Accompanying Notes on Data and Methods: The Economics of Hurricanes in the United States

William D. Nordhaus
December 21, 2006

This document describes the procedures used and background data for William Nordhaus, "The Economics of Hurricanes in the United States," dated December 21, 2006. The data are included in a spreadsheet, "hurricanes_data_december122106.xls" at http://www.econ.yale.edu/ ~nordhaus/homepage/recent_stuff.html.

I. Data Sources

1. The data on hurricanes is generally from "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones From 1851 to 2005," *NOAA Technical Memorandum NWS TPC-4*, Eric S. Blake, Jerry D. Jarrell, and Edward N. Rappaport and Christopher W. Landsea, Hurricane Research Division, Miami, Florida, Updated July 2006 (Appendix A) downloaded from http://www.nhc.noaa.gov/Deadliest_Costliest.shtml. The data are from *Appendix A: Chronological List of All Hurricanes which Affected the Continental United States: 1851-2005*. (Updated from Jarrell et al. 1992 and reflecting official HURDAT reanalysis changes through 1914. Note that from 1915 through 1979, no official wind speed estimates are currently available.)

2. Best track data were taken from the HURDAT database, which has best track data for all hurricanes in the data set. (http://www.aoml.noaa.gov/hrd/hurdat/)

3. Inconsistencies were checked with the hurricane chronologies in the Monthly Weather Review or the National Hurricane Center chronologies (http://www.aoml.noaa.gov/general/lib/lib1/nhclib/libpage13.htm).

4. Landfall data are taken from the chronologies and the best track data. Some NWS chronologies include landfall data.

5. Emanuel's power and SST data were provided by him (personal communication, October 16, 2006). I used the unsmoothed data. Time series tests did not indicate smoothing was warranted, and Emanuel stated that there are no reasons of fundamental physics to do so.

6. All major data are provided in the spreadsheet named "hurricane_data_december122106.xls" and available at http://www.econ.yale.edu/~nordhaus/homepage/recent_stuff.html. These include the data on individual hurricanes, the GEcon data for the subgridcells, and the capital vulnerability indexes described in the Appendix and below.

II. Further Data Preparation

1. The basic data include 281 storms. No missing storms were located from other data sets. The missing data were estimated as follows. 7 observations include no mb data (central pressure). These were estimates from a regression of mb on the SS scale. There are only 169 observations on maximum wind speed from the original data set (no maximum wind in the data for 1915-1979). Thus, there were 112 observations on maximum wind speed at landfall missing. All observations since 1964 and a few in the 1915-63 period were taken from the chronologies or the "best track" data. This left 41 missing data for maximum wind speed that were in the cost data. The missing observations were estimated from a regression of maximum wind speed on SS scale and mb.

2. Hurricanes with "no damages" are generally entered between $10,000 and $100,000 after a reading of the historical accounts. Three hurricanes had questionable data but were nonetheless included: Hurricane Diane of 1955 (problems with damages confounded with Connie and Ione), Hurricane Gerda of 1969 (a double hit), and Hurricane Bob of 1985 (a double hit). Hurricane Carol 1953 is omitted from the capital vulnerability index calculations because it was not a landfall within the GEcon data set.

3. The damages from major hurricanes are primarily from Pielke and Landsea (http://www.aoml.noaa.gov/hrd/Landsea/USdmg/data.html) for the period through 1995. These were generally verified from the historical record, and several changes have been made where the P/L data set appeared inconsistent with the Monthly Weather Service hurricane reports (http://www.nhc.noaa.gov/pastall.shtml). There were no large discrepancies. Note that these data differ from those used by the reinsurance estimates; for example, they are smaller that estimates from Swiss Re for the period 1998 on (*Sigma*, No 2/2006, Swiss Re, Zurich contains the estimates for 2005.) More recent data for individual hurricanes are taken from the NWS chronologies.

