

CLOUD CHEMISTRY- TOWERING CUMULUS

Case Description

This case is derived from the Chemical transformation and Transport by Clouds (CTC) study that was part of the 2004 ICARTT Intensive [Fehesenfeld, 2006]. The observations were conducted from the National Research Council of Canada Convair 580 as part of. The major relevant instrumentation are listed in Appendix 1. The aircraft was based out of Cleveland, Ohio from July 20, 2004 to August 18, 2004. The main objectives of CTC were:

- to understand the role of cloud chemical processes in the transformation and transport of pollutants, and
- to use the observational dataset to evaluate and identify areas for improvement in the modelling of cloud chemical processing.

This towering cumulus case is derived from flight #21 conducted from approximately 18:46 UT to 21:55 UT on August 16, 2004. The flight consisted of a climb out of Cleveland to the southwest towards Mansfield, Ohio, a continuous vertical profile from about 3 km-MSL down to about 400 m-MSL in an approach at Mansfield airport, followed by sampling at successive levels below and in cloud as the aircraft ascended to 2.4 km, then sampling at successive levels in and below cloud as the aircraft descended to 1.1 km, after which it returned to Cleveland. Winds at the surface were light as a high pressure system was centred over the sampling area (Figures 1 and 2 of the power point file). The forecast tephigrams for Cleveland (Figures 3 and 4) predicted cumulus based about 1.5 km and topped about 3 km. Two GOES satellite images from the flight time (Figures 5 and 6) show cumuli over the sampling region and much of the general area downwind of the lake shores. As discussed below, the sampled clouds were based about 1.4 km and topped about 2.7 km.

The flight track plotted on emissions maps for NO_x and SO₂ are shown in Figures 7 and 8. The emissions map is from <http://www.ngdc.noaa.gov/maps/interactivemaps.html>. The flight was conducted in an area of relatively lighter emissions, but for the local area of Mansfield. The in- and below-cloud sampling portion of the flight track is detailed in Figure 9.

As an overview, Figure 10 shows a time series of altitude, SO₂, CO and cloud liquid water content (LWC) for the most of the flight. Based on the 2-D imaging probes (PMS 2DGrey and 2DP), no precipitation was observed during the flight. The yellow line indicates when sampling by certain instruments was conducted through the counter-flow virtual impactor (CVI) inlet. The CVI samples only particles larger than several microns from the airstream (e.g. Noon et al., 1988), thus permitting the sampling of cloud droplets separated from the cloud interstitial aerosol. Inside the CVI inlet, the droplets are dried and the residual particles are sampled by selected instruments. During ICARTT, the Aerodyne Quadrupole Aerosol Mass Spectrometer (Q-AMS), the TSI-SMPS and the TSI 3022 CPC were switched to sample off the CVI inlet when sampling through cloud. Because the switching from the normal aerosol inlet to the CVI was done manually and because of the longer sampling times of the AMS and SMPS, no attempt was made to

switch back-and-forth between aerosol and CVI inlets when out of cloud until either above or below the altitudes of the clouds. The calculated separation size of the CVI used on the Convair was 7-8 μm , however, comparison of the number concentrations from the CPC sampling from the CVI s with the outboard FSSP100s (two probes: serial #s 096 and 124) indicate the cut size of the CVI to be about 10 μm . In other words, the collection efficiency of the cloud droplets drops significantly when the droplet sizes are less <10 μm . This is illustrated for Flight 21 in Figures 11 and 12. Figure 11 shows the mean volume diameter (MVD) of the cloud droplets as measured with one of the FSSP100 probes. At the highest level, the MVDs were above 10 μm and reaching values of 12-14 μm . At lower levels, the MVDs were lower. In Figure 12, the residual particle number concentrations from the CVI, measured with the CPC and corrected for the CVI enhancement factor, are shown with the droplet number concentrations from one of the FSSP 100. Reasonable agreement is evident for the highest level in cloud, and the CPC number concentrations decrease both absolutely as well as relative to the FSSP for sampling conducted lower down in the cloud. Thus, the results of residual sampling are considered only for the highest cloud sampling altitude.

The shaded sections of Figures 10-12 indicate the part of the flight selected as the focus for this case. There are two reasons for this: visual observations during the flight suggested that the clouds sampled earlier in the flight were dissipating whereas later in the flight (shaded period) the clouds were in the stage of development, and the concentrations of particles and gases at cloud base were less variable during the shaded period (Figures 10 and 18).

