CARVE: The Carbon in Arctic Reservoirs Vulnerability Experiment

Charles E. Miller
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-6294
Charles.E.Miller@jpl.nasa.gov

Steven J. Dinardo
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-4212
Steven.J.Dinardo@jpl.nasa.gov

The CARVE Science Team

Abstract—**The Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) is a NASA Earth Ventures (EV-1) investigation designed to quantify correlations between atmospheric and surface state variables for the Alaskan terrestrial ecosystems through intensive seasonal aircraft campaigns, ground-based observations, and analysis sustained over a 5-year mission. CARVE bridges critical gaps in our knowledge and understanding of Arctic ecosystems, linkages between the Arctic hydrologic and terrestrial carbon cycles, and the feedbacks from fires and thawing permafrost. CARVE's objectives are to: (1) Directly test hypotheses attributing the mobilization of vulnerable Arctic carbon reservoirs to climate warming; (2) Deliver the first direct measurements and detailed maps of CO_2 and CH_4 sources on regional scales in the Alaskan Arctic; and (3) Demonstrate new remote sensing and modeling capabilities to quantify feedbacks between carbon fluxes and carbon cycle-climate processes in the Arctic (Figure 1). We describe the investigation design and results from 2011 test flights in Alaska.**

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1. Introduction

The Arctic[1] is warming dramatically, yet we lack the sustained observational time series and accurate physical models to know with confidence how the Arctic ecosystems and carbon cycle will respond to direct forcings from climate change or to poorly understood climate feedbacks such as fire and permafrost thaw. Fundamental elements of the Arctic hydrologic-carbon-climate system are poorly quantified and the sensitivity of the Arctic carbon cycle to climate change during the remainder of the 21[st] century is highly uncertain. Arctic carbon cycle and ecosystem response to climate change is an issue of global concern since climate forcings may initiate transformations that are irreversible on century time scales and have the potential to cause rapid changes in the Earth system [1].

Permafrost soils are warming even faster than Arctic air temperatures. Osterkamp et al. observed increases of 1.5 – 2.5°C at 20 m depth in North slope bore holes in just the last 30 years [2]. The efficient penetration of heat from the surface to these depths threatens to mobilize massive reservoirs of organic C that have been sequestered for tens of thousands of years. There are an estimated 1400 – 1850 PgC (1 PgC = 1×10^{15} gC) stored in permafrost across the Arctic [1], with the majority located in the most vulnerable top soils: ~200 PgC stored at depths from 0 – 30 cm, ~500 PgC stored at depths from 0 – 100 cm, and ~1000 PgC stored at depths from 0 – 300 cm [3]. This raises several critical questions: How much permafrost C is vulnerable to mobilization into dynamic carbon cycling? How fast might it be released? How much will be released as CO_2? How much will be released as CH_4? Are there signatures that an irreversible permafrost tipping point is approaching?

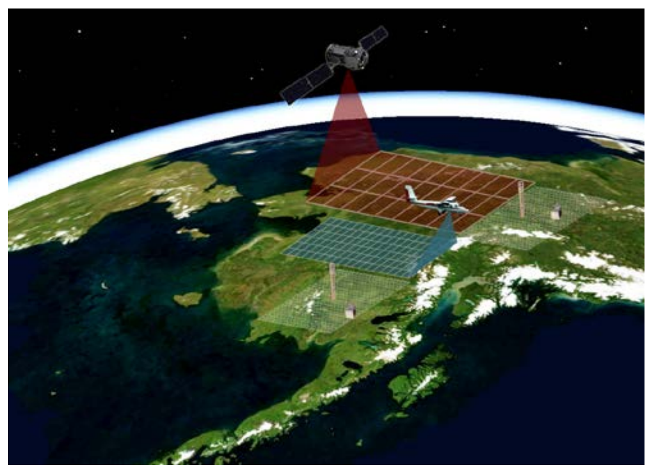

Figure 1 – In addition to delivering unique, high priority science, CARVE air-borne observations connect satellite and ground-based measurements with vastly different spatio-temporal characteristics.

[1] We define the Arctic to be the Arctic ocean and all of the land areas that drain into the Arctic Ocean and its marginal seas, extending to the southern edge of discontinuous permafrost (~45º N) and including northern wetlands, peatlands, and much of the boreal forest zone [1].

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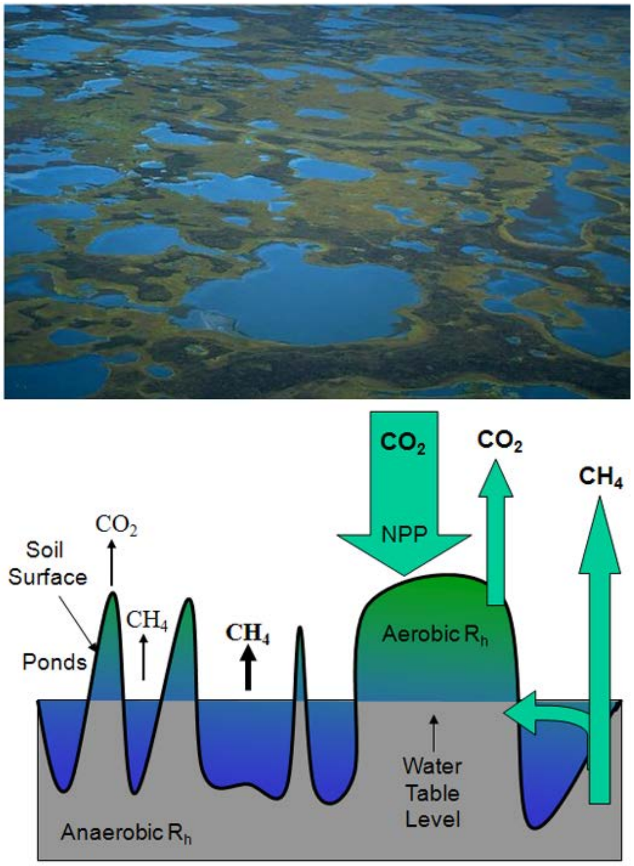

Figure 2 – Ubiquitous thermokarst wetlands exemplify the inseparable linkage between the Arctic carbon and hydrologic cycles. Microtopography, water table level, and active layer depth dictate the partitioning of soil respiration into aerobic (CO_2 release) and anaerobic (CH_4 release) processes. Seasonal and interannual variations in water availability and wetlands extent leads to high uncertainty in the CO_2/CH_4 partitioning of carbon fluxes from Arctic ecosystems.

Whether climate change leads to a warmer, wetter Arctic or a warmer, drier Arctic will dictate how old permafrost C re-enters dynamic carbon cycling. Warmer, wetter conditions favor anaerobic respiration and the conversion of old C into CH_4, while warmer, drier conditions favor aerobic respiration and the conversion of old C into CO_2 (Fig. 2). The CH_4/CO_2 fractioning is crucial to quantifying carbon cycle-climate feedback since the radiative forcing from CH_4 is 22 more effective than CO_2 on a per molecule basis [4].

In May 2010, NASA selected the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) as one of the first Earth Ventures (EV-1) investigations. CARVE is a 5-year mission designed to quantify correlations between atmospheric concentrations of CO_2 and CH_4 with surface-atmosphere carbon fluxes and surface state control variables (soil moisture, freeze-thaw state, inundation state, surface soil temperature) and elucidate the sensitivities of Arctic carbon cycle processes to climate change.

2. Science Objectives

The carbon balance of ecosystems in the Alaskan Arctic is not known with confidence since fundamental elements of the complex biological-climatologic-hydrologic system are poorly quantified. No other current or planned space-based or sub-orbital system provides *coincident* measurements of surface controls and atmospheric concentrations required to quantify these processes. CARVE's science objectives are to fill this critical gap in science knowledge by:

(1) Directly testing hypotheses attributing the mobilization of vulnerable Alaskan Arctic carbon reservoirs to climate warming;

(2) Delivering the first direct measurements and detailed maps of CO_2 and CH_4 sources on regional scales in the critical Alaskan Arctic ecozone; and

(3) Demonstrating new remote sensing and modeling capabilities to quantify feedbacks between carbon fluxes and carbon cycle-climate processes in the Alaskan Arctic region.

CARVE measurements and integrated science data will provide unprecedented experimental insights into Alaskan Arctic carbon cycling and its response to climate change. The quantified correlations between surface controls and atmospheric composition determined from CARVE data will provide powerful new tools for understanding current Alaskan ecosystems, their role within the pan-Arctic region, and retrospective analyses that extend this understanding over the entire length of various satellite sensor data records. The CARVE investigation also establishes the foundation for a community-wide Arctic-based undertaking such as the decade-long Arctic-Boreal Vulnerability Experiment (ABOVE), currently under consideration by NASA's Carbon Cycle and Ecosystems program [5].

