15 August 2023

**SABRE 2023 High Latitude Deployment End-of-Mission Summary**

Prepared by

Troy Thornberry and Eric Jensen, SABRE Mission Scientists

and

the SABRE 2023 Science Team

This statement provides a summary of the 2023 Stratospheric Aerosol processes, Budget and Radiative Effects (SABRE) airborne science mission research and activities. The core mission objectives of the deployment were to sample the late winter high latitude Northern Hemisphere stratosphere during flights from Eielson AFB (Fairbanks), Alaska, with additional lower latitude sampling of the upper troposphere and lower stratosphere from NASA Ellington Field (Houston), Texas and on the transit flights between Ellington Field and Eielson AFB. The mission was sponsored by the NOAA Earth Radiation Budget Initiative, and the airborne platform used was a NASA WB-57F aircraft.

SABRE 2023 team photo at Eielson AFB, Alaska, 22 March 2023. Photo credit: Max Dollner.

## Introduction

Stratospheric aerosols are an important component of Earth's albedo, and therefore energy balance, and provide surface area for heterogeneous chemistry, which can lead to stratospheric ozone loss. Acquiring an extensive database of detailed stratospheric aerosol, trace gas and dynamical observations is essential for

(1) Establishing the baseline state and background variability of the stratosphere

(2) Developing a complete understanding of stratospheric dynamical and chemical processes that influence aerosol microphysics, radiative properties and heterogeneous chemistry

(3) Evaluating the stratospheric response to natural and anthropogenic perturbations including climate change, volcanic eruptions, space launch activities and potential climate intervention efforts

(4) Strengthening the scientific foundation of any future policy decisions related to regulating global emissions that impact the stratosphere (e.g., ozone depleting substances, rocket exhaust) and the potential introduction of material into the stratosphere to offset global warming.

**SABRE Science Objectives and Goals**

The SABRE mission, a component of the NOAA Earth Radiation Budget (ERB) program, is an extended airborne science campaign to study the formation, transport, chemistry, microphysics and radiative properties of aerosols in the upper troposphere and lower stratosphere (UTLS). The multiple executed and planned aircraft deployments will provide extensive detailed measurements of stratospheric aerosol size distributions, composition and radiative properties along with relevant trace gas species in different regions and seasons. These observations are critical for improving the ability of global models to accurately simulate the radiative, dynamical and chemical impacts of changes in stratospheric aerosol loading.

Specific SABRE science objectives include:

- Characterize stratospheric aerosol size distributions, composition, and optical properties, as well as their spatial and temporal variability. Determine the sources and chemical, dynamical, and microphysical processes that determine the observed size distributions
- Constrain the sulfur budget of the background stratospheric aerosol layer and evaluate the chemistry of sulfur species in the stratosphere
- Determine the occurrence of new particle formation in the upper troposphere / lower stratosphere and its influence on stratospheric aerosol number and size distribution
- Quantify the contribution of organic species to aerosol formation and growth in the tropical upper troposphere and lower stratosphere, and their influence on aerosol radiative properties and chemical impacts
- Characterize the evolution of stratospheric aerosol properties (microphysics, composition, and optical properties) following injection of aerosol and gas-phase aerosol precursors into the stratosphere by volcanic eruptions, wildfire pyrogenic events and anthropogenic activities such as rocket launches
- Quantify the impact of stratospheric aerosol variations on stratospheric ozone chemistry and stratospheric dynamics
- Quantify radiative forcing terms associated with anthropogenic perturbations to stratospheric aerosol (e.g. air traffic, rockets)

**SABRE 2023 Operations and Measurements**

The 2023 SABRE field operations began in late January with instrument integration onto the WB-57 aircraft, test flights, and three science flights from NASA JSC Ellington Field in Houston, Texas. The Houston local science flights included a southern sortie to survey aerosol and trace gases in the subtropical UTLS; a midlatitude UTLS survey over the central US, and a flight to Cape Canaveral targeting the exhaust plume of a SpaceX Falcon-9 launch. The outbound deployment transit flights on February 21–22 from Ellington Field to Beale AFB near Sacramento, CA and from Beale to Eielson AFB in Alaska were conducted as high altitude (aircrew suited) science flights and provided the opportunity to survey the UTLS across the latitude range 30° - 64° N. 12 local science flights were conducted from Eielson AFB (64.6° N, 147.1 W) during the period February 28 – March 23. These flights included: surveys of high-latitude UTLS aerosols and trace gases in aged Arctic air masses outside the polar vortex; sampling of air transported down from the mesosphere through the polar vortex to the lower


