Downward Trend in Methane Detected in a Northern Colorado Oil and Gas Production Region Using AIRS Satellite Data

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Abstract

The oil and gas (O&G) sector is estimated to be the largest contributor to anthropogenic methane (CH4) emissions in Colorado. Since 2004, the State of Colorado has implemented multiple regulations to significantly reduce emissions from the O&G sector. The Denver-Julesburg Basin (DJ Basin) is a significant O&G producing region in northern Colorado, and O&G production here has steadily increased over the last decade. To assess CH4 trends in Northern Colorado, we selected CH4 retrievals from the NASA Atmospheric Infrared Sounder (AIRS) instrument for 2003-2020. The study grid cell includes Denver, Boulder, and much of the dense O&G production in the DJ Basin. We computed mean June-August ascending node AIRS 700 hPa CH4 for each year and subtracted mean June-August CH4 sampled at NOAA's Niwot Ridge (NWR) station, a high-altitude background site. Differences represent estimated enhancement over background. Linear regression shows an annual change of -2.84 ppb +/- 0.8 ppb from 2012-2020 (R-squared 0.90) and an estimated reduction of 56% for 2012-2020, despite substantial increases in O&G production. Local CH4 enhancement is strongly correlated with surface measurements of ethane at Platteville which is in the center of the O&G fields (correlation coefficient 0.96), and this is evidence that reductions in O&G emissions are driving reductions in CH4. We conclude that AIRS CH4 can be used to measure the efficacy of emissions control programs in this region and that regulatory requirements are having an effect.

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Key Points:

- Despite substantial increases in local oil and gas production, methane enhancement in the northern Colorado study area declined significantly from 2012-2020.
- Decreases in both methane enhancement and ethane support the conclusion that emissions reduction efforts have been effective.
- AIRS satellite methane retrievals can detect changes in boundary-layer concentrations when mixing heights and source emissions are large.

Abstract

The oil and gas (O&G) sector is estimated to be the largest contributor to anthropogenic methane (CH_4) emissions in Colorado. Since 2004, the State of Colorado has implemented multiple regulations to significantly reduce emissions from the O&G sector. The Denver-Julesburg Basin (DJ Basin) is a significant O&G producing region in northern Colorado, and O&G production here has steadily increased over the last decade. To assess CH_4 trends in Northern Colorado, we selected CH_4 retrievals from the NASA Atmospheric Infrared Sounder (AIRS) instrument for 2003-2020. The study grid cell includes Denver, Boulder, and much of the dense O&G production in the DJ Basin. We computed mean June-August ascending node AIRS 700 hPa CH_4 for each year and subtracted mean June-August CH_4 sampled at NOAA's Niwot Ridge (NWR) station, a high-altitude background site. Differences represent estimated enhancement over background. Linear regression shows an annual change of -2.84 ppb +/- 0.8 ppb from 2012-2020 (R-squared 0.90) and an estimated reduction of 56% for 2012-2020, despite substantial increases in O&G production. Local CH_4 enhancement is strongly correlated with surface measurements of ethane at Platteville which is in the center of the O&G fields (correlation coefficient 0.96), and this is evidence that reductions in O&G emissions are driving reductions in CH_4. We conclude that AIRS CH_4 can be used to measure the efficacy of emissions control programs in this region and that regulatory requirements are having an effect.

1 Introduction

According to the Colorado Department of Public Health and Environment (CDPHE) (2021), the oil and gas (O&G) sector is estimated to be the largest industrial contributor to anthropogenic methane (CH_4) emissions in Colorado. The Denver-Julesburg Basin (DJ Basin) is a significant O&G producing region in the northern portion of the State. O&G production in the DJ Basin has steadily increased over the last decade. Figure 1 shows O&G production trends for 2003-2020 for the Wattenberg Field, the primary resource area in the DJ Basin (data from the Colorado Oil and Gas Commission, October 2021, https://cogcc.state.co.us/data.html.) Oil production increased by 343% and gas production by 297% between 2012 and 2020.

For a variety of reasons, including the fact that a portion of the state that includes the DJ Basin has been designated an ozone nonattainment area by the Environmental Protection Agency (EPA), Colorado has implemented regulations to significantly reduce emissions of CH_4 and volatile organic compounds (VOCs) from O&G production facilities. Although initial regulations were focused on ozone reduction goals, many control requirements had associated CH_4 emission reduction co-benefits. One of the most significant of these regulatory changes since 2004 was in February 2014 when the Colorado Air Quality Control Commission (AQCC) fully adopted EPA's New Source Performance Standards (NSPS), 40 CFR Part 60, Subpart OOOO, into AQCC Regulation No. 6 and adopted more stringent control requirements for VOCs and hydrocarbons for a variety of O&G sources in AQCC Regulation No. 7. The changes to Regulation No. 7 in early 2014 included expanded control requirements for hydrocarbon liquid storage tanks, pneumatic controllers, glycol dehydrators, and components; implementation of a leak detection and repair program; and limitations to venting associated with maintenance and liquids unloading from storage tanks. Since 2014, the AQCC has continued to adopt additional measures to reduce CH_4 and VOCs from O&G sources, and this is anticipated to continue through 2021 and beyond. The Regional Air Quality Council (RAQC) and CDPHE (2020) projected that O&G VOC emissions would decline from 279.7 to 119 tons per day from 2011 to 2020 within the Denver Metro and North Front Range Ozone Nonattainment Area (a 57% reduction).

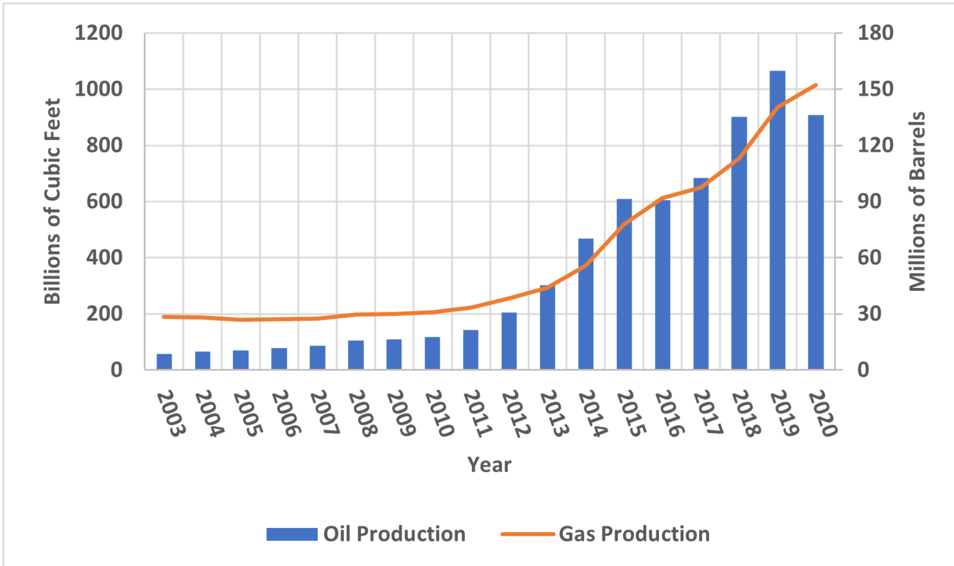

Figure 1. O&G production in the Wattenberg Field within the DJ Basin. The greatest growth occurs between 2012 and 2020.

If these controls have been effective, then we would expect to see reductions in CH_4 in the region after the implementation of new rules in 2014. In order to understand the efficacy of past O&G regulations and drivers for future emission control regulations, this analysis uses satellite and surface measurements to examine CH_4 trends and reductions over the past two decades in an area of Northern Colorado that includes the Denver metropolitan area and a portion of the DJ Basin north of Denver that contains a high density of O&G wells. While a variety of government agencies, researchers, and other groups have assessed CH_4 and VOC concentrations in Colorado from surface and aerial measurements, satellite CH_4 data has not yet been widely used to assess CH_4 trends in Colorado.

Three recent papers consider trends in surface measurements of CH_4 or non-methane hydrocarbons (NMHCs) in our study area for shorter time periods within our temporal domain (2003-2020). Oltmans et al. (2021) recently reported trends in CH_4 using air samples collected at the National Oceanic and Atmospheric Administration (NOAA) Boulder Atmospheric Observatory (BAO) tower near Erie in southwestern Weld County. For 2008-2016 they found no statistically significant trends in CH_4 relative to background values when flows were from the DJ Basin. Ortega et al. (2021) found a positive trend of 0.9 ppb ± 0.3 % per year for ethane at a site north of Boulder from 2010-2019 using a solar absorption Fourier Transform InfraRed instrument. In a source-apportionment study that considered trends from 2013 to 2016, Lyu et al. (2021) show a reduction of approximately 50% in nonmethane hydrocarbons at the CDPHE Platteville site which is located within the DJ Basin in Weld County. They report that "new regulations implemented by the state as well as changes in operating practices made by the industry for other reasons might explain the observation that NMHC mixing ratios at the

Platteville site were lower in 2016 than in 2013." We will show that our results are generally consistent with those from each of these studies and also point to a statistically significant decline in CH_4 extending from 2012 through 2020.

Satellites and aircraft studies are now common tools for calculating emissions fluxes and the contributions of O&G sources to ambient concentrations of CH_4 and VOCs, and because of greater spatial coverage these can yield data more representative of regional emissions than a limited number of surface monitoring sites. In addition, satellite measurements are made on a regular basis and typically provide greater temporal coverage than aircraft studies. Recently, de Gouw et al. (2020) published analyses of CH_4 data from the TROPOspheric Monitoring Instrument (TROPOMI) on board the Copernicus Sentinel-5 Precursor satellite, which was launched in October of 2017. In their paper, the authors have identified and quantified CH_4 enhancements over many O&G basins in the United States. TROPOMI has high spatial resolution and greater signal sensitivity than older satellite instruments, but there is not yet a long enough data record to identify long-term trends.