Three key science questions drive the CARVE investigation. Each is associated with a hypothesis that will be tested by the CARVE measurements and analyses.

Question 1) What are the sensitivities of the Arctic carbon cycle and ecosystems to climate change? Historically, Arctic ecosystems have been net sinks for atmospheric CO_2 due to the predominance of cold, wet soils that effectively reduce organic matter decomposition rates [6]. As the Arctic warms, carbon release from permafrost soils is expected to occur through accelerated decomposition of organic matter. Model projections for a dramatic rise in Arctic land temperatures during the 21st century [7] and the high probability for climate amplification at high northern latitudes [8] threaten significant positive feedback on the climate system from rapid, large-scale mobilization of carbon sequestered in permafrost soils. Gruber et al. [9] estimate that warming may release as much as 100 Pg of organic carbon to the atmosphere by 2100; however, the size of vulnerable Arctic carbon pools and their exchange with the atmosphere is

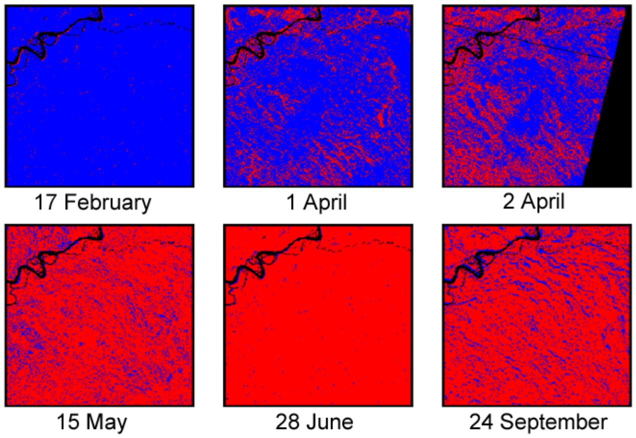

Figure 3 – Patterns of frozen (blue) and thawed (red) vegetation near Bonanza Creek, AK during 1998 determined from JERS L-band satellite imagery [Podest 2005, Entekhabi et al. 2004]. Scale: 30 km × 30 km. Rapid thawing was observed from 1 to 2 Apr. Soil thaw generally lags vegetation thaw. Refreeze in September–October is typical.

poorly quantified [10].[2] It is not know with confidence how Arctic terrestrial ecosystems will respond to direct climate forcings such as warming, or to indirect forcings from poorly understood climate feedbacks such as fire and permafrost thaw [8]. The rate of carbon release from permafrost soils is highly uncertain, but crucial for predicting the strength and timing of this feedback [11-12]. Determining the climate sensitivity of constraints to organic matter decomposition in northern wetlands, peatlands and permafrost soils is key to understanding the evolution of the Arctic carbon cycle [13].

Hypothesis: There exist early warning signatures that identify the tipping point for rapid release of vulnerable Arctic soil C reservoirs into the atmosphere

Lenton et al. [14] identify permafrost as a "tipping element"—those subsystems of the Earth system that are at least sub-continental in scale and can be switched into a persistent and qualitatively different state by small perturbations. The ice-water phase change near 0°C is a critical threshold (Fig. 3), or "tipping point," which, when crossed, can cause order of magnitude changes in permafrost decomposition rates [15]. Dlugokencky et al. [16] observed an increase in Arctic CH_4 coinciding with anomalously high temperatures in 2007; however, this CH_4 increase did not persist in 2008, suggesting that the Arctic had not yet reached a tipping point.

Approach: CARVE will search for early warning signatures of an Arctic carbon release tipping point by quantifying correlations between observations of surface controls, coincident surface-atmosphere fluxes, and atmospheric CO_2 and CH_4, directly linking observations of carbon dynamics to the variables most likely to influence those dynamics.

Question 2) How does interannual variability in surface controls (e.g., soil moisture) affect landscape-scale atmospheric concentrations and surface-atmosphere fluxes of CO_2 and CH_4? Soil moisture dynamics dictate the magnitude and CO_2/CH_4 partitioning of soil carbon flux in a warming climate [17]. A patchwork of dry and flooded areas is driven by microtopography (scales < 1 km) and seasonal water availability from snow melt and runoff. Fast aerobic decomposition consumes most of the C-pool in drier thaw areas, leading to large CO_2 fluxes. Slower anaerobic decomposition occurs in flooded thaw areas, producing CH_4 emissions almost exclusively [13]. Northern wetlands can switch rapidly between being sources or sinks of atmospheric carbon in response to climatic forcing [18-19]. Validated, high spatial resolution maps of northern wetlands extent and distribution are essential for accurately estimating sources, sinks, and net fluxes of atmospheric CO_2 and CH_4 and for providing a baseline against which to assess future spatial variability in northern wetlands [20]. The annual freeze/thaw cycle in the northern high latitudes drives the length of the growing season in these landscapes, determining annual productivity and associated exchange of CO_2 with the atmosphere. Variations in both the timing of spring thaw and the resulting growing season length have been found to have a major impact on vegetation productivity and atmospheric CO_2 source/sink strength within boreal regions [21-24]. Studies indicate that boreal evergreen forests accumulate approximately 1% of their annual net primary productivity (NPP) each day immediately following seasonal thawing [25]. The timing of the spring thaw can influence boreal carbon uptake dramatically through low temperature and moisture controls on photosynthesis and respiration processes [26-27].

Hypothesis: Local surface-atmosphere fluxes of CO_2 (or CH_4) correlate with coincident surface controls or atmospheric concentrations of CO_2 (or CH_4).

Figure 4 [28] shows the strong correlation between observed CH_4 fluxes and soil temperature. This correlation captures >90% of CH_4 flux variability. We anticipate that similar strong CH_4 flux correlations exist with other surface controls throughout Arctic terrestrial ecosystems.

[2] McGuire et al. estimated the soil carbon storage of northern high latitude terrestrial ecosystems to be between 1400 and 1850 PgC, approximately 50% of the estimated global subsurface organic carbon pool. For comparison, northern high latitude ecosystems are estimated to store 60–70 PgC in vegetation and Arctic ecosystem carbon cycling results in a net sink from the atmosphere of 0.0–0.8 PgC/year as CO_2 and a net source to the atmosphere of 0.03–0.11 PgC/year as CH_4 [1].

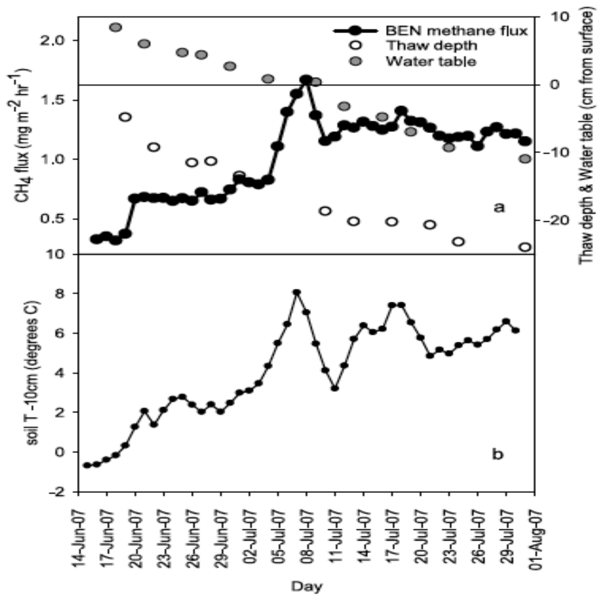

Figure 4 – (a) Daily averaged CH_4 fluxes, thaw depth and water table, and (b) soil temperature at 10 cm depth at an Alaskan test site [Zona et al. 2009]. Note the correlation between soil temperature and CH_4 flux.

Approach: CARVE will make coincident measurements of soil moisture, inundation state, freeze/thaw state and soil surface temperature along with total column CO_2 and CH_4 on spatial scales ≤ 1 km to test this hypothesis.

Question 3) What are the impacts of fire and thawing permafrost on the Arctic carbon cycle and ecosystems? Disturbance can alter ecosystem structure and permafrost dynamics rapidly [29]; however, investigators currently lack the observations and models to understand the response of disturbance regimes to climate warming and to quantify this terrestrial feedback on the climate system. Increased disturbance could promote permafrost degradation, peatland expansion, and increase carbon storage across the landscape [30]. Fire is the dominant episodic process controlling soil carbon transfer rates to the atmosphere from thawed permafrost [10]. Our understanding of disturbance effects on permafrost is inadequate to permit quantitative estimates of the future rates of change of permafrost, hydrology, and terrestrial ecosystems [8]. Continued development of the model physics and biogeophysics (e.g., dynamic wetlands, dynamic vegetation) is required to better represent the impact of climate change on permafrost and the feedbacks of permafrost degradation on regional and global climate [31]. The phase transition from ice to liquid water in permafrost soils represents a non-linear threshold whose effects on ecosystem dynamics are poorly captured with current modeling approaches [10]. Global circulation models are just beginning to include simple permafrost dynamics [12,31-32], but are still far from coupling physical permafrost dynamics to hydrology and biogeochemistry to properly represent the C-cycle in thawing permafrost and can yield highly inaccurate results [12,33].