Figure 1. SABRE 2023 flights from Ellington Field, Houston, Texas (3), Eielson AFB, Fairbanks, Alaska (12) and transit flights between (4).

stratosphere; sampling of intrusions of low latitude, polluted air into the polar lowermost stratosphere; and UTLS surveys south of Eielson. The return transit flights on March 27–28 were again conducted as high altitude science flights and provided another opportunity for measurements across a wide latitude range.

The 2023 SABRE payload (see Table 1) included measurements of aerosol microphysical properties and composition as well as trace gas species relevant for analysis of both dynamics and photochemical processes. The measurements were made by instrument teams from the NOAA Chemical Sciences Laboratory, the NOAA Global Monitoring Laboratory, the University of Colorado Cooperative Institute for Research in Environmental Sciences, NASA Langley Research Center, NASA Ames Research Center, the University of Vienna and Harvard University.

Aerosol size distributions were measured in situ from ultrafine, nucleation-mode sizes (3–50 nm), through the accumulation-mode size range (80 nm – 1 µm), and out to coarse-mode particle sizes (> 1 µm) using multiple instruments. A single-particle mass spectrometer provided detailed, size-dependent information about particle composition, including sulfate, organic, nitrate, meteoric, and metallic content. Bulk aerosol optical extinction and the concentration and mass of light-absorbing black carbon in stratospheric aerosol were also measured.

Trace gas species measured included sulfur species $SO_2$ and OCS, both of which are oxidized in the stratosphere to produce $H_2SO_4$ that then condenses on aerosols. Much of the background (non-volcanic) stratospheric aerosol layer mass results from this condensation process, predominantly from OCS. A number of gas-phase tracer species were measured, including $N_2O$, $SF_6$, CFCs, $H_2O$, CO, $CO_2$, and $O_3$. These tracers provide information about the origins of sampled air masses as well as their transport pathways and time since entry into the stratosphere (age of air). Measurements of reactive nitrogen oxides (NO, $NO_2$ and the sum of reactive oxidized nitrogen, $NO_y$) and halogen species were included to investigate impacts of aerosols on stratospheric chemistry through processes such as denitrification and halogen species activation.

The University of Wisconsin-Madison Space Science and Engineering Center provided daily flight planning support during the mission. This included global chemical and aerosol forecasts from the Realtime Air Quality Modeling System (RAQMS) combined with ensemble trajectory-based diagnostics of the histories on flight altitudes covering the range of the WB-57. RAQMS assimilates stratospheric ozone profile retrievals from the Microwave Limb Sounder (MLS), resulting in good agreement with the WB-57 in situ ozone measurements (correlations generally greater than 0.95 and biases generally less than 0.05 ppmv). Prior to the 2023 deployment, a latitude and altitude dependent bias correction (as a percentage adjustment) was applied to the RAQMS $N_2O$ data using a comparison with MLS observations during January, 2022. This one time bias correction applied on January 1, 2023 resulted in a significant improvement in RAQMS $N_2O$ predictions during the SABRE 2023 mission. With improved RAQMS $N_2O$ predictions, the SABRE flight planning team successfully sampled thin filaments of aged polar vortex air with the WB-57.