To assess long-term CH_4 trends in Northern Colorado, we selected the Atmospheric Infrared Sounder (AIRS) instrument launched in 2002 on the Aqua Satellite, because of its almost 20 years of data, its ongoing use, and its provision of an accurate estimate of the rates of change in CH_4 from year-to-year. Zhang et al. (2020) concluded that AIRS CH_4 data are suitable for analyses of spatial and temporal patterns across the globe. They demonstrated that AIRS CH_4 data are closer to surface concentrations than CH_4 data from the SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY) satellite instrument or the Greenhouse Gases Observing Satellite (GOSAT). AIRS has been used by researchers to quantify regional and national CH_4 changes and trends over both short and reasonably long-time scales (Rendana et al., 2021; Yang and Wang, 2020; and Ribeiro et al., 2016). Wu et al. (2019) recently completed a comprehensive, long-term, analysis of CH_4 trends across China using AIRS data from 2002-2016. They conclude that AIRS CH_4 concentrations "showed good consistency with the ground measurements of surface CH_4 concentration from the World Data Centre for Greenhouse Gases (WDCGG) ($R^2 = 0.83$, $p < 0.01$), indicating that the remotely-sensed CH_4 reflected the spatial and temporal variations of surface CH_4 concentration". Rendana et al. (2021) also found good agreement between AIRS and surface CH_4 measurements with an R^2 of 0.86.

Our goal is to generate an initial estimate of changes in CH_4 and an AIRS-based metric for tracking rates of change in CH_4 that can eventually be linked with potentially more robust trend studies using TROPOMI and future higher resolution satellite instruments.

2 Data Sources and Methods

We used June through August 2020 AIRS Version 7 retrievals for the 700 hPa level for 2003-2020 (https://giovanni.gsfc.nasa.gov/giovanni/). Details of this product are provided here: https://disc.gsfc.nasa.gov/datasets/AIRS3STM_7.0/summary. Summer season data were chosen in part to optimize the relevance of our results to assessments of trends in local O&G VOC emissions that contribute to ozone exceedances and also because of the higher sensitivities of the AIRS product when surface mixed layers are deep. The AIRS product is particularly well suited for several reasons. Specifically, we selected the AIRS data for this study due to its long period of record, the frequency and timing of overflights, and relatively low uncertainty for CH_4.

We used NOAA Global Monitoring Laboratory (GML) monthly mean CH_4 data collected at Niwot Ridge (https://gml.noaa.gov/) (Dlugokencky et al., 2021) to estimate local, continental background concentrations. Niwot Ridge (NWR) is a high-altitude site at 40.053°N, 105.586°W, and 3,523 meters above sea level (MSL) west of the study area. According to Lan et al. (2022), GML calculates monthly means after first extracting weekly values from a smoothing curve applied to all valid data using the method described by Thoning et al. (1989).

We also acquired vertical profile data for CH_4 from aircraft flights from the NASA summer 2014 field campaign "Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality" (DISCOVER-AQ) (https://www-air.larc.nasa.gov/missions/discover-aq/P3B-Profiles.co2014.html). With these data we assessed the representativeness of AIRS retrieval concentrations.

AIRS CH_4 data were also compared with Colorado Department of Public Health and Environment (CDPHE) median annual ethane data measured at Platteville and the Denver CAMP station (from: https://www.colorado.gov/airquality/tech_doc_repository.aspx). The Platteville site is at 40.209°N, 104.824°W, and 1,469 meters MSL. The CAMP station is at 39.75°N, 104.99°W, and 1,593 meters. Monitoring at these sites was initiated in late 2011. Three-hour samples were collected with summa canisters from 6-9 AM every six days, and the chemical constituents were analyzed following EPA Compendium Method TO-15 (USEPA, 1999). Ethane and NMHC concentrations at Platteville are largely from O&G sources (Lyu et al., 2021). Ethane trends at this site are representative of O&G emission trends. The representativeness of Platteville monitoring for the O&G fields was tested with the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) back trajectories (Stein et al., 2015; Rolph et al., 2017) for 2018.

The study area for the trend analysis is presented in Figure 2, and it includes most of the Denver-Boulder metro area and most of the O&G wells in the DJ Basin (the grid cell area will be referred to as the DDJB). The AIRS satellite flies over the DDJB region once every 12 hours. The afternoon overflights occur at approximately 13:30 MST and are referred to as ascending node overflights. We used ascending node data for 2003-2020 for a 1° by 1° grid cell centered at 40°N and 105°W. This is a standard grid cell from the NASA AIRS CH_4 product.

We obtained mean June-August 500 hPa heights from the National Center for Environmental Prediction (NCEP) Reanalysis (https://psl.noaa.gov/cgi-bin/data/timeseries/timeseries1.pl) for a 2.5° by 2.5° grid cell centered on 40°N 105°W, and this contains our study area. The NCEP Reanalysis meteorological data product is described by Kalnay et al. (1996). We correlated year-to-year changes in ethane and CH_4 enhancements with year-to-year changes in 500 hPa heights to see if meteorology plays a role in the trends we identified. To provide evidence that the AIRS 700 hPa ascending node CH_4 retrievals for the study area are sensitive to planetary boundary layer (PBL) heights, we calculated the correlation between monthly mean AIRS data and monthly mean PBL heights from the NASA Modern-Era Retrospective analysis for Research and Applications MERRA version 2 (MERRA-2) for 2012-2020 (https://giovanni.gsfc.nasa.gov/giovanni/).

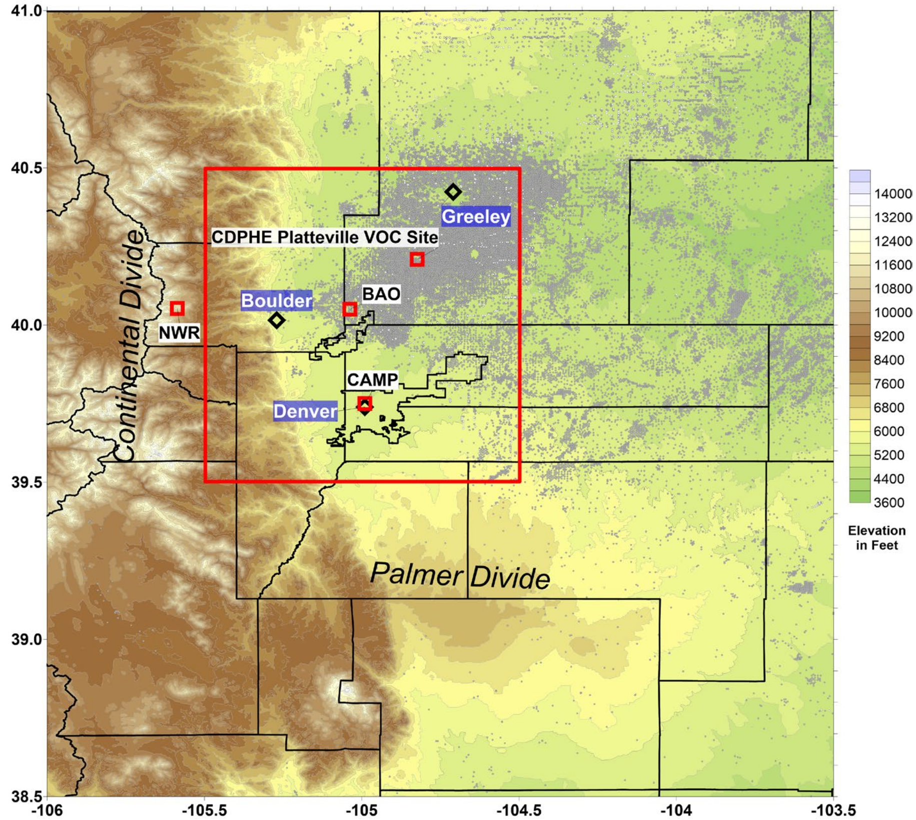

Figure 2. Grid cell for the NASA AIRS CH_4 product centered on 40°N and 105°W in northern Colorado. The grid cell includes most of the Denver-Boulder metro area and most of the O&G wells (gray dots) in the southwestern portion of the DJ Basin. The grid cell covers mostly lower elevation terrain (~1,500 meters MSL). The foothills account for a small fraction of the grid cell area.

NASA has averaged AIRS data for nine single-footprint measurements in this grid cell. The grid cell covers much of the Wattenberg field, an O&G field located in the DJ Basin, as well as the Denver-Boulder metro area. The high density of O&G wells in the northeast corner of the AIRS grid cell is associated with the Wattenberg Field. Thermally driven upslope flows prevail along Colorado's Front Range at 13:30 MST (the satellite overflight time) during the summer (Toth and Johnson, 1985; Reddy and Pfister, 2016; Pfister et al., 2017; Flocke et al., 2019). These flows will often transport CH_4 westward and southwestward from the O&G fields into and across the grid cell by 13:30 MST. For example, using data available from an Iowa State University website (https://mesonet.agron.iastate.edu/sites/dyn_windrose.phtml?station=EIK&network=CO_ASOS) we calculated that winds at Erie at the southern end of the Wattenberg were calm or from the north through east-southeast 71% of the time from 9 to 13 MST from June-August, 2015-2020.

The AIRS CH_4 uncertainty depends on a variety of factors. Uncertainty for an individual footprint and a given day will be much greater than for monthly or seasonal averages or gridded data sets such as the ones we used that include data from multiple footprints. Kulawik et al. (2021) report decreases in AIRS CH_4 errors with increasing averaging times, and for a single footprint uncertainty decreases significantly for seasonal averages. Xiong et al. (2015) report a bias of 0.27 % and a root mean square error (RMS) of 0.87 % for AIRS CH_4 data for 555 hPa to 777 hPa based on intercomparisons with aircraft data and using version 6 of the standard NASA AIRS product. Interpreting the findings of Xiong et al. (2015), Kulawik et al. (2021) report a standard deviation of 16 ppb for 555 hPa to 777 hPa when compared with aircraft data and a bias of 5 ppb near the mid-troposphere.