Hypothesis: Fires in boreal forests or tundra will accelerate permafrost thaw, mobilizing vulnerable C reservoirs into dynamic carbon cycling and increasing the seasonal amplitude of high latitude atmospheric CO_2 concentrations.

Burned area in boreal forests of North America has increased over the last several decades as a consequence of climate warming [34-36]. Substantial increases in burned area and fire emissions are expected in the future based on predictions of intensifying drought and warming trends in boreal regions [37-38]. Bottom-up estimates of boreal fire emissions are central to many carbon cycle and air quality emissions calculations; however, many terms used to generate the estimates are associated with significant uncertainty (e.g., the emission factor used to convert total carbon emissions into emissions for a particular trace gas) [39]. MOPITT (Measurements of Pollution in the Troposphere), AIRS (Atmospheric Infrared Sounder) and TES (Tropospheric Emission Sounder) satellite observations of CO offer important top-down constraints on carbon emissions from boreal fires and, combining these observations with atmospheric models, it is possible estimate surface CO fluxes from fires with high precision [40-41]. However, the molar emission ratios ($CO:CO_2$ and $CO:CH_4$) needed to convert observations of CO emissions to total carbon release from boreal forest fires are not known as a function of fire weather, soil moisture, or vegetation type, nor is it known how they vary on seasonal or

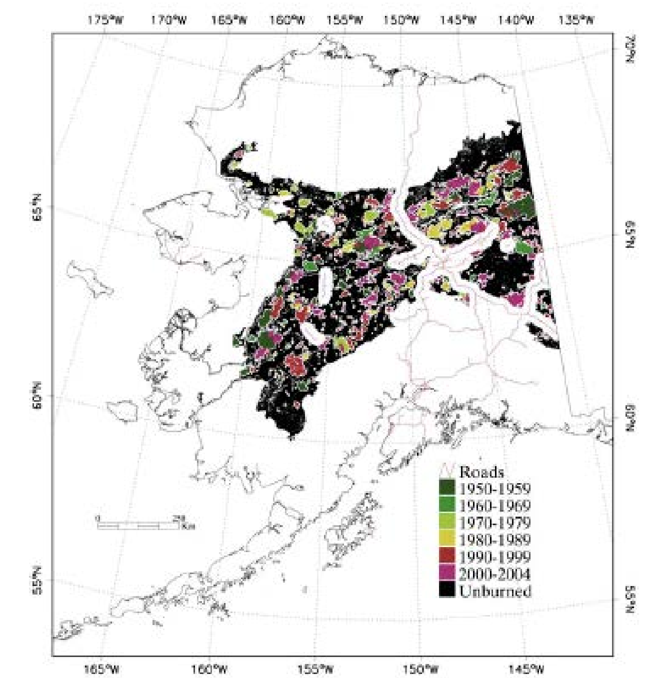

Figure 5 – Distribution of fire burn areas and recovery zones in the Alaskan interior [Lyons et al. 2008]. Ecosystem recovery times >50 years have been monitored; however, the impact recovery has on CO_2 and CH_4 fluxes is unquantified.

Table 1. CARVE Science Team Members and Responsibilities

Name	Institution	Responsibilities
C. Miller	JPL	Principal Investigator
L. Bruhwiler	NOAA-ESRL	Estimate Arctic CH_4 fluxes using CARVE data and CarbonTracker-CH_4
J. Fisher	JPL	Land surface model calculations of Arctic carbon fluxes
I. Fung	UC Berkeley	Coupled hydrologic-biogeochemical-climate modeling
C. Koven	LBL	Develop improved permafrost dynamics models, validate with CARVE data
I. Leifer	UCSB	Coordinate AVIRIS CH_4 observations in Alaska with CARVE flights; compare CARVE, AVIRIS, GOSAT, and SCIAMACHY CH_4
K. McDonald	CCNY	Model surface remote sensing data, including modeling of active and passive microwave measurements for interpretation of the PALS aircraft as well as PALSAR and AMSR satellite datasets; develop Level 2 surface state products from the PALS and satellite data sets.
J. Miller	NOAA-ESRL	Analyze $\delta^{13}C$, $\delta^{14}C$, $\delta^{18}O$, and δD of CO_2, CH_4, and CO for source attribution and process studies; Science Flight Planning Team
W. Oechel	SDSU	Acquire and analyze CO_2 flux, CH_4 flux, H_2O flux, energy balance, and micrometerological observations
E. Podest	JPL	Analyze scaling across the surface-aircraft-satellite datasets; interpret CARVE data to assess surface controls to the land-atmosphere carbon flux
J. Randerson	UC Irvine	Ingest CARVE data into CASA-GFEDv2 and GEOS-CHEM to model the landscape distributions of carbon fluxes; model fire carbon-release and intensity using CARVE correlations with MODIS, MOPITT, TES, and AIRS
P. Rayner	Univ Melbourne	Atmospheric transport and inversion analysis of CARVE observations to generate top-down estimates of Arctic carbon fluxes
D. Rider	JPL	FTS instrument operations, data analysis and interpretation
C. Sweeney	NOAA-ESRL	Analyze and model in situ aircraft data; Science Flight Planning Team
P. Wennberg	Caltech	Use TCCON observations to assess the importance of biomass burning, high latitude wetlands, and urban sources on CO_2, CH_4, and CO budgets
S. Wofsy	Harvard	Use aircraft in situ CO_2, CH_4, and CO data in high spatial resolution regional scale modeling using STILT; Science Flight Planning Team

interannual timescales.

Approach: CARVE will measure atmospheric CO_2, CH_4, and CO in and around Arctic fire events to quantify the carbon release to the atmosphere. Additionally, CARVE airborne deployments will monitor well characterized burn-recovery chronosequences of different ages and disturbance intensities (Fig. 5) to determine the impact of fires on Arctic ecosystems and their carbon balance, building on baseline data collected during ARCTAS.

CARVE Science Team

The investigation will be implemented by the CARVE Science Team. Their roles and responsibilities are described in Table 1.

3. Science Instrument Payload

The CARVE investigation employs a suite of three instruments: (1) JPL's Passive Active L-band System (PALS); (2) a Fourier transform spectrometer (FTS) with optical filters optimized to meet CARVE science requirements; and (3) an In Situ Gas Analyzer Suite (ISGAS) for continuous CO_2, CH_4 and CO measurements and whole air sampling at discrete locations (Fig. 6). All instruments are controlled by a master computer system (Data Acquisition and Distribution System, DADS). Data are logged and UTC time stamped at 1 Hz intervals. DADS also records GPS data (Lat, Lon, elevation), aircraft pitch, roll, and yaw, as well as basic meteorological data from onboard instruments.

Passive Active L-band System (PALS)

PALS remotely senses soil moisture, inundation state, temperature, and freeze/thaw state. This instrument consists of a polarimetric radiometer and radar that time-share a single planar-array antenna. PALS measures microwave radiance and radar backscatter coefficients in multiple polarizations from which the surface state parameters are derived. This instrument has an extensive flight history on several NASA and NASA-contracted aircraft including the Twin Otter.

The radiometer measures microwave radiance in two polarizations at 1420 MHz, which is related to the radiometric brightness temperature (T_b) of the surface within the FOV of the antenna. Brightness temperature is related to the microwave emissivity (ε) by $T_b = \varepsilon T$, where T is the thermodynamic temperature measured independently by the PALS infrared pyrometer. The emissivity is correlated with the liquid water content of the soil and the PALS infrared pyrometer independently measures the soil temperature. The

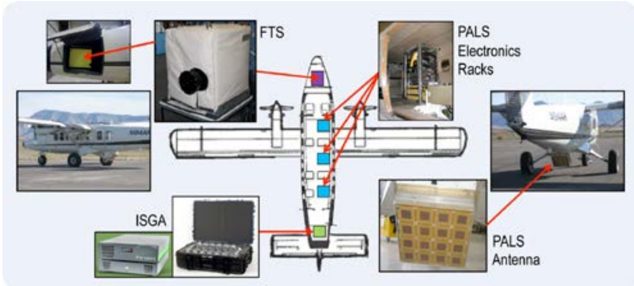

Figure 6 – The CARVE science instrument payload as it would be deployed aboard a Twin Otter.

