999-2008*

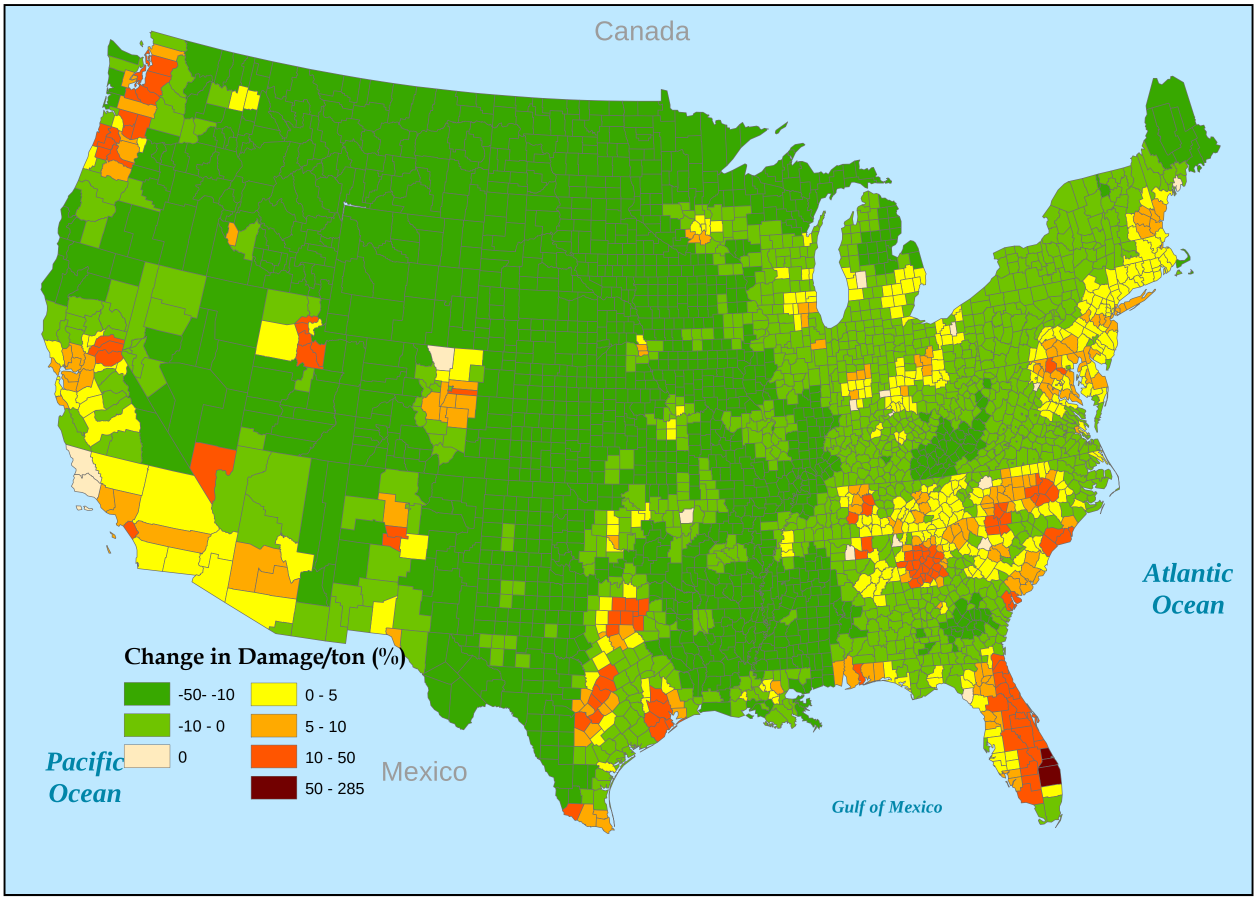

Figure 7: *Per cent change in VOC marginal damages: ground level emissions 1999-2008*

Table A1. *Bilateral price indices with ambient $PM_{2.5}$ as the quantity base*

1999/2005	**Paasche (P_P)**	**Laspeyres (P_L)**	**Fisher (P_F)**	**Tornquist (P_T)**	**Fisher (Δ)**	**Tornquist (Δ)**
NH_3	0.986	0.853	0.916***	0.914***	-0.082	-0.101
	(0.041)	(0.054)	(0.047)	(0.069)	(0.001)	(0.001)
$PM_{2.5}$	0.975	0.984	0.979***	0.980***	-0.002	-0.002
	(0.004)	(0.003)	(0.004)	(0.004)	(0.000)	(0.000)
SO_2	1.015	1.007	1.011***	1.011***	-0.009	-0.009
	(0.006)	(0.005)	(0.005)	(0.005)	(0.000)	(0.000)
2002/2005	**Paasche (P_P)**	**Laspeyres (P_L)**	**Fisher (P_F)**	**Tornquist (P_T)**	**Fisher (Δ)**	**Tornquist (Δ)**
NH_3	1.082	0.831	0.948***	0.831***	-0.046	-0.158
	(0.044)	(0.086)	(0.062)	(0.096)	(0.001)	(0.002)
$PM_{2.5}$	1.048	1.049	1.048***	1.049***	0.004	-0.004
	(0.002)	(0.002)	(0.002)	(0.002)	(0.000)	(0.000)
SO_2	1.075	1.072	1.074***	1.073***	-0.010	-0.010
	(0.004)	(0.004)	(0.004)	(0.004)	(0.000)	(0.000)
2008/2005	**Paasche (P_P)**	**Laspeyres (P_L)**	**Fisher (P_F)**	**Tornquist (P_T)**	**Fisher (Δ)**	**Tornquist (Δ)**
NH_3	0.756	0.363	0.524***	0.323***	0.023	-0.073
	(0.045)	(0.049)	(0.049)	(0.043)	(0.001)	(0.001)
$PM_{2.5}$	1.024	1.021	1.022***	1.023***	0.008	-0.008
	(0.003)	(0.002)	(0.003)	(0.003)	(0.000)	(0.000)
SO_2	1.157	1.153	1.155***	1.155	-0.001	-0.000
	(0.011)	(0.011)	(0.011)	(0.011)	(0.000)	(0.000)

All index numbers computed with 2005 as base year.
Values in parentheses are bootstrap standard errors.
Asterisks denote significance level of mean comparison tests of indices with emission-base indices: * = 0.10, ** = 0.05, *** = 0.01.
(Δ) = numerical difference between concentration indices and emission indices.

Table A2. *Nominal GED price and quantity decomposition with ambient $PM_{2.5}$ quantity base: 1999 – 2008*

Pollutant	**Fisher (P_F)**	**Fisher (Q_F)**	**ΔGN**	**ΔGN (Δ)**
NH_3	0.563	0.463	0.262	-0.173***
	(0.044)	(0.046)	(0.041)	(0.002)
$PM_{2.5}$	1.042	0.470	0.490	-0.031***
	(0.004)	(0.016)	(0.017)	(0.000)
SO_2	1.146	0.564	0.646	0.022***
	(0.010)	(0.018)	(0.021)	(0.000)

All indices are chain type.
Values in parentheses are bootstrap standard errors.
$\Delta GN = P_F \times Q_F$.
Asterisks denote significance level of mean comparison tests of indices with emission-base indices: * = 0.10, ** = 0.05, *** = 0.01.
(Δ) = numerical difference between concentration indices and emission indices.

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