Profile Data

Profile data are drawn from throughout the flight. Figure 13 shows profiles of temperature and dew point temperature from the continuous descent during the first part of the flight and from the stepped descent during the latter part (shaded) of the flight. Profiles of potential temperature and relative humidity for the initial descent profile are shown in Figure 14. The profile data show cloud base to be between 1400 m and 1500 m. The in-flight observations that indicated a cloud base of approximately 1400 m, at 1400 m the aircraft was occasionally in cloud bases. Cloud tops reached about 2700 m.

CO, O₃ and particle number concentration (PCASP; >130 nm diameter) for the same profiles are shown in Figure 15. Also included is the number concentration from one of the FSSP100 probes to indicate when cloud was intercepted. Ozone is relatively constant throughout the depth of the profile. CO is relatively constant up to about 1800 m at close to 150 ppbv. Above 1800m, the CO drops to 125-130 ppbv, but it is also more variable. Increases in the CO are evident at about 2300 m and 2600 m associated with sampling in cloud indicating lifting of boundary layer CO. Ozone show little change, except a slight decrease in the cloud about 2600 m. Particle number concentration, from the PCASP, is similar to the CO. It is relatively constant up to about 1800 m at about 1800 particles cm^{-3} and then drops from there to below 500 cm^{-3} above 2600 m. Although results from the PCASP can be somewhat ambiguous in cloud, the first profile shows that in the boundary layer the PCASP drops when in cloud, a result of the activation of many of the particles. In contrast, at 2600 m in cloud the PCASP increases indicating vertical transport of

boundary layer particles in the cloud. This result may indicate that not all PCASP particles are involved in the activation process, but it can also be affected by drying of cloud droplets internally in the PCASP. In-cloud data from the PCASP must be carefully considered.

Profiles of SO₂, NO₂, H₂O₂ and HCHO are shown in Figure 16 along with LWC. This profile was done near Mansfield, which has some significant sources of SO₂ and NO_x (Figures 7 and 8). We think that the increases in SO₂ and NO₂ below 1200 m reflect these local emissions, and that our sampling relative to these sources was also the reason for higher variability in some of the gas-phase quantities during the first half of the flight; note that CO is also slightly enhanced (Figure 15), coincident with the low-level NO₂ plume. Above 1200 m, NO₂ in the first profile is relatively low and variable. In the second profile, NO₂ is steady at about 0.5 ppbv from 1200-2000 m and above 2000 m it goes to below detection limit (BDL), except in cloud. SO₂ is higher in the second profile up until about 2000 m after which it drops to BDL except in cloud. H₂O₂ is relatively constant throughout the first profile at just under 1 ppbv. In the second profile it is slightly lower and shows some suggestion of increasing with altitude over this shorter profile. Depletion of H₂O₂ in cloud is not evident in these profiles due to the long response time of the instrument. HCHO is between 1 and 1.5 ppb throughout most of the initial profile, and approaches 2 ppbv below 2000 m in the second profile.

Cloud Microphysics and Gusts

Figure 17 shows the time series of vertical gusts, droplet number concentrations (N_d) and LWC for the cloud focus of this flight (shaded section in Figure 10). The below-cloud sampling, conducted immediately after the in-cloud sampling is also included to indicate the gusts at that point.

The N_d are similar at all three altitudes, about 1200±100 cm⁻³, with some tendency for the slightly higher N_d associated with larger gusts. For the clouds with the stronger gusts, which may indicate a developing cloud and less effect of mixing on the peak LWC, the peak LWCs are higher.

Observations at cloud base

The sampling of cloud base after cloud sampling was initiated at about 1400 m at 21:27 UT. However, as some cloud was still encountered, the aircraft descended further to about 1150 m and sampled for about six minutes 200-300 m beneath cloud (21:30-21:36). Figure 18 shows a time series of N_a, measured with the PCASP, and CO from 21:27-21:36, including the time at 1400 m and that at 1150 m. During this time, CO varied between 135 ppbv and 150 ppbv and the N_a varied from 1300 cm⁻³ to 2200 cm⁻³.

