

Sensitivity of US air quality to mid-latitude cyclone frequency and implications of 1980–2006 climate change

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Abstract

We show that the frequency of summertime mid-latitude cyclones tracking across eastern North America at 40°–50° N (the southern climatological storm track) is a strong predictor of stagnation and ozone pollution episodes in the eastern United States. The NCEP/NCAR Reanalysis, going back to 1948, 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. A GISS general circulation model (GCM) simulation including historical forcing by greenhouse gases reproduces the cyclone trend seen in the NCEP/NCAR data. Such a long-term decrease in mid-latitude cyclone frequency over the 1980–2006 period would have offset by about a factor of 2 the ozone air quality gains from reductions in anthropogenic emissions in the northeastern United States. We find that if mid-latitude cyclone frequency had not declined, the northeastern US 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 trend needs to be considered in air quality management.

1 Introduction

Regional pollution episodes in the eastern US develop under summertime stagnant conditions with clear skies, a situation associated with weak high-pressure systems (Logan, 1989; Vukovich, 1995; Hegarty et al., 2007). The pollution episode ends when the warm, stagnant air mass is pushed to the Atlantic by the cold front of a passing mid-latitude baroclinic cyclone and replaced with cooler, cleaner air (Dickerson et al., 1995; Merrill and Moody, 1996; Cooper et al., 2001; Li et al., 2005). We show here with 1980–2006 data that interannual variability in the frequency of these mid-latitude cyclones is a major predictor of the interannual variability of pollution episodes, as

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measured by indices for stagnation and elevated surface ozone. Greenhouse-driven climate change is expected to decrease mid-latitude cyclone frequency, and we present tentative evidence that such a decrease may have already taken place over the 1980–2006 period. As we show, this would have major implications for pollution trends in the eastern US and significantly offset the benefits of decreasing anthropogenic emissions.

Figure 1 illustrates the role of mid-latitude cyclones in ventilating the eastern US with an example from the summer of 1988. That summer experienced the worst regional air quality of the 1980–2006 record (Lin et al., 2001). On 14 June the daily maximum 8-h average ozone concentrations exceeded 100 ppb across most of the region, a result of accumulation over several days of stagnant high-pressure conditions. Over the next two days, a mid-latitude cyclone moved along a westerly track across southeastern Canada. The associated cold front swept the pollution eastward to the North Atlantic, leaving much cleaner air with lower ozone concentrations in its wake. The westerly track across southeastern Canada illustrated in Fig. 1 is typical of mid-latitude cyclones traveling across North America. The frequency of these cyclones varies considerably from year to year (Zishka and Smith, 1980; Whittaker and Horn, 1981).

General circulation model (GCM) simulations of greenhouse-forced 21st-century climate change indicate a poleward shift in the preferential storm tracks (Yin, 2005) and a decrease in the frequency of northern mid-latitude cyclones (Geng and Sugi, 2003; Yin, 2005; Lambert and Fyfe, 2006; Meehl et al., 2007). These effects result from a shift and reduction of baroclinicity forced by weakened meridional temperature gradients (Geng and Sugi, 2003; Yin, 2005). One would expect an adverse effect on US air quality. A GCM simulation by Mickley et al. (2004) including pollution tracers found a 20% decrease in the frequency of summertime mid-latitude cyclones ventilating the US by 2050 and an associated increase in the frequency and intensity of pollution episodes. Two subsequent studies of US air quality in 21st-century climates, using global chemical transport models driven by GCM output, confirmed the increase of ozone pollution episodes due to decreased frequency of mid-latitude cyclones (Murazaki and Hess, 2006; Wu et al., 2008), but another study using a regional climate

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model did not (Tagaris et al., 2007).

Decreasing trends in mid-latitude cyclones over the past decades have been identified in the observational record. A study by Zishka and Smith (1980) using daily weather maps for North America found a significant decrease of 4.9 cyclones per decade in July and 9.0 cyclones per decade in December for 1950–1977. Similar trends have been found in studies using meteorological reanalyses (i.e. assimilated meteorological data). Gulev et al. (2001) found a decrease of 12.4 cyclones per decade in the Northern Hemisphere and 8.9 cyclones per decade over the Atlantic Ocean during winter 1958–1999. McCabe et al. (2001) found a significant decrease in cyclones at mid-latitudes (30°–60° N) and an increase at high-latitudes (60°–90° N) during winter 1959–1997. Previous studies have generally focused on winter, the season with the strongest climate change signal. In this study we focus on summer, which is of most interest from an air quality standpoint.

A large number of statistical studies have related air quality to local meteorological variables such as temperature, humidity, wind speed, or solar radiation, often with the goal of removing the effect of interannual meteorological variability in the interpretation of air quality trends (Bloomfield et al., 1996; Thompson et al., 2001; Camalier et al., 2007; Gégó et al., 2007; Zheng et al., 2007). Ordóñez et al. (2005) found that the number of days since the last frontal passage was a significant predictor of ozone air quality in Switzerland and Hegarty et al. (2007) related the interannual frequency and intensity of sea level pressure patterns over eastern North America to ozone, CO, and particulate matter concentrations. Mid-latitude cyclone frequency is an attractive meteorological predictor for interannual air quality on several accounts. First, it encapsulates to some extent the information in the local meteorological predictors (temperature, solar radiation, wind speed), while additionally providing direct information on boundary layer ventilation. Second, it represents a non-local single metric to serve as an explanatory variable for air quality on a regional scale. Third, since mid-latitude cyclones are an important aspect of the general circulation of the atmosphere, the frequency of these cyclones can be expected to be robustly simulated by GCMs and thus provide a

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useful and general metric for probing the effect of climate change on air quality.

