

UC Irvine

UC Irvine Previously Published Works

Title

Tropospheric hydroxyl and atomic chlorine concentrations, and mixing timescales determined from hydrocarbon and halocarbon measurements made over the Southern Ocean

Permalink

<https://escholarship.org/uc/item/0xr587s2>

Journal

Journal of Geophysical Research, 104(D17)

ISSN

0148-0227

Authors

Wingenter, Oliver W
Blake, Donald R
Blake, Nicola J
[et al.](#)

Publication Date

1999-09-20

DOI

10.1029/1999jd900203

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed

Tropospheric hydroxyl and atomic chlorine concentrations, and mixing timescales determined from hydrocarbon and halocarbon measurements made over the Southern Ocean

Oliver W. Wingenter,¹ Donald R. Blake, Nicola J. Blake, Barkley C. Sive,² and F. Sherwood Rowland

Department of Chemistry, University of California, Irvine

Elliot Atlas and Frank Flocke

Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, Colorado

Abstract. During the First Aerosol Characterization Experiment (ACE 1) field campaign, 1419 whole air samples were collected over the Southern Ocean, of which approximately 700 samples were collected in the marine boundary layer (MBL), 300 samples were taken in the free troposphere (FT), and the remainder were collected in the buffer layer (BuL), the layer between the MBL and FT. Concentrations of tetrachloroethene, ethane, ethyne, and propane decayed over the 24 day duration of the intensive portion of the field campaign, which began November 18, 1995. This decline was consistent with what is known about seasonal increase of HO and the seasonal decrease in biomass burning. Using a simple empirical model, the best fit to the observations was obtained when the average [HO] was $6.1 \pm 0.3 \times 10^5$ HO cm⁻³, and an average [Cl] of 720 ± 100 Cl cm⁻³. The corresponding exchange times were 14 ± 2 days between the MBL and FT, and $49 +40/-13$ days between the MBL in the intensive campaign region and the MBL region to the north (nMBL).

1. Introduction

Knowledge of the oxidative capacity of the atmosphere, and the contributions to it from various short-lived free radicals such as hydroxyl (HO), atomic chlorine (Cl), and nitrate (NO₃), is crucial in assessing the lifetimes and impacts of many greenhouse and/or ozone-depleting gases, such as methane and methyl chloroform. In the troposphere, many important trace gases, such as hydrocarbons, hydrohalocarbons, carbon monoxide, and dimethyl sulfide (DMS), are primarily removed from the atmosphere by reaction with HO radicals. In some polluted air masses, oxidation by Cl and NO₃ can be significant [Blake *et al.*, 1993; Wingenter *et al.*, 1996]. The oxidation of DMS and its products can lead to the formation of sulfate aerosols, which affect the Earth's radiative budget [Charlson *et al.*, 1987]. Several articles addressing the oceanic and atmospheric distribution of DMS in the First Aerosol Characterization Experiment (ACE 1) study region can be found in the first ACE 1 special section and in this issue [e.g., Curran *et al.*, 1998; De Bruyn *et al.*, 1998; Blake *et al.*, this issue].

¹Now at School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta.

²Now at Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder.

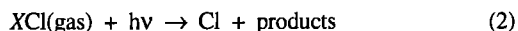
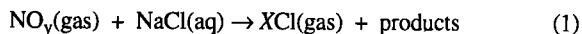
Copyright 1999 by the American Geophysical Union.

Paper number 1999JD900203.
0148-0227/99/1999JD900203\$09.00

On a global and quarter hemispheric scale, HO concentrations and seasonality have been determined by methyl chloroform inference [Singh *et al.*, 1979; Prinn *et al.*, 1995]. Local quantification of HO mixing ratios has been achieved during only a limited number of field experiments, either by measurement [e.g., Wennberg *et al.*, 1994; Eisele *et al.*, 1994; Poppe *et al.*, 1994], or indirectly from temporal changes in nonmethane hydrocarbon (NMHC) concentrations in well defined air masses [e.g., Wingenter *et al.*, 1996; Blake *et al.*, 1993; Roberts *et al.*, 1984]. Unfortunately, many of these experiments employing NMHCs with different reactivities have yielded a wide range of [HO] estimates within the same data set [Singh *et al.*, 1981; Roberts *et al.*, 1984; Blake *et al.*, 1993]. This variation has been attributed to atmospheric dilution effects [McKeen *et al.*, 1990; Parrish *et al.*, 1992; McKeen and Liu, 1993; Jobson *et al.*, 1994a], or to the influence of Cl chemistry [Finlayson-Pitts, 1993]. By simultaneously optimizing calculated mixing ratios of several different NMHCs to their observed mixing ratios, Wingenter *et al.* [1996] calculated HO and Cl concentrations and the amount of vertical mixing. Recently, Ehhalt *et al.* [1998] provided an outline on the use of NMHC data along with various model types for the determination of HO concentrations.

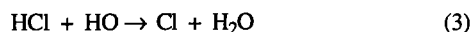
There has been considerable interest in recent years regarding the quantification of tropospheric Cl radicals and their impact on the oxidative capacity of the troposphere [Singh and Kasting, 1988; Keene *et al.*, 1990; Finlayson-Pitts, 1993; Graedel and Keene, 1995; Singh *et al.*, 1996a, b; Wingenter *et al.*, 1996]. Three types of Cl atom precursor

reactions have been identified, all of which require sea-salt aerosol and either NO_y (NO , NO_2 , N_2O_5 , HNO_3 , etc.), degassing of HCl , or the oxidation of Cl^- by O_3 , HO , or HO_2 . The NO_y reactions generally proceed as



where XCl is an easily photolyzed Cl species, such as Cl_2 , NOCl , ClNO_2 , or HOCl , which can accumulate overnight and dissociate within about 1 hour after sunrise [Green, 1972; Finlayson-Pitts, 1983; Zetzsch et al., 1988; Finlayson-Pitts et al., 1989].

Degassing of HCl is enhanced under polluted conditions, namely, when acidic compounds such as H_2SO_4 or HNO_3 are present. The subsequent reaction with HO ,



produces Cl [Clegg and Brimblecombe, 1985; Singh and Kasting, 1988]. Chlorine atoms are also produced in the reactions of HO , HO_2 , or O_3 with Cl^- associated with sea-salt aerosols [see Keene et al., 1990 and references therein].

Recently, attempts have been made to estimate the average tropospheric Cl mixing ratio [Singh et al., 1996b; Rudolph et al., 1996]. The two dimensional (2-D) models used in these studies relied on assessing the budget of tetrachloroethene, which is emitted by anthropogenic sources and whose emissions are thought to be accurately inventoried. Once all the source and sink terms for tetrachloroethene are accounted for, the loss by reaction with Cl atoms is invoked to balance the budget. This method requires the accurate determination of the tetrachloroethene emissions, tetrachloroethene burden, and the HO field. Initial estimates have yielded average tropospheric Cl concentrations in the low 10^3 Cl atoms cm^{-3} range, with considerable uncertainty [Singh et al., 1996b; Rudolph et al., 1996].

Observations of the seasonal variation of halocarbons and hydrocarbons not only provide information on the average oxidative capacity of the atmosphere, but also on its seasonality. Seasonal variations of NMHCs and tetrachloroethene in the northern hemisphere (NH) [e.g., Blake and Rowland, 1986; Singh and Zimmerman, 1992; Penkett et al., 1993; Rudolph, 1995; Wang et al., 1995] have been reported but few observations exist for the southern hemisphere (SH) [Blake and Rowland, 1986; Rudolph et al., 1989; Wang et al., 1995]. Maximum background hydrocarbon levels are observed in winter months, with minimum levels occurring during summer. In the NH, longer lived gases tend to reach their minimum concentration later in the solar year compared to gases that react more quickly with HO [e.g., Penkett et al., 1993; Jobson et al., 1994b; Goldstein et al., 1995].

