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AIRMAPS 2024 Colorado
Airborne Methane Mass Balance Emissions in Colorado



A 2024 NOAA OAR investigation of emissions of greenhouse gases and air pollutants and factors that regional air quality in the Denver-Julesburg Oil and Gas Basin and the adjacent Denver Metropolitan Area. Major Objectives include the following.

1. Quantify methane emissions from Oil and Gas (O&G) operations and other sources in the Denver-Julesburg Basin (DJB) using airborne mass balance.
2. Compare airborne mass balance methane fluxes to other methods and assess emissions trends relative to prior studies in this region.
3. Assess emissions of air pollutants and greenhouse gases in both the DJB and the wider Denver Metropolitan Area (DMA).
4. Investigate the chemical regime and meteorological mechanisms that leads to summertime ozone in the DMA.

NOAA Chemical Sciences Laboratory: Sunil Baidar, Alan Brewer, Caroline Womack, Steven Brown, Carsten Warneke and Brian McDonald

NOAA Air Resources Laboratory (ARL): Xinrong Ren, Winston Luke, Phillip Stratton, Paul Kelley, and Jiayang Sun

NOAA Global Monitoring Laboratory (GML): Colm Sweeney, Jeff Peischl and Kathryn McKain

University of Colorado Atmospheric Spectroscopy Lab: Rainer Volkamer

Collaborators and Partners: Colorado Department of Public Health and Environment (CDPHE), NOAA/NESDIS, NIST, NASA JPL

Introduction

Oil and natural gas (O&G) production has increased substantially in the past two decades in both the United States and in Colorado (Figure 1). The Niobrara-Codell shale formation that lies in northern Colorado and stretches into Wyoming accounts for slightly more than 2% of current U.S. total natural gas production. Gas production there increased sharply from 2014-2020 and is at or near its peak as of 2024. This shale formation includes the Denver-Julesburg Basin (DJB) with a high density of O&G wells to the northeast of the city of Denver. Statewide oil production in Colorado (not shown) is approximately 4% of total U.S. production. These increases have led to concerns about greenhouse gas (GHG) emissions and air quality impacts. Methane (CH_4) is a potent GHG, and leakage from O&G production is estimated to represent 27-41% of total U.S. methane emissions [1, 2]. Emissions of nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC) from the O&G sector are also substantial and contribute to the formation of secondary pollutants such as ozone and particulate matter.

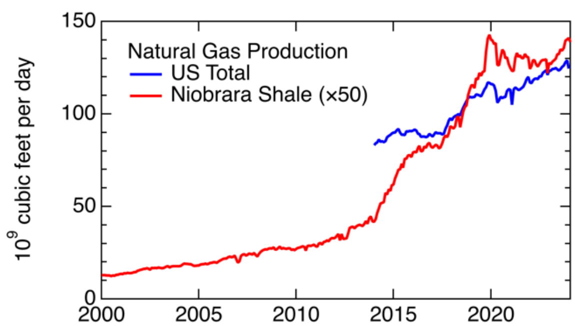

Figure 1. Monthly average natural gas production in the United States since 2014 and in the Niobrara-Codell shale formation (multiplied by 50 to place it on the same scale) since 2000. Data from the U.S. Energy Information Administration.

There have been numerous studies of DJB methane emissions in the last two decades. Petron *et al.* [3] first assessed methane and NMVOC emissions based on measurements from a 300 m tall tower and drives of a mobile laboratory in 2008. They found methane emissions that had a median value of 4% of total production and a factor of two larger than bottom-up inventories, but with a large uncertainty. A follow up aircraft mass balance study (see below for methods) on two days in May 2012 by the same authors found O&G methane emissions of 19.±7 tons hr^{-1}, or 4.1±1.5% of total production [4]. Peischl *et al.* [5] analyzed mass balance flights of the NOAA P-3 aircraft conducted in March 2015 and determined a similar methane emissions (18±8 tons hr^{-1}), but representing a smaller fraction (2.1±0.9%) of DJB production, which had increased by a factor of 1.7 between 2012 and 2015. This emissions fraction agreed with analysis of 2014 mobile laboratory drives in the DJB determining well pad emissions of 2.1% (1.1-3.9% range) of production [6]. Measurements of total column methane, ethane and ammonia from a network of three ground-based spectrometers in the Colorado Front Range, also in March of 2015, assigned 63, 25 and 12% of methane to O&G, agriculture and other sources, respectively [7]. Analysis of airborne mass balance flights of the University of Maryland Cessna aircraft in September and October 2021 determined similar O&G methane emission fluxes of 18.0±6.3 tons hr^{-1} based on 2 flight days analyzed out of 9 total flight days [8]. The nearly exact agreement in mass flux with the 2015 flights despite a twofold increase in O&G production between 2015 – 2021 suggested a continuing decrease in the methane emission fraction. Mobile laboratory drives through the DJB in 2021 determined emission factors from a series of O&G facilities showed a threefold decrease in emission factors over ten years, consistent with trends inferred from other studies [9]. Mead *et al.* [10] determined O&G and agricultural methane emissions from stationary observations using advanced spectroscopic instruments and inverse modeling within an 850 km^2 footprint centered at the NOAA Platteville Atmospheric Observatory (PAO) in Weld County. They present a synthesis of the studies referenced above to show declining O&G methane emission factors until 2017, but relatively constant values thereafter (Figure 2). The top down emissions determinations suggest a steeply declining methane emission intensity that has reduced total emissions despite large increases in natural gas production.

