Sensitivity of United States Air Quality to Mid-Latitude Cyclones and Implications of 1980-2006 Climate Change

Eric M. Leibensperger (eleibens@fas.harvard.edu), Loretta J. Mickley, Daniel J. Jacob

HARVARD
School of Engineering and Applied Sciences

Harvard University Atmospheric Chemistry Modeling Group

ABSTRACT
A51E-0158

SUMMARY

We show that the frequency of summertime mid-latitude cyclones tracking across eastern North America at 40°-50°N is a strong predictor of stagnation and ozone pollution days in the eastern United States.

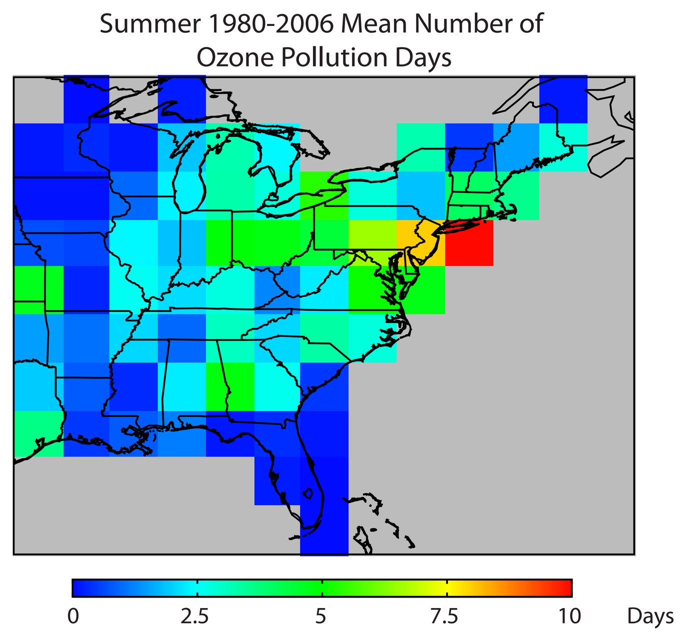
The NCEP/NCAR Reanalysis shows a significant long-term decline in the number of summertime mid-latitude cyclones in that track starting in 1980 (-0.15 a^{-1}). The more recent but shorter NCEP/DOE Reanalysis (1979-2006) shows similar interannual variability in cyclone frequency but no significant long-term trend. Analysis of NOAA daily weather maps for 1980-2006 supports the trend detected in the NCEP/NCAR Reanalysis 1. A GISS general circulation model (GCM) simulation including historical forcing by greenhouse gases reproduces this decreasing cyclone trend starting in 1980.

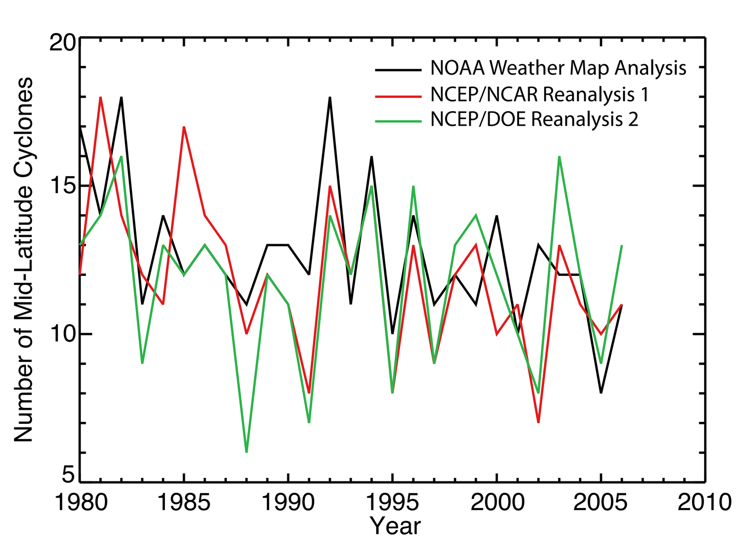
Such a long-term decrease in mid-latitude cyclone frequency over the 1980-2006 period may have offset by half the ozone air quality gains in the northeastern U.S. from reductions in anthropogenic emissions.

