CSA ASC

INNOVATION
EXPLORATION
OBSERVATION
INSPIRATION

CSA Contribution to the CEOS Workshop on GHGs

18-19 June 2018, Ispra, Italy

Dr. M. Dejmek
Sun-Earth System Sciences
Space Utilization

Presentation Outline

Canada’s Radarsat-2 and SCISAT missions,
GHGs measured, integration into modeling, in-situ measurements, ECCC and GHGs, national inventories.

Canadian Space Agency Agence spatiale canadienne

Canada

Active Canadian Assets Monitoring Earth

LAND & OCEAN

2007 (Canada)

RADARSAT-2

Monitors sea ice, land, glaciers and natural disasters

ATMOSPHERE

2006 (USA, Canada)

CloudSat

Measures vertical structure of clouds

ATMOSPHERE

2001 (Sweden, Canada)

OSIRIS on Odin

Measures profiles of ozone, NO2, and aerosols

ATMOSPHERE

2003 (Canada)

SCISAT

Measures profiles of ozone, greenhouse gases and over 40 trace gases and aerosols

ATMOSPHERE

1999 (USA, Canada)

MOPITT on Terra

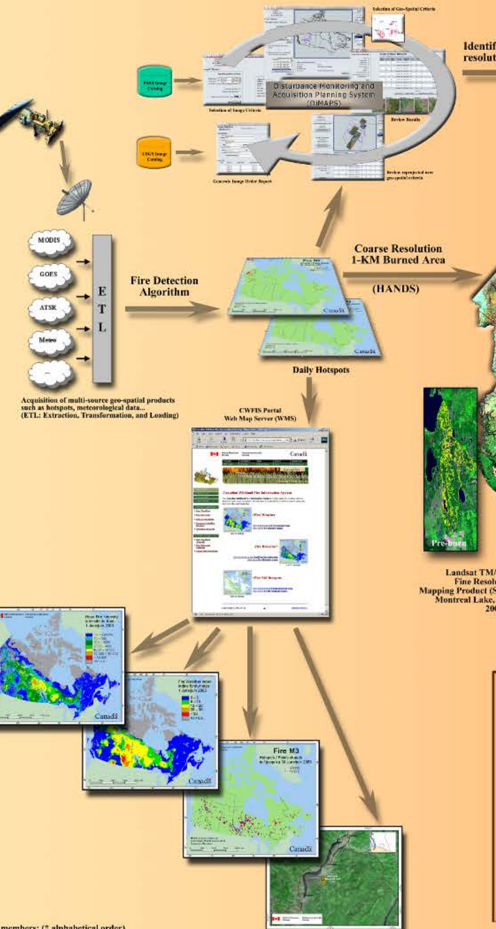
Measures carbon monoxide in the lower atmosphere

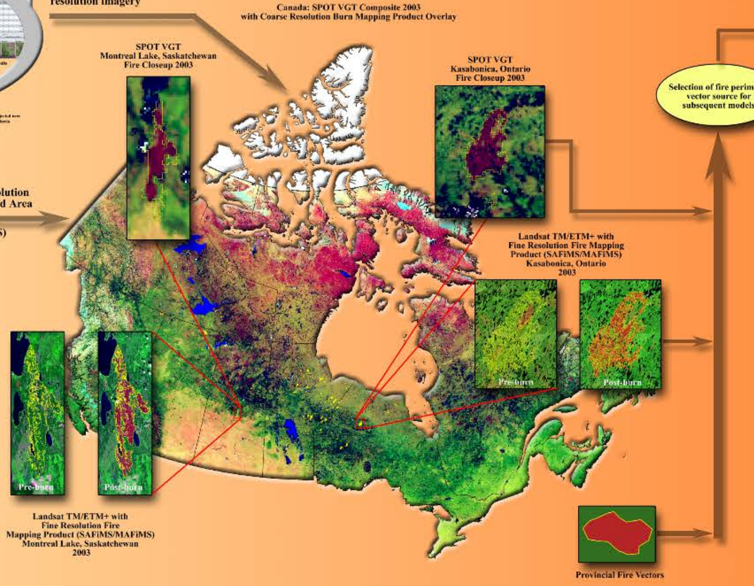
Listed for each sensor: Primary target, launch date, partner countries, name, principal function

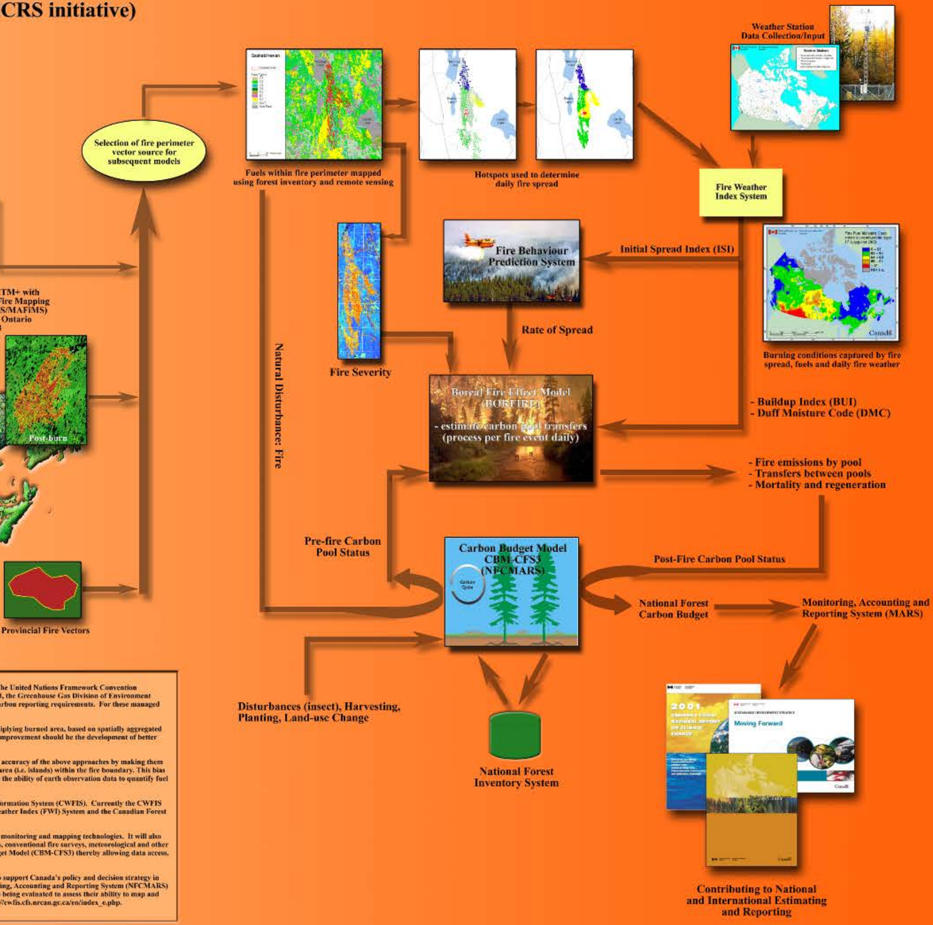
The Canadian Wildland Fire Information System (CWFIS):

The Role of CWFIS within NRCan/CFS National Carbon Accounting and Sustainable Development Framework

(a joint CFS and ESS/CCRS initiative)







Forest fires represent a major source of atmospheric carbon emissions for Canada, equivalent to about 18% of C02 emissions from the energy sector. The United Nations Framework Convention on Climate Change (UNFCCC), ratified by Canada in 1992, requires annual reporting of emissions and removals of greenhouse gases. To meet this need, the Greenhouse Gas Division of Environment Canada annually submits Canada's Greenhouse Gas Inventory (CGHGI) to the UNFCCC Secretariat. The 1997 Kyoto Protocol will further increase carbon reporting requirements. For these managed forests, carbon emissions from biomass burning (including wildfires) will have to be calculated over the first commitment period of 2008-2012.

The method currently used to calculate wildfire emissions for UNFCC reporting does not account for variability in burning conditions. It involves multiplying burned area, based on spatially aggregated statistics, by a constant fuel consumption and emission factor. Regarding this approach, the 2002 CGHGI suggests that, "a priority for methodological improvement should be the development of better tools to estimate the emissions from the wood production forest."

Since 1998, several new technologies were developed under NRCan's Fire Monitoring, Mapping and Modeling (FireM3) System that could improve the accuracy of the above approaches by making them more spatially and temporally explicit. Conventional methods for mapping burned area could be overestimating emissions by not removing unburned area (i.e. islands) within the fire boundary. This bias can be removed by using fine resolution satellite imagery to map a sample of fires in greater detail. Additional field measurements will further improve the ability of earth observation data to quantify fuel consumption.

To respond to the above and other national forest fire reporting issues, an expanded framework is being established for the Canadian Wildland Fire Information System (CWFIS). Currently the CWFIS includes the spatial Fire Management Systems (sFMS) that show explicit fire danger maps consisting of the components of the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System, and FireM3 for fire mapping and monitoring.

With support from the Canadian Space Agency (CSA), the CWFIS will grow to integrate the CFS's fire management systems with the CCRS's satellite monitoring and mapping technologies. It will also provide the framework for an operational fire emissions reporting system. The system will integrate burned area and active fire products from satellites, conventional fire surveys, meteorological and other geo-spatial data, and modeled fire behavior from the FBP System. It will also establish and support data exchange protocols with the CFS Carbon Budget Model (CBM-CFS3) thereby allowing data access, production and distribution of national reporting products related to forest fires on a timely basis.