Satellite and airborne remote sensing instruments have recently begun to provide emissions estimates for U.S. methane emissions, including O&G producing areas [11, 12]. In the DJB for example, Cusworth *et al.* [13] used data from airborne imaging spectrometers and the TROPOMI instrument [14] to determine methane emissions in July and September 2021, producing total flux estimate (including O&G and other sectors) comparable to previous estimations but with differences between the airborne and satellite based inversions for total methane. Shen *et al.* [15] inverted TROPOMI observations to determine a DJB methane flux of 6.0 tons hr^{-1} between 2018-2020. Lu *et al.* [16] used a combination of surface and satellite remote sensing measurements to determine annual emissions in major U.S. O&G basins and showed a strong negative trend from 2010-2019 for the DJB.

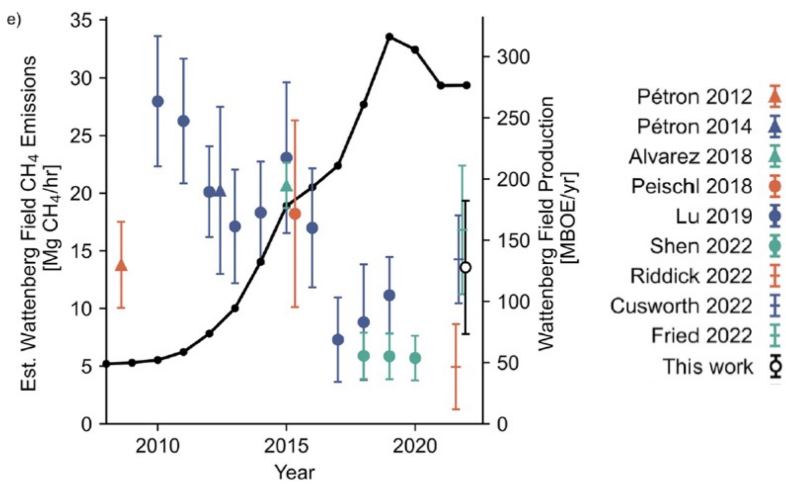

Figure 2. Synthesis of literature values for top-down methane emission determinations from the Wattenberg field, the largest natural gas producing area of the DJB, from 2008 - 2023. The right axis shows natural gas production in millions of barrels of energy equivalent. Reproduced from Mead *et al.* [10].

Rapid O&G development and production also leads to air quality impacts in the Denver Metropolitan Area. These impacts are of particular concern for ozone (O_3) since O&G production is a known source of ozone precursors, nitrogen oxides ($NO_x = NO + NO_2$) and NMVOC (hereafter VOC). Nitrogen oxide emissions and concentrations have been falling nationwide and in the Denver Metro Area for two decades, and in many parts of the U.S., ozone concentrations have also been decreasing. In the DMA, however, ozone levels have remained relatively constant, and the region has remained in non-attainment of the current National Ambient Air Quality Standard of 70 parts per billion (ppb) in an 8-hour average (Figure 3).