The International Global Atmospheric Chemistry (IGAC) sponsored First Aerosol Characterization Experiment (ACE 1) field campaign intensive period, mid-November to mid-December 1995, was conducted over the pristine Southern Ocean region south of Australia. The primary focus of ACE 1 was to observe the formation and growth of new particles from their precursors and observe their effect on cloud formation and radiative properties [Bates et al., 1998]. Measurements were made at two coastal sites, aboard two research ships, and aboard the National Center for Atmospheric Research (NCAR) C-130 aircraft, from which UC Irvine collected whole air

samples [Bates et al., 1998]. One of the principal objectives for the UCI NMHC and halocarbon measurements was to indicate when any of the air masses sampled by the NCAR C-130 had been influenced by recent emissions [see also Blake et al., this issue].

Two Lagrangian experiments, similar to those that were performed during the Atlantic Stratocumulus Transition Experiment/Marine Aerosol and Gas Exchange (ASTEX/MAGE) experiment in the North Atlantic [Wingenter et al., 1996] were conducted during ACE 1. However, with the exception of ethane [Sive, 1998], the much cleaner Southern Ocean boundary layer exhibited NMHC mixing ratios that were too low to observe temporal changes during the short timescale of these Lagrangian experiments. By contrast, temporal changes were observed during the period of the entire campaign, allowing an Eulerian reference frame to be employed. An Eulerian reference frame is one in which the observer moves relative to the air mass sampled. For example, a moving platform such as a ship steaming into the wind, or by remaining stationary on an island with air masses being advected past. This paper describes Eulerian observations of NMHCs and tetrachloroethene made during the intensive portion of ACE 1. From these observations, concentrations of HO and Cl , as well as the vertical and horizontal mixing timescale between air masses, have been calculated using a simple, empirical three-box model. Lower tropospheric aircraft measurements of in situ HO concentrations were also made on board the NCAR C-130 [Mauldin et al., 1998]. The time average concentration of the in situ HO measurements is compared with the HO estimate derived from our Eulerian observations of NMHCs and tetrachloroethene.

2. Experiment

More than 2500 whole air samples were collected during 33 ACE 1 flights on board the NCAR C-130 aircraft. The samples were assayed for various halocarbons and NMHCs. Data used for part of this paper are the tetrachloroethene, ethane, ethyne, and propane mixing ratios made from more than 1500 samples collected on 18 local flights flown November 18 through December 12, 1995, out of Hobart, Tasmania, Australia (40°S - 55°S latitude and 135°E - 160°E longitude) and two transit flights made just north of this area on November 10 and December 15, 1995. The air sampling apparatus used for ACE 1 was very similar to the ASTEX system [Blake et al., 1996]. A maximum of 96 samples per flight could be collected. NMHCs and halocarbons from each whole air sample were quantified by complementary five-column gas chromatography using three electron capture detectors (ECD) and three flame ionization detectors (FID). Five different separation columns were contained in four independently programmed Hewlett-Packard 5890 Series II gas chromatographs (GCs). In the first GC a 50 m x 0.32 mm $\text{Al}_2\text{O}_3/\text{Na}_2\text{SO}_4$ porous layer open tubular (PLOT) column was coupled to an FID to separate and quantify C_2 - C_5 NMHCs. Installed in GC two was a 60 m x 0.25 mm DB-1 column with a 1 mm film thickness. The effluent separated by the DB-1 column was split. A portion of the flow was directed to an ECD, which measured C_1 and C_2 halocarbons, and the remainder of the flow went to an FID for quantification of C_3 - C_{10} NMHCs. In the third GC, a 60 m x 0.25 mm DB-5 MS column with the film thickness of 0.5 mm was coupled to an

ECD for separating and quantifying halocarbon compounds. The fourth GC contained two columns; a 60 m x 0.25 mm CD-B/Cyclodex column coupled to an FID, which separated and detected higher molecular weight NMHCs, and a composite column, which consisted of a 30 m of DB-1 column spliced to 30 m of a DB-5 MS column, which along with an ECD, separated and detected C₁ and C₂ halocarbons. The detector signals were sent to six Spectra Physics 4400 computing integrators and an IBM 486 personal computer using Labnet software for data capture and storage. This configuration allowed for six simultaneous yet separate chemical analyses from the same sample.

For ACE 1, a 1520 cm³ (at STP) aliquot of each sample was trapped on a preconcentration loop filled with 3 mm diameter glass beads, immersed in liquid nitrogen. Once the sample was trapped, the preconcentration loop was isolated and warmed to 80°C, then injected and directed by hydrogen carrier gas to the GCs. The split was reproduced with high precision, and 27.0% of the carrier flow was directed to the PLOT column, 18.9% was directed to the DB-1/ECD, 16.1% was directed to the DB-1/FID, 16.2% was directed to the DB-5MS/ECD, 11.0% was directed to the Cyclodex-B/FID, and 10.8% was directed to the DB-1/DB-5MS/ECD composite column. A 40 L x 2000 psig whole air sample collected at the Scripps Institute for Oceanography pier, La Jolla, California, was used as the working standard. The standard was assayed after every four samples in the same manner used to analyze the canister samples [Blake *et al.*, 1996]. Two other pressurized whole air standards were periodically assayed to ascertain the integrity of the working standard over time.

An upper estimate of the measurement precision for the gases quantified during the ACE 1 local flights can be determined from eight samples collected in the MBL, at about 500 feet, during a 34 min period of flight 16. The mean mixing ratios, along with the corresponding 1 σ precisions were (in parts per trillion by volume (pptv)): Tetrachloroethene, 1.39 ± 0.05 ; ethane, 314.4 ± 1.0 ; ethyne, 20.4 ± 1.4 ; and propane, 6.3 ± 1.5 . The absolute calibration of these standards and further analytical details are described by Blake *et al.* [1992, 1994], and Sive [1998].

3. Eulerian Observations and Model Description

Meteorological parameters provided by NCAR describing relative humidity, temperature, potential temperature (THETA), and equivalent potential temperature (THETA E) enabled the samples from each flight to be grouped into three vertical layers, the marine boundary layer (MBL), free troposphere (FT), and buffer layer (BuL). Typically, the MBL extended from the surface to about 500-1000 m, while the FT was above an altitude of approximately 3000 m. One example from flight 18 is shown in Figure 1. Figure 2 displays the average concentrations and one standard deviation of the mean error bars for tetrachloroethene, ethane, ethyne, and propane for each of the local flights. Best fit curves to the average temporal mixing ratio data were calculated, employing a function with two exponential terms, in order to approximately describe atmospheric mixing and photochemistry. The average FT mixing ratios are plotted in Figure 3.

Comparison of Figures 2a and 3a reveals that there is no statistical difference between the tetrachloroethene mixing ratios measured in the MBL and the FT. Because 93% of

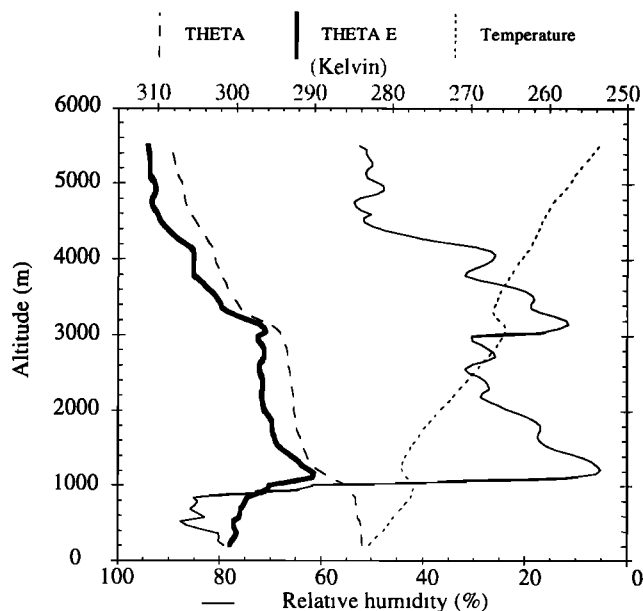


Figure 1. Potential temperature, equivalent potential temperature, temperature, and relative humidity observed during the first sonding of flight 18. The transitions at about 900 m mark the height of the MBL, and the transitions at approximately 3000 m indicate the top of the BuL.