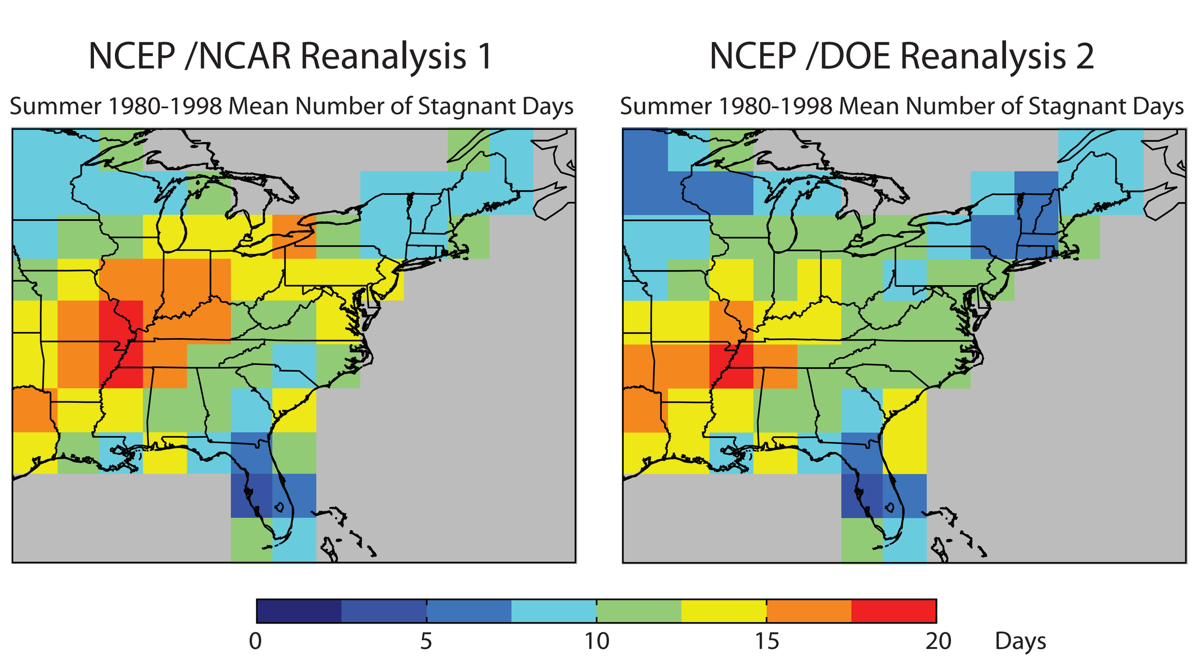
We find that if mid-latitude cyclone frequency had not declined, the northeastern U.S. would have been largely compliant with the ozone air quality standard by 2001. Mid-latitude cyclone frequency is expected to decrease further over the coming decades in response to greenhouse warming and this will necessitate deeper emission reductions to achieve a given air quality goal.

