EPA-2512

Lesley Jantarasami/DC/USEPA/US
12/01/2009 12:28 PM

To William Perkins
cc Mae Thomas
bcc
Subject Re: Fw: mental health reference

Hi Mae,

Here is another one from 2.7 (2008) that should go into Vol 3, Section 3.2.

Thanks,

Lesley


Freud_8847.pdf

William Perkins Mae, Lesley has found some reference... 12/01/2009 12:25:08 PM

From: William Perkins/DC/USEPA/US
To: Mae Thomas <Mae.Thomas@erg.com>
Cc: Lesley Jantarasami/DC/USEPA/US@EPA
Date: 12/01/2009 12:25 PM
Subject: Fw: mental health reference

Mae,

Lesley has found some references on the FTP site today in Section 2.7 that are miscategorized. This is one of them; would it be possible to move to human health? Thank you.

Cheers,

Bill

Bill Perkins
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----- Forwarded by William Perkins/DC/USEPA/US on 12/01/2009 12:24 PM -----

From: Lesley Jantarasami/DC/USEPA/US
To: Jason Samenow/DC/USEPA/US@EPA
Cc: William Perkins/DC/USEPA/US@EPA
Date: 12/01/2009 12:23 PM
Subject: mental health reference

Jason,

Here is the mental health paper I mentioned. Bill - this paper is miscategorized under section 2.7 (2007) on the FTP site. We may want to tell ERG to move into the health section.

[attachment "Weems_150439.pdf" deleted by Lesley Jantarasami/DC/USEPA/US]

Thanks,

Lesley

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Atmospheric Chemistry and Physics

Robust relations between CCN and the vertical evolution of cloud drop size distribution in deep convective clouds

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Abstract. In-situ measurements in convective clouds (up to the freezing level) over the Amazon basin show that smoke from deforestation fires prevents clouds from precipitating until they acquire a vertical development of at least 4 km, compared to only 1–2 km in clean clouds. The average cloud depth required for the onset of warm rain increased by ∼350 m for each additional 100 cloud condensation nuclei per cm^3 at a super-saturation of 0.5% ($CCN_{0.5\%}$). In polluted clouds, the diameter of modal liquid water content grows much slower with cloud depth (at least by a factor of ∼2), due to the large number of droplets that compete for available water and to the suppressed coalescence processes. Contrary to what other studies have suggested, we did not observe this effect to reach saturation at 3000 or more accumulation mode particles per cm^3. The $CCN_{0.5\%}$ concentration was found to be a very good predictor for the cloud depth required for the onset of warm precipitation and other microphysical factors, leaving only a secondary role for the updraft velocities in determining the cloud drop size distributions.

The effective radius of the cloud droplets (r_e) was found to be a quite robust parameter for a given environment and cloud depth, showing only a small effect of partial droplet evaporation from the cloud's mixing with its drier environment. This supports one of the basic assumptions of satellite analysis of cloud microphysical processes: the ability to look at different cloud top heights in the same region and regard their r_e as if they had been measured inside one well developed cloud. The dependence of r_e on the adiabatic fraction decreased higher in the clouds, especially for cleaner conditions, and disappeared at $r_e \geq \sim 10\,\mu$m. We propose that droplet coalescence, which is at its peak when warm rain is formed in the cloud at $r_e = \sim 10\,\mu$m, continues to be significant during the cloud's mixing with the entrained air, cancelling out the decrease in r_e due to evaporation.

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1 Introduction

During every dry season in Amazonia, many thousands of forest- and agricultural fires are set by the land owners and farmers, thus creating the "biomass burning" season. A deforestation rate of about 24 000 km^2 $year^{-1}$ causes the smoke emitted from the fires to cover vast areas. The smoke particles are quite efficient as cloud condensation nuclei (CCN), with 40–60% nucleation activity (CCN/CN ratio) at supersaturation (henceforth SS) of 1% (Andreae et al., 2004). Therefore the smoke and other small aerosols cause the formation of an increased number of small droplets for a given amount of cloud water, as Twomey (1974 and 1977) has suggested. This anthropogenic effect on clouds has already been documented using remote sensing methods (e.g., Coakley et al., 1987; Radke et al., 1989 (both showing ship tracks) and Kaufman and Fraser, 1997), in-situ measurements (e.g., Eagan et al., 1974; Costa et al., 2000 and Andreae et al., 2004) and cloud models (e.g., Khain et al., 2004). The smaller droplets will not coalesce efficiently to form precipitation particles. Rosenfeld (1999), Rosenfeld and Woodley (2003) and Rosenfeld et al. (2002) have shown, using satellite images and radar echoes, that polluted clouds have to develop to heights of more than 6 km in order to precipitate, compared to only 3 km in clean clouds. The change in vertical distribution of the precipitation processes causes changes in latent heat release (Andreae et al., 2004). In addition, the smoke

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both absorbs and scatters sunlight, causing the ground to cool and the smoky layers to heat up, which stabilizes the lower troposphere and can inhibit the formation of new clouds (Koren et al., 2004). These two types of aerosol induced changes (cloud mediated and direct or semi-direct radiative forcings) can transfer the perturbations to much larger scales (Nober et al., 2003). The inadequate knowledge about these processes and the resulting great uncertainty are main reasons for climate models being difficult to reconcile with observations (Kaufman and Fraser, 1997).

This study is based on a deeper analysis of the data collected during the LBA-SMOCC project, which took place in the Amazon basin from 23 September to 18 October 2002. Andreae et al. (2004) discuss the initial results of the LBA-SMOCC experiment. Some of their main findings were as follows:

- Despite different creation mechanisms, CCN efficiency for natural biogenic and manmade pyrogenic cloud-processed aerosols is quite similar (∼70% at 1% SS). Fresh smoke has a slightly lower CCN efficiency (∼50%).
- The sensitivity of the clouds to the sub-cloud aerosol concentration increases with height and cloud vertical development. Therefore the height of precipitation onset is very sensitive to aerosol concentration. Unlike previous results, Andreae et al. (2004) did not find that this sensitivity reaches saturation at a certain aerosol concentration, probably because the pyroclouds that they have measured had stronger updrafts, which could cause greater super-saturations and further nucleation of cloud droplets.
- Although the smoke causes a negative radiative forcing at ground level, and despite the lack of evident differences in thermodynamic profile, the clouds that develop in smoky regions tend to be more vigorous and sometimes produce lightning and hail, which are otherwise scarce in the very clean environments.
- The invigorated deep convective clouds transport aerosols more efficiently from the boundary layer to higher altitudes.
- Smoky clouds can be at least partially responsible for the observed increase in upper tropospheric and stratospheric water content, because of the inhibition of rain at lower altitudes and the invigoration of the clouds that are then more likely to penetrate into the stratosphere (Rosenfeld et al., 2007).

This paper is the outcome of further analysis of this data set. It aims to give better support to some of the aforementioned findings. Moreover, this paper will concentrate on the relations between cloud water content, effective radius and cloud depth in the various aerosol regimes, highlighting and providing insights to some profound physical processes that dominate the evolution of the clouds' drop size distributions.

In Sect. 2 we will provide the background to the field campaign and the instrumentation used, including some problems that we have encountered. Section 3 will show how the vertical change in drop diameter of modal liquid water content (D_L) and the cloud depth required for the onset of warm rain are highly dependent on the pollution regime. Section 4 will show that CCN concentration at 0.5% SS ($CCN_{0.5\%}$) below cloud base can very well represent the important microphysical properties, such as the height for onset of warm rain. The relations obtained are tight, even when not considering cloud base updrafts, for which we have inadequate measurements. In Sect. 5 we will discuss the factors that determine the cloud droplet size distributions, as expressed by the effective radii of the cloud droplets (r_e). Section 6 will present the summary and conclusions.

2 Field campaign and instrumentation

2.1 Field campaign

Our work is based on the data that was collected during LBA-SMOCC (**L**arge-Scale **Bi**osphere-**A**tmosphere Experiment in Amazonia – **Smo**ke, Aerosols, **C**louds, Rainfall, and **C**limate). The field campaign started at the middle of the dry season of 2002, when every day thousands of forest fires were active and released smoke to the boundary layer (BL). It went on until the beginning of the wet season the same year. The project had a ground station near the town of Ji Parana, in the state of Rondonia, where detailed measurements of aerosol physical and chemical properties and meteorological parameters were made. Two research aircraft were performing measurements during a shorter period, from 23 September to 18 October. The aircraft of the Instituto Nacional de Pesquisas Espaciais (INPE) was equipped with instruments for trace gases and aerosol measurements and was flying outside the clouds, and the other aircraft, of the Universidade Estadual do Ceará (UECE), was fitted with instruments for cloud microphysical measurements and also CCN spectra on some occasions. Ji Parana's airfield (10°52′ S 61°51′ W) served as the home base of the two aircraft, and most of the flights were conducted within few hundred km of the town, where the air was polluted for the entire duration of the aircraft campaign due to the fires in the region. In order to compare aerosols and clouds in a clean environment with the clouds in the smoky environment under relatively similar thermodynamic conditions (CAPE of the lower 5km in the range of 0–150 J/Kg), the two planes flew to the western Amazon Basin and the UECE aircraft flew subsequently to northeastern Brazil (off the coast and a little inland) as well. Both regions were not affected by the forest fires, in contrast to the region around Ji Parana (Andreae et al., 2004). In this

paper we present results that were derived primarily from the data collected by the UECE cloud microphysics aircraft.

2.2 Pollution regimes

Since one of the main goals of the project was to examine the effects of biomass burning aerosols on the vertical microphysical development of the clouds, the flights were made in a wide variety of aerosol loadings. Each cloud DSD (drop size distribution) vertical profile was related to the relevant CCN and CN (condensation nuclei) measurements. The closest correspondence of DSD and CCN in space and time was naturally available from the UECE CCN and DSD sensors. The INPE aircraft provided additional CN and CCN measurements in part of the cases, which were considered when the aerosols measurements had been made within 100 km and two hours from the measured clouds. In order to minimize the instrument related variability, only the UECE-measured aerosols are used quantitatively in this study.

Each cloud vertical profile was subjectively attributed to one of five aerosol regimes, quite similar to those suggested by Andreae et al. (2004), using aerosol measurements from both aircraft. We also used the ground aerosol measurement station at Fazenda Nossa Senhora (FNS) for the flights that were done in its vicinity. The flights of 23, 24, and 28 September, as well as 8, 9, 12 and 13 October were made at a distance of up to ∼100 km from FNS. Figure 1 shows $PM_{2.5}$ (particulate matter with diameter smaller than 2.5 μm) levels at FNS using a Tapered Element Oscillating Microbalance instrument ("TEOM" – Patashnick and Rupprecht, 1991, Parikh, 2000). It can be seen that the period of measurement can be divided into three shorter periods regarding the $PM_{2.5}$ levels: before 8 October when $PM_{2.5}$ levels were generally higher than 50 $\mu g\,m^{-3}$, after that and before 31 October when levels were generally around 20 to 40 $\mu g\,m^{-3}$ and afterwards when levels were very low and close to background values. Flights done on and after 8 October in the vicinity of FNS, after the passing of the extensive squall line (Fig. 2) that caused a dramatic reduction in aerosol load (Fig. 1), were therefore attributed to a cleaner regime than flights done before that. Also the Differential Mobility Particle Sizer ("DMPS" – Rissler et al., 2004) that was used during the field campaign to measure aerosol size distributions, provided similar relative changes between the days and showed a high correlation with the TEOM measurements (Rissler et al., 2006).

The aerosol-cloud microphysical regimes that we use here are the same Blue ocean, Green ocean and Pyrocloud regimes as in Andreae et al. (2004), although the measurements of the Pyroclouds are somewhat problematic due to instrumental limits, which will be discussed in Sect. 2.4. The Smoky clouds regime is referred to in this paper as Polluted regime and we also use an additional regime, the Transition regime. This regime includes the flights done either in a transition area between Polluted and Green ocean regimes, or in the

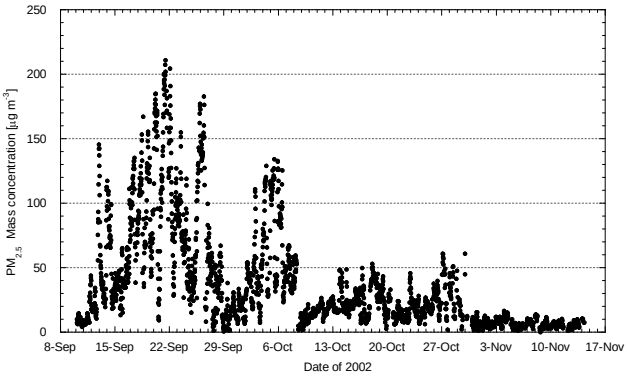

Fig. 1. Half-hour $PM_{2.5}$ mass concentrations at Fazenda Nossa Senhora (FNS) using a TEOM instrument for the whole period of the LBA-SMOCC field experiment. It can be seen that the entire measuring period can be roughly divided into three sub periods, ending at 8 Oct, 30 Oct and 14 Nov 2002, respectively.

period after 8 October near FNS, during the transition time to the wet season. During this time the frequency and areas of rainfall increased. This accelerated the wet deposition of the aerosols and consequently cleaned the lower troposphere, and also caused the farmers to reduce the number of new fires.

The large variability in aerosol loading over the Amazon Basin makes it possible to examine the pollution-induced impacts on clouds while minimizing the synoptic or/and thermodynamic effects, which are also known to influence the microphysical development of the clouds. It can be seen in Fig. 3 that the temperature profiles do not change much from day to day and sounding to sounding, despite large distances between sounding locations and the changing seasons, except for the differences within the BL caused by: 1) the diurnal cycle (Leticia sounding from 5 October was launched at 12:00 UTC (08:00 LT) and shows the remnants of the nocturnal ground inversion) 2) the marine BL with its inversion at the top (Fortaleza sounding of 12:00 UTC 18 October) and 3) the passing of a squall line (as can be seen in Fig. 2 and as is expressed in Fig. 1) a few hours prior to the launch of the sounding from FNS (18:00 UTC 8 October), which caused cooling of the BL. But most important is the narrow range of variation in the convective available potential energy (CAPE) in the lower 5 km of the troposphere as calculated for the different soundings. Table 1 shows that CAPE values are relatively low and vary only between 0 to ∼110 $J\,kg^{-1}$ with no apparent changes between the different pollution regimes. This shows that on none of the days was the lower troposphere unstable enough to favor vigorous updrafts. Therefore we can assume that the variations in thermodynamic conditions encountered during the campaign are not the main cause for the measured variations in the microphysical parameters.

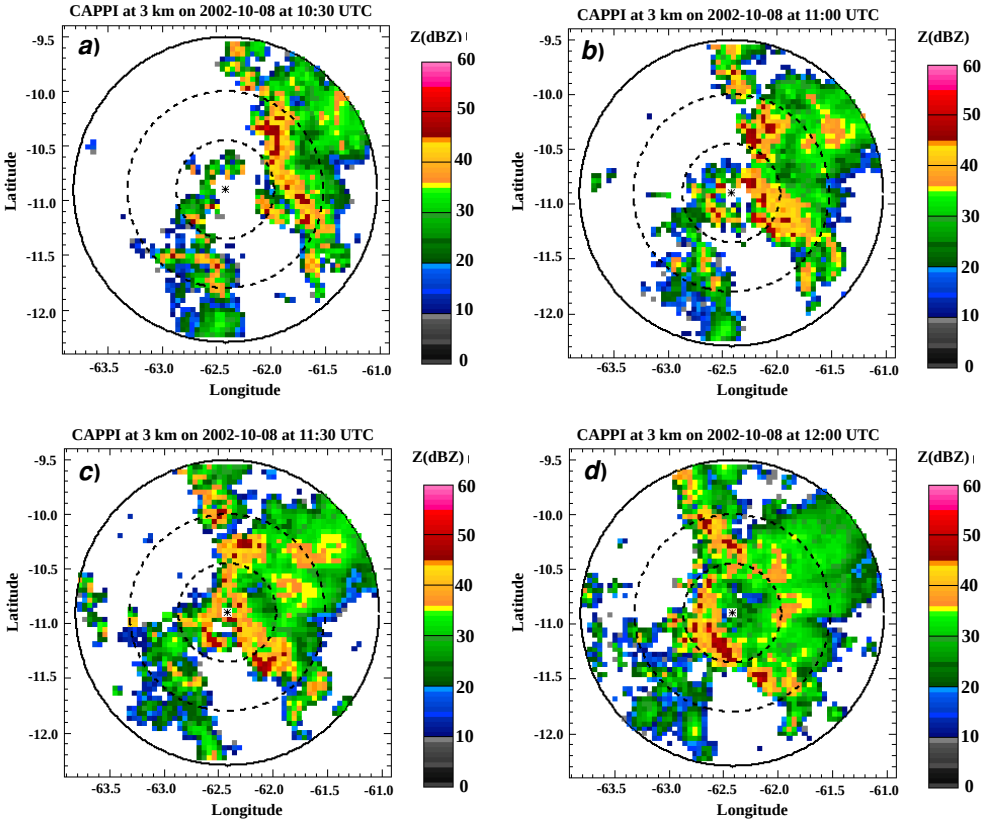

Fig. 2. A sequence of precipitation radar reflectivity images at a constant height of 3 km around FNS (located at the asterisk in the center of each panel) for 30 min increments, starting at 10:30 UTC 8 Oct. 2002 (panels **a** through **d**). It can be seen that a squall line, seen as the high reflectivity areas (yellow and red) located to the east of FNS at 10:30 UTC, is moving westwards and crosses FNS at around 11:30 UTC (panel c). The passing of the squall line is linked to the drastic drop in $PM_{2.5}$ concentration at the same time shown in Fig. 1.

Table 1. A list of the radiosondes that recorded the atmosphere's thermodynamic profile to match (in time and space) the aircraft's CCN measurements. The calculated Convective Available Potential Energy (CAPE) for the lower 5 km (the flights' height limit) of the troposphere is also shown in order to see whether the thermodynamic profiles were comparable.

Date (of 2002)	Time	Location	CAPE (0–5 km) [J/kg]
23 Sep	18:00 UTC	FNS	45
30 Sep	18:00 UTC	FNS	111
5 Oct	12:00 UTC	Leticia	86
8 Oct	18:00 UTC	FNS	0
9 Oct	18:00 UTC	FNS	21
11 Oct	18:00 UTC	FNS	93
12 Oct	18:00 UTC	FNS	53
18 Oct	12:00 UTC	Fortaleza	1

2.3 Instrumentation

The UECE cloud physics aircraft was equipped with the standard aircraft instruments for measuring height/pressure, temperature and flight velocity, and also had a nose weather radar. In addition, it had a GPS (Garmin) for retrieving the location of the plane as well as a dry temperature sensor (EG&G 137-C3-S3), hot wire for measuring cloud water content (CSIRO-King), forward scattering spectrometer probe for measuring cloud droplet spectra (FSSP-100 with DMT's SPP-100 package), 200X and 200Y optical array probes for measuring sizes and concentration of the hydrometeors and a cloud condensation nuclei counter (CCNC UW 83-1).

The principle of the operation of the hot wire instrument is that the cloud droplets change the electrical resistance of the hot wire by cooling it upon collision with it and evaporation. The voltage is proportional to the amount of cloud water. The error of the measurement is less than 15% (King et al., 1985).

The principle of operation, construction and the calibration method of the DH Associates static thermal-gradient CCN counter onboard the UECE cloud physics aircraft is

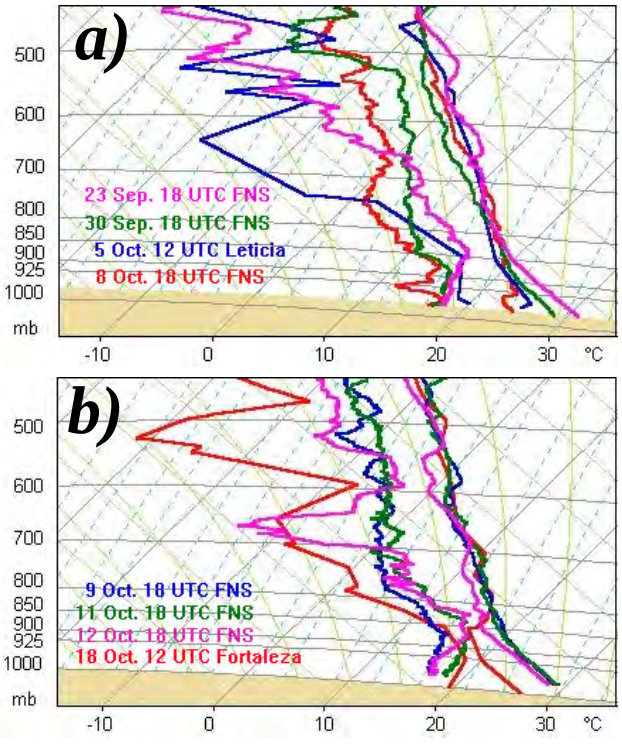

Fig. 3. Temperature (T) and dew point (T_d) profiles (T_d is to the right of T for each profile represented by a different color) on a Tephigram as derived from radiosonde measurements from all dates and near all places where below-cloud CCN measurements were done. Notice the small variance in T above 850 hPa height.

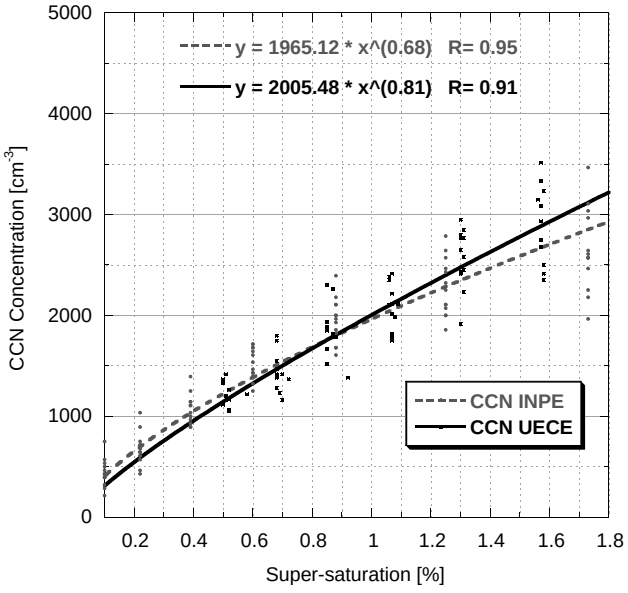

Fig. 4. A comparison of the CCN spectra derived from the two CCN counters on board the airplanes (INPE in grey; UECE in black) while operating in parallel on the ground on 3 Oct 2002 between 15:09 and 16:03 UTC.

thoroughly described in Oliveira and Vali (1995). Another static thermal-gradient CCN chamber was mounted on the INPE aircraft. It was calibrated with monodisperse NaCl and $(NH_4)_2SO_4$ particles in the field (Andreae et al., 2004), and its concentration measurement error is ±30% at the lowest SS of 0.2% and ±10% at SS of 1%. The error of the SS due to temperature fluctuations is up to ±0.05% (Roberts et al., 2001). The two CCN counters were inter-compared on 3 October 2002 by running for more than an hour in parallel next to each other. Figure 4 shows that the derived CCN spectra of both instruments for the parallel measurement are comparable. The absolute concentrations and their dependence on super-saturation are quite alike because they are within the variability of the measurements.

The FSSP-100 measures the size spectrum of the cloud droplets in the range of 2 to 47 μm, based on their scattering of the laser beam that crosses the sampling volume. The size range of the droplets is divided into 30 bins with equal width of 1.5 μm each. By using the droplet spectra one can derive the cloud droplets' effective radius (r_e), the cloud liquid water content (LWC), and other parameters that describe the droplet size spectra.

2.4 Coincident droplets in the FSSP-100

Baumgardner et al. (1985) and Cooper (1988) discuss the instrumental problem in which two or more cloud droplets are present in the sampling volume of the FSSP at the same time, so that before one droplet finishes crossing the laser beam, another one is starting to cross it. As a consequence, the instrument gets a longer signal, which can either cause the rejection of both droplets or be interpreted and counted as one large droplet. In either case, there will be an underestimation in the total number of droplets, which can reach 20% when the measured droplet concentration is about 1000 cm^{-3} (Baumgardner et al., 1985). This problem can also cause an artificial widening of the droplet spectrum due to the counting of several smaller droplets as one large (Cooper, 1988).

