The Canadian High Arctic: a Window into Climate, Ozone & Global Air Quality

Dan Weaver

Sigma Xi Distinguished Lecture Series

19 November 2015

Introductions

Dan Weaver

- Ph.D. Candidate, Dept. of Physics
- Travel to PEARL for annual winter/spring campaigns

  (since 2012)
- I also run campaign communications

Motivation for atmospheric research in the high Arctic?

Understanding planetary atmospheric and environmental change

Why study the atmosphere?

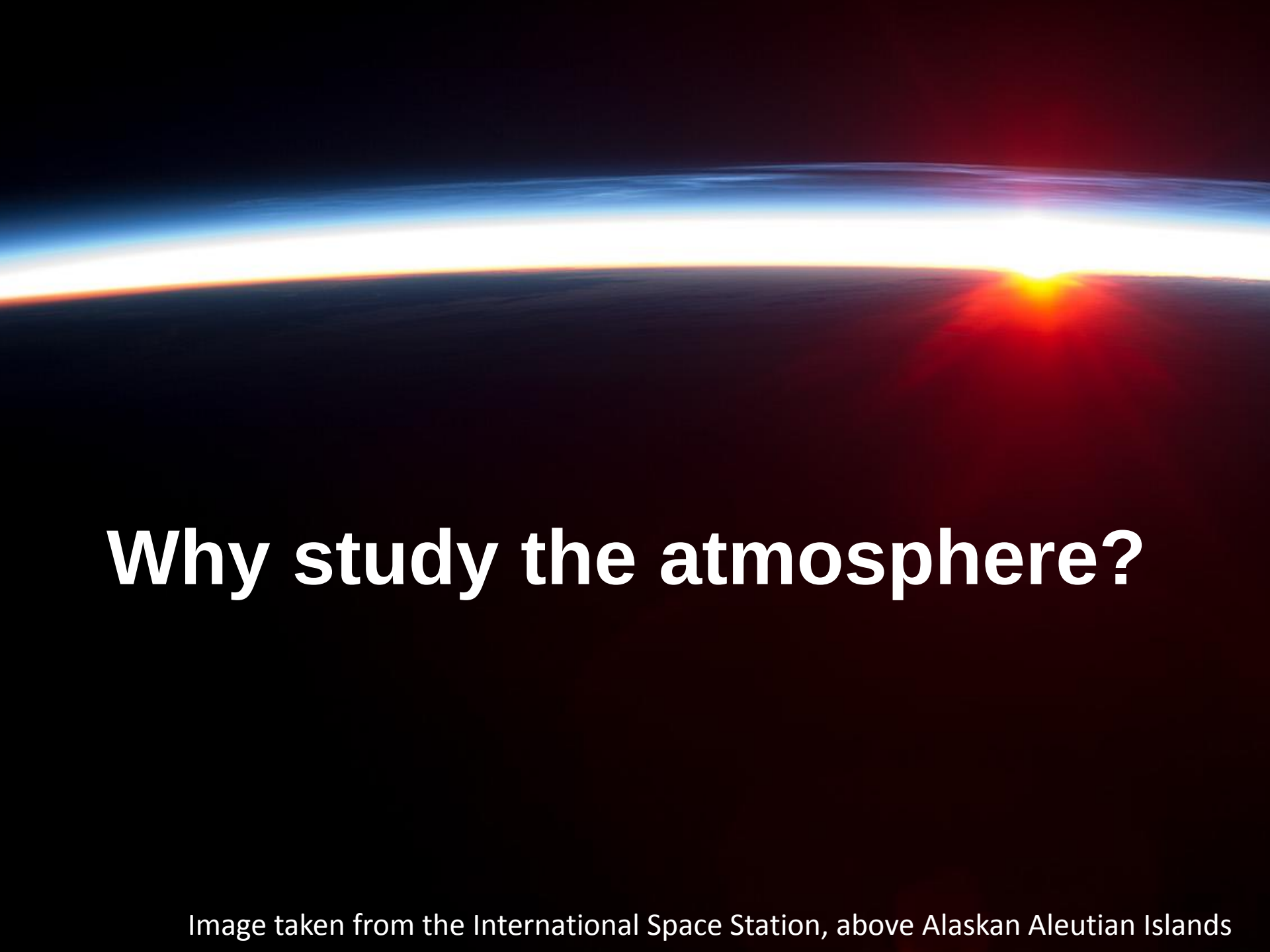
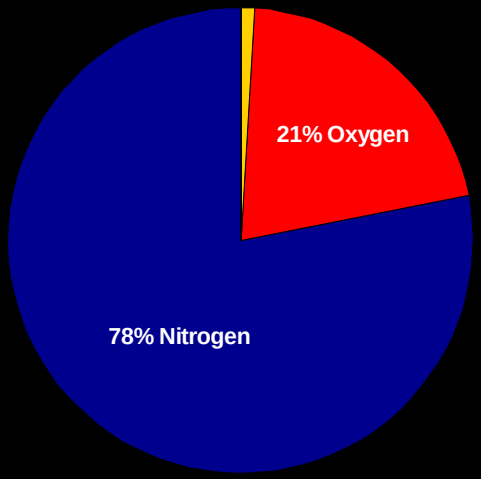