The mass concentrations measured across the cloud base are shown in Figure 19. The concentrations of three components of the fine particle aerosol as measured from the AMS are shown: total, sulphate and nitrate. The difference between the total and the sum of sulphate plus nitrate is accounted for almost completely by organic material. The AMS data have been scaled for collection efficiency according to the ratio of sulphate from the PILS with the AMS, a factor of 2.65 in this case. The other mass concentration

curve is that estimated from the particle size distribution measurements (SMPS+APS). This estimate assumes the particle density of the particles was 1.5 g cm^{-3} , and it includes only particles in the size range efficiently transmitted into the AMS (about 100-600 nm geometric diameter, Liu et al., 2007). The total of the AMS is about 60-70% of that estimated from the size distribution measurements. Given that sulphate is the dominant component of the fine-particle aerosol mass and the particle density estimate is lower than that for most observed sulphate compounds, it is expected that the agreement should be closer and even biased in the opposite way. Although there may be many possible explanations for the discrepancy, this issue will not be dwelled upon here. The size distributions measured from the SMPS+APS are used to define the cloud base aerosol for activation, and the relative composition of the aerosol for 100-600 nm is assumed from the AMS observations. Details of the cloud-base aerosol size distribution are given later.

Time series of CO, O₃, SO₂, NO₂ and H₂O₂ for the below-cloud interval are shown in Figure 20. The variability in each of CO, O₃ and H₂O₂ is less than 10%, and SO₂ varies over about 20%. In contrast, a plume of NO₂ was encountered approximately one minute wide (5-6 km). It appears that there are four cycles in the NO₂ during the period 21:30 to 21:36 with diminishing peak concentrations. There is an indication of a similar cyclic behavior in both the CO and SO₂. Averages and standard deviations of the cloud base values are given in the bottom row of Table 1.

Observations in cloud

The time series of SO₂ and LWC for the shaded interval (Figure 10) are shown in Figure 21. Elevated SO₂ coincident with cloud is evident for the periods of highest LWC at the uppermost level. There is little or no indication of SO₂ elevated in the cloud at the middle and lowest cloud sampling levels as SO₂ outside of cloud and in the interstitial cloud are similar. That the SO₂ in cloud at 2.35 km reaches close to 1.5 ppbv in two or three cases suggests that the primary factor reducing SO₂ from the middle sampling level to the uppermost level was mixing. The oxidation of SO₂ appears to have been oxidant limited for air entering from cloud base and being entrained at lower levels. Above 1.8-2 km, H₂O₂ was higher than SO₂ and the oxidation of entrained air was likely more limited by the availability of SO₂.

The time series of HCHO and H₂O₂ are shown in Figure 22. The instruments used to make these measurements had very low responses. There is some indication that H₂O₂ decreased going into cloud, however the time spent in these clouds (10-20 s) was such that the signal could not respond outside of the overall variability. Overall, H₂O₂ was higher at the higher level and lower towards cloud base, and HCHO is the opposite.

Ozone and NO₂ are shown in Figure 23. Decreases in ozone of up to 5 ppbv are associated with being in cloud, whereas the NO₂ increases in cloud. As the profiles of ozone showed no particular bias with altitude. The reductions in cloud may indicate some titration of ozone in cloud by NO_x.

Figure 24 shows CO during the cloud sampling on the second half of the flight. At lower levels, the overall level of CO was higher and increases in cloud are not evident. At the

upper level, 2.35 km, CO outside of cloud was between 130 ppbv and 140 ppbv. Inside cloud, CO exceeded 140 ppbv and reached 150 ppbv in some cases. The coupling of changes in CO with cloud is shown more closely in Figure 25 that focuses on a smaller periods of the flight at 2.35 km and includes the measured vertical gust speeds. It must be noted that the gust measurement is unreliable when the aircraft is turning. Many turns are required for the sampling of individual cumulus or a few clouds within a small area (Figure 9). Since the aircraft was level for entering and exiting a cloud, the gust measurements are reasonable at least both shortly before and shortly after each cloud penetration. While CO increases in cloud are clearer in this plot, it is interesting that most but not all increases are associated with upward gusts. A strong downdraft accompanies the cloud penetration about 20:45:30. There is still some liquid water in this downdraft and a significant increase in CO suggesting that this downdraft was carrying with it outflow of the cumulus.