4. Note that the total damages are usually estimated as two times the insured damages. Similar data for floods were tested by M., J. Downton, Z. B. Miller and R. A. Pielke, Jr., 2005. "Reanalysis of U.S. National Weather Service Flood Loss Database," *Natural Hazards Review*, 6:13-22 (although not for hurricanes). They found close agreement between different sources for floods over $500 million, but considerable inaccuracy from floods less than $10 million. It seems highly likely that this methodology

introduces errors in measuring damages, however. Measurement errors will not bias the statistical estimates.

5. The cumulative power index for each year is calculated as the sum of the maximum wind speed cubed for each six-hour period from the HURDAT data set. Emanuel (based on Landsea) notes that the early years have systematic biases, but we have not made any correction for these. It is clear as well that the "best track" data have many missing observations at the extremes for early years (before 1920). A check of the archives found no major omissions of storms.

6. The base OLS regression for the entire sample reported in Table 1 is the following:

```
Dependent Variable: LOG(COSTGOOD2/GDP)
Method: Least Squares
Date: 12/21/06   Time: 07:58
Sample (adjusted): 98 281
Included observations: 142 after adjustments
==========================================================================
        Variable          Coefficient    Std. Error    t-Statistic    Prob.
==========================================================================
           C               -93.77302      15.57964      -6.018945    0.0000
      LOG(MWGOOD)           7.300206      0.860524       8.483446    0.0000
         YEAR               0.029329      0.007249       4.045789    0.0001
==========================================================================
R-squared                   0.355746   Mean dependent var          -3.190484
Adjusted R-squared          0.346476   S.D. dependent var           2.710883
S.E. of regression          2.191500   Akaike info criterion        4.427950
Sum squared resid           667.5713   Schwarz criterion            4.490397
Log likelihood             -311.3844   F-statistic                  38.37676
Durbin-Watson stat          1.991200   Prob(F-statistic)            0.000000
==========================================================================
```

III. Drift Factors

We looked at several reasons why the damage/GDP ratio might change (conditional on a given hurricane intensity).

1. The nominal national capital output ratios – whether total, for structures, or for residential structures – have changed little over the 1929-2004 period, so there is little difference between normalizing hurricane damages by capital or by output (this is from BEA data at www.bea.gov).

2. However, the value of household tangibles and real estate has risen sharply according to the flow of funds data. These include land and increases in Tobin's Q on housing. Regressions over the 1952-2006 period indicate that the time trend is 0.15 and 0.20 percent per year for all tangibles and real estate, respectively.

3. There has been some rise in the population in vulnerable Atlantic coastal counties (primarily in Florida), with the vulnerable coastal proportion rising by between 1 and 1½ percent per year from 1960 to 2000 depending upon time and region.

4. Average housing values in southern coastal regions have tended to rise less rapidly than the national average.

5. We collected data on gross state product (1963-2004) and personal income (1940-2004). Florida's shares of GDP and personal income have both rises about 2.0 % p. a. over the 1960-2004 period. Personal income rose slightly more rapidly in the 1940-60 period (3.2 % p. a.). The increase has essentially stopped in the last five years. (Data from BEA and Census.)

6. The ratio of casualty premiums is from *Historical Statistics online* at http://hsus.cambridge.org/HSUSWeb (Table Cj751-765. Property liability insurance-business assets, policyholders' surplus, and premiums written: 1931-1998). There is a very small trend, but the data are too far from the desirable ones to be useful for estimating drift.

7. Florida appears the relevant region for comparisons. Taking all hurricanes that intersect with the U.S. by grid cell, Florida has had (776/3312) of US land observations from Hurdat data set; it has had (2.24/6.31) of the kts^3 hurricane power. This would contribute about 2/3 % per year to the damage GDP ratio.

8. The sea-level rise calculation is more speculative. These are described below.

IV. Background Estimates and Calculations

1. The general assumption is that storm frequency will not be affected by warming. This is clearly not the case for the North Atlantic basin, where frequency is clearly related to SST. Using the Hadley SST data for the Northern Hemisphere, we find that an estimate using a Poisson distribution of number of hurricanes has a positive coefficient on SST with a t-statistic of 7.4 ($p < .0005$). For the 1951-2005 period, using Emanuel's data (personal communication above), the t-statistic is 5.1 ($p < .0005$). A more intuitive OLS estimator find that the semi-elasticity of number of hurricanes with respect to SST is 0.800 ± 0.139 for the first period and data; and 0.637 ±0.148 for the second period and data (see eq_freq_ke in page "enso_ke" in "newhurr_121806_ns_reg.wf1" for the latter; no ARMA terms were significant).