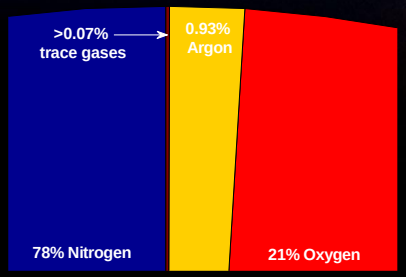
Image taken from the International Space Station, above Alaskan Aleutian Islands

What is air?



Trace Gases include:

- Argon
- Water vapour
- Carbon dioxide
- Methane
- Nitrous oxide
- Ozone
- Many others



Small amounts of gases can have a BIG impact on the planet!

Why is this research important now?

1793

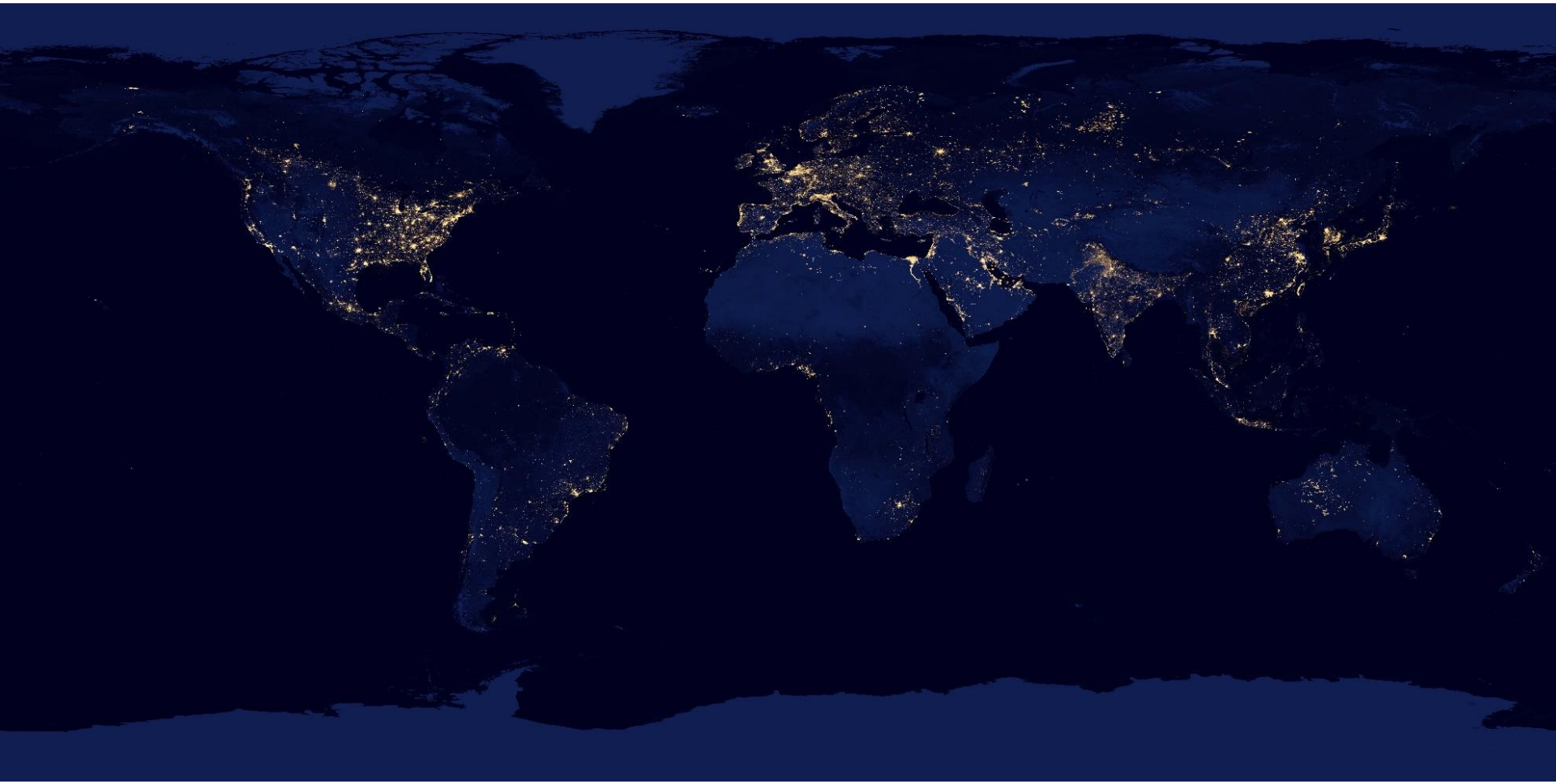
Painting by Elizabeth Simcoe,
from the City of Toronto "*The History of Toronto: An 11,000-Year Journey*" web page

