THE EFFECT OF CLIMATE CHANGE ON THE LOCAL DISPERSION OF AIR POLLUTANTS

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INTRODUCTION

Increasing recognition of ongoing changes to our climate has prompted a range of studies of the impact of air pollution on climate change, and more recently of the local impact of climate change on air pollution (e.g. *AQEG*, 2006). This study investigates the interaction between air pollutant dispersion and climate change. In particular, it considers the effects of climate change on i) the frequencies of dispersion conditions, and ii) the impacts of plumes under specific source-receptor situations.

For a tall industrial stack there are generally two dispersion conditions that deliver high ground level impacts: i) high wind speeds that suppress plume-rise by 'knock-down' lowering the effective stack height of the source, and ii) unstable convective conditions that cause 'plume-looping' down to ground-level. For a low-level source, on the other hand, high ground-level impacts are generally delivered by stable low-wind-speed conditions. This study investigates how the occurrence of these high ground-level peak impact conditions may be affected by changes in dispersion climate. For this purpose we consider two aspects of dispersion from industrial plants. Firstly, we consider changes in dispersion climate between two climatically contrasting periods, and secondly, we consider how these changes will alter impacts for specific source-receptor geometries.

We use a new tool, the 'dispersion calendar' to summarise the frequencies of different dispersion conditions under a given climatic regime. The calendar uses hourly data on observed variables related to dispersion (time of day, time of year, wind speed and cloud cover) which are summarised into 24 time-divisions (4 seasonal and 6 diurnal) and 108 meteorological sub-divisions (9 cloud cover and 12 wind speed) (Figure 1).

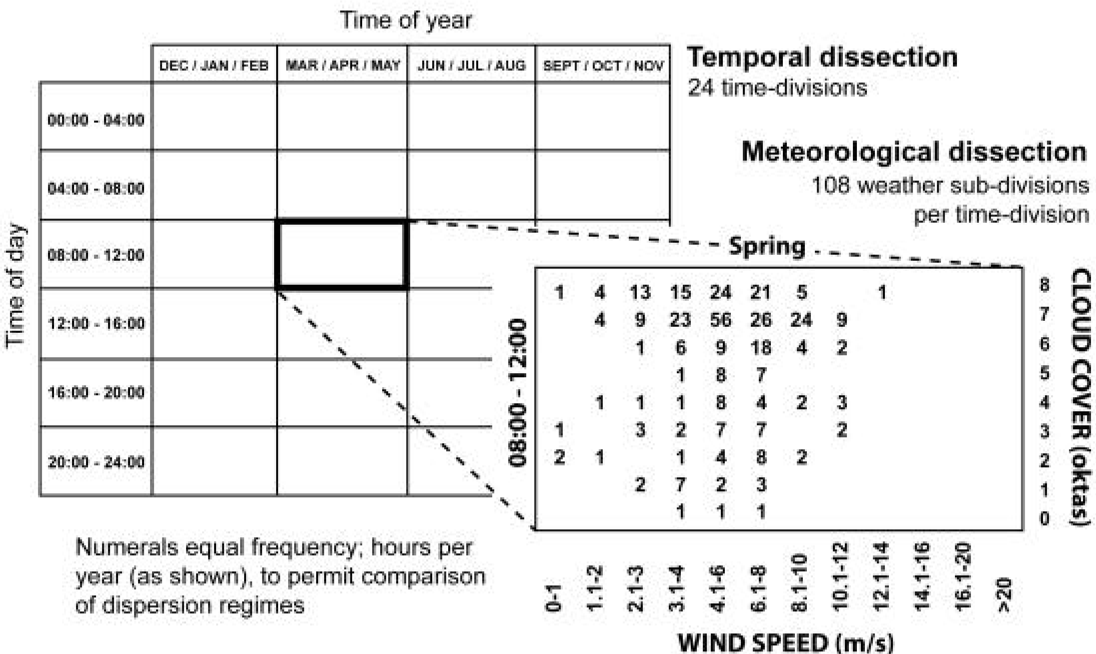

Fig. 1; The Dispersion Calendar

For a given year or climatic regime, the calendar allows us to i) characterise the full range of meteorological conditions experienced into defined dispersion 'sub-divisions', ii) determine the frequency of different dispersion conditions, and thus iii) compare dispersion climates between periods so as to identify changes that are statistically significant relative to inter-annual variability.

To examine the interaction between air quality and climate change, we consider two sources of meteorological data: modelled meteorology from a Global Circulation Model (GCM) (e.g. *Carruthers et al.,* 2006 and *Knowlton et al.,* 2004), and observed meteorology from the historical record. For each source of data, we compare the dispersion climate between two time periods.