PALS radar measures the decrease in radar backscatter coefficient σ^0 due to soil inundation state. As the percentage of liquid water increases, so does the conductivity of the surface, this decreases the penetration depth and increases the adsorption of the surface resulting in a decrease in σ^0. This subsystem is an L-band (1260 MHz) polarimetric scatterometer with an approved NASA radar license. The transmitting polarization is alternated between vertical (V) and horizontal (H) from pulse to pulse and two receivers detect the V- and H-polarized radar echoes simultaneously providing measurements of VV, HH, VH, and HV polarized radar response [42]. Before PALS is transported to the aircraft for installation, the passive channels are calibrated to an accuracy of 0.1 K using liquid nitrogen and a precision hot load reference and the PALS radar channels are calibrated by transmitting into standard loads.

Fourier Transform Spectrometer (FTS)

The CARVE FTS acquires high-resolution near-infrared spectra of solar radiance reflected from the Earth's surface, from which column abundances of CO_2, CH_4, and CO are retrieved using algorithms of the type developed for OCO [43-46]. The FTS telescope has a 10 degree field of view, which will yield data with ~100 m x ~1000 m spatial resolution at a 1 Hz readout rate under nominal flying conditions. The column abundances retrieved from the FTS will complement the measurements of CO_2, CH_4 and CO from the In Situ Gas Analyzer (see below), and provide a driect link to the column measurements made from space by the GOSAT, SCIAMACHY, MOPITT and OCO-2 sensors.

The CARVE FTS is a slightly modified version of the flight-proven *Tsukuba* FTS built by ABB Bomem for the Japanese Aerospace Exploration Agency (JAXA) as the airborne precursor for the Greenhouse gases Observing SATellite (GOSAT) [47]. The heart of the CARVE FTS is Bomem's Generic Flight Interferometer (GFI) which was the basis for a series of airborne and spaceborne remote-sensing FTS including: *Paris*, *Tokyo*, the Atmospheric Chemistry Experiment (ACE) FTS on SciSat [48] and the Crosstrack Infrared Souder (CrIS) FTS for the Joint Polar Satellite System (JPSS).

The CARVE FTS is on schedule for delivery in the Fall of 2011. It will be integrated onto the aircraft for engineering test flights in early 2012 and ready to deploy to Alaska for the start of science operations in Spring 2012.

In Situ Gas Analyzer (ISGA)

CARVE's instrument suite is completed by the ISGA which contains a Picarro G1401 analyzer for continuous in situ measurements of CO_2, CH_4 and CO, and a number of 12-flask Programmable Flask Packages (PFPs) to acquire whole air samples. The ISGA complements the column measurements of CO_2, CH_4, and CO derived from FTS spectra, and delivers high-precision, in-situ concentrations of 50 other gases and stable isotopologues.

The ISGA is fed from two separate inlets, one leading to each of the ISGA components. The inlets are aft facing, installed above the cockpit and before the engines to avoid intake of any exhaust fumes. Synflex tubing is used to avoid contamination of the inlet air and minimize changes in concentrations due to desorption from the tubing walls. The inlet was constructed based on the flight proven design used by the NOAA Aircraft Program.

Continuous measurements from the Picarro analyzer are calibrated against on-board standard gas samples once every 30 minutes by an automated system. Allan variance analyses of the Picarro signals against calibrated gas samples demonstrated excellent performance. Measured precisions (1σ) for 2.5-second integration times are 0.012 ppm for CO_2, 0.118 ppb for CH_4 and 2.319 ppb for CO. This outstanding performance provides CARVE with high sensitivity to rapid changes in atmospheric concentrations of these gases.

PFPs have become the benchmark for assessing the accuracy and traceability of in-situ measurements of greenhouse gases (CO_2, CH_4, CO, N_2O, and SF_6) and other trace gas species. PFPs have been operationally deployed on aircraft since 2003 and on tall towers since 2006. Air sample collection is manually controlled from the DADS system and takes approximately 2 minutes from the time the PFP collection is triggered. Data acquisition is timed to coincide with the overflight of a ground site of interest, or when interesting geophysical conditions are encountered. The baseline plan is to collect 12 PFP samples per flight, although multiple PFP units may be used on some flights.

Whole air samples collected in the PFPs will be analyzed for CO_2, CH_4, CO, N_2O, and SF_6 on automated systems currently used to analyze samples from the NOAA/ESRL ground, tall tower, and aircraft network. These systems consist of a custom-made gas inlet system, gas-specific analyzers, and system-control software. The gas inlet systems use a series of stream selection valves to select an air sample or standard gas, pass it through a trap for drying maintained at ~–80°C, and then to an analyzer. CO_2 is measured by a non-dispersive infrared analyzer (±0.03 ppm; values in parentheses after each instrument description are average repeatabilities determined as 1 standard deviation of ~20 aliquots of natural air measured from a cylinder.) [49];

CH_4 by gas chromatography (GC) with flame ionization detection (±1.2 ppb) [50], CO by GC followed by reacting it with HgO and detecting Hg by resonance absorption (±0.3 ppb) [51], or by detecting CO directly by resonance fluorescence at ~150 nm (±0.2 ppb) [52]; and N_2O (±0.26 ppb) and SF_6 (±0.03 ppt) by GC with electron capture detection [53]. All measurements are reported as dry air mole fractions relative to internally-consistent standard scales maintained at NOAA which are directly traceable to the WMO calibration scales. In addition to greenhouse gases, analyses of more than 30 different hydrocarbons and halocarbons will be performed by GC mass-spectrometric measurements on ~200 ml aliquots taken from the PFP flask samples and pre-concentrated with a cryogenic trap at ~80 K. PFP flask sample responses are calibrated against whole air working reference gases which are calibrated with respect to gravimetric primary standards (NOAA scales: CFC-11 on NOAA-1992, CFC-12 on NOAA-2001, HFC-134a on NOAA-1995, benzene on NOAA-2006 and all non-CH_4 hydrocarbons on NOAA-2008). Absolute uncertainties for these analyses will be <5%.

Stable and radioisotope analyses will be performed at the University of Colorado's Institute for Arctic and Alpine Research (INSTAAR) Stable Isotope Laboratory and Radiocarbon Laboratory, respectively. Both laboratories are global leaders in achieving the highest possible precision measurements [54-55]. For radiocarbon analyses, samples of CO_2 as small as 0.4 mg C, obtained either via cryogenic distillation of air or by combustion of CH_4 [56], are reduced to elemental graphite and analyzed for their $^{14}C/^{12}C$ ratio ($\Delta^{14}C$) on an accelerator mass spectrometer (AMS) to a precision of 2‰ or better at the UCI AMS facility [Turnbull et al. 2007]. A new high-throughput automated extraction system for CO_2 has recently been installed; a CH_4 combustion system using the design of Lowe et al. [56] is planned. Measurement precision for $\delta^{13}CO_2$ is 0.01‰, $\delta^{18}O$ of CO_2 is 0.03‰, $\delta^{13}CH_4$ is 0.1‰ and dD of CH_4 is 1‰.

4. COMPLEMENTARY MEASUREMENTS

CARVE ground-based observations capture temporal variability, provide sub-grid-scale dynamics for model validation, and establish a context for up-scaling observations from local to regional scales (Fig. 7). Ground measurements enable us to establish correlations between CARVE aircraft measurements and geophysical parameters that are not part of the CARVE measurement suite. Ground-based measurement sites serve as anchor points for CARVE flight tracks. Repeated flights over these locations will be crucial for assessing temporal trends and ensuring accurate calibration/validation for the CARVE instruments. The CARVE investigation leverages ongoing investigations, existing infrastructure and long-term data records through a number of collaborations.

CARVE ground sites include CO_2 and CH_4 flux towers and energy balance measurements [57] as well as hourly measurements of vegetation, soil and air temperatures, soil moisture and xylem sap flow within selected trees from the Alaska Ecological Transect (ALECTRA) [58-59]. TCCON total column CO_2, CH_4, and CO measurements [60] and in situ measurements from the NOAA/ESRL network provide strong constraints on Arctic carbon fluxes and long range transport of CO_2, CH_4, and CO into the study domain.

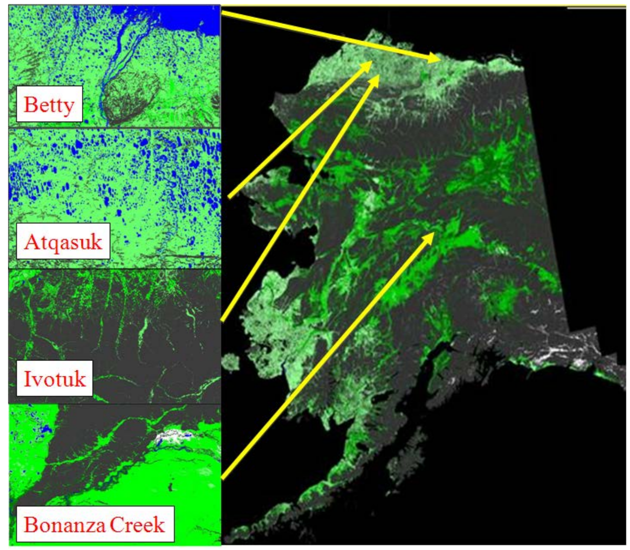

Figure 7 – A 100 m resolution wetlands map of Alaska generated from JERS L-band satellite radar imagery [Whitcomb et. al 2009]. The map is based on dual-season summer-winter backscatter for 1997 and 1998. Insets show selected CARVE ground sites.