2. An alternative power index for the North Atlantic is an index known as Accumulated cyclone energy (ACE), calculated by the National Oceanic and Atmospheric Administration (NOAA). ACE expresses the activity of Atlantic hurricane seasons. It uses an approximation of the energy used by a tropical system over its lifetime and is calculated every six-hour period. The ACE is calculated by summing the *square*s of the estimated maximum sustained velocity of every active tropical storm (wind speed 35 knots or higher), at six-hour intervals.

3. The estimation of the *VCI* (Vulnerable Capital Index) require an estimate of the distance-wind speed relationship. For this, we relied on data on 11 storms from Corene J. Matyas, "Relating Tropical Cyclone Rainfall Patterns To Storm Size," University of Florida, Gainesville, Florida (ams.confex.com/ams/pdfpapers/108831.pdf). We calculate distance using the great circle estimate at the mean of the long, lat for the data with landfalls (41.6, -70.9), which is (111.1, 95.3). We then estimated the relationship between wind speed and distance. The relationships are slightly different from gales (34+ knots), tropical storms (48+ knots), and hurricanes (64+ knots). The estimated coefficient for TS and hurricanes is 0.34, shown as follows:

```
Dependent Variable: ALLDIST
Method: Least Squares
Date: 09/04/06   Time: 13:17
Sample: 12 25
Included observations: 14
Convergence achieved after 3 iterations
ALLDIST= (1/C(2))*MAXLESSBENCH

                           Coefficien
                                    t    Std. Error    t-Statistic    Prob.
```

C(2)	0.347146	0.047927	7.243154	0.0000

R-squared	0.308602	Mean dependent var	91.14286
Adjusted R-squared	0.308602	S.D. dependent var	60.04083
S.E. of regression	49.92415	Akaike info criterion	10.72764
Sum squared resid	32401.47	Schwarz criterion	10.77328
Log likelihood	-74.09345	Durbin-Watson stat	1.806405

In this equation, "alldist" is the distance from the center and "maxlessbench" is the difference between the maximum speed and the cut off for TS or hurricanes.

V. Estimates of Power and Vulnerable Capital

The estimation of the four vulnerable capital indexes is described fully in the Appendix to the main paper. Potential problems with this procedure should be noted:

1. Any inaccuracies in the GECON-H data will carry over to the calculation. Spot checks found some displacements but no major errors. However, the data were truncated in the inland regions more than 300 miles from the coast, so some inland storms will be missed.
2. The calculations do not take into account storm direction and therefore will underestimate damage on the “right” side of the storm.
3. It does not currently include accurate hurricane sizes. The storm size is a stylized estimate.
4. It does not allow for low wind velocity in the storm eye.