1. CYCLONES, STAGNATION & OZONE

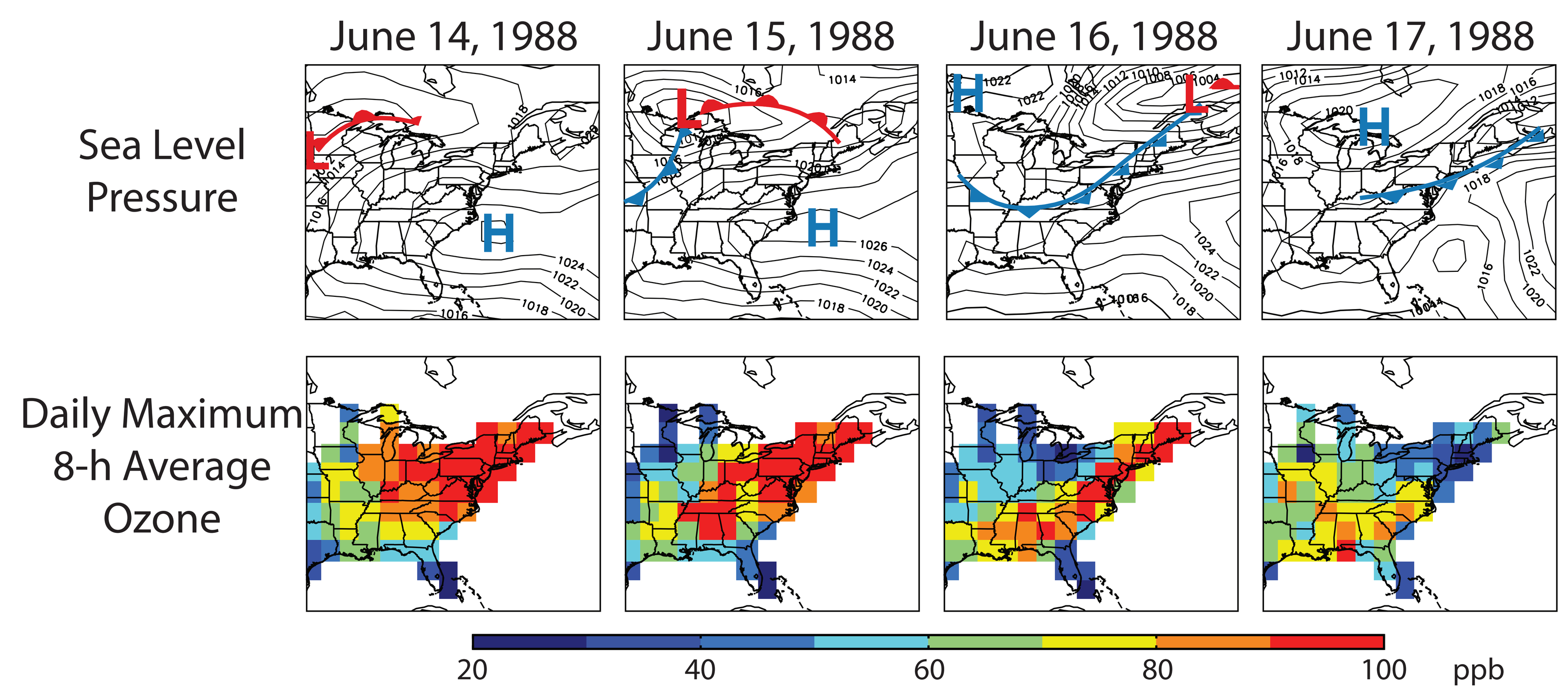
- Surface ozone observations were retrieved from EPA's Air Quality System and averaged onto a 2.5° x 2.5° grid. A time series of the number of summertime exceedances of the ozone National Ambient Air Quality Standard of 0.08 ppm was generated from this data.
- The June-August frequency of mid-latitude cyclones was derived from SLP NCEP Reanalyses 1 and 2 SLP data. We used the SLP minimum tracking algorithm of Bauer and Del Genio (2007).
- Mid-latitude cyclones were also counted by visual inspection of the NOAA daily weather maps.
- We found that cyclones tracking through 70-90°W and 40-50°N are most important for summer air quality.
- Stagnation was calculated using the method of Korshover and Angell (1982) and the Reanalysis data.