The existence of this problem implies that the droplets are distributed inhomogeneously within the cloud; otherwise this problem would not exist even in Pyroclouds, which have the largest droplet concentrations (as we will see in this section). This is because the distances between adjacent droplets would have been too large for them to cross the laser beam simultaneously (without a signal reset in between). Trying to predict a measured droplet spectrum from a known spectrum is a statistically and mathematically complex issue, and even more so the inverse calculation of the real size distribution from a measured one. For any measured distribution, there could be many different solutions for the real distributions that may have produced it. Therefore there is a large uncertainty concerning the accuracy of the measured droplet size spectra, especially in Pyroclouds, where this problem is most

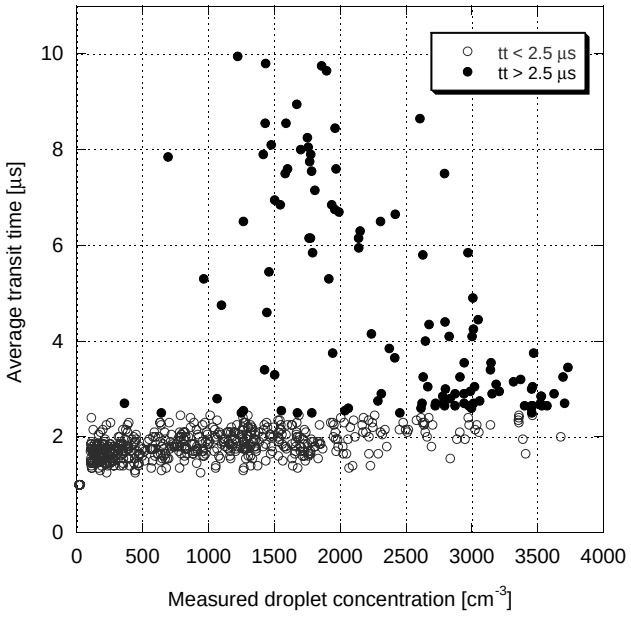

Fig. 5. The average droplet transit time (*tt*) across the laser beam in the FSSP-100 instrument versus the droplet concentration measured by the FSSP while flying in heavily polluted clouds around 19:00 UTC on 4 Oct 2002. Each point represents the average value along half-a-second of flight (∼40 m). Measurements with *tt* larger than 2.5 μs are suspected to be significantly affected by the "coincidence problem" and are marked with bold points, whereas measurements with a smaller *tt* are marked with circles.

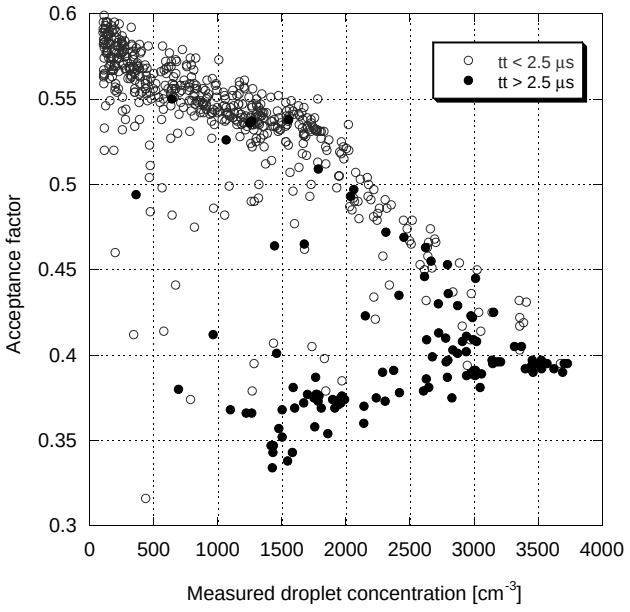

Fig. 6. The acceptance factor (*af* – see text for definition) as reported for each measurement versus the FSSP droplet concentration for the exact same measurements as presented in Fig. 5. Measurements with *tt* larger than 2.5 μs (see Fig. 5) are marked with bold points and show significantly smaller *af* than those with smaller *tt* (in circles).

severe because of the high aerosol concentration and strong updrafts, which have the potential to nucleate a large number of cloud droplets. In addition, the strong turbulence in the Pyroclouds causes greater inhomogeneities in drop concentrations compared to other clouds.

This instrumental problem, and the resulting underestimation in the total droplet number concentration and the artificial widening of their spectra, probably makes the Pyroclouds appear less "continental" (microphysically) compared to what they really are. Any "signal" detected by the FSSP, which will distinguish Pyroclouds from other Polluted regime clouds and show that they are more "continental", would probably be more pronounced in reality. Despite that, we chose to treat with a great deal of caution those measurements that we suspected to be influenced by coincidence, and to not base any strong conclusions upon them. Due to the complexity of this problem, which requires a comprehensive study of its own, and the uncertainty in the correction methods, we chose not to try to correct the measured droplet spectra in this work. We only show here some evidence for the existence of this problem using the FSSP's "housekeeping" variables.

The width of our FSSP's laser beam is 0.2 mm. It cannot take more than 2.5 μs for a small droplet at the average flight speed of 80 m s^{-1} to cross the laser beam along its diameter. The half-second (2 Hz) average transit time for the droplets should be even less than 2.5 μs, since not all droplets cross the laser beam along its diameter. Figure 5 shows average transit times of up to 10 μs, which implies that long sequences of droplets have crossed the laser beam (at least an average of 5 droplets per sequence for a measurement with a transit time of 10 μs) causing a record of long signal by the FSSP. Those measurements with an average transit time of more than 2.5 μs are marked as bold points. All measurements shown in Fig. 5 were done during the second flight leg on 4 October 2002. When examining carefully the exact times of the flight at which most of the long average transit times were recorded, we see that the aircraft was flying inside a Pyrocloud (by using the flight reports). This does not surprise us because it is in the Pyroclouds where we expect to encounter the coincident droplets due to the very high aerosol concentration and strong updrafts, which should nucleate many of them, and where the strong turbulence should clump the droplets.

The acceptance factor, which is shown in Fig. 6, is defined as the ratio between the number of accepted strobes (a strobe is a period of time during which a scattering particle is crossing the laser beam and produces a signal) and the total strobes. The accepted strobes are analyzed and translated into the sizes of the scattering droplets. The rejection of strobes could be either because the strobe was too short, which means that the droplet had crossed the laser beam too

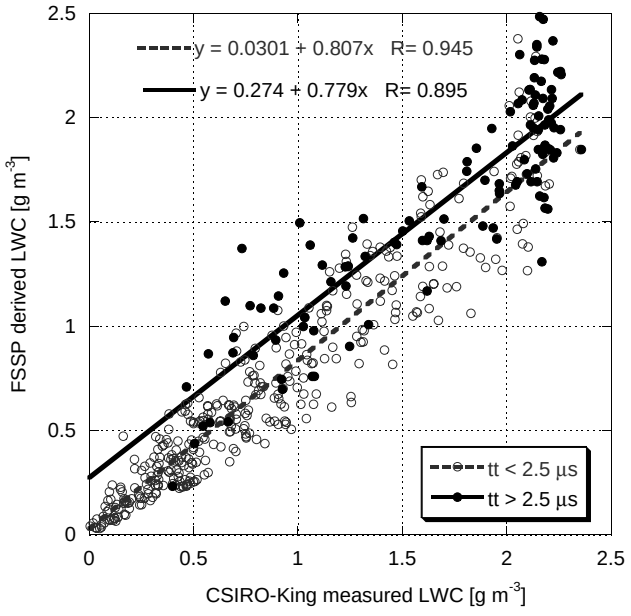

Fig. 7. The relation between FSSP-derived (cloud) Liquid Water Content (*LWC*) and the LWC measured by the hot-wire King probe for the same measurements as presented in Figs. 5 and 6. Again, the bold points represent the measurements with a *tt* larger than 2.5 μs. A linear regression line is shown for each group of measurements (according to their *tt*) suggesting similar slopes (p-value is 0.94 when testing for equal values) but the intercepts are slightly different (p-value is 0.024).

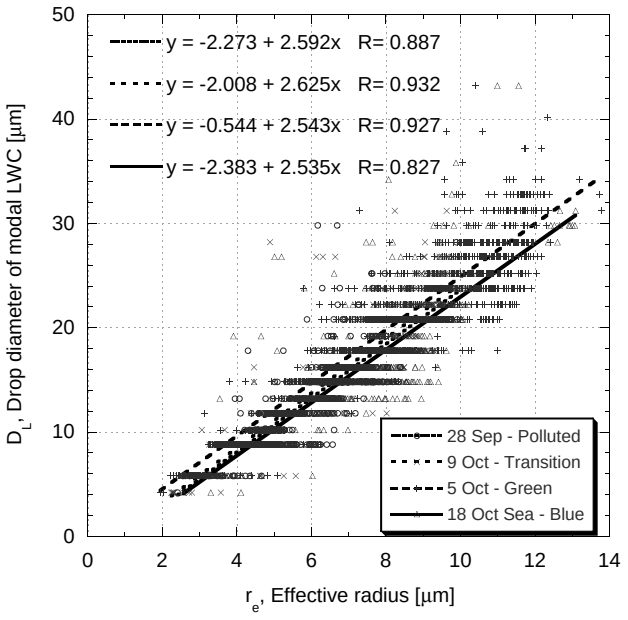

Fig. 8. The relation between the drop diameter of modal LWC (D_L) and the effective radius (r_e) for four representative flight legs in the different pollution regimes. Each point represents half-a-second measurement. It can be seen that there is quite a strong relation between these variables and that this relation is not strongly dependent on the pollution regime. The discrete nature of the D_L values, due to the use of size-bins by the FSSP, is also noticeable.

close to its edge for the FSSP to be able calculate its size correctly, or because the droplet's pass was not in the instrument's depth of field and hence could not be analyzed correctly. According to the FSSP's operating manual, the acceptance factor, which is determined by the geometry of the instrument, should be close to 0.6. Therefore an acceptance factor of 0.4, for example, appears to suggest that we could just add 50% to the measured droplet concentration in order to get the real concentration. However, because each additional rejected strobe below the acceptance factor of ∼0.6 is due to at least two coincident droplets, the real concentration is probably at least double the measured one. Figure 6 shows that many of the coincidence-suspected measurements (with average transit times of more than 2.5 μs, bold points) have an acceptance factor smaller than 0.4 and therefore are probably underestimated at least by a factor of two. The apparent "folding" of the relation between acceptance factor and measured droplet concentration, at about 3500 cm^{-3}, implies that there are actually much greater true concentrations than the maximum of 3500 cm^{-3} for the indicated lower concentrations with low acceptance factor.

The importance of the effect of the artificial broadening of the droplet spectra is shown in Fig. 7. There seems to be quite a good agreement between the CSIRO-King and the FSSP instruments regarding the cloud's LWC, despite the fact that they use completely different methods for obtaining this value. But looking at the linear trend line, we see a shift between the coincidence-suspected measurements and the other measurements. For a given LWC measured by the King hot wire (which is not susceptible to the coincidence problem but on the other hand saturates at ∼2.3 g m^{-3}) the FSSP-derived LWC shows slightly larger values in general, despite the underestimation in the total droplet concentration. The only reasonable explanation for that is that there is an artificial widening of the droplet spectra, which adds more cloud water content than the loss due to the underestimation in droplet number, probably because the LWC is strongly dependent on the size of the droplets (by the power of three), so a small artificial addition of large droplets gives more water mass than the loss of many small droplets.

3 Modal drop size and onset of rain

Andreae et al. (2004) have shown how the size distributions of cloud droplets change with the vertical development of the clouds. They have done so by choosing one representative flight for each of their pollution regimes. Although this kind of presentation shows the whole size spectra, it is difficult to compare the change with height for different flights or/and pollution regimes. In order to facilitate this comparison, we

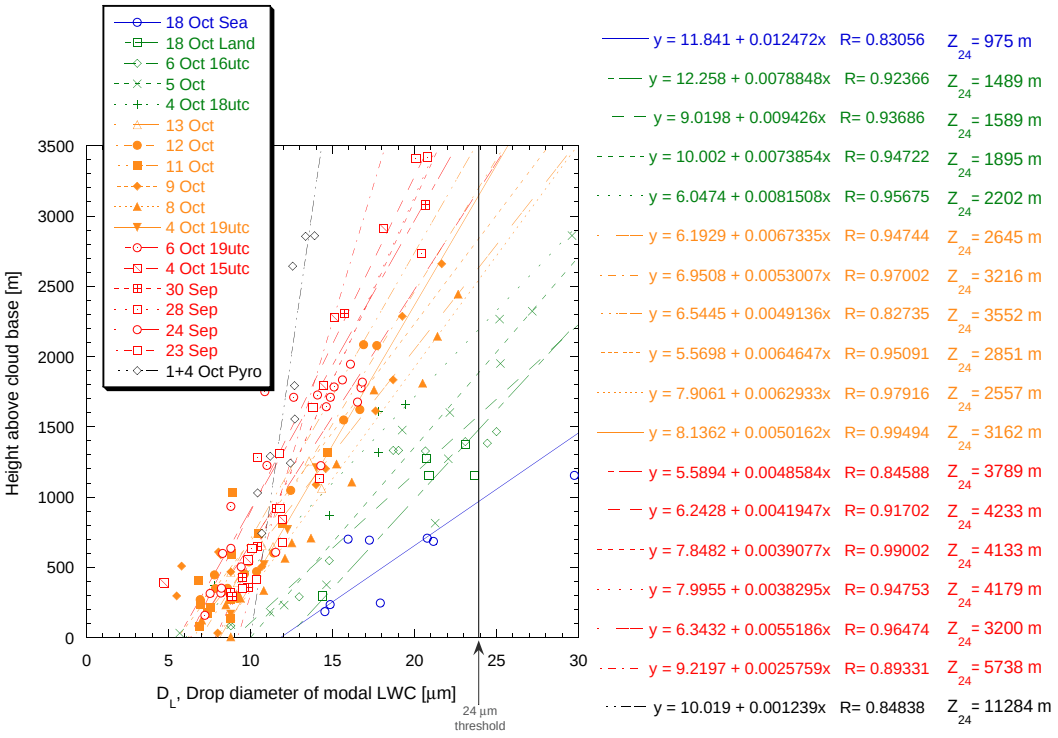

Fig. 9. The growth of D_L with cloud depth for all flights that included a vertical cloud profile of at least 1 km depth. Each point represents the averaged D_L for one horizontal penetration at a certain height. The color scheme is based on the pollution regime in the following way: in blue are Blue Ocean measurements, in green – Green Ocean, in orange – Transition Regime, in red – Polluted Regime and in black – Pyroclouds. Each profile was named after its date and if necessary, its time and additional self-explanatory information. The order of the profiles' appearance in the legend corresponds to the order of the equations of the best-fit linear regressions shown to the right. The 24 μm threshold for the onset of warm rain is marked on the figure. The cloud depth at which D_L crosses this threshold for each profile – Z_{24}, is shown at the extreme right. It can be seen that in the more polluted regimes, the clouds need to have a larger vertical extent in order for D_L to reach the 24 μm warm rain threshold, compared to the clouds in the cleaner regimes.

have chosen here to characterize the whole spectrum by one single parameter: the modal diameter of the droplet size distribution (by mass), D_L. This parameter is strongly correlated with the droplet effective radius (R=0.92), and its relation to r_e is not noticeably dependent on the pollution regime (see Fig. 8). D_L is also less affected by the coincidence problem in comparison to r_e and LWC, which are usually overestimated because of the artificial widening of the spectra (stretching the tail of the distribution does not change its mode), or the total droplet concentration, which is underestimated. Figure 9 shows how D_L changes with cloud depth (to account for the differences in cloud base elevation) for all flights that included a vertical profile of at least 1000 m in depth. The color scheme represents the pollution regime, so that warmer colors depict more polluted environments. The vertical line at a droplet diameter of 24 μm is the threshold D_L for the onset of warm precipitation, as it normally coincided with the appearance of echoes on the aircraft radar and visible impacts of raindrops on the windshield (Andreae et al., 2004). Because the measurements in the Transition regime, Polluted regime and Pyroclouds did not extend high enough in the cloud to reach this threshold, we have extrapolated the (good) linear fit in order to get an estimated value for Z_{24}, which is the cloud depth at which D_L crosses the 24 μm threshold. It can be clearly seen that clouds in the more polluted regimes need to reach larger depths in order to produce rain by warm processes. If we add the average cloud base height (about 1500 m) in the Polluted regime to the cloud depth required for warm rain to start in these clouds (more than 4000 m), we reach heights where the temperature is well below freezing and hence the raindrops produced by coalescence readily freeze and continue to grow as graupel and hail.

The profile of the Pyrocloud in Fig. 9 is only presented for comparison with the rest of the profiles. The values of the parameters shown have a large uncertainty because of the coincidence problem and the fact that the profile was constructed by using two different flights so the profile would be deep enough. Furthermore, it is difficult to determine accurately the cloud base height, and also the updrafts at the Pyroclouds' bases were probably significantly stronger than the updrafts in the other cases, due to the heat released

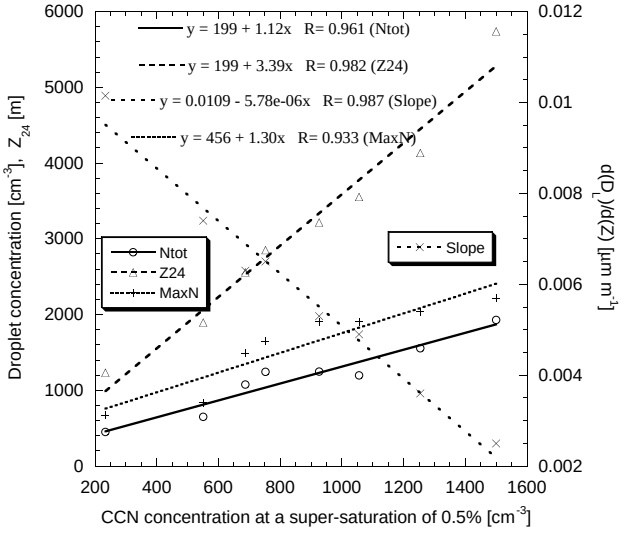

Fig. 10. The relations between CCN concentration at 0.5% SS and four FSSP derived microphysical parameters: N_{tot} – the average droplet concentration, Z_{24} – the required cloud depth for the onset of warm rain, max$N$ – averaged maximum droplet concentration and Slope – the derivative of D_L with height. Each point represents one complete profile, which is based on at least five cloud penetrations at a range of heights of more than 1 km. Clear linear relations between these independent measurements are seen for all variables.

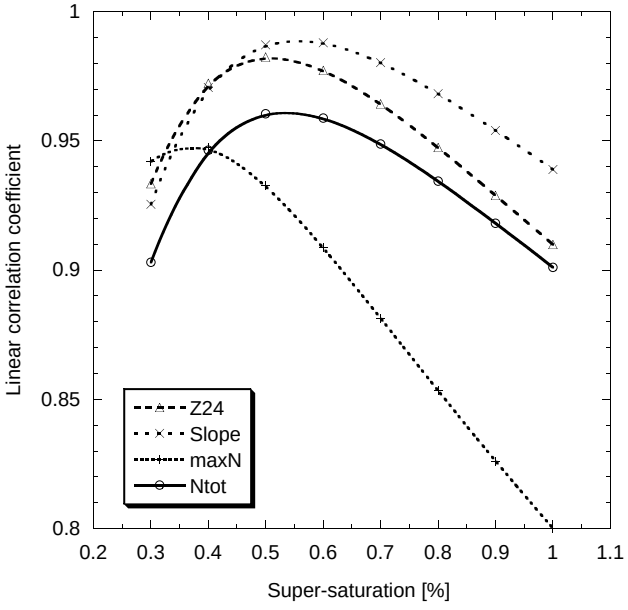

Fig. 11. The linear correlation coefficients between each microphysical parameter shown in Fig. 10 and the interpolated CCN concentration at different super-saturations (SS) that was based on the measurements of the CCNC. It can be seen that the correlation coefficients peak at SS of 0.5–0.6% for all variables but max$N$.

by the fire. The stronger updrafts could have caused higher super-saturations at cloud base, which would have nucleated a larger fraction of the CN into cloud droplets that would have then grown slower by diffusion and coalescence.

4 CCN measurements

The variability in aerosol concentration during the burning season in the BL is quite large due to the heterogeneous spatial distribution of the fires and the scattered rain events, which can reduce the aerosol concentration locally. Therefore it is not very useful to compare cloud microphysical properties and aerosol measurements done on/from the ground or by the other aircraft, unless it was measuring directly below the cloud analyzed microphysically. For the same reason it is difficult to compare the development of a specific cloud to the aerosol load or aerosol optical depth derived from satellite data, which have a high uncertainty over land, rarely match in time and space, and retrieve a value for the whole column of air. The best way to have some independent and more objective measurements of the aerosol properties and their effects on the microphysical development of the clouds in this heterogeneous area is to measure the aerosols below the bases of the penetrated clouds. For this purpose, a CCN counter was mounted on the UECE cloud physics aircraft. It was unfortunately not used for every cloud vertical profile, but we did obtain eight coupled measurements (below cloud and in cloud), which Fig. 10 is based on. In this figure we can see how $\mathrm{CCN}_{0.5\%}$ (derived from the best fit power equation for the whole measured CCN spectra) below cloud base is related to the microphysical properties of the same cloud, derived from the FSSP-100 measurements. The Pyroclouds are not included, but there still is a large span of CCN concentrations.

We have used linear fits in Fig. 10, not necessarily because of physical principles, but because it is the simplest model and still it shows a surprisingly good fit for all variables. The SS value of 0.5% was used because it was in the range of all measurements so that no extrapolation was needed, and because it is a typical value of SS near cloud base. This is evident by the observation that the average droplet concentrations that were measured (N_{tot}) are quite similar to the CCN concentration at that SS. Figure 11 also supports this choice by showing that the strength of the linear relations of CCN concentrations with all the variables shown in Fig. 10 indeed peaks at around SS=0.5%.

The deviations from the relation shown between $\mathrm{CCN}_{0.5\%}$ and average droplet concentration (Fig. 10) can be, among other things, the consequence of slightly different SS at the cloud bases. But the finding that the variance in Z_{24} is slightly better explained by $\mathrm{CCN}_{0.5\%}$ than by average droplet concentration (96.5% compared to 94.4%, the latter not shown here), which should already take the differences in the updrafts into account, suggests that the updrafts near the bases of the different clouds were comparable, as already

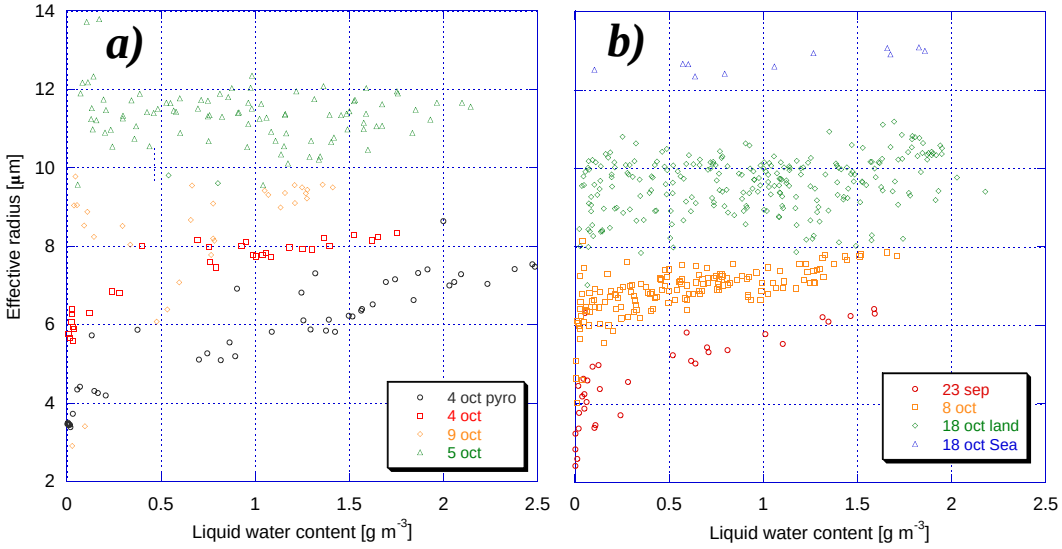

Fig. 12. The dependence of the effective radius (r_e) on the Liquid Water Content (LWC) for the different pollution regimes (each represented by one flight leg) at a nearly constant cloud depth of 2700 m in panel **(a)** and of 1200 m in panel **(b)**. Each point represents one measurement averaged on circa 40 m of horizontal flight. The color scheme is the same as in Fig. 9. r_e shows only a small variance compared to LWC and its value is higher for the cleaner regimes when looking at a nearly constant height.

suggested by the small values of CAPE in the lower 5 km of the troposphere (Table 1). The very strong relation between CCN concentration and Z_{24} suggests that it is not necessary to know the updraft velocities at cloud base (which were not measured objectively) in order to determine the height for the onset of warm precipitation (within $\pm$300 m), at least for the wide variety of conditions that encompass the transition from the polluted to clean environments and from the dry to the wet season in the western Amazon. It will be interesting to see if this relation extends to other seasons or regions.