Barrow AK (BRW)

Continuous in situ measurements of CO_2, CH_4 and CO at Barrow AK (BRW), 71.323N, 156.611W, 11 masl, provide a long-term record and historical trends for the Arctic. Barrow has been operational since 1973 and is a baseline station in the NOAA Global Monitoring Network. It is about 8 km northeast of the village of Barrow and has a prevailing east-northeast wind off the Beaufort Sea. BRW is located so that it receives minimal influence from anthropogenic effects. BRW is best characterized as having an Arctic maritime climate affected by variations of weather and sea ice in the Central Arctic. <http://www.esrl.noaa.gov/gmd/obop/brw/summary.html>

Frequent flights over Barrow will be important for establishing the linkage and variability between ground and airborne measurements in the Barrow area with airborne measurements made across the North Slope and throughout the remainder of the CARVE experimental domain. CARVE will augment the Barrow measurements with monthly collection of ~600 L whole air samples for atmospheric $^{14}CH_4$ analysis.

BRW is located near the National Weather Service (NWS) weather observing facility and CO_2 flux towers (see below). Additionally, the DOE Atmospheric Radiation and Monitoring North Slope Alaska (NSA) site is centered at

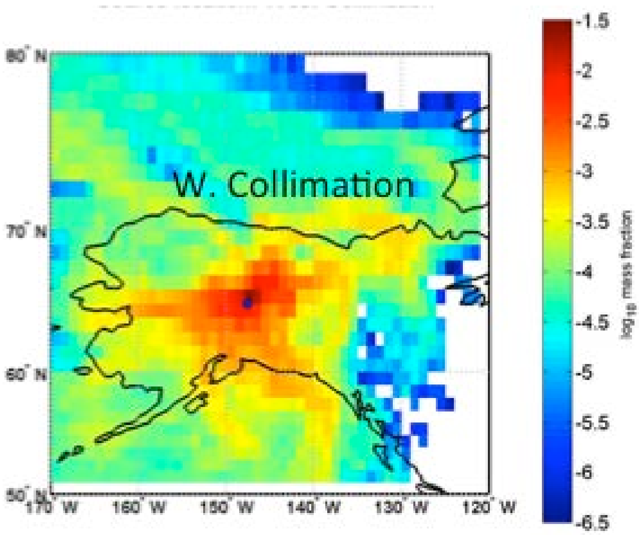

Figure 8 – Hysplit calculations of the sensitivity of continuous in situ measurements at the West Collimation Tower in Fox, AK to air parcels originating in different locations. Hysplit was run at 1 degree resolution over 7 days and driven by NCEP global reanalysis data from 2009. [C. Sweeney and A. Karion, unpublished].

Barrow <http://www.arm.gov/sites/nsa>, extending south to Atqasuk.

Fox AK Tall Tower

CARVE team installed continuous in situ measurements of CO_2, CH_4 and CO and PFP sampling at the West Collimation tower at the NOAA Gilmore Creek facility in Fox AK. The tower is located off Brier Road at 64.9863N, 147.5979W, 586 masl atop a ridgeline in the White Mountains approximately 20 miles northeast of Fairbanks. Back trajectory analyses show that this site provides excellent atmospheric sampling of the Alaskan interior (Fig 8). The Fox tall tower measurements will also include monthly collection of 600 L whole air samples for atmospheric $^{14}CH_4$ analysis. Frequent overflights of the tower are planned given the close proximity of this site to the base of operations in Fairbanks. Measurements from the Fox tower will also support understanding of the column CO_2, CH_4 and CO measurements made with the Poker Flat FTS.

Poker Flat FTS

Vertical profiles of CH_4 have been retrieved from high-resolution solar-viewing FTS operated at the UAF Aeronomy Laboratory (64.11N, 147.42W, 610 masl) in Poker Flat Research Range since 2000. The FTS will be converted to TCCON standards during the winter of 2011/2012, with the intent to begin delivering regular measurements of column CO_2, CH_4 and CO starting in March 2012. This site will provide critical validation of the CARVE airborne FTS measurements. Frequent overflights are planned given the close proximity of Poker Flat to the base of operations in Fairbanks. The FTS data will have excellent synergy with the continuous in situ measurements from the Fox tall tower.

Flux Towers

Since the early 1990s, Oechel and coworkers have operated series of North Slope flux towers on a transect extending south from Barrow to Atqasuk and Ivotuk. Measurements include energy, water and CO_2 fluxes. Provide unique opportunity to compare and correlate atmospheric CO_2 and CH_4 concentrations measured form the CARVE aircraft with the surface atmosphere C fluxes measured at these sites. A key element of the CARVE investigation is to provide mesoscale context of the flux measurements – extend them beyond the immediate vicinity/fetch of the tower (typically < 1 km). Portable flux towers are periodically deployed nearby the Barrow, Atqasuk and Ivotuk towers to assess local flux variability associated with thermokarsting, inundation/saturation, etc.

Flux towers are also planned to start operations on the Seward Peninsula at Council and Kougerok as part of the DOE Next Generation Ecological Experiment (NGEE) [61]. This would extend the tower transect from the Artic Ocean limits of the North Slope tundra south through the western maritime ecosystems,

There are several other flux towers that CARVE will use as flight line anchor points: the Bonanza Creek and Caribou-Poker Creek Watershed towers that are part of the BNZ LTER; towers within the Toolik Lake LTER and the Anaktuvuk River fire scar; and 8 Mile Lake. We will also target lakes known to have large CH_4 ebuliation [18].

ALECTRA

ALECTRA monitors a variety of vegetation species and soil conditions to capture representative temperature regimes of the landscape sites [58-59]. The ALECTRA sites record hourly measurements of xylem flow within the tree, and temperature of the air, snow, soil, and vegetation.

IARC Permafrost Boreholes

Romanovsky and coworkers have established a network of more than 50 permafrost boreholes throughout Alaska [62]. Permafrost temperatures are measured to depths of up to 100 m. Many sites offer additional measurements including surface soil temperature; surface, 1 m and 3 m air temperatures and wind speed; snow depth; and soil moisture. CARVE flight lines use many of these sites as anchor points, especially for the Interior AK and Deadhorse AK loops. <http://permafrost.gi.aslaska.edu/sites_map>

NOAA CCGG Aircraft Program Flights

CARVE will leverage ongoing flights made by science team members as part of the the NOAA/ESRL Carbon Cycle Greenhouse Gases (CCGG) group's aircraft program.

Since June 1999 aircraft profiles have been flown on average once every 17 days at Poker Flat AK (65.0700 N, 147.2900 W, 210 masl), approx. 30 miles northeast of the CARVE base of operations in Fairbanks. Each flight collects 12 PFP samples at altitudes from the boundary layer (129 magl) through free troposphere (~7600 magl). Samples are analyzed for CO_2, CH_4, CO, N_2O, H_2, and SF_6, as well as isotopes of CO_2 and CH_4, and multiple halo- and hydrocarbons. These measurements provide important vertical information for comparison with the continuous in situ measurements from the Fox Tower as well as validation of the profile and column retrievals of CO_2, CH_4 and CO from the Poker Flat FTS.

Since 2009, the CCGG Aircraft Group has collaborated with the U.S. Coast Guard on biweekly missions around Alaska on a Hercules C-130 aircraft as part of the Arctic Domain Awareness mission. The C-130 payload includes PFPs, continuous in situ $CO_2/CH_4/H_2O$ measurements, and a continuous ozone monitor. A window has been replaced with a specially manufactured inlet window for our instrumentation, and three of NOAA's calibrated CO_2/CH_4 standards are also on board for calibration of the in-situ continuous analyzer. The inlet plate includes dedicated inlets for ozone, continuous CO_2/CH_4, and flask samples, as well as a Vaisala HMP-50 temperature and relative humidity sensor. Alaska Coast Guard (ACG) flights generally depart from Kodiak in the south, perform an altitude profile over Galena just south of the Brooks Range, descend again to low altitude over Kivalina on the coast, continue at low altitude to Barrow, and then (sometimes) continue over Prudhoe Bay before returning at cruising altitude back to Kodiak (Fig. 9). Flight paths range from ground level to 8500 masl.