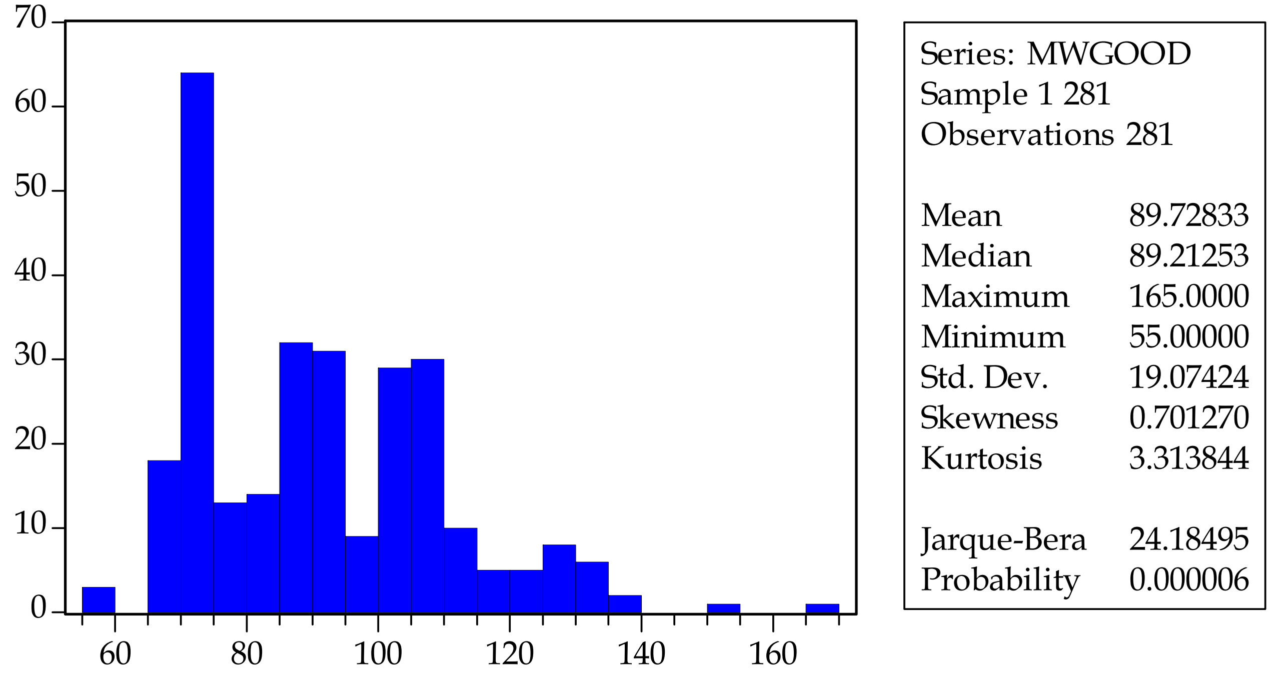
VI. Simulation of frequency distribution of impacts of climate change

The simulations of climate change were undertaken as follows:

1. We assumed that the distribution of hurricanes followed a Poisson distribution with a mean of 1.8 tropical cyclones per year.

2. Conditional on a hurricane, the intensity uses the historical distribution from 1851-2005. For informational purposes, the histogram is as follows for maximum wind

speed:



```
Series: MWGOOD
Sample 1 281
Observations 281

Mean          89.72833
Median        89.21253
Maximum       165.0000
Minimum       55.00000
Std. Dev.     19.07424
Skewness      0.701270
Kurtosis      3.313844

Jarque-Bera   24.18495
Probability   0.000006
```

VII. The Monte Carlo Estimate of the Frequency Distribution for Annual Damages

The distribution of total annual economic impacts draws upon equation (1) in the main text. The program used to develop the estimates is shown as Table SN-1, which is written in code for EViews 5.0. The procedure is as follows:

$$(4) \qquad V_t = \sum_{nt=0}^{mnt} f[Maxw(nt)]\, h[(Maxw(nt)]$$

where V_t = economic impact of all tropical cyclones in simulation year t ($t = 1, ..., 10{,}000$); nt = tropical cyclone number n for year t, mnt = maximum number of tropical cyclones in year t (from the Poisson distribution); $Maxw(nt)$ = maximum wind per tropical cyclone for storm nt; $f[(Maxw(nt)]$ = distribution of tropical cyclone intensity from the 1851 - 2005 distribution; and v = $h[Maxw(nt)]$ is the normalized impact (impact divided by GDP). The distribution of costs is given by $ln(v) = const + 8.5\, ln(Maxw) + N(0, 0.65)$, where $N(0, 0.65)$ is a normal distribution with mean 0 and standard deviation 0.094, and *const* is a constant that adjusts the mean to equal the mean cost for the period 1933 - 2005. For the "no global warming" simulation, we calculate the distribution according to equation (2). For the "global warming" simulation, we substitute the global warming distribution of intensities in (2), where the cumulative distribution function of $f(Maxw)$, which is $F(Maxw)$, shifts by 8.7 percent. That is, $F(Maxw)$ with global warming = $F(Maxw \times 1.087)$. We use the same realizations of the random numbers for the two simulations.