Investigations of VOC composition and sources during a 2011 wintertime study at a tall tower in Weld County, CO showed large impacts from O&G [17, 18], with O&G VOCs responsible for up to 55% of OH reactivity, a common metric to assess VOC ozone forming potential. Analysis and photochemical modeling of data taken from the same site during the summers of 2013 and 2014 showed that O&G VOCs were responsible for ~80% of the total VOC mass, ~50% of the OH reactivity and 18% of the average local photochemical ozone production [19]. Ground based and mobile laboratory data taken in the summer of 2014 during the Front Range Air Pollution and Photochemistry Experiment (FRAPPE) showed high levels of benzene and other air toxics [20], and individual ozone events that were consistent with a large contribution of O&G VOCs [21]. Similarly, analysis of aircraft data during the 2014 study identified the contribution of O&G NO_x, and primary and secondary O&G VOCs as contributors to ozone produced locally and during transport to remote locations in the Rocky Mountains [22]. More recent studies of O_3, NO_x, VOC and hazardous air pollutants largely corroborate previous analyses that O&G is a large VOC source that contributes to local ozone formation and air toxics [23-26].

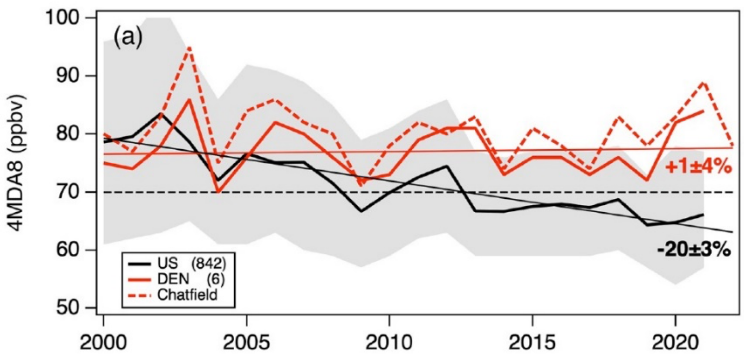

Figure 3. Spatially averaged fourth highest maximum daily 8-hour average ozone (MDA8) for the entire U.S. (black) and for 6 sites in the Denver Metro Area (red) for 2000 – 2021. The red dashed line shows a single site at Chatfield. Taken from Langford *et al.* [27].

NOAA will conduct a series of observations from mobile and stationary platforms in northern Colorado in early July 2024 to address emissions and air quality impacts from O&G operations, agriculture, industry and urban sources. This two-week study, the Airborne Methane Mass Balance Experiment in Colorado (AMMBEC) is part of the larger, multi-year Airborne and Remote Sensing Methane and Air Pollutant Surveys (AIRMAPS) initiative. The scientific objectives of AMMBEC / AIRMAPS 2024 are as follows.

- Quantify methane emissions from Oil and Gas (O&G) operations and other sources in the Denver-Julesburg Basin (DJB) using airborne mass balance.
- Compare airborne mass balance methane fluxes to other methods and assess emissions trends relative to prior studies in this region.
- Assess emissions of air pollutants and greenhouse gases in both the DJB and the wider Denver Metropolitan Area (DMA).
- Investigate the chemical regime and meteorological mechanisms that leads to summertime ozone in the DMA.

Platforms and Methods

The NOAA Chemical Sciences Laboratory (CSL), Air Resources Laboratory (ARL), Global Monitoring Laboratory (GML) and the University of Colorado Atmospheric Spectroscopy Lab will conduct observations in the DJB & DMA using mobile and stationary platforms from July 1 – 15, 2024. These platforms include a NOAA Twin Otter aircraft, the NOAA Air Resources Laboratory Car (NOAA's ARC), the Pick-Up based Mobile Atmospheric Sounder (PUMAS), the Tunable Optical Profiler for Aerosol and oZone (TOPAZ) lidar and potentially the CSL Mobile Laboratory. The following sections describe each platform and deployment logistics.

NOAA Twin Otter

The NOAA Twin Otter measurement systems (Figure 4) will consist of a scanning Doppler lidar, developed by the NOAA CSL Atmospheric Remote Sensing program, which will measure profiles of horizontal and vertical winds, turbulence and aerosol backscatter intensity through the atmospheric boundary layer. With support from the Colorado Department of Health and Environment (CDPHE, see below), researchers from the University of Colorado will deploy an Airborne Multi-Axis Differential Optical absorption Spectrometer (AMAX-DOAS) to measure total columns and vertical profiles of nitrogen dioxide (NO_2), formaldehyde (HCHO), glyoxal (CHOCHO), and other visible absorbing trace gases. An upward/downward multispectral radiometer will provide information on land usage, cloud cover and atmospheric haze conditions. The aircraft is equipped with an AIMMS-20 meteorological probe for fast response vertical and horizontal winds and other parameters.