Table 1 gives the averages for SO₂, NO, NO₂, O₃, CO, HCHO and H₂O₂ in cloud and out of cloud at the three cloud sampling levels plus the averages in clear air below cloud base. As discussed above, both SO₂ and CO were higher in the clouds than outside. NO_x is higher in cloud than outside based on the straight averages, but the differences between in and out of cloud are small. Ozone is not significantly different between in and out of cloud in contrast to the above discussion. Since the reductions in ozone that appear in Figure 23 are limited to a few seconds in each case and are only a few ppbv, it may be that the net affect on the average is not evident in the averaging. Also, since the ozone measurement was lagged slightly, failure to match the timing exactly may negate any indication from the averages of a reduction of ozone in the cloud. There is no evidence of a significant change in the averages of either HCHO or H₂O₂ between in cloud and outside of cloud.

The levels of sulphate and nitrate in the bulk cloudwater samples as well as SO₂ and NO₂ are shown in Figure 26. Three bulk samples were collected, one at each altitude level and each integrated over all cloud penetrations at that level. The liquid concentrations decrease with altitude principally due to the increase in the liquid water. While there was little or no particulate nitrate (Figure 19), HNO₃ was measured (using a coil sampler to absorb HNO₃ from the gas-phase into water and measure the resulting nitrate using IC). Samples for HNO₃ were integrated over 10 minutes, and the mean of four samples collected at cloud base was 4.0 with a SD of 0.6. Thus there was HNO₃ available for absorption by the cloud droplets, and this can account for the nitrate in the cloudwater (Hayden et al., 2007).

The cloud droplet residual sulphate and nitrate, as indicated by the AMS measurements downstream of the CVI intake, are shown in Figure 27. Note that the CVI inlet was only used until about 21:26 after which the AMS sampled from the standard aerosol inlet. There are a few things to note from this figure. First the residual sulphate is higher at higher altitude. This results primarily from the sampling efficiency of the CVI increasing with droplet MVD as discussed above. Second the residual nitrate is relatively low compared with the sulphate when contrasted with the bulk cloudwater. Although this was not always the case (Hayden et al., 2007), it suggests that the absence of a sufficient

buffer in the cloud droplets resulted in the re-volatilization of the HNO_3 . Finally, the cloud residual concentrations at the upper level are similar to those at cloud base measured with the standard inlet. This is somewhat fortuitous as the CVI residual concentrations have not been corrected for the inertial enhancement factor of the CVI as well as for the limited time spent in cloud. Although these factors are compensating to some degree, it is difficult to assess them completely. Thus, we use the residual data only as a relative indicator.

Table 2 gives the ion chemistry of the bulk cloudwater samples collected at 2.35 km, 2.06 km and 1.76 km.

Aerosol particle size distributions

Figure 28 shows a time series for most of the flight of the number concentration of aerosol particles measured with one of the PCASPs (outboard), the number concentrations of aerosol particles >130 nm as measured from the combination of the SMPS+APS, and the N_d . The point of this figure is threefold: it demonstrates the consistency between the outboard PCASPs and the inboard instruments used to measure the more complete size distribution of the aerosol; it shows how the N_d compare with the aerosol number concentrations, and third it marks the times where the below-cloud aerosol size distributions are taken.

The three below-cloud particle number size distributions are shown in Figure 29. For contrast and completeness, the distribution measured at 2.9 km near the beginning of the flight is also shown. The latter indicates the dominance of particles smaller than about 40 nm to the number distribution. There are strong similarities among the three cloud base distributions with the notable difference being that the particles of distribution 3, which follows the cloud sampling and is the focus of this case, are slightly larger than those of the other distributions. The SMPS+APS distributions were collected every two minutes. The six distributions making up the average of cloud base 3 are shown in light blue, and they indicate little variability over the 12 minute average.