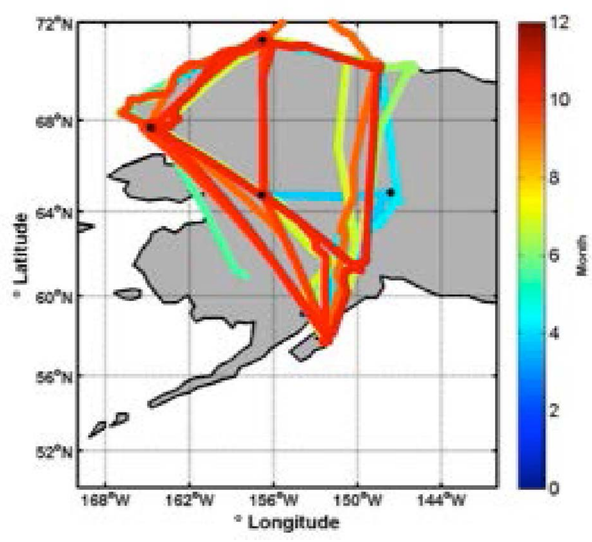

Figure 9 – NOAA ACG flight paths for 2009. See http://www.esrl.noaa.gov/gmd/ccgg/aircraft/alaska.html for additional details. Note the complementarity to the CARVE flight paths (Figs. 10 & 13)

5. Flight Operations

The CARVE Investigation is designed to reconcile Alaskan Arctic carbon fluxes estimated from atmospheric concentrations of CO_2 and CH_4 measured with remote sensing and in-situ techniques (top-down approach) with carbon fluxes estimated from coincident remote sensing measurements of surface state controls (bottom-up approach). The CARVE Science Investigation entails intensive seasonal deployments in Alaska during the spring thaw, summer draw-down, and fall refreeze of the Arctic growing season over multiple years. CARVE flight plans sample multiple permafrost domains and ecosystems, and deliver detailed measurements over ground-based measurement sites, fires, and disturbance recovery chrono-sequences. Large schedule margins provide resiliency against poor weather and the flexibility to exploit unusual findings or geophysical conditions.

The CARVE science observing profile is designed to sample the locations and times when we expect to observe the largest signals from the impacts of surface controls, fire, and permafrost thaw on the carbon cycle dynamics of Arctic ecosystems. CARVE flight operations will be based out of Fairbanks, AK. CARVE flight paths (Fig 10) will concentrate observations on three study domains: the North Slope, the interior, and the Yukon River valley.

North Slope flights (gold path) are anchored by the flux towers in Barrow, Atqasuk, and Ivotuk, regions of tundra

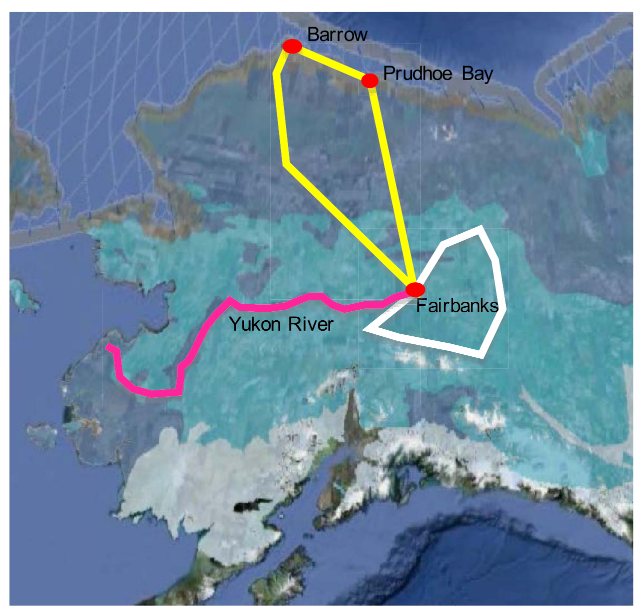

Figure 10 – CARVE flight plans deliver measurements over continuous (dark blue), discontinuous (light blue), sporadic (gray) and subsea (hatched) permafrost regimes. Each colored loop represents a single day's flight path. The gold flight path is anchored by flights over 5 flux towers which will be used to validate measurements from CARVE aircraft instruments. See text for additional details. Permafrost data from [63].

and continuous permafrost. These sites have been successfully used to quantify linkages between tundra photosynthetic biomass, surface temperatures, energy, water and CO_2 exchange along regional land cover, moisture and thermal gradients [6].

Flights to Prudhoe Bay characterize the CO_2 and CH_4 emissions from the oil and natural gas processing plants.

Flights over the interior (white path) sample discontinuous permafrost, boreal forests, and wetlands. These flight paths are anchored by the ALECTRA sites. Detailed measurements in the interior are also critical for observing the impacts of fires and well-characterized burn-recovery chronosequences of ages from <5 to >50 years.

Flights along the Yukon River (pink path) sample regions dominated by discontinuous permafrost and likely to yield large seasonal variations in carbon release. The impact of warm, fresh water on carbon fluxes near the Yukon Delta will be a focal point of research.

CARVE deployments exploit the natural seasonal variability of Arctic surface-atmosphere carbon fluxes (Fig. 11). The baseline mission entails deployments during the carbon flux increases of the spring thaw (~15 Apr–15 May), the transition from sources to sinks during the summer draw-down (~15 Jun–15 Jul), and the transition from sinks back to sources during autumn (~15 Aug–15 Sep). Fig. 11 shows the timings for a North Slope site; these timings occur earlier/later for spring thaw/autumn at lower latitudes. This gives flexibility to the CARVE campaigns, increasing each deployment window and allowing the team to deploy when weather patterns and geophysical conditions are optimal.

Ground-based CO_2 and CH_4 flux measurements quantify CO_2/CH_4 partitioning and establish essential long-term temporal context and short-term variability for CARVE airborne observations. Atmospheric CO_2, CH_4 and CO measurements are vital for separating the background signal from local signals. Fig. 12 shows winter and summer CO_2/CH_4 correlations from Alaska ACG flights [Sweeney, unpublished]. Winter shows a very tight correlation, driven by sources from lower latitudes transported to the Arctic by storm systems in the North Atlantic. These correlations vanish in the summer when local sources dominate the atmospheric CO_2 and CH_4 concentrations. These arguments hold for correlations with CO, with the summer months showing especially high variability driven by the episodic nature and intensity of fires. TCCON column measurements will provide important additional constraints on regional CO_2/CH_4/CO correlations [Wunch et al. 2009.].

6. Spring 2011 Test Flights

In April 2011 CARVE deployed to Alaska to test the flight system and logistics in preparation for full science operations in 2012. A reduced instrument payload was installed aboard a DeHavilland DH-6 Twin Otter in Grand Junction, CO during March 2011 for these flights. It contained PALS, a Picarro with CO_2 and CH_4 channels, its calibration gases and PFPs. After successful engineering and safety test flights, the plane transited to its base of operations in Fairbanks, AK. It arrived on 6 April 2011 after a 5-day trip. Four test flights were performed (Fig. 13):

1. 4/9/11 – Interior Alaska
2. 4/12/11 – Fairbanks – Deadhorse
3. 4/16/11 – Yukon River valley
4. 4/21/11 – Fairbanks – Barrow

The results and operational lessons learned from each flight

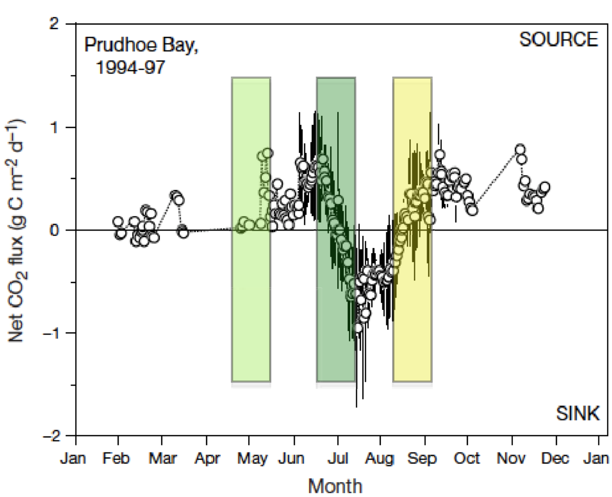

Figure 11 – Daily integrated CO_2 flux for a coastal tundra ecosystem near Prudhoe Bay (70N, 148W) [6]. CARVE campaigns are timed to capture the spring thaw source (May), the transition to the summer draw-down (~15 Jun–15 Jul), and the transition to the autumn source (~15 Aug–15 Sep).