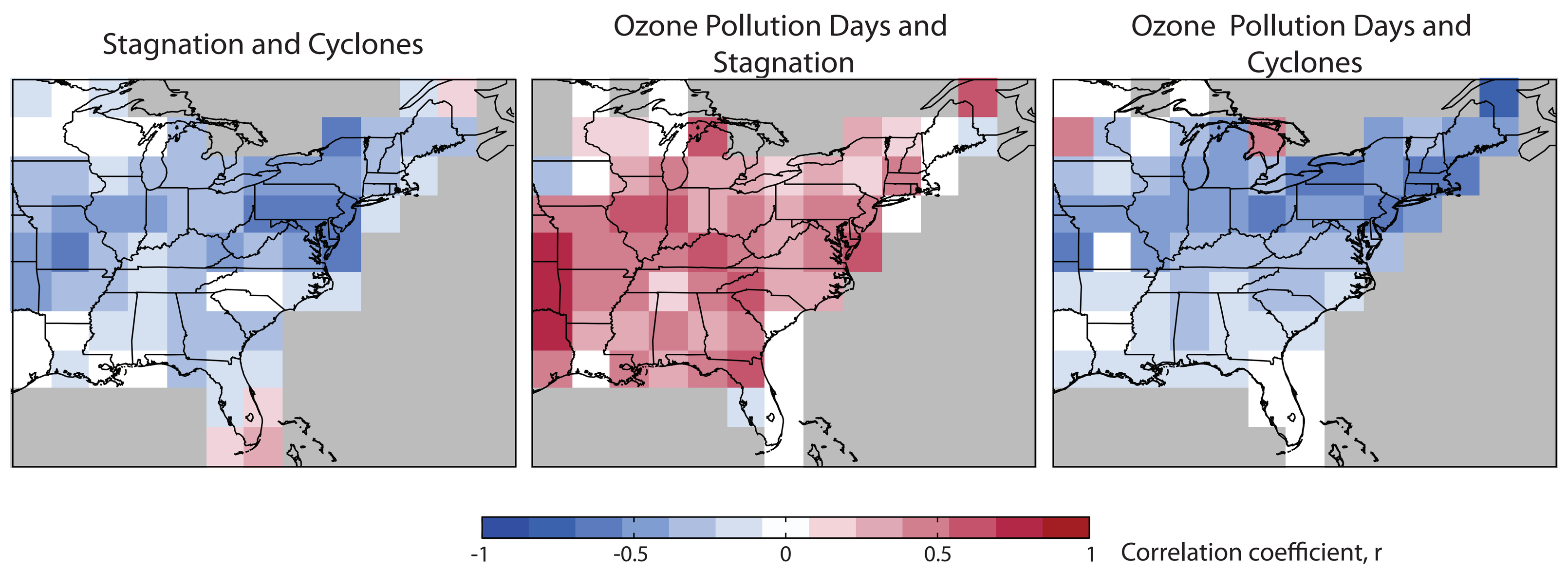




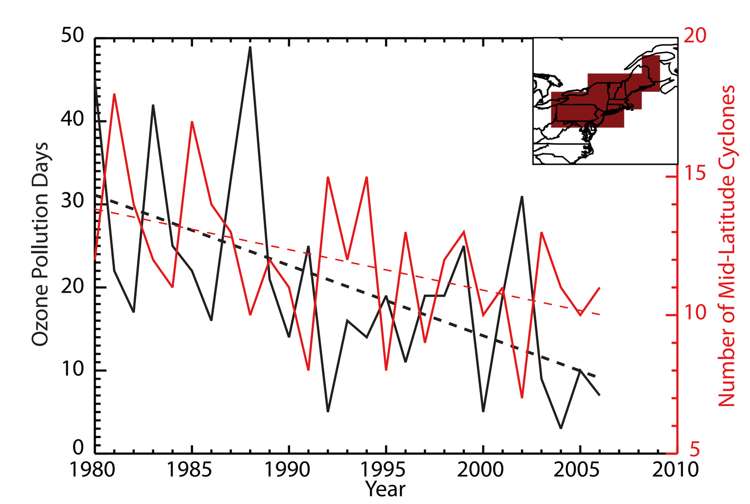
2. RELATIONSHIP BETWEEN CYCLONES, STAGNATION, & OZONE POLLUTION

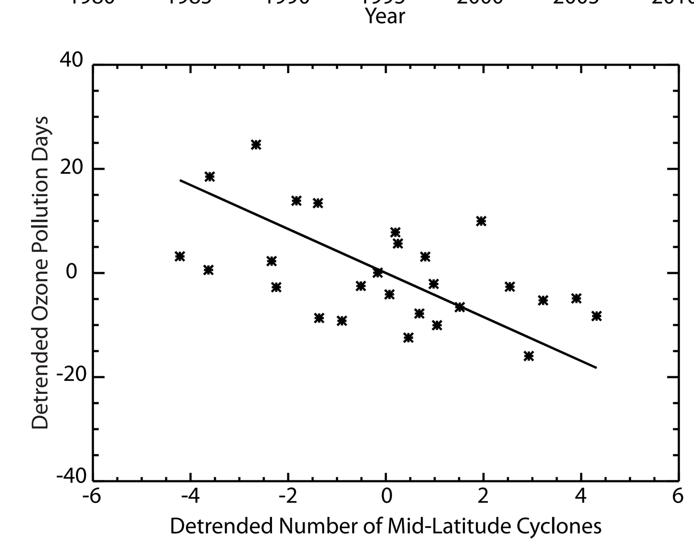


The figure above shows an example of a passing mid-latitude cyclone and its associated cold front sweeping eastward, dramatically lowering ozone concentrations across the eastern United States.