Figure 10 also shows that the CCN concentration correlates strongly with the derivative of D_L with height and with max$N$, which is defined as the average of the maximum droplet concentrations measured during each penetration within the same profile/cloud. This parameter is more sensitive than N_{tot} to the exact path of the plane in the cloud (whether the plane has passed through the core of the cloud or just nearby) and to the coincidence problem. Moreover, each maximum value is the average along a $\sim$40 m path (because of flight speed and measurement frequency), so the retrieved value does not necessarily correspond to the real maximum value in the same way for each penetration. These reasons could cause the smaller correlation coefficients of max$N$ with CCN concentrations compared to N_{tot}, as can be seen in Fig. 11 for all levels of SS above 0.4%. They can also be a part of the explanation for the shift in the peak of the curve of max$N$ in the same figure. Therefore we consider N_{tot} as more representative of cloud properties than max$N$. The rate of change in D_L with height (Slope in Figs. 10 and 11) is strongly linked to Z_{24} and shows a very high correlation coefficient as well.

5 The effective radius

The cloud droplet effective radius (r_e) is often used as a representative parameter for the droplet size spectra. It is also the only droplet size dependent parameter that can be retrieved from the analysis of satellite data, due to considerations of radiative transfer theory. It can also be derived from the measured droplet spectra. Because of its strong link to cloud mediated radiative processes, we wanted to find out which are the factors that determine the value of r_e and to what extent. It has already been shown that clouds in polluted regions tend to have smaller r_e compared to similar clouds in cleaner environments (e.g., Kaufman and Fraser, 1997; Rosenfeld and Lensky, 1998; Rosenfeld, 2000). It is also known that r_e below the precipitation forming level increases with cloud depth. As the cloud droplets travel to colder temperatures higher in the cloud, the excess water vapor can condense on them and they can also coalesce into larger droplets, both of which will increase r_e. Therefore it is important to separate the cloud depth effects from the aerosol load effects on r_e. Figure 12 does so by presenting r_e (measured at 2 Hz) for all different pollution regimes, at two almost constant cloud depths (2700 m in panel *a* and 1200 m in panel *b*). It can be clearly seen that for a given cloud depth, the cleaner the environment the larger are the effective radii. It can also be seen that for a given environment and height, r_e is very robust, i.e., it does not change much (within a range of $\sim$2 μm, except for Pyroclouds where falsely large effective radii are expected due to coincident droplets in the FSSP) regardless of the measured LWC or adiabatic fraction. The adiabatic fraction (ratio between measured LWC and adiabatic

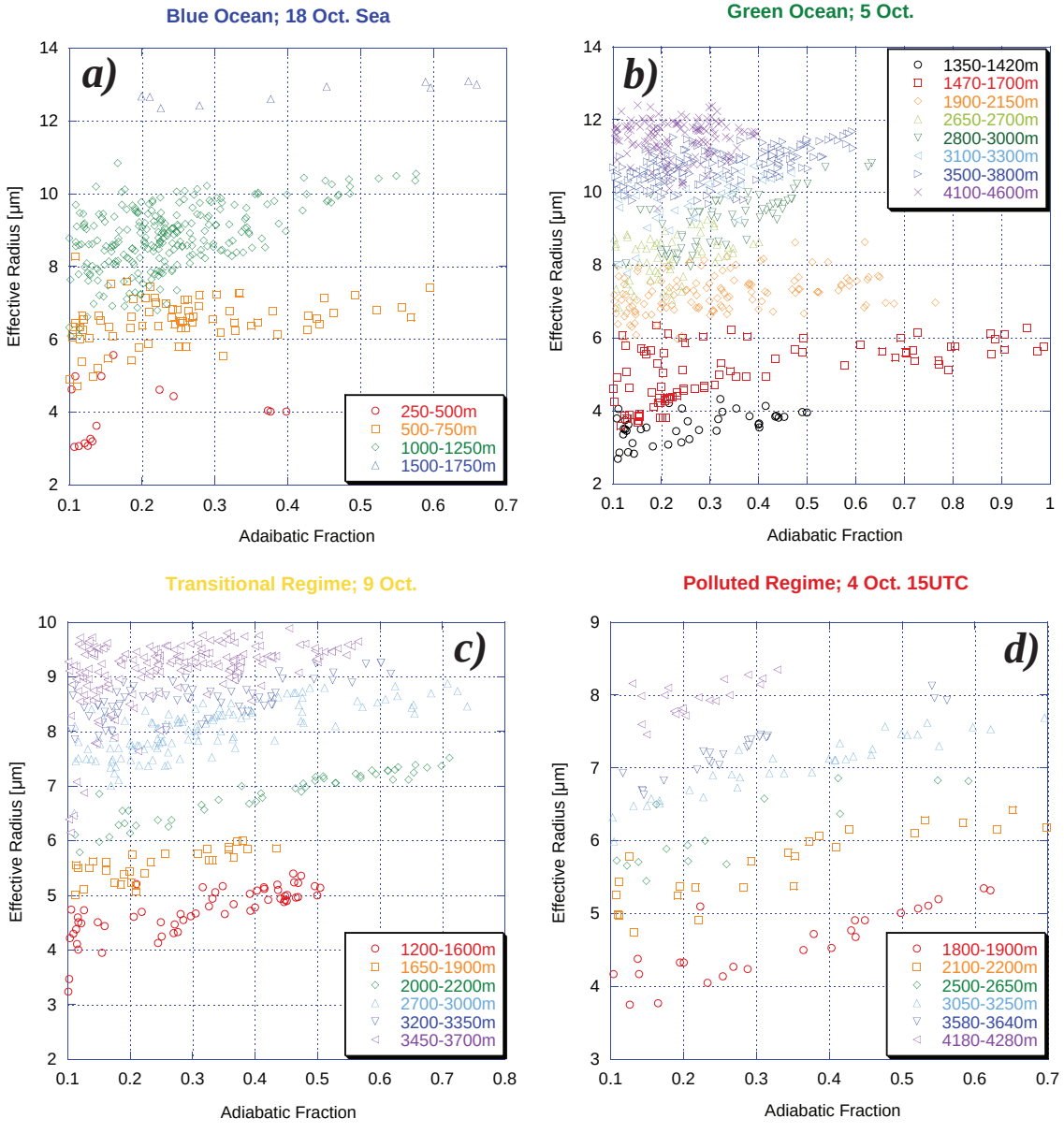

Fig. 13. The dependence of r_e on the adiabatic fraction for all measurements done in the same flight leg, grouped by the different heights (above sea level). Panels **(a)**, **(b)**, **(c)** and **(d)** display the measurements of representative flight legs for the Blue Ocean, Green Ocean, Transition and Polluted regimes, respectively. Each point represents one measurement averaged on circa 40 m of horizontal flight. It can be seen that within each group of heights, r_e is quite robust and also that its value is generally increasing with increasing height, for all regimes.

maximum theoretical water content) is determined by the degree of cloud dilution due to entrainment of droplet-free air from the surroundings of the cloud. This, and the fact that the measurements were not limited to only one cloud in each leg, strengthen one of the basic assumptions on which satellite data analysis relies, which is the ability to look at different cloud tops (at different heights) in the same region and regard their effective radii as if they were measured inside one well developed cloud, revealing the microphysical processes that take place in the cloud (Rosenfeld and Lensky, 1998).

Figure 13 examines each regime separately and shows the changes in r_e with cloud depth and with the liquid water content (LWC) normalized to adiabatic fraction. Each cloud depth interval in Fig. 13 shows a relatively small variability in r_e, as seen in Fig. 12. In addition, the value of r_e is constantly increasing with height for each aerosol regime. Furthermore, careful examination of Figs. 12 and 13 shows that r_e depends less on LWC for larger values of r_e. The dependence vanishes altogether when r_e exceeds ~10 μm, which is equivalent to D_L=24 μm (see Fig. 8), the threshold for onset

of warm rain processes. This threshold for r_e is smaller by 2–4 μm than the threshold reported by Rosenfeld and Gutman (1994) based on the analysis of satellite images, due to the ability to separate the precipitation particles, which increase r_e, from the cloud droplets in in situ measurements.

We suggest that r_e becomes somewhat smaller with reduced LWC for clouds with small drops because such drops grow mainly by condensation. Entrainment of dry air from the surroundings of the cloud causes partial evaporation of the droplets and therefore decreases LWC and r_e. The decrease of r_e with LWC is relatively small because the smaller droplets evaporate first, leaving the largest drops in the cloud.

We suggest the following explanation for the lack of sensitivity of r_e to LWC for clouds with drops that are sufficiently large for significant coalescence, i.e., for $r_e > \sim 10\,\mu$m: The maturation of the cloud is associated with the opposing processes of droplet evaporation and coalescence, which nearly cancel each other leaving the cloud drops with the same r_e with maturation. These effects are evident in Figs. 12 and 13.

As far as we know, this gradual change in the relation between r_e and LWC has not been documented before. Previous studies in clean maritime stratus and stratocumulus clouds have shown that r_e is not dependent on LWC (Brenguier et al., 2000; Gerber, 1996; Gerber et al., 2001). These authors, as well as Baker et al. (1980), explain this finding with the inhomogeneous mixing theory, which claims that droplet evaporation is a very quick process compared to turbulent mixing, so that when undersaturated air is being entrained, it causes instant droplet evaporation. When the air reaches saturation, further mixing will only dilute the cloud and hence cause a decrease in droplet concentration and LWC, but will have no effect on droplet size spectra and r_e. In other words, this theory suggests that the cloud is made up of micro-parcels with a variety of LWC and droplet numbers according to the history of their mixing, but with a rather constant effective radius.

Blyth and Latham (1991) have also observed independence of r_e on LWC, but in clean cumulus clouds in Montana. Although it is possible to notice it in their published results, they do not mention that there seems to be a small r_e dependency on LWC when r_e is smaller than $\sim 10\,\mu$m. On the other hand, Reid et al. (1999) have found a positive correlation between r_e and LWC, such as we have seen here for the smaller values of r_e. Their measurements were, however, confined to "non-precipitating cumulus clouds" and they did not take the cloud depth factor into account, and therefore could not see its effect on the r_e-LWC relation. These findings somewhat contradict the inhomogeneous mixing theory, because r_e is decreasing slightly with decreasing LWC and does not remain constant. Furthermore, Reid et al. (1999) came to the conclusion that the effective radii are not dependent on the level of aerosol loading beyond a threshold of 3000 cm^{-3} (accumulation mode, >100 nm), but only on LWC. We did not see this saturation in the aerosol effect, despite flying in Pyroclouds where aerosol concentrations are larger by an order of magnitude (Andreae et al., 2004). The effective radii measured in Pyroclouds were smaller than in other polluted clouds (Fig. 12a) although there is an overestimation in r_e due to coincidence. The same can also be seen in Fig. 9 by the smaller D_L (which is not significantly affected by coincidence) at greater cloud depths in Pyroclouds.

The apparent reason for Reid et al. (1999) not being able to detect a different r_e-LWC relation between the Pyrocloud ("Fumulus" in their paper) and other, less polluted clouds is that they did not measure high enough in the cloud (their maximum measured LWC was 1.5 g m^{-3} which is typical for a cloud depth of ~1000 m). At small cloud depths it is impossible to unambiguously identify differences in r_e or in D_L between Pyrocloud, Polluted and Transition regimes, because small changes of depth induce large changes in r_e. Just above cloud base even Green ocean clouds have similar values of D_L and r_e as the more polluted clouds at slightly greater depth. It is possible to detect significant differences between the pollution regimes only by measuring at greater cloud depths, as indicated by the divergence of the data with height in Figs. 9 and 14. In addition to that, Fig. 14 also shows how the standard deviation of r_e for all regimes is quite small, despite including all adiabatic fractions, and that the standard deviations of the different regimes do not overlap at cloud depths greater than ~1500 m. Once again, this shows that, for a given height or temperature, r_e is robust enough to be used in remote sensing to give information on aerosol-cloud interactions. Similar robust relations between aircraft measured r_e and height about convective cloud base were documented previously in Indonesia by Rosenfeld and Lensky (1998).

Another potentially important factor that might affect the r_e-LWC relation is the sampling frequency, because the sampling frequency determines the horizontal scale of the measurements. The micro-parcel interactions with each other as well as the turbulence scales may not be resolved due to the inevitable spatial averaging caused by the limited sampling frequency. Therefore higher sampling frequency is needed in order to separate the physical processes effects on r_e-LWC relation from the small scale mixing interactions.

6 Summary and conclusions

In this study we have analyzed in detail the in situ measurements made inside convective clouds during the LBA-SMOCC project in the Amazon Basin in the late dry season 2002. The main goals of this work were 1) to strengthen the conclusions of previous studies regarding the aerosol effects on cloud microphysical development and 2) to determine how r_e, as a representative parameter of the cloud droplet spectra, is affected by other factors.

To accomplish the first goal, each of the 32 flight legs has been assigned to one of five aerosol/cloud microphysical

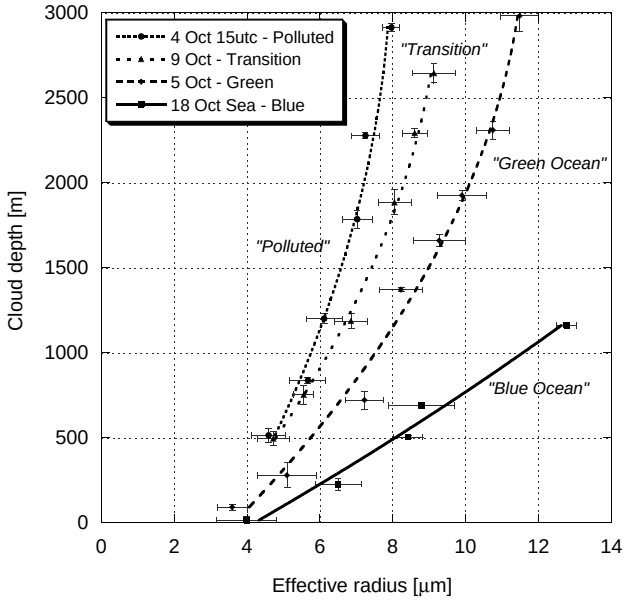

Fig. 14. The growth of r_e with cloud depth for different flight legs from the different regimes. Each point shows the average r_e and the average cloud depth based on the altitude-grouping and the data shown in Fig. 13 for all adiabatic fractions. The standard deviations for both r_e and the cloud depth are shown as well, in order to see whether there are significant differences between the different regimes' r_e profiles and whether their standard deviations overlap. The standard deviations for the cloud depth are quite small because of the horizontal cloud-penetrations at discrete heights. It can be seen that all four profiles start with r_e of $\sim$4 μm, but then there is a divergence further up in the cloud, so that at cloud depths of 1500 m and above there is no overlap in the standard deviations of r_e, despite not using all adiabatic fractions.

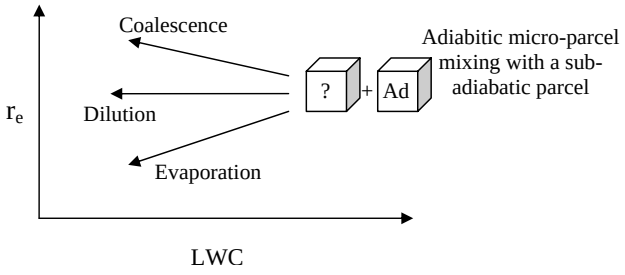

Fig. 15. Schematic illustration of the probable effects of the evaporation, dilution and coalescence processes on the r_e-LWC relation when an adiabatic parcel mixes with another sub-adiabatic parcel. The box marked with "Ad" represents the adiabatic parcel and its location on the r_e-LWC plane is meaningful, while the box marked with a question mark represents the sub-adiabatic parcel and its location on the plane is variable although its LWC has to be smaller than the adiabatic parcel (when there are no falling-from-above precipitation particles). The final location of the newly mixed parcel on the r_e-LWC plane will be determined by the relative importance of the above mentioned processes.

regimes, because in most cases no adequate method for retrieving aerosol data below cloud base was available. Despite a significant coincidence problem in the FSSP-100, especially during Pyrocloud penetrations, significant differences in the rate of D_L growth with cloud depth were observed between the various aerosol regimes.

Because of the slow increase in D_L with cloud depth in the polluted clouds, they did not reach the 24 μm threshold for the onset of warm rain at temperatures above freezing. Therefore, the droplets were too small to rain out at lower levels and could be transported to heights where they were likely to freeze and continue growing as graupel or hail. The relatively small droplets in the polluted cases, which have a smaller chance of freezing, could provide large amounts of supercooled water, which could encourage the formation of hail and lightning as suggested by Andreae et al. (2004). In addition, the separation between Polluted regime and Transition regime showed to be useful because the Transition regime clouds that were fed by the less polluted BL clearly showed a less "continental" microphysical behavior.

Moreover, the CCN concentrations below cloud base, in particular $CCN_{0.5\%}$, were found to be very good predictors for the cloud depth required for onset of warm rain, leaving only a secondary role for the updraft velocity at cloud base in the sampled clouds. On average, the addition of 100 $CCN_{0.5\%}$ cm^{-3} would increase the cloud depth required for the onset of warm rain by $\sim$350 m. It will be interesting to see whether this strong relation extends to other seasons or/and locations.

Regarding the second goal of this study, it was shown that r_e depends first of all on depth above cloud base, and the rate of its growth with the cloud depth depends on the aerosols that feed into the cloud base. The effective droplet radius at cloud base is always very small, but it strongly diverges with cloud depth for the various aerosol regimes.

It was also apparent that for a given height and cloud, r_e is somewhat dependent on the liquid water content, which is limited by the adiabatic water and is controlled by the degree of the cloud's mixing with entrained air. According to the measurements, this dependence seems to be less and less evident as r_e increases, until it is not noticeable when r_e reaches $\sim$10 μm. In previous studies only the "limits" of this dependence have been discussed and not the gradual change that is reported here. Most likely, we were able to detect this gradual change because of the relatively deep vertical profiles that our results are based upon. To explain this gradual change in the dependence of r_e on LWC in deep convective clouds, we propose the following hypothesis, which can also explain the observations reported in previous studies and in different types of clouds:

The maximum LWC is limited by the adiabatic water content (L_{ad}) for any given height. A cloud parcel that has started to rise from cloud base and reached its height without

mixing with a diluted cloud parcel or dry ambient air will have the adiabatic water content and an effective droplet radius depending on the aerosol properties that it was formed from and the conditions at cloud base. Assuming no coalescence or evaporation of the droplets, r_e should be proportional to r_{ad}, which is the "adiabatic radius", and in case of monodisperse droplets it should equal:

$$r_e = r_{ad} = \left(\frac{3}{4}\pi\rho_w\right)^{\frac{1}{3}} \left(\frac{L_{ad}}{N_{ad}}\right)^{\frac{1}{3}} \quad \text{(Blyth and Latham, 1991)}$$

Where ρ_w is the water density and N_{ad} is the number of droplets in the adiabatic parcel.

When this adiabatic parcel eventually mixes with a sub-adiabatic parcel (or with dry ambient air as the extreme case) the LWC will inevitably decrease but the new value of r_e will be determined by the relative weight of three processes: evaporation, dilution and coalescence (see Fig. 15 for illustration). If the entrained parcel is under-saturated, the droplets will partially evaporate and r_e will decrease. Because the smaller droplets evaporate faster, they will evaporate completely and leave a residual population of large drops that decreased only slightly in size. Therefore, r_e is reduced only slightly with decreasing adiabatic fraction (see Fig. 13). If the entrained air is also saturated, there will only be cloud dilution and r_e will remain unchanged. When r_e is sufficiently large to be affected significantly by droplet coalescence ($r_e > \sim 10\,\mu$m), the selective evaporation of the smaller drops along with the continued coalescence of the large drops cancel each other out, leading to stability of r_e with the adiabatic fraction. The effective radius could even increase with maturation and dilution of a cloud with very large droplets and strong coalescence.

According to this hypothesis, a horizontally extended shallow stratocumulus that is not affected much by entrainment of dry environmental air, except for at its top and boundaries will be mostly adiabatic and there will not be large variations in LWC or r_e. If a bubble of dry air is entrained by this cloud, it will quickly become saturated and then will dilute the adiabatic cloud and introduce larger variations in LWC and droplet concentration while leaving r_e practically unchanged. Such a behavior was documented by Brenguier (2000) and Gerber (1996). Their observations as well as the high frequency (1 kHz) measurements done by Gerber et al. (2001) in clean cumulus clouds, contradict the homogeneous mixing theory which expects the cloud to be uniform (and therefore r_e must also remain constant for a given height). The aforementioned studies claimed that the mixing in the clouds is inhomogeneous, i.e., that there are adiabatic micro parcels that are either evaporated instantly and completely, or only diluted upon mixing with entrained air and therefore r_e will remain constant and not be dependent on LWC as long as the droplets do not evaporate completely.

The decrease in r_e with mixing in cumulus clouds, shown in this paper and by Reid et al. (1999), who have measured cumulus clouds with r_e of up to $\sim 9\,\mu$m, implies that the micro parcel theory is too extreme assuming instant evaporation (compared to the time of turbulent mixing), since the observed effect of the mixing is a small reduction in r_e caused by the partial evaporation of the droplets. When coalescence becomes more effective, it starts compensating for the reduction of r_e due to evaporation. When r_e reaches $\sim 10\,\mu$m, coalescence becomes sufficiently active to completely balance the effect of the evaporation on r_e. In cumulus clouds, the dilution effect has an insignificant role compared to the evaporation and the coalescence effects and compared to its role in stratiform clouds. The hypothesis proposed here is potentially very useful, as it can provide a comprehensive and general description of the r_e-LWC relationship, but since it is based on a relatively small number of cases, it is essential to validate it with more cases from different regions, other cloud types and using higher sampling frequencies, in order to learn how the small scale mixing processes affect this relationship.

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EPA-2513

Jason Samenow/DC/USEPA/US
12/01/2009 12:29 PM

To Lesley Jantarasami
cc William Perkins
bcc
Subject Re: mental health reference

we refer to this paper in a response in vol 5.

thanks.

jason

Lesley Jantarasami Jason, Here is the mental health pa... 12/01/2009 12:23:32 PM

From: Lesley Jantarasami/DC/USEPA/US
To: Jason Samenow/DC/USEPA/US@EPA
Cc: William Perkins/DC/USEPA/US@EPA
Date: 12/01/2009 12:23 PM
Subject: mental health reference

Jason,

Here is the mental health paper I mentioned. Bill - this paper is miscategorized under section 2.7 (2007) on the FTP site. We may want to tell ERG to move into the health section.