tetrachloroethene emissions occur in the NH (P. Midgley, personal communication, 1997) and its lifetime is of the order of 4 months, tetrachloroethene is expected to be well mixed in the SH. However, the scatter about the curve is larger in the FT, indicating greater atmospheric variability compared to the MBL. In contrast to tetrachloroethene, the FT ethane mixing ratios shown in Figure 3b are considerably greater than in the MBL (Figure 2b). Ethane has a lifetime of approximately 2.5 months (these lifetimes are based on our HO and Cl estimates and the rate constants evaluated by DeMore *et al.* [1997]). Thus a substantial southern hemispheric source of ethane originating outside the high southern latitude region is necessary to maintain this observed vertical gradient. The most likely source of ethane into this region is from biomass burning [Rudolph, 1995; Blake *et al.*, this issue].

As seen in Figure 2, the best fit curve for tetrachloroethene and ethane appear to be at the inflection of their seasonal cycles, and closer to their maximums than ethyne and especially propane, which are closer to their minimums as indicated by their decreasing negative slopes. These springtime NMHC trends are consistent with NH observations of [Penkett *et al.* [1993], Jobson *et al.* [1994b], Goldstein *et al.* [1995].

An empirical three-box model was constructed to represent the MBL and FT in the region of the ACE 1 intensive. The model is designed to estimate [HO] and [Cl] in the MBL, and the exchange times between the MBL and the FT (τ_{ex1}), as well as between the MBL and the nMBL, τ_{ex2} . The concentrations in the buffer layer (BuL) were very similar to those measured in the MBL, and mixing between the MBL and the BuL mainly recycles air between these two layers. Thus this layer acts to "buffer" dilution by impeding direct mixing with the FT as described by Wingenter *et al.* [1996]. Therefore this layer was not included in the following calculations. A detailed

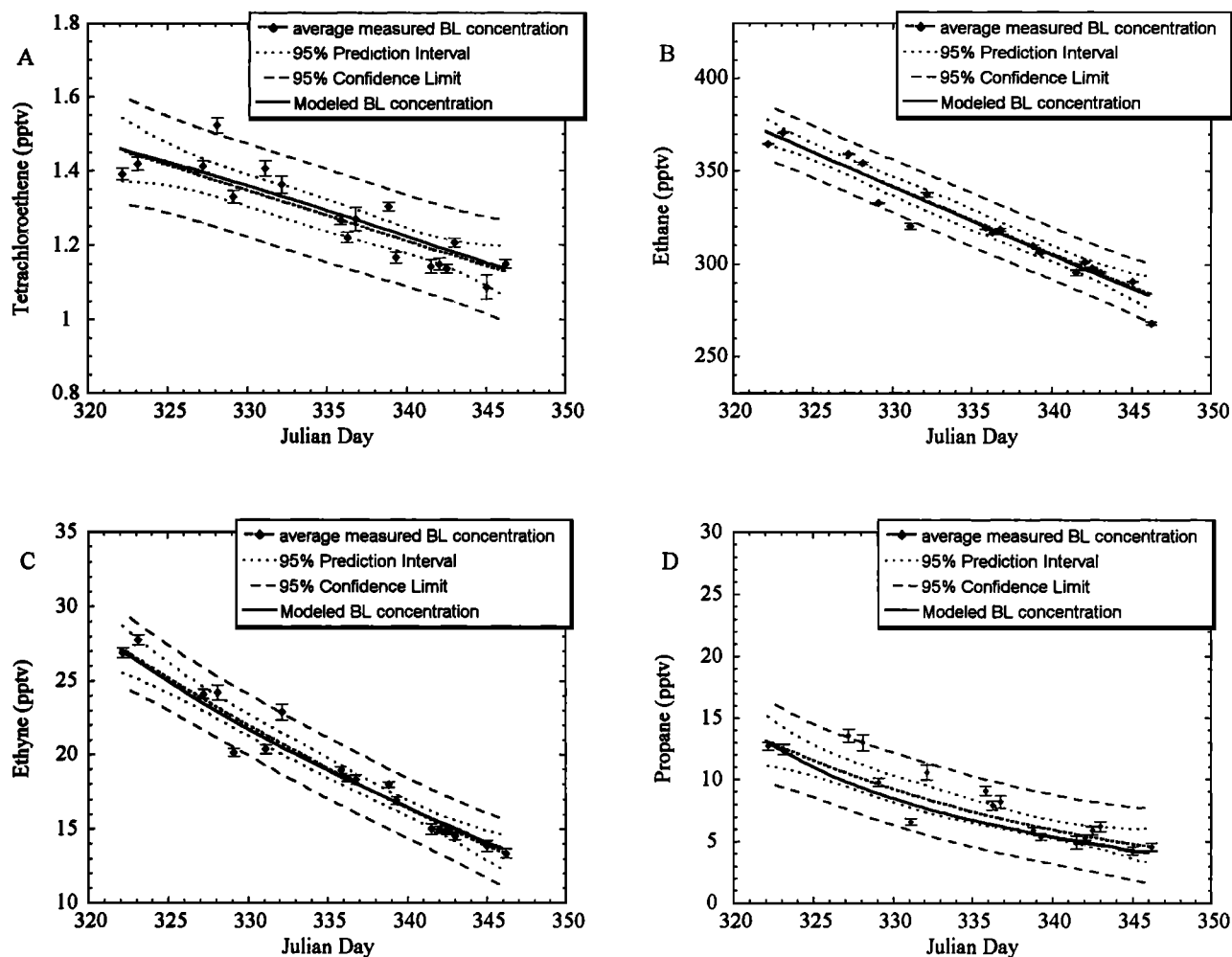


Figure 2. Measured and modeled MBL results for (a) tetrachloroethene, (b) ethane, (c) ethyne, and (d) propane ACE 1 local flights. The diamonds represent the average measured MBL concentration with standard deviation of the mean error bars. The innermost dashed line is the best fit curve (having two exponential terms) of the measurements. The dotted curves represent the 95% prediction interval for the best fit curve. The outer dashed curves represent the 95% confidence interval for the measurements. The solid curve represents the modeled MBL concentrations.

description of the BuL observed during ACE 1 is given by *Russell et al.* [1998]. Thus the average mixing time constant calculated for the exchange between the MBL and the FT (and similarly the exchange between the MBL and nMBL) represents the time needed to reduce the gradient between the MBL and the FT by a factor of 69% (the natural log of 2) in the absence of any other sources or sinks. The MBL and FT concentrations used in the model were taken from the measurements shown in Figures 2 and 3 and those from the marine boundary layer directly to the north (nMBL). The nMBL concentrations employed in the model are from the linear fit to the average concentrations of samples collected between 30°S and 40°S on the transit flights before and after the ACE 1 intensive flights (Table 1).