Table 1. The SABRE 2023 WB-57 Instrument Payload

| | Instrument | Investigator | Measurement | Science |
|---|---|---|---|---|
| **Aerosols:** | NMASS | Charles Brock<br>NOAA CSL | Size distribution<br>3 – 56 nm | |
| | UHSAS | Charles Brock<br>NOAA CSL | Size distribution<br>80 nm – 1 µm | |
| | CMASS | Adam Ahern<br>CIRES/NOAA CSL | Size distribution<br>400 nm – 4 µm | |
| | CAPS | Bernadette Weinzierl<br>University of Vienna | Aerosol and cloud particle size distribution 0.5 – 100 µm | |
| | SOAP | Adam Ahern<br>CIRES/NOAA CSL | Aerosol extinction, aerosol absorption | |
| | PALMS-NG | Gregg Schill<br>NOAA CSL | Size-resolved aerosol composition | |
| | SP2 | Joshua Schwarz<br>NOAA CSL | Black carbon particle mass and number | |
| | MOUDI | Frank Keutsch<br>Harvard University | Particle composition and morphology | |
| **Trace Gases:** | ACOS | Colin Gurganus<br>CIRES/NOAA CSL | OCS, CO and $CO_2$ mixing ratios | Aerosol precursor (sulfur budget), emissions tracer, age of air |
| | LIF-SO2 | Andrew Rollins<br>NOAA CSL | $SO_2$ mixing ratio | Aerosol precursor (sulfur budget), volcanic emissions |
| | UASO3 | Troy Thornberry<br>NOAA CSL | $O_3$ mixing ratio | |
| | UCATS | Fred Moore, Eric Hintsa<br>CIRES/NOAA GML | $N_2O$, $SF_6$ and CFC mixing ratios | Air mass age, transport |
| | DLH | Glenn Diskin<br>NASA LaRC | $H_2O$ mixing ratio | |
| | LIF-NOy | Eleanor Waxman<br>CIRES/NOAA CSL | NO, $NO_2$ and total reactive oxidized nitrogen ($NO_y$) mixing ratios | Stratospheric ozone chemistry, transport |
| | StratCIMS | Gordon Novak<br>CIRES/NOAA CSL | $N_2O_5$, $ClONO_2$ and Halogen species | Stratospheric ozone chemistry |
| **State Parameters:** | MMS | Paul Bui<br>NASA ARC | Temperature, pressure and winds | Atmospheric state |
| **Radiation:** | jNO2 | Eleanor Waxman<br>CIRES/NOAA CSL | UV radiation | Photolysis rates |

**Balloon Sonde Measurements from Utqiagvik, Alaska**

In addition to the SABRE aircraft measurements, four balloon sonde profile measurements were conducted from Utqiagvik (Barrow), Alaska (71.28° N, 156.79° W) during the SABRE 2023 deployment in collaboration with the NOAA Baseline Balloon Stratospheric Aerosol Profiles ($B^2SAP$) project. The sonde measurements provide vertical profiles of aerosol size distribution (140 nm – 2.5 µm) and ozone and water vapor mixing ratio from the surface to 24 km. Three of the launches were coordinated with WB-57F overflights near Utqiagvik and provide valuable insight into the vertical structure of the atmosphere in which the SABRE measurements were made.

**Arctic Polar Vortex Conditions During SABRE 2023**

A major sudden stratospheric warming (SSW) occurred on February 16, 2023. The mid-stratosphere warmed 20 °C in the week prior to the SSW. The core of the Arctic polar vortex was displaced eastwards towards Europe and then Asia, as the stratospheric Aleutian high grew in intensity. A secondary perturbation to the displaced vortex lobe occurred about a week later, destroying the remainder of the polar vortex in the mid-stratosphere. In the lowermost stratosphere, remnants of the polar vortex remained intact, but the persistent Aleutian high kept the polar vortex air over Eurasia for several weeks, with relatively high ozone (mid-latitude air) over the Alaska region for most of February and early March. In mid-March, this high pressure dome receded, allowing at first filaments, and then the core, of the remaining lower stratospheric vortex to move over Alaska, before moving back towards the pole by the last week of March. The vortex in the mid-stratosphere reformed in mid-March, leading to a later than average seasonal transition of the vortex to its easterly summertime state.
The evolution of the Arctic polar vortex over the SABRE 2023 study period played a major role in setting the science goals for individual research flights. The ridge over Alaska during the early part of the deployment led to flight plans targeting intrusions of lower latitude air and then as the ridge broke down, flight plans targeted vortex filaments. When the residual vortex passed over the study region, the research flight tempo was increased with back-to-back flights providing extensive sampling of the lowermost edge of the vortex itself.