We used AIRS monthly average data from 2003 to 2020. We computed June-August averages from these monthly means. We also used the GML monthly averages of weekly flask sample data for NWR to estimate local continental background CH_4 and computed June-August averages from these monthly means. Oltmans et al. (2021) also used NWR data for western continental background estimates in their assessment of CH_4 trends at the BAO tower near Erie, Colorado. They point out that upslope conditions at NWR during July "led to a somewhat elevated median mole fractions that likely overestimate the background concentration".

Butterworth (2011) reports that summer upslope flows at NWR, when they are present, typically begin at 12:00 MST, and upslope persisting for at least two consecutive hours occurs on 34.8% of summer days. All but 7 of the NWR sample days for 2012-2020, the key period of our study, were taken prior to 12:00 MST. We subtracted mean June-August Niwot Ridge (NWR) CH_4 concentrations from the mean June-August AIRS DDJB CH_4 values. The difference represents an estimate of the CH_4 enhancement from local and regional sources.

Unlike aircraft studies in this area which use upwind and downwind flights to quantify CH_4 enhancements (see Petron et al., 2014), our approach may not account for the influences of upwind surface sources on background and the calculated DDJB CH_4 enhancements. Both the presence of some DDJB CH_4 transport to NWR in July and the transport of CH_4 into the DDJB from the east could introduce biases of unknown magnitude in our estimates of local enhancement. If July NWR overestimates background to some degree, then this could introduce a high bias in the calculated percentages of decline in DDJB CH_4. If the calculated local enhancement includes a relatively unchanging contribution from sources upwind of the DDJB, then this could introduce a low bias in the calculated percentages of decline in DDJB CH_4. In addition, there are likely other unknown biases inherent in the approach and methods we have used.

We initially chose June-August AIRS data because it coincides with the summer ozone season when VOC precursors from the DDJB have the greatest impact on area ozone concentrations but also because the signal for local CH_4 enhancement was positive and stronger for this time of year. Box plots of cycles in monthly NWR CH_4 and AIRS 700 hPa ascending CH_4 are plotted in Figure 3. NWR has a minimum in the summer and a peak in the winter through spring. Tropospheric concentrations in the northern hemisphere can increase in the winter because of a seasonal decline in hydroxyl radical concentrations. The hydroxyl radical gradually destroys CH_4 in the summer when photochemistry is more active. This is presumably the cause of winter maxima at this site.

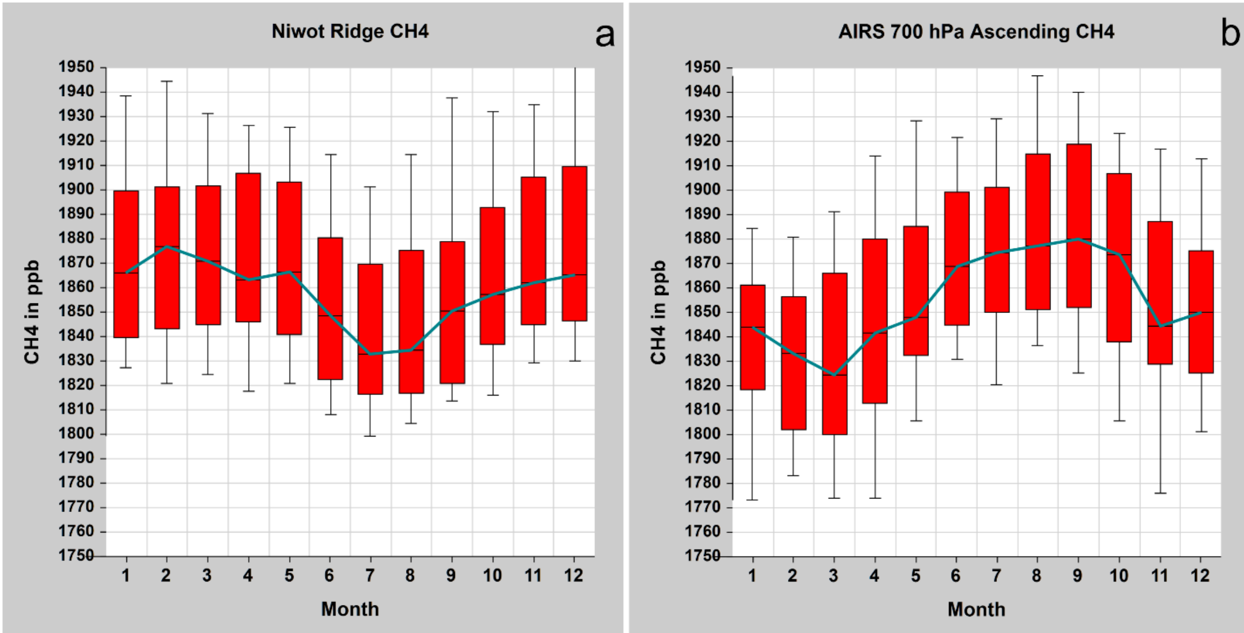

Figure 3. Box plots of (a) monthly NWR CH_4 for 2003-2020 and (b) monthly AIRS 700 hPa ascending node CH_4 for 2003-2020, with interquartile ranges and lines connecting medians. The larger signal for AIRS data in the warmer months is attributed to greater PBL heights.

In contrast to NWR, the AIRS 700 hPa ascending CH_4 peaks in July through October. The differences in seasonal cycles between NWR and DDJB AIRS 700 hPa CH_4 are likely the result of seasonal differences in how the PBL concentrates or disperses local CH_4 as well as the effects of retrieval constraints on the representativeness of the 700 hPa CH_4 product in the PBL. Kavitha et al. (2018), for example, described a peak AIRS underestimation of measured surface concentrations in the winter when shallow boundary layers concentrated CH_4 near the surface. Rakitin et al. (2015) found lower correlations between AIRS CH_4 and surface measurements at Beijing when mixing heights were below 700 meters AGL, since the satellite spectrometer is less sensitive to CH_4 when it is concentrated in a shallow surface layer. They also noted that correlations between surface and satellite measurements for most of their study sites were higher in the summer when surface mixed layers were deeper.

According to maps of ERA5 reanalysis estimates presented by Zhang et al. (2020b), the mean daytime peak PBL height over the plains in the DDJB in the winter is 800-1,000 meters above ground level (AGL), and, in the summer it is greater than 2,400 meters AGL. Lower elevations of the DDJB are at ~ 1,500 meters MSL, and NWR is at 3,523 meters MSL. This means that NWR CH_4 is likely representative of the free troposphere in the winter and a well-mixed troposphere with surface influences in the summer. McGrath-Spangler and Denning (2012) estimated mean June-August afternoon PBL heights for North America using the North American Regional Reanalysis (NARR) and the NASA MERRA reanalysis. Maps of their results show that summer afternoon PBL heights were ~3,000 to ~3,500 meters AGL over the DDJB. They also calculated mean summer afternoon PBL heights from aerosol backscatter measurements made by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite. These PBL heights were ~2,500 meters AGL over the DDJB. AIRS is primarily sensitive to CH_4 above 2,000 meters MSL (Kulawik et al., 2021). Consequently, it should be sensitive to CH_4 from surface sources mixed within the deep summer PBL over the DDJB. The altitude of our study area and resulting deep, summer-afternoon, boundary layers (with mean mixing heights between ~4,000 to ~5,000 meters MSL or ~650 to ~550 hPa) should result in an increased sensitivity of AIRS CH_4 to PBL concentrations during the summer months.

In contrast to our data in Figure 3b, Oltmans et al. (2021) show a winter peak and summer minimum in CH_4 at the BAO tower in the Wattenberg Field (Figure S3 in their paper). Their analysis for 2008-2015 shows that the median and 95th percentile values are above 1,900 ppb and 2,100 ppb, respectively, during the peak month of February, a month with shallower boundary layers. The February mean at NWR for these years is 1872 ppb, and it is only 1831 ppb for the AIRS 700 hPa product in the DDJB. These high concentrations at BAO are clearly associated with surface sources and emissions concentrated in the boundary layer, and the boundary layer in February is likely too shallow for reasonable representation of surface concentrations of CH_4 in the Platte Valley using the AIRS product.

To provide additional evidence that the DDJB AIRS 700 hPa ascending CH_4 retrieval is sensitive to PBL heights, we calculated the correlation between monthly AIRS data and monthly PBL heights from the MERRA-2 reanalysis (Global Modeling and Assimilation Office, 2015) for all months from 2012-2020. Describing the MERRA-2 reanalysis product, Gelaro et al. (2017) state that reanalysis "is the process whereby an unchanging data assimilation system is used to provide a consistent reprocessing of meteorological observations… The process relies on an underlying forecast model to combine disparate observations in a physically consistent manner, enabling production of gridded datasets for a broad range of variables, including ones that are sparsely or not directly observed." The correlation coefficient between DDJB AIRS CH_4 and the MERRA-2 PBL heights in the DDJB was 0.46, suggesting that the retrieval signal is stronger when the boundary layer is not shallow. We would expect this correlation to be higher in a comparison using afternoon-only mixed-layer heights. The monthly mean PBL heights (for all hours) in January and July were 540 meters and 1,507 meters AGL, respectively.

We did not use descending node AIRS data because local flow regimes are not typically moving DJ Basin emissions into and across the grid cell at night (see Toth and Johnson, 1985), and shallow boundary layers can concentrate CH_4 near the surface. Similarly, we did not use colder season data since the AIRS retrievals might underestimate daytime CH_4 when persistent shallow inversions concentrate CH_4 near the surface.