The CWFIS is expanding to include fire statistics, respond to the development of a reliable and defendable forest fire emissions reporting system, and to support Canada's policy and decision strategy in respect to UNFCCC, C&I and Kyoto reporting obligations. CWFIS reporting capability will meet requirements of the National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS) and Environment Canada's Greenhouse Gas Division through the Monitoring, Accounting, and Reporting System (MARS). These technologies are also being evaluated to assess their ability to map and monitor the threat from wildfire to the safety of Canadians and communities. The results will continue to be presented via the CWFIS web portal http://cwfis.cfs.nrcan.gc.ca/en/index_e.php.

members: (* alphabetical order)

n/ESS-CCRS (SDKI)*: Vincent Decker, Robert Fraser, David Jacques, Robert Landry, Don Raymond, Joost van der Sanden

NRCan/Canadian Forest Service (NOFC)*: Kerry Anderson, Ed Banfield, Richard Carr, Bill deGroot, Peter Englefield, Mike Gartrell, Ron Hall, Kelvin Hirsch, John Little, Vern Peters, Janet Pritchard, Rod Suddaby

NRCan/Canadian Forest Service (GLFC)*: Jin Ji-Zhong, Mike Flannigan, Tim Lynham

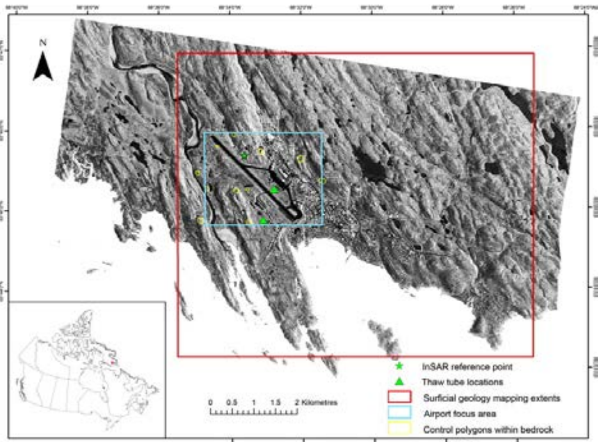
NRCan/Canadian Forest Service (PFC)*: Werner Kurz

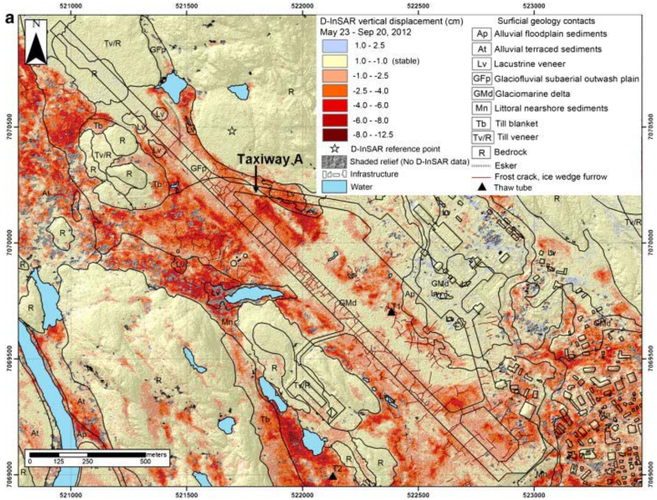
Natural Resources Canada
Ressources naturelles Canada
Canada

Monitoring Permafrost with Radarsat-2

- Because climate change affects the Arctic at twice the rate of other areas, the seasonal freeze and thaw of the region's permafrost layer has altered over the last decade;

- Radarsat-2 D-InSAR stack data used to derive seasonal ground displacement information for permafrost regions, reflect thaw settlement properties of surficial geology, validated with ground-based measurements, resulting in sub-cm agreement in dry areas;





Canada's SCISAT satellite

OBJECTIVE : *MONITOR EARTH'S ATMOSPHERE*

Improve our understanding of the chemical and dynamical processes that control the distribution of ozone in the stratosphere and upper troposphere.

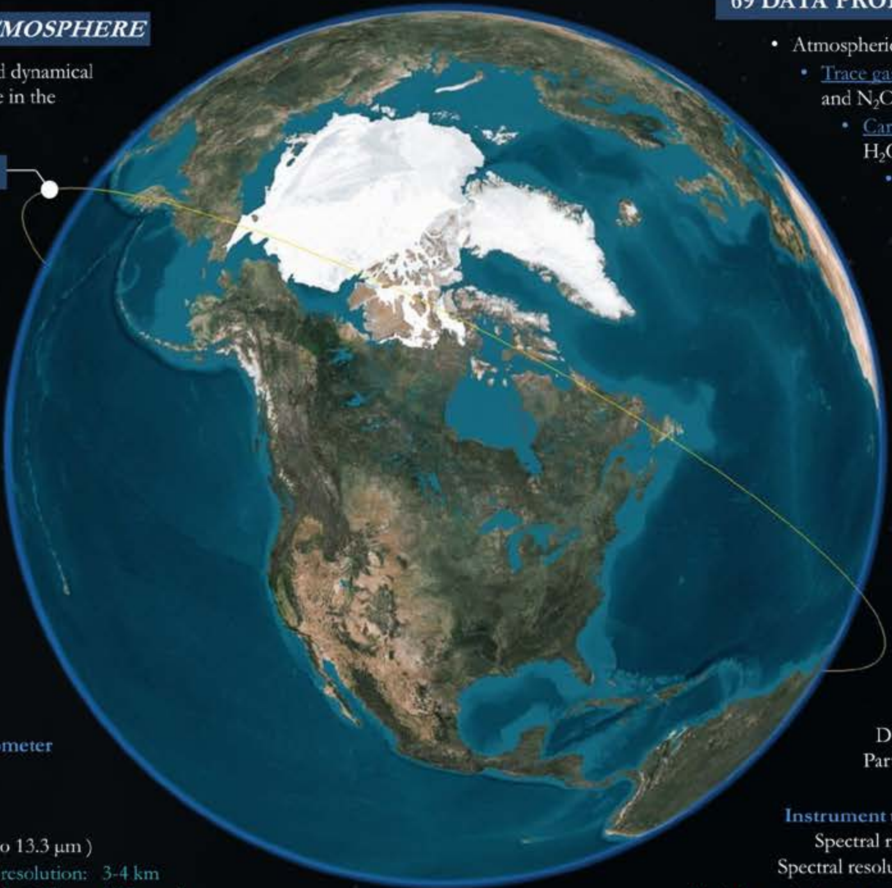
SATELLITE: *650 KM ALTITUDE*

Operator: Canadian Space Agency
Contractor: Bristol Aerospace (Magellan)
Launch: August 12th, 2003
Location: Vandenberg AFB, California
Altitude: 650km
Inclination: 73.9°
Orbit: Nearly circular, precessing
Size: 1.12m diameter
1.04m high
Mass: 152 kg
Power: 175 W (at its peak)
Data volume : 2Gb/day

INSTRUMENT: *FTS*

Contractor: ABB-Bomem
Mass: 41 kg
Power: 37W
Data Rate: 30 occultations/day
Altitude range: 5-150 km
Downlink/uplink data rates: 4,2,1,0.5 and 0.04 Mbs/4kbs

Instrument type: Michelson interferometer
Spectral resolution: 0.025 cm^{-1}
Spectral stability: 3x10 mrs
Signal-to-noise ratio: 1000:1
Spectral range: 750 - 4400 cm^{-1} (2.2 to 13.3 μm)
Vertical resolution: 3-4 km
Field of View: 1.25 mrad



69 DATA PRODUCTS

- Atmospheric temperature and pressure
  - Trace gases: O_3, H_2O, N_2O, NO, NO_2, H_2O_2, HNO_3, N_2, HO_2NO_2 and N_2O_5.
    - Carbon-containing gases: CH_4, CO_2, CO, CH_3OH, HCOOH, H_2CO, OCS, HCN, C_2H_2, C_2H_4 and C_2H_6.
      - Halogen-containing gases: HCl, HF, SF_6, CF_4, CCl_4, COF_2, CH_3Cl, $COCl_2$, COClF, $ClONO_2$, CCl_2F_2 (CFC-12), CCl_3F (CFC-11), $CHClF_2$ (HCFC-22), $C_2Cl_3F_3$ (CFC-113), $C_2H_3Cl_2F$ (HCFC-141b) and $C_2Cl_2F_2$ (HCFC-142b).
        - Isotopologues: HDO, $H_2{}^{18}O$, $O^{13}CS$, $O^{17}OO$, $^{18}OO_2$, $O^{18}OO$, $O^{12}C^{17}O$, $OC^{17}O$, $O^{13}CO$, $H_2{}^{17}O$, ^{15}NNO, $O^{13}C^{18}O$, $OC^{18}O$, $^{13}CH_4$, $OC^{34}S$, $OC^{33}S$, $C^{18}O$, $C^{17}O$, $HD^{18}O$, ^{13}CO, $N_2{}^{17}O$, $N^{15}NO$, CH_3D and $N_2{}^{18}O$.
          - Reasearch Species: ClO, SO_2, $CH_3COO_2NO_2$ (PAN), CHF_3 (HFC-23), C_3H_6O (acetone) and CH_3CN (acetonitrile).