Downtown Toronto

1890s

2014

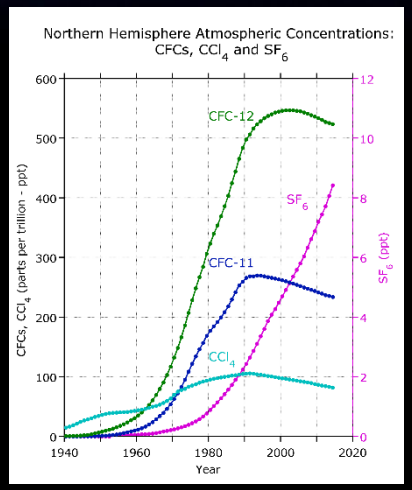
Earth at night, 2015

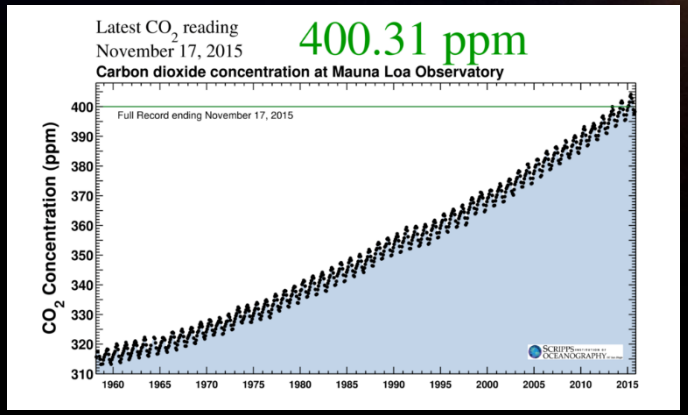


Credit: NASA