VI. Adaptation and Sea Level Rise

1. We describe in detail the methodology for calculating the economic impact of SLR.

2. The calculation of the impact of retreat and sea level rise is as follows: From the G-Econ data, we estimate the distribution of the capital stock as a function of altitude as $K^V = f(h)$, where K^V is the vulnerable capital stock and h is altitude. From standard estimates of the relationship between hurricane intensity and storm surge, we calculate the height of flooding as a function of the maximum sustained winds, $h = g(max\,wind)$, where $g(\bullet)$ is the impact of maximum sustained wind speed on storm surge. Finally, we estimate the distribution of maximum wind speed from the historical data. Combining these, we have the frequency distribution of vulnerable capital stock, $\varphi(K^V | h_0)$ where h_0 is a parameter representing the average height of the vulnerable capital stock; this parameter will change either if sea level rises or if policies (flood insurance or regulation) lead to higher or lower location of the capital stock. The expected value of the vulnerable capital stock is $E(K^V | h_0)$. If h_0 is lower because of sea level rise, then the expected value of vulnerable capital increases, whereas if the capital stock migrates to higher altitudes, the higher h_0 will reduce the expected value of the vulnerable capital stock.

3. To apply this approach, we take, from the G-Econ experiment described in the text, all sub-grid-cells less than 20 km from the coast. We then define a vulnerable sub-grid-cell as one with mean elevation at or less than the storm surge associated with different intensities of hurricanes from the SS scale (e.g., 1.4 meters for SSS = 1). We use the landfall frequency given by the historical distribution of intensities. This provides an estimate of the expected value of the vulnerable capital stock in 2005, $E(K^V | h_0)$, of \$58 billion for current sea level and distribution of capital. Using the methodology just described, we estimate the semi-elasticity of vulnerable capital with respect to capital height, $d\,ln[E(K^V | h_0)]/dh_0$, where h_0 is in meters. This semi-elasticity is 1.03 per meter for sea-level rise and 1.34 per meter for coastal retreat. This indicates that the expected value of the vulnerable capital stock rises 1.03 percent per cm of SLR and falls 1.34 percent for every 1 cm of upland retreat. To a first approximation, this indicates that hurricane vulnerability doubles or halves with every meter of SLR or upland retreat.

4. The details of the adaptation and sea-level rise calculations are the following. We first estimated the distribution of capital stock by altitude for all Atlantic coastal sub-grid-cells less than 20 km from the coastline. This yielded the following results:

Mean alt (m)	Sum (billions, 2005)
1	58.1
2	313
3	360
4	226
5	226
6	89.9
7	66.8
8	120
9	318

[Source: GEcon data set.]

5. We next determined the storm surge associated with hurricanes of different intensities. The following is the standard estimates for the SSS:

SSS	Storm surge (ft)	Storm surge (m)
1	4.5	1.4
2	7.0	2.1
3	10.5	3.2
4	15.5	4.7
5	21.0	6.4

[Source: National Hurricane Center]

6. We then used our basic data to fit a function of maximum wind speed to this, and combined these with the historical frequency of storms of different SSS, yielding the following:

Height	Cumulative prob (%/decade)
0	
1	15.682
2	13.250
3	5.882
4	2.362
5	0.957
6	0.402
7	0.177
8	0.081
9	0.039
10	0.010
11	0.005
12	0.002