OPERATIONS: *14+ YRS*

Spacecraft: Canadian Space Agency (CSA)
Instruments: UofW and UofT
Data production: UofW and UofT

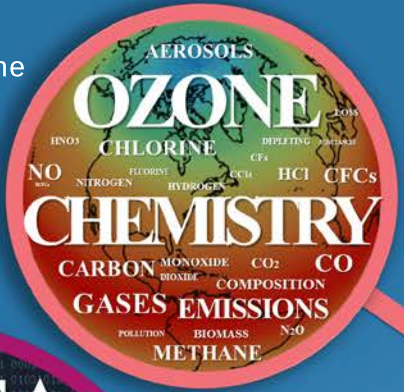
INSTRUMENT: *MAESTRO*

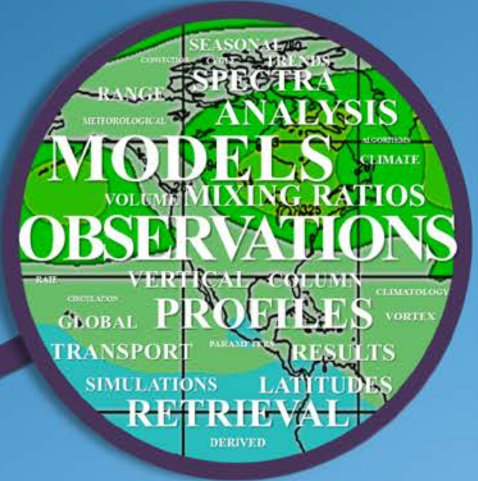
Mass: 8 kg
Power: 15W
Data Rate: 30 occultations/day
Partnership: Environment and Climate Change Canada, the University of Toronto and EMS Technologies

Instrument type: Dual spectrophotometer
Spectral range: 0.285-0.550μm and 0.525-1.02 μm.
Spectral resolution: 1-2nm
Vertical resolution: 1 km

AREAS of STUDY USING SCISAT DATA

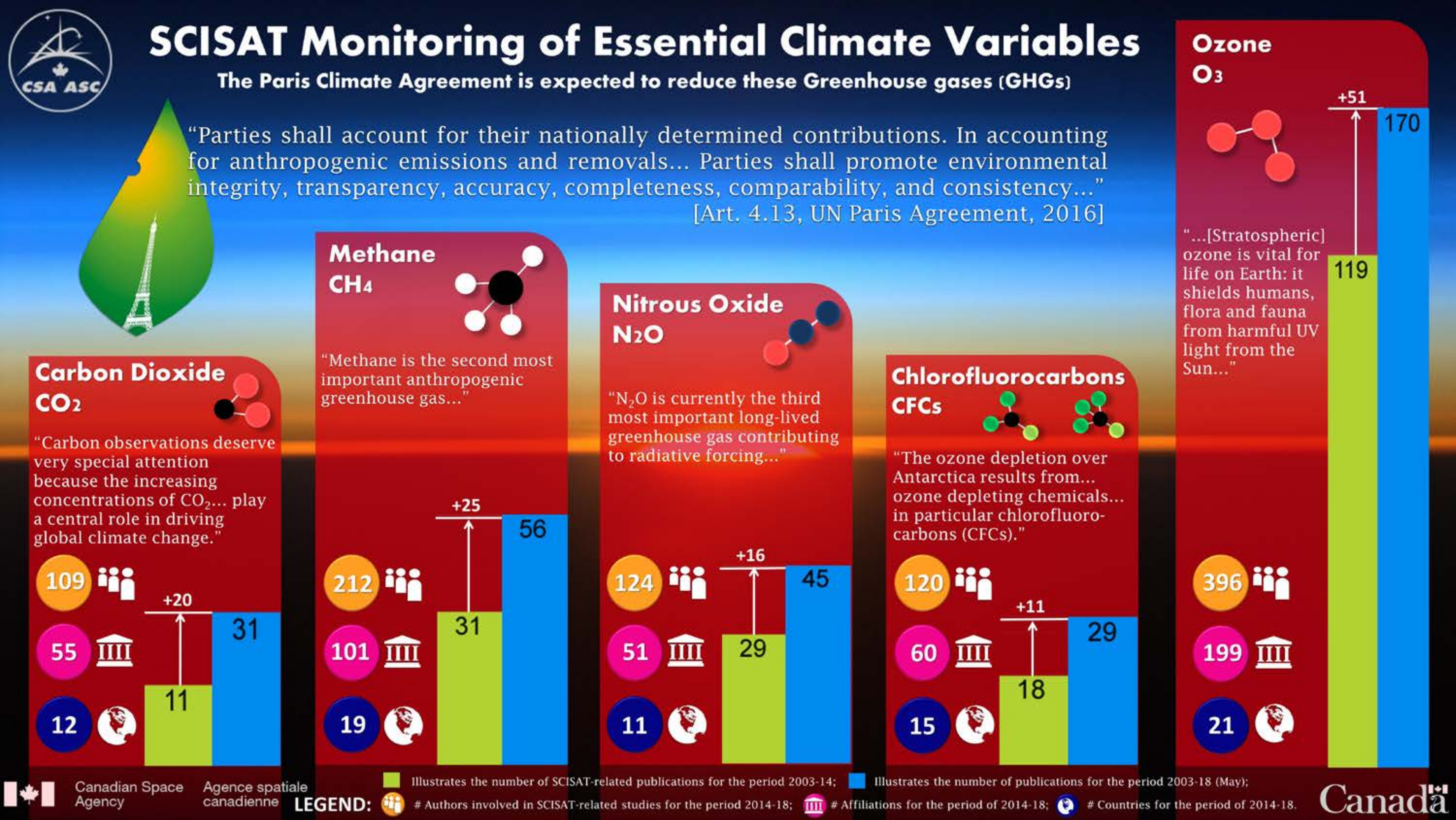
Original objective:
Monitor ozone and ozone depleting substances (UN Montreal Protocol)
Now: only satellite measuring many critical gases





Strategic objective:
ECV-quality datasets to be used by decision-makers.
Now: Contribute to UN Montreal Protocol reporting; begin reporting on Paris Climate Agreement and Kigali Amendment to UN Montreal Protocol.

Strategic objective:
Produce ECV-quality data products.
Now: ECCC and UN reports acknowledge SCISAT's unique measurements.


CSA ASC
SCISAT Monitoring of Essential Climate Variables
The Paris Climate Agreement is expected to reduce these Greenhouse gases (GHGs)
"Parties shall account for their nationally determined contributions. In accounting for anthropogenic emissions and removals… Parties shall promote environmental integrity, transparency, accuracy, completeness, comparability, and consistency…"
[Art. 4.13, UN Paris Agreement, 2016]
Carbon Dioxide
CO_2
"Carbon observations deserve very special attention because the increasing concentrations of CO_2… play a central role in driving global climate change."
109
55
12
+20
11
31
Methane
CH_4
"Methane is the second most important anthropogenic greenhouse gas…"
212
101
19
+25
31
56
Nitrous Oxide
N_2O
"N_2O is currently the third most important long-lived greenhouse gas contributing to radiative forcing…"
124
51
11
+16
29
45
Chlorofluorocarbons
CFCs
"The ozone depletion over Antarctica results from… ozone depleting chemicals… in particular chlorofluoro-carbons (CFCs)."
120
60
15
+11
18
29
Ozone
O_3
"…[Stratospheric] ozone is vital for life on Earth: it shields humans, flora and fauna from harmful UV light from the Sun…"
396
199
21
+51
119
170
Canadian Space Agency
Agence spatiale canadienne
LEGEND:
Illustrates the number of SCISAT-related publications for the period 2003-14;
Illustrates the number of publications for the period 2003-18 (May);
Authors involved in SCISAT-related studies for the period 2014-18;
Affiliations for the period of 2014-18;
Countries for the period of 2014-18.
Canada

Interaction with Space Data Teams

- SABER: Consistent results for vertical profile and trends up to ~100km, at 100km – trend is within estimated uncertainties;
- MIPAS: Very good agreement below 100 km with best agreement during solstice (±5%) differences increase with altitude after 100km, agreement is excellent in equinox when CO_2 gradients are generally less pronounced; SCIAMACHY: Showed reasonable agreement

Interaction with Modeling Teams

- WACCM:
  - Data used from 2004-2013;
  - Generally reasonable agreement found with few differences;
  - ACE-FTS generally showing higher trend (8-9%) and faster rate of increase above 80km.

CO_2

Interaction with In-Situ: Aircraft

- HIPPO – HIAPER Pole-to-Pole Observations
- CONTRAIL – Comprehensive Observation Network for Trace gases by Airline
- CARIBIC - Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container

- In-situ observations give a latitude gradient between 45 and 65 degrees at 10km in boreal spring of 6ppm, while ACE-FTS shows gradients of 5, 6, 4, and 1ppm at 9.5, 10.5, 11.5, and 12.5km respectively, showing agreement

109

55

12

Future Work and Lessons Learned

- Validation and trends of the new 14+ year ACE-FTS v4.0 CO_2 profile data product;
- More detailed trend analysis of MIPAS CO_2 data, retrieve CO_2 vmr, application of alternative retrieval algorithms for CO_2;
- Further analysis of WACCM model to produce CO_x/CO_2 trends on par with ACE-FTS and SABER in the lower thermosphere;
- Need more and longer data sets;
- Increase temporal and spatial coverage of ACE-FTS instrument.

Authors involved in SCISAT-related studies for the period 2014-18; # Affiliations for the period of 2014-18; # Countries for the period of 2014-18.

Interaction with Space Data Teams

- TANSO-FTS – Overall good agreement; below 15km: 4%, above 15km ~0%;
- MIPAS – Overall good agreement; 17km: 15%, 20–65 km: 12%, 38 km: 12%, above 50 km: 3%; higher CH_4 mixing than ACE-FTS;
- HALOE – Below 40km – 5% lower, 40-65km – 10-15% lower;
- SCIAMACHY ONDP – Good agreement above 20km, weaker agreement below 20km;
- AIM SOFIE – Qualitative good agreement found when combining all seasons, Summer: close agreement within ~5% for ~40-65km in NH and SH, Fall: difference of ~5% at ~30-50km with ~±20% difference above and below that range.

CSA ASC

Interaction with Modeling Teams

- WACCM – Good agreement up to ~20km, weaker agreement above 20km;
- BASCOE – Good agreement within ~10%, weaker agreement in tropical lower stratosphere;
- TM5/LMDz – Average XCH_4 bias reduced from 38.1 to 13.7 ppb, from 8.7 to 4.3 ppb for TM5 and 6.8 to 4.3 ppb for LMDz;
- CMAM30 – Good agreement for NH polar winter or spring;
- ENS (Experiment) – Good agreement with differences mostly below 10%.

CH_4

Interaction with In-Situ: Ground-Based

- NDACC FTIR – Statistically good agreement: differences not significant for N high latitudes, N mid-latitudes, tropical regions, S mid-latitudes, and S high latitudes;
- PARIS-IR – CH4 columns good agreement: 3% difference, partial column agreement within estimated uncertainty;
- Bruker 125HR FTS – High correlation even with ~20% differences, partial column agreement within: ±8.0%.

212

101

19

Future Work and Lessons Learned

- Resolve differences between land and ocean regions;
- Reduce differences between satellite-borne XCH_4 data and models.
- Increase number of aircraft profiles;
- Develop greater sensitivity/altitude range, and reduced biases;
- Validation of MIPAS data in the tropics;
- Resolve unexpected vertical oscillation of CH_4 profiles;

Authors involved in SCISAT-related studies for the period 2014-18; # Affiliations for the period of 2014-18; # Countries for the period of 2014-18.