[attachment "Weems_150439.pdf" deleted by Jason Samenow/DC/USEPA/US]

Thanks,

Lesley

Lesley Jantarasami
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202.343.9929
202.343.2202 (fax)
Jantarasami.Lesley@epa.gov

EPA-2514

Ben DeAngelo/DC/USEPA/US
12/01/2009 12:41 PM

To "Hatfield, Jerry", ljoyce
cc
bcc Lesley Jantarasami
Subject may need to call you on some endangerment items

Jerry, Linda,

In addition to the TSD which you helped review for us we're going through and responding to a voluminous number of public comments on ag and forestry and other sectors. There are a few responses to comments that I think we'd like your input on if you'd be available sometime over the next few days?? We could go over the issues fairly easily by phone. For one (b)(5) Deliberative

We're flexible timewise over the next few days if there are any particular times that might work for you?

Thanks in advance for any help!

-Ben

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deangelo.ben@epa.gov

EPA-2515

Marcus Sarofim/DC/USEPA/US
12/01/2009 12:45 PM

To David Chalmers
cc
bcc
Subject Re: is this in 4.1?

(b)(5) Deliberative

Marcus C. Sarofim, PhD
phone: 202-343-9993
fax: 202-343-2202
1310 L Street 256C
AAAS Science & Technology Policy Fellow
with the EPA Climate Division

David Chalmers comment excerpt: (b)(5) Deliberative 12/01/2009 12:32:50 PM

From: David Chalmers/DC/USEPA/US
To: Marcus Sarofim/DC/USEPA/US@EPA
Date: 12/01/2009 12:32 PM
Subject: is this in 4.1?

comment excerpt: (b)(5) Deliberative

Response: (b)(5) Deliberative .

Carol's comment: Make sure this specific comment is addressed in 4.1

I recall seeing something on this but wanted to double check.

thanks.

David Chalmers
ORISE Fellow
U.S. EPA, Climate Change Division
202.343.9814

EPA-2516

Ben DeAngelo
04/06/2010 04:57 PM

To
cc
bcc
Subject UPLOAD C:\Documents and Settings\owner\My Documents\Endangerment\Response to Public Comments\RTC_draft_Volume_6_Forestry_only 120109 BJD.doc

(b)(5) Deliberative - RTC_draft_Volume_6_Forestry_only 120109 BJD.doc

EPA-2517

Lesley Jantarasami
04/01/2010 03:51 PM

To
cc
bcc
Subject UPLOAD C:\Documents and Settings\ljantara\My Documents\Endangerment\02_Comments and Responses\Vol 6 stuff\RTC_draft_Volume_6_Forestry_only 120109 BJD.doc

(b)(5) Deliberative - RTC_draft_Volume_6_Forestry_only 120109 BJD.doc

EPA-2518

Michael Kolian/DC/USEPA/US
12/01/2009 01:22 PM

To Ben DeAngelo
cc Jeremy Martinich, Mike Kolian, Lesley Jantarasami, Rona Birnbaum
bcc
Subject Re: Revised forestry volume

Terrific!
I will do a sweep and clear some of the track changes while leaving significant comment bubbles in there, unless resolved. Great idea to talk with AG.

Thanks,
Mike

Ben DeAngelo Now turning to Ag. I think one of the lar... 12/01/2009 12:19:22 PM

From: Ben DeAngelo/DC/USEPA/US
To: Mike Kolian <kolian.michael@epa.gov>
Cc: Lesley Jantarasami/DC/USEPA/US@EPA, Rona Birnbaum/DC/USEPA/US@EPA, Jeremy Martinich/DC/USEPA/US@EPA
Date: 12/01/2009 12:19 PM
Subject: Revised forestry volume

Now turning to Ag.

I think one of the larger issues here is to reconcile our statements about [redacted] (b)(5) Deliberative

I also [redacted] (b)(5) Deliberative

-Ben

[attachment "RTC_draft_Volume_6_Forestry_only 120109 BJD.doc" deleted by Michael Kolian/DC/USEPA/US]

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EPA-2519

Lesley Jantarasami/DC/USEPA/US
12/01/2009 02:13 PM

To Jeremy Martinich
cc
bcc
Subject more ecosystem questions

Hey there,

Whenever you are ready to turn to ecosystem stuff, we should probably also talk about (b)(5) Deliberative [redacted]

Thanks,

Lesley

PS-- btw, here are comments i copied and pasted from Michaels re: ecosystems

Michaels (3596.2) – page 74

Amphibian Phenology and Mortality (Page 114, Second and Fourth Bullets)
TSD states on page 114, second bullet, that "Several frog species now initiate breeding calls 10-13 days earlier than a century ago". The primary citation for this is Gibbs and Breisch (2001). Their study was confined to the area around Ithaca, New York. It compared records of the earliest calling dates during the first decade of the 20th century to the data collected in the 1990s. This was a prime example of ignoring important data. The figure below (Figure 46) gives the all the November-June average temperatures, from 1900 through 1999, and decadal averages (data from the National Climatic data center). The periods Gibbs and Breisch studied are highlighted. It is obvious that there are several decades that were quite similar to the 1990s long before any possible anthropogenerated warming. This represents a very uncritical reading of the scientific literature by the TSD.

On page 144, bullet 4, TSD states, "Reduced water depth, related to recent warming, in Oregon lakes has increased exposure of toad eggs…leading to increased mortality…" The primary reference here is Kiesecker et al, (2001). Their argument is: The lake levels are related to El Niño…The more frequent El Niño is, the lower the precipitation…Global warming is increasing El Niño frequency (a highly debatable proposition). Kiesecker et al, (2001) examined the period 1900-1999.
Kiesecker et al, or for that matter, Fields et al., (the IPCC AR4 citation in which this appears) could have actually checked the October-March (El Niño-related) precipitation record, but they did not. Here it is, from the National Climatic Data Center (Figure 47): There is obviously no downward trend in precipitation. In fact, there's nothing unusual about their study period, either. Again, this represents a very uncritical reading of the scientific literature by the TSD.

TSD Butterfly Population Changes (Page 114, Fifth Bullet)

TSD states on Page 115, fifth bullet, that Edith's checkerspot butterfly has become locally extinct in the southern, low elevation portion of its western North American range [Northern Mexico], but has extended its range 90 km north [Southern British Columbia].
The primary citation is Parmesan, 1996, *Nature* . The argument is warming is causing extinction in this non-migratory butterfly in the southern part of its range, and expanding it northward. Again, neither Parmesan nor the TSD seemed to check the related temperature records, available from the Climate Research Unit at the University of East Anglia. The top one is for the region of maximum butterfly extinction in Northern Mexico, the bottom one is from southern British Columbia (Figure 48). Neither shows any net warming trend for the last fifty years of record. They are the records that she would have found when she published her paper in 1996.

EPA-2520

Dina Kruger/DC/USEPA/US
12/01/2009 02:13 PM

To "Vickie Patton"
cc
bcc
Subject Re: Endangerment Determination

Thank you for resending these -

Sent by EPA Wireless E-Mail Services

From: "Vickie Patton" [vpatton@edf.org]
Sent: 12/01/2009 12:56 PM EST
To: Dina Kruger
Cc: "Mark MacLeod" <mmacleod@edf.org>; "Nathaniel Keohane" <nkeohane@edf.org>
Subject: Endangerment Determination

Dear Ms. Kruger,

As you know, EDF strongly supports EPA's proposed endangerment determination on the basis of public health and welfare. Indeed, EDF believes the Agency has a duty to make such determination, in carrying out the Clean Air Act consonant with law and science.

For administrative ease, EDF's comments on the endangerment proposal and related comments on the light-duty proposal are attached.

We also submitted joint comments with the Institute for Policy Integrity on the light-duty proposal that are focused sharply and exclusively on the Social Cost of Carbon. Those too are attached.

Please let us know if you have any questions.

Sincerely yours,
Vickie Patton

<<COMMENTS - FINAL - June 23 - 2009.pdf>> <<EDF Comments - Nov 27 - 2009 - FINAL TRANSMIT.pdf>>
<<EDF-IPI-JointComments11-27-09 FINAL TRANSMIT.pdf>>

EPA-2521

Lesley Jantarasami/DC/USEPA/US
12/01/2009 02:35 PM

To Mike Kolian, Ben DeAngelo
cc
bcc
Subject Re: Revised forestry volume

Mike - I didn't see the supportive forestry comments in there, so can you add the following? Ben, feel free to edit (it's basically the same as the supportive comments in Ag). Thanks!

Comment:
(b)(5) Deliberative

Response:
(b)(5) Deliberative

Ben DeAngelo Now turning to Ag. I think one of the lar... 12/01/2009 12:19:22 PM

From: Ben DeAngelo/DC/USEPA/US
To: Mike Kolian <kolian.michael@epa.gov>
Cc: Lesley Jantarasami/DC/USEPA/US@EPA, Rona Birnbaum/DC/USEPA/US@EPA, Jeremy Martinich/DC/USEPA/US@EPA
Date: 12/01/2009 12:19 PM
Subject: Revised forestry volume

Now turning to Ag.

I think one of the larger issues here is (b)(5) Deliberative

I also (b)(5) Deliberative

-Ben

[attachment "RTC_draft_Volume_6_Forestry_only 120109 BJD.doc" deleted by Lesley Jantarasami/DC/USEPA/US]

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deangelo.ben@epa.gov

EPA-2522

William Perkins/DC/USEPA/US
12/01/2009 02:59 PM

To Rona Birnbaum
cc Lesley Jantarasami
bcc
Subject Volume 8 (Round 2) for your review

Rona,

Enclosed -- I am also bringing a hard copy by for you momentarily. As we discussed, this is significantly different and much longer from what you and Dina saw the first time around from the response to your, her, and Carol's comments, additional comment/response sets that have been added since then, and the relocated Section 8.4 Vulnerable Populations. Thank you.

Cheers,

Bill

(b)(5) Deliberative

RTC draft Volume 8 120109.doc

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(C) (b)(6)

EPA-2523

"Mae Thomas" <Mae.Thomas@erg.com>
12/01/2009 03:32 PM

To Lesley Jantarasami, William Perkins
cc "Mae Thomas"
bcc
Subject Re: Fw: mental health reference

Ok, will do ... move this one and the one in Bill's earlier email.

>>> <Jantarasami.Lesley@epamail.epa.gov> 12/1/2009 12:28 PM >>>
Hi Mae,

Here is another one from 2.7 (2008) that should go into Vol 3, Section 3.2.

Thanks,

Lesley

(See attached file: Freud_8847.pdf)

|------------>
| From: |
|------------>

>----------
|William Perkins/DC/USEPA/US
|

>----------
|------------>
| To: |
|------------>

>----------
|Mae Thomas <Mae.Thomas@erg.com>
|

>----------
|------------>
| Cc: |
|------------>

>----------
|Lesley Jantarasami/DC/USEPA/US@EPA
|

>----------
|------------>

Date:
12/01/2009 12:25 PM
Subject:
Fw: mental health reference

Mae,

Lesley has found some references on the FTP site today in Section 2.7 that are miscategorized. This is one of them; would it be possible to move to human health? Thank you.

Cheers,

Bill

Bill Perkins
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----- Forwarded by William Perkins/DC/USEPA/US on 12/01/2009 12:24 PM -----

From:
Lesley Jantarasami/DC/USEPA/US
To:

>----------
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|Jason Samenow/DC/USEPA/US@EPA
|

>----------
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|---------->
| Cc: |
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>----------
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|William Perkins/DC/USEPA/US@EPA
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| Date: |
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|12/01/2009 12:23 PM
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| Subject: |
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|mental health reference
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Jason,

Here is the mental health paper I mentioned. Bill - this paper is miscategorized under section 2.7 (2007) on the FTP site. We may want to tell ERG to move into the health section.

[attachment "Weems_150439.pdf" deleted by Lesley Jantarasami/DC/USEPA/US]

Thanks,

Lesley

Lesley Jantarasami
US EPA, Climate Change Division

Climate Science & Impacts Branch
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202.343.2202 (fax)
Jantarasami.Lesley@epa.gov

EPA-2524

John Hannon/DC/USEPA/US
12/01/2009 03:37 PM

To Ben DeAngelo
cc Mike Kolian, Rona Birnbaum, Jason Samenow
bcc
Subject Re: AQ inserts for TSD, and use in RTC and possibly Findings

Ben, could you send me the IA? The insert refers to a Table from it.

A quick reaction to the insert:

(b)(5) Deliberative

[redacted]

[redacted]

[redacted]

I still have a lot of questions on this, we should talk..

John Hannon
Office of General Counsel
U.S. Environmental Protection Agency
1200 Pennsylvania Ave. NW (MC 2344A)
Washington, D.C. 20460
Phone (202) 564-5563
Fax (202 564-5603

Ben DeAngelo John, Here are additions we got from... 12/01/2009 11:44:58 AM

From: Ben DeAngelo/DC/USEPA/US
To: John Hannon/DC/USEPA/US@EPA
Cc: Mike Kolian <kolian.michael@epa.gov>, Rona Birnbaum/DC/USEPA/US@EPA
Date: 12/01/2009 11:44 AM
Subject: AQ inserts for TSD, and use in RTC and possibly Findings

John,

Here are additions we got from ORD to better explain results from their underlying report largely in response to your comments on a previous version of the RTC for air quality.

This language is now in the updated RTC on health/air quality you just received from Jason.

-Ben

[attachment "TSD p 90 to 91 Ozone insert.doc" deleted by John Hannon/DC/USEPA/US]

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deangelo.ben@epa.gov

EPA-2525

John Hannon/DC/USEPA/US
12/01/2009 03:38 PM

To Rona Birnbaum
cc Ben DeAngelo, Carol Holmes, David Chalmers, Dina Kruger, Jason Samenow, Lesley Jantarasami, Michael Kolian, Suzanne Kocchi, William Perkins
bcc
Subject Re: The latest Volume 5

This is the e-mail I just sent him on that:

Ben, could you send me the IA? The insert refers to a Table from it.

A quick reaction to the insert:

(b)(5) Deliberative

[redacted]

[redacted]

[redacted]

I still have a lot of questions on this, we should talk..

John Hannon
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U.S. Environmental Protection Agency
1200 Pennsylvania Ave. NW (MC 2344A)
Washington, D.C. 20460
Phone (202) 564-5563
Fax (202 564-5603

Rona Birnbaum hi John, I believe Ben sent you an emai... 12/01/2009 03:16:40 PM

From: Rona Birnbaum/DC/USEPA/US
To: John Hannon/DC/USEPA/US@EPA
Cc: Ben DeAngelo/DC/USEPA/US@EPA, Carol Holmes/DC/USEPA/US@EPA, David Chalmers/DC/USEPA/US@EPA, Dina Kruger/DC/USEPA/US@EPA, Jason Samenow/DC/USEPA/US@EPA, Lesley Jantarasami/DC/USEPA/US@EPA, Michael Kolian/DC/USEPA/US@EPA, Suzanne Kocchi/DC/USEPA/US@EPA, William Perkins/DC/USEPA/US@EPA
Date: 12/01/2009 03:16 PM

Subject: Re: The latest Volume 5

hi John, I believe Ben sent you an email earlier today that pulled that out for you to have a look. see if that helps.

thanks, Rona

John Hannon Since this is not in RLSO, is there a wa... 12/01/2009 03:00:40 PM

From: John Hannon/DC/USEPA/US
To: Jason Samenow/DC/USEPA/US@EPA
Cc: Ben DeAngelo/DC/USEPA/US@EPA, Carol Holmes/DC/USEPA/US@EPA, David Chalmers/DC/USEPA/US@EPA, Dina Kruger/DC/USEPA/US@EPA, Lesley Jantarasami/DC/USEPA/US@EPA, Michael Kolian/DC/USEPA/US@EPA, Rona Birnbaum/DC/USEPA/US@EPA, Suzanne Kocchi/DC/USEPA/US@EPA, William Perkins/DC/USEPA/US@EPA
Date: 12/01/2009 03:00 PM
Subject: Re: The latest Volume 5

Since this is not in RLSO, is there a way to quickly point me to the new ozone stuff?

John Hannon
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Phone (202) 564-5563
Fax (202 564-5603

Jason Samenow We've made quite a few edits to Volu... 12/01/2009 11:03:57 AM

From: Jason Samenow/DC/USEPA/US
To: William Perkins/DC/USEPA/US@EPA, Ben DeAngelo/DC/USEPA/US@EPA, Michael Kolian/DC/USEPA/US@EPA, Dina Kruger/DC/USEPA/US@EPA, John Hannon/DC/USEPA/US@EPA, Rona Birnbaum/DC/USEPA/US@EPA, David Chalmers/DC/USEPA/US@EPA, Rona Birnbaum/DC/USEPA/US@EPA
Cc: Carol Holmes/DC/USEPA/US@EPA, Lesley Jantarasami/DC/USEPA/US@EPA, Suzanne Kocchi/DC/USEPA/US@EPA
Date: 12/01/2009 11:03 AM
Subject: The latest Volume 5

We've made quite a few edits to Volume 5 to respond to John's comments (b)(5) Deliberative [redacted] There are undoubtedly still unresolved issues to work through, but this is getting closer. Comment bubbles remain in the margins where we have issues to address (though it's possible in a few cases we actually addressed the comment but neglected to delete the bubble).

Please find the Volume attached.

Thanks for everyone's collective efforts on working through this challenging, and lengthy volume.

Jason

[attachment "RTC Vol 5 120109.doc" deleted by John Hannon/DC/USEPA/US]

EPA-2526

Lesley Jantarasami
04/01/2010 03:49 PM

To
cc
bcc
Subject UPLOAD C:\Documents and Settings\ljantara\My Documents\Endangerment\02_Comments and Responses\Supportive Comments for Redistrib\Supportive Comments for Vol 6.doc

(b)(5) Deliberative [redacted] - Supportive Comments for Vol 6.doc

EPA-2527

Ben DeAngelo/DC/USEPA/US
12/01/2009 03:56 PM

To John Hannon
cc Carol Holmes, David Chalmers, Dina Kruger, Jason Samenow, Lesley Jantarasami, Michael Kolian, Rona Birnbaum, Suzanne Kocchi, William Perkins
bcc
Subject Re: The latest Volume 5

Here's the underlying IA. Am continuing to work on ag for now.


GCAQ report 4-8-09.pdf

John Hannon This is the e-mail I just sent him on that:... 12/01/2009 03:38:38 PM

From: John Hannon/DC/USEPA/US
To: Rona Birnbaum/DC/USEPA/US@EPA
Cc: Ben DeAngelo/DC/USEPA/US@EPA, Carol Holmes/DC/USEPA/US@EPA, David Chalmers/DC/USEPA/US@EPA, Dina Kruger/DC/USEPA/US@EPA, Jason Samenow/DC/USEPA/US@EPA, Lesley Jantarasami/DC/USEPA/US@EPA, Michael Kolian/DC/USEPA/US@EPA, Suzanne Kocchi/DC/USEPA/US@EPA, William Perkins/DC/USEPA/US@EPA
Date: 12/01/2009 03:38 PM
Subject: Re: The latest Volume 5

This is the e-mail I just sent him on that:

Ben, could you send me the IA? The insert refers to a Table from it.

A quick reaction to the insert:

(b)(5) Deliberative

[redacted]

[redacted]

[redacted]

I still have a lot of questions on this, we should talk..

John Hannon
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U.S. Environmental Protection Agency
1200 Pennsylvania Ave. NW (MC 2344A)
Washington, D.C. 20460
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Fax (202 564-5603

Rona Birnbaum | hi John, I believe Ben sent you an emai... | 12/01/2009 03:16:40 PM

From: Rona Birnbaum/DC/USEPA/US
To: John Hannon/DC/USEPA/US@EPA
Cc: Ben DeAngelo/DC/USEPA/US@EPA, Carol Holmes/DC/USEPA/US@EPA, David Chalmers/DC/USEPA/US@EPA, Dina Kruger/DC/USEPA/US@EPA, Jason Samenow/DC/USEPA/US@EPA, Lesley Jantarasami/DC/USEPA/US@EPA, Michael Kolian/DC/USEPA/US@EPA, Suzanne Kocchi/DC/USEPA/US@EPA, William Perkins/DC/USEPA/US@EPA
Date: 12/01/2009 03:16 PM
Subject: Re: The latest Volume 5

hi John, I believe Ben sent you an email earlier today that pulled that out for you to have a look. see if that helps.

thanks, Rona

John Hannon | Since this is not in RLSO, is there a wa... | 12/01/2009 03:00:40 PM

From: John Hannon/DC/USEPA/US
To: Jason Samenow/DC/USEPA/US@EPA
Cc: Ben DeAngelo/DC/USEPA/US@EPA, Carol Holmes/DC/USEPA/US@EPA, David Chalmers/DC/USEPA/US@EPA, Dina Kruger/DC/USEPA/US@EPA, Lesley Jantarasami/DC/USEPA/US@EPA, Michael Kolian/DC/USEPA/US@EPA, Rona Birnbaum/DC/USEPA/US@EPA, Suzanne Kocchi/DC/USEPA/US@EPA, William Perkins/DC/USEPA/US@EPA
Date: 12/01/2009 03:00 PM
Subject: Re: The latest Volume 5

Since this is not in RLSO, is there a way to quickly point me to the new ozone stuff?

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Jason Samenow | We've made quite a few edits to Volu... | 12/01/2009 11:03:57 AM

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Cc: Carol Holmes/DC/USEPA/US@EPA, Lesley Jantarasami/DC/USEPA/US@EPA, Suzanne Kocchi/DC/USEPA/US@EPA
Date: 12/01/2009 11:03 AM

Subject: The latest Volume 5

We've made quite a few edits to Volume 5 to respond to John's comments (b)(5) Deliberative . There are undoubtedly still unresolved issues to work through, but this is getting closer. Comment bubbles remain in the margins where we have issues to address (though it's possible in a few cases we actually addressed the comment but neglected to delete the bubble).

Please find the Volume attached.

Thanks for everyone's collective efforts on working through this challenging, and lengthy volume.

Jason

[attachment "RTC Vol 5 120109.doc" deleted by John Hannon/DC/USEPA/US]

EPA/600/R-07/094F
April 2009

Assessment of the Impacts of Global Change on Regional U.S. Air Quality: A Synthesis of Climate Change Impacts on Ground-Level Ozone

An Interim Report of the U.S. EPA Global Change Research Program

National Center for Environmental Assessment
Office of Research and Development
U.S. Environmental Protection Agency
Washington, DC 20460

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LIST OF ABBREVIATIONS

AGCM	Atmospheric General Circulation Model
AOGCM	Atmosphere-Ocean General Circulation Model
AQ	air quality
BC	boundary conditions
BEIS	Biogenic Emissions Inventory System
CAA	Clean Air Act
CAM	Community Atmosphere Model
CACM	Caltech Atmospheric Chemistry Mechanism
CICE	The Los Alamos Sea Ice Model
CCM3	Community Climate Model version 3
CCSM	Community Climate System Model
CSIM	Community Sea Ice Model
CLM	Community Land Model
CMAQ	Community Multiscale Air Quality Model
CMIP	Coupled Model Intercomparison Project
CTM	Chemical Transport Model
EC	elemental carbon
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
GCTM	Global Chemical Transport Model
GISS	Goddard Institute for Space Studies
GMAO	Global Modeling and Assimilation Office
HadCM3	Hadley Centre Coupled Model
IC	initial condition
IGSM	Integrated Global System Model
LANL	Los Alamos National Laboratory
LWC	liquid water content
MDA8	Maximum Daily 8-hour Average Ozone Concentration
MM	Mesoscale Model
MM5	Mesoscale Model (Version 5)
MARKAL	MARKet Allocation Model
MOSIS	Meteorology Office Surface Exchange Scheme
MPMPO	Model to Predict the Multiphase Partitioning of Organics
NAAQS	National Ambient Air Quality Standard
NCAR	National Center for Atmospheric Research
NH_4^+	ammonium ion
NO_3^-	nitrate ion
OC	organic carbon
O_3	ozone
OGCM	Oceanic General Circulation Model
PAN	peroxyacetylnitrate
PBL	planetary boundary layer
PCM	Parallel Climate Model

LIST OF ABBREVIATIONS (continued)

PCTM	PCM/CCSM Transition Model
POP	Parallel Ocean Program
RACT	reasonably available control technology
RCM	Regional Climate Model
RCMS	Regional Climate Modeling System
RCTM	Regional Chemical Transport Model
RH	relative humidity
RRF	relative reduction factor
$PM_{2.5}$	particulate matter with aerodynamic diameter below 2.5 μm
SIP	State Implementation Plan
SAPRC	statewide air pollution research center
SMOKE	Sparse Matrix Operator Kernel Emissions
SOA	secondary organic aerosols
SO_2	sulfur dioxide
$SO_4^=$	sulfate ion
SRES	special report on emissions scenarios
SST	sea surface temperature
THC	thermohaline circulation
TKE	turbulent kinetic energy
UKMO	United Kingdom Meteorology Office
VOC	volatile organic compound

FOREWORD

The Global Change Research Program (GCRP) in EPA's Office of Research and Development (ORD) is an assessment-oriented program with primary focus on evaluating the potential consequences of global change—particularly climate change and climate variability—for air and water quality, aquatic ecosystems, and human health in the United States. The program investigates adaptation options to improve society's ability to effectively respond to the risks presented by global change. The program also has begun to evaluate alternative strategies for reducing greenhouse gas emissions and the environmental implications of those strategies.