2 Data and methods

2.1 Detection and tracking of mid-latitude cyclones

Various metrics can be used to diagnose mid-latitude cyclone activity, including eddy kinetic energy (Hu et al., 2004), temporal variability of sea level pressure, temperature or meridional wind (Harnik and Chang, 2003), the meridional temperature gradient, and the Eady growth rate (Paciorek et al., 2002). Some studies have used the probability distribution of sea level pressure as a diagnostic of cyclone frequency (Murazaki and Hess, 2006; Lin et al., 2008; Racherla and Adams, 2008). A problem with these metrics for application to air quality is that they convolve cyclone frequency and intensity. Air quality is sensitive to cyclone frequency, not intensity. We generate cyclone tracks instead by locating and tracking sea level pressure (SLP) minima, following the algorithm of Bauer and Del Genio (2006) as described below.

We use sea level pressure datasets from two different meteorological reanalyses for independent comparison of cyclone statistics: the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis 1 (<http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.html>) (Kalnay et al., 1996; Kistler et al., 2001) for June–August 1948–2006 and the NCEP/Department of Energy (NCEP/DOE) Reanalysis 2 (<http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis2.html>) (Kanamitsu et al., 2002) for June–August 1979–2006. Reanalysis 2 is an updated version of Reanalysis 1 incorporating updated physical parameterizations and various error fixes. However, it does not cover as long a period. The reanalysis datasets have a spatial resolution of $2.5^\circ \times 2.5^\circ$ and a temporal resolution of six hours. The previously mentioned studies of long-term mid-latitude cyclone trends (Geng and Sugi, 2001; Gulev et al., 2001; McCabe et al., 2001) all used Reanalysis 1.

The cyclone tracking algorithm of Bauer and Del Genio (2006) is an upgraded ver-

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sion of the scheme used by Chandler and Jonas (1999). For each 6-h time step the algorithm searches for sea level pressure minima extending 720 km or more in radius. The low-pressure center is tracked through time by assuming that the strongest sea level pressure minimum in the next 6-h time step within 720 km is the same system. In order to remove spurious minima, the system must be tracked for at least 24 h and have a central pressure no higher than 1020 hPa.

Figure 2 shows 28-year July climatologies of cyclone density, obtained by tallying the number of cyclone tracks passing through $5^\circ \times 5^\circ$ grid squares. The data represent the total number of cyclones over the 28 years of data. Results from the climatological analysis of Zishka and Smith (1980), which used monthly compilations of 6-h weather maps, are compared to the climatologies that we produced by applying the algorithm of Bauer and Del Genio (2006) to Reanalyses 1 and 2. Patterns and magnitudes are in good agreement, lending confidence in our application of the algorithm to the reanalysis data. Cyclone density is maximum over east-central Canada, corresponding to the two northern climatological cyclone tracks across North America identified by Zishka and Smith (1980) and Whittaker and Horn (1981). These studies also identified a less intense southern climatological track that begins in the central US and moves northeastward along the US-Canada border before merging with the northern tracks along the east coast of Canada. As we will see, it is this southern climatological track that is of most interest for US air quality.

Figure 3 shows individual cyclone tracks for June–August 1979–1981 over eastern North America in Reanalyses 1 and 2. We will show in Sect. 3 that the number of cyclones passing through the southern climatological cyclone track identified by the red box (70° – 90° W, 40° – 50° N) is a strong seasonal predictor of US pollution episodes. By contrast, we find that the number of cyclones passing through the northern climatological tracks (70° – 90° W, 50° – 60° N, green box in Fig. 3) is not a successful predictor. We focus on the southern track in the rest of this paper.

Figure 4 shows the time series of the 1980–2006 summertime frequency of mid-latitude cyclones in the southern climatological cyclone track (number of cyclones

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tracking through 70–90° W, 40–50° N) from Reanalyses 1 and 2. The two datasets have comparable statistics (Reanalysis 1: 11.9 ± 2.6 cyclones summer⁻¹, Reanalysis 2: 11.8 ± 2.7 cyclones summer⁻¹) and are strongly correlated ($r=0.75$, $p<0.001$). Reanalysis 1 has a significant decreasing trend for 1980–2006 but Reanalysis 2 does not. We discuss these long-term trends in Sect. 4.

2.2 Detection of stagnation episodes

The number of stagnant days was calculated from Reanalyses 1 and 2 data for June–August 1980–1998 with the metric described by Wang and Angell (1999), which is similar to the original version by Korshover and Angell (1982). A day is considered stagnant if the daily mean sea level pressure geostrophic wind is less than 8 m s^{-1} , the daily mean 500 hPa wind is less than 13 m s^{-1} , and there is no precipitation. Daily gridded precipitation data obtained from the NOAA Climate Prediction Center (<http://www.cdc.noaa.gov/cdc/data.unified.html>) with a resolution of $0.25^\circ \times 0.25^\circ$ were used to supplement both reanalysis datasets. Gridded precipitation data are available past 1998 but not from the same source. To ensure consistency we limit our analysis of stagnation episode statistics to 1980–1998. Unlike Korshover and Angell (1982) and Wang and Angell (1999), we do not have a stagnation length requirement; we count all days which meet the above requirements. Figure 5 shows the mean number of stagnant days per summer for 1980–1998 from Reanalyses 1 and 2. The frequency of stagnant days in both datasets is highest in a band stretching from Texas to Ohio, similar to results of Wang and Angell (1999).