SCISAT Monitoring of Hydrofluorocarbons (HFCs)

The Montreal Protocol

"The phase-down of HFCs under the Montreal Protocol has been under negotiation by the Parties since 2009 and the successful agreement on the Kigali Amendment continues the historic legacy of the Montreal Protocol."

[UN Fact Sheet on the Kigali Amendment, 2016]

The Kigali Amendment

"Each Party shall ensure that... its calculated level of consumption of the controlled substances in Annex F [HFCs]... does not exceed the percentage, set out for the respective range of years specified..."

[Art. I-2J, Kigali Amendment, 2016]

Usage of HFCs

"HFCs are currently used in refrigeration and air-conditioning, aerosols, fire protection equipment and the manufacture of insulation foam..."

[UN Briefing Note on The Kigali Amendment, 2017]

Impact of HFCs

"While not ozone depleting substances themselves, HFCs are greenhouse gases which can have high or very high global warming potentials (GWPs), ranging from about 121 to 14,800 [CFC-23]."

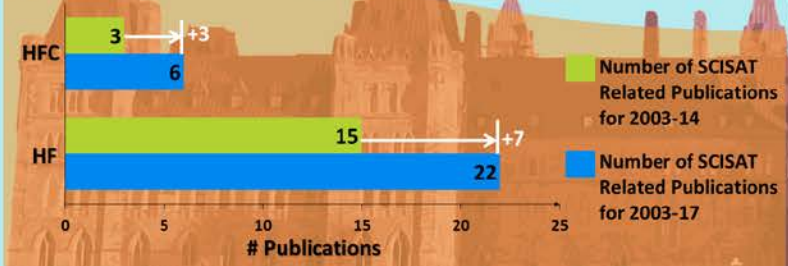
[UN Fact Sheet on the Kigali Amendment, 2016]

Family of Controlled HFCs

HFC-134, HFC-134a, HFC-143, HFC-245fa, HFC-365mfc, HFC-227ea, HFC-236cb, HFC-236ea, HFC-236fa, HFC-245ca, HFC-43-10mee, HFC-32, HFC-125, HFC-143a, HFC-41, HFC-152, HFC-152a, HFC-23.

[Art. I-Annex F, Kigali Amendment, 2016]

Current HFCs measureable by SCISAT



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15

10

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LEGEND: # Authors involved in SCISAT-related studies for the period 2014-17; # Affiliations for the period of 2014-17; # Countries for the period of 2014-17

Canada

Data Analysis Advancement in Earth System Sciences

CSA ASC

Project Status

Project	Status
OTSA	Project on track
EMIS	Project on track
AMIR	Project on track
CMEV	Project with six month delay
URDC	Project on track
LSSP	Project on track
MODE	Project with six month delay
MPTN	Project on track
SNOW	Project on track
COBF	Project with six month delay
ACIA	Project with six month delay
OMTR	Project on track

- Project on track
- Project with six month delay

Legend

- Number of projects using the satellite data
- Number of projects advancing the numerical model
- Number of manuscripts published or under development
- Number of ECCC researchers using the satellite data
- Number of academic researchers using the satellite data

Government of Canada Priorities

CSA
"Canada's exploration of space and provision of space services ... meet the nation's needs for scientific knowledge, innovation and information."

Laws and Agreements
- UN Montreal Protocol (Ozone)
- Canadian Environmental Protection Act
- Paris Climate Agreement (GHGs)
- Kigali Amendment (HFCs)
- CAN-US Air Quality Agreement

ECCC
- "Manage substances ... that directly or indirectly harms human health or the environment."
- "Provide Canadians with high-quality information on immediate and long-term environmental conditions."

National and International Science Policy Reporting

CEOS · UN/WMO CMIP6 · UN/WMO Ozone · GAW · ECCC's AQHI · IPCC

Projects contribute results to the UN Ozone Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) and the Coupled Model Intercomparison Project (CMIP).

Earth and Climate Model Advancement

GEOS-Chem 3 · CanAM5 1 · GEM-MACH 1 · CanESM5 2 · CMAM 1

Projects advance Canadian numerical models such as the Canadian Middle Atmosphere Model (CMAM), Canadian Earth System Model (CanESM5) and Canadian Atmospheric General Circulation Model (CanAM5).

Analysis of Space-based Datasets 6

Aircraft
- IceBridge

Ground-based
- TCCON (NDACC)
- PEARL

CPR on CloudSat 4 · SCISAT 8 · MOPITT on Terra 4 · OSIRIS on Odin 5 · TropOMI on Sentinel 5P 4 · ALADIN on ADM-Aeolus 3 · SLSRC on Sentinel 3 7

CANADIAN HIGH ARCTIC SATELLITE VALIDATION CAMPAIGN

OBJECTIVE: *Validate atmospheric climate data from Canadian instruments onboard two satellites.*

LOCATION: *Polar Environment Atmospheric Research Laboratory (PEARL), Eureka, NU.*

DATES: *23 February to 3 April, 2017*

INSTRUMENTS: 11 — *11 ground-based instruments are used in the campaign.*

SATELITE DATA: 100 — *Approximately 100 Canadian satellite measurements are analyzed per campaign.*

BALLOONS: 107 — *Over 100 balloon launches are conducted during a campaign.*

INSTITUTIONS: 7 — *Six Canadian research institutions are involved, along with one from France.*

RESEARCHERS: 9 — *Seven researchers from across Canada participate in the campaign, with two from France.*

TRAINING: 12 — *12 masters and doctorate students and post-doctoral fellows participate in the campaign.*

DATA SUPPORT: 5 — *Five organizations or data networks provide supporting data for the campaign.*

PUBLICATIONS: 26 — *A total of 26 peer-reviewed publications have resulted from the campaign to date.*

COMMUNICATION: 40 — *About 40 conference and workshop presentations are made per year by participants.*

SATELLITES INVOLVED

Fourier Transform Spectrometer (ACE-FTS) Instrument on SCISAT

13 gases from the ACE-FTS instrument are studied during the campaign.

O_3, CH_4, H_2O, NO, HCl, $ClNO_3$, CO, NO_2, HNO_3, CCl_2F, N_2O, HF, CCl_3F

These are gases measured by **no other** space-based instrument worldwide.

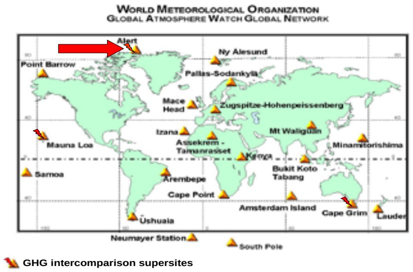
Optical Spectrograph and InfraRed Imager System (OSIRIS) on Odin

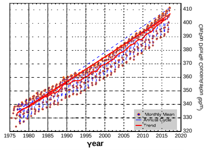
4 gases and aerosols from the OSIRIS instrument are studied.

O_3, NO_2, BrO, Aerosols

ECCC's Climate Research Activities Related to GHGs

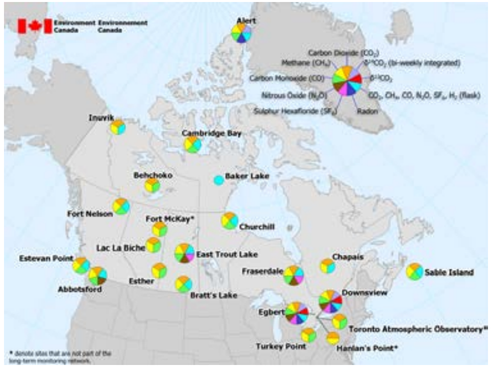
Operation of the Dr. Neil Trivett Global Atmosphere Watch (GAW) Observatory at Alert, NU





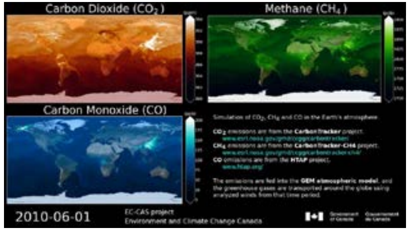
Alert is one of three global GHG inter-comparison sites, alongside Mauna Loa (U.S.) and Cape Grimm (Australia). Its data record is one of the longest in the world.

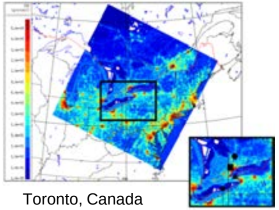
Operation of the long-term atmospheric measurement program for greenhouse gases



Research on integration of surface and space-based observations to estimate GHG sources and sinks using data assimilation techniques at national, sub-national, and urban scale

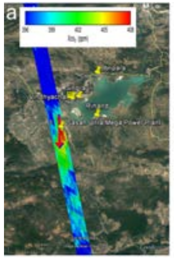
Environment and Climate Change Canada's Carbon Assimilation System:

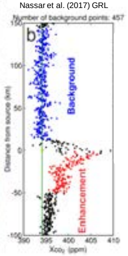


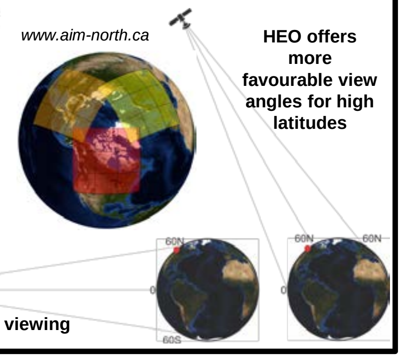


Toronto, Canada

Research on development and evaluation of technology for improving space-based observations of GHGs