The model calculates [HO], [Cl], and the two exchange times by varying these parameters such that the sum of the weighted residuals, simultaneously calculated from the predicted MBL values of tetrachloroethene, ethane, ethyne, and propane and the measured mixing ratios in the MBL, are minimized. This is described as follows:

$$C_{i\text{MBLcalc}}(t) = C_{i\text{MBL}}(0) - [C_{i\text{MBL}}(0)/\tau + \{C_{i\text{FT}} - C_{i\text{MBL}}\}/\tau_{\text{ex1}} + \{C_{i\text{nMBL}} - C_{i\text{MBL}}\}/\tau_{\text{ex2}}]t \quad (4)$$

where $C_{i\text{MBLcalc}}(t)$ is the calculated MBL concentration of species i , either tetrachloroethene, ethane, ethyne, or propane in the MBL at time t and $C_{i\text{MBL}}(0)$ is the initial concentration. $C_{i\text{MBL}}(0)/\tau$ is the change in concentration due to chemical loss, where τ is in the sum of the HO and Cl lifetimes ($1/\tau = \{k_{i\text{HO}}[\text{HO}] + \{k_{i\text{Cl}}[\text{Cl}]\}$). The rate constants, $k_{i\text{HO}}$ and $k_{i\text{Cl}}$, are taken from *DeMore et al.*, [1997] (see Table 2), and [HO] and [Cl] represent the time-averaged concentrations of HO and Cl. The next term, $\{C_{i\text{FT}} - C_{i\text{MBL}}\}/\tau_{\text{ex1}}$, is the change in concentration resulting from mixing of FT air with the MBL. Similarly, the last term is the change in concentration in the MBL as a result of exchange with the nMBL. It is noted here that the model does not have direct sources and all input occurs because of mixing. Figure 4, for example, shows that no plumes were observed in the MBL, supporting this assumption [*Blake et al.*, 1999, and this issue].

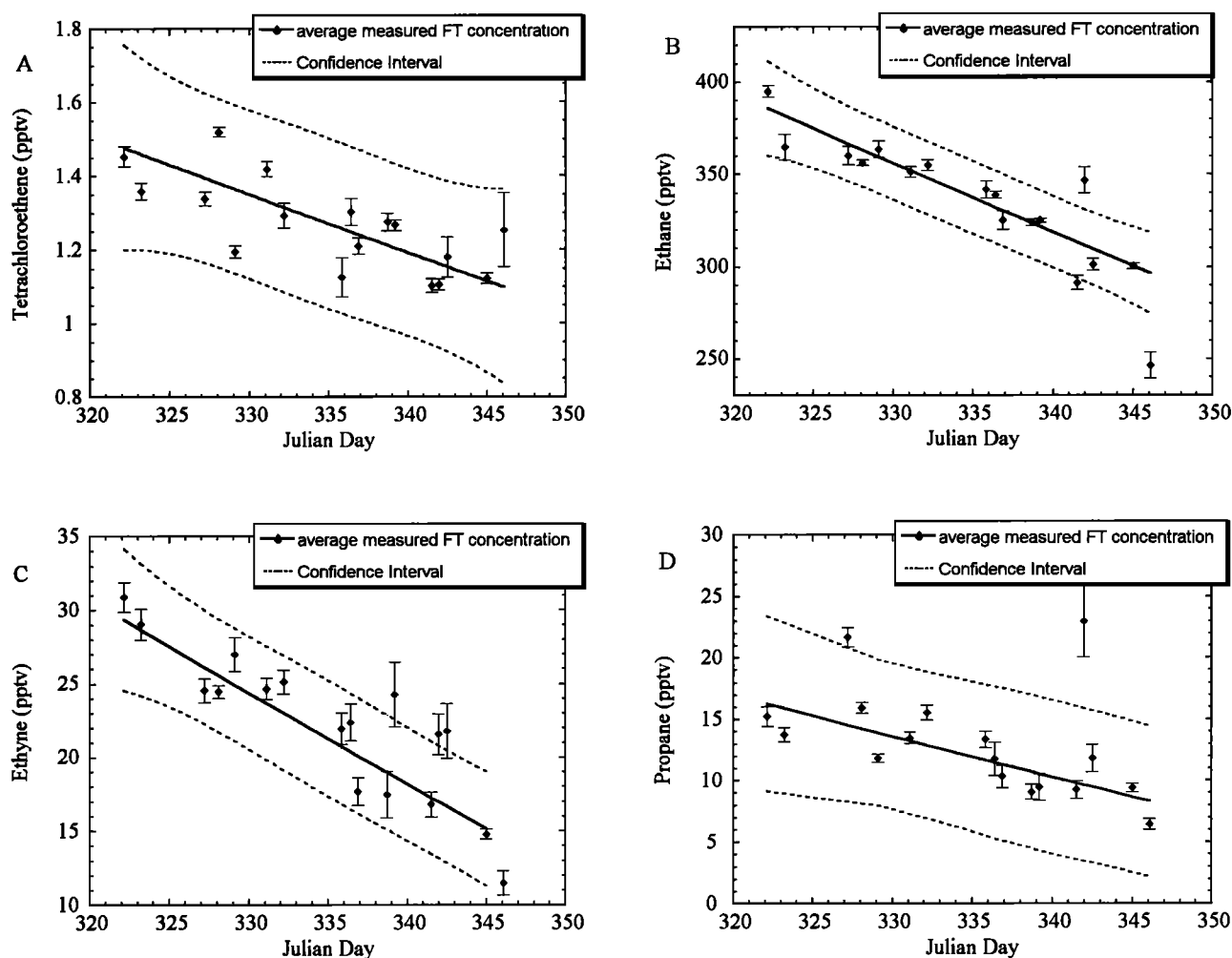


Figure 3. Measured FT (a) tetrachloroethene, (b) ethane, (c) ethyne, and (d) propane results for the ACE 1 local flights. The diamonds represent the average measured concentration with standard deviation of the mean error bars. The solid curve is the best fit (having two exponential terms) of the measurements. The outer dashed curves represent the 95% confidence interval for the measurements.

The program simultaneously recalculates equation (4), for all four gases to minimize S , the sum of individual X^2 in equation (5), until it obtains the best fit for the parameters used:

$$S = \sum w_i [C_{\text{MBLObs}}(t) - C_{\text{MBLcalc}}(t)]^2 \quad (5)$$

w_i is the statistical weight defined in equation (6),

$$w_i^{-1} = \sigma R_{\text{MBLObs}}(t)^2 \quad (6)$$

where σ is the estimated error (the sum of the relative analytical error and the scatter of the data about the best fit curve) and $R_{\text{MBLObs}}(t)$ is the ratio of the observations at t over the initial observations.

The model MBL values, average MBL concentrations, and the prediction intervals for the best fit curves to the average MBL measurements are plotted in Figure 2. In Figure 2a the modeled tetrachloroethene values compare well with the tetrachloroethene best fit to the data. The model values were on average 0.01 pptv greater than the best fit curve. The modeled ethane values in Figure 2b agree to within an average of 0.5 pptv with the best fit curve of the measurements.

Ethyne values predicted by the model agree well with the best fit curve to the data, with a maximum deviation from the curve of 0.3 for pptv (Figure 2c). Predicted propane values were on average 0.6 pptv below the measurement best fit, but still within the 2σ prediction interval of the best fit to the data. In general, the predicted values agree well with the measurements.

Optimal model fits were obtained when HO and Cl values were $6.1 \pm 0.3 \times 10^5$ HO cm^{-3} and 720 ± 100 Cl cm^{-3} , with

Table 1. Average Mixing Ratios for Samples Collected in the MBL North of the Intensive MBL Before and After the Hobart Local Flights

	Flight 8	Flight 29
Tetrachloroethene	1.47 ± 0.03	1.09 ± 0.02
Ethane	369.9 ± 1.2	253.8 ± 0.8
Ethyne	31.6 ± 0.3	14.3 ± 0.04
Propane	11.0 ± 0.4	5.4 ± 0.5

Mixing ratios are in pptv.