2.3 Surface ozone data

We generated time series of daily maximum 8-h average ozone concentrations for June–August 1980–2006 from hourly observations of ozone concentrations retrieved from EPA’s Air Quality System (AQS, <http://www.epa.gov/ttn/airs/airsaqs/>), representing a network of over 2000 sites in the contiguous United States. The average number

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of sites providing ozone data since 1980 is about 1000 per summer; this number has increased over time. The daily maximum 8-h average ozone concentrations from all AQS sites were averaged onto the $2.5^\circ \times 2.5^\circ$ grid of the NCEP Reanalyses, producing a daily time series for 1980–2006 (Fig. 1 was produced from that time series). The number of days with a daily maximum 8-h average ozone concentration greater than 84 ppb was tallied for each summer, creating a 27-year time series of the seasonal number of ozone pollution episodes for each grid square corresponding to an exceedance of the 0.08 ppm US air quality standard. Spatial averaging causes an underestimate of the number of ozone pollution episodes, but enhances statistical robustness by removing data extremes and improving continuity. Spatial averaging also enables comparison to the identically gridded reanalysis products. Not every grid square included measurements for all 27 years. A grid square was analyzed only if it had 5 or more years of data.

Figure 6 shows the mean number of summertime ozone pollution episodes for 1980–2006 on the $2.5^\circ \times 2.5^\circ$ grid. The highest values (>6 days) are in the New York City–Washington, D.C. corridor, but high values (2–6 days) extend over much of the industrial Midwest and Northeast, and in some areas of the Southeast.

2.4 GCM simulations

We conducted two simulations with the Goddard Institute for Space Studies (GISS) GCM 3 (Rind et al., 2007) to investigate the effect of 1950–2006 climate change on mid-latitude cyclone frequencies. The first simulation was conducted for 1950–2006 using reconstructed time-dependent concentrations of greenhouse gases, aerosol forcing, and solar radiation (Hansen et al., 2002). The second (control) simulation was conducted in radiative equilibrium (greenhouse gas and aerosol concentrations were held at their 1950 levels), also for 1950–2006. The GCM has a horizontal resolution of 4° latitude \times 5° longitude and 23 vertical layers extending from the surface to 0.002 hPa in a sigma-pressure coordinate system (Rind et al., 2007). The simulations use a “qflux” representation for ocean heat transport (Hansen et al., 1988), which allows temporal

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variation in sea surface temperature and sea ice, but holds constant the horizontal heat transport fluxes in the ocean to values derived from present-day sea surface temperature distributions.

5 Mid-latitude cyclones are detected and tracked from the GCM sea level pressure output with the same algorithm used for the reanalysis data (Sect. 2.1). The GCM cyclone climatology is compared to the observational and reanalyses data in Fig. 2. Agreement is excellent. The number of GCM cyclones passing through the southern climatological track (red box in Fig. 3) is 10.8 ± 2.4 per summer, consistent with the reanalyses (Sect. 2.1).

10 **3 Mid-latitude cyclones as predictors of stagnation and ozone pollution**

The data and methods of Sect. 2 provide totals for individual summers of the number of cyclones passing through the southern climatological cyclone track (1948–2006 for Reanalysis 1, 1979–2006 for Reanalysis 2), as well as the numbers of stagnation days (1980–1998) and ozone pollution episodes (1980–2006) in each $2.5^\circ \times 2.5^\circ$ grid square of the eastern United States. We use the linear Pearson correlation coefficient to correlate these different variables on an interannual basis, and a Student's t-test to determine the significance of the correlation. To avoid the aliasing effects of long-term trends on the correlations, we removed linear trends from all individual time series that had significant trends at the 95% level. Long-term trends in ozone pollution episodes and mid-latitude cyclones will be discussed in Sect. 4.

Figure 7 (top two panels) shows the interannual correlation between the number of stagnant days and the number of mid-latitude cyclones. The correlation is generally significant and negative, indicating that less frequent mid-latitude cyclones in a given summer are associated with more frequent stagnant conditions. The negative correlation is strongest in the northeastern and midwestern United States. This is because the cold fronts associated with mid-latitude cyclones generally do not extend to the southern US (see Fig. 1); moist convection is a more important ventilation pathway in

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that region (Li et al., 2005).

The middle panels of Fig. 7 show the interannual correlation between the number of stagnant days and the number of ozone pollution episodes. There is strong positive correlation throughout the eastern US, with the exception of grid squares on the edge of the domain where wind direction (i.e. advection of pollution from upwind) is a more important predictor (Camalier et al., 2007). The positive correlation extends into the southern US, unlike the correlation between the number of stagnant days and number of mid-latitude cyclones.

The bottom panels of Fig. 7 show the interannual correlation between the number of ozone pollution episodes and the number of mid-latitude cyclones. There is widespread negative correlation, somewhat stronger than that of stagnation episodes with mid-latitude cyclones (top panels). The negative correlation is strongest ($r < -0.5$) in the Northeast, reflecting the dominant role of cold fronts in driving boundary layer ventilation in that region.