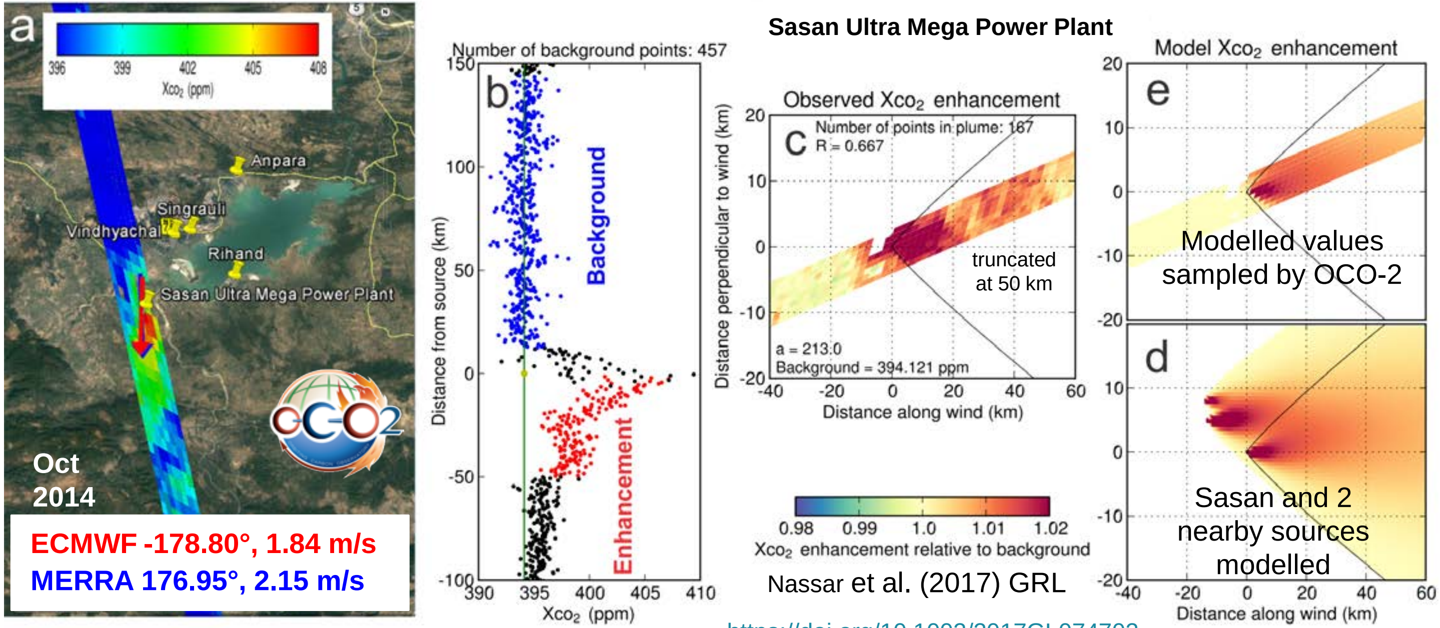






Quantifying CO_2 Emissions from Power Plants with OCO-2

- Collaborative work between Environment and Climate Change Canada (ECCC) and NASA
- Where direct overpasses or close flybys of mid- to large-sized coal power plants occur, XCO_2 enhancements observed with OCO-2's limited imaging capability are fit to a Gaussian plume model that was run with a priori emissions, yielding an a posteriori emission estimate.

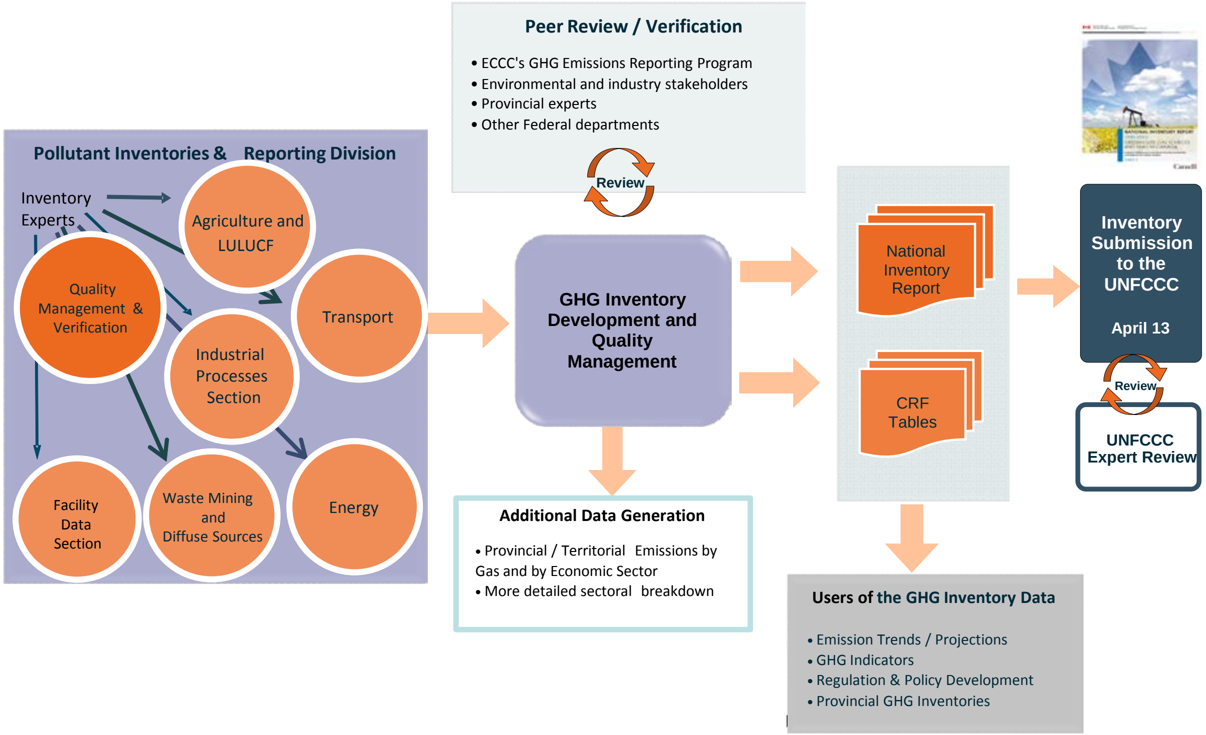


Nassar et al. (2017) GRL

https://doi.org/10.1002/2017GL074702

- Total uncertainty on the daily emission estimate is determined from uncertainties in wind speed, the background definition, biases in the data and any secondary sources in the area.
- Demonstrated on US power plants with emissions from EPA, then applied to India & S. Africa
- Sasan reported annual value equivalent to **60.2 kt/day** and we estimate **67.9±10.0 ktCO_2/day**

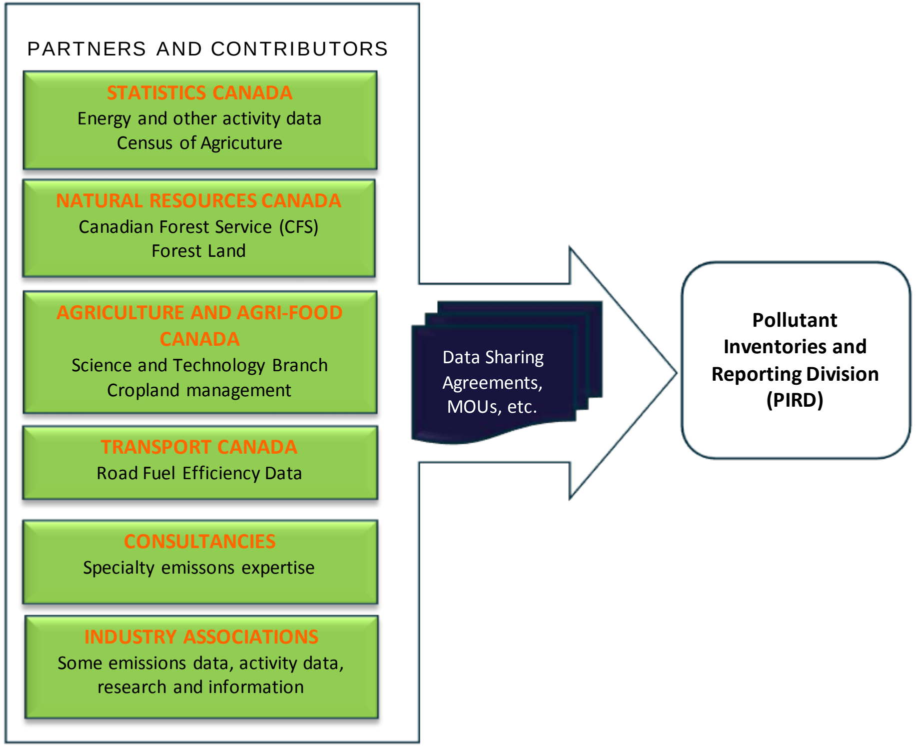
ECCC develops, compiles and publishes the NIR annually



Inventory Scope and Features

- Time series coverage (2017 NIR): 1990-2015
- Inventory estimates emissions of 7 GHGs:
  - Carbon dioxide (CO_2)
  - Methane (CH_4)
  - Nitrous Oxide (N_2O)
  - Sulfur hexafluoride (SF_6)
  - Perfluorocarbons (PFCs)
  - Hydrofluorocarbons (HFCs)
  - Nitrogen Trifluoride (NF_3)
- Presented by individual gas and combined as CO_2eq

The NIR is supported by an extensive national network

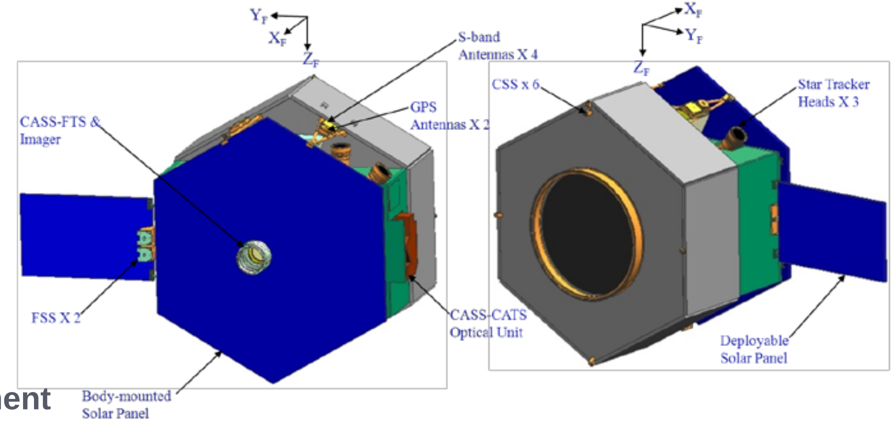


Using the following Scientific Basis:

- National GHG Inventories must follow the rigorous methodological framework by the IPCC
  - Transparency, Completeness, Consistency, Comparability and Accuracy
- Flexibility to refine methods and data to better reflect national circumstances
- Methods are based on activity (e.g. quantities of fuel consumed, livestock populations, deforested area, quantities and composition of waste landfilled etc.) and processes (fuel oxidation, organic matter decay); mass balance must be preserved.
- Refined methods allow to incorporate specific fuel properties, impact of technologies, practices, regional ecosystem or climate parameters.