This initial report, entitled *Assessment of the Impacts of Global Change on Regional U.S. Air Quality: A Synthesis of Climate Change Impacts on Ground-Level Ozone*, was prepared by the GCRP to provide air quality managers and scientists with timely and useful information about the potential effects of climate change on air quality in the United States. It represents an integrated, multidisciplinary research and assessment effort that includes contributions from multiple Laboratories and Centers in ORD, and it was done in partnership with EPA's Office of Air and Radiation (OAR), which is interested in developing a foundation for considering the effects of climate change in the Agency's air quality management programs. Additional contributors included partners in other federal agencies. I would like to thank the many people in ORD, OAR, the Regional Offices, the academic community, and our external review panel for their many contributions.

The GCRP began an initial assessment of the implications of climate change on air quality in 2000, because available scientific evidence suggested that climate and air quality are closely coupled through atmospheric chemical, radiative, and dynamic processes. It was known that meteorology plays an essential role in whether or not a metropolitan area meets the National Ambient Air Quality Standards (NAAQS) set by EPA for pollutants considered harmful to public health and the environment. It was also known that a warming climate will lead to significant changes in regional meteorological patterns. However, it was not known how a changing climate will affect air quality for a given region, and how climate change will affect a region's ability to meet the NAAQS.

The GCRP's long-term climate change/air quality assessment goals therefore are the following:

1. Provide an answer to the basic question, "Is global change something we will have to account for when moving forward with U.S. air quality policy?"
2. Develop research tools and a knowledge base to answer science questions about the potential impacts of global change on regional U.S. air quality.

3. Deliver to the air quality policy and management community an improved understanding of the behavior and complexities of the global change/air quality system as well as the strengths and limitations of the available scientific tools and methods.
4. Provide a foundation for applying these scientific insights and tools to help answer specific policy and management questions.

It is important to ascertain whether climate change should be considered in the formulation of future air quality policy. To do so, we must gain an understanding of the importance of climate change relative to other stressors on air quality (e.g., changes in land-use) and the relative difficulty of coping with all stressors. However, this assessment design called for first providing insights about how air quality may respond to future changes in climate before tackling the additional complexities of incorporating potential future changes in anthropogenic emissions and long-range pollutant transport. This report is therefore an initial assessment that evaluates the effects of climate change alone on air quality across the United States.

The assessment focuses primarily on the impact of climate change out to 2050 on ground-level ozone, which is mainly a summertime pollutant in the United States. Possible changes in "biogenic" emissions (i.e., emissions from natural sources), such as emissions of volatile organic carbon (VOC) from vegetation, were considered. Future assessment reports will focus on other regulated pollutants, including particulate matter (PM) and mercury, as well as on the combined effects of both climate and human-caused emissions changes, to provide a more complete understanding of the range of possible impacts of global change on air quality.

Caution must be exercised in interpreting the results presented here. First, this report does not address the question of whether regulatory standards for particular pollutants (e.g., ozone) should change because of climate change. Rather, the report sheds light on the question of whether climate change will make attainment of any standard—wherever it is set—more difficult. It presents scientific findings that, in combination with other information, will inform policymaking. Second, our understanding of the linkages between climate and air quality is still at an early stage. There remains considerable uncertainty in climate modeling, and our knowledge of certain aspects of atmospheric chemistry are still lacking. With these caveats, this report includes results useful to national and regional air quality planners.

This report represents a significant advancement in our understanding of the possible impacts of climate change on regional air quality in the United States. It is our hope that the information contained in this report will enhance our ability as a nation to protect air quality and human health, even as our climate changes.

Lek Kadeli
Acting Assistant Administrator
Office of Research and Development

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EXECUTIVE SUMMARY

It is increasingly recognized that the science and policy communities need to explore the potential impact of long-term (multi-decadal), global climate change on regional air quality—specifically the possibility that such change may complicate air quality managers' ability to attain their management goals. These concerns are grounded in information derived from observational studies, basic atmospheric chemistry, and modeling of short-term air pollution episodes. For example, these analyses have established the major role that weather patterns play in establishing conditions conducive to ozone (O_3) formation and accumulation, such as abundant sunshine, high temperatures, and stagnant air. It is now well understood that year-to-year variability in summer climate is strongly correlated with the number of days that exceed O_3 air quality standards.

Historically, air pollution has been studied mostly in terms of immediate local and regional concerns, rather than as a global change issue. In 2001, the EPA Office of Research and Development's Global Change Research Program initiated an effort to increase understanding of the multiple complex interactions between long-term global climate change and atmospheric chemistry which have the potential to influence air pollution in the United States.

The overall goal of the assessment effort is to enhance the ability of air quality policy makers and managers to consider global climate change in their decisions through this increased understanding.

A phased approach has been used to systematically achieve progress toward this overall goal. Phase I focused on building coupled modeling systems capable of capturing the range of processes from global climate to regional air quality and applying these systems to study the sensitivity of U.S. air quality to climate change, with a particular emphasis on O_3. Phase I considers the impact of climate change on air quality in isolation, without including the interacting effects of changes in the emissions of pollutants from human systems. Phase II, in progress, focuses on the combined impacts of changing climate and changing human-caused air pollutant emissions. It builds on Phase I by: extending the modeling systems developed under Phase I to explore additional pollutants and processes; investigating more comprehensively the key modeling uncertainties uncovered in Phase I; and integrating changes in climate with the changes in emissions that might result from changes in air quality regulations, population growth and economic development, changes in energy technologies, and land use change.

This report provides a synthesis of the major results from Phase I of the overall assessment. The findings presented here are interim, as Phase II is currently ongoing, and future reports will update and extend our knowledge of the potential impacts of global change on air quality.

Specifically, this report provides a synthesis of the EPA-funded modeling studies that have been carried out to date under Phase I, primarily for O_3. Future interim reports will provide syntheses of additional topics, e.g., particulate matter. These projects have all adapted and combined existing tools from diverse fields, such as global climate models, global chemistry and transport models, regional meteorological models, and regional air quality models, into systems capable of carrying out numerical experiments to explore the sensitivity of U.S. air quality to changes in global climate. These linked modeling systems have simulated nationwide changes in O_3 concentrations, primarily for summertime, as a result of simulated climate change a few decades into the future. The numerical experiments discussed in this report held human-caused emissions of O_3 precursor pollutants constant at present-day levels, but allowed climate-sensitive natural emissions, like volatile organic compounds (VOCs) from vegetation, to vary in response to the simulated changes in climate.

Coupling atmospheric chemical processes and the climate system presents considerable challenges because of the large number of physical, chemical, and biological processes involved, many of which are poorly understood, all interacting in complex ways. The types of modeling systems developed under this assessment permit the detailed exploration of the potential responses of air quality to climate change over the next few decades in a way that would be difficult or impossible with other approaches. For example, they permit the exploration of climate changes well outside of the envelope of historical experience. In addition, they permit the systematic investigation of the multiple competing climate- and weather-related drivers of air quality interactions on the regional scale, which produce aggregate patterns of air quality change.

This effort represents the first systematic attempt to use linked global-to-regional climate and air quality modeling systems from multiple research groups to jointly investigate the regional dimensions of potential climate-induced air quality changes across the United States.

The major findings from this suite of experiments are

First, while these modeling studies cannot tell us what the future will hold, they demonstrate the potential for global climate change to make U.S. air quality management more difficult, and therefore future air quality management decisions should begin to account for the impacts of climate change.

Second, the science of modeling climate and atmospheric chemistry for the purposes of understanding the sensitivity of regional air quality to climate change is in its early stages. This effort highlights a number of uncertainties that limit the information that can be provided to support decision-making, as well as what work is needed (some currently underway) to begin addressing these uncertainties.

The synthesis of scientific information in this report supports the scientific community and air quality managers and policy makers by

- Providing an improved understanding of the richness and range of behaviors of the global change-regional air quality system;
- Providing an appreciation for the strengths and limitations of the scientific tools and methods used to develop this improved understanding;
- Creating the foundation for a suite of collaborative activities between the scientific research and air quality policy and management communities to investigate specific air quality policy and management questions.

The two major findings rest on a foundation of a number of more detailed conclusions drawn from the modeling studies. In support of the first major finding

- For every region of the country, at least one (usually multiple) of the modeling groups found that simulated climate change caused increases in summertime O_3 concentrations.
- These climate-induced increases, averaged over the summer season, were in the range of approximately 2-8 parts per billion (ppb) for Maximum Daily 8-hour Average O_3 concentration, a key metric for regulating U.S. air quality.
- The climate sensitivity of O_3 was greatest for the peak pollution episodes that tend to occur over a number of days each summer, resulting in substantially larger increases for these times than for the overall seasonal average.

While the results from the different research groups agreed on the above points, their modeling systems did not necessarily simulate the same regional patterns of climate-induced O_3 changes, with the individual simulations showing regions of little change, or even decreases, in addition to the O_3 increases. This speaks to the second major finding of this report, articulated above, of important modeling uncertainties. Certain regions show greater agreement than others: for example, there is very generally more agreement on the spatial patterns of climate-induced increases for the eastern half of the country than for the West, though parts of the Southeast show some of the strongest disagreements across the modeling groups. These differences in the regional patterns of O_3 change result, in large part, from differences in how the different modeling systems, composed of different combinations of climate models, chemistry models, greenhouse gas scenarios, and number of years modeled, simulated the competing regional influences of changes in key meteorological drivers of air quality, especially the amount of sunlight reaching the surface and near-surface air temperature.

In general, differences between climate simulations tend to be more pronounced at the regional scales considered in this report than at the global scale. This is because of differences across models and simulations in the representation of large-scale circulation patterns that strongly affect regional meteorology, like the mid-latitude storm tracks and the subtropical high pressure systems. In addition, there are differences between models in how they capture small-scale processes, like clouds and precipitation, which also are important for air quality. In the studies discussed in this report, these modeling uncertainties strongly influenced the O_3 simulations, producing much of the difference in regional patterns of change between studies. For example, there were differences across modeling groups in the regions of the country where simulated increases in cloud cover, and hence decreases in the amount of sunlight reaching the surface, partially counteracted the effects of warming temperatures on O_3 concentrations in these regions. This highlights current limitations in our ability to understand regional impacts of global climate change.

The results from the modeling studies discussed in this report clearly show that a complex interplay between multiple meteorological factors drives regional O_3 changes. Simply considering a single variable, such as temperature, may not provide a sufficient basis for determining future air quality risks due to climate change in every region.

Another important impact is that climate change leads to changes in the natural emissions of VOCs., e.g., isoprene from vegetation. All of the modeling groups found climate-induced increases in these biogenic VOC emissions over most of the United States, with especially pronounced increases in the Southeast. However, there are large disagreements across the different groups as to the degree to which these increases affect O_3 concentrations, with some simulations showing large O_3 increases while others show little change. An important factor that helps explain these differences is the differing representation of isoprene nitrate chemistry in the different modeling systems, another key uncertainty in the science.

In addition to the issues discussed above, most of the groups examined the importance of year-to-year variability on their results to some degree. These groups found that the climate-induced differences in O_3 concentrations are roughly the same size as present-day year-to-year variability. This implies that simulated future O_3 change can be strongly affected by the choice of present-day and future years to compare. It also implies that climate change has the potential to push O_3 concentrations in extreme years beyond the envelope of current natural year-to-year variability.

Finally, while this report focuses mainly on summertime results, some of the modeling groups also found climate-induced increases in O_3 concentrations in some regions for the spring and fall, suggesting a possible future extension of the O_3 season that would present additional challenges for air quality managers.

Moving forward, this report has highlighted key areas for improving integrated climate and air quality modeling systems that can deliver improved information to meet evolving climate policy and air quality management decision support needs. These include:

- Using recent advances in global and regional models, parameterizations, and downscaling techniques to build more advanced coupled climate and air quality modeling systems;
- Developing ensembles of multiple modeling systems over many years of simulation to develop more robust results of air quality sensitivity to climate change;
- Carrying out more extensive evaluations of climate models for their ability to represent processes (and timescales) that strongly influence regional air quality, such as regional-scale stagnation events.
- Carrying out more extensive evaluations of atmospheric chemistry models for their ability to represent certain chemical pathways that lead to O_3 climate change sensitivity, such as the chemical fate of isoprene nitrate.

Finally, this report provides a preview of ongoing and upcoming work under Phase II of the overall assessment: exploring the uncertainties discussed above; extending the modeling systems to investigate the climate sensitivity of additional pollutants (i.e., particulate matter and mercury) in greater detail; exploring feedbacks between chemistry and climate; and assessing the integrated effects of changes in climate and changes in emissions of pollutants by changes in human systems, such as population growth and migration, economic development, new regulations, energy use and technology, and land use.

SUMMARY OF POLICY RELEVANT FINDINGS

The recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) states, "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (IPCC, 2007). Directly relevant to EPA's mission to protect human health and the environment is the IPCC finding that, "Future climate change may cause significant air quality degradation by changing the dispersion rate of pollutants, the chemical environment for ozone and aerosol generation and the strength of emissions from the biosphere, fires and dust. The sign and magnitude of these effects are highly uncertain and will vary regionally." Climate change impacts have not yet been explicitly considered in air quality program planning—accounting for them will be a critical challenge for the air quality management system in the coming decades.

In partnership with EPA's Office of Air and Radiation (OAR) and several Regional offices, the EPA's Office of Research and Development (ORD) Global Change Research Program began an assessment effort to increase scientific understanding of the multiple complex interactions between climate and atmospheric chemistry. The ultimate goal of this assessment is to enhance the ability of air quality managers to consider global change in their decisions through improved characterization of the potential impacts of global change on air quality. An integrated framework for the assessment was designed that leveraged the research and development strengths within the EPA, within other agencies, and within the academic research community. This framework calls for first developing insight into the range of possible air quality responses to future climate changes alone (Phase I) before tackling the additional complexities of integrating the effects of potential future changes in anthropogenic emissions and long-range pollutant transport with these climate-only impacts (Phase II). The core approach of the assessment is the development of integrated modeling systems capable of capturing these effects and applying them in simulations to explore the global change-air quality problem.

This interim report provides an update on the progress in this first phase of the assessment. Its primary focus is on the potential changes in U.S. regional air quality due to global climate change alone, including direct meteorological impacts on atmospheric chemistry and transport, and the effect of these meteorological changes on climate-sensitive natural emissions of pollutant precursors. The aim in this phase was to consider the effects of climate change in isolation, without accompanying changes in anthropogenic emissions of precursor pollutants expected to occur over the same timeframe. Future reports will explore the potential impacts when also considering possible changes in future air pollution emissions.

Two "grand challenges" have emerged in the course of developing and conducting this assessment. The first arises from the Global Change Research Program's emphasis on decision support, namely, to provide the best possible scientific basis for understanding potential climate change impacts on air quality and air quality policies in a useful form and a timely manner as one key set of inputs to help managers develop pollution control strategies. The second "grand challenge" is to convey to the scientific research community the knowledge gaps that limit our understanding of the problem and/or create barriers to the use and interpretation of scientific information by decision makers.

The discussion below summarizes information that has emerged from the assessment to date. Most of the discussion centers on topics related to tropospheric ozone (O_3) since our understanding of O_3 is more complete at this time than that of particulate matter (PM). Preliminary findings related to PM are presented where available. Unless otherwise indicated, to isolate the impacts of climate change, all model results discussed are for simulations that assumed no future changes in the anthropogenic emissions of precursor pollutants. Also, unless otherwise indicated, "future" refers to the time period around 2050.

The organization of the rest of this Summary is as follows: In the first sub-section, what has been learned about possible impacts of climate change on O_3 (and PM) concentrations is presented. With this information in hand, in the second sub-section, it is then possible to focus on those meteorological drivers important for air quality and highlight complexities in the interaction between these drivers and pollutant concentrations, such as reinforcing or competing effects of individual drivers. The third sub-section discusses climate change impacts on climate-sensitive natural emissions of pollutant precursors. The fourth and fifth sub-sections discuss important modeling uncertainties, and preliminary sensitivity tests comparing the first-order impacts of climate and anthropogenic emissions changes, respectively, as previews of issues that will receive more attention in the next phase of the assessment.

I. Summary of Impacts on O_3 (and PM) Concentrations

A. *Climate change has the potential to produce significant increases in near-surface O_3 concentrations throughout the United States.*

1. A large number of earlier observation- and model-based studies have demonstrated connections between meteorological variability and O_3 concentrations and exceedances, implying the possibility of climate change leading to increasing O_3 levels in some regions.
2. The new modeling studies discussed in this report show increases in summertime O_3 concentrations over substantial regions of the country as a result of simulated 2050 climate change. These results were obtained under the assumption of anthropogenic emissions of precursor pollutants held constant at present-day levels while allowing

for some changes in climate-sensitive natural emissions. For nearly every region of the country, at least one (usually multiple) of the modeling groups found that climate change caused increases in summertime O_3 concentrations.

3. Where these increases occur, the amount of increase in summertime average Maximum Daily 8-hour Average (MDA8) O_3 concentrations across all the modeling studies tends to fall in the range 2−8 ppb, as illustrated in the figures shown in Section 3.
4. The largest increases in O_3 concentrations in these simulations occur during peak pollution events. (For example, the increases in 95th percentile of MDA8 O_3 tend to be significantly greater than those in summertime-mean MDA8 O_3.)
5. Though in agreement on the above points, the different modeling systems did not necessarily simulate the same regional patterns of climate-induced O_3 changes, with the individual simulations showing some regions of little change, or even decreases, in addition to the O_3 increases.
6. As will be discussed in Sections II and III below, these disagreements in the spatial patterns of future O_3 changes can largely be attributed to the wide variations across simulations in the patterns of changes of key meteorological drivers (e.g., temperature and cloud cover), along with the differing representations of key chemical mechanisms in the various model systems.
7. There is greater agreement across simulations in these O_3 changes for certain regions than for others. For example, there is generally more agreement on the spatial patterns of climate-induced increases for the eastern half of the country than for the West, though parts of the Southeast show some of the strongest disagreements across the modeling groups.
8. A subset of results also suggests that climate change effects on O_3 grow continuously over time, with evidence for significant impacts (in the same direction as described above) emerging as early as the 2020s. For example, the Columbia research group (which simulated only the eastern half of the United States) found significant summertime O_3 increases across broad swathes of the Midwest and Mid-Atlantic by the 2020s, with greater increases by the 2050s and 2080s.

Relevance for air quality policy: These studies suggest that EPA's Office of Air Quality Planning and Standards should begin to consider climate change, for example, in the next update of EPA's ozone modeling guidance, especially for planning horizons in 2020 and beyond. In other words, they may need to account for a "climate penalty" that could influence the amount of controls needed in some locations. Conflicting results among simulations for certain regions of the country suggest that evaluations of the potential effectiveness of future controls in those regions will be particularly sensitive to uncertainties in the modeling systems. The findings also indicate that, where climate-change-induced increases in O_3 do occur, damaging effects on ecosystems, agriculture, and health may be pronounced, due to increases in the frequency of extreme pollution events.

B. ***Climate change has the potential to push O_3 concentrations in extreme years beyond the envelope of current natural year-to-year variability. In addition, it has the potential to lengthen the O_3 season.***

1. Interannual variability in weather conditions plays an important role in determining average O_3 levels and exceedances in a given year. For example, statistical analyses of current O_3 observations show that, for several U.S. cities that have not attained the current O_3 NAAQS, weather-related interannual variability can increase or decrease observed mean O_3 concentrations by as much as 10 ppb from the 25-year (1981−2006) mean.
2. The subset of modeling groups that examined multiple simulation years for both present-day and future climate found that, in many regions, increases in summer O_3 concentrations due to climate change were comparable in magnitude to, or even greater than, simulated present-day interannual variability.
3. Similarly, a subset of the future climate simulations showed that, for parts of the country with a defined summertime O_3 season, climate change expanded its duration into the fall and spring.

Relevance for air quality policy: Multi-year simulations may be necessary to support the development of long-term air quality control strategies, to capture the effects of both natural meteorological variability and climate-induced changes. Air quality managers may also need to plan to extend the season over which they monitor O_3 concentrations and be prepared to issue air quality alerts earlier in the spring and later into the fall.

C. ***Climate change is expected to cause a decrease in O_3 concentrations in remote areas with low ambient NO_x levels.***

1. The global modeling studies described in this report simulate general decreases in O_3 concentrations over remote areas with low NO_x concentrations (e.g., oceans) as a result of climate change. Consistent with current understanding of O_3 chemistry, this is due to increased O_3 destruction in an atmosphere with more water vapor.
2. This decrease is in contrast to the significant climate-related increases for many already-polluted areas.
3. The relative impact of these changes in remote background O_3 on simulated U.S. O_3 concentrations is unclear. One potential influence pathway seen in some of the modeling results is an increased mixing of clean air into coastal areas, via stronger ocean-land flow combined with the reduced O_3 concentrations over the oceans.

Relevance for air quality policy: Changes in O_3 concentrations as a result of climate change will depend, in part, on whether an area is clean or polluted, and/or on the degree of influence of air masses from adjacent clean or polluted areas. For example, under low NO_x conditions, a reduced atmospheric lifetime for O_3 in the future due to increased humidity may imply reductions in the quantity of O_3 transported downwind.

D. ***The potential impact of climate change on PM is less well understood than that on O_3. Preliminary results from the modeling studies show a range of increases and decreases in PM concentrations in different regions and for different component chemical species in the same region.***

1. Precipitation is a more important primary meteorological driver of PM than of O_3, due to its role in removing PM from the atmosphere (wet deposition). Precipitation is particularly difficult to model and tends to show greater disagreement across simulations than other variables.
2. Aerosol chemical processes, especially those concerning the formation of organic aerosols and aerosol/cloud interactions, are not fully understood and therefore not well characterized in current regional air quality models.
3. In addition, increase in wildfire frequency associated with a warmer climate has the potential to increase PM levels in certain regions, but the relative importance of this effect is not well characterized.
4. Preliminary simulation results suggest that the PM response reflects the combined climate change responses of the individual species that make up PM (e.g., sulfate, nitrate, ammonium, black carbon, organic carbon, etc.). Depending on the region, these individual responses can be in competing directions, producing either increases or decreases in PM (on the order of a few percent).

Relevance for air quality policy: The more limited scientific understanding and greater modeling uncertainties concerning the production and loss of PM highlight the need for future research. Assessing the effects of a changing climate on PM on an airshed-by-airshed basis may be helpful for considering the detailed chemical characteristics of local PM, the possible range of changes in local precipitation, and the potential influence of changing wildfire frequency. An upcoming EPA report that is expected to incorporate new research findings will address the impacts of climate change on PM in more detail.