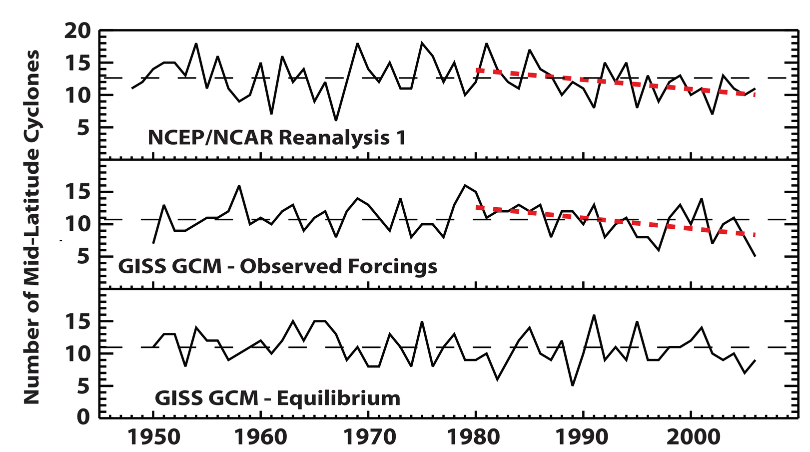
- The correlation of the interannual variability between cyclones and stagnation is significantly **negative**, **positive** between stagnation and ozone pollution days, and **negative** between cyclones and ozone pollution days (as seen above).
- **We thus see that there is a clear cause-to-effect link, at least in the Midwest and Northeast, between mid-latitude cyclones, stagnation days, and ozone pollution days.** This allows us to confidently use mid-latitude cyclones as a seasonal predictor of ozone air quality.
- We derive a sensitivity of -4.2 ozone pollution days per cyclone in the Northeast (right).