Chemical and Aerosol Sounding Satellite
(CASS)

Science mission using small satellite platform in LEO
- Combining IR occultation and limb scattering techniques;
- Inclined circular orbit – non-sun synchronous
  - ~650 km altitude, ~65 degree inclination
  - Minimum 3 year lifetime considered, 10yr goal with nothing limiting operations (e.g., no consumables)



Rationale for IR Fourier Transform Spectrometer (FTS) Instrument

High spectral resolution (same as ACE-FTS: 0.02 cm^{-1})
- Range of species while making no assumptions about which are present; monitoring of composition changes and detect new compounds.

Mid-infrared fingerprint region (nominally: 750-4400 cm^{-1})
- High density of information in IR region on atmospheric composition; >30 different species can be retrieved.

High vertical resolution (target 1.5km) while maintaining high signal-to-noise ratio in spectral measurements
- High sensitivity is needed to detect low abundance species.

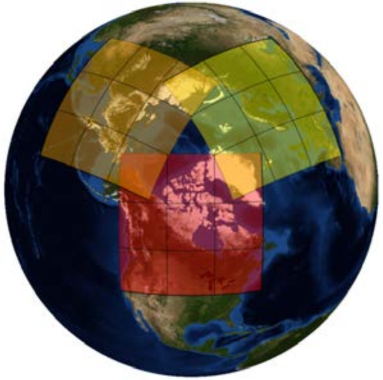
www.aim-north.ca

AIM-North

The Atmospheric Imaging Mission for Northern Regions

Geostationary satellites cover low to mid-latitudes, but have significantly reduced performance above mid-latitudes and none at high latitudes. Selecting a Highly Elliptical Orbit (HEO) with an apogee over the Polar regions enables quasi-geostationary observations of high latitudes with similar advantages as viewing the Earth from geostationary orbit. At the time of writing, no HEO mission has been selected, but Canada has been investigating mission concepts for HEO for many years (Nassar et al., 2014).
In the longer term, an optimized constellation could be envisaged that includes a combination of observations from satellites in LEO, GEO and HEO orbits, using a variety of different contribution mechanisms, e.g., dedicated space segments, contributing missions, third party data provider agreements and more. The architecture of the monitoring and verification support capacity should include the flexibility to exploit this range of potential sources of satellite observations.

[Pinty et al., 2017]



Potential viewing from AIM-North

- AIM-North entered Phase 0 in June 2018 with a baseline plan of 2 satellites in HEO for continuous viewing of northern regions (~40-80°N)
- High spectral resolution near / shortwave infrared (NIR-SWIR) Imaging Fourier Transform Spectrometer (IFTS) for CO_2, CH_4, CO and vegetation fluorescence
- Ultraviolet Visible Spectrometer (UVS) for O_3, NO_2, BrO, SO_2, HCHO, aerosols, … for air quality studies but could also assist in anthropogenic CO_2 emission estimates
- Both instruments could give 3x3 km^2 resolution *images* of atmospheric composition over land every ~90 min daylight, beginning in late 2020s

Environment and Climate Change Canada / Environnement et Changement climatique Canada

CSA ASC

Canada

CSA ASC

asc-csa.gc.ca

Canada

Interaction with Space Data Teams

- Aura-MLS – Good temporal agreement (2004-2010), agreement within -20 to +10% up to 35km, AM vs PM data above 35 km has agreement (~10%);
- MIPAS – agreement within -9 to +7% up to 35 km, good agreement above 30km, combined error lower than expected deviation.

Interaction with Modeling Teams

- BASCOE (Belgian Assimilation System for Chemical ObsErvations) – Showed good agreement;
- ENS (Experiment) – Showed good agreement with differences usually below ±10%.

N_2O

Interaction: Aircraft and Ground-Based

Aircraft:

- HALO – Uncertainty is 15% (5–30 km)

Ground-Based:

- PARIS-IR – High correlation but uncertainty of ±3.5%;
- Bruker 125HR FTS – Good agreement, difference is roughly half of estimated uncertainty of ±3.7%.

Future Work and Lessons Learned

- Study N_2O, NO_y , and O_3 variations in more sophisticated 3D models;
- Validation of MIPAS in tropics;
- More detailed work to determine if global adjustments can be made to UARS MLS HNO_3 data.

124 51 11

Authors involved in SCISAT-related studies for the period 2014-18; # Affiliations for the period of 2014-18; # Countries for the period of 2014-18.

Interaction with Space Data Teams

- MIPAS – 18-28km: Good agreement (deviations of ~10 pptv or 3-10%), above 28km: Weaker agreement (~50 pptv or 25%), Tropics above 20km: differences up to 50%.

Interaction with Modeling Teams

- EMAC – Consistent lifetime estimates in good agreement;
- CLaMS – Consistent lifetime estimates in good agreement.

CFC

Interaction with In-Situ: Balloon-Based

- **MkIV** – 68ºN CFC-11 above ~16km: deviations of 40%, 68ºN CFC-12 above ~16km: best agreement of 5-10%.
- **FIRS-2** - CFC-11: above 12km difference of 10% and 20% below 12km; CFC-12: 12-28km difference of 10%

Future Work and Lessons Learned

- Produce temporally stable CFC-12 data sets;
- New IR limb or occultation satellite measurements with high vertical resolution would help further improve CFC lifetime recommendations and their error estimates.

120 | 60 | 15

Authors involved in SCISAT-related studies for the period 2014-18; # Affiliations for the period of 2014-18; # Countries for the period of 2014-18.

Recent Discoveries with SCISAT

Oct. 2014

Water Vapour Increase and Decrease

Trends in the vertical structure of stratospheric water vapour, a powerful greenhouse gas (GHG), have been derived from a new approach to merge satellite data, including measurements from SCISAT. It was discovered that water vapour records have a long-term decrease in the lower and mid-stratosphere, whereas a long-term increase is found in the upper stratosphere. The results "highlight the need for independent and redundant global measurement systems characterized by high long-term accuracy (and precision) ..." See *Hegglin et al., Nature Geoscience v7, 768, 2014*

Nov. 2014

Slowdown in Atmospheric Circulation

SCISAT data shows an increase in chlorine gas (HCl) in the lower stratosphere of the northern hemisphere. This trend discovered a slowdown in the atmospheric circulation in the northern hemisphere. See *Mahieu et al., Nature, v515, p104, 2014*

July 2015

Growth in Short-Lived Chemicals

SCISAT measurements were used to discover a growth in stratospheric chlorine from short-lived chemicals not controlled by the UN Montreal Protocol. These substances enhance ozone (O_3) loss rates in the lower stratosphere, where O_3 concentrations have a relatively large impact on climate. See *Hossaini et al., GRL 42, 4573, 2015*

Sep. 2015

Increase in Carbon Dioxide

Using SCISAT data, carbon dioxide (CO_2) was discovered to increase by ~5% per decade at ~80km above the earth's surface and below. The trend of this main driver of climate change is larger in the Northern Hemisphere above 80km. This suggests that the rate of increase is considerably larger than previously explained. See *Yue et al., GRL 42, 7149, 2015*

March 2016

Continuous Productions of Greenhouse Gas

Measurements of nitrous oxide, an important greenhouse gas caused by humans and potentially the most important ozone-depleting substance currently being emitted into the atmosphere, were made by SCISAT to discover that the gas is continuously produced in the lower thermosphere and enhanced at all latitudes, during all seasons. See *Sheese et al., GRL 43, 067353, 2016*

May 2017

Regulating Earth's Temperature

SCISAT measurements of sulfur dioxide were used to confirm a ~5x reduction in global SO_2 levels across the tropical tropopause from 2004 to 2010. Such gases may maintain stratospheric aerosol levels that are important in regulating the Earth's temperature. See *Rollins et al., GRL 44, 4280, 2017*

June 2017

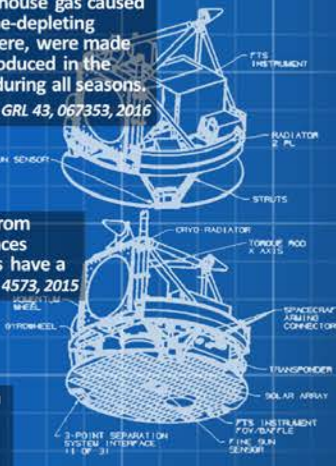
Fires Increase Poisonous Gas Levels

A global increase of poisonous hydrogen cyanide (HCN) was discovered throughout 2016 due to the intense peatland fires in Indonesia brought on by El Niño in 2015. See *Sheese et al., GRL 44, 5791, 2017*

June 2017

Antarctic Ozone Levels

SCISAT data was used to discover the depletion of ozone, and chlorine and nitrogen oxide species, in the lower Antarctic polar vortex. This new knowledge is important to improve chemistry climate models. See *Jurkat et al., GRL 44, 6440, 2017*