The Twin Otter aircraft will also be equipped with instruments for in-situ measurements of both greenhouse gases and air quality relevant species. Greenhouse gases and tracers include H_2O, CO_2, CH_4, CO and ethane (C_2H_6). Air quality relevant species include O_3, NO, NO_2, NO_y, CO and ethane to characterize photochemistry and the spatial extent of air pollution. NO_y is total oxidized nitrogen or the sum of NO_x and its oxidation products (e.g., nitric acid, HNO_3). Measurements of the spatial distribution of these species, along with meteorological data, will enable better understanding of factors that contribute to ozone in the DMA. It will also enable determination of emissions fluxes of all measured trace gases via airborne mass balance (see below). Table 1 lists the planned measurements on the NOAA Twin Otter.

A similar aircraft package has recently flown in the New York region as part of the Coastal Urban Plume Dynamics Study (CUPiDS) in July – August 2023. Data from that study are currently being analyzed to determine urban methane and NO_x emissions from New York City. The algorithms developed for CUPiDS will directly inform similar measurements in the Front Range. NOAA CSL and ARL have also recently partnered with Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado to provide airborne and ground-based measurements of methane, other trace gases and transport during September – October 2021, and Airborne Measurements and analysis of Emissions over the Denver-Julesburg and Piceance (AMED) campaign in October – November 2023. That study used ground based mobile Doppler lidar (PUMAS) measurements for boundary layer depth and wind fields. Measurements in summer 2024 will complement these recent data with measurements during the summer ozone season, and with direct airborne wind lidar data.

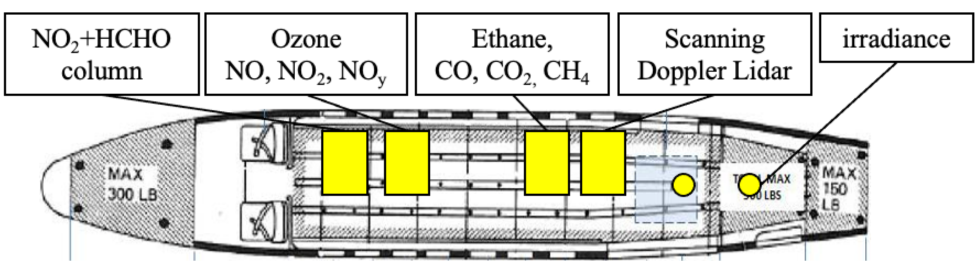

Figure 4. The proposed payload of the NOAA Twin Otter for AMMBEC / AIRMAPS 2024.

Table 1: NOAA Twin Otter payload for AMMBEC / AIRMAPS 2024

Instrument	Measured species
Scanning Doppler Lidar	3-D Wind and Aerosol Profiles, Boundary layer depth
Picarro G2401-m	CO_2, CH_4, CO and H_2O
Aeris Ultra Mid-IR absorption	C_2H_6
2B UV Ozone Analyzer	O_3
Direct Optics CRDS	NO, NO_2
Teledyne CAPS + Thermo dissociation	NO_y
AMAX-DOAS	NO_2, HCHO, CHOCHO column
Radiometers	Irradiance, surface temperature, jNO_2
AIMMS probe	Flight level temperature, pressure, winds

NOAA's Air Resources Car

NOAA's Air Resources Car (NOAA's ARC) mobile lab will be deployed in this study to conduct surface mobile measurements of air pollutants and GHGs that will complement the aircraft measurements. We will coordinate with the Twin Otter to make simultaneous mobile and aircraft measurements to better characterize spatial distribution and transport of air pollutants and GHGs. As we have done previously, we may also make mobile measurements in disadvantaged communities of concern in the Denver Metro Area to address ongoing and recently identified environmental justice issues [28]. These communities most suffer from a combination of economic, health, and environmental burdens. NOAA's ARC has already made drives in the DMA and DJB as part of the recent AMED campaign.

Figure 5. Pictures showing the instrumentation in NOAA's Air Resources Car mobile lab.