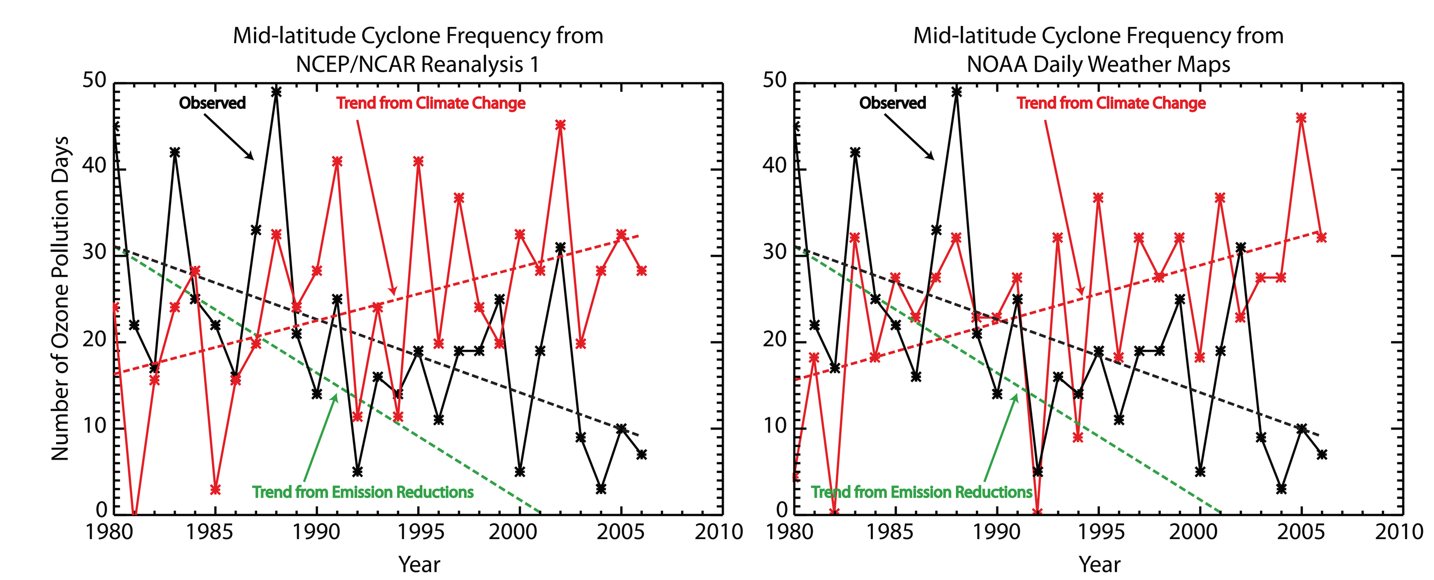


3. TRENDS IN CYCLONES & OZONE

- Over the last few decades, EPA has restricted emissions of volatile organic compounds (VOCs) and nitrogen oxides ($NO_x \equiv NO + NO_2$) in order it improve ozone air quality. The success of these efforts is evident in the time series of ozone pollution days within the Northeast, which shows a decreasing trend of -0.84 a^{-1}.
- The time series of summertime mid-latitude cyclones contains a significant decreasing trend of -0.14 a^{-1}. This trend is not found in our analysis of the NCEP Reanalysis 2 data, but a comparable trend is within the 95% confidence interval of the data. In addition, a decreasing trend exists within our manual analysis of the daily NOAA Weather Maps with a magnitude of -0.15 a^{-1}.
- We applied the cyclone tracking algorithm to two simulations of the NASA Goddard Institute for Space Studies GCM 3. The first was run for 50-years with the concentrations of greenhouse gases and aerosols fixed at their 1950 levels. The second simulation used reconstructed time-dependent concentrations of greenhouse gases and aerosols.
- **We find that the trend in mid-latitude cyclones can only be explained by increasing levels of greenhouse gases.**



4. IMPACT ON OZONE AIR QUALITY



- The observed trend in ozone pollution days, *n*, is driven by trends in emissions *E* and in the number of cyclones *C*, allowing us to decompose the trend: $\frac{dn}{dt} = \left[\frac{dn}{dt}\right]_E + \left[\frac{dn}{dt}\right]_C$
- The trend due to changes in the frequency of cyclones, shown in **red** above, can then be expressed as: $\left[\frac{dn}{dt}\right]_C = \frac{\partial n}{\partial C}\frac{\partial C}{\partial t}$
- We conclude from our data that without emission reductions, the number of ozone pollution days in the Northeast would have increased by 0.63 a^{-1}.
- Rearranging the equation from above reveals the trend in ozone pollution days that would have occurred had there been no change in the number of mid-latitude cyclones (**green**, above). We find that the trend in ozone pollution days would have been -1.5 a^{-1}, rather than the observed valued of -0.84 a^{-1}.
- This result implies that **decreases in mid-latitude cyclone frequency over the past three decades has deteriorated air quality in the Northeast and offset, by half, the benefit of emission controls.** This demonstrates the effect climate change can have on the accountability of emission reductions.
- Further attention to this issue is necessary given the consistent prediction of lowered frequency of mid-latitude cyclones by GCM simulations of the 21st century (Lambert and Fyfe, 2006) and previous work linking future air quality degradation to reduced frontal passages across the eastern United States (Mickley et al., 2004).

Acknowledgements:
This work has been funded by the Electrical Power Research Institute (EPRI), the Environmental Protection Agency Science to Achieve Results (EPA-STAR) Program, and an EPA-STAR Graduate Fellowship. The EPA has not officially endorsed this publication and the views expressed herein may not reflect those of the EPA.

References:

Bauer, M. and A.D. Del Genio (2006), Composite analysis of winter cyclones in a GCM: Influence of climatological humidity, *J. Clim.*, *19*, 1652-1672.

Korshover, J. and J.K. Angell (1982), A review of air stagnation cases in the eastern United States during 1981 - Annual Summary, *Mon. Weather Rev.*, *110*, 1515-1518.

Lambert, S.J. and J.C. Fyfe (2006), Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: results from the models participating in the IPCC diagnostic exercise, *Clim. Dyn.*, *26*, 713-728.

Leibensperger, E.M. et al. (2008), Sensitivity of US Air Quality to Mid-Latitude Cyclones and Implications of 1980-2006 Climate Change, *Atmos. Chem. Phys.*, *9*, 7075-7086.

Mickley, L.J., et al. (2004), Effects of future climate change on regional air pollution episodes in the United States, *Geophys. Res. Lett.*, *31*, L24103, doi:10.1029/2004GL021216.

Rind, D., et al. (2007), Effects of resolution and model physics on tracer transports in the NASA Goddard Institute for Space Studies general circulation models, *J. Geophys. Res.-Atmos.*, *112*, D09315, doi:10.1029/2006JD007476.