II. Impacts on Meteorological Variables that Directly Affect O_3 Concentrations

A. *Climate change has the potential to impact a number of meteorological variables important for O_3. Whether changes in these variables lead to increases, decreases, or no change in O_3 concentrations in a given region depends on whether the effects of these individual changes on O_3 act in concert or compete with each other. This discussion of meteorological mechanisms is intended to provide additional detail to the general conclusions summarized in Section I above.*

1. The simulations discussed in this report all show significant future changes in meteorological quantities such as temperature, cloud cover, humidity, precipitation, wind speed and pattern, and mixing depth.
2. However, there is significant variability across simulations in the spatial patterns of these future changes.
3. As noted above in Section I.A, these variations across simulations help explain the disagreements in the spatial patterns of simulated future O_3 changes. Each simulation produces its own unique pattern of changes in these key meteorological drivers. The combined effects of all of these changes in individual O_3 drivers in turn help create the unique pattern of future O_3 changes across regions seen for each simulation.
4. For example, the different simulations provide examples of regions where both temperature increased and surface solar radiation increased (due to a decrease in cloudiness). These regions tended to experience increases in future O_3 concentration.

In contrast, regions where the changes in these variables were in opposite directions tended to have mixed O_3 results.

5. In general, variations in individual meteorological drivers are not independent of each other. This is because these variables are linked through underlying atmospheric processes, and thus there will tend to be consistent variations across groups of variables as a result of specific changes in pressure and cloud patterns. It is through such changes in short-term weather that the effects of long-term climate change on O_3 are expressed.

Relevance for air quality policy: It is the interrelationships between the many meteorological variables important for O_3 that determine O_3 concentrations at a particular time and place. Evaluating the potential influence of climate change on air quality and the potential effectiveness of future control strategies will require accounting for these sometimes complex interactions. These complexities can best be appreciated through the use of integrated modeling systems capable of simulating interactions among drivers in a realistic and self-consistent way. Current modeling uncertainties lead to disagreements about the spatial patterns of future changes in meteorological variables and, hence, the specific regional distributions of future O_3 changes across the United States.

B. ***Global climate change is expected to produce changes in planetary-scale circulation systems, thereby influencing regional weather patterns. These changes have the potential to strongly affect regional O_3 concentrations, since O_3 episodes are driven by synoptic meteorological variability.***

1. Observations suggest that the extratropical storm tracks have moved poleward over the last few decades. A number of recent modeling studies suggest that this trend could continue into the future (IPCC, 2007), resulting in significant changes in winds, precipitation, and temperature patterns in mid-latitudes, with implications for the simulated frequency and duration of synoptic stagnation events and resulting extreme O_3 episodes.

2. Some of the modeling studies discussed in this report simulate increases in the duration and frequency of extreme O_3 events in the Midwest and Northeast that can be directly traced to the weaker frontal systems and decreased frequency of surface cyclone activity due to a poleward storm track shift.

3. There remains some disagreement across models of the effects of climate change on the summertime mid-latitude storm tracks and stagnation, however, as other studies discussed in this report do not seem to simulate these circulation changes as strongly, and/or do not simulate the corresponding O_3 increases.

4. Similarly, differences in simulations of the climate response of other key large-scale circulation patterns, like the Bermuda High off the U.S. east coast, also can produce significant differences in the amount and spatial distribution of simulated future O_3.

Relevance for air quality policy: Changes in large-scale circulation systems can have a significant impact on O_3 throughout the country. For example, understanding and accounting for changes in synoptic stagnation events resulting from large-scale storm track shifts is critical for understanding potential changes in future O_3 concentrations in the northern portion of the United States. At present, modeling uncertainties persist, and

further research is needed. Consideration of historic patterns in local meteorology versus current observations may help determine whether and where changes in stagnation should be addressed in city-level air quality planning.

III. Impacts on Climate-Sensitive Natural Emissions of O_3 Precursors

A. *Climate change has the potential to increase biogenic emissions of O_3 precursors, but significant uncertainties remain about the impact of these emissions changes on O_3 concentrations in a given region. Increases in lightning NO_x production may also be a factor in future O_3 changes. It is important to note that the modeling results discussed in this report do not account for all climate-sensitive natural emissions of chemical precursors, excluding, for example, oceanic dimethyl sulfide and sea-salt, mineral dust, methane from wetlands, and wildfire emissions.*

1. Earlier observational studies suggest that increases in biogenic emissions of volatile organic compounds (VOCs) would occur in many regions as a result of the higher temperatures associated with expected future climate change.
2. The modeling studies discussed in this report generally simulate increases in biogenic VOC emissions over most of the country as a result of climate change, with particularly substantial increases in certain regions, notably the Southeast.
3. However, these biogenic emissions increases do not necessarily correspond with large O_3 concentration increases, depending on the region and modeling system used. One reason for this appears to be because the response of O_3 to changes in biogenic VOC emissions depends strongly on how isoprene chemistry is represented in the models.
4. Globally, an increase in the rate of natural production of NO_x by lightning is expected in a warmer and wetter climate. Some of the simulations discussed here examined this issue and did, in general, see future increases. As the significance of these results for regional U.S. O_3 concentrations is unclear given the research available at this time, these findings are not highlighted in this report.

Relevance for air quality policy: Resolving uncertainties in the response of O_3 to biogenic emissions changes is important to improve the understanding of potential climate change impacts on O_3. For example, the success of regional O_3 control strategies in regions like the southeastern United States may be highly sensitive to this uncertainty—additional anthropogenic emissions controls may need to be considered to offset climate-induced increases in biogenic emissions, but only if these emissions increases will lead to large O_3 increases. A better understanding of the chemical reactions involving isoprene nitrate is critical for resolving this issue. Regional O_3 control strategies in areas where biogenic VOC emissions are projected to increase due to climate change are likely to continue to be NO_x-limited areas and thus continue to respond to NO_x emissions decreases with O_3 concentration decreases. In addition, local- and regional-scale O_3 modeling does not typically consider NO_x production from lightning. Given potential future changes in lightning NO_x emissions, long-term air quality management strategies may need to account for growth in this source as well.

IV. Modeling Uncertainties

A. *Simulated future U.S. regional air quality is highly sensitive to model configuration choices in the integrated global-to-regional climate and air quality modeling systems used in this assessment.*

1. As discussed in Section II above, there are large differences across modeling groups, and/or across different model configurations used by the same group, in the specific spatial patterns of future simulated changes in meteorology that lead to differences in simulated future concentrations of O_3.
2. These differences in simulated meteorology can largely be traced to differences in a number of elements of model system configuration. Key elements include which global climate model (GCM) was used to simulate future global climate change, whether the output from this GCM was "downscaled" to much higher resolution over the United States with a regional climate model (RCM), and which model physical parameterizations were used, for example for representing cumulus convection.
3. Sensitivities of air quality-relevant meteorology to other parameterizations (e.g., for turbulent mixing, radiative transfer, microphysics, and land-surface processes) may also be important but have yet to be examined systematically.
4. The specific techniques used to implement the downscaling of the GCM output with an RCM may also significantly affect the results, but this issue is still to be examined systematically as well.
5. As discussed above, there are also significant sensitivities of simulated O_3 concentrations to uncertainties in the representation of key chemical processes in the models.
6. The choice of future greenhouse gas scenario also affects the future GCM climate simulation, though in 2050, as opposed to the end of the century, the range in greenhouse gas forcing across the various IPCC scenarios used in this assessment is still relatively small.

Relevance for air quality policy: It is important to carefully select and describe the GCM, RCM, model physical parameterizations, and downscaling techniques used as part of any model-based analysis of potential future changes in air quality. Interpretation of the causes of simulated air quality changes will, in general, be highly sensitive to these components. Additional efforts to understand and quantify the uncertainties associated with these components (as planned for Phase II) will aid in the interpretation of results produced by these modeling systems. Furthermore, work is needed on new strategies for incorporating information from climate models into uncertainty analysis while accounting for all sources of uncertainty.

V. Combined Impacts of Climate and Anthropogenic Emissions Changes

A. *Preliminary work suggests that the impacts of climate change on future U.S. regional O_3 concentrations remain significant when also considering possible future anthropogenic O_3 precursor emissions changes. Several major efforts to address the combined impacts are underway and will be the subject of another EPA Global Change Research Program report in 2012.*

1. A number of the modeling teams whose results are discussed in this report also carried out simulations with modified future air pollutant emissions constructed using spatially non-explicit scaling factors generally derived from the assumptions used to formulate the various IPCC greenhouse gas emissions scenarios.
2. These preliminary tests found that the combined effects of climate and anthropogenic precursor emissions changes are highly sensitive to the assumptions about future emissions trajectories.
3. For example, simple scaling of future emissions to match the gross assumptions of the IPCC A1B or B1 Special Report on Emissions Scenarios (SRES) scenario (IPCC, 2000) resulted in substantial reductions of U.S. NO_x emissions in 2050, which in turn resulted in corresponding reductions in simulated future O_3 concentrations. In contrast, using future emissions consistent with the weaker pollutant control assumptions in the "dirtier" A2 or A1Fi scenarios tended to result in higher future O_3 concentrations.
4. The size of the climate change impact on air quality is highly dependent on the emissions levels. In other words, the effects of climate and emissions changes were not, in general, additive.
5. These results highlight the need for emissions scenarios with greater regional detail, consistency between global and regional assumptions, and consistency between greenhouse gases and precursor emissions. Meeting this need is a major focus of Phase II of the assessment effort.

Relevance for air quality policy: While existing air quality controls will likely continue to produce significant benefits, to the extent that climate change may increase O_3 concentrations in some areas and therefore threaten the ability of an area to attain or maintain air quality standards, additional controls (i.e., a climate penalty) may be required. Preliminary results suggest that the magnitudes of additional controls could be significant in certain regions but also that they are highly dependent on detailed assumptions about future emissions. Exploring these assumptions and improving our understanding of the fundamental emissions drivers, as part of Phase II of this assessment, is expected to lead to the creation of improved scenarios of future emissions that in turn will be integrated into the climate and air quality modeling systems to produce more robust estimates of potential climate impacts on control policies.

This is an interim report, and, therefore, these findings should be considered to be preliminary. Future reports will update, refine, and augment the synthesis contained herein.

Finally, it is important to emphasize that this assessment is a science assessment, not a policy assessment. In other words, the primary means by which this assessment will achieve its ultimate goal of enhancing the ability of air quality managers to consider global change in their decisions is through the development of tools and a knowledge base to answer science questions about the potential impacts of global change on air quality. The resulting improved understanding of the behavior and complexities of the system can then provide a basis for a suite of parallel, collaborative activities between the science and policy audiences of this report. Such

activities would be aimed at answering specific air quality management questions and might include, for example, the development of new tools and models, designed with an explicit focus on decision support, that incorporate the new scientific and technical knowledge gained as a result of this assessment. The initiation of such collaborative efforts would represent a significant assessment outcome.

1 INTRODUCTION TO THE PROBLEM

1.1 INTRODUCTION

The recent Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) found that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (IPCC, 2007). The IPCC also found that "Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." Furthermore, of particular importance for the U.S. Environmental Protection Agency's (EPA) mission to protect human health and the environment was the IPCC's finding that "Future climate change may cause significant air quality degradation by changing the dispersion rate of pollutants, the chemical environment for ozone and aerosol generation and the strength of emissions from the biosphere, fires and dust. The sign and magnitude of these effects are highly uncertain and will vary regionally."

The National Research Council (NRC), in 2001, posed the question "To what extent will the U.S. be in control of its own air quality in the coming decades?" noting that "…changing climatic conditions could significantly affect the air quality in some regions of the U.S." (NRC, 2001). The NRC called for the expansion of weather and air quality studies to include "studies of how air quality is affected by long-term climatic changes." To address this concern, the EPA's Office of Research and Development (ORD) Global Change Research Program initiated a research effort to increase our understanding of the multiple complex interactions between climate and atmospheric chemistry. The *ultimate goal* of EPA's air quality assessment is to enhance the ability of air quality managers to consider global change in their decisions through improved characterization of the potential impacts of global change on air quality.

This ultimate goal will be achieved via three distinct assessment sub-goals:

- To develop tools and a knowledge base to answer *science questions* about the impacts of global change on air quality.
- To deliver the *general benefits* to the air quality policy and management community that derive from addressing these science questions, namely, an improved understanding of the behavior and complexities of the global change-air quality system, an appreciation for the strengths and limitations of the scientific tools and methods used to develop this improved understanding, and an answer to the first and most basic "policy" question, "is climate change something we will have to account for when moving forward with U.S. air quality policy?"

- To *set the stage* for determining how to apply these scientific insights and tools to help answer specific, detailed policy and management questions.

This last sub-goal anticipates a separate activity, or set of activities, branching off from this science assessment, that will coalesce around specific air quality decision support needs. These activities might include, for example, developing new tools and models designed explicitly for decision support (rather than primarily for scientific research).

This interim assessment report provides an update on the progress toward these three sub-goals. As will be discussed in more detail in Section 1.4 below, and in Section 2, the assessment design calls for first providing insight into possible air quality responses to future climate changes before tackling the additional complexities of incorporating potential future changes in anthropogenic emissions and long-range pollutant transport. Therefore, its primary focus is on the potential changes in U.S. regional air quality due to global climate change alone, including direct meteorological impacts on atmospheric chemistry and transport, and the effect of these meteorological changes on climate-sensitive natural emissions of pollutant precursors. As such, this interim report cannot fully address questions related to the importance of changing future anthropogenic emissions of air pollutants. Meeting this need is a major focus of Phase II of the assessment effort.

The following sub-sections will present the major themes that run through this report, provide background on the potential links between climate and air quality that motivate the science questions underlying the assessment research, outline the structure and design of the overall assessment, identify the assessment stakeholders, discuss issues related to handling scientific uncertainty, and present a roadmap to the rest of the report.

1.2 MAJOR THEMES OF THE INTERIM ASSESSMENT REPORT

In the course of conducting this assessment, two “grand challenges” have emerged. The first stems directly from the EPA Global Change Research Program’s emphasis on decision support. The challenge is to provide the best possible scientific basis for understanding the potential range of impacts of climate change on air quality, and air quality policies, in a useful form and a timely manner, as one important set of information inputs to help managers develop appropriate pollution control strategies. Having these improved insights into the way the global change-air quality system works may yield new options for addressing air quality issues or minimize the potential for introducing policies with significant unintended consequences. At the same time, the complexity of the problem, and hence the data, models, and techniques used to address it, means that many unanswered scientific questions and unresolved uncertainties will exist at a given point in the decision-making timeline. These must be understood and accurately

conveyed to policy makers so they have a sense of the levels of confidence underlying individual elements of this scientific understanding.

The second "grand challenge" is to convey to the scientific research community the key knowledge gaps that limit our understanding of the problem and/or create barriers to the use and interpretation of scientific information by decision makers. These range from the sensitivity of regional climate simulations to the parameterizations and methods used in downscaling to how the intricate details of the chemical mechanisms are represented in the models. For example, as will be discussed in Section 3, there are a number of meteorological metrics that are crucial for modeling regional air quality for which the climate modeling community has not yet systematically evaluated the skill of their modeling systems. Similarly, future emissions scenarios that are consistent across pollutants and geographic scales and that incorporate important processes such as fire, land use, biogenic emissions, and technological change are lacking, limiting the kinds of studies that can be accomplished at this time.

It is possible to think of these challenges as informing two parallel "readings" of this report, one tuned to the perspective of a "science" audience and the other to that of a "policy" audience. While these obviously intersect and overlap, each would highlight its own distinct set of issues, falling broadly under two questions: "What do we know, scientifically, about the climate change-air quality problem?" and "What might this knowledge mean for me, as an air quality manager?"

For example, for the scientific audience, this report generates additional information by synthesizing across the findings from multiple research groups. This synthesis improves our understanding of the potential for climate change to impact air quality in different regions of the United States and the complex interplay between air quality and its different climatic and meteorological drivers. It also throws into relief scientific and technical uncertainties that will be helpful in guiding future research efforts.

For the policy audience, the scientific findings presented in this report begin to answer the question raised above: "Is climate change something we will have to account for when moving forward with U.S. air quality policy?" In addition, by illuminating the subtleties and complexities of the interactions between climate, meteorology, and air quality, these findings can inform thinking about policy responses. This knowledge can be carried forward into the next phase of the assessment, which will consider added complications such as changes in anthropogenic emissions drivers. Furthermore, this report provides a basis for evaluating the relative robustness of these scientific findings in light of the uncertainties that surround them. Finally, all of these general insights create a foundation for targeted efforts to solve specific air quality management problems.

1.3 BACKGROUND

1.3.1 Air Pollution

EPA's mission is to protect human health and the environment. To achieve this mission, EPA implements a variety of programs under the Clean Air Act that reduce ambient concentrations of air pollutants, including those that cause smog, haze, and acid rain. Pollutants such as ozone (O_3) are not emitted directly into the atmosphere: instead they are created by chemical reactions between nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of heat and sunlight. VOCs are emitted from a variety of sources, including motor vehicles, chemical plants, refineries, factories, consumer and commercial products, other industries, and natural (biogenic) sources. NO_x is emitted from motor vehicles, power plants, other sources of combustion, and natural sources including lightning and biological processes in the soil. EPA's efforts have been successful: between 1980 and 2007, emissions of VOCs and NO_x decreased by 50 and 39 percent respectively, even though gross domestic product increased 124 percent, vehicle miles traveled increased 103 percent, and energy consumption increased 30 percent (U.S. EPA, 2008; see also http://www.epa.gov/airtrends/sixpoll.html).

Air pollution, however, continues to be a widespread public health and environmental problem in the United States. In 2007, approximately 158 million people lived in counties that exceeded at least one of the National Ambient Air Quality Standards (NAAQS). The health effects of air pollution range from increased mortality to chronic effects on respiratory and cardiovascular health (e.g., see Jerrett et al., 2009). Air pollution also has been associated with increased use of health care services, including visits to physicians and emergency rooms and admissions to hospitals. Other effects include reduced visibility, damage to crops and buildings, and acidifying deposition on soil and in water bodies, where the chemistry of the water and resident aquatic species are affected.[1] Moreover, there is growing concern that global change may make it more difficult to reach these goals. The air quality assessment effort itself does not address health and other effects. However, it will provide information that will be used in the Global Program's climate and air quality health assessments, the first of which focuses on O_3.

1.3.2 Climate Change and Air Quality Linkages

The NRC, in 2001, highlighted the linkages between climate and regional air quality and the need for a comprehensive research strategy:

> Air pollution is generally studied in terms of immediate local concerns rather than as a long-term 'global change' issue. In the coming decades, however, rapid

[1] See, for example the Ozone Criteria Document, at http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=149923, and the Particulate Matter Criteria Document, at http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=149923.

> population growth and urbanization in many regions of the world, as well as changing climatic conditions, may expand the scope of air quality concerns by significantly altering atmospheric composition over broad regional and even global scales. … Although air quality and climate are generally treated as separate issues, they are closely coupled through atmospheric chemical, radiative, and dynamical processes. … A better understanding is needed in order to make accurate estimates of future changes in climate and air quality and to evaluate options for mitigating harmful changes.

Coupling atmospheric chemical processes and the climate system remains a challenge to the science and modeling communities, however, because a large number of physical, chemical, and biological processes are involved (see Figure 1-1), and many of these are poorly understood.

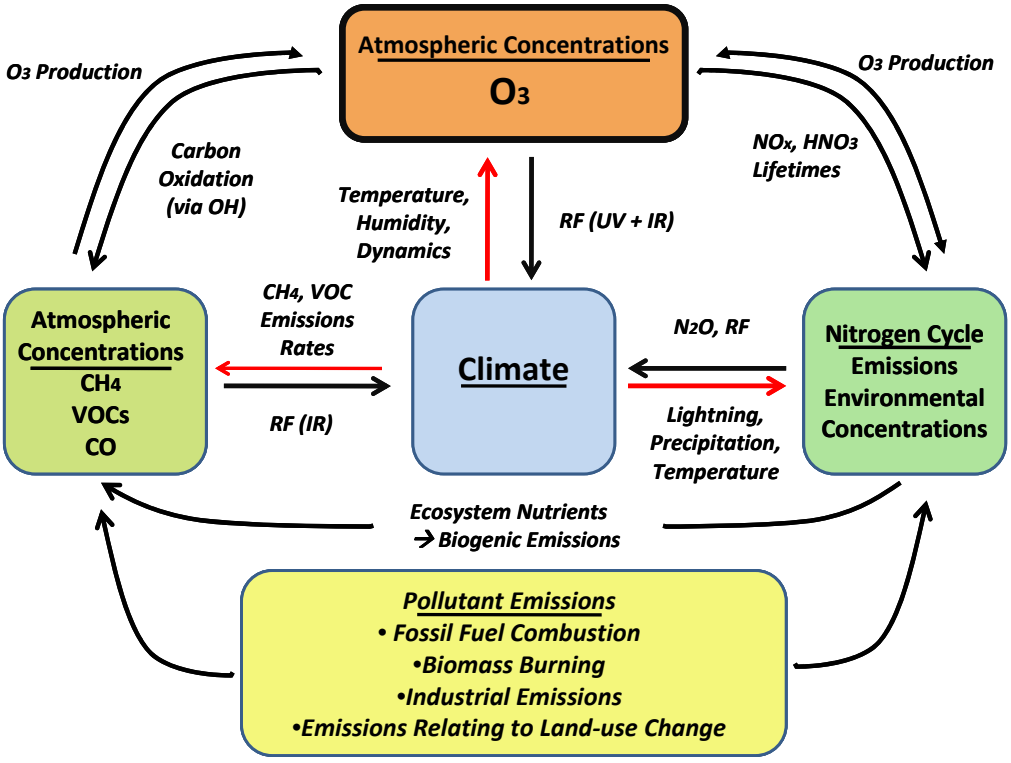

Figure 1-1. Schematic representation of the multiple interactions between tropospheric chemical processes, biogeochemical cycles, and the climate system. RF represents radiative forcing, UV represents ultraviolet radiation, and IR represents infrared radiation. The red arrows, discussed below in Section 1.4.1, represent the scope of EPA's assessment effort. (Adapted from IPCC, 2007.)

1.3.2.1 *Air Quality Impacts on Climate Change*

Prior to the mid-1970s, anthropogenic climate change was largely viewed as a CO_2-driven phenomena. This picture began to change with a series of papers on non-CO_2 reactive gases including:

- The impact of Chlorofluorocarbons (CFCs) on the greenhouse effect (e.g., Ramanathan, 1975);
- The impact of NO_x on stratospheric O_3 (a strong greenhouse gas) (e.g., Crutzen, 1972);
- The identification of methane (CH_4) and nitrous oxide (N_2O) as greenhouse gases (e.g., Wang et al., 1976); and
- The contribution of tropospheric O_3 (and therefore CO, VOCs, and NO_x) to global warming (e.g., Fishman et al., 1980).

A World Meteorological report published in 1985 concluded that trace gases other than CO_2 contributed as much anthropogenic climate forcing as CO_2 since the industrial revolution (Ramanathan et al., 1985), and our understanding of the multiple strong and complex links between climate and air quality have continued to evolve (Ramanathan and Feng, 2009).

Air pollution emissions can also affect concentrations of the hydroxyl radical (OH), the primary cleansing agent of the lower atmosphere, with increases in NO_x tending to elevate OH levels, while increases in CO have the opposite effect. Changes in OH affect the lifetime and thus the concentrations of reactive greenhouse gases such as CH_4, HFCs, and HCFCs (NRC, 2001). The nitrogen cycle itself plays a key role in climate and atmospheric chemistry, contributing N_2O (a greenhouse gas), NO_x (an O_3 precursor, with indirect effects on CH_4 via shortening of atmospheric lifetime), and ammonia (NH_3), which contributes to the formation of sulphate and nitrate aerosols (IPCC, 2007).

Aerosol particles affect climate by scattering and absorbing radiation (the “direct effect”) and through their impact on clouds (the “indirect effect”). Aerosols interact with clouds and precipitation in a variety of ways: e.g., by acting as cloud condensation nuclei and/or ice nuclei; through effects on the albedo or reflectivity of the cloud; and by impacting cloud lifetimes. Such effects can change precipitation patterns as well as cloud extent and optical properties (CCSP, 2009).

1.3.2.2 *Climate Change Impacts on Air Quality*

Concerns about the impacts of climate change on air quality are grounded in information derived from a wealth of observational studies, knowledge of basic atmospheric chemistry, and, more recently, modeling studies (see Appendix A for more details about these lines of evidence).