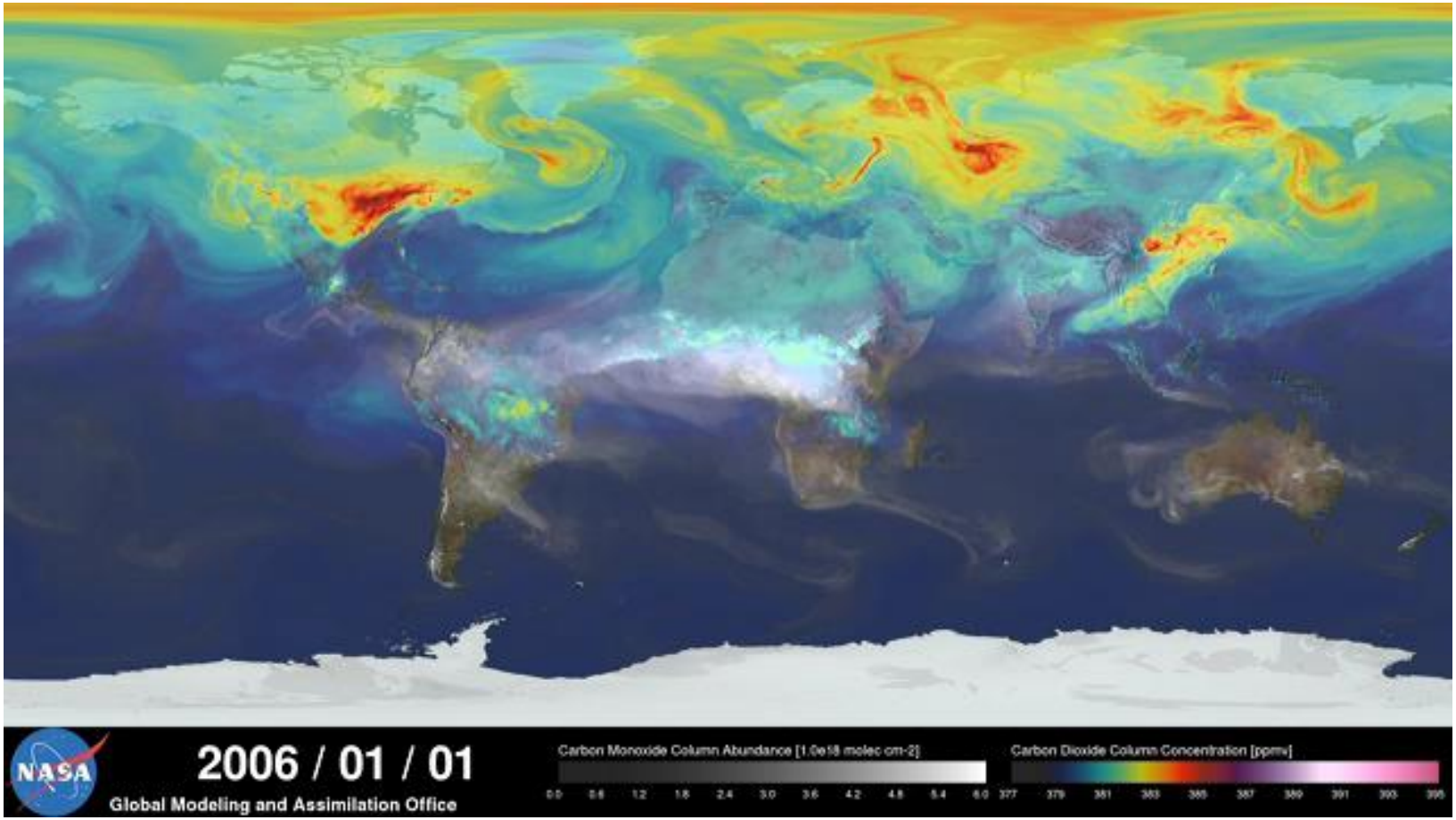
Atmospheric science

aims to measure & understand the changing atmosphere



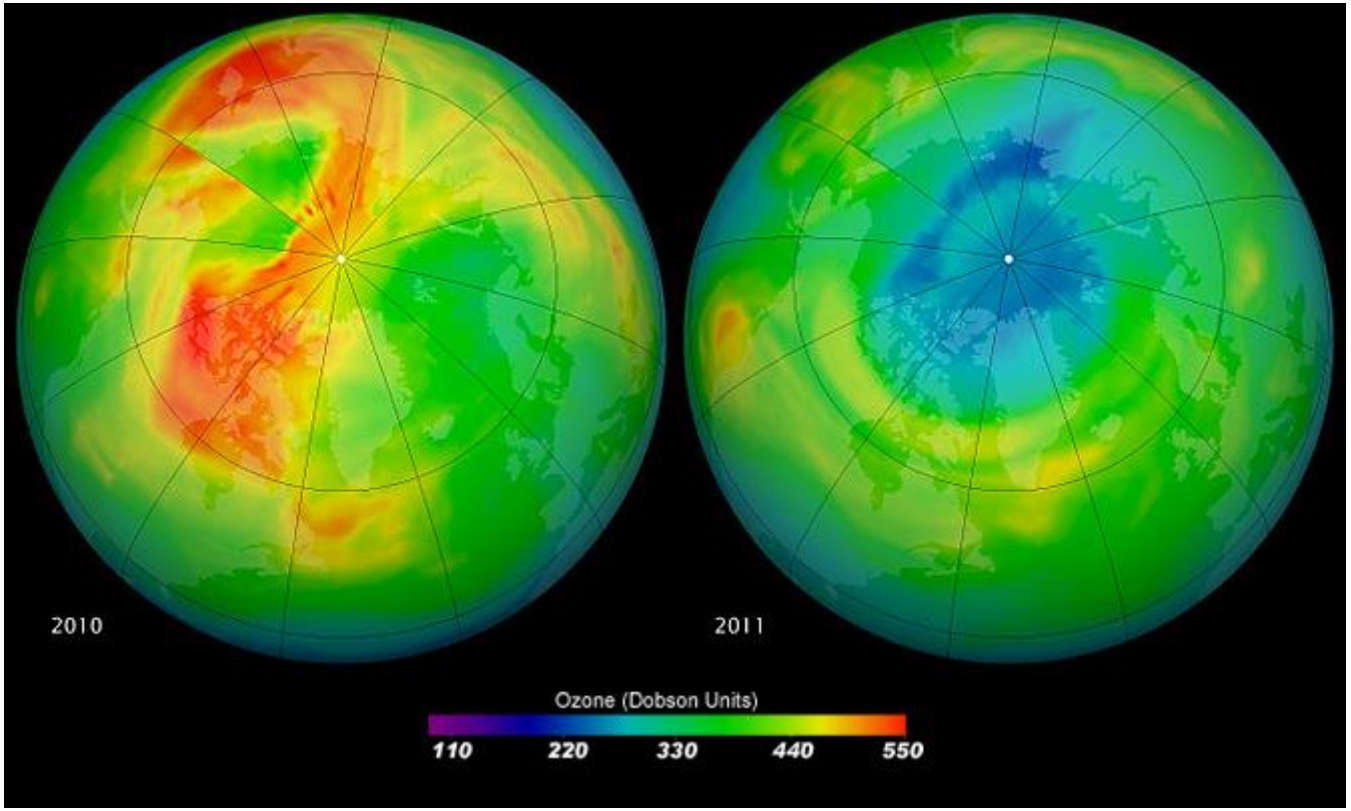


CO_2