Three particle mass distributions are shown in Figure 30. The SMPS+APS distribution is estimated from the cloud base 3 number distribution shown in Figure 29. It is derived assuming spherical particles with specific gravity of 1.5 g cm^{-3} . The red curve is the corresponding AMS mass distribution of sulphate for cloud base 3, and the blue curve is the cloud residual sulphate measured from all the cloud penetrations at 2.35 km. Only the upper level cloud is used because, as discussed earlier, the CVI efficiency was optimal at that level. Only sulphate from the AMS is shown because it was the only species with sufficient signal from which a size distribution could be generated. The two cloud base distributions agree reasonably well in terms of size as the AMS distribution is shown as a function of vacuum aerodynamic diameter (VAD), and this converts to a geometric diameter by simple division by the specific gravity of the particles if they are spherical (e.g. Jimenez et al., 2003). The peak of the SMPS+APS distribution is about 300 nm and that of the cloud base AMS is about 480 nm. These differ by a factor 1.6, which is consistent with a predominantly sulphate aerosol and the factor of 1.5 used in converting the physical number distribution to mass. The AMS sulphate distribution is

much lower in total than that derived from the number distribution in part because the latter includes species other than sulphate, but also because the collection efficiency was relatively low in this case as discussed w.r.t. Figure 19. The cloud residual sulphate distribution is lower still in large part because the time spent in any cloud was always ≤ 20 seconds whereas the AMS collected 30 second averages. No attempt has been made to correct the AMS residual data for the various collection issues (see discussion above also). The peak of the residual sulphate distribution is at about 570 nm VAD. Reduced sampling pressure ahead of the critical orifice of the AMS does lead to a change in the apparent size distribution of particles due changes in altitude. This has been evaluated for this particular AMS (Hayden et al., 2007), and it was found that for a reduction in pressure at the sampling orifice of the AMS of 20% sulphate particles shifted up in size by about 100 nm VAD. In this case, the pressure change from cloud base to the upper cloud sampling level was about 13%, and thus some of the shift in the cloud residual sulphate may have been due to aqueous-phase oxidation of SO_2 .

The particle number concentration at cloud base (Figure 18) as measured with one of the two PCASPs varies from about 1300 cm^{-3} to about 2000 cm^{-3} . In order to determine the number concentration to best represent cloud base, the number concentration from the PCASP is plotted with RH (Figure 31). There is a broad anti-correlation of the number and RH. Initially this could be due to a change in altitude, however it is also evident across the level period. Since cloud is more likely to result from the air parcels with higher RH, a range of lower number concentrations, $1300\text{-}1700 \text{ cm}^{-3}$, is assumed to best represent the cloud base aerosol.

Carbonyls

Concentrations of some OVOCs sampled with canisters at various points in the flight are shown in Figure 32. Concentrations of the same species measured in the bulk cloudwater samples are shown in Figure 33, and Figure 34 shows how the carbonyls in the cloudwater relate to HCHO in the cloudwater. The ratio of HCHO to the other carbonyls increases with altitude (sample 21-2 is from 2.35 km), consistent with the general observation for the ICARTT measurements (Leithhead et al., 2007). Figure 35, from Leithhead et al. shows the mass closure for HCHO in this case. The sum of the interstitial HCHO in cloud with the cloudwater HCHO agrees well with the cloud base HCHO. Helping this closure are the facts that the fraction of HCHO in the cloudwater is only a few percent and that variations of gas-phase HCHO in the vertical are relatively small.

Some questions to address:

- How much sulphate is produced in cloud, and to what extent does this affect the boundary layer sulphate?
- How does NO_x influence the chemistry in this case, and does H_2SO_4 production in aqueous-phase lead to nitrate exclusion in droplet residuals? Is ozone reduced slightly in cloud?
- How is the aerosol number/mass distribution changed in this situation?
- How do the dynamics of the Cu affect the chemistry? Does the entrainment of air with increased H_2O_2 and reduced SO_2 into a cloud with lower H_2O_2 and higher SO_2 change the rate of sulphate production? The peak LWCs are low relative to adiabatic, how does this impact sulphate production?

- How do the models scavenge carbonaceous compounds, and is an increase in HCHO relative to other carbonyls predicted? How can CO be used to indicate cloud processing?

Model simulations: initialization and output requirement

The time period for the comparison is 20 – 22 UT, August 16, 2004. Possible model applications are as follows:

- 1) 2- or 3-D cloud resolving model (CRM) simulating either the field of towering cumulus or a single cloud initiated with a warm/moist thermal to match observed cloud structure (cloud base, top, LWC as described above). Conduct the simulation for up to 3 hours.
- 2) parcel model with or without the consideration of entrainment (which can be optional sensitivity simulations). For parcel model simulations, statistics of the vertical gust velocities are give in the excel sheet labeled with “gust velocity statistics”.