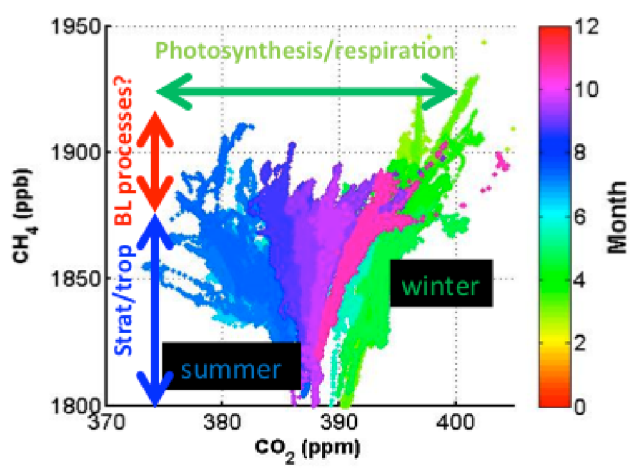

Figure 12 – CO_2/CH_4 correlations for in situ aircraft observations over Alaska. Winter conditions are characterized by tight, consistent correlations observed at all locations, indicating that this air has been trans-ported to the Arctic from mid-latitudes. Summer conditions still exhibit tight correlations, but slopes vary markedly with location and degree of CO_2 drawdown [C. Sweeney, unpublished].

are summarized below.

Flight #1: 4/9/11 – Interior AK

The pre-flight plan included flight lines over the Bonanza Creek LTER site (BNZ), the flux tower at 8 Mile Lake (Healy, AK), Delta Junction, and the Caribou-Poker Creek Watershed (CPCRW). The actual flight was shortened due to low level fog and intermittent rain to the south and east. The surface appeared predominantly frozen with extensive snow and ice, and no visible areas of open water. Surface soil temperatures ranged from -10 to -15C based on in-flight measurements from the onboard IR camera.

Despite the abbreviated flight, we made successful passes over the BNZ LTER, 8 Mile Lake, and CPCRW. There were no air traffic restrictions in these areas. Baseline measurements and flight lines were validated. The timing for triggering of the PFP sample collection was optimized.

Post-flight analysis showed that the on-board calibration of the continuous in situ CO_2 measurements agreed with the absolute calibration from the PFP samples with a mean offset of 0.08 ppm and a RMS precision of 0.15 ppm. Similarly, the continuous in situ CH_4 measurements agreed with the absolute calibration from the PFP samples with a mean offset of 0.4 ppb and a RMS precision of 1 ppb. These results confirm the excellent performance of the continuous in situ sampling system.

Analysis of the PALS data showed high sensitivity to flight lines crossing rivers, oxbows, and other larger bodies of frozen water. We also encountered several unexpected areas of RF interference. These locations have been marked and will be further characterized during future repeat flights.

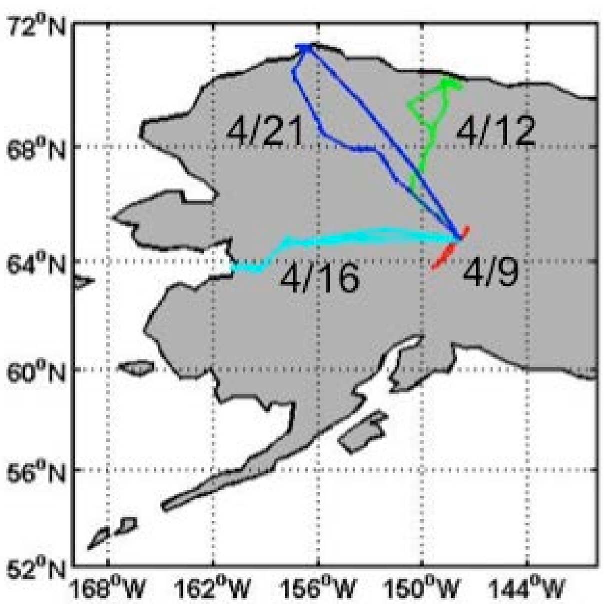

Figure 13 –Flight tracks for the CARVE Spring 2011 engineering test flights in Alaska. All flights began and ended in Fairbanks and took less than 10 hours.

Figure 14 – The CARVE team at Deadhorse, AK

Flight #2: 4/12/11 – Deadhorse AK

The pre-flight plan was to fly from Fairbanks to Deadhorse with a flight line roughly parallel to the Haul Road on the outbound leg, perform a spiral from the ground to 6000 meters above sea level (masl) over Deadhorse, descend, refuel, and return to Fairbanks via the Anaktuvuk River fire scar. This plan also included flight lines over more than a dozen interior and North Slope permafrost boreholes located along the Haul Road. The flying conditions were ideal with clear skies and little wind along the entire flight track. We encountered a strong atmospheric inversion as soon as we left the mountains and entered the North Slope, with an air temperature of -15C at the 1500 masl cruise altitude and surface soil temperatures of -25 to -30C based on in-flight measurements from the onboard IR camera. The North Slope appeared completely frozen with unbroken snow and ice visible in all directions (Fig. 14).

The continuous in situ measurements exhibited minimal variability (±0.5 ppm for CO_2 and ± 2-3 ppb for CH_4) during the northward leg, indicative of background winter conditions. However, elevated CO_2 and CH_4 were observed in plumes of 100 – 300 m thickness between 3000 and 4000 masl during the spirals over Deadhorse. These were most likely due to emissions from the local oil and gas processing operations.

Air traffic control at Deadhorse was not overly restrictive and we executed the spirals as planned. Deadhorse airport refueling and logistical support was excellent and efficient.

The return leg featured a ~100 km flight line down the center of the entire length of the Anaktuvuk River fire scar. This took approximately 30 minutes of actual flight time, confirming that multiple flights over this region on a given day will require at least two refueling opportunities.

Flight #3: 4/16/11 – Yukon River Valley

The pre-flight plan was to fly from Fairbanks northwest to the Yukon River, follow the river towards the Bering Sea

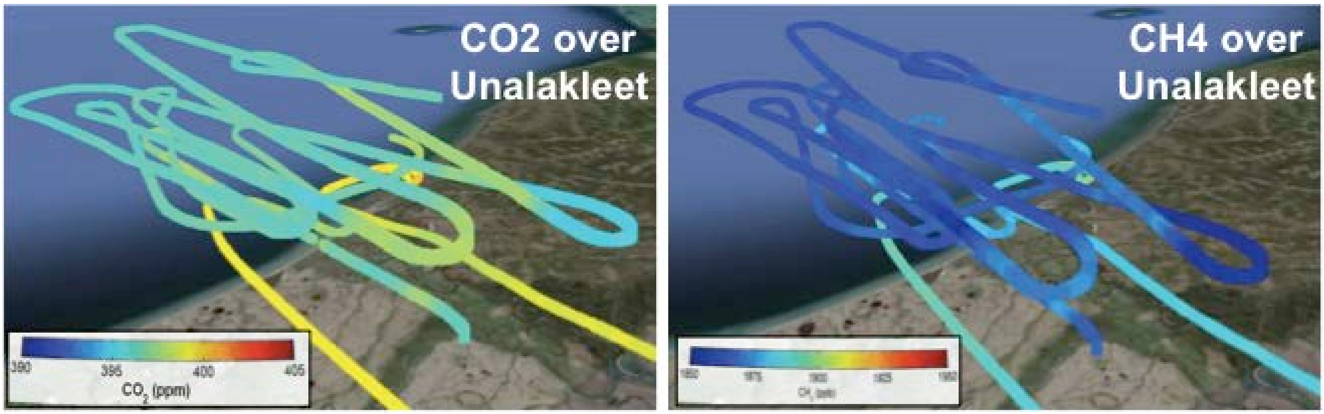

Figure 15 – In situ profiles of CO_2 and CH_4 measured over Unalakleet, AK on 4/16/11.

coast, divert towards Unalakleet, AK, perform a spiral from the ground to 6000 masl over the town and coastal sea ice, refuel, and return to Fairbanks along the same path. There are no ground sites that anchored this flight. The flying conditions were excellent. Air temperatures were warmer than for previous flights and surface soil temperatures ranged from -10 to -2C based on in-flight measurements from the onboard IR camera. The Yukon River valley showed signs of thawing and there was evidence of elevated CO_2 and CH_4 concentrations over oxbows in the flood plain.

There were no air traffic restrictions along the entire flight path. Unalakleet airport refueling and logistical support went without incident. There also exists the opportunity to refuel in Galena, AK for this flight track.

During the spiral over Unalakleet, we observed exceptionally low CO_2 and CH_4 concentrations between 3500 and 3800 masl (Fig. 15). This may have been an intrusion of stratospheric air, which an onboard ozone sensor would have immediately confirmed.

We took advantage of the return leg to calibrate the instruments. PALS calibration measurements were recorded by flying at 200 magl (meters above ground level) along the middle of the Yukon River for ~10 minutes. This provided cold, stable surface emissivity for the radar and radiometer. "Null measurement" experiments were performed on the ISGA to test its sensitivity to level flight rolls, as well as shallow ascent/descent. In these experiments, the plane flew level, left and right 5 degree turns for 30-60 seconds at a time, or 5 degree ascents or descents for similar times. The additional acceleration did not alter the continuous CO_2 or CH_4 measurement characteristics and the cavity pressure within the unit remained constant within our measurement uncertainty.