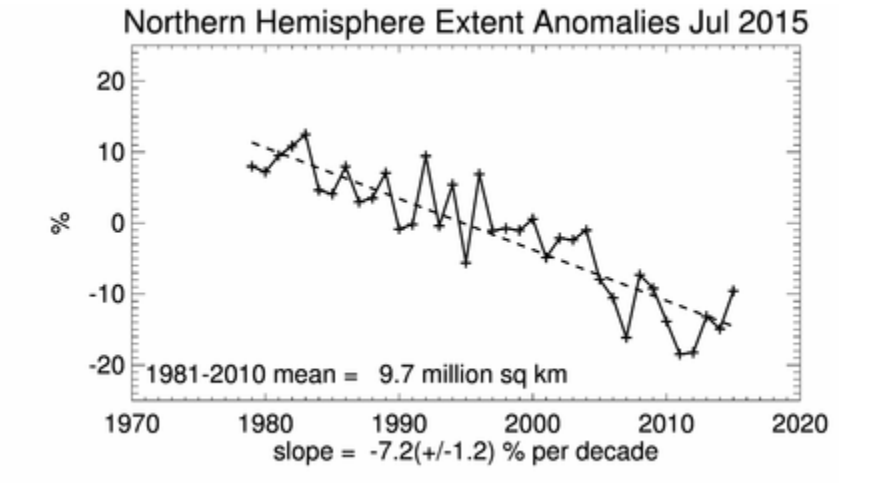

NASA
2006 / 01 / 01
Global Modeling and Assimilation Office
Carbon Monoxide Column Abundance [1.0e18 molec cm-2]
0.0 0.6 1.2 1.8 2.4 3.0 3.6 4.2 4.8 5.4 6.0