**SABRE 2023 Science Questions, Initial Findings and Outlook**

1. **How do the aerosol number, mass, size distribution and composition evolve with age of stratospheric air?**

Measurements of aerosol size distribution and composition were made in air masses spanning a wide range of mean age, including fresh stratospheric air just above the tropical tropopause, air with ages of weeks-to-months that had been transported to midlatitudes through the lower branch of the Brewer-Dobson circulation, air with ages of 3–4 years that had been transported to middle and high latitudes through the upper branch of Brewer-Dobson circulation, and air with ages of several years that had been transported to the mesosphere followed by descent to the lower stratosphere in the polar vortex. Gas-phase tracer measurements (e.g., $N_2O$, $SF_6$, and $O_3$) provide measures of mean age since air mass entry into the stratosphere. Preliminary analysis shows the evolution of stratospheric aerosol size distribution and concentration with age due to coagulation, condensation, and mixing processes. These measurements will provide a powerful constraint to the new generation of global models that simulate the full aerosol size distributions.

**2. How does conversion of sulfur species in the stratosphere occur and contribute to aerosol mass?**

Measurements of $SO_2$ and OCS in tropical, midlatitude, polar, and vortex air masses will be used to quantify the conversion of gas phase sulfur species to aerosol mass in the stratosphere. The simultaneous aerosol size distribution measurements allow quantification of how sulfur conversion processes lead to condensation of sulfuric acid on stratospheric aerosol. The measurements of mean air mass age are also helpful in understanding sulfur chemistry processes in different parts of the stratosphere. OCS values near zero were observed in polar vortex air masses where tracer measurements indicated the highest mean age. The measurements across a range of mean ages will be used to estimate the OCS contribution to the stratospheric sulfate mass.

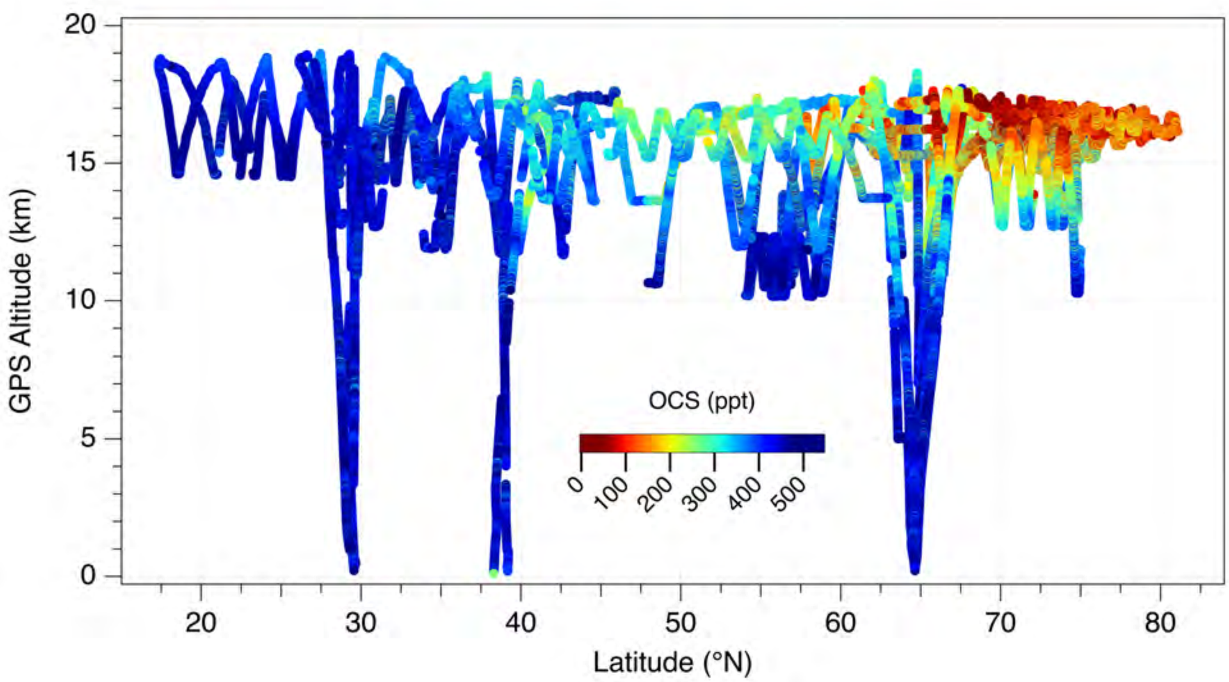


Figure 2. Altitude vs Latitude plot showing measured OCS mixing ratios.