AIRS CH_4 retrieval concentrations for specific levels of the atmosphere are not independent of concentrations at other levels in the atmosphere and are not a true measure of an ambient concentration at a specific level. In the mid-latitudes of the northern hemisphere, the AIRS CH_4 retrievals at 400 hPa have the highest sensitivity to CH_4 concentrations. The AIRS 400 hPa CH_4 retrieval concentrations also have the greatest independence from CH_4 at other levels in the atmosphere (Xiong et al., 2015). AIRS 400 hPa CH_4, however, is not as sensitive to surface mixed layer concentrations as retrievals at lower levels of the atmosphere.

The amount that each vertical region of the atmosphere contributes to an AIRS retrieval for a standard level is characterized by a curve called an averaging kernel. In their Figure 2, Kulawik et al. (2021) show the averaging kernels for nominal AIRS altitude levels for a tropical location. The shapes of these curves vary by region, but, in general the 700 hPa product level (which is actually designated as 681 hPa) has greater sensitivity to concentrations from 800 hPA to 500 hPa than products for higher up in the atmosphere. Averaging kernel sensitivities to near-surface CH4 approach zero with increasing altitudes.

For all these reasons we selected AIRS CH4 700 hPa AIRS product. The AIRS 700 hPa retrievals are representative of a deep layer of the atmosphere and are characterized by the broad averaging kernel. These retrievals are sensitive to near-surface concentrations as well as concentrations in layers extending up to the stratosphere. The summer 700 hPa level data are anticipated to be strongly correlated with concentrations at the surface in the DDJB.

3 Results and Discussion

The sensitivity of AIRS 700 hPa CH_4 to local near-surface conditions was evaluated using aircraft data collected by the DISCOVER-AQ campaign in July and August of 2014. NASA completed 16 flights with repeated vertical spirals over the DDJB. All 6 DISCOVER-AQ vertical spiral or airport missed-approach sites were in the AIRS DDJB grid cell, except for the Ft Collins spiral site. Roughly 50% of the flight samples from the surface to 3,000 meters were collected between 10:30 and 15:15 MST. Figure 4 presents statistics for the DISCOVER-AQ flight measurements of CH_4 and ethane for 500-meter altitude bins. These represent all flight hours and not just the hour of peak PBL height which is generally 13 MST (Zhang et al., 2020b). The median CH_4 concentration for the bin centered at the 1,750-meter MSL level was ~1,900 ppb which is the closest of all the altitude bin medians to the July-August 2014 average AIRS 700 hPa CH_4 of 1,886 ppb. This suggests that the AIRS 700 hPa retrieval concentrations were sensitive to CH_4 in the mixed layer and can be used to track changes associated with emissions into the boundary layer.

The representativeness of NWR CH_4 concentrations for background conditions is further supported by comparison of NWR CH_4 to aircraft CH_4 measurements made during DISCOVER-AQ. In Figure 4, CH_4 above 3,000 meters drops to background levels and ethane approaches zero indicating that the 3,000 to 5000-meter level was generally free from strong influences from boundary layer emissions from O&G sources. The median CH_4 concentrations measured by DISCOVER-AQ from 3,000 to 5,000 meters MSL are ~1830-1840 ppb, and these are comparable to the NWR July-August 2014 average CH_4 concentration of 1,852 ppb at 3,523 meters MSL. This is additional evidence that NWR is a reasonable choice for background CH_4 in our study.

Three-hour HYSPLIT back trajectories were obtained for the highest 20 percentile, 40-60 percentile, and lowest 20 percentile Platteville ethane concentration samples for all of 2018 using 40 km Eta Data Assimilation System (EDAS) meteorological fields (https://www.ready.noaa.gov/edas40.php). These coincided with the 6-9 AM MST sample window for each daily measurement. These show that the Platteville site is representative of emissions and ambient concentrations in the southern Wattenberg field. Figure 5 presents a map of the 3-hour back trajectory points for 6-9 AM MST which indicates that Platteville ethane and VOC samples are representative of an area that extends far beyond the local footprint of the monitoring site. This is clear evidence that even under the reduced surface wind speed and vertical mixing regimes expected in the early morning when samples are collected, the Platteville site is representative of emissions across a wide area of the DJ Basin between Denver and Greeley.

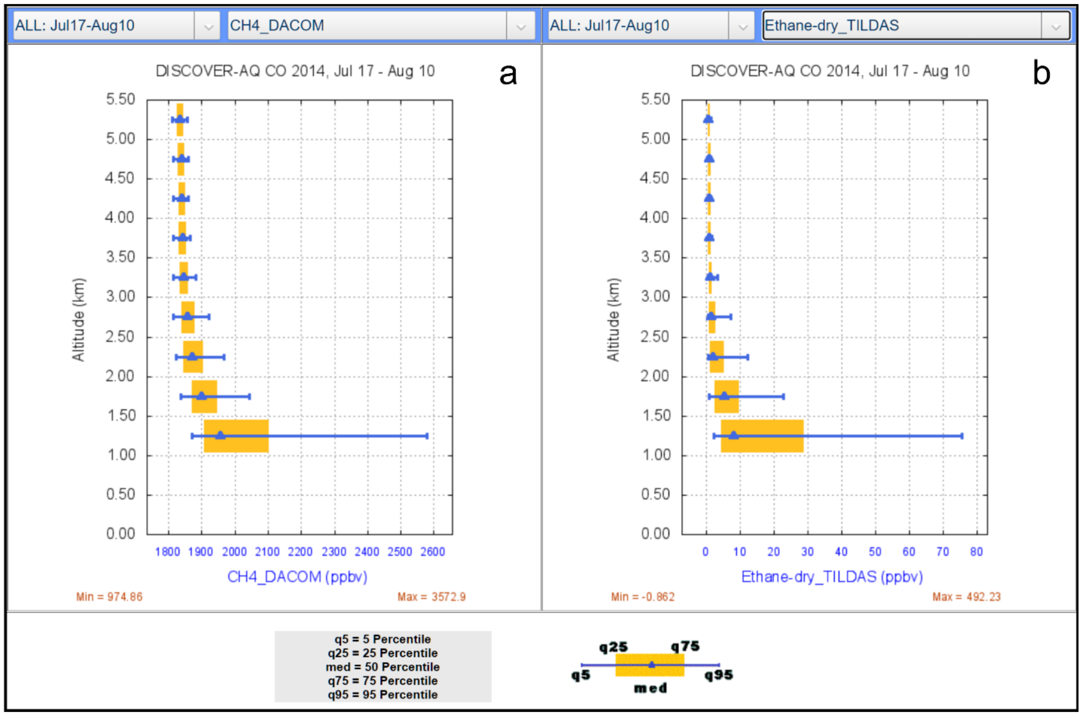

Figure 4. Percentile plots of CH_4 (left) and ethane (right) for all flights and spirals of the DISCOVER-AQ P3-B in July and August 2014. Blue triangles are medians, orange bars represent the 25th through 75th percentile range, and horizontal blue lines represent the 5th through 95th percentile range. The 1.25 km level represents missed runway approaches just above ground level near Greeley.

We acquired plots of ethane concentrations and winds from the experimental forecasting system that is run by the National Center for Atmospheric Research (NCAR) and based on the Weather Research and Forecasting (WRF) model with chemistry (WRF-Chem) (Kumar et al., 2020) (https://www.acom.ucar.edu/firex-aq/forecast.shtml). Plots are for 5:00 MST on 30 January 2022 and 23 July 2021. These are shown in Figure 6. Elevated ethane concentrations are largely from O&G sources. Toth and Johnson (1985) and Neff (1997) describe the features of early morning slope and drainage flows as they move eastward from the foothills west of Denver and northward from the Palmer Divide which is south of Denver and converge as southerly drainage flows along the Platte River Valley from Denver to Platteville. Drainage winds eventually curve eastward following the river valley east of Greeley. These conditions are typical when stronger synoptic-scale winds are not present.

Modeled ethane concentrations and winds capture these flows and their effects on ethane and show that ethane pools in the area surrounding Platteville and the O&G field. In addition, Pfister et al. (2017) show average modeled O&G tracer concentrations for 6:00-12:00 MST during the 2014 Front Range Air Pollution and Photochemistry Éxperiment in Figure 8 of their paper. The O&G tracer plot places Platteville in the center of a large area with fairly uniform high concentrations, and the spatial distribution is comparable to the fairly uniform high-concentration footprints in Figure 6. Platteville is suitably located to sample ethane and other O&G trace gases within the O&G field during the morning hours.

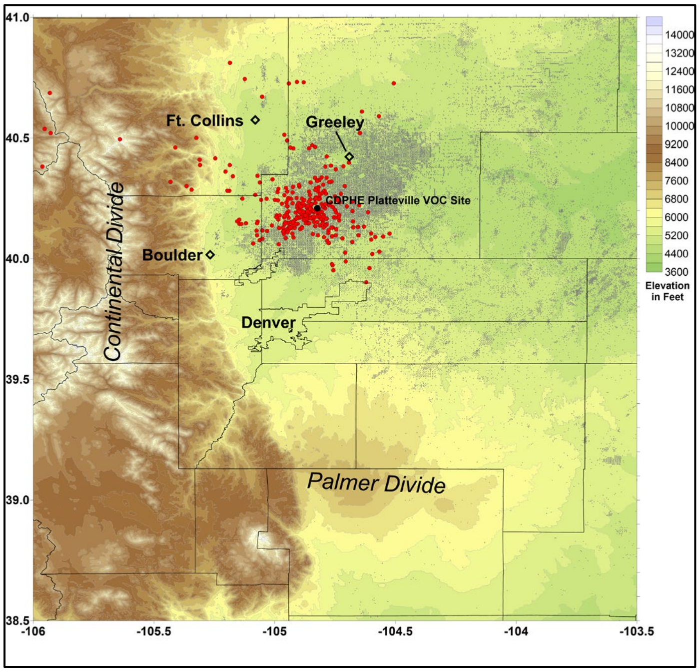

Figure 5. HYSPLIT three-hour back trajectory points (shown as red dots) for 6-9 AM MST for the CDPHE Platteville monitor in 2018. Oil and gas wells are plotted as grey dots.