Flight #4: 4/21/11 – Barrow AK

The pre-flight plan was to fly from Fairbanks to Bettles, AK, refuel, fly north with flight lines over the flux towers at Ivotuk, Atqasuk, and Barrow, spiral from the ground to 6000 masl over Barrow, descend and refuel at Barrow, then return to Barrow. Flying conditions in the Barrow area were poor, and had been unfavorable for the previous week due to persistent ice fog, despite the fact that weather south of the Brooks Range was clear. After standing down on four previous attempts to fly to Barrow, the decision was made on 21 April to fly as far as Bettles, and then reassess the conditions near Barrow. Refueling in Bettles took over 2 hours and highlighted the logistical challenges in minor Alaskan airports. Conditions remained optimal until halfway through the Gates of the Arctic where we encountered dense fog and cloud cover. We climbed to 5000 masl and proceeded towards Barrow. Conditions did not improve significantly the rest of the way to Barrow. Additionally, logistical support in Barrow added nearly 3 hours to the flight day.

Surface soil temperatures of -25 to -30C based on in-flight measurements from the onboard IR camera, and the western North Slope still appeared completely frozen. Analysis of CH_4/CO_2 correlations showed significant changes in the slope and less compactness in the correlations, indicating contributions from thawing soils to the winter background signals.

The major conclusion from this test flight was that persistently poor weather and uncertain forecasts made for a challenging Go/No-Go flight decision process.

7. SUMMARY AND FUTURE PLANS

The successful engineering test flights in Alaska during April 2011 give us high confidence in the flight readiness of the CARVE team and flight system for full science operations in Spring 2012. CARVE flight planning, the flight system, and logistics were rigorously tested under real flight conditions in our actual experimental domain. A number of modifications to our system and processes will be required, but the basic framework of the investigation design performed as desired. The experience from these flights will enable more efficient use of deployment time in Alaska during science operations in 2012-2015. We have also verified that much of the data acquired during the engineering test flights meets our standards for CARVE science and it will be included in the CARVE modeling and analyses (Fig. 16).

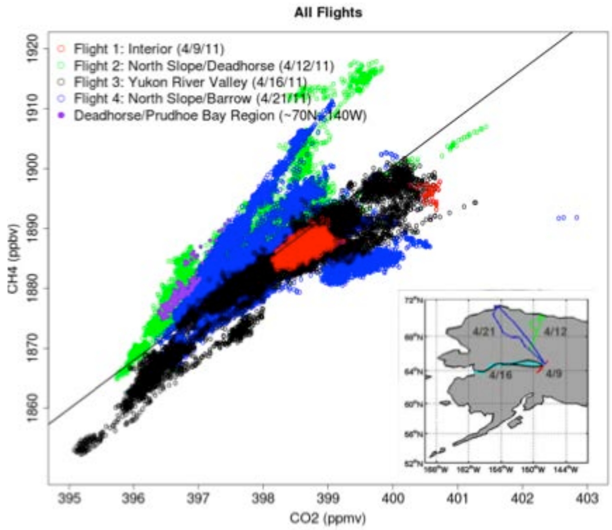

Figure 16 – CO_2/CH_4 correlations for in situ aircraft observations over Alaska during the CARVE Spring 2011 engineering test flights. Note the change in the slope of the correlations as the spring thaw progressed and more respiration occurred (higher CH_4). Compare to the full seasonal cycle in Fig. 12. Inset: flight tracks for individual measurement days.

Operational Logistics

With respect to operational logistics, the most important finding was the need to deploy to Alaska early enough to ensure we record background winter conditions. Our measurements and data from local ground stations indicate that the thaw was already well under way in the Fairbanks area when we arrived on 4/6/11. The 2012 campaign will deploy by mid-March for a short set of flights to capture winter conditions, the team will then stand down for a few weeks, then resume operations in April-May to capture the freeze thaw transition throughout the experimental domain. An examination of Alaskan meteorological records for the last 40 years reveals that interannual variability may shift the thaw onset by 2-4 weeks in any given year. Similar variability is expected for the summer drawdown and fall refreeze. Therefore, CARVE campaign scheduling will require a similar degree of flexibility.

Flights to Barrow were far more difficult to green light than anticipated. Our future flight planning will have a decision tree in which a Yes/No decision on Barrow flights will be the top priority each flight day given the limited number of good flying days in the Barrow region.

Flight tracks over burn recovery chronosequences have been identified in the Alaskan interior south of the Yukon River that can be flown as part of the Yukon River Valley loop. The burn regions here allow for 10-40 km long flight lines over burn recovery zones of a constant age (Fig. 17). These flight lines will complement flight lines over burn recovery zones on the Interior AK loop (Fairbanks-Healy-Delta Junction-Caribou Creek).

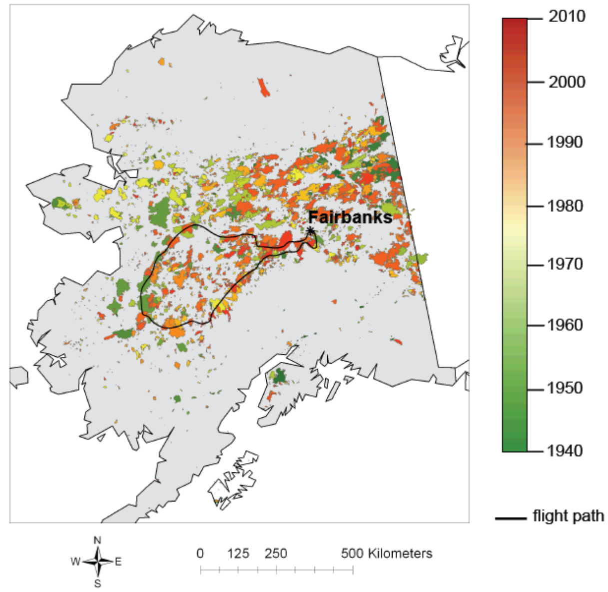

Figure 17 – A map of burn areas in interior Alaska. The color scale shows the time since the most recent burn. Most areas have burned at least once on the last 70 years and fires occur primarily in low elevation areas. A notional flight track south of the Yukon River to sample large burn areas of different recovery age is shown.

Flights of Opportunity

Occasionally CARVE campaign schedules will be modified to accommodate high priority needs of the SMAP project for the PALS instrument (PALS is the aircraft prototype of the SMAP satellite sensor). There are two SMAP validation experiments of special note: SMAPVEX12 (July - August 2012, Winnipeg, Canada), the pre-launch algorithm development campaign and SMAPVEX15 (mid-summer 2015, TBD location in North America), the post-launch validation campaign. The CARVE aircraft and payload will participate in both of these campaigns, exploiting the opportunity to integrate CARVE measurements and analysis with SMAP measurements, models and data products.

There are additional opportunities for CARVE to provide valuable contributions to NASA and the scientific community beyond the CARVE investigation. For example, the CARVE FTS can help validate space-based measurements of column CO_2 from OCO-2 and OCO-3. CARVE flights extending beyond the nominal lifetime of the CARVE investigation could also provide key data for the proposed ABoVE community activity, especially when flown in conjunction with the AirMOSS payload. We continue to investigate other potential uses for this novel aircraft instrument suite.

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BIOGRAPHIES

Charles Miller *received a B.S. in Chemistry and History from Duke University, and a Ph.D. in Chemical Physics from the University of California, Berkeley. He is a Project Scientist with the Earth Atmospheric Science Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. He is Principal Investigator of the CARVE investigation, a member of the Orbiting Carbon Observatory (OCO-2) Science Team, and a member of the GOSAT RA Science Team; he was Deputy Principal Investigator of the original OCO mission. He conducts research in carbon cycle science, atmospheric photochemistry, molecular spectroscopy, and developing new solutions for satellite remote sensing of greenhouse gases.*

Steven J. Dinardo *received the B.S.E.E degree from California State University, Los Angeles in 1983. He has been with the NASA Jet Propulsion Laboratory (JPL), Pasadena, CA, since 1978. At JPL, he has been involved in various projects, including very long baseline interferometry (VLBI), mobile VLBI, orbiting VLBI, GPS receiver development, and international GPS service. From 1995 through 1997, he was responsible for the deployment of the JPL aircraft polarimetric wind radiometers on NASA's DC-8 and P-3. He successfully coordinated the Hurricane Ocean Wind Experiment, sponsored by NASA and NPOESS, resulting in the first airborne Ku-band scatterometer and multifrequency polarimetric radiometer flights over hurricanes. He has also been responsible for development and deployment of JPL's aircraft rain radar and a 94-GHz cloud profiling radar on NASA's DC-8. He is currently involved in the development of low-noise microwave radiometers and radar systems for aircraft and spacecraft for remote sensing of soil moisture and ocean salinity.*

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