For any source-receptor relationship (i.e. a given downwind distance and direction from a source), these dispersion changes affect ground-level air-quality impacts. We therefore perform an ADMS-modelling comparison for a range of source-receptor scenarios, using the dispersion calendar to relate peak impact scenarios to the dispersion conditions that deliver them. This gives us a better understanding of the meteorological conditions that cause high impacts in specific situations, and also of how the frequency of these conditions may alter in future due to climate change.

Modelled Meteorology

We investigate the dispersion climate change of Met Office modelled meteorology for a present and future climate scenario. Four years (1971, 1976, 1981 and 1986) represent the current climate, and a further four years (2071, 2076, 2081 and 2086) represent a future climate under the medium-high A2 emissions scenario. Climate changes were modelled using the coupled atmosphere-ocean model HadCM3, with improved resolution from the atmosphere-only model HadAM3H. Hourly meteorology was downscaled to the nearest grid point to Glasgow using the Regional Climate Model HadRM3H.

Plotting the modelled meteorology in the dispersion calendar shows that sub-divisions experiencing a significant ($p<0.05$) change in frequency (between the 1970s/80 and 2070s/80s) are relatively rare. Across the entire calendar the total number of sub-divisions undergoing significant change at any significance level, is no greater than that we would expect to occur by chance. There is, however, some seasonal biasing towards a greater frequency of significant changes in summer months. These changes represent a decrease during daytime of high cloud cover/moderate wind speed conditions, and is reflected by a statistically significant increase in the frequency of convective (Pasquill-Gifford class B) conditions. This is consistent with UKCIP predicted changes for summer weather by the 2080's (*Hulme et al.,* 2002). Overall, however, the level of significance of the changes in dispersion climate for these small samples (2 x 4-years) is too low to be able to examine the dispersion climate change in depth.

The dispersion calendar also highlights further limitations of using modelled meteorology for dispersion climate change studies. By comparing the frequency of hours occurring under all cloud cover conditions for 1971 (observed meteorology versus modelled meteorology), the unrealistic nature of cloud cover conditions becomes apparent (Table 1). It can be seen that the modelled meteorology is biased towards high cloud cover conditions and clear skies, with very few hours occurring with approximately half covered skies.

Table 1. Comparison of observed and modelled cloud cover conditions for 1971

Cloud cover (oktas)	0	1	2	3	4	5	6	7	8
Observed (hours)	247	740	415	385	325	446	792	2691	2671
Observed (% of yr)	3	8	5	4	4	5	9	31	31
Modelled (hours)	1500	75	57	3	6	9	1776	1023	4143
Modelled (% of yr)	17	1	1	<0	<0	<0	21	12	48

Observed Meteorology

Given the limited length of available modelled time series, the unrealistic simulation of cloud cover and the high uncertainty of future wind projections between different GCM's (*Pryor et al.,* 2005), we investigate the potential for using a long observed meteorological record as an alternative approach to examining the effects of climate change on dispersion.

Our approach has been to look for periods in the historical record when the climate has varied from the longer-term average, on the assumption that these periods may contain features of a future climate after alteration by greenhouse gases. In particular, we have examined the past 50 years because this is comparable to the lifetime of some major industrial plants. Bearing in mind the importance for ground-level impacts of high wind speed 'knock-down', convective 'plume-looping' and stable low wind speed conditions, we have selected decadal periods based upon i) hotter/cooler summers and a greater incidence of convective conditions, and ii) increased/decreased winter storminess and greater/lesser frequency of westerly winds. This is also consistent with UKCIP projections for our climate by the 2080's. We use Central England Temperature (CET) anomalies and the winter North Atlantic Oscillation (NAO) Index to select two climatically contrasting periods.

In contrast to the modelled data for 4-year periods, comparison of two decades of dispersion climate from the observed record (1962-71 v. 1997-06) shows that a relatively large number of sub-divisions in the dispersion calendar underwent significant change. At 95% significance ($p<0.05$), on average, 27% of sub-divisions undergo significant change; these most commonly occur in spring and summer, and reflect increases in low wind speed dispersion conditions. Throughout the year there are also significant increases in unstable convective conditions (Pasquill-Gifford classes B and C).