7. We estimated the frequency of hurricanes from the Gray data averaged over coastline lengths, yields the final table:

Height	f(k)	F(K|h0)	National p	Average cell p	E(K|h0)	F(K|h0+1)	E(K|h0+1)	K(m-1)	F(K|h0-1)
0	0.0	0	1000	1.000	0.00	58.10	58.10	0.00	0.00
1	58.1	58.1	15.682	0.063	3.64	371.10	23.28	0.00	0.00
2	313.0	371.1	13.250	0.053	19.67	731.10	38.75	58.10	3.08
3	360.0	731.1	5.882	0.024	17.20	957.10	22.52	313.00	7.36
4	226.0	957.1	2.362	0.009	9.04	1183.10	11.18	360.00	3.40
5	226.0	1183.1	0.957	0.004	4.53	1273.00	4.87	226.00	0.87
6	89.9	1273	0.402	0.002	2.05	1339.80	2.16	226.00	0.36
7	66.8	1339.8	0.177	0.001	0.95	1459.80	1.03	89.90	0.06
8	120.0	1459.8	0.081	0.000	0.47	1777.80	0.58	66.80	0.02
9	318.0	1777.8	0.039	0.000	0.27	2077.80	0.32	120.00	0.02
10	300.0	2077.8	0.010	0.000	0.08	2377.80	0.10	318.00	0.01
11	300.0	2377.8	0.005	0.000	0.05	2677.80	0.05	300.00	0.01
12	300.0	2677.8	0.002	0.000	0.02	0.00	0.00	300.00	0.00
				1.2					
Total vulnerable capital					58.0		162.9		15.2
Historical damage					8.3		8.3		8.3
				ln(change)					
				Semielasticities					
					1 meter slr		1.03		
					1 meter retreat		1.34		
					average		1.19		

VII. Creation of G-Econ data set for hurricane analysis

1. The detailed data for the geographical analysis were developed as follows. First, we estimated population for sub-grid cell from the GPW 3.1 data base (gecon.yale.edu). We trimmed these so that they included only coastal regions from the Texas coast through Long Island, New York. The resolution for these sub-grid cells was 1/6 degree x 1/6 degree.

2. We then merged these with the 1 degree x 1 degree G-Econ GDP estimates for 1990. The estimates for the sub-grid cells were then equal to the per capita GDP for the grid cell times the population for the sub-grid cell.

3. We then scaled the values up to 2004 capital stock by multiplying by the ratio of 2004 capital stock to 1990 GDP, as shown in the table below. We then put these into 2005 prices using the 2005 GDP price index.

4. The basic data for the sample are the following:

Variable	**Value**
Area (sq. km.)	1,217,358.8
Population (million)	100.5
Subgrid cells	
Total	5,873
With area	4,658
With population	4,617
GDP (1990, 1995$, billion)	
Coastal East	2,711.5
US total	6,520.5
Capital stock (2004, 2004$, billion)	
Coastal East	15,639.7
US total	37,610.3