Where to Find our GHG Data

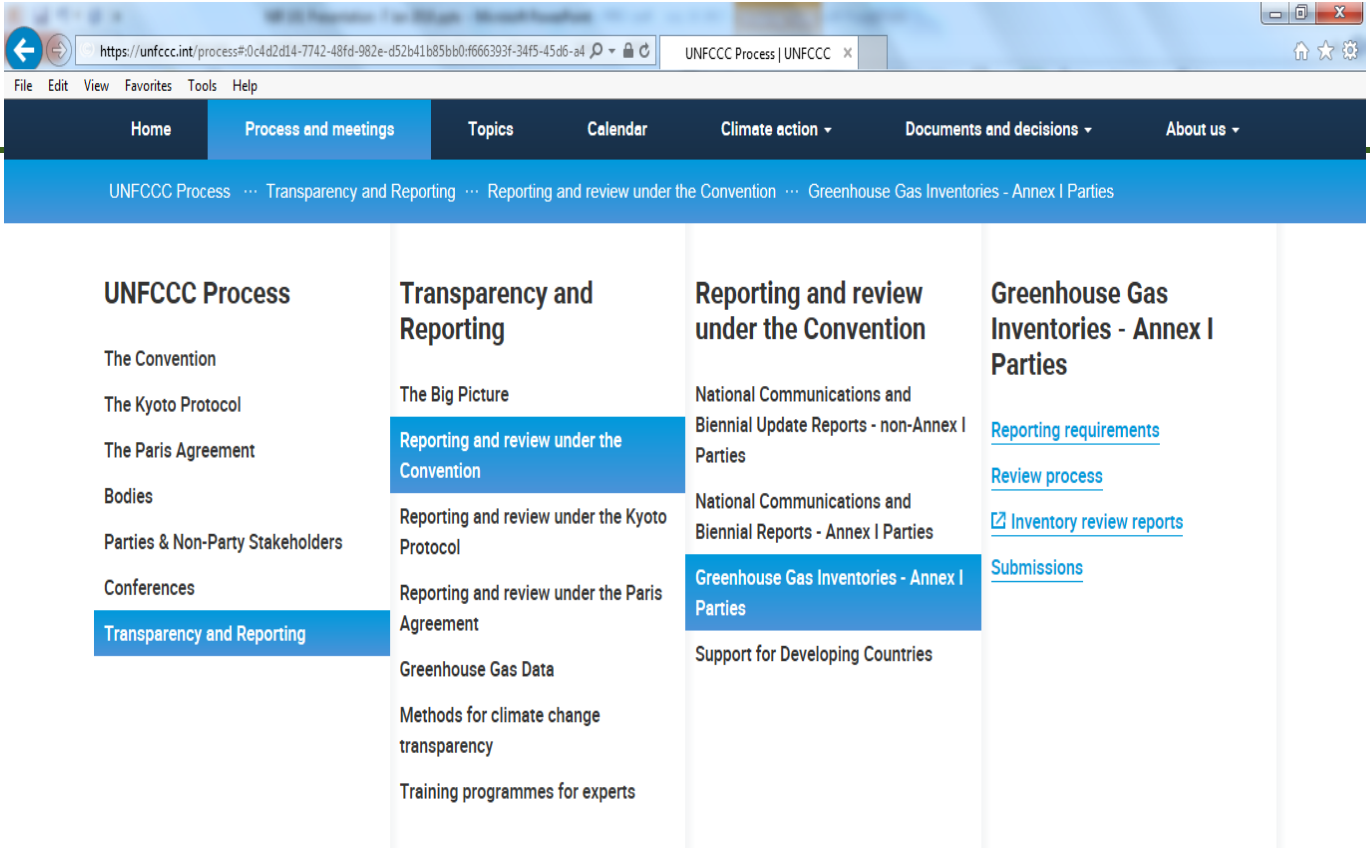
National GHG Inventory data:
http://open.canada.ca/data/en/dataset/6bed41cd-9816-4912-a2b8-b0b224909396

Facility data:
http://open.canada.ca/data/en/dataset/a8ba14b7-7f23-462a-bdbb-83b0ef629823

NIR Executive Summary
http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=83A34A7A-1

Overview Report of Facility data:
http: //www.ec.gc.ca/ges-ghg/default.asp?land=En&n=82BA1E22-1

Full NIR submitted to the UNFCCC:
www.unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/10116.php


https://unfccc.int/process#:0c4d2d14-7742-48fd-982e-d52b41b85bb0:f666393f-34f5-45d6-a4
UNFCCC Process | UNFCCC
File Edit View Favorites Tools Help
Home
Process and meetings
Topics
Calendar
Climate action
Documents and decisions
About us
UNFCCC Process ··· Transparency and Reporting ··· Reporting and review under the Convention ··· Greenhouse Gas Inventories - Annex I Parties
UNFCCC Process
The Convention
The Kyoto Protocol
The Paris Agreement
Bodies
Parties & Non-Party Stakeholders
Conferences
Transparency and Reporting
Transparency and Reporting
The Big Picture
Reporting and review under the Convention
Reporting and review under the Kyoto Protocol
Reporting and review under the Paris Agreement
Greenhouse Gas Data
Methods for climate change transparency
Training programmes for experts
Reporting and review under the Convention
National Communications and Biennial Update Reports - non-Annex I Parties
National Communications and Biennial Reports - Annex I Parties
Greenhouse Gas Inventories - Annex I Parties
Support for Developing Countries
Greenhouse Gas Inventories - Annex I Parties
Reporting requirements
Review process
Inventory review reports
Submissions

SPACE-BASED INSTRUMENTS VALIDATED, COMPARED OR CALIBRATED WITH SCISAT DATA

METEOP-A
Instruments
Infrared Atmospheric Sounding Interferometer (**IASI**)
Global Ozone Monitoring Experiment 2 (**GOME-2**)

TERRA
Instruments
Measurement of Pollution in the Troposphere (**MOPITT**)
Moderate Resolution Imaging Spectroradiometer (**MODIS**)

SPOT-3
Instrument
Polar Ozone and Aerosol Measurement II (**POAM II**)

CALIPSO
Instrument
Cloud-Aerosol Lidar with Orthogonal Polarization (**CALIOP**)

ERS-2
Instrument
Global Ozone Monitoring Experiment (**GOME**)

TSX

NIMBUS-7
Instrument
Limb Infrared Monitor (**LIMS**)

ERBS
Instrument
Stratospheric Aerosol and Gas Experiment II (**SAGE II**)

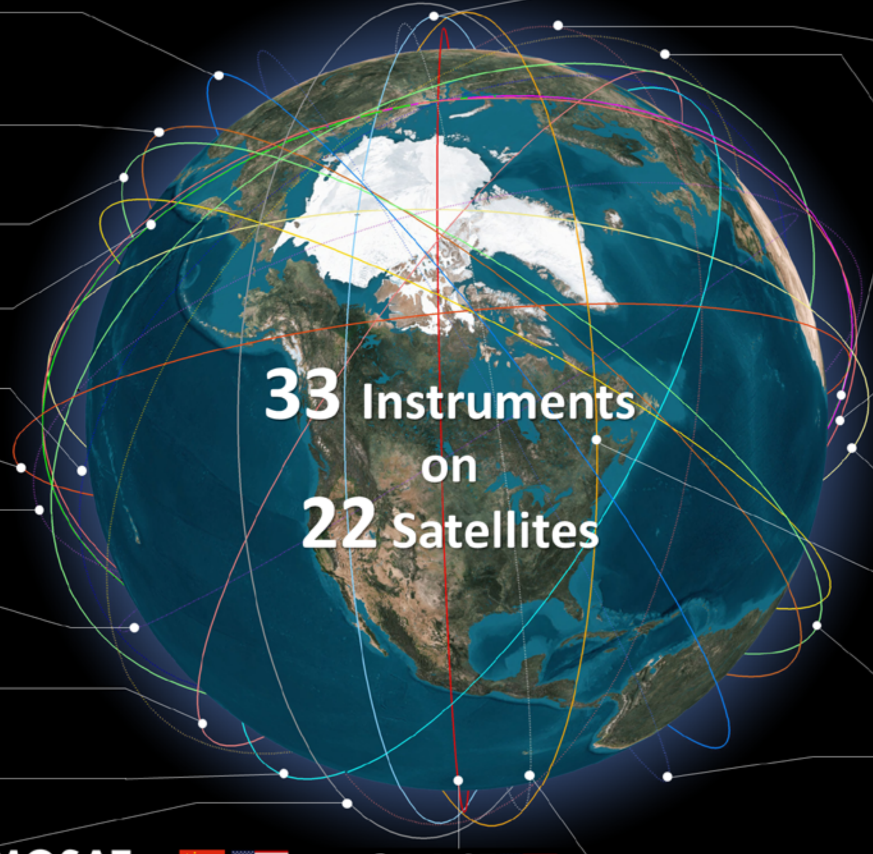
AIM
Instrument
Solar Occultation for Ice Experiment (**SOPHIE**)

ISS
Instruments
Stratospheric Aerosol and Gas Experiment III (**SAGE III**)
Superconducting Submillimeter-Wave Limb Emission Sounder (**SMILES**)

COSMIC (FORMOSAT-3)

GRACE

CHAMP



Odin
Instruments
Optical Spectrograph and InfraRed Imager System (**OSIRIS**)
Sub-millimeter Radiometer (**SMR**)

UARS
Instruments
Halogen Occultation Experiment (**HALOE**)
High Resolution Doppler Imager (**HRDI**)
Microwave Limb Sounder (**MLS**)

ADEOS-II
Instrument
Improved Limb Atmospheric Spectrometer-II (**ILAS-II**)

AURA
Instruments
High Resolution Dynamics Limb Sounder (**HIRDLS**)
Microwave Limb Sounder (**MLS**)
Ozone Monitoring Instrument (**OMI**)
Tropospheric Emission Spectrometer (**TES**)

AQUA
Instrument
Atmospheric Infrared Sounder (**AIRS**)

GOSAT
Instrument
Thermal And Near-infrared Sensor for carbon Observation Fourier Transform Spectrometer (**TANSO-FTS**)

TIMED
Instrument
Sounding of the Atmosphere using Broadband Emission Radiometry (**SABER**)

SPOT-4
Instrument
Polar Ozone and Aerosol Measurement III (**POAM III**)

ENVISAT
Instruments
Global Ozone Monitoring by Occultation of Stars (**GOMOS**)
Michelson Interferometer for Passive Atmospheric Sounding (**MIPAS**)
SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (**SCIAMACHY**)

CSA ASC

International Importance of Measurements by SCISAT

Ozone — O_3

"...[Stratospheric] ozone is vital for life on Earth: it shields humans, flora and fauna from harmful UV light from the Sun ... As a result of phasing-out harmful CFCs*, the ozone layer is now recovering and continuing observations are needed to monitor this recovery."