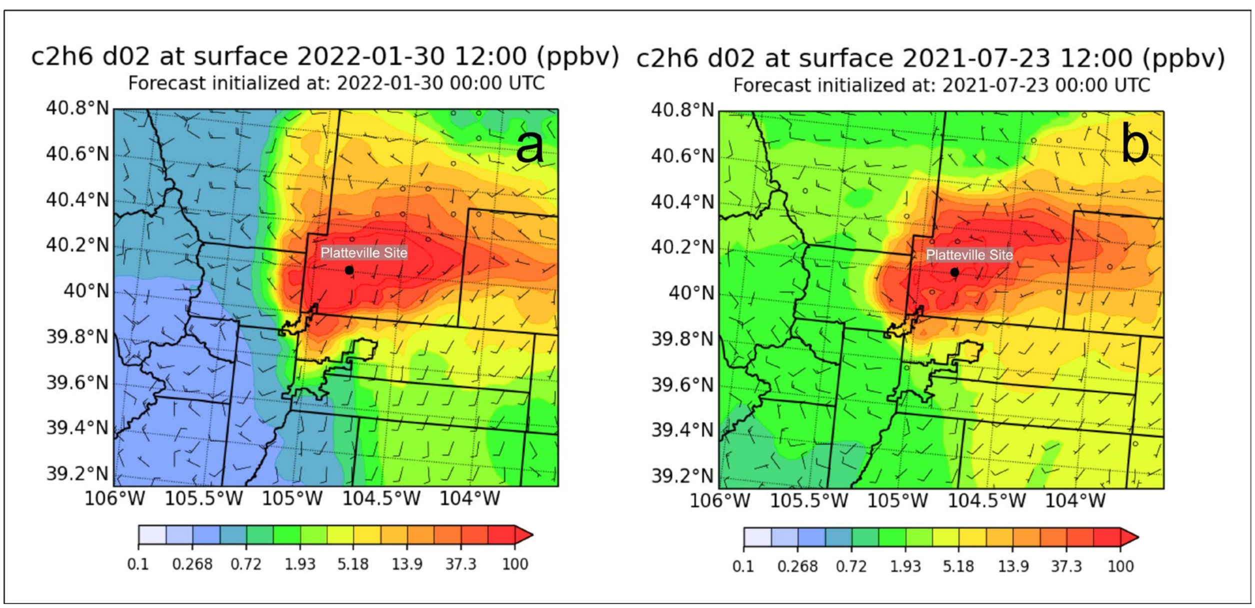

Figure 6. NCAR WRF-Chem surface wind and ethane concentration forecasts for (a) 5:00 MST 30 January 2022 and (b) 5:00 MST 23 July 2021. These show the effects of typical morning slope and drainage flows that pool ethane near Platteville and transport ethane eastward near Greeley following the curve in the Platte River valley. The Platteville location and label have been added.

Annual ethane means, medians, and statistics for 2012-2020 are presented for Platteville and Denver CAMP in Tables 1 and 2, respectively. We used annual data for increased sample sizes and because summer data for 2016 were limited. Table 3 lists the June-August mean DDJB AIRS 700 hPa CH_4, the number of AIRS retrievals, the June-August NWR CH_4, the calculated DDJB enhancement in CH_4, and Platteville annual median ethane. We used the median ethane data in this case to reduce the influence of high values associated with shallow surface mixed layers. Table 3 shows that the estimated DDJB CH_4 enhancement decreased by 55% between 2013 and 2020. Platteville median ethane decreased by 73% during the same period. The choice of 2013 as the starting year was based on the peak enhancement in 2013. Since there is the possibility of influences from unexplained cofactors each year, the true enhancement peak might have occurred in either 2012 or 2013. Later we show a slightly more conservative estimate for CH_4 based on a linear regression for 2012-2020, and this reduction is 56%. Similarly, the reduction in median Platteville ethane based on the linear regression for 2012-2020 was 77%.

Table 1. Platteville Ethane Annual Means, Medians, and Statistics for 2012-2020.

Year	Mean ethane (ppb)	Median ethane (ppb)	Standard deviation (ppb)	95% confidence level (ppb)	Number of samples
2012	213.9	196	155.4	32.4	91
2013	277.4	212	250.5	70.5	51
2014	187.5	132	222.0	59.4	56
2015	155.0	143	108.9	31.6	48
2016	155.3	119	117.5	30.9	58
2017	177.3	79.6	358.4	91.8	61
2018	100.7	87.2	77.8	19.9	61
2019	97.5	65.3	90.8	23.5	60
2020	81.2	57.3	62.4	16.9	55

Table 2. Denver CAMP Ethane Annual Means, Medians, and Statistics for 2012-2020.

Year	Mean ethane (ppb)	Median ethane (ppb)	Standard deviation (ppb)	95% Confidence level (ppb)	Number of samples
2012	23.5	18.6	15.3	3.2	88
2013	29.5	20.9	23.4	6.2	57
2014	24.3	18.5	19.0	5.0	58
2015	27.8	21.3	18.3	5.2	50
2016	34.9	23.8	27.0	7.0	60
2017	28.0	23.5	19.1	4.9	61
2018	32.2	24.0	24.5	6.3	61
2019	32.5	23.0	27.8	7.1	61
2020	33.6	23.6	24.4	7.8	40

Table 3. AIRS DDJB CH_4, NWR CH_4, DDJB Enhancement, and Platteville Ethane for 2003-2020.

Year	Mean June-August AIRS CH_4 DDJB (ppb)	Number of AIRS retrievals June-August	Mean June-August Niwot Ridge CH_4 (ppb)	DDJB CH_4 minus Niwot Ridge CH_4 (ppb)	Platteville annual median ethane (ppb)
2003	1829.7	76	1814.1	15.6	
2004	1840.3	73	1805.9	34.4	
2005	1841.6	72	1819.8	21.7	
2006	1841.6	76	1805.6	36.0	
2007	1848.8	71	1813.3	35.4	
2008	1854.9	73	1826.4	28.5	
2009	1864.2	78	1826.6	37.6	
2010	1860.1	68	1834.9	25.2	
2011	1871.5	68	1839.5	32.0	
2012	1877.8	71	1839.0	38.8	196
2013	1881.4	74	1841.6	39.8	212
2014	1884.0	76	1853.6	30.4	132
2015	1896.0	75	1860.4	35.6	143
2016	1904.3	71	1872.4	31.9	119
2017	1907.8	72	1882.7	25.1	79.6
2018	1920.0	67	1896.8	23.2	87.2
2019	1916.9	75	1897.6	19.3	65.3
2020	1927.8	60	1910.1	17.8	57.3
Percent Reduction 2013 to 2020				55%	73%

Peischl et al. (2018) and Petron et al. (2014) conclude that O&G sources account for 75% of local CH_4 sources. Consequently this 55-56% reduction may underestimate the percent reduction in CH_4 from O&G sources. It is reasonable that the percent reduction in ethane was greater than the percent reduction in CH_4, since O&G sources account for almost all the ethane at Platteville.

In addition, CDPHE estimates that O&G systems accounted for 59% of CH_4 statewide in 2019 (CDPHE, 2021, Exhibit 1-5). While emissions estimates are not specific to the DDBJ grid cell, only the statewide O&G sector is estimated to have meaningful emissions reductions from 2010 to 2019 (CDPHE, 2021). All other sectors have CH_4 emissions changes that are either negligible (e.g., residential, commercial, industrial, transportation, and electric power), slightly increasing (e.g., agriculture and waste management), or are not emitting CH_4 in the DDJB grid cell (e.g., coal mining). Consequently, it is reasonable to assume that the trends in the DDJB CH_4 enhancement are predominantly affected by changes within the O&G sector.

Figure 7 shows the estimated long-term trends in DDJB CH_4 enhancement based on AIRS measurements in the DDJB grid cell. NWR flask samples are collected weekly for a total of ~13 samples for June-August, while an average of 72 AIRS retrievals are available for each June-August period. In many cases the sample and retrieval days do not match, and the means of each dataset can represent different conditions of continental background and transport for Colorado. This could introduce noise in the DDJB CH_4 enhancement time series. Consequently, a four-point median smoother and a LOESS curve (Cleveland, 1979) have been fitted to the data to show the general trends throughout the entire period.

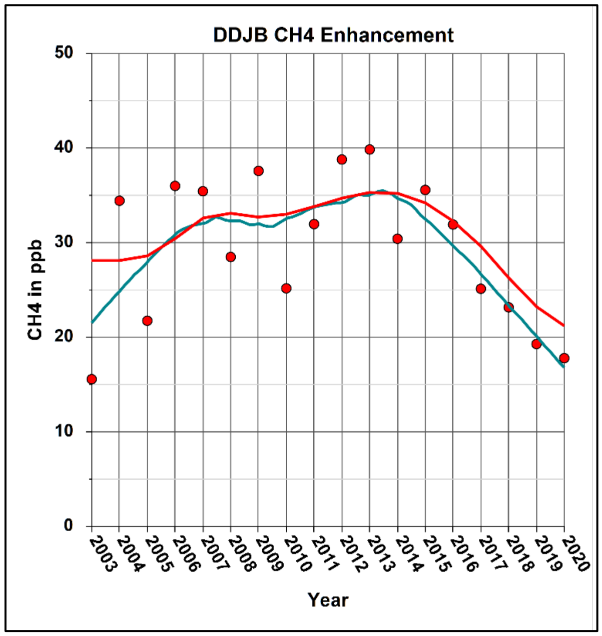

Figure 7. DDJB June-August CH_4 enhancement from 2003 through 2020 fitted with a 4-point median smoother (red) and a LOESS curve with a 0.4 smoothing parameter (green).