Table 2. NOAA's Air Resources Car payload for AMMBEC / AIRMAPS 2024

Instrument	Measurement Species
2B UV Ozone Analyzer	O_3
Direct Optics CRDS	NO-NO_2-NOx
Picarro G2401-m	CO_2, CH_4, CO and H_2O
Aeris Ultra Mid-IR absorption	C_2H_6
7-λ Aethalometer	Black Carbon
Picarro Isotope CRDS	$^{13}CO_2$/$^{13}CH_4$
Whole air samples with GC-MS or GC-FID	VOCs
Vaisala Met Sensors	T, P, RH

Pick-Up based Mobile Atmospheric Sounder (PUMAS)

The NOAA CSL PUMAS instrument is a microjoule class, scanning Doppler lidar (MicroDop) installed in the bed of a pickup truck that measures vertical profiles of horizontal and vertical winds, turbulence and aerosol backscatter intensity while driving at highway speeds. These variables can be used to infer boundary layer height. PUMAS will complement the airborne Doppler lidar system installed on the Twin Otter to provide additional constraints on transport processes during research flight days in support of airborne mass balance measurements. This instrument participated in the October – November 2023 AMED campaign, where it supported airborne mass balance flights of the University of Maryland Cessna aircraft.

Figure 6. The NOAA CSL PUMAS instrument during the 2023 AWAKEN campaign in Kansas and Oklahoma.

Tunable Optical Profiler for Aerosol and oZone (TOPAZ)

The NOAA CSL TOPAZ instrument utilizes Differential Absorption Lidar (DIAL) to measure vertical profiles of ozone and aerosol backscatter. TOPAZ is part of the NASA Tropospheric Ozone Lidar Network (TOLNet) for ground-based profiling of tropospheric ozone, validation of satellite ozone measurements, and a long-term data record for ozone vertical profiles. TOPAZ has a 2-axis zenith and azimuth scanner to enable measurements from a few meters above ground level through its maximum range of 6–8 km. TOPAZ will make intensive measurement during daylight hours from the NOAA David Skaggs Research Center (DSRC) in Boulder on flight and drive days during the two-week measurement period. NOAA CSL will also continuously operate a stationary ground based Doppler lidar alongside TOPAZ at the DSRC site during the two-week measurement period to provide additional context and constraint to flight days. These data will help to meet the air quality research goals for AMMBEC / AIRMAPS 2024.

CSL Mobile Laboratory

The CSL Mobile Laboratory (CSL-ML) is an instrumented Ford Transit van that has recently been acquired and upgraded to accommodate measurements of detailed chemical composition using a suite of instruments that include greenhouse gases, nitrogen oxides, speciated VOCs, speciated oxidized nitrogen, particulate matter size distributions and total mass, meteorological parameters and other data. The CSL-ML will participate in the Utah Summer Ozone Study (USOS) in the summer of 2024 in Salt Lake City, Utah, which will begin immediately following AMMBEC. Integration of instrumentation will take place in spring 2024. Test drives of the CSL-ML may contribute to the data set for AMMBEC during the first two weeks of July 2024, but this contribution will depend on the availability of this platform for the Colorado measurements.

Further details on the planned measurements from the CSL-ML are available at the USOS web site linked above.

Deployment Plans and Methodology

The NOAA Twin Otter, NOAA's ARC mobile lab, PUMAS and TOPAZ will be deployed to Denver Metro Area / Northern Colorado Front Range / Denver Julesburg Basin from July 1 – 15, 2024. The Twin Otter will base at Rocky Mountain Metropolitan Airport in Broomfield, Colorado and will conduct research flights on 6 – 8 days during the two-week period, contingent on meteorological conditions and aircraft readiness. Each flight day consists of up to two flights of 3 – 3.5 hours duration for a total of 6 – 7 flight hours per day and 30 – 60 total flight hours for the campaign. The ARC and PUMAS will make mobile measurements where / when there will be flights conducted. TOPAZ will operate on flight / drive days. The CSL-ML will make drives of opportunity as part of its preparation for USOS on an as-available basis.