Table AN-1. Simulation program for impacts of hurricanes with global warming

[Note: this program is written for EViews 5.0]

```
' Program for poisson matrix of number of hurricanes
' uses "sim_gw_121906.wf1" page "gw-and_nogw"
' This program is "sim_impact_v5a_both.prg"

tic
'wfopen C:\MAJOR\Res-clim\Hurricanes\GlobWarm\sim_gw_121906.wf1
pageselect gw_and_nogw
!numsim=10000
!gw_maxwincrease=0.087
!gw_freq_increase=0.0


' Parameters of impact equation estimated for TC with maxwind>90 (n = 37)
' The standard deviation of the impact equation from the historical sample is
1.53. We have substituted the standard deviation
' of the log from the GEcon data base smpl if elev<10 and distnew<7 and rig>.01
(n=31)

!intercept= -40.5
!exponent= 8.5
'!var_impacts=0
!var_impacts=.65

smpl 1 10000

'd poweryear_gw v_maxw_gw impactsim_gw impactyear_gw maxwsim_gw perm_v_maxw_gw
powersim_gw ssumwindyear_gw  poweryear_nogw v_maxw_nogw impactsim_nogw
impactyear_nogw maxwsim_nogw perm_v_maxw_nogw powersim_nogw SIMPACTYEAR_GW
SIMPACTYEAR_NOGW SPOWERYEAR_GW SPOWERYEAR_NOGW SUMWINDYEAR_GW SUMWINDYEAR_NOGW
ssumwindyear_nogw  mrandimp randimp nhurr

'stop
' Poisson parameter
!a = 1.8

' Random impact variable
series randimp=nrnd
matrix(10000) mrandimp
stom(randimp,mrandimp)

series nhurr = @rpoisson(!a)
'series nhurr =1
stom(maxw,v_maxw_nogw)
stom(maxw,v_maxw_gw)
matrix(10000,15) maxwsim_nogw
matrix(10000,15) powersim_nogw
matrix(10000,15) impactsim_nogw
matrix(10000,15) maxwsim_gw
matrix(10000,15) powersim_gw
matrix(10000,15) impactsim_gw
vector(10000) poweryear_nogw
```

```
vector(10000) impactyear_nogw
vector(10000) sumwindyear_nogw
vector(10000) poweryear_gw
vector(10000) impactyear_gw
vector(10000) sumwindyear_gw

maxwsim_nogw=na
powersim_nogw=na
impactsim_nogw=na
maxwsim_gw=na
powersim_gw=na
impactsim_gw=na

' Routine for simulating maxwind speed, number of hurricanes, for 10000 years
' zeroth hurricane
for !iii = 1 to !numsim
!nnn=nhurr(!iii)+1

!truncwind=.001
maxwsim_nogw(!iii,1)=!truncwind
powersim_nogw(!iii,1)=!truncwind^3/10^6
impactsim_nogw(!iii,1)=!truncwind^9/10^18
maxwsim_gw(!iii,1)=!truncwind
powersim_gw(!iii,1)=!truncwind^3/10^6
impactsim_gw(!iii,1)=!truncwind^9/10^18
next


'positive TSs
for !iii = 1 to !numsim
!nnn=nhurr(!iii)+1
for !jjj=2 to !nnn

matrix perm_v_maxw_nogw=@permute(v_maxw_nogw)
matrix perm_v_maxw_gw=perm_v_maxw_nogw*(1+!gw_maxwincrease)

maxwsim_nogw(!iii,!jjj)=perm_v_maxw_nogw(!iii)
powersim_nogw(!iii,!jjj)=maxwsim_nogw(!iii,!jjj)^3/10^6
impactsim_nogw(!iii,!jjj)=exp(!intercept+!exponent*log(maxwsim_nogw(!iii,!jjj))
+!var_impacts*mrandimp(!iii))

maxwsim_gw(!iii,!jjj)=perm_v_maxw_gw(!iii)
powersim_gw(!iii,!jjj)=maxwsim_gw(!iii,!jjj)^3/10^6
impactsim_gw(!iii,!jjj)=exp(!intercept+!exponent*log(maxwsim_gw(!iii,!jjj))+!va
r_impacts*mrandimp(!iii))

next
next

' Estimate by year

for !iii = 1 to !numsim
poweryear_nogw(!iii)=0
impactyear_nogw(!iii)=0
sumwindyear_nogw(!iii)=0
poweryear_gw(!iii)=0
impactyear_gw(!iii)=0
sumwindyear_gw(!iii)=0
```

```
!nnn=nhurr(!iii)
for !jjj=1 to !nnn+1
poweryear_nogw(!iii)=powersim_nogw(!iii,!jjj)+poweryear_nogw(!iii)
impactyear_nogw(!iii)=impactsim_nogw(!iii,!jjj)+impactyear_nogw(!iii)
sumwindyear_nogw(!iii)=maxwsim_nogw(!iii,!jjj)+sumwindyear_nogw(!iii)
poweryear_gw(!iii)=powersim_gw(!iii,!jjj)+poweryear_gw(!iii)
impactyear_gw(!iii)=impactsim_gw(!iii,!jjj)+impactyear_gw(!iii)
sumwindyear_gw(!iii)=maxwsim_gw(!iii,!jjj)+sumwindyear_gw(!iii)
next
next

mtos(poweryear_nogw,spoweryear_nogw)
mtos(impactyear_nogw,simpactyear_nogw)
mtos(sumwindyear_nogw,ssumwindyear_nogw)
mtos(poweryear_gw,spoweryear_gw)
mtos(impactyear_gw,simpactyear_gw)
mtos(sumwindyear_gw,ssumwindyear_gw)

if !numsim<10000 then
smpl !numsim+1  10000
poweryear_nogw=na
simpactyear_nogw=na
ssumwindyear_nogw=na
spoweryear_gw=na
simpactyear_gw=na
ssumwindyear_gw=na
else
endif
smpl 1 !numsim
toc
```