A gradual increase which may be associated with growth in O&G extraction activities is followed by a steep downward trend after 2013, and we attribute the decline to DJ Basin O&G emissions reductions. A linear regression through this data for 2003-2012 yields a statistically insignificant trend of 1.25 +/- 1.8 ppb. Oltmans et al. (2021) found no significant trend in BAO CH_4 near Erie in the southwest portion of the Wattenberg from 2008 through mid-2016. We also found no significant trend for the DDJB AIRS enhancement from 2008 through 2016. A plot of our results for this period is presented in Figure 8(a). When we consider 2012-2020 (see Figure 8(b)), however, we find that there is a nearly linear and statistically significant downward trend with an R^2 of 0.90. CH_4 declined in the DDJB grid cell at a rate of -2.84 +/- 0.8 ppb (based on the 95% confidence interval) per year. In addition, a linear regression of the ratio of DDJB CH_4 to NWR CH_4 against year (which is independent of local enhancement estimates) shows a decline from 1.022 to 1.008 during this period (R^2 of 0.91).

The trends in 2012-2020 annual median Platteville and Denver CAMP ethane (see Figure 9) show a statistically significant linear decrease in Platteville ethane of -19.1 ppb +/- 5.9 ppb per year (based on the 95% confidence interval, R^2 of 0.90) and a statistically significant linear increase in Denver CAMP ethane of 0.7 ppb +/- 0.4 ppb per year (based on the 95% confidence interval, R^2 of 0.68). Lyu et al. (2021) report a 33%-56% contribution from O&G sources to 6-9 AM MST Denver CAMP NMHC. Ortega et al. (2021) found a positive trend of 0.9 ppb ± 0.3 % per year for ethane north of Boulder from 2010-2019. Denver and Boulder ethane have been increasing at a similar rate, although the rate for the former is based on morning-only measurements.

Rossabi et al. (2021) analyzed west-east gradients in CH_4 at several sites for 9 to 11 three-day periods during July and August of 2014. They found a high Pearson correlation coefficient of 0.77 between CH_4 and ethane in eastern Boulder County and concluded that it is highly likely that natural gas extraction activities are the dominant source of ethane in the region. Their sites extended from the higher terrain west of Boulder, across Boulder, and into the southwestern edge of the Wattenberg Field. Figure 3 of their study shows that CH_4 at the Boulder County Public Health site in Boulder was ~ 6 ppb higher than estimated background. Their Figure 3 also shows that CH_4 at two sites in or near the southwestern edge of the Wattenberg Field was ~12 ppb higher than background. Their results, other work we have cited, and our results for ethane at Platteville and Denver show steep spatial gradients in O&G impacts across the region. Nominal increases in ethane at Boulder and Denver are not necessarily inconsistent with steep declines at Platteville, which is in the center of the Wattenberg Field; and we have concluded that the Platteville site is representative of the Wattenberg, based on HYSPLIT back trajectories and cited studies.

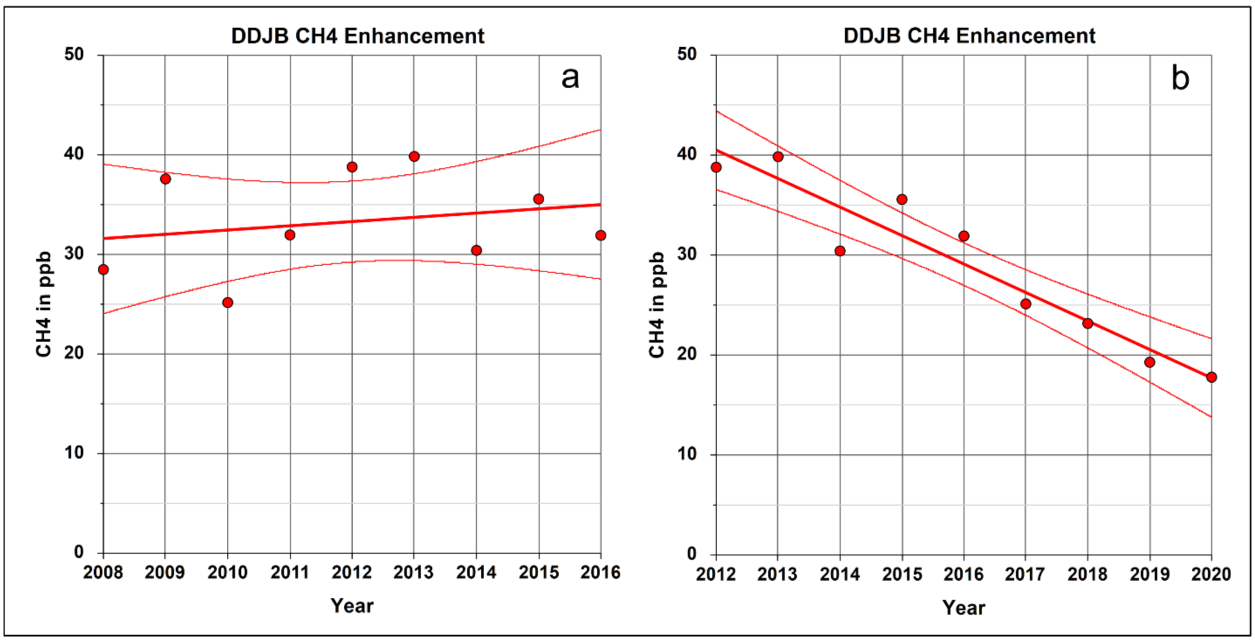

Figure 8. DDJB June-August CH_4 enhancement versus year with linear regression and 95% confidence limits for (a) 2008-2016 and (b) 2012-2020. No statistically significant trend was found for CH_4 from 2008-2016 at BAO (Oltmans et al., 2021) or in our analyses for the DDJB, but a robust downward trend is evident for the DDJB from 2012-2020.

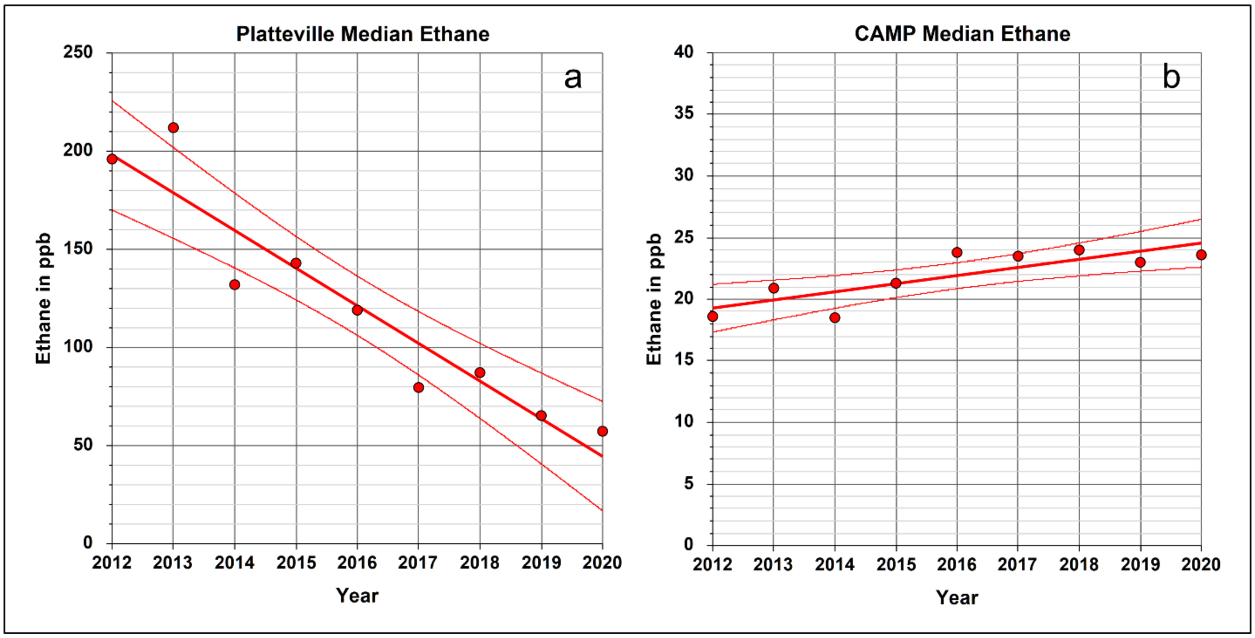

Figure 9. Linear regression and 95% confidence limits for l (a) annual median Platteville ethane and (b) annual median Denver CAMP ethane, versus year for 2012-2020. Trends for both sites are statistically significant.

A regression between the June-August DDJB CH_4 enhancement and annual median Platteville ethane are plotted in Figure 10. The regression is statistically significant and has an R^2 of 0.93, and the Pearson correlation coefficient is 0.96. If Platteville ethane which is largely from O&G sources were reduced to zero, the regression in Figure 10 would yield a remaining CH_4 enhancement of 12 ppb or 30% of the 2012 regression value in Figure 8(b). This is comparable to the 25% local contribution from non-O&G sources in 2012 estimated by Petron et al. (2014).