15 **4 Long-term trends in mid-latitude cyclone frequency and ozone in the northeast**

Reanalysis 1 features a statistically significant decreasing trend of the number of cyclones in the southern climatological track between 1980 and 2006 (-0.15 a^{-1} , $p < 0.01$), although Reanalysis 2 does not (Fig. 4). Previously derived trends in mid-latitude cyclones have used a longer record of the Reanalysis 1 data (Geng and Sugi, 2001; Gulev et al., 2001; McCabe et al., 2001). The top panel of Fig. 8 extends our time series of summertime mid-latitude cyclone frequencies for the southern climatological track from Reanalysis 1 to the entire dataset period of 1948–2006. The 1948–1980 period shows strong interannual variability but no trend. The trend is confined to 1980–2006.

Figure 8 also shows the time series of the number of mid-latitude cyclones derived from the GCM simulations described in Sect. 2.4. The simulation with historical

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changes in greenhouse gases, aerosols, and solar forcing shows a 1980–2006 decreasing trend in the number of cyclones frequency (-0.16 a^{-1} , $p < 0.01$), with no trend prior to 1980, similar to Reanalysis 1. The GCM control simulation, conducted in radiative equilibrium, with greenhouse gas and aerosol concentrations and solar activity held at their 1950 levels, does not exhibit any significant trend over the 1950–2006 record. These GCM results thus suggest that the trend in summertime mid-latitude cyclones seen in Reanalysis 1 is consistent with that expected from increasing greenhouse gases over the past decades.

Figure 9 shows the trend in the number of ozone pollution episodes in the Northeast (defined as the New England and mid-Atlantic regions; see inset of Fig. 9). We focus on the Northeast because of its high number of ozone pollution episodes (Fig. 6) and the strong relationship of these episodes to mid-latitude cyclone frequency (Fig. 7). The data in black represent the number of days over the course of the summer where one of the $2.5^\circ \times 2.5^\circ$ grid squares in the Northeast experienced a daily maximum 8-h average ozone concentration exceeding 84 ppb. The number of ozone pollution episode days in the Northeast decreased at a rate of 0.84 a^{-1} over the 1980–2006 period, a trend that can be credited to gradual reduction of anthropogenic emissions of ozone precursors, including nitrogen oxides ($\text{NO}_x \equiv \text{NO} + \text{NO}_2$) and volatile organic compounds (VOCs) (Lin et al., 2001; Gégo et al., 2007). This improvement in ozone air quality occurred despite the concurrent decreasing trend of mid-latitude cyclones diagnosed from Reanalysis 1 (also shown in Fig. 9). The detrended anomalies of the cyclone and ozone episode time series are strongly anticorrelated, as is manifest from Fig. 9. A reduced major axis linear regression of the detrended anomalies (Fig. 9) indicates a dependence of the number n of ozone pollution episodes on the number C of mid-latitude cyclones, $\partial n / \partial C = -4.2$. This points to a major effect of 1980–2006 climate change on the observed ozone trends, as discussed below.

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5 Effect of 1980–2006 climate change on ozone air quality

A long-term decreasing trend in mid-latitudes cyclones over the 1980–2006 period, as indicated by Reanalysis 1 and by the GISS GCM simulation, would imply increasing stagnation and thus a more favorable meteorological environment for ozone pollution episodes. This could have offset some of the gains from decreases in anthropogenic emissions of ozone precursors, so that the return from emission controls would have been less than expected. Understanding such an effect is of great importance for the accountability of air quality policy (National Research Council, 2004).

With the understanding that the 1980–2006 cyclone trend from Reanalysis 1 is tentative (since it is not seen in Reanalysis 2, but it is supported by the GCM simulation), we estimate here how it would have affected the 1980–2006 trend in ozone air quality in the Northeast. The observed trend in the number of ozone pollution episodes per summer, dn/dt , is -0.84 a^{-1} (Fig. 9). Let us assume that this observed trend is driven by trends in emissions E and in the number of cyclones C . We can then decompose the observed total derivative into partial derivatives:

$$\frac{dn}{dt} = \left[\frac{dn}{dt} \right]_E + \left[\frac{dn}{dt} \right]_C \quad (1a)$$

with

$$\left[\frac{dn}{dt} \right]_E = \frac{\partial n}{\partial E} \frac{\partial E}{\partial t} \quad (1b)$$

$$\left[\frac{dn}{dt} \right]_C = \frac{\partial n}{\partial C} \frac{\partial C}{\partial t} \quad (1c)$$

where $[dn/dt]_E$ describes the trend due to changing emissions in the absence of climate change, and $[dn/dt]_C$ describes the trend due to climate change in the absence of change in emissions. We previously derived $\partial n / \partial C = -4.2$ and $\partial C / \partial t = -0.15 \text{ a}^{-1}$ in

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Sect. 4. Thus the trend in number of ozone pollution episodes due to climate change is $[dn/dt]_C = 0.63 \text{ a}^{-1}$. Replacing into Eq. 1a yields a trend in the number of ozone pollution episodes due to changing anthropogenic emissions $[dn/dt]_E = -1.5 \text{ a}^{-1}$. We conclude from this analysis that decreasing mid-latitude cyclone frequency over the 1980–2006 period has offset the benefit of emission controls almost by half.