Mass Balance and Air Quality Flights

Aircraft mass balance and air quality flights in the Northern Colorado Front Range will quantify emissions of GHGs (CH_4 and CO_2) and other air pollutants such as CO, C_2H_6 and NO_y. This method relies on the assumptions of constant emissions and well-mixed stationary planetary boundary layer (PBL) depth during a given experiment period and has been proven to be robust for the estimate of total emissions from a given area. Wind carrying background concentrations of GHGs blows over the source region, where it picks up GHG and air pollutant emissions. Horizontal transects are flown perpendicular to the wind direction downwind of the target area, and enhancements in GHG above background are intercepted and detected. The GHG emission rate from the area can be calculated [5, 29, 30].

$$Emission \quad Rate = \int_0^z \int_{-x}^{+x} \left([C]_{ij} - [C]_b \right) \times U_{\perp ij} \, dx dz$$

Here, $[C]_{ij}$ is the concentration of a GHG or air pollutant at a downwind location (xi, zi) ; $[C]_b$ is the background concentration detected upwind or on the downwind edges; $U_{\perp ij}$ is the perpendicular wind speed at a downwind location of (xi, zi); [-x, +x] defines the horizontal width of the plume from the surveyed area; and [0, z] defines the PBL height.

The Doppler lidar system that will be deployed on the Twin Otter has the potential to significantly improve the efficiency and accuracy of the traditional mass balance approach. The custom airborne lidar system measures the vertically resolved wind field (both horizontal and vertical) above and below the aircraft, together with the depth of the planetary boundary layer. This capacity resolves some assumptions inherent in the use of in-situ winds alone and reduces the requirement for frequent vertical profiling to assess boundary layer depth.

Based on forecasts for wind conditions and severity of air quality on any given day, flights will be conducted over either the Denver Julesburg Basin or the Denver Metro Area. The primary focus of DJB flights will be GHG and air pollutant mass balance. The primary focus of DMA flights will be assessment of air quality impacts of regional emissions on summertime ozone. Figures 7 and 8 give notional examples of single, ~3.5 hour flights for mass balance and air quality flights, respectively. The Twin Otter can fly twice on each research day, such that the flights shown below could be repeated twice, or a mass balance and air quality flight could be conducted in sequence on the same day. For the DJB mass balance flight in Figure 7, the Twin Otter endurance allows for nominally three transits around the dense area of O&G wells. Such a flight plan is feasible for any wind direction but is optimal for easterly or westerly flow approximately perpendicular to the longest flight legs. The plan shows nominal cruising altitude at approximately 500 m above ground (AGL), although the actual flight altitudes may vary to make best use of the in-situ, lidar and remote sensing column instruments. For the DMA air quality flight in Figure 8, transects along the eastern and southern edges of the urban area from Fort Collins to Denver characterize the receptor sites along the mountains (e.g., Rocky Flats, NREL, Chatfield, Fort Collins) under generally easterly wind flow. Additional flight plans may incorporate transects above urban Denver or the DJB to make best use of remote sensing instruments for satellite validation (see below).