The profile data of T, P, RH, particle number concentrations from the PCASP, number concentrations from the FSSP100 and FSSP300 as well as gaseous species (CO, SO₂, H₂O₂, NO, NO₂, O₃, and HCHO) are provided in a separate excel file labeled profile data. These are the same data as those shown in Figures 13-16.

An Excel file with the dN and dV of the cloud base aerosol particle size distributions (both 2 and 3) is also attached. The data cover 10 nm to 3 μm. Beyond 3 μm, we think that losses of coarse particles during sampling were a problem.

The combined data from the AMS and PILS measurements indicates that the cloud base aerosol was comprised of 60% sulphate, 21% organics, 17% ammonium and 2% nitrate by mass. There were no measurements to show at what level the chemical components of the particles were mixed, and we should not only assume that the aerosol was completely internally mixed. The mass distribution is comprised of two modes, as in Figure 32, with geometric mass mean diameters of about 75 nm and 300 nm. The following two below-cloud aerosol particle chemical size distributions are recommended:

- a) The entire size distribution is internally mixed and composed as 60:2:17:21 (sulphate: nitrate: ammonium: organics)
- b) The smaller mode is internally mixed and composed of 53% organics, 40% sulphate, 3% ammonium and 4% nitrate. The larger mode is internally mixed and made up of 67% sulphate, 13% organics, 18% ammonium and 2% nitrate.

The excel file with the cloud base dN and dV as a function of diameter includes the separate modes as well as the fractional composition to use at each size interval to accommodate the above.

Cloud base trace gas concentrations for initialization are given in table 1 of the pdf files with the figures, as discussed above.

Required output for comparison

For all (CRM and parcel model)

- Precipitation water content or flux
- LWC, droplet number concentration and spectrum, bulk cloud-water $\text{SO}_4^{=}$, NO_3^- , NH_4^+ , HCHO, and cloud droplet residual SO_4 and NO_3 (size distribution), trace gas concentrations (O_3 , CO, SO_2 , NO_2 , H_2O_2 , HNO_3 , HCHO) at all three levels above cloud base (1.4 km): 350m, 600m, and 950m ;
- at cloud top after evaporating all cloud droplets at the end of simulation, $\text{SO}_4^{=}$, NO_3^- , NH_4^+ , aerosol particle size distribution and trace gas concentrations.

From CRM

- Distribution of updraft; entrainment/detrainment fluxes and distribution.

Other studies

- Sensitivities of LWC, droplet number concentration, cloud chemistry, and processed aerosol to the entrainment rate and to the cloud base aerosol;
- at a later stage of the intercomparison study, consider to incorporate the results of entrainment/detrainment from the CRM into entraining parcel models.
- Effect of multiple cloud processing cycles on droplet number concentration, cloud chemistry, and processed aerosol.
- Scavenging of carbonyls from the gas phase by cloud droplets and comparison with observations (*formaldehyde, acetaldehyde, acetone, propionaldehyde, butylaldehyde, benzaldehyde, pentanal*)

References

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APPENDIX 1 – NRCC Convair 580 Instrumentation during ICARTT 2004

The Convair 580 is a pressurized twin engine turboprop. Details:

- gross weight is 26400 kg
- cabin volume is 70 m³
- maximum payload is 2300 kg
- project electrical power is 40 kW
- cruise speed 90-140 m s⁻¹
- stall speed 45 m s⁻¹
- max speed 160 m s⁻¹
- ceiling 23000'
- typical VFR endurance 5.5 hrs
- typical IFR endurance 4.5 hrs
- field length 4100 ft
- deice - boots air

Instrumentation

State Parameters

- Temperature Rosemount Temperature Sensor (de-iced)
- Temperature Rosemount Temperature Sensor (non-deiced)
- Temperature Reverse Flow Temperature Sensor (NCAR design)
- Dewpoint Cambridge Dewpoint Hygrometer (chilled mirror)
- Static Pressure Static Pressure Ports on fuselage and in 858 probe
- Static Pressure Rosemount 858 (boom TO, PMS pod CV580)
- Static Pressure Pitot static system on LWC boom
- Aircraft Altitude Bendix radar altimeter (<800 m)
- Aircraft Altitude TRT radar altimeter (< 7500 m)
- True Airspeed Pitot under wing (CV580) and Rosemount 858
- True Airspeed Rosemount 858 (boom TO, PMS pod 858)
- True Airspeed Pitot static system on LWC boom
- Humidity LICOR LIC2G2 water vapour/CO2 measurement device
- Humidity Russian chilled mirror and UV hygrometer