Figure 11 shows the time series of DDJB CH_4 enhancement and Platteville ethane and the year-to-year changes in each. Results in Figures 10 and 11 provide compelling evidence that the calculated DDJB CH_4 enhancement is sensitive to and tracks with surface boundary layer concentrations. These results also show that DDJB CH_4 has been responsive to reductions in O&G emissions within the grid cell. Recall that Rossabi et al. (2021) concluded that it is highly likely that natural gas extraction activities are the dominant source of ethane in the region. In addition, using positive matrix factorization and chemical mass balance methods, Lyu et al. (2021) found that O&G activities accounted for 92%-96% of NMHC at Platteville for 2013-2016. The strong correlation and the fact that there have not been substantial changes in ethane in Denver or Boulder suggest that reductions in O&G emissions in the Wattenberg are driving the observed declines in AIRS CH_4 within the DDJB. The correlation between DDJB CH_4 enhancement and median Denver ethane is -0.66.

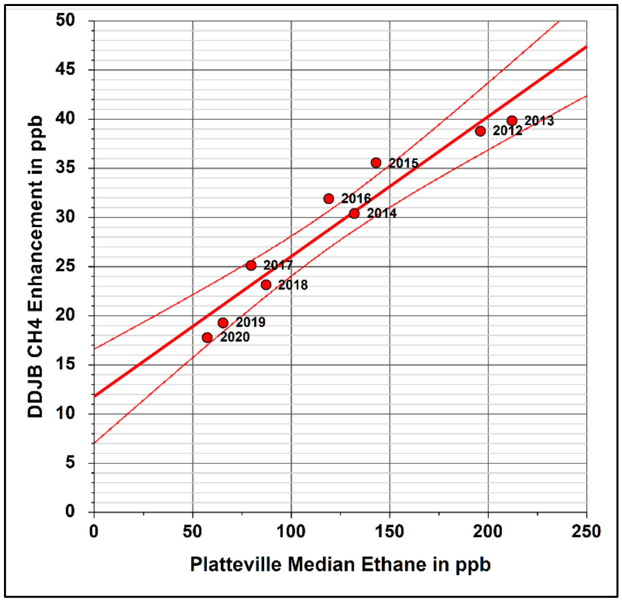

Figure 10. Linear regression between June-August mean 2012-2020 DDJB CH_4 enhancement and annual median Platteville ethane (with plotted 95% confidence limits). The fit is robust with an R^2 of 0.93.

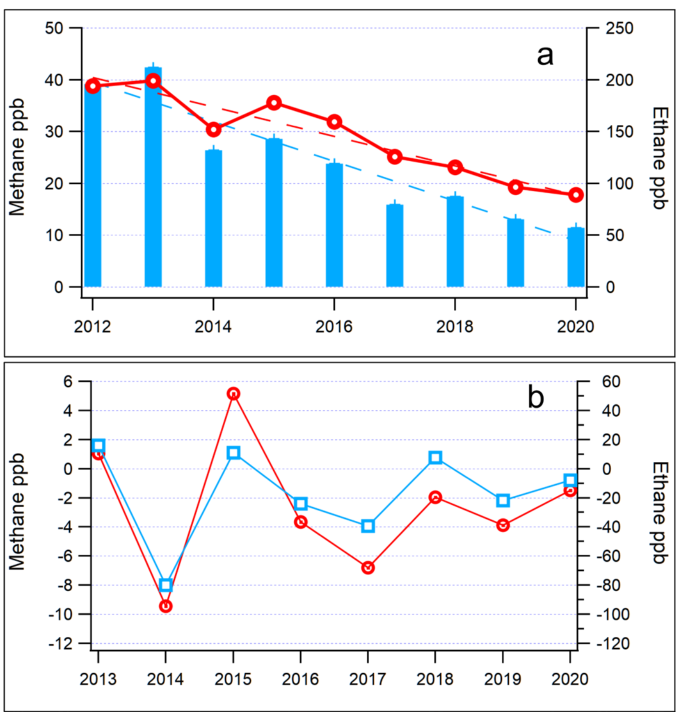

Figure 11. Trends in June-August DDJB CH_4 enhancement and annual median Platteville ethane in ppb. Panel (a) illustrates June-August mean 2012-2020 DDJB CH_4 enhancement in red with open circles and annual median Platteville ethane shown with blue bars (with plotted regression lines) and panel (b) shows year-to-year changes in these, with CH_4 in red with open circles and ethane in blue with open squares.

Feng et al. (2022) find that interannual variability in meteorology (especially wind speeds) plays a significant role in trends in CH_4 in the US. Reddy and Pfister (2016) demonstrated that maximum surface ozone concentrations in and near the DDJB are highly correlated with 500 hPa heights. They state that “upper level ridges decrease winds and allow cyclic terrain-driven circulations to reduce transport away from sources”. We obtained mean June-August 500 hPa heights from the NCEP Reanalysis for a grid cell centered on 40°N 105°W, and this contains the DDJB. The correlation coefficients for interannual differences in Platteville ethane, DDJB CH_4 enhancement, and NWR CH_4 versus the interannual differences in 500 hPa heights were calculated for 2013-2020; and these are 0.69, 0.74, and 0.26 for Platteville, the DDJB, and NWR, respectively. Even though we used annual data for ethane, it appears that the impacts of summer meteorology are strong enough to have a significant effect on variations in yearly values. The correlation is very high for DDJB CH_4 enhancement and low for NWR CH_4. While reductions of emissions in the DDJB are likely responsible for the overall trends, the more subtle variations in Figure 11 are probably caused, at least in part, by year-to-year changes in meteorology. The strong correlations with weather for both ethane and CH_4 enhancement support the hypothesis that the AIRS product is detecting real changes in year-to-year CH_4 within the PBL.

Oltmans et al. (2021) estimated background propane, a tracer for O&G emissions, at the BAO tower near Erie in the DJ Basin and subtracted this from ambient data. Using only data from 2008-2015 and scaling the annual changes in local contribution to 2011 data, they projected a -1.5% change per year in propane through 2021 and compared this with the RAQC’s projected emissions inventory reductions of -6.5% per year. We have not estimated background ethane, also an O&G tracer, at the Platteville monitor, but we used the regression statistics for median Platteville ethane versus year and scaled the -19.1ppb slope by the 2012 regression value of 197.8 ppb to obtain an average annual decline of -9.7% from 2012 through 2020 (with a range of -12.6% to -6.7%, based on the lower and upper 95% confidence intervals for the slope).

This rate of decline is not based on data from an earlier period but on an analysis of data through 2020, and the rate of decline of the emissions inventory is just above the upper limit of the calculated range for 2012-2020 at Platteville. Trends in both Platteville ethane and the DDJB CH_4 enhancement provide evidence that the regulatory requirements reflected in the emissions inventories are having a significant effect.

The focus of this paper is CH_4 trends within the DDJB, but to further verify our method and the ability of the AIRS 700 hPa CH_4 product to detect warm-season trends in the high-altitude western US, we completed a preliminary analysis of trends in CH_4 enhancements for the Uintah Basin O&G fields in Utah, a major O&G production region in the western US. The floor of the basin is at ~1,500 meters MSL, and summer mean peak PBL heights are comparable to those in the DDJB (McGrath-Spangler and Denning, 2012; Zhang et al., 2020b). We used the standard AIRS version 7 product for the two AIRS grid cells that contain the basin (see supplementary Figure S1). We calculated June-August mean AIRS CH_4 and subtracted the mean June-August NWR CH_4 data calculated for our study.

The resulting trend for the Uintah Basin CH_4 enhancement for 2014-2020 is plotted in Figure 12. Lin et al. (2021) show that basin natural gas production increased rapidly, peaking in 2012 and 2013, and then declined rapidly. The number of producing gas wells peaked in 2015 and then declined rapidly. They also show that oil production and the number of oil wells peaked in 2014-2015, and then declined unevenly after this. They found that decreases in CH_4 after 2015 were related to declining O&G production and not to a reduction in CH_4 leaks. We show a statistically significant linear decrease of -2.77 ppb +/- 2.47 ppb (R^2 of 0.62) from 2014-2020.

Lin et al. (2021) calculated basin CH_4 enhancement by taking the difference between surface concentrations at a site in the center of the O&G field and one on the far western edge of the basin. For a trend analysis with linear regression, they used afternoon-only concentrations for April-September to avoid cold pooling events that concentrate CH_4 in shallow surface layers. Using monthly means, they found a decreasing trend of -4.63 ppb with an R^2 of 0.241 for 2015-2020. Their enhancements (from the regression line) range between ~20 ppb to ~45 ppb, whereas the AIRS-based summer season enhancements are from 7 ppb to 29 ppb.

Using a combination of measurements and modeling, Lin et al. (2021) report that emissions decreased by approximately 50% during this period, and we calculate a 60% reduction in CH_4. This percentage was derived from the regression values for 2015 and 2020. There is reasonable agreement between the AIRS-based results and theirs. This is further evidence that the AIRS 700 hPa CH_4 product can be used to detect changes consistent with surface concentrations in and near a major O&G production area for periods and locations with deep vertical mixing.

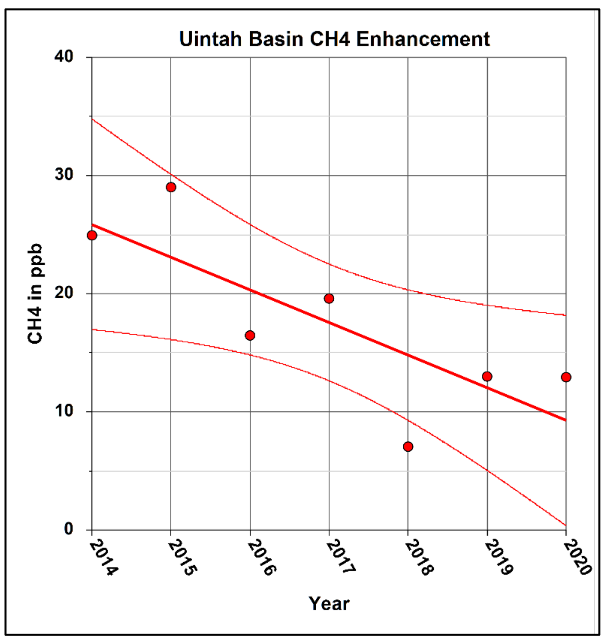

Figure 12. AIRS 700 hPa CH_4 enhancement for the Uintah Basin in Utah with a linear regression and 95% confidence limits for 2014-2020. The fit is statistically significant with an R^2 of 0.62.