Carbon Dioxide Column Concentration [ppmv]
377 379 381 383 385 387 389 391 393 395

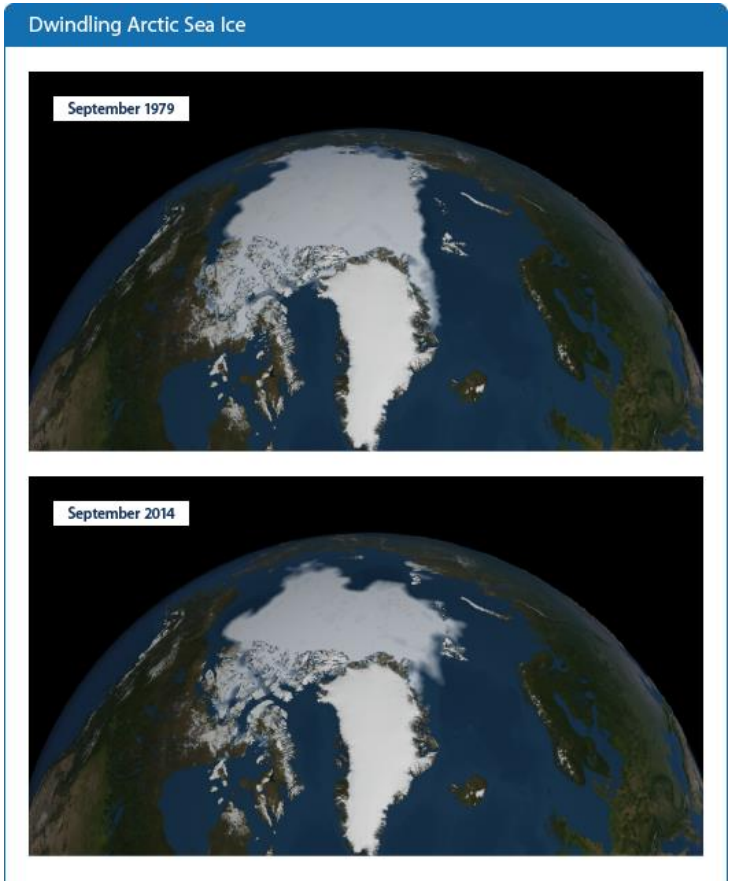
Arctic ozone change