Figure 10 shows this result graphically. The time series of the number of ozone pollution episode days observed in the Northeast, as previously displayed in Fig. 9, is shown in black. The corresponding regression line $dn/dt = -0.84 \text{ a}^{-1}$ is also shown. The time series predicted from the number of mid-latitude cyclones (Fig. 9) and the dependence, $\partial n/\partial C = -4.2$, derived in Sect. 4 is shown in red, with the corresponding regression line $[dn/dt]_C = 0.63 \text{ a}^{-1}$ representing the expected trend in ozone pollution episodes from climate change had emissions remained constant. We see that the frequency of ozone pollution episodes would have doubled over the 1980–2006 period as a result of climate change, were it not for concurrent decreases in anthropogenic emissions. The green line in Fig. 10 shows the trend in ozone pollution episodes that would have been realized from the decrease in anthropogenic emissions in the absence of climate change, i.e. $[dn/dt]_E = dn/dt - [dn/dt]_C = -1.5 \text{ a}^{-1}$. We see that the expected number of ozone pollution episodes would have dropped to zero by 2001, instead of remaining a significant problem (expected value of 10) by 2006.

6 Conclusions

We showed that the frequency of mid-latitudes cyclones tracking across eastern North America in the 40° – 50° N latitudinal band (southern climatological track) is a strong predictor variable of the frequency of summertime pollution episodes in the eastern United States. Cold fronts associated with these cyclones effectively ventilate the US boundary layer. We constructed cyclone tracks using the algorithm of Bauer and Del Genio (2006) applied to assimilated meteorological data from the NCEP/NCAR Reanalysis 1 (1948–2006) and the NCEP/DOE Reanalysis 2 (1979–2006); the two re-

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analyses agree closely in the locations and frequencies of cyclone tracks, and also agree well with cyclone statistics constructed directly from weather maps. Statistical analysis of 1980–2006 summer data shows large interannual variability in the number of cyclones in the southern climatological track (11.9 ± 2.6) and reveals strong negative interannual correlations between the number of cyclones and both the number of stagnation days and the number of ozone pollution episodes.

The frequency of mid-latitude cyclones in the 40° – 50° N band is of particular interest as a predictor variable for US air quality. First, it encapsulates in a single synoptic-scale variable the effects of known local predictor variables including temperature, wind speed, and solar radiation. Second, mid-latitude cyclones are a feature of the general circulation of the atmosphere and are therefore amenable to trend analysis and prediction using GCMs. They can thus be used to diagnose and project the effects of climate change on US air quality.

Greenhouse warming is expected to decrease mid-latitude cyclone frequencies (Geng and Sugi, 2003; Yin, 2005; Lambert and Fyfe, 2006; Meehl et al., 2007), and such a decrease has been observed in climatological analyses of 1950–2000 data (Zishka and Smith, 1980; Gulev et al., 2001; McCabe et al., 2001). We examined more specifically the historical trend in the number of summer cyclones in the North American southern climatological track (40° – 50° N) responsible for ventilating the eastern United States. The NCEP/NCAR Reanalysis 1 shows a significant decreasing trend for 1980–2006 (-0.15 a^{-1}) and no trend prior to 1980. No significant trend in summertime mid-latitude cyclone frequency emerges from the NCEP/DOE Reanalysis 2. To explore this issue further, we conducted a transient-climate simulation for 1950–2006 with the GISS GCM 3 including historical greenhouse and aerosol forcing. This simulation shows a decrease in the number of cyclones for 1980–2006 (-0.16 a^{-1}), and no trend prior to 1980, in close agreement with Reanalysis 1. A control GCM simulation for 1950–2006 with no greenhouse and aerosol forcing shows by contrast no trend over the whole period.

A 1980–2006 decrease in cyclone frequency as indicated by the NCEP/NCAR Re-

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analysis 1 has important implications for the success and accountability of emission control strategies directed at improving US air quality. Our analysis of the surface ozone data indicates a decrease in the observed number of summertime ozone pollution episode days in the Northeast by 0.84 a^{-1} over the 1980–2006 period, from an expected value of 31 (1980) to 10 (2006). This decrease can be credited to reduction of anthropogenic emissions, but we find that the benefit of these reductions may have been significantly offset by climate change. Taking the relationship between the number of summertime cyclones and the number of ozone pollution episodes from our correlation analysis, combined with the cyclone trend from Reanalysis 1, we deduce that the number of ozone pollution episodes would have doubled over the 1980–2006 period as a result of climate change if anthropogenic emissions had remained constant. Correcting the observed decrease of ozone pollution episodes for this climate trend, we find that the number of ozone pollution episodes would have dropped to an expected value of zero by 2001 in the absence of climate change.

If the 1980–2006 cyclone trend apparent from the NCEP/NCAR Analysis 1 is correct, it would have offset almost half of the air quality gains from reducing anthropogenic emissions over the 1980–2006 period. This suggests that climate change may have had already a major effect on the accountability of emission control strategies over the past 2–3 decades, preventing achievement of the ozone air quality standard. It demonstrates the potential of climate change to dramatically affect air quality on decadal scales relevant to air quality policy. Future attention to this issue is necessary in view of the consistent predictions from GCMs that 21st-century climate change will decrease the frequency of mid-latitude cyclones (Lambert and Fyfe, 2006).

Our analysis has focused on ozone air quality because of the availability of long-term records with high spatial density. We would expect mid-latitude cyclone frequency to also be a good predictor of particulate matter (PM) air quality, which is similarly affected by stagnation, but further analysis using PM observational records is necessary. Also, our analysis has focused on the eastern US, but similar analyses would be of value for western Europe and China, where mid-latitudes cyclones are also major agents

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for pollutant ventilation (Liu et al., 2003; Ordóñez et al., 2005). We have found in the eastern US that although mid-latitude cyclone frequency is a good predictor of pollution episodes in the Northeast and Midwest, it is less effective in the South. Other large-scale meteorological metrics should be sought there and in the West to enable robust assessments of the effect of climate change on air quality.