Measured $SO_2$ levels in the UT/LS in both mid- and high latitudes were low, rarely exceeding 20 to 30 ppt. During the first several flights from Eielson AFB, enhanced $SO_2$ features near the tropopause predicted by the RAQMS model were targeted, including an intrusion of air originating from Asia. In general, the modeled $SO_2$ features were in the correct locations but the measured values were slightly lower than predicted by the model. The preliminary model-measurement agreement was significantly better than that observed during the 2022 ACCLIP campaign where measured $SO_2$ values were similar to those measured in SABRE, but the models (NCAR MUSICA, NASA GEOS) generally predicted significantly higher $SO_2$. Detailed model-measurement comparisons including the vertical profiles in different latitude regions will be useful in evaluating model transport and removal processes of $SO_2$ to better constrain the contribution of $SO_2$ to background stratospheric aerosol.

**3. How prevalent is extra-terrestrial meteoric material in stratospheric aerosol?**

Single-particle mass spectrometry measurements show meteoric material is present in most of the aerosols transported down through the polar vortex, consistent with previous measurements of enhanced number fractions of refractory aerosol residuals in Arctic vortex air. In high latitude sampling, a strong positive (negative) correlation was observed between the fraction of aerosols containing meteoric material and the $O_3$ ($N_2O$) mixing ratio. Measurements of the meteoric component in stratospheric aerosols across a range of latitudes and air mass ages will be used to investigate mixing and transport of stratospheric aerosol.

**4. Does new particle formation occur in the polar vortex?**

Measurements in the polar vortex unequivocally show increasing particle mixing ratio with altitude and mean age of air, indicating a source of particles at higher altitudes. Measured aerosol concentrations and size distributions in air masses with a range of inside vortex/outside vortex mixing states, as well as across a wide range of latitudes and heights, will be used to quantify the contribution of this particle source to the overall stratospheric aerosol budget.

**5. What is the impact of meteoric smoke particles on the properties of stratospheric sulfate aerosols?**

The SABRE 2023 observations that a large fraction of aerosol particles in vortex air contain meteoric material is suggestive of a role for meteoric smoke particles in sulfate aerosol formation in descent of air from the mesosphere and upper stratosphere. Model simulations that include meteoric smoke particles, condensation of sulfuric acid on the meteoric smoke, homogeneous nucleation of sulfate aerosols from the vapor, and coagulation of the different particle types will be required to definitively answer this question. The combination of single-particle mass spectrometry composition measurements and full size distributions in the lower part of the polar vortex will provide a powerful constraint to such model simulations.

**6. How does intrusion of polluted tropospheric air impact the lowermost stratospheric aerosol abundance, composition, and extinction?**

Measurements in lower latitude, polluted air intrusions from Asia into the Arctic lowermost stratosphere on February 28 and March 5 show enhanced particle concentrations and enhanced $SO_2$ mixing ratios in the lower 1–2 km of the stratosphere. Size distribution measurements and single-particle mass spectrometry measurements will be used to quantify the contribution of these intrusions to lower stratospheric aerosol extinction and composition, respectively.

## 7. What is the origin of abundant small aerosol particles frequently observed in the Arctic tropopause region?

Williamson et al. (2021) noted the existence of abundant ultrafine particles in the extreme lowermost stratosphere at high-latitudes in the Northern Hemisphere based on measurements from the NASA DC-8 during the ATom mission. The SABRE 2023 Arctic flights also revealed the common occurrence of enhanced aerosol mixing ratios in the lowermost stratosphere near the tropopause; however, the higher ceiling of the WB-57 shows that this layer disappears quickly with increasing height above the tropopause. The additional depth of the SABRE sampling will allow a more detailed evaluation of different hypotheses for the origins of these ultrafine particles, such as new particle formation, aircraft emissions, or isentropic transport from equatorward tropospheric sources.

## 8. Stratospheric aerosol sources and transport

The SABRE 2023 flights sampled the lower stratosphere from ~17° N to ~82° N latitude. Examining gradients in stratospheric aerosol composition (organic, meteoric-containig, pure sulfate, etc.) across this latitude range and as a function of altitude will provide insight into the processes by which particles are transported into, formed in and distributed through the stratosphere. Future SABRE deployments will expand this analysis through repeated measurements and measurements across an expanded latitudinal range.