4 Conclusions

We selected a one-degree NASA AIRS grid cell centered at 40°N and 105°W in northern Colorado to assess changes in CH_4 from 2003 through 2020. This grid cell includes Denver, Boulder, and Greeley, Colorado, and much of the Wattenberg O&G field in the Denver Julesburg O&G basin. O&G emissions from this area are a significant source of CH_4, ethane, and VOC precursors to ozone. Colorado implemented regulations to significantly reduce emissions from O&G sources in early 2014 and has implemented additional emissions control requirements since (Colorado Regulation No. 3, No. 7, and No. 22, https://cdphe.colorado.gov/aqcc-regulations). Our study was designed to use AIRS CH_4 to assess the effects of these controls (and operational changes implemented by the industry voluntarily) on ambient CH_4 and to determine whether this approach could be used to track the effectiveness of emissions controls. Surface measurements alone have limited spatial coverage compared with satellite instruments. Aircraft studies are typically limited in temporal coverage. Newer and more advanced satellite instruments such as TROPOMI do not provide data prior to about 2016-2017. Our study shows that AIRS data can serve as a bridge to more robust analyses based on TROPOMI and other satellite instruments that will soon become operational.

We computed mean June-August ascending node AIRS 700 hPa CH_4 for each year and subtracted June-August mean NWR CH_4. NWR is a high-altitude surface monitoring site immediately west of our grid cell. The differences represent the enhancement over background within the grid cell. Vertical profiles of CH_4 from aircraft flights within the grid cell during the July-August 2014 DISCOVER-AQ field campaign were used to verify the sensitivity of the 700 hPa AIRS product to near-surface concentrations and to confirm that the Niwot Ridge site is a reasonable choice for background concentrations.

We find 55% and 73% reductions in DDJB CH_4 enhancement and Platteville ethane, respectively, between 2013 and 2020 and a 56% reduction in DDJB CH_4 enhancement using a linear regression for 2012-2020. These significant reductions occurred even though oil production increased by 343% and gas production by 297% from 2012-2020. The reduction in CH_4 is comparable to the projected 57% reduction in O&G VOC emissions for 2011-2020 from the 2020 draft ozone State Implementation Plan for the ozone nonattainment area that includes the DDJB (RAQC and CDPHE, 2020). We are unable to calculate biases or uncertainties for the 55-56% CH_4 reduction, but our estimates of CH_4 enhancements for the Uintah basin suggest that biases inherent in this approach may be minimal.

Smoothing curves applied to the grid cell enhancement show a gradual increase in CH_4 through 2013 followed by a noticeable decline. A linear regression of grid cell enhancement versus year shows a 2.84 ppb +/- 0.8 ppb decrease per year from 2012 through 2020 with an R^2 value of 0.90. Grid cell enhancement is strongly correlated with Platteville ethane. Platteville is in the center of the O&G fields. Using HYSPLIT back trajectories for 2018, we demonstrated that this site is representative of a large area of the Wattenberg field, a major source region for CH_4. The correlation coefficient between grid cell CH_4 enhancement and Platteville ethane was 0.96, and the R^2 for a linear regression between these was 0.93. Platteville ethane dropped from 196.0 ppb in 2012 to 57.3 ppb in 2020. Based on a linear regression, we calculate an annual rate of change of -9.7% relative to 2012 (with a range of -12.6% to -6.7%). Denver median ethane concentrations ranged from 18.5 to 24.0 ppb during the period with a slight increasing trend of 0.7 ppb +/- 0.4 ppb per year.

A preliminary analysis of trends in CH_4 enhancement for the Uintah Basin O&G production area based on AIRS 700 hPa CH_4 and NWR data compares well with the decline of surface CH_4 described by Lin et al. (2021). This is additional evidence that the AIRS product can detect changes directly related to surface concentrations for periods and locations with deep vertical mixing.

The grid cell CH_4 enhancement should be considered an estimate that is representative of and proportional to true enhancement above background within the boundary layer. The strong correlation between grid cell CH_4 enhancement and Platteville ethane and the relative stability of Denver and Boulder ethane concentrations over time suggest that reductions in O&G emissions are driving the reductions in CH_4 that are evident in the AIRS CH_4 product. We conclude that AIRS CH_4 can be used to measure the efficacy of O&G emissions control programs in this region and that these controls, as well as other voluntary design changes such as tankless systems and process centralization, are having an effect. Further intercomparisons between AIRS and TROPOMI CH_4 trends for the years of overlapping records would help scientists quantify percent reductions in CH_4 in recent years and understand the biases and uncertainties in these estimates. A comprehensive picture of the effects of emissions controls will require continued analyses of surface, aircraft, and satellite measurements for this region. Evidence and results presented here also suggest that the AIRS CH_4 data could be useful in tracking progress in achieving DDJB greenhouse gas emissions reductions.

Acknowledgments

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Open Research

The primary datasets used in this study include AIRS and MERRA-2 reanalysis data from the NASA Giovanni website, NCEP Reanalysis data from the NOAA Physical Sciences Laboratory, ethane monitoring data from the CDPHE Air Pollution Control Division, and monthly CH_4 data for Niwot Ridge from the NOAA Global Monitoring Laboratory. Key datasets are available in a data repository (https://doi.org/10.5281/zenodo.7038756). Statistical calculations were completed with NCSS 8.0 and Microsoft Excel. Graphs, plots, and maps were prepared with NCSS 8.0, Surfer 12, Excel, and Igor Pro.

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Supporting Information for

Downward Trend in Methane Detected in a Northern Colorado Oil and Gas Production Region Using AIRS Satellite Data

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Introduction

This document contains supplementary figure S1 which shows the location of the standard AIRS version 7 product grid cells that contain the Uintah Basin oil and gas production region in Utah.

S1. The AIRS Version 7 Grid Cells Over the Uintah Basin

AIRS Version 7 grid cells were obtained from the NASA Giovanni website (https://giovanni.gsfc.nasa.gov/giovanni/). Details of this product can be found here: https://disc.gsfc.nasa.gov/datasets/AIRS3STM_7.0/summary. The two cells are 1° by 1° in size and have been joined in Figure S1. One grid cell is centered on 40°N, 110°W, and the other is centered on 40°N, 109°W.

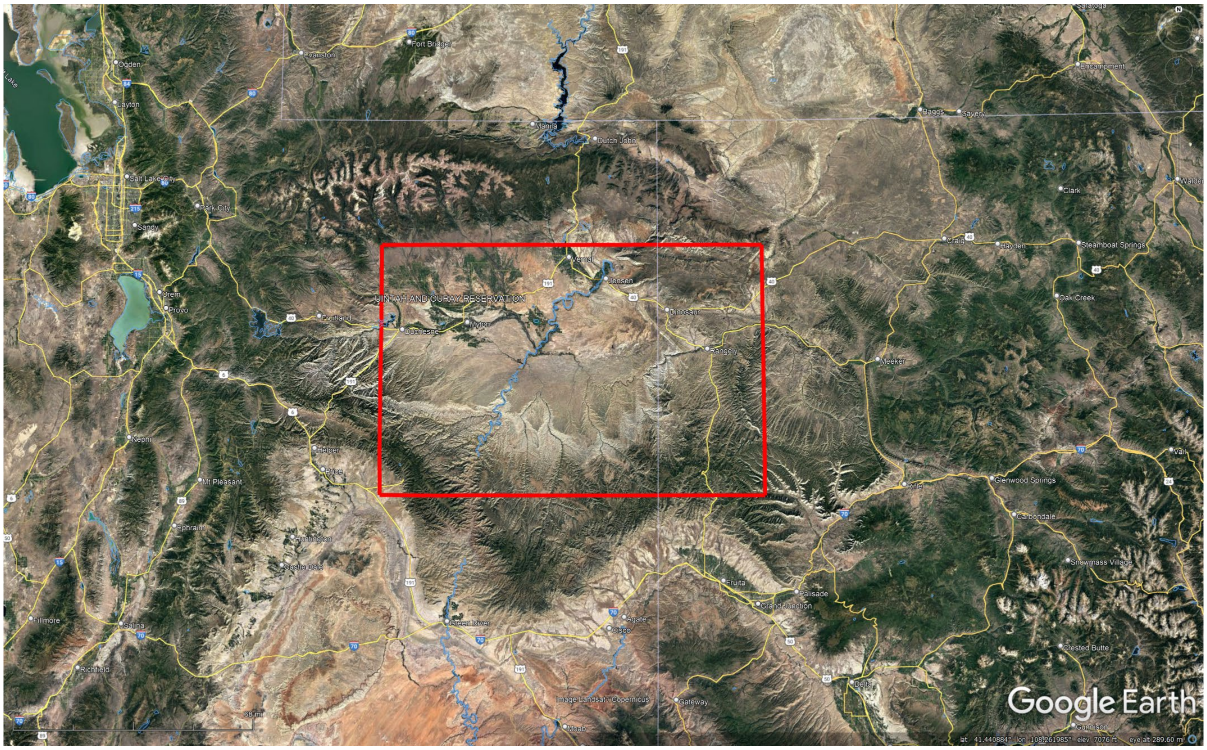

Figure S1. Merged AIRS grid cells covering the Uintah Basin in Utah. The map source is Google Earth.