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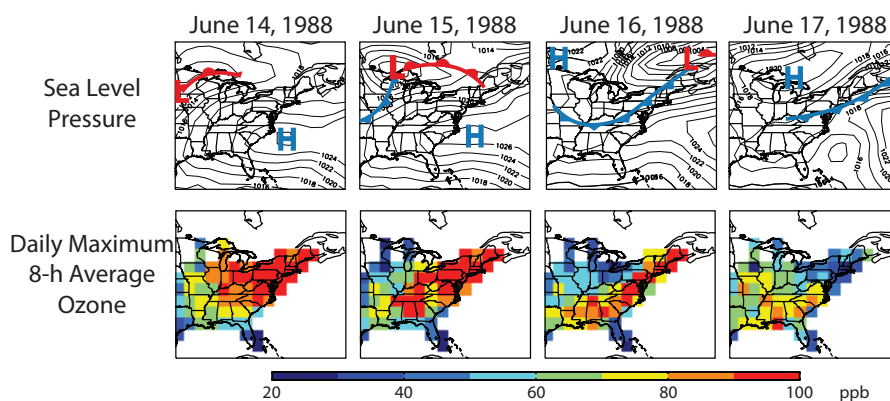


Fig. 1. Evolution of surface ozone concentrations in the eastern US during the passing of a mid-latitude cyclone (14–17 June 1988). The top row shows instantaneous sea level pressure fields at 12Z from NCEP/NCAR Reanalysis 1, while the bottom row shows daily maximum 8-h average ozone concentrations from monitoring sites of the US Environmental Protection Agency (<http://www.epa.gov/ttn/airs/airsaqs/>). The contour interval for sea level pressure is 2 hPa. The ozone data have been averaged on a $2.5^{\circ} \times 2.5^{\circ}$ grid.

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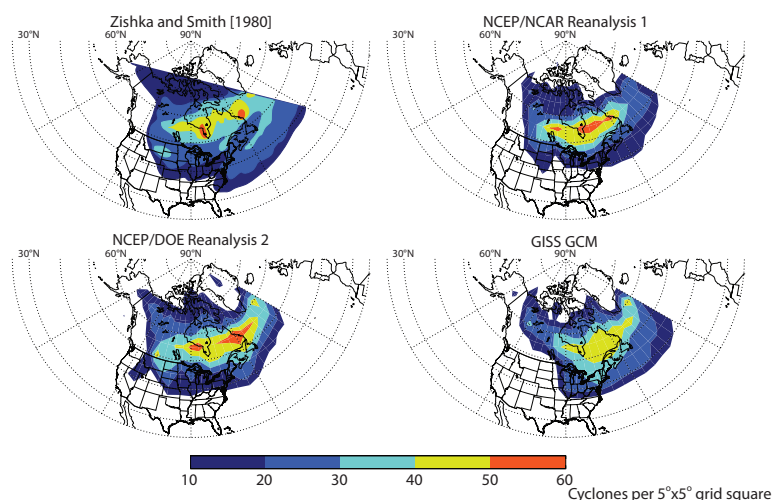


Fig. 2. 28-year July climatologies of cyclone tracks across North America, counting all cyclone tracks that pass through $5^{\circ} \times 5^{\circ}$ grid squares. The Zishka and Smith (1980) climatology is for 1950–1977 and based on monthly compilations of 6-h weather maps; the data shown here are adapted from their Fig. 3. The NCEP/NCAR Reanalysis 1 and NCEP/DOE Reanalysis 2 climatologies are for 1950–1977 and 1979–2006, respectively. The GISS GCM climatology is for 1950–1977 in a transient-climate simulation including historical trends in greenhouse gases and aerosols.

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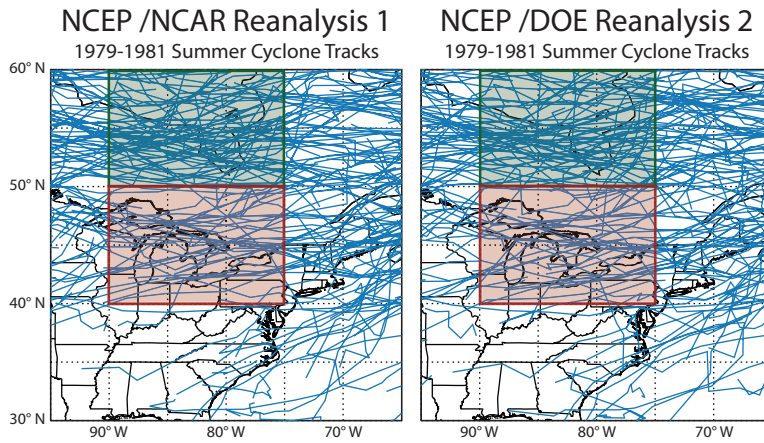


Fig. 3. Mid-latitude cyclone tracks for June–August 1979–1981 in the NCEP/NCAR Reanalysis 1 (left) and NCEP/DOE Reanalysis 2 (right). The red box (70° – 90° W, 40° – 50° N) is used to diagnose the frequency of mid-latitude cyclones traveling along the southern climatological cyclone track. The green box (70° – 90° W, 50° – 60° N) is used for the northern climatological cyclone tracks.