Table 2. HO and Cl Rate Constants, Ratios of Rate Constants, and Calculated Percent Contribution of HO and Cl to Chemical Loss

	kHO	kCl	kHO/kCl	Calculated Percent Loss By ^a	
				HO	Cl
Tetrachloroethene ^b	1.2E-13 ^c	4.0E-11	323	72	28
Ethane	1.8E-13	5.6E-11	304	74	26
Propane	9.2E-13	1.4E-10	150	85	15
Ethyne ^{b,d}	6.7E-13	5.9E-11	88	91	9
Methane	4.0E-15	7.0E-14	17	98	2
Methyl chloroform	6.7E-15	4.4E-15	0.7	100	0
DMS ^e	4.7E-12	3.3E-10	70	92	8
Methyl bromide	2.0E-14	3.3E-13	16	98	2

All rate constants (*DeMore et al.* [1997] or *Stickel et al.* [1992]) are expressed as second-order reactions having units of $\text{cm}^3 \text{molecules}^{-1} \text{s}^{-1}$. The average MBL temperature used was 277 K.

^aPercent loss is $kX \cdot [X]/(kHO \cdot [HO] + kCl \cdot [Cl])$; where X is either HO or Cl.

^bThe kCl is the three-body rate constant taken at a pressure equivalent to 350 m.

^cRead 1.2E-13 as 1.2×10^{-13} .

^dThe kHO is the three body rate constant taken at a pressure equivalent to 350 m.

^eHere kCl is from *Stickel et al.* [1992].

vertical mixing between the MBL and FT 14 ± 2 days and horizontal mixing $49 \pm 40/-13$ days. Error estimates are arbitrarily based on varying one parameter while holding the other three constant until S (equation (5)) was 3 times greater than the best fit.

4. Discussion and Comparison of ACE 1 Eulerian Results

Four day back trajectory analysis [*Whittlestone et al.*, 1998] (for an overview of the meteorology, see also *Hainsworth et al.* [1998]) shows that the air parcels reaching the intensive sampling region originated between 40°S and 60°S latitude, with a mostly westerly flow. This indicates that the air masses were representative of the mid-latitude/subpolar

region. Potential interference with our results could occur if direct emissions of tetrachloroethene, ethane, ethyne, and propane were introduced upstream of the ACE 1 intensive region, and remained in the MBL. However, the homogeneous air masses encountered indicate a lack of recent emissions in the region (see Figure 4 and Table 3 and *Blake et al.* [this issue]), and NOAA advance very high resolution radiometer (AVHRR) satellite imagery shows virtually no biomass burning occurring in any part of this region for either November or December 1993, the most recent year in which the data are fully processed for these regions (<http://shark1.esrin.esa.it/>). In addition, 93% of tetrachloroethene is emitted in the NH (*P. Midgley*, personal communication, 1997) and is well mixed in this region (Figures 2a and 3a). The largest emissions of ethane, ethyne

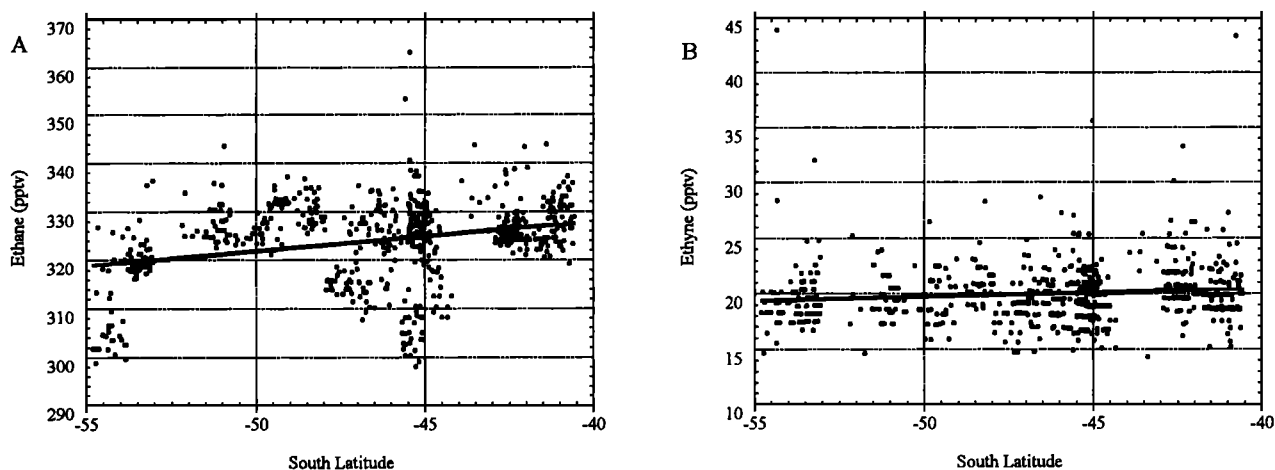


Figure 4. Latitudinal profile of more than 700 (a) ethane, and (b) ethyne samples collected in the ACE 1 intensive MBL. The samples were normalized for the temporal trend shown in Figure 2 to the midpoint time of the experiment. The solid curve is the linear least squares best fit.

Table 3. Summary of Results for the Linear Regressions Plotted in Figure 4

	Gradient pptv/Latitude	R ²	Total ^a pptv	Average Mixing Ratio ^b pptv	Percent ^c
Tetrachloroethene	1.1E-03	1.1E-03	1.5E-02	1.29	1.1
Ethane	6.1E-01	8.0E-02	8.5E+00	326	2.6
Ethyne	7.5E-02	1.1E-02	1.1E+00	19.7	5.3
Propane	1.1E-02	1.2E-04	1.6E-01	8.7	1.8

^aTotal change in concentration over the entire latitudinal range.

^bThe average mixing ratios were determined from the best fit curves in Figures 2-5 at midpoint time.

^cTotal divided by the average mixing ratio multiplied by 100.

and propane in the SH are from seasonal biomass fires [Rudolph, 1995; Singh and Zimmerman, 1992; Andreae et al., 1994]. The majority of these emissions occur in the southern Tropics between July and October [Justice et al., 1996; Cahoon et al., 1992]. The lack of recent direct emissions contributed to the homogeneity of the region. This coupled with the large number of observations and the considerable time period of the experiment allowed for the observation of the decay of tetrachloroethene, ethane, ethyne, and propane in an Eulerian reference frame.

4.1. Comparison of Inferred HO With Measurements

Our diurnally averaged HO values compare well with the diurnal averaged HO measurements of Mauldin et al. [1998] made on board the NCAR C-130 during this project. From the in situ measurements it is apparent that HO noontime mixing ratios have a bimodal distribution with average diurnal concentrations of 1×10^6 and 4×10^5 HO cm⁻³ depending on whether clear-sky or cloudy conditions, respectively, were encountered. Satellite imagery of the region suggests approximately 60-70% cloudy conditions, yielding average diurnal concentration of 6×10^5 HO cm⁻³ based on the direct measurements. However, simply averaging the measurements diurnally for each flight also yields an average diurnal HO concentration of 6×10^5 HO cm⁻³ during the study period. Thus our calculated [HO] is in excellent agreement with experimental values.

4.2. Comparison of [Cl] in Polluted and Pristine Environments

The springtime Southern Ocean Cl concentration estimate of 720 ± 100 Cl cm⁻³ are 2 orders of magnitude lower than estimated for polluted NH air masses [Wingenter et al., 1996; Pszenny et al., 1993]. During the ASTEX/MAGE project, Cl concentrations were estimated from a single polluted air mass [Wingenter et al., 1996] with high sea-salt aerosol concentrations [Clarke et al., 1996]. The ACE 1 Cl concentration estimate is the diurnal average over 24 days, which included periods after storms when sea-salt aerosol had been washed out [Clarke et al., 1998a]. Ozone and HO concentrations during ACE 1 were not low enough in comparison to ASTEX/MAGE to account for the 2 order of magnitude differences in calculated Cl. However, concentrations of NO_y were most likely very much lower during ACE 1 (e.g., reactions (1) and (2)) because these air masses were clean marine. Unfortunately, NO_y was not

measured during ACE 1. Furthermore, the low concentrations of NO, observed in the boundary layer on board the NCAR C-130 (~3 pptv) during ACE 1, shifts the ClO_x photostationary state in favor of reduced Cl and increased ClO. In comparison with the pristine background conditions over the Southern Ocean, it appears that polluted NH air masses considerably favor the production of atomic Cl compared to clean southern hemispheric marine air masses.