ADMS-Urban Dispersion Modelling

Using these two decades of observed meteorology, we examine the impact of dispersion change on the spatially variable maxima of ground-level ADMS modelled concentrations. Sulphur dioxide is emitted from a typical coal-fired power station with a 200m stack, in line with a typical diurnal and seasonal cycle of power generation at an average rate of 1400g/s. The gases are emitted at an exit velocity of 27m/s and at an exit temperature of 130 C. The power station is at the centre of a 32km x 32km grid. The maxima of various percentile statistics at any grid location, approximating the SO_2 National Air Quality Standards are investigated. As shown in Table 2, there is a significant change (relative to inter-annual variability) in the '10-year average' of spatial maxima of all percentile statistics:

Table 2. 10-year averages of spatially variable maxima of modelled SO_2 concentrations (μgm^{-3}) from a typical coal-fired power station for contrasting dispersion climates 1962-71 and 1997-06.

Statistic	Annual average	99.18th percentile	99.73rd percentile	99.9th percentile
Averaging period	1-hr means	24-hr means	1-hr means	15-min means
1962-1971	0.56	80.02	9.85	45.99
1997-2006	0.75	101.64	11.11	53.81
Change between epoch averages	+ 32%	+ 27%	+13%	+ 17%
Significance of t-test	$p < 0.01$	$p < 0.01$	$p < 0.05$	$p < 0.01$

Because air quality and climate change interactions are highly dependent on location, we are usually more concerned with air quality impacts at specific points, i.e. receptor lying at defined distances and directions from a source. We therefore investigate air quality impacts at a series of receptors along a downwind transect from the power station. Receptors along a transect running east from the source (thus receiving westerly winds) show some significant changes to ground-level concentrations.

In the far-field (10km east of the source), there are significant but moderate increases in the average hourly concentration (3.3μgm^{-3} to 4.0μgm^{-3}) and the 95th percentile of hourly concentrations (25.5μgm^{-3} to 29.6μgm^{-3}). These simple statistics, however, conceal the mechanisms by which changes to dispersion climate affect peak impact scenarios. Unstable dispersion conditions (hourly meteorology characterised as P-G class B) deliver more frequent ground-level impacts in the most recent epoch (1997-06 when compared to 1962-71) and these changes in frequency lead to significantly higher percentile statistics. This reflects a greater incidence of airborne pollutants brought down to ground level by convective turbulence. Neutral dispersion conditions (hourly meteorology characterised by P-G class D) also deliver higher peak ground-level impacts in the most recent epoch. The dispersion calendar shows that peak ground-level concentrations delivered by neutral conditions for this source-receptor scenario are not pure high wind speed cases, but involve a combination of lowered plume rise (due to high wind speed) and convection. In the near field (2km east of the source), there are no significant changes to ground-level concentration modelled at the receptor.

CONCLUSIONS

By developing a methodology to investigate the impact of climate change on the dispersion of air pollutants, we have highlighted current limitations in the availability of high-resolution hourly GCM data. The eight years we examined are only a small sample of years from longer model runs, however, extracting longer, continuous time series is both time consuming and expensive. To make effective use of GCM data, therefore, dispersion climate change studies require access to longer hourly, high resolution model outputs. Given the uncertainty of the future wind regime between alternative GCM's, it would also be useful to compare dispersion climates predicted by different models.

As an alternative to using modelled data, we show that the historical record can be used to isolate meteorological conditions that are predicted to become more frequent in the future (hot, summer convective conditions and a stronger winter pressure gradient). We can thus speculate about future dispersion impacts and also demonstrate a method for analysing changes in dispersion climates. Our results show that the interactions between dispersion climate change and plume impacts are highly geography-specific i.e. they depend substantially on whether the impacted receptor is located in the near- or far-field. We also highlight the importance of 'hybrid' dispersion conditions in delivering peak ground level impacts from a tall stack i.e. a combination of moderate wind-speeds and convective turbulence.

We present a new tool, the dispersion calendar that i) enables us to characterise a year or epoch of meteorology into defined dispersion conditions and thus perform an effective comparison of dispersion regimes, and ii) permits auditable tracking of links between changes in dispersion climate and air quality, enabling us to see the governing mechanisms behind changes to ground-level impacts. This is an advance on previous pictorial methods, which have primarily examined changes to long-term concentration contour plots. While it is recognised that GCM's produce inaccurate amounts of intermediate cloud cover for example, the dispersion calendar can be used to allow us to see the consequence of these limitations for specific-source receptor relationships and air quality management.

The results of this study have implications for the regulation of local air quality under climate change, in particular for the regulation of large releases from tall-stacks. While the dispersion calendar has been used here to investigate the dispersion of inert primary pollutants, it could be extended to reactive and secondary pollutants and to a variety of emission release heights.

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