For example, there have been many empirical analyses showing that weather patterns play a major role in establishing conditions conducive to O_3 formation and accumulation, given sufficient levels of precursor pollutants such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs): e.g., year-to-year variability in warm-season climate is strongly correlated with variability in O_3 exceedances. Generally speaking, meteorological conditions favorable to high levels of O_3 include sunshine, high temperatures, and stagnant air (NRC, 1991). However, this NRC report also cautioned about the potential complexities of the problem arising from interactions between key drivers, noting that, for example, the relationship between temperature and O_3 "cannot readily be extrapolated to a warmer climate because higher temperatures are often correlated empirically with sunlight and meteorology."

A variety of statistical methods have been successfully applied to weather, O_3, and other data to obtain short-term air quality forecasts (U.S. EPA, 1999), estimate time trends (Thompson et al., 2001; Bloomfield et al., 1996; Cox and Chu, 1993; Camalier et al., 2007), and increase understanding of underlying mechanisms (Sillman and Samson, 1995). There are substantially fewer observations for particulate matter (PM), as monitoring networks have been in place for a much shorter time period. This should improve over time as more data become available.

Two early modeling studies (Morris et al., 1995; U.S. EPA, 1989) of the effect of a warming climate on U.S. O_3 levels considered a uniform 4°C increase in temperature across horizontal, vertical, and temporal scales.[2] The EPA study modeled specific episodes and simulated changes in daily 1-hour maximum O_3 concentrations ranging from +3 to +20% for Central California and from −2.4 to +8% for the Midwest and Southeast. Morris et al. (1995) included the effect of warmer conditions on mobile source and biogenic emissions in their simulation of a 4-day episode in the Northeast, simulating O_3 concentration increases of 15−25 parts per billion by volume (ppb) in much of the modeling domain above baseline daily one-hour maximum concentrations of 110−120 ppb and 120−140 ppb (i.e., increases of 10−20%).

The results of these early studies suggested that regional air quality may be sensitive to a warming climate, creating an additional challenge for air quality managers. However, as noted by the authors, their studies were constrained by the limitations of the tools and data available at the time. It was recognized that the relationship between climate change and air quality was not a simple one of "higher temperatures equals worse air quality" (NRC, 1991; U.S. EPA, 1989). The number of meteorological factors, and the complex interactions between and among them and air pollutants (see Box 1-1), highlight the need to use sophisticated modeling tools and experimental designs to help understand the multiple ways that climate change can affect

[2] Because of the technical hurdles existing at the time in adapting climate model output to be input to a regional air quality model, the researchers elected to make this simplifying assumption.

regional air quality. Fortunately, modeling capabilities have improved substantially since that time and continue to improve.

Box 1-1. Climate Change Factors Important for Regional Air Quality
Adapted from U.S. EPA (1989)

Changes in the following affect air quality:

- The average maximum or minimum temperature and/or changes in their spatial distribution and duration leading to a change in reaction rate coefficients and the solubility of gases in cloud water solution;
- The frequency and pattern of cloud cover leading to a change in reaction rates and rates of conversion of SO_2 to sulfate aerosols, leading to acid deposition;
- The frequency and intensity of stagnation episodes or a change in the mixing layer leading to more or less mixing of polluted air with background air;
- Background boundary layer concentrations of water vapor, hydrocarbons, NO_x, and O_3, leading to more or less dilution of polluted air in the boundary layer and altering the chemical transformation rates;
- The vegetative and soil emissions of hydrocarbons and NO_x that are sensitive to temperature and light levels, leading to changes in their concentrations;
- Deposition rates to vegetative surfaces whose absorption of pollutants is a function of moisture, temperature, light intensity, and other factors, leading to changes in concentrations; and
- Circulation and precipitation patterns leading to a change in the abundance of pollutants deposited locally versus those exported off the continent.

1.4 DESIGN OF THE GLOBAL CHANGE AND AIR QUALITY ASSESSMENT

To address the need for an improved understanding of the potential impacts of global change on U.S. regional air quality, building on the scientific understanding summarized above, an integrated assessment framework was designed that blends the research and development strengths within the EPA with those of other agencies and the academic research community. The assessment program was designed to provide the scientific information and modeling capabilities to answer the following types of questions:[3]

- What are the effects of plausible future changes in climate, climate variability, and land-use patterns on air quality, specifically ground-level O_3 and PM?
- What is the range of potential impacts of climate change on air quality relative to the range of potential impacts of emissions changes due to pollution controls, technological development, and land-use change?
- How might the effectiveness of air quality management be affected by climate change, i.e., can changes in emissions, technology, and land use offset air quality changes due to climate change?

[3] These questions were adapted from the November 2002 EPA Global Change Research Program Research Strategy (EPA/600/R-02/087), which can be found at: http://www.epa.gov/ncea/pdfs/glblstrtgy.pdf.

1.4.1 Scope of the Assessment Effort

The discussion in Section 1.3.1 is not a comprehensive description of all the potential linkages between climate and atmospheric chemistry. Instead, it is meant to highlight the fact that these linkages are complex, involve nonlinear coupling among numerous processes, and that many of these are not well quantified. The scientific enterprise required to elucidate all of the linkages exceeds the resources available to the EPA's Global Change Research Program.

Accordingly, the Program elected to focus its efforts on the impact of climate change on regional air quality (the red arrows emanating from the "Climate" box in Figure 1-1) to inform and support EPA's air quality programs. The NRC (2004) identified climate change as an important new challenge to the air quality management (AQM) system. The report concluded that "The AQM system must be flexible and vigilant in the coming decades to ensure that pollution mitigation strategies remain effective and sufficient as our climate changes." Focusing on climate effects on air quality also takes advantage of the considerable expertise within EPA in regional air quality modeling. Other federal agencies have active research programs investigating other aspects of Figure 1-1, such as the feedback effects of aerosols and atmospheric chemistry on the climate system. The Atmospheric Composition research element of the U.S. Climate Change Science Program (CCSP) coordinates research on atmospheric chemistry and climate system interactions across the federal government.[4]

The assessment addresses its questions in two phases. Phase I of the effort focuses on augmenting, linking, and applying existing climate and atmospheric chemistry models to investigate the range of current and potential future meteorological effects on air quality. It does not include changes in air pollutant emissions other than those that are explicitly linked to meteorological variables and incorporated within the models (e.g., biogenic VOC emissions, evaporative emissions, lightning NO_x, depending on the modeling system).

Phase II of the assessment focuses on the combined impact of changing climate and changing air pollutant emissions on air quality. It builds on the findings from the first phase by extending the linked modeling systems developed therein, and also by exploring the scientific uncertainties more comprehensively. Simultaneously, it integrates plausible, spatially detailed scenarios of U.S. criteria pollutant emissions 50 years in the future with the climate and air quality modeling efforts initiated in the first phase. The development of the tools to create plausible scenarios of technology, land use, and demographic changes needed to derive these emissions scenarios is a critical aspect of this phase of the assessment.

[4] See http://www.usgcrp.gov/usgcrp/ProgramElements/atmosphere.htm.

1.4.2 What is Covered in this Report

The problem and challenge of air quality is defined by its local impacts combined with its global dimensions and the linkages across scales and disciplines needed to address it. The purpose of this interim assessment report is to provide an update on our progress toward the development of tools and a knowledge framework that encompasses these linkages in the investigation of global change impacts on U.S. air quality. It is not intended to provide a comprehensive assessment of the literature. There have been several recent state-of-the-science reviews that provide such assessments (e.g., see IPCC, 2007 Chapter 7; Jacob and Winner, 2009; U.K. Royal Society, 2008).

By design, the emphasis in this report is on EPA, and EPA-funded, work carried out under the EPA Global Change Research Program's assessment. In Section 3, the focus is on results emerging from the subset of participating intramural and extramural research groups that are currently producing model simulations of the impacts of climate change on air quality, as part of Phase I of the assessment. This is a mid-course overview of the findings to date from the several parallel efforts to build, test, and apply individual versions of these linked climate and air quality modeling systems. Notably, this is the first systematic effort to apply combined global and regional climate and air quality models to investigations of potential climate change impacts on future U.S. regional air quality. Though the focus is on EPA, and EPA-funded, research, this body of work does in fact represent the large majority of the research to date in the area of applying these types of linked modeling systems to the problem of regional U.S. air quality (e.g., see Jacob and Winner, 2009).

From a scientific perspective, the main goal is to assess the larger meaning of the various research groups' model simulation results when examined all together. The aim is to synthesize the simulated air quality changes in different regions of the United States, as well as the dependence of these changes on different climatic drivers. By highlighting scientific and technical uncertainties to which these findings are sensitive, the synthesis helps identify future research needs.

From a policy perspective, this synthesis across scientific findings begins to answer the question: "Is climate change something we will have to account for when moving forward with U.S. air quality policy?" In addition, by illuminating the subtleties and complexities of the interactions between climate, meteorology, and air quality, it helps build up intuition about the way the coupled system works. Section 3 also provides an extended discussion of the challenges and uncertainties associated with the modeling approach that underpins the assessment, to create an improved understanding about the level of confidence in the scientific findings, and an appreciation for the limits on what questions the science can answer now, and may be able to answer in the future.

Changes in anthropogenic forcing (i.e., fossil fuels, biomass burning, and land use) are not covered in this report. However, they will be addressed in the second phase of the assessment effort. Section 4 provides an overview of Phase II. Ongoing activities include investigation of modeling uncertainties (for example, through the use of ensemble approaches), additional model development (for example, the incorporation of dynamic vegetation sub-models), and examination of additional pollutants including PM and mercury. Preliminary results for PM are provided, but a more comprehensive presentation awaits future assessment reports focusing on these additional pollutants. Future assessment reports also will cover the combined impacts of changing climate and air pollutant emissions on air quality. Initial results from combined climate and emissions sensitivity studies and ongoing work on the drivers of emissions changes—e.g., technology, population growth and geographic distribution, economic growth, and land use—are also described in Section 4.

1.5 THE CLIENT COMMUNITIES

Section 1.2 referred to the two broadly defined themes, audiences, and readings of this report that flow from the two "grand challenges." Though this conceptualization provides a useful roadmap to the major purposes of the report, it is also important to identify specific groups that are potential beneficiaries of the information contained herein, and that supply the audiences and perspectives to which the report speaks. These include air quality managers, employees of agencies working as part of the overall U.S. federal climate change research effort, and the climate change and air quality research and modeling communities.

1.5.1 EPA Office of Air and Radiation (OAR), State, Tribal, and Local Air Quality Planners

The EPA's Global Change Research Program engages in activities that support EPA's mission to protect human health and the environment. As the specific focus of this report is air quality, OAR is a major client for this work. Recent air quality regulations, such as the NO_x State Implementation Plan (SIP) Call,[5] Clean Air Interstate Rule (CAIR),[6] Heavy Duty Highway Diesel Rule,[7] and Non-road Diesel Rule,[8] are expected to bring many urban areas of the United

[5] "Finding of Significant Contribution and Rulemakings for Certain States in the Ozone Transport Assessment Group Region for the Purposes of Reducing Regional Transport of Ozone ("NOx SIP Call")." U.S. EPA Technology Transfer Network: O3 Implementation.

[6] "Clean Air Interstate Rule." U.S. EPA: Clean Air Rules of 2004. http://www.epa.gov/cair/.

[7] "Clean Diesel Trucks, Buses, and Fuel: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements (the "2007 Heavy-Duty Highway Rule")." U.S. EPA. http://www.epa.gov/otaq/highway-diesel/regs/2007-heavy-duty-highway.htm.

[8] "Clean Air Nonroad Diesel – Tier 4 Final Rule." U.S. EPA. http://www.epa.gov/nonroad-diesel/2004fr.htm.

States into attainment with current PM and O_3 standards by 2015. However, as noted by the NRC (2004),

> The AQM system will need to ensure that pollution reduction strategies remain effective as the climate changes, because some forms of air pollution, such as ground-level ozone, might be exacerbated. In addition, emissions that contribute to air pollution and climate change are fostered by similar anthropogenic activities, that is, fossil fuel burning. Multi-pollutant approaches that include reducing emissions contributing to climate warming as well as air pollution may prove to be desirable.

Furthermore, air quality management involves policy decisions with consequences that can last for decades. For example, policy guides the choices made for electricity production investment and the emissions and fuel efficiencies of motor vehicles. Power plant and motor vehicle fleet replacement involves very long lead-times (see, e.g., U.S. EPA, 1992). In this context, it will be important to consider the air quality impacts of global change to identify actions that accomplish air quality goals with the least long-term cost to society. Information and tools supporting the creation of holistic, robust decisions are thus very much needed. Similarly, information and tools supporting new and innovative approaches to existing and emerging issues are needed as well. As introduced in Section 1.1 above, providing a foundation for developing such decision support instruments that can be transferred to national, regional, state, and local decision-makers is a critical goal of the overall air quality assessment effort.

1.5.2 U.S. Climate Change Science Program (CCSP)

The CCSP integrates federal research on climate change, as sponsored by 13 federal agencies and overseen by the Office of Science and Technology Policy (OSTP), the Council on Environmental Quality (CEQ), the National Economic Council (NEC), and the Office of Management and Budget (OMB). The primary EPA role within the CCSP is to develop an understanding of the potential consequences of global change on human health, ecosystems, and socioeconomic systems in the United States. Currently, EPA's ORD, within which the Global Change Research Program is located, is focusing on topics that include impacts on future water and air quality, risks to coral reefs and watersheds, and impacts on biological criteria and aquatic invasive species, as well as developing decision support methods and resources.

The impact of climate change on air quality is one of the overarching questions guiding the Atmospheric Composition research element of the CCSP (CCSP, 2003; see Box 1-2). The CCSP Atmospheric Composition Interagency Working Group coordinates research that focuses on how the composition of the global atmosphere is altered by human activities and natural phenomena and how such changes influence climate, O_3, PM, ultraviolet radiation, pollutant exposure, ecosystems, and human health. Atmospheric composition issues involving

interactions with climate variability and change—such as the potential effects of global climate change on regional air quality—are important research topics. Several federal agencies, including the National Oceanographic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE), are involved in research activities in this area, including satellite observations, aircraft field campaigns, laboratory studies, and global modeling studies. EPA contributes its expertise in regional air quality modeling and anthropogenic emissions, along with research support in other air quality-relevant topic areas.

Box 1-2. Contributions to CCSP

The EPA Global Change Research Program Air Quality Assessment addresses a number of CCSP research and development elements, as described in the CCSP strategic plan (CCSP, 2003), including

Chapter 3. *Atmospheric Composition*
Question 3.3: What are the effects of regional pollution on the global atmosphere and the effects of global climate and chemical changes on regional air quality and atmospheric chemical inputs to ecosystems?
Question 3.5: What are the couplings and feedback mechanisms among climate change, air pollution, and ozone layer depletion, and their relationship to the health of humans and ecosystems?

Chapter 9. *Human Contributions and Responses to Environmental Change*
Question 9.2: What are the current and potential future impacts of global environmental variability and change on human welfare, what factors influence the capacity of human societies to respond to change, and how can resilience be increased and vulnerability reduced?
Question 9.4: What are the potential human health effects of global environmental change, and what climate, socioeconomic, and environmental information is needed to assess the cumulative risk to health from these effects?

Chapter 11. *Decision Support Resources Development*
Goal 11.1: Prepare scientific syntheses and assessments to support informed discussion of climate variability and change issues by decision-makers, stakeholders, the media, and the general public.
Goal 11.2: Develop resources to support adaptive management and planning for responding to climate variability and climate change, and transition these resources from research to operational application.
Goal 11.3: Develop and evaluate methods (scenario evaluations, integrated analyses, alternative analytical approaches) to support climate change policymaking and demonstrate these methods with case studies.

In addition to contributing to efforts under the Atmospheric Composition element, the scientific and technical accomplishments of the current assessment are enlarging the database of information needed to address questions under a number of other CCSP elements (see Box 1-2). Information from the ongoing air quality assessment is included in the CCSP Synthesis and Assessment Product 4.6: "Analyses of the effects of global change on human health and welfare and human systems" (CCSP, 2008).

1.5.3 Climate Change Research Community

Understanding potential impacts of global change on U.S. air quality is a particularly challenging task, given the varying climate regimes contained within the continental United States and the 3-dimensional modeling at high spatial and temporal resolution that is required to capture effects of importance to policy planners. The larger climate change research community, including other government science agencies and academia, plays a crucial role in the EPA Global Change Research Program's research and development process by assuming the task of advancing the capabilities of global and regional climate models and global and regional atmospheric chemistry models. Beyond the many challenges of understanding potential future global climate change itself, the problem of impacts on air quality adds additional dimensions. For example, the global climate modeling community has typically focused on long-term average meteorological parameters on continental and planetary scales, while adverse regional air quality events are often determined by finer-scale geographic and temporal variability. Successfully simulating the impact of climate change on air quality requires advances in the climate sciences and climate modeling, with particular attention to these spatial and temporal needs. The research synthesis portion of this report (Section 3) looks across the modeling studies conducted as part of this assessment, studies that represent an initial step toward addressing this challenge.

In addition, the modeling work in this assessment provides an important test of some methodologies used for linking (downscaling) global and regional climate models, a key aspect of climate impacts work in general. Further advances in meeting the demanding requirements of simulating climate change impacts on U.S. air quality will improve our capabilities to assess other global change impacts of great importance to the environmental policy community, including impacts on water quality, aquatic ecosystems, water resources, agriculture, and forests, in addition to the quantification of air quality-related human health effects.

1.5.4 Air Quality Research Community

Developing coupled climate and air quality modeling systems challenges the capabilities of regional air quality models. Improvements in our ability to model chemistry of air pollution are needed in a number of areas to better understand the influence of climate change on air quality. For example, enhancing linkages between climate/meteorology models and air quality models, developing suitable initial and boundary conditions for all important chemical species, and producing plausible future emission scenarios are all required. Comprehensive examinations like this assessment effort also reveal key uncertainties in chemical mechanisms and processes that can be used to prioritize future modeling improvements. Notable among these is the need to introduce the ability to simulate two-way interactions between climate and chemistry: for

example, changes in the distribution of particulates as a result of climate or emissions changes could have important impacts on the Earth's radiation budget, thereby further influencing climate. Finally, the extremely large data files involved in this assessment effort have required the development of automated data management and quality control tools and highlighted the need for new data distribution systems.

1.6 CONSIDERING UNCERTAINTY IN THE ASSESSMENT EFFORT

Characterization of the uncertainty in a given finding, judgment, or prediction, and communication of this uncertainty in clear, precise, objective language, are important components of scientific assessments. Large global change assessment efforts, such as those conducted by the IPCC and CCSP, have produced general guidance on handling uncertainty in assessment reports (see CCSP, 2009; IPCC, 2005). For example, a fundamental principle is that basic differences between descriptions of uncertainty in terms of likelihood of an outcome and level of confidence of the science underlying a finding must be recognized.

Likelihood is relevant when assessing the chance of defined future occurrence or outcome. When the maturity of the scientific knowledge base warrants it, it is considered best practice to assign numerical probabilities to qualifiers such as "probable," "possible," "likely," "unlikely," etc., to avoid differing interpretations among people and contexts.

Level of confidence refers to the degree of belief in the scientific community that available understanding, models, and analyses are accurate, expressed by the degree of consensus in the available evidence and its interpretation. One way to think about the level of confidence concept is to consider two attributes of the state of knowledge underlying a given finding or judgment: the amount of evidence available to support it and the degree of consensus within the scientific community about the interpretation of that available evidence.

The study of climate impacts on air quality is a still-emerging field of research. In addition, the modeling studies discussed herein were designed to be sensitivity studies, not predictions. Therefore, this report does not attempt to express the findings from the scientific synthesis in terms of the probabilities ("likelihoods") of particular future events. Instead, the report provides information to help evaluate the relative levels of confidence in the findings. Findings for which multiple lines of evidence are presented, and for which there is general agreement across these lines of evidence, should be viewed with higher confidence than findings for which there is a paucity of observations and/or model simulation results or for which there are competing interpretations of the results that are available. For example, as will be discussed in Section 3, there is broad agreement across the modeling studies, consistent with scientific understanding from theory and observations, that simulated future climate change leads to increases in biogenic VOC emissions in the southeastern United States, but there is significant

disagreement as to whether these emissions increases lead to large increases in O_3 concentrations due to uncertainty about how to represent isoprene nitrate chemistry.

Section 3 provides a detailed discussion of the major uncertainties associated with the coupled climate and air quality modeling systems upon which rests the science synthesis presented in this report. Moving forward into the second phase of the assessment, the complexity of the problem will grow when the multiple dimensions of climate and emissions changes are fully integrated. In anticipation of the challenges that multiple, interacting categories of uncertainties will present for interpretation of the assessment findings, EPA convened an expert workshop in November 2006 to begin the process of identifying a set of guiding principles to assist in evaluating uncertainty as the assessment moves forward. Participants included experts in global and regional climate modeling, socioeconomic modeling and emissions projection, atmospheric chemistry, regional air quality modeling, and uncertainty analysis and communication, along with key stakeholders from OAR and the EPA regions. The workshop findings suggested emphases on the following issues: building a healthy, collaborative process involving both scientists and policy makers; identifying formal uncertainty analysis techniques appropriate for complex, computationally expensive linked climate and air quality modeling systems; evaluating the potential contributions of complementary methods, such as expert elicitation; communications strategies; and the need for future workshops to focus on specific technical issues. The workshop and its findings are summarized in Appendix B.

1.7 STRUCTURE OF THIS REPORT

This report presents the progress made toward the overall assessment goals. It is divided into five sections (including this one):

The Summary of Policy Relevant Findings, which precedes this section, seeks to draw some preliminary connecting lines between the scientific findings of the assessment to date and the issues of concern to air quality managers. Analogous to the approach taken in the IPCC Summary for Policymakers, OAR was substantially engaged in the writing of this section in order to ensure the salience of the results for air quality policy.

Section 2 discusses in greater detail the design of the assessment effort, including the process used to develop this design, key decisions made by the research team, research priorities, and program capabilities. The focus on developing and applying linked global-to-regional climate and air quality modeling systems is in recognition of the complexities of the global change-air quality problem, including its multi-scale (i.e., from global to local; from decadal to diurnal) dimensions.

Section 3 synthesizes the results emerging from the initial applications of these modeling systems to the simulation of U.S. air quality under potential future climate change. It highlights

the sensitivities in the climate-air quality system and the uncertainties associated with the modeling tools.

Section 4 discusses the next phase of the assessment. It summarizes ongoing work that seeks to increase our understanding of key modeling issues and develop new capabilities for simulating future changes in anthropogenic emissions.

Appendix A describes the meteorological variables to which U.S. air quality is known to be sensitive, e.g., the basis for the anticipated effects of changing climate on future air quality. *Appendix A* also discusses early research results on the role of climate in future air quality. *Appendix B* describes the 2006 workshop convened by EPA NCEA to identify the essential issues that must be addressed in identifying and communicating the uncertainties inherent in this assessment, and other complex, model-based assessments. *Appendix C* describes the 2001 expert workshop convened by EPA NCEA to evaluate the research and assessment framework developed by the EPA Global Change Research Program for identifying and quantifying the effects of global change on U.S. regional air quality. Finally, *Appendices D, E,* and F expand upon the descriptions provided in the main report of the internal EPA ORD programs contributing the GCRP assessment effort. A glossary has been provided to assist readers who are unfamiliar with the terms that are frequently used in the discussion of climate and air quality research and policy.

2 OVERVIEW OF APPROACH

2.1 INTRODUCTION

The NRC stated in 2001 that, "improving our understanding of linkages between climate, atmospheric chemistry, and air quality and our ability to assess future states of the atmosphere will require coupling local- and regional-scale air quality models with global-scale climate and chemistry models" (NRC, 2001). The EPA's Global Change Research Program initiated a research program designed to meet the "grand challenges" introduced in Section 1 that is consistent with EPA's traditional "place-based" regional assessment approach, and that focuses on spanning the breadth of issues from global-scale drivers of climate and air quality to developing regional-scale inputs for air quality modeling.