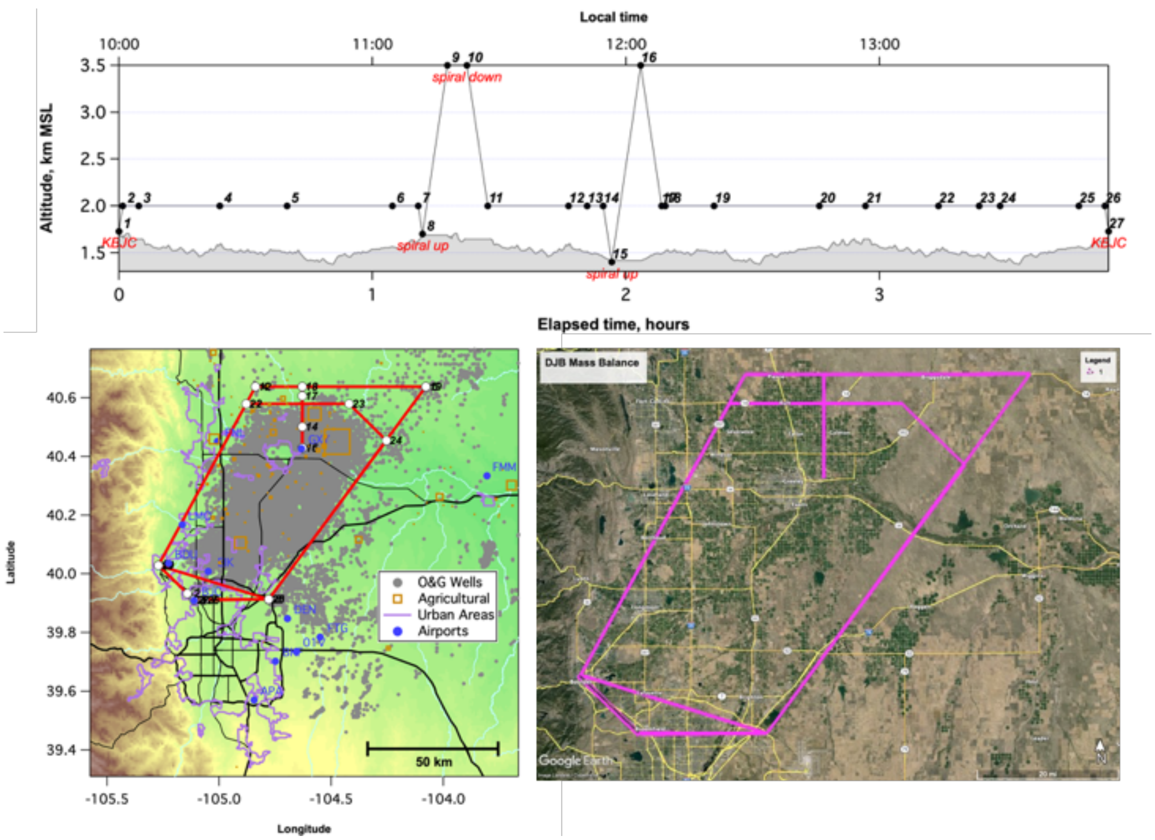

Figure 7. Example Denver Julesburg Basin mass balance flight plan. *Top:* Altitude vs time showing level legs at approximately 500 m AGL. Missed approaches and spirals at Broomfield and Greeley characterize boundary layer structure. *Bottom left:* Map showing flight track with O&G wells, agricultural facilities sized by number of animals, urban boundaries and airfields. *Bottom right:* Google Earth image of flight track.