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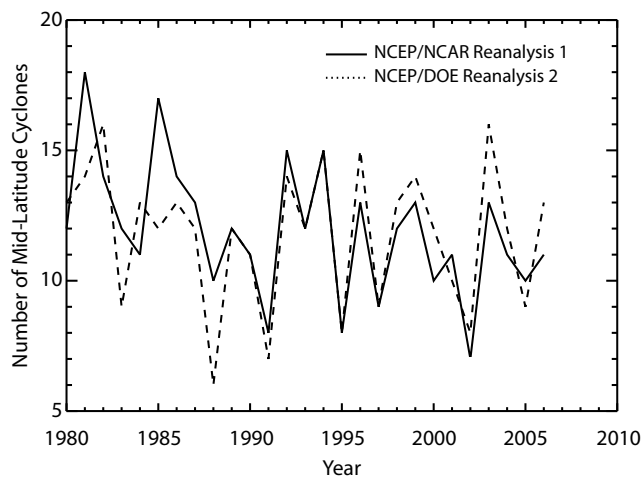


Fig. 4. June–August 1980–2006 time series of the number of mid-latitude cyclones passing through the red box of Fig. 3, corresponding to the southern climatological cyclone track across North America. Results are shown for the NCEP/NCAR Reanalysis 1 (solid line) and NCEP/DOE Reanalysis 2 (dashed line).

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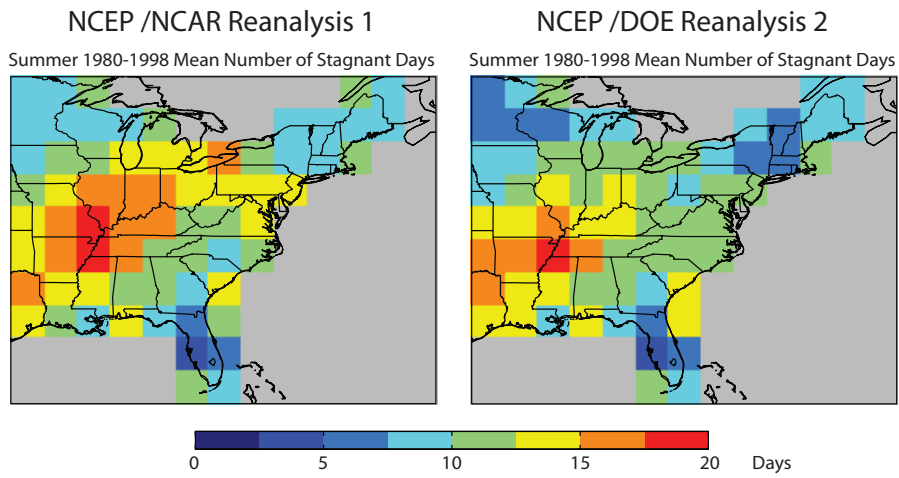


Fig. 5. Seasonal mean number of June–August stagnant days in the 1980–1998 records from NCEP/NCAR Reanalysis 1 (left) and NCEP/DOE Reanalysis 2 (right).

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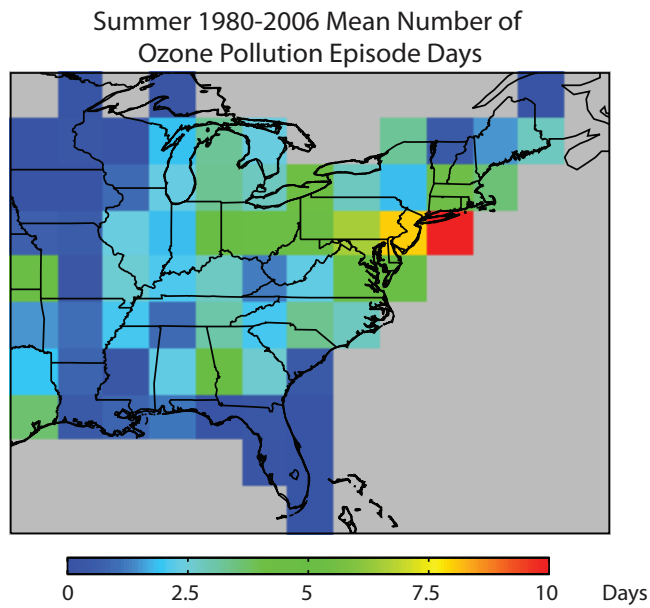


Fig. 6. Seasonal average number of June–August ozone pollution episodes for the 1980–2006 period. A pollution episode occurs when the mean daily maximum 8-h average ozone concentration averaged over observational sites within a $2.5^\circ \times 2.5^\circ$ grid square is greater than 84 ppb.

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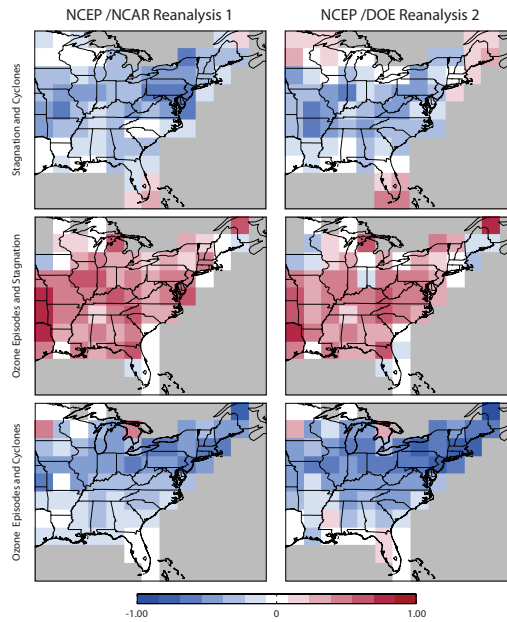


Fig. 7. Interannual correlation coefficients (r) between the summer total numbers of mid-latitude cyclones (1980–2006), stagnation events (1980–1998), and ozone pollution episodes (1980–2006). The data are as described in Sect. 2. Numbers of cyclones and stagnation events are from the NCEP/NCAR Reanalysis 1 (left) and the NCEP/DOE Reanalysis 2 (right).