## 9. Stratospheric age of air

The SABRE 2023 deployment sampled the winter high latitude lower stratosphere where some of the oldest ages of air in the atmosphere are present. $SF_6$ and $N_2O$ measurements (age of air tracers) allow us to estimate the stratospheric mean age in this region and compare to previous campaign measurements from over two decades ago. Changes in the mean age of air will be used to investigate possible circulation changes in the NH winter high latitudes as well as to identify how the increase in $SF_6$ mesospheric loss over this time affects the $SF_6$ mean age bias.

## 10. Stratospheric chemical processes

The high latitude flights from Alaska allowed sampling deep into the stratosphere, with $O_3$ mixing ratios of up to 3500 ppb compared to < 1500 ppb observed in the mid-latitude lower stratosphere during flights from Houston. The higher $O_3$ and lower actinic flux (and therefore photolysis frequencies) produced a clear decrease in the NO to $NO_2$ ratio. Much higher $NO_2$ and $NO_y$ mixing ratios were found on the high latitude flights, and preliminary analysis show similar $NO_y$ / $O_3$ ratios as reported on previous stratospheric chemistry campaigns (~ 3 ppb / ppm). Analysis goals for this campaign include comparing the measured $NO/NO_2$ ratios against those calculated using the photostationary state, comparing the data with previous measurements from high latitude missions such as POLARIS and SOLVE, and investigating the major sources of $O_3$ destruction inside and outside of the vortex in conjunction with the StratCIMS halogen data.

The new StratCIMS instrument flown during SABRE 2023 measured $N_2O_5$, BrO, and ClO mixing ratios at 1 s time resolution. Additional species, including $ClNO_3$, $HNO_3$, HOBr, and HOCl, may also be reported pending laboratory calibration and assessment of potential inlet artifacts.

These data will be used to 1) provide in situ constraints on heterogeneous uptake of reactive species such as dinitrogen pentoxide ($N_2O_5$) and chlorine nitrate ($ClNO_3$) under diverse chemical and meteorological regimes in the UT/LS, and 2) investigate processes that influence the abundance of reactive halogen species that participate in catalytic ozone destruction cycles.

Inlet artifacts are a concern for some of the reactive nitrogen and halogen species of interest due to combination of cold inlet surfaces and high ambient $O_3$ and HCl mixing ratios encountered during the campaign. An $O_3$ and $N_2O_5$ source was flown with the instrument to partially characterize these effects and data from flights across sunset will also be used to assess inlet chemistry by comparing observed photochemical profiles against expected behavior in the day-to-night transition. Extensive post-campaign laboratory calibrations will be conducted to assess the impact of these inlet artifacts for species of interest.

### 11. Measurement – Model comparison

Comparisons between RAQMS modeled values and SABRE 2023 in situ $NO_y$ measurements showed that RAQMS systematically underestimated $NO_y$ by more than a factor of 5 in the lower stratosphere. Further comparisons between RAQMS and MLS $HNO_3$ showed that this bias extends throughout the stratosphere. This has significant implications for RAQMS stratospheric chemistry and will be a subject of investigation.

Photo credit: Max Dollner

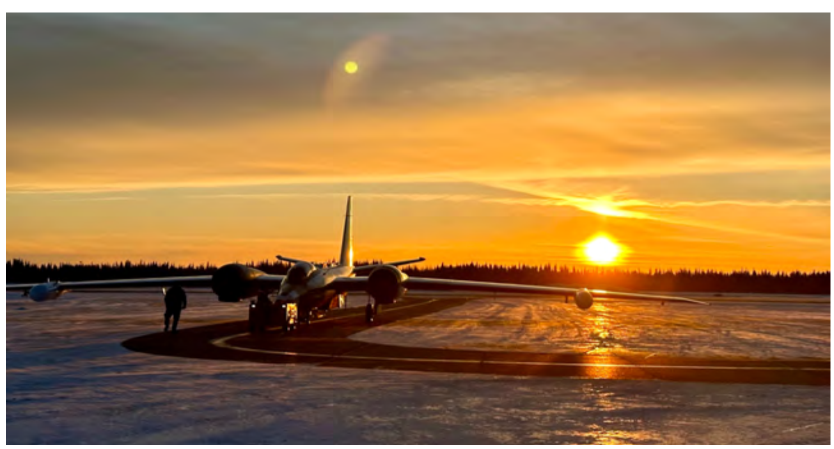

Photo credit: Nic Beres