- CEOS-CGMS* Response to GCOS* 2010 Implementation Plan, 2015*

Nitrogen Oxides — NOx

"NOx is a dominant factor in the photochemical catalytic production of O_3 ... and thus it plays a critical role in determining the oxidizing efficiency of the troposphere."

- IGACO Theme Report, 2014*

Nitrous Oxide — N_2O

"N_2O is currently the third most important long-lived greenhouse gas contributing to radiative forcing (after CO_2 and methane)."

- UN WMO* Ozone Assessment Report, 2014*

Water — H_2O

"Water vapour is the most abundant and important greenhouse gas in the atmosphere ... Human activities also influence water vapour through CH_4 emissions ..."

- IPCC 5th Assessment Report, 2013*

Carbon Monoxide — CO

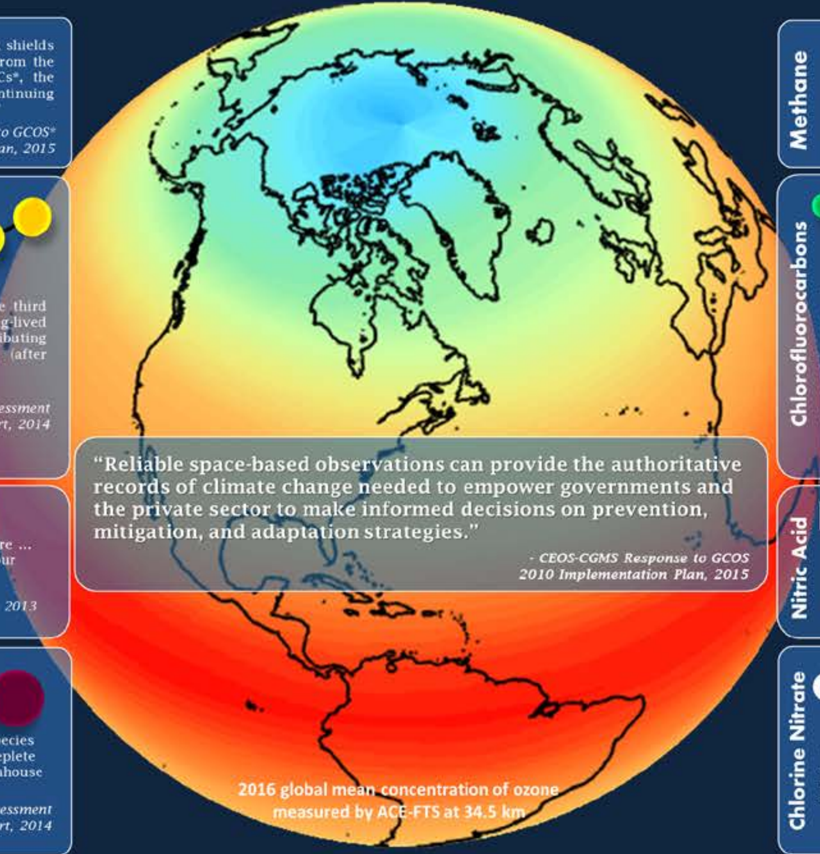
"Emissions of CO ... affect climate indirectly as precursors to tropospheric O_3 and aerosol formation ..."

- IPCC 5th Assessment Report, 2013

Hydrogen Fluoride — HF

"Stratospheric reservoir species such as HF gases do not deplete ozone but are potent greenhouse gases ..."

- UN WMO Ozone Assessment Report, 2014



2016 global mean concentration of ozone measured by ACE-FTS at 34.5 km

"Reliable space-based observations can provide the authoritative records of climate change needed to empower governments and the private sector to make informed decisions on prevention, mitigation, and adaptation strategies."

- CEOS-CGMS Response to GCOS 2010 Implementation Plan, 2015

Methane — CH_4

"Methane is the second most important anthropogenic greenhouse gas ... Understanding the sources and sinks for ... CH_4 is crucial. One of the challenges is to distinguish between natural and anthropogenic sources, for which accurate global measurements are required."

- CEOS-CGMS* Response to GCOS* 2010 Implementation Plan, 2015*

Chlorofluorocarbons — CFCs

"The ozone depletion over Antarctica results from the combined actions of very cold conditions, the return of sunlight in the Antarctic spring, and ozone depleting chemicals, which mostly come from human-produced compounds, in particular chlorofluorocarbons (CFCs)."

- CEOS-CGMS Response to GCOS 2010 Implementation Plan, 2015

Hydrochloric Acid — HCl

"HCl is estimated to account for >95% of total stratospheric chlorine at altitudes above ~50 km."

- UN WMO Ozone Assessment Report, 2010

"Anthropogenic chlorine is the primary culprit leading to the thinning of the ozone layer, especially at polar latitudes."

- IGACO Theme Report, 2004

Nitric Acid — HNO_3

"HNO_3 is the most important reservoir for odd nitrogen [NO_y] in the atmosphere ... removal of ... NO_y in the Arctic lower stratosphere ... increases ozone loss by as much as 30% ... in the spring."

- IGACO Theme Report, 2004

Chlorine Nitrate — $ClONO_2$

"... chemical reactions convert chlorine from HCl and $ClONO_2$ reservoirs to active, ozone-destroying species ..."

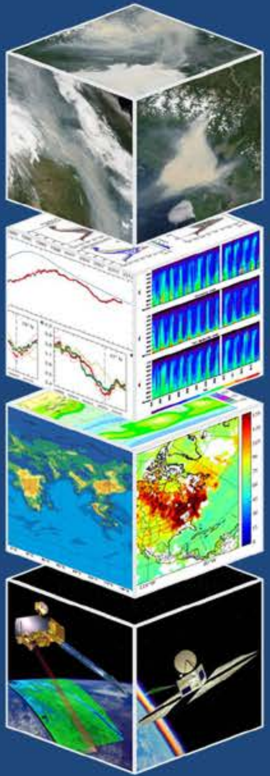
- UN WMO Ozone Assessment Report, 2014

Dinitrogen Pentoxide — N_2O_5

N_2O_5 is an important nocturnal reservoir for ozone depleting NOx species and is listed as one of the satellite measurements for polar studies in the UN WMO Ozone Assessment Report, 2014.

* CEOS is the Committee on Earth Observation Satellites; CFCs are chlorofluorocarbons ; CGMS is the Coordination Group for Meteorological Satellites; GCOS is the Global Climate Observing System; IGACO is Integrated Global Atmospheric Chemistry Observations, a strategic element of the Global Atmospheric Watch project of the WMO; IPCC is the Intergovernmental Panel on Climate Change; ODS is Ozone Depleting Substances; UN is the United Nations; and the WMO is the World Meteorological Organization.

Canada's SCISAT, Government Policy, and the UN Montreal Protocol



Building Block #4
Making Decisions

Records of ozone and aerosol concentrations can be used by national and provincial governments to mitigate effects of ozone depleting substances and create more resilient societies to climate change.

Building Block #3
Applying Climate Data Records

Long-term measurements of atmospheric ozone and aerosols result in improved monitoring, understanding, and prediction of ozone holes and air quality.

Building Block #2
Producing Climate Data Records

Limb profile observations are transformed into precise measurements of over 60 molecules. This information is documented and preserved.

Building Block #1
Gathering Raw Data from Space

Limb profile observations of the atmosphere by ACE-FTS are gathered and transmitted back to Earth.

FIGURE: An end-to-end example of the climate monitoring, research and services building blocks applied to Canada's ACE-FTS instrument on SCISAT. Removing any one building block will topple all those above.

"The Parties to this Protocol" are "determined to protect the ozone layer by taking precautionary measures to control equitably total global emissions of substances that deplete it, with the ultimate objective of their elimination on the basis of developments in scientific knowledge."

- Montreal Protocol on Substances that Deplete the Ozone Layer

"The primary goals of SCISAT include… exploring the relationship between atmospheric chemistry and climate change… Data on the distribution and concentration of a large number of ozone depleting substances, many of which are powerful GHGs, provide valuable information on the depletion/recovery of the ozone layer."

- Canada's Sixth National Report on Climate Change, 2014

"SCISAT data are used extensively in the current United Nations UNEP/WMO Ozone Assessment required by the Vienna Convention."

- NASA Letter of Support to the SCISAT Review: 2014

"The SCISAT/ACE data are also widely used by the WMO/UNEP Ozone Assessments to track changes in vertical profiles of ozone and ozone depleting substances."

- ECCC Letter of Support to the SCISAT Review: 2014

"Canada was one of the first countries to ratify the Montreal Protocol,… is the host of the Protocol's Multilateral Fund Secretariat in Montreal, and… is hosting the World Ozone and UV Radiation Centre"

- ECCC IEA Factsheet – Montreal Protocol, 2016

"Actions taken under the Montreal Protocol have led to decreases in the atmospheric abundance of controlled ozone-depleting substances (ODSs), and are enabling the return of the ozone layer toward 1980 levels."

- UN WMO Scientific Assessment of Ozone Depletion: 2014

UN Protocol and SCISAT Timeline

- 1984 – Discovery of Antarctic ozone hole
- 1987 – Montreal Protocol is signed by 24 countries
- 2003 – Launch of SCISAT
- 2006 – UN WMO Ozone Assessment report No. 50
- 2009 – Montreal Protocol. First treaty in history to achieve universal ratification
- 2010 – UN WMO Ozone Assessment report No. 52
- 2011 – Discovery of Arctic ozone depletion
- 2014 – UN WMO Ozone Assessment report No.55
- 2015 – Inclusion of HFCs in the Montreal Protocol; CoP21, Paris Agreement: the world unites to fight climate change
- 2016 – ACE-FTS continues to measure 60+ species.