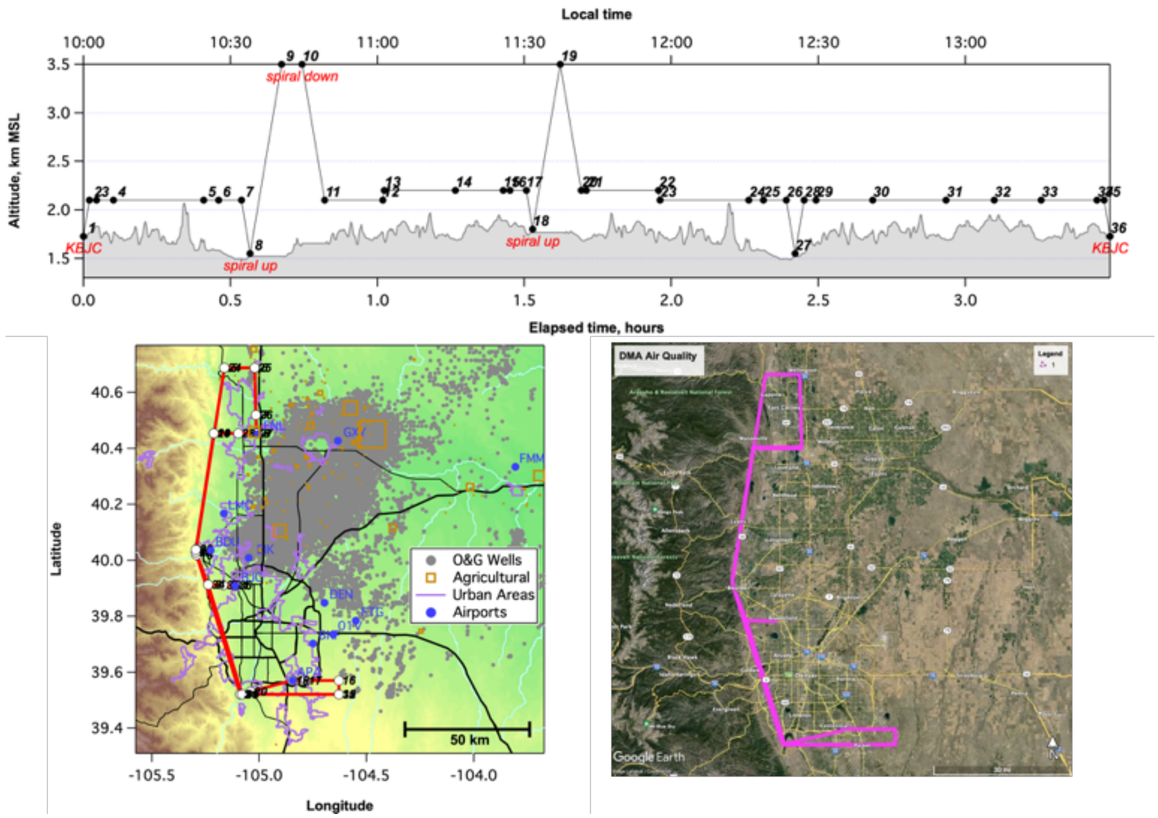

Figure 8. Example Denver Metro Area air quality flight. Graphs are the same as Figure 8. Missed approaches and spirals at Fort Collins and Centennial (south Denver) characterize the boundary layer structure.

Collaboration and Partnership

AMMBEC / AIRMAPS 2024 has a number of coordinating activities and support, as described further below.

Colorado Department of Public Health and Environment

The Colorado Department of Public Health and Environment (CDPHE) is providing support for the NOAA Twin Otter and NOAA's ARC deployment costs. The airborne mass balance flights follow a series of campaigns using this method and others to determine O&G emission fluxes from the DJB. Such measurements provide assessment of the efficacy of state policies to reduce emissions from the O&G industry. Figure 2 shows the methane emissions have declined over time, and that they have declined steeply with respect to natural gas production. Air quality research flights in the DMA will provide data to the state of Colorado to inform ozone mitigation strategies.

NASA JPL AVIRIS NG

The NASA Airborne Visible / Infrared Imaging Spectrometer – Next Generation (AVIRIS NG) has mapped methane plumes across the U.S. and international locations. At the time of this writing NASA JPL investigators are exploring coordinated flights during AMMBEC / AIRMAPS 2024.

Methane Air

MethaneAir is an airborne imaging spectrometer complementary to the recently launched MethaneSat. MethaneAir will be deployed on the NSF G-V aircraft during summer 2024 and also based at Rocky Mountain Metro Airport, the same location as the Twin Otter. At this time, coordinated flights are planned in Salt Lake City, Utah during the USOS campaign, but not for the Twin Otter Colorado deployment. NOAA will maintain contact with MethaneAir investigators in the event that coordinated flights of opportunity are possible in the first two weeks in July.

US Greenhouse Gas Center

The US GHG Center has recently been established through a partnership between NASA, NIST, EPA and NOAA to provide a single portal for access to GHG data collected by different agencies and to coordinate GHG research capacity and activities. NOAA is utilizing contacts through this center to coordinate measurements with other federal agencies and is investigating methods for the center to host data and results from the center.

Satellite Validation

Collaborating with NOAA NESDIS and other satellite partners on satellite data validation is crucial for ensuring the accuracy and reliability of observations from space-based instruments. Leveraging measurements of air pollutants and greenhouse gases (GHGs) obtained from AMMBEC / AIRMAPS 2024 can contribute to the validation efforts of satellites such as TEMPO, TROPOMI, GOES-ABI and others, thereby improving the quality of satellite-derived data for GHG and air pollutants. Measurements from AMMBEC / AIRMAPS 2024, including those from ground-based instruments and aircraft vertical profiles, offer valuable ground truth data that can be compared and validated against satellite observations. Specifically, observations of air pollutants such as NO_2, HCHO and CHOCHO from the CU AMAX-DOAS instrument and TEMPO can be validated and intercompared with ground-based measurements and aircraft vertical profiles. Similarly, assessments of GHG columns from satellites like TROPOMI and MethaneSat can benefit from the validation provided by the airborne measurements. This collaborative effort strengthens the scientific basis for addressing environmental challenges and informs decision-makers about the state of the atmosphere and potential impacts on human health and ecosystems.

Expected Outcomes

The DJB Twin Otter flights and drives aim to identify and quantify methane emissions from O&G activities. By identifying and quantifying methane and other air pollutant emissions from this sector, the project seeks to provide valuable insights to CDPHE and the state of Colorado to assess the efficacy of current and future emissions mitigation strategies.

The project anticipates generating a new airborne air quality data set for the Denver Metropolitan Area during the summer of 2024. The data set will include spatial and temporal variations in pollutant concentrations, identification of pollution hotspots, and an assessment of factors that lead to summertime ozone. The findings will contribute to the development of targeted air quality improvement strategies.

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