Singh et al. [1996b] estimate that because Cl is generated by sea-salt aerosol, about 90% of tropospheric chlorine atoms resides in the MBL. Employing this assumption would lead to an integrated tropospheric Cl value over the Southern Ocean in springtime of approximately 100 Cl cm⁻³. This estimate is an order of magnitude less than the global estimates of Singh et al. [1996b] and Rudolph et al. [1996].

4.3. Comparison of the Oxidative Capacity of HO and Cl

Chemical loss by Cl in the MBL during the springtime Southern Ocean is significant for tetrachloroethene, ethane, propane, and to a lesser extent ethyne (Table 2). Chemical loss by Cl and HO at the concentrations determined in this work are also compared in Table 2 for some stratospheric ozone-depleting substances such as methyl bromide and methyl chloroform, the greenhouse gas methane, and DMS, the main precursor to new sulfate particle growth in the clean MBL [Clarke et al., 1998b]. At the average Cl levels encountered during ACE 1, Cl oxidation has little impact on methyl bromide, methyl chloroform, or methane. However, 8% of the chemical removal of DMS in the MBL is a result of Cl oxidation.

4.4. Vertical Transport of Methyl Nitrate

Transport times from the boundary layer to the FT can also be estimated by employing the vertical distribution of short-lived gases having surface sources [Davis et al., 1996]. Methyl nitrate concentrations of the 1419 samples collected during the ACE 1 intensive experiment were partitioned into 0.5 km bins. The averages are plotted versus altitude in Figure 5. The ocean is the only known significant direct source of methyl nitrate to the atmosphere (E. Atlas et al., manuscript in preparation, 1999). The primary removal process for methyl nitrate is photolysis, having a lifetime of about 29 days in the midlatitude MBL near the equinox [Talukdar et al., 1997] and a hydroxyl lifetime of about a 100 days at 6×10^5 HO cm⁻³ for an overall MBL lifetime of about 22 days. During ACE 1 the average MBL methyl nitrate mixing ratio was about 19 pptv,

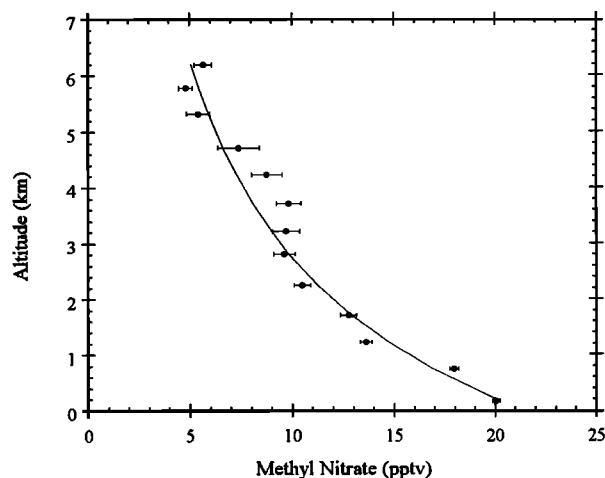


Figure 5. Vertical distribution and best fit curve (having two exponential terms) of methyl nitrate, during the ACE 1 intensive experiment.

decreasing to about 5.5 pptv at 5.3 km. This change in concentration is expected, in the absence of dilution, if the MBL concentration was allowed to decay one lifetime with no further input from its source. Therefore, because dilution played some role in the transport from the MBL to the FT, an upper limit of about 22 days is estimated. This is in good agreement with our 14 day MBL exchange time estimated above by employing the three-box model. Note, in Figure 5 there appears to be transitions at 1 km and about 4.5 km, marking the approximate upper limits to the MBL/BuL and BuL/FT transitions.

4.5. Model Limitations

This three-box model has certain limitations, namely, the concentrations of the three hydrocarbons and tetrachloroethene to the south of the intensively studied MBL were not measured before and after the project, so that the effects on the ACE 1 intensive MBL from the southern area cannot be directly ascertained. However, when the temporal decrease is removed from the four gases in question and their normalized concentrations are plotted versus latitude, as shown, in Figure 4, along with the best linear fit, very shallow latitudinal gradients are apparent with R^2 of 0.011 at best to 0.00012 (see Table 3 for results). This, and the fact that surface winds were predominantly zonal, leads to the conclusion that meridional mixing was not a major factor in the ACE 1 study region. This point was examined further by not including the nMBL in a model simulation. Although S increased by a factor of 10, the values for HO, Cl, and vertical mixing remained unchanged within the uncertainties cited above. Therefore, if the southern region influence was similar in magnitude to the nMBL, our estimates of HO, Cl, and vertical mixing are still accurate.

Another limitation of this model is that four parameters are being predicted from the time series of only four gases. Unfortunately, shorter lived gases such as butanes or larger hydrocarbons were often times below detection limit and therefore, unsuitable for the analysis in this paper. Gases such as CFCs or HCFCs are too long lived in comparison to the timescale of this experiment to be useful. Therefore, other

possible factors, which are unknown, cannot be detected by their impact on the time series of any other additional gases. However, the close agreement between measured and inferred HO gives confidence to the model. The close agreement between the vertical mixing timescale estimated by the three box model and the methyl nitrate vertical profile also increases the confidence in the model. In fact, the very good agreement between the measured and modeled time series for tetrachloroethene, ethane, ethyne and propane leads to the conclusion that no other parameters are likely significant in contributing to the atmospheric MBL burden of these gases in the ACE 1 intensive study region.

5. Conclusion

The average hydroxyl estimate of $6.1 \pm 0.3 \times 10^5$ HO cm^{-3} for the MBL over the Southern Ocean during the springtime ACE 1 project agrees well with the measured diurnal average. The corresponding Cl concentration estimate in this pristine region of 720 ± 100 Cl cm^{-3} may help elucidate the mechanism(s) responsible for Cl production. Although Cl concentrations were 3 orders of magnitude less than HO, Cl is a significant oxidizer for some trace gases in the MBL because of its greater reactivity with these compounds. Transport times from the MBL to the FT and from the nMBL to the MBL in the intensive study region were 14 ± 2 days and $49 + 40/-13$, respectively. The methyl nitrate vertical gradient was employed for validation of the MBL/FT exchange time calculated using the three-box model. Results from this study may help constrain 2-D and 3-D model values of HO and Cl concentrations as well as transport time scales in this region.

Acknowledgments. We would like to express our appreciation to the excellent team at UCI who worked so hard to produce this data set. They are John Bilicska, Tim Blake, Nancy Coneybeare, Kathi Farrow, Mike Gilligan, Adam Hill, Jenn Lapierre, Brent Love, and Murray McEachern. We are also grateful to Barbara Yu for her help during the project and with the manuscript preparation. This paper benefited from the thorough reviews by C. E. Reeves and an anonymous reviewer. This research is a contribution to the International Global Atmospheric Chemistry (IGAC) Core project of the International Geosphere-Biosphere Program (IGBP) and is part of the IGAC Aerosol Characterization Experiments (ACE). National Science Foundation Grant ATM-9418773

References

- Andreae, M. O., B. E. Anderson, D. R. Blake, J. D. Bradshaw, J. E. Collins, G. L. Gregory, G. W. Sachse, and M. C. Shipham, Influence of plumes from biomass burning on atmospheric chemistry over the equatorial and tropical South Atlantic during CITE 3, *J. Geophys. Res.*, **99**, 12,793-12,808, 1994.
- Bates, T. S., B. J. Huebert, J. L. Gras, F. B. Griffiths, and P. A. Durkee, The International Global Atmospheric chemistry (IGAC) project's First Aerosol Characterization Experiment (ACE 1): Overview, *J. Geophys. Res.*, **103**, 16,297-16,318, 1998.
- Blake, D. R., and F. S. Rowland, Global atmospheric concentration and source strength of ethane, *Nature*, **321**, 231-233, 1986.
- Blake, D. R., D. F. Hurst, T. W. Smith Jr., W. J. Whipple, T. Y. Chen, N. J. Blake, and F. S. Rowland, Summertime measurements of selected nonmethane hydrocarbons in the Arctic and subarctic during the 1988 Arctic Boundary Layer Experiment (ABLE-3A), *J. Geophys. Res.*, **97**, 16,559-16,588, 1992.
- Blake, D. R., T. W. Smith Jr., T. Y. Chen, W. J. Whipple, and F. S. Rowland, Effects of biomass burning on summertime nonmethane hydrocarbon concentrations in the Canadian wetlands, *J. Geophys. Res.*, **99**, 1699-1719, 1994.
- Blake, D. R., N. J. Blake, T. W. Smith Jr., O. W. Wingenter, and F. S. Rowland, Nonmethane hydrocarbon and halocarbon distributions

- during Atlantic Stratocumulus Transition Experiment/Marine Aerosol and Gas Exchange, June 1992, *J. Geophys. Res.*, *101*, 4501-4514, 1996.
- Blake, N. J., S. A. Penkett, K. C. Clemitshaw, P. Anwyl, P. Lightman, A. R. W. Marsh, and G. Butcher, Estimation of atmospheric hydroxyl radical concentrations from the observed decay of many reactive hydrocarbons in well-defined urban plumes, *J. Geophys. Res.*, *98*, 2851-2864, 1993.
- Blake, N. J., et al., Influence of southern hemispheric biomass burning on mid-tropospheric distributions of nonmethane hydrocarbons and selected halocarbons over the remote South Pacific, *J. Geophys. Res.*, in press, 1999.
- Blake, N. J., et al., Aircraft measurements of the latitudinal, vertical, and seasonal variations of NMHCs, methyl nitrate, methyl halides and DMS during ACE 1, *J. Geophys. Res.*, this issue.
- Cahoon, D. R., Jr., B. J. Stocks, J. S. Levine, W. R. Cofer III, and K. P. O'Neill, Seasonal distribution of African savanna fires, *Nature*, *359*, 812-815, 1992.
- Charlson, R., J. Lovelock, M. O. Andreae, and S. Warner, Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate, *Nature*, *326*, 655, 1987.
- Clarke, A. D., T. Uehara, and J. N. Porter, Lagrangian evolution of an aerosol column during the Atlantic Stratocumulus Transition Experiment, *J. Geophys. Res.*, *101*, 4351-4362, 1996.
- Clarke, A. D., J. L. Varner, F. Eisele, R. L. Mauldin, D. Tanner, and M. Litchy, Particle production in the remote marine atmosphere: Cloud outflow and subsidence during ACE 1, *J. Geophys. Res.*, *103*, 16,397-16,409, 1998a.
- Clarke, A. D., et al., Particle nucleation in the tropical boundary layer and its coupling to marine sulfur sources, *Science*, *282*, 89-92, 1998b.
- Clegg, S. L., and P. Brimblecombe, Potential degassing of HCl from acidified NaCl droplets, *Atmos. Environ.*, *19*, 465-470, 1985.
- Curran, M. A. J., G. B. Jones, and H. Burton, Spatial distribution of dimethylsulfide dimethylsulfoniopropionate in the Australasian sector of the Southern Ocean, *J. Geophys. Res.*, *103*, 16,677-16,689, 1998.
- Davis, D., J. Crawford, S. Liu, S. McKeen, A. Bandy, D. Thornton, F. S. Rowland, and D. Blake, Potential impact of iodine on tropospheric levels of ozone and other critical oxidants, *J. Geophys. Res.*, *101*, 2135-2147, 1996.
- DeBruyn, W. J., T. S. Bates, J. M. Caine, and E. S. Saltzman, Shipboard measurements of dimethyl sulfide and SO₂ southwest of Tasmania during the First Aerosol Characterization Experiment (ACE 1), *J. Geophys. Res.*, *103*, 16,691-16,710, 1998.
- DeMore, W. B., S. P. Sander, D. M. Golden, C. E. Kolb, R. F. Hampson, M. J. Kurylo, C. J. Howard, A. R. Ravishankara, and M. J. Molina, Chemical kinetic and photochemical data for use in stratospheric modeling, *12, JPL Publ.*, 97-4, 1997.
- Ehhalt, D. H., F. Rohrer, A. Wahner, M. J. Prather, and D. R. Blake, On the use of hydrocarbons for the determination of tropospheric OH concentrations, *J. Geophys. Res.*, *103*, 18,981-18,997, 1998.
- Eisele, F. L., G. H. Mount, F. C. Fehsenfeld, J. Harder, E. Marovich, D. Parrish, J. Roberts, M. Trainer, and D. Tanner, Intercomparison of tropospheric OH and ancillary trace gas measurements at Fritz Peak Observatory, Colorado, *J. Geophys. Res.*, *99*, 18,605-18,626, 1994.
- Finlayson-Pitts, B. J., Reaction of NO₂ with NaCl and atmospheric implications of NOCl formation, *Nature*, *306*, 676-677, 1983.
- Finlayson-Pitts, B. J., Chlorine atoms as a potential tropospheric oxidant in the marine boundary layer, *Res. Chem. Intermed.*, *19*, 235-249, 1993.
- Finlayson-Pitts, B. J., M. J. Ezell, and J. N. Pitts, Formation of chemically active chlorine compounds by the reaction of atmospheric NaCl particles with gaseous N₂O₅ and ClONO₂, *Nature*, *337*, 241-244, 1989.
- Goldstein, A. G., C. M. Spivokovsky, and S. C. Wofsy, Seasonal variations of nonmethane hydrocarbons in rural New England: Constraints on OH in northern midlatitudes, *J. Geophys. Res.*, *100*, 21,023-21,033, 1995.
- Graedel, T. E., and W. C. Keene, The tropospheric budget of reactive chlorine, *Global Biogeochem. Cycles*, *9*, 47-78, 1995.
- Green, W. D., Maritime and mixed maritime-continental aerosol along the coast of Southern California, *J. Geophys. Res.*, *77*, 5152-5160, 1972.
- Hainsworth, A. H., A. L. Dick, and J. L. Gras, Climatic context of the First Aerosol Characterization Experiment (ACE 1): A meteorological and chemical overview, *J. Geophys. Res.*, *103*, 16,319-16,340, 1998.
- Jobson, B. T., H. Niki, Y. Yokouchi, J. Bottenheim, F. Hopper, and R. Leaitch, Measurements of C₂-C₆ hydrocarbons during the Polar Sunrise 1992 Experiment: Evidence for Cl atom and Br atom chemistry, *J. Geophys. Res.*, *99*, 25,355-25,368, 1994a.
- Jobson, B. T., Z. Wu, H. Niki, and L. A. Barrie, Seasonal trends of isoprene, C₂-C₅ alkanes, and acetylene at a boreal site in Canada, *J. Geophys. Res.*, *99*, 1589-1599, 1994b.
- Justice, C. O., J. D. Kendall, P. R. Dowty, and R. J. Scholes, Satellite remote sensing of fires during the SAFARI campaign using NOAA advanced very high resolution radiometer data, *J. Geophys. Res.*, *101*, 23,851-23,863, 1996.
- Keene, W. C., A. A. P. Pszenny, D. J. Jacob, R. A. Duce, J. N. Galloway, J. J. Schultz-Tokos, H. Sievering, and J. F. Boatman, The geochemical cycling of reactive Cl through the marine troposphere, *Global Biogeochem. Cycles*, *4*, 407-430, 1990.
- Mauldin, R. L., G. J. Frost, G. Chen, D. J. Tanner, A. S. H. Prevot, D. D. Davis, and F. L. Eisele, OH measurements during the First Aerosol Characterization Experiment (ACE 1): Observations and model comparisons, *J. Geophys. Res.*, *103*, 16,713-16,728, 1998.
- McKeen, S. A., and S. C. Liu, Hydrocarbon ratios and photochemical history of air masses, *Geophys. Res. Lett.*, *20*, 2363-2366, 1993.
- McKeen, S. A., M. Trainer, E. J. Hsie, R. K. Tallamraju, and S. C. Liu, On the indirect determination of atmospheric OH radical concentration from reactive hydrocarbon measurements, *J. Geophys. Res.*, *95*, 7493-7500, 1990.
- Parrish, D. D., C. J. Hahn, E. J. Williams, R. B. Norton, F. C. Fehsenfeld, H. B. Singh, J. D. Shetter, B. W. Gandrud, and B. A. Ridley, Indication of photochemical histories of Pacific air masses from measurements of atmospheric trace gas species at Point Arena, California, *J. Geophys. Res.*, *97*, 15883-15901, 1992.
- Penkett, S. A., N. J. Blake, P. Lightman, A. R. W. Marsh, P. Anwyl, and G. Butcher, The seasonal variation of nonmethane hydrocarbons in the free troposphere over the North Atlantic Ocean: Possible evidence for extensive reaction of hydrocarbons with the nitrate radical, *J. Geophys. Res.*, *98*, 2865-2885, 1993.
- Poppe, P., et al., Comparison of measured OH concentrations with model calculations, *J. Geophys. Res.*, *99*, 16,633-16,642, 1994.
- Prinn, R. G., R. F. Weiss, B. R. Miller, J. Huang, F. N. Alyea, D. M. Cunnold, P. B. Fraser, D. E. Hartley, and P. G. Simmonds, Atmospheric trends and lifetime of CH₃CCl₃ and global OH concentration, *Science*, *269*, 187-192, 1995.
- Pszenny, A. P., W. C. Keene, D. J. Jacob, S. Wan, J. R. Maben, M. P. Zetwo, M. Springer-Young, and J. N. Galloway, Evidence of organic Cl gases other than hydrogen chloride in marine surface air, *Geophys. Res. Lett.*, *20*, 699-702, 1993.
- Roberts, J. M., F. C. Fehsenfeld, S. C. Liu, M. J. Bollinger, C. Hahn, D. L. Albritton, and R. E. Sievers, Measurement of atmospheric hydrocarbon ratios and NO_x concentrations in the rural troposphere: Observation of air mass photochemical aging and NO_x removal, *Atmos. Environ.*, *18*, 2421-2432, 1984.
- Rudolph, J., The tropospheric distribution and budget of ethane, *J. Geophys. Res.*, *100*, 11,369-11,381, 1995.
- Rudolph, J., A. Khedim, and D. Wagenbach, The seasonal variations of light nonmethane hydrocarbons in the Antarctic troposphere, *J. Geophys. Res.*, *94*, 13,039-13,044, 1989.
- Rudolph, J., R. Koppmann, and C. Plass-Dülmer, The budgets of ethane and tetrachloroethene--Is there evidence for an impact of reactions with chlorine atoms in the troposphere, *Atmos. Environ.*, *30*, 1887-1894, 1996.
- Russell, L. M., D. H. Lenschow, K. K. Laursen, P. B. Krummel, S. T. Siems, A. R. Bandy, D. C. Thornton, and T. S. Bates, Bidirectional mixing in an ACE 1 marine boundary layer overlain by a second turbulent layer, *J. Geophys. Res.*, *103*, 16,411-16,433, 1998.
- Singh, H. B., and J. F. Kasting, Chlorine-hydrocarbon photochemistry in the marine troposphere and lower stratosphere, *J. Atmos. Chem.*, *7*, 261-285, 1988.
- Singh, H. B., and P. B. Zimmerman, Atmospheric distribution and sources of nonmethane hydrocarbons, in *Gaseous Pollutants: Characterization and Cycling*, edited by J. O. Nriagu, pp. 177-235, John Wiley, New York, 1992.
- Singh, H. B., L. J. Salas, H. Shigeishi, and E. Scribner, Atmospheric halocarbons, hydrocarbons, and sulfur hexafluoride: Global distributions, sources, and sinks, *Science*, *203*, 899-903, 1979.
- Singh, H. B., J. R. Martinez, D. R. Hendry, R. J. Jaffe and W. B. Johnson, Assessment of the oxidant-forming potential of light saturated hydrocarbons in the atmosphere, *Environ. Sci. Technol.*, *15*, 113-119, 1981.

- Singh, H. B., et al., Low ozone in the marine boundary layer of the tropical Pacific Ocean: Photochemical loss, chlorine atoms, and entrainment, *J. Geophys. Res.*, *101*, 1793-1808, 1996a.
- Singh, H. B., A. N. Thakur, Y. E. Chen, and M. Kanakidou, Tetrachloroethene as an indicator of low Cl atom concentrations in the troposphere, *Geophys. Res. Lett.*, *23*, 1529-1532, 1996b.
- Sive, B. C., Atmospheric nonmethane hydrocarbons: Analytical methods and estimated hydroxyl radical concentrations, Ph.D. dissertation, Univ. of Calif., Irvine, 1998.
- Stickel, R. E., J. M. Nicovich, S. Wang, Z. Zhao, and P. H. Wine, Kinetic and mechanistic study of the reaction of atomic chlorine with dimethyl sulfide, *J. Phys. Chem.*, *96*, 9875-9883, 1992.
- Talukdar, R. K., J. B. Burkholder, M. Hunter, M. K. Gillis, J. M. Roberts, and A. R. Ravishankara, Atmospheric fate of several alkyl nitrates, 2. U. V. absorption cross sections in photodissociation quantum yields, *J. Chem. Soc. Faraday Trans.*, *93*, 2797-2805, 1997.
- Wang, C. J.-L., D. R. Blake, and F. S. Rowland, Seasonal variations in the atmospheric distribution of a reactive chlorine compound, tetrachloroethene (CCl₂=CCl₂), *Geophys. Res. Lett.*, *22*, 1097-1100, 1995.
- Wennberg, P. O., et al., Removal of stratospheric O₃ by radicals: In situ measurements of OH, HO₂, NO, NO₂, ClO, and BrO, *Science*, *266*, 398-404, 1994.
- Whittlestone, S., J. L. Gras, and S. T. Siems, Surface air mass origins during the First Aerosol Characterization Experiment (ACE 1), *J. Geophys. Res.*, *103*, 16,341-16,350, 1998.
- Wingenter, O. W., M. K. Kubo, N. J. Blake, T. W. Smith, D. R. Blake, and F. S. Rowland, Hydrocarbon and halocarbon measurements as photochemical and dynamical indicators of atmospheric hydroxyl, atomic chlorine, and vertical mixing obtained during Lagrangian flights, *J. Geophys. Res.*, *101*, 4331-4340, 1996.
- Zetzsch, C., G. Pfahler, and W. Behnke, Heterogeneous formation of chlorine atoms from NaCl aerosols in a smog chamber, *J. Aerosol Sci.*, *19*, 1203-1206, 1988.
-
- E. Atlas and F. Flocke, Atmospheric Chemistry Division, NCAR, 1850 Table Mesa Drive, Boulder, CO 80307.
- D. R. Blake, N. J. Blake, and F. S. Rowland, Department of Chemistry, University of California, Irvine, CA 92697. (drblake@uci.edu; nblake@uci.edu; rowland@uci.edu)
- B. C. Sive, Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80303. (sive@lasp.colorado.edu)
- O. W. Wingenter, Department of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332. (oliver@eas.gatech.edu)

(Received October 5, 1998; revised March 18, 1999; accepted March 22, 1999.)