Navigational Systems

- Position IRS (Litton 91), and LORAN
- Position GPS (CV580: Marconi, Northstar, Novotel)
- Attitudes, accelerations, true heading, and ground speeds IRS (Litton 91)
- 3 axis velocities wrt ground IRS (Litton 91)

Winds and Gusts

- Horizontal Winds, and 3 axis gust velocities IRS (inertial velocities), Rosemount 858 (Pod) and TAS derived

Aerosol Particles

- Aerodyne Aerosol Mass Spectrometer (AMS)/ SO₄, NO₃, NH₄, Organics; 60 nm to 1 µm aerodynamic diameter
- Particle In Liquid Sampler (PILS) for inorganic ions and a few organic ions
- Scanning Mobility Particle System (SMPS) for particle size distributions from 5-300 nm in geometric diameter

- Aerodynamic Particle Sizer (APS) for aerosol particle size distribution from 0.5-20 μm aerodynamic diameter
- Volume nephelometer for particle light scattering at 3 wavelengths (Sharma, Leaitch) inboard
- PSAP
- Particle Measuring Systems (PMS) Passive Cavity Aerosol Spectrometer Probe (PCASP) for aerosol size distributions from 0.14-3 μm geometric diameter - wingpod
- PMS Forward Scattering Spectrometer Probe 300 (FSSP300) for particle size distribution from 0.3-20 μm geometric diameter - wingpod

Trace Gases

- SO_2 (modified TECO 43C)
- CO (Aerolaser)
- O_3 (Teco 49)
- NMHCs (canisters)
- NO, NO_2
- H_2O_2
- Hg0
- HNO_3 (coil sampler and IC)
- HCHO (Aerolaser)

Cloud Chemistry

- Bulk cloudwater sampling
- AMS and SMPS sampling cloud droplet residuals from a Counter Virtual Impactor (CVI)

Cloud Microphysical Measurements

- Droplet Liquid Water Content PMS King Probe (long version)
- Droplet Liquid Water Content PMS King Probe (short version)
- Droplet Liquid Water Content Johnson Williams LWC Meter
- Droplet Liquid Water Content Nevzorov LWC probe
- Total water content and phase ratio Nevzorov TWC/LWC probe
- Droplet Spectrum (2-30 μm) PMS FSSP 100 Probe
- Droplet Spectrum (5-95 μm) PMS FSSP 100 Probe
- Small cloud particle imaging and spectra (2.3-2000 μm) SPEC Cloud Particle Imaging Probe (CPI)
- Cloud Particle Spectrum and images(25-800 μm) PMS 2D-C and PMS 2D2-C mono probes
- Cloud Particle Spectrum and images(25-1600 μm) PMS 2D-C Grey Probe
- Cloud Particle Spectrum and images(12.5-800 μm) Droplet Measurement Technologies Cloud Imaging Probe (CIP)
- Precipitation Spectrum and images(200-6400 μm) PMS 2D-P (mono) Probe
- Large Precipitation Spectrum and images(400 μm -5 cm) SPEC HVPS
- Cloud extinction Nevzorov (direct measurement)

Radiative Measurements

- Downwelling UV solar radiation Eppley UV radiometers (295-385 nm)

- Upwelling UV solar radiation Eppley UV radiometer (295-385 nm)
- Upwelling visible solar radiation Kipp and Zonen pyranometer-(305-2800 nm)
- Downwelling visible solar radiation Kipp and Zonen pyranometer (305-2800 nm)
- Upwelling IR radiation Eppley IR radiometers (3.5-50 um)
- Downwelling IR radiation Eppley IR radiometer (3.5-50 um)

Video Systems

- Surface video Side looking video cameras, narrow and wide angle
- Surface video Forward/down looking, and side looking cameras

Data Recording and Display

- Aircraft Data Systems:
 - IAR VME DAS
 - MSC SEA Model 200 DAS