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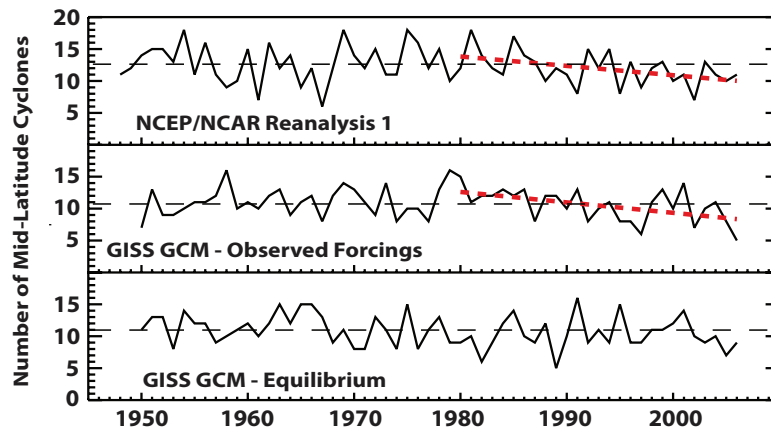


Fig. 8. Time series of the number of June–August mid-latitude cyclones tracking through 40° – 50° N, 70° – 90° W (the southern climatological cyclone track, see Fig. 3) for 1948–2006. Results from the NCEP/NCAR Reanalysis 1 (top) are compared to the GISS GCM 3 simulation including historical radiative forcings (middle), and to a GISS GCM 3 simulation in radiative equilibrium (bottom). The dashed lines show the long-term means for each time series. Red dashed lines show 1980–2006 regressions for the top two panels, where the trends are significant.

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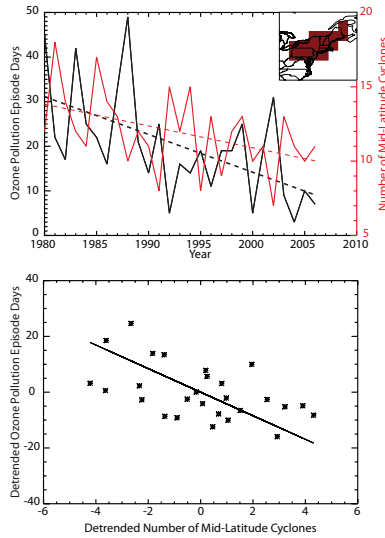


Fig. 9. Long-term trends and correlations of the number of ozone pollution episode days in the Northeast and the number of mid-latitudes cyclones in the southern climatological track. The top panel shows the summer 1980–2006 time series of the number of ozone pollution episode days (black) and the number of mid-latitude cyclones passing through the southern climatological track (red). Ozone pollution episode days are defined by the occurrence of a daily maximum 8-h average ozone concentration exceeding 84 ppb in one of the $2.5^\circ \times 2.5^\circ$ grid squares of the Northeast (inset). Cyclone data are from the NCEP/NCAR Reanalysis 1 and are as in Fig. 4. Dashed lines show the linear trends ($p < 0.01$). The bottom panel shows a scatterplot of the number of ozone pollution episode days (n) vs. the number of mid-latitude cyclones in the southern climatological track (C), for individual years in the 1980–2006 record and after removal of the long-term linear trend. The dashed line is the reduced major axis regression of the detrended data, which indicates a sensitivity $\partial n / \partial C = -4.2$.

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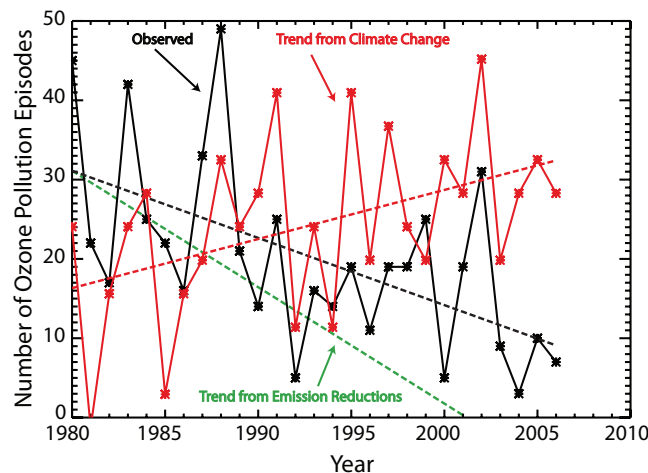


Fig. 10. 1980–2006 time series of the number of ozone pollution episode days in the northeast United States (inset of Fig. 9). Observations are shown in black and are as in Fig. 9. The red line shows the number of ozone pollution episode days predicted from the number of mid-latitude cyclones (Fig. 9) and the dependence $\partial n / \partial C = -4.2$ derived in Sect. 4. Corresponding reduced-major-axis regression lines are shown and represent the observed trend (dn/dt in black) and the trend expected from climate change in the absence of change in anthropogenic emissions ($[dn/dt]_C$, in red). The green dashed line shows the trend expected from reductions in anthropogenic emissions in the absence of climate change, $[dn/dt]_E = dn/dt - [dn/dt]_C$.

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