In the design of this program, the EPA recognized three key linkages inherent to the global change and air quality issue: those across spatial scales, those across temporal scales, and those across disciplines. The processes linking global to regional scales, symbolized in Figure 2-1, and the requirements for modeling them, were identified as a first step in the assessment design. Similarly, while air quality is defined, studied, and managed most readily on the synoptic timescales associated with meteorological and air quality episodes, global climate change is manifested on timescales of decades and longer, imposing significant research challenges to bridge this gap. Finally, given the inherently multi-disciplinary nature of the problem, it was recognized that merging the efforts of the climate change, air quality, emissions inventory, land use, energy, and transportation economics research communities would be critical to bring about advances required for this assessment. Developing the modeling tools and knowledge base to achieve these linkages is a fundamental task of the assessment.

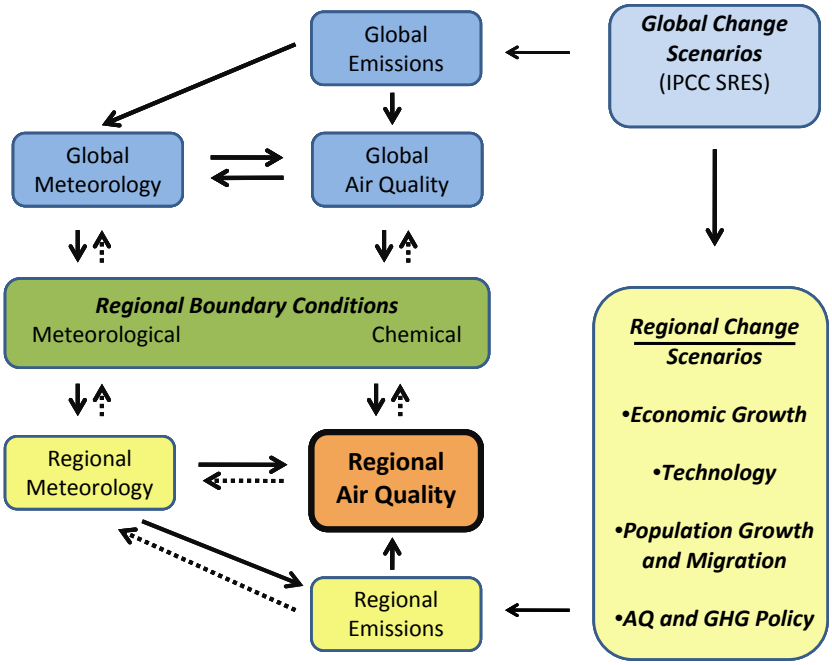

Figure 2-1. Links between global and regional climate and atmospheric chemistry processes with anthropogenic activities governing air pollution emissions. The dashed arrows represent feedbacks not considered as part of this assessment.

2.1.1 Process for Developing the Global Change-Air Quality Assessment Effort

In 1997, the EPA's Global Program underwent a major redirection, including the development of a new Strategic Plan in 1999. As part of that effort, the global change-air quality assessment was designed. Specifically, a small workgroup was formed, made up of scientists knowledgeable about various aspects of the issue, including atmospheric and emissions modeling, technology, socioeconomics, climate modeling, and air quality programs. The workgroup included members from all of the Labs and Centers involved in the EPA's Global Change Research Program, and input from several offices within OAR was also solicited to help guide the effort. An iterative process within the workgroup was used to define the purpose, goals, and issues to be addressed; to identify appropriate EPA participants and stakeholders; and to develop an initial conceptual framework for organizing the assessment effort, leading to a white paper describing the proposed framework and timeline for accomplishing key milestones.

To review this draft framework and help EPA identify priority research needs, a workshop was held in Research Triangle Park, North Carolina in December 2001 that brought together technical experts from ORD and OAR, as well as invited international experts. The goal of the workshop was to identify the important processes and inputs and to discuss the design and implementation of the assessment. Participants included experts in climate modeling, air quality modeling, anthropogenic emissions inventory development, and biogenic emissions inventory development. The workshop agenda included presentations by a panel of experts on regional climate modeling, future emissions inventory development, regional air quality modeling, biogenic emissions and wildfires, and socioeconomic and technological change projection methods. The workshop participants were assembled into four groups to discuss specific issues related to the EPA Global Change Research Program's objectives: (1) the Regional Climate Modeling Group, (2) the Emission Drivers and Anthropogenic Emissions Group, (3) the Biogenic Emissions and Wildfires Group, and (4) the Air Quality Modeling Group. Each examined charge questions about possible approaches, and each developed recommendations for research required to meet the needs of the assessment. Here, the key recommendations from the workshop that define the approach used in the assessment are summarized (for further details see Appendix C).

2.2 WORKSHOP RECOMMENDATIONS

2.2.1 Modeling

The three key conceptual linkages introduced above, i.e., across spatial scales, temporal scales, and disciplines, are embodied in the foundational technical challenge of the assessment: linking available modeling tools to span the climate, meteorology, air quality, and human dimensions of the problem. As will be described in more detail below, the primary focus of this

2007 interim report is the potential for future climate change to impact air quality, independent of changes in anthropogenic emissions. The individual research communities use a number of different types of models, described in Box 2-1, to study the various aspects of this sub-problem.

Box 2-1. Climate and Chemistry Modeling Tools

General Circulation Model (GCM): Comprehensive model of Earth system, including components that simulate 3-D flow in atmosphere and ocean, exchange of energy and water with land and ocean surface, and growing and melting of ice sheets and sea ice, ultimately in response to amount of solar energy received over time across planet; typically operated with horizontal grid spacing of 100-500 km to examine climate variables at continental to global scales; most often applied in simulations of how long-term climate statistics evolve over years, decades, or centuries in response to past or future changes in outside forcings (e.g., variations in solar input, volcanic aerosols, and changes in anthropogenic greenhouse gas emissions). [Note: The use of "GCM" as an acronym for "Global Climate Model" and "Global Circulation Model" reflects current usage as well.]

Global Chemistry and Transport Model (GCTM): Type of model that blends representations of chemical reactions and physical chemical transformations with meteorology supplied either from gridded observational analyses or a GCM simulation; applied to study how transport by winds, deposition onto or emissions from surface, and atmospheric chemistry control long-term distributions of important gases and aerosols within the atmosphere (e.g., O_3, carbon monoxide, sulfates, and black carbon, among many others); chemistry/transport can also be built directly into a GCM for similar applications.

Regional Climate Model (RCM): Similar to a high-resolution (e.g., 10-50 km) version of a GCM but only applied to limited area of globe (e.g., continental United States); designed to capture more accurately role of fine-scale forcings (e.g., topography, land-surface heterogeneity) and atmospheric processes (e.g., nonlinear dynamics of fronts, development of convective rainfall systems) hard to represent at coarse scales of a GCM; derived primarily from weather prediction models but including some additional features that allow simulations longer than typical several-day timescale of weather forecasts; driven at boundaries by gridded analyses of observational data or output from a GCM to study in greater detail how long-term, large-scale climate variability is expressed in weather events over shorter timescales and in particular locations.

Regional Air Quality Model (RAQM): Developed to account for impact of meteorological transport and mixing, atmospheric chemistry, and surface deposition/emission of multiple chemical species, particularly regulated pollutants; most often applied by air quality management community to evaluate impact of control strategies and practices; also frequently used in research mode to develop improved understanding of chemical and physical interactions in atmosphere; typically operated on time and space scales characteristic of air pollution episodes, i.e., a metropolitan area or larger region over period of a few days.

These different modeling tools have historically been developed for distinct purposes. The assessment design reflects the need for bridging the gaps between these standard applications to move toward more comprehensive, integrated systems capable of addressing the breadth of the problem of potential climate change impacts on air quality.

As such, one core recommendation that emerged from the workshop was to use these tools separately and in combination in multiple modeling approaches to investigate the relevant space and time scales and physical/chemical processes governing the connections between climate and air quality. These approaches are

- Comprehensive modeling approach: This approach uses linked global and regional climate and chemistry models to simulate fine regional details of present-day and future air quality while simultaneously accounting for global drivers like changes in anthropogenic emissions of greenhouse gases. Output from GCM simulations of long-term climate change is used as input into a higher-resolution RCM, which "downscales" the climate and meteorological variables to the scales required for input into an RAQM. This approach is the most computationally expensive and methodologically complex, with concerns such as the length of simulation required to extract a meaningful climate change signal from interannual climate variability.
- Intermediate modeling approach: This approach relies primarily on GCMs and GCTMs to capture the broader impacts of climate change on air quality. The emphasis in this approach is on the potential for increases or decreases in air pollution events as the climate changes over a long simulation period. The results from such modeling work can be used to guide the comprehensive modeling approach (e.g., by guiding the selection of time periods for the higher-resolution simulations).
- Sensitivity approach: This approach applies detailed, state-of-the-art RAQMs at regional and even urban scales. Rather than a dynamic linkage, air quality simulations are carried out by varying key meteorological and emissions parameters to examine the sensitivity of the air quality outputs over particular, identified meteorological and air quality episodes. The sensitivity approach might permit use of more detailed descriptions of important processes, i.e., aerosol processes.

Initially, the assessment team proposed to move forward primarily with the Comprehensive approach. The workshop participants endorsed this plan as effective and reasonable, but they also suggested the other two strategies to complement the Comprehensive approach and add richness to the assessment.

Another key model-related discussion was the need to address uncertainty by sampling over multiple GCMs, RCMs, GCTMs, RAQMs, as well as the need to examine sensitivities to model parameterizations and downscaling methodologies. A critical challenge is to quantify the uncertainty produced by the system of linked models required to simulate changes in air quality driven by climate change. It was also acknowledged that an important research gap was the evaluation of the climate models for their ability to simulate air quality-relevant variables and air quality-relevant weather patterns at the appropriate space and time scales.

Finally, the assessment team was urged to consider in more detail the role of hemispheric-scale air pollutant transport and to support the development of appropriate initial and boundary conditions for regional-scale air quality modeling efforts.

2.2.2 Time Horizon Selected

A key consideration is the timeframe for building future scenarios and carrying out future climate and air quality simulations. It was decided to focus on a time horizon of roughly 2050 in order to balance the following considerations:

Natural meteorological variability versus climate change: Because meteorology varies from year-to-year, the signal from the changing climate needs to be relatively strong to discern climatically driven effects on air quality. In its Third Assessment Report (TAR) (IPCC, 2001), the IPCC projected that global average temperatures could increase from 1.4−5.8ºC (2.5−10.4ºF) by 2100, and that the warming is expected to be larger than the global average for land areas in the mid- and high latitude regions. These findings are consistent with the most updated projections from the IPCC AR4 (IPCC, 2007). This trend is expected to lead to intermediate levels of warming in the intervening decades. For example, the U.S. National Assessment (NAST, 2001) based their findings on average U.S. temperature increases of 0.5−2.0ºF by 2025, 1.5−4.0ºF by 2050, and 3.0−9.0ºF by 2100. Therefore, the longer the timeframe, the stronger the climate change signal captured relative to natural interannual and interdecadal variability.

Uncertainties in GCM climate projections: The IPCC AR4 (IPCC, 2007) documents significantly greater divergence in the climate change projections for 2100 compared to 2050, largely because the various driving greenhouse gas emissions scenarios from the IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000) have diverged relatively little by 2050. Even though the climate change signal is stronger in 2100, the spread between model projections created using different scenarios is not as wide. Choosing 2050 thus constrains somewhat one of the potential sources of uncertainty in the assessment.

Uncertainties in the assumptions concerning long-term change in emissions drivers: The uncertainty in projections of economic growth, patterns of land-use and land-cover change, energy use, migration, transportation patterns, and technological development needed to develop projections of anthropogenic emissions increases significantly over longer time horizons. An assessment timeframe of, e.g., 2100, would likely be too speculative for practical application to current air quality management planning.

Current EPA decision processes: In areas such as investment in electricity production, motor vehicle emissions, and power plant and fleet replacement, the EPA already makes air quality management decisions with long lead times of one to several decades. Therefore, a time horizon of the next half-century for assessing the potential consequences of climate change on air quality is consistent with this planning timescale.

2.2.3 Dual-Phase Assessment Approach

It is well recognized that anthropogenic emissions levels are a dominant factor in determining air quality, as evidenced by the dramatic improvements that took place with the implementation of emissions controls beginning in the mid-20th Century in the United States and other developed countries. Understanding how changes in air quality due to changing climate might confound long-term management of these emissions for NAAQS attainment and maintenance is a critical assessment goal. To more readily achieve this understanding, a second core recommendation from the workshop was to investigate possible regional air quality responses to future climate and meteorological changes alone, before tackling the additional complexities of accounting for changes in other aspects of the system, such as anthropogenic emissions and long-range pollutant transport.

The assessment research program was, therefore, designed in two phases. Phase I focuses on developing tools, capabilities, and a knowledge base, and then applying these in research to address the impacts of climate change on air quality with anthropogenic emissions held constant between present and future. Phase II builds on the insights from Phase I, by extending the capabilities of the modeling systems developed therein (e.g., to more comprehensively explore uncertainties, encompass additional pollutants, and investigate climate and air quality feedbacks) and by adding the effects of changing patterns of anthropogenic emissions (e.g., due to population, land-use, and energy and transportation technologies changes). In this second phase, emissions will be projected into the future, accounting for factors such as differential population growth and migration, economic growth, and technology change.

As described in Section 1.4.2, the major focus of this interim assessment report is the progress to date under Phase I, presented in Section 3. The Phase II work will be the subject of follow-on reports. A summary of research efforts already ongoing to support Phase II is provided in Section 4.

One of the key challenges in executing the comprehensive approach described in Section 2.2.1 lies as much with maintaining logical consistency in linking the many models as with the technical difficulties of simulating changes to 2050. The O_3 simulations in Phase I, reflecting the climate in 2050, have been accomplished while holding air pollution emissions constant at present-day levels. In the strictest sense, this therefore introduces an internal inconsistency, i.e., between emissions of greenhouse gases and those of conventional air pollutants, which in reality are coupled. The model results from this first phase serve as sensitivity tests—to determine the potential effect on climate-induced meteorological changes on air quality and to better understand the characteristics of the linked modeling systems—and cannot be construed in any way as future predictions.

2.2.4 Research Priorities to Support Phase II

Finally, we briefly summarize some key workshop recommendations on additional research needed to support Phase II of the assessment.

Processes governing biogenic emissions: Algorithms will have to be developed that describe chemical emissions of major vegetative species response to climate change for use in current and biogenic emission forecasting. Projections of land-use changes will have to be integrated with forest physiological models to project current and future biogenic VOC emissions.

Wildfires: There is a need to develop methods to define fire emissions as a function of fire intensity, extent, and frequency. Simultaneously, there is a need to develop methods to relate fire intensity, extent, and frequency to current and future land use, land management, fuel loading, socioeconomic conditions, and climate.

Anthropogenic emissions projections: Plausible scenarios for future emissions need to be developed that account for changes in urbanization, population growth, migration, industrialization, fuel, technology, etc. Also needed is normalization of procedures for emissions calculations across regions and countries and reconciliation between global and regional emission inventories. Principles of downscaling socioeconomic scenarios to more detailed geographic scales must be applied. There is also a need to incorporate feedbacks of climate change on energy use, economic development, land use, and migration.

Air quality modeling: Improvements in our ability to model the chemistry of air pollution in a number of areas will be required to more accurately simulate the influence of climate change on air quality. These areas include representations of aerosol physical and chemical processes, two-way linkages between climate/meteorology models and air quality models, the availability of suitable initial and boundary conditions for all important chemical species, and stratosphere-troposphere exchange.

2.3 RESEARCH PARTNERSHIPS

To implement the workshop recommendations and achieve the goals of the assessment, the EPA's Global Change Research Program designed a joint intramural and extramural research program. The goal is to harness the unique capabilities of the EPA research laboratories and the academic community to build a broad program.

Within the EPA's intramural effort, the National Exposure Research Laboratory (NERL) is the primary developer of the Community Multiscale Air Quality (CMAQ) model that predicts air quality pollutant transport and fate (Byun and Schere, 2006). CMAQ, which, as of December 2006, has undergone three external peer reviews, is being used by the Office of Air Quality Planning and Standards (OAQPS) within OAR for current rulemakings, as well as by the

research community for a range of research applications including climate and air quality interactions. Via a partnership between EPA and NOAA, a team at NERL is charged under this assessment with leading the development of a series of regional-scale air quality simulations using CMAQ under current and future climate scenarios. This effort, the Climate Impacts on Regional Air Quality (CIRAQ) project, was initiated in 2002 following the above-mentioned workshop. This team provides the air quality modeling expertise to develop these simulations, to interpret the sensitivity of air quality to the future climate changes simulated, and to consider regulatory implications of potential changes in air quality.

In addition, NERL researchers are key contributors to the development of models of environmentally influenced emissions from the air-surface interface for regional and global emissions inventories and application to air quality modeling, such as biogenic emissions (the Biogenic Emission Inventory System; BEIS) and wildfire emissions (based on the Blue Sky wildfire model). NERL was also the primary ORD collaborator in the development of the Sparse Matrix Operator Kernel Emission (SMOKE) modeling system. SMOKE assembles input data from anthropogenic emission inventories, and biogenic, mobile, and wildfire emission models into the hourly, gridded, speciated form required by air quality models such as CMAQ. These emissions models are needed for both retrospective and future air quality modeling scenarios. More information on aspects of the NERL effort is contained in Appendix E.

Simultaneously, researchers in the National Risk Management Research Laboratory (NRMRL) are focused on evaluating the potential impact of technological evolution on future-year air pollutant emissions, in coordination with the NERL efforts. This process involves characterizing future energy demands and technologies, and using this information within energy system models to estimate emissions over a wide range of alternative scenarios. In addition, NRMRL researchers have developed a suite of analytical and visualization tools for examining the flexibility available in meeting future emission targets and for evaluating sensitivity to uncertainties in model parameters and inputs. NRMRL is applying these methods and tools to examine the system-wide implications on fuel use and emissions of the penetration of new transportation and electric generation technologies. This work directly addresses the need, identified in the 2001 workshop, to develop realistic future emissions scenarios that are regionally plausible and also consistent with assumptions about global trends. Together, NERL and NRMRL have the expertise required to contribute crucially to both Phase I and Phase II of the overall assessment. For additional information, see Appendix F and Section 4.

The assessment effort benefits substantially from a strong collaboration with the extramural research community. The EPA's National Center for Environmental Research (NCER), through its competitive Science To Achieve Results (STAR) grants program, funded a

number of leading university research groups through the following Requests for Applications (RFAs):

- 2000: *Assessing the Consequences of Interactions between Human Activities and a Changing Climate*
- 2002: *Assessing the Consequences of Global Change for Air Quality: Sensitivity of U.S. air quality to climate change and future global impacts*
- 2003: *Consequences of Global Change for Air Quality: Spatial Patterns in Air Pollution Emissions*
- 2004: *Regional Development, Population Trend, and Technology Change Impacts on Future Air Pollution Emissions*
- 2005: *Fire, Climate and Air Quality*
- 2006: *Consequences of Global Change for Air Quality*

These RFAs, most of which derive from the recommendations of the 2001 workshop, encompass roughly 25 projects, totaling over $20 million, covering topics including projection of population, development, and transportation trends; observations of biosphere-air quality interactions; coupled climate and air quality modeling; and human health effects. Many of the current projects involve collaboration across disciplines to link models. All of this is emblematic both of the breadth of the issue and EPA's commitment to build and populate a comprehensive framework to address it. Further details are provided in Appendix D.

Finally, the National Center for Environmental Assessment (NCEA) has unique expertise in preparing the air quality criteria documents upon which the NAAQS are based, conducting environmental assessments, and performing synthetic analyses of the type presented in Section 3. NCEA's global change assessment team has the primary responsibility for developing the reports synthesizing the results of the broad inter-laboratory and extramural research effort represented in this assessment.

3 RESULTS AND SYNTHESIS

3.1 INTRODUCTION

The goal of this section is to synthesize the EPA, and EPA-funded, climate and air quality modeling research that has emerged in Phase I of the assessment. The material presented here is intended to map onto each of the two intertwining readings introduced in Section 1, i.e., "science" and "policy," that run through the report and reflect the two "grand challenges" of evaluating the state of the science and providing a foundation on which effective decision support can be built.

Section 3.2 provides brief summaries of activities and key findings to date from each of the participating modeling groups. Section 3.3 attempts to assess the larger meaning of the groups' results when they are examined all together, focusing on inter-group comparisons of the simulation outputs that are largely common to all (or most)—it provides a preliminary synthesis by taking a broad view across this subset of assessment results. Section 3.4 discusses the challenges and uncertainties associated with the modeling approach that underpins the assessment.

As the EPA's assessment activities continue, overall understanding will grow richer and techniques will become more refined. Thus, it will be possible to build on the foundation provided by this first attempt to interpret this evolving body of work.

3.2 SUMMARY OF RESULTS FROM INDIVIDUAL GROUPS

Results discussed throughout the rest of this section are drawn from the intramural, EPA work, as well as from several STAR-funded extramural initiatives. More detailed descriptions of the experimental designs and results of the extramural (Appendix D) and intramural (Appendix E) efforts are given in the appendices to this report.

The projects highlighted here largely share similar fundamental goals and approaches and can be divided into two major groups: (1) those that, to date, have primarily used global climate and chemistry models to focus on the large-scale changes in future U.S. air quality,[9] and (2) those that have used nested, high-resolution, global-to-regional modeling systems to focus on the regional details of the potential future changes.[10] All of these projects adapt existing modeling tools (as described in Section 2) as components for assembling their systems, including GCTMs,

[9] The Harvard University and Carnegie Mellon University teams.

[10] The EPA National Exposure Research Laboratory (NERL), Columbia University, University of Illinois, Washington State University, University of California, Berkeley, and Georgia Institute of Technology (GIT)-Northeast States for Coordinated Air Use Management (NESCAUM)-Massachusetts Institute of Technology (MIT) teams.

GCMs, RCMs, and RAQMs, along with emissions models and a number of boundary and initial conditions datasets. They all apply these modeling systems in numerical experiments designed broadly to investigate the impacts of future global climate change on U.S. air quality for present-day and future time periods.

It is important to consider both the global model simulations and the downscaled regional simulations together, because each method has its strengths and weaknesses. The global models simulate the whole world in an internally self-consistent way across both climate and chemistry, but because of computational demand must use coarse spatial resolution, thereby potentially missing or misrepresenting key processes. Dynamical downscaling with an RCM dramatically increases the resolution and process realism for the region of interest, but at the expense of introducing lateral boundary conditions into the simulation. Section 3.4 provides additional discussion of these relative advantages and trade-offs. Examining both sets of results gives us a more complete picture of the overall climate-air quality system.

In addition to any similarities in approach, however, each project brings unique and complementary differences in emphasis to these tasks. In aggregate, these differences add greatly to the richness of the overall assessment. Below are brief summaries of selected key themes and findings from each of these research efforts as a prelude to the more focused inter-group comparisons of Section 3.3.

3.2.1 GCTM-Focused Modeling Work

3.2.1.1 *Application of a Unified Aerosol-Chemistry-Climate GCM to Understand the Effects of Changing Climate and Global Anthropogenic Emissions on U.S. Air Quality: Harvard University*

In early work for this project, the Harvard research group examined the role of potential changes in atmospheric circulation by carrying out GCM simulations, using the Goddard Institute for Space Studies (GISS) GCM version II′, for the period 1950−2052, with tracers representing carbon monoxide (CO) and black carbon (BC) (Mickley et al., 2004). They based the concentrations of greenhouse gases for the historical past on observations, while future greenhouse gases followed the A1b IPCC SRES scenario. A key result from these simulations is a future 10% decrease in the frequency of summertime mid-latitude surface cyclones moving across southeastern Canada and a 20% decrease in cold surges from Canada into the Midwest. Since these events typically clear air pollution in the Midwest and Northeast, pollution episodes in these regions increase in duration (by 1−2 days) and intensity (by 5−10% in pollutant concentration) in the future. These simulated future circulation changes are consistent with findings from some other groups in the broader climate modeling community, and the Harvard model also successfully reproduces the observed 40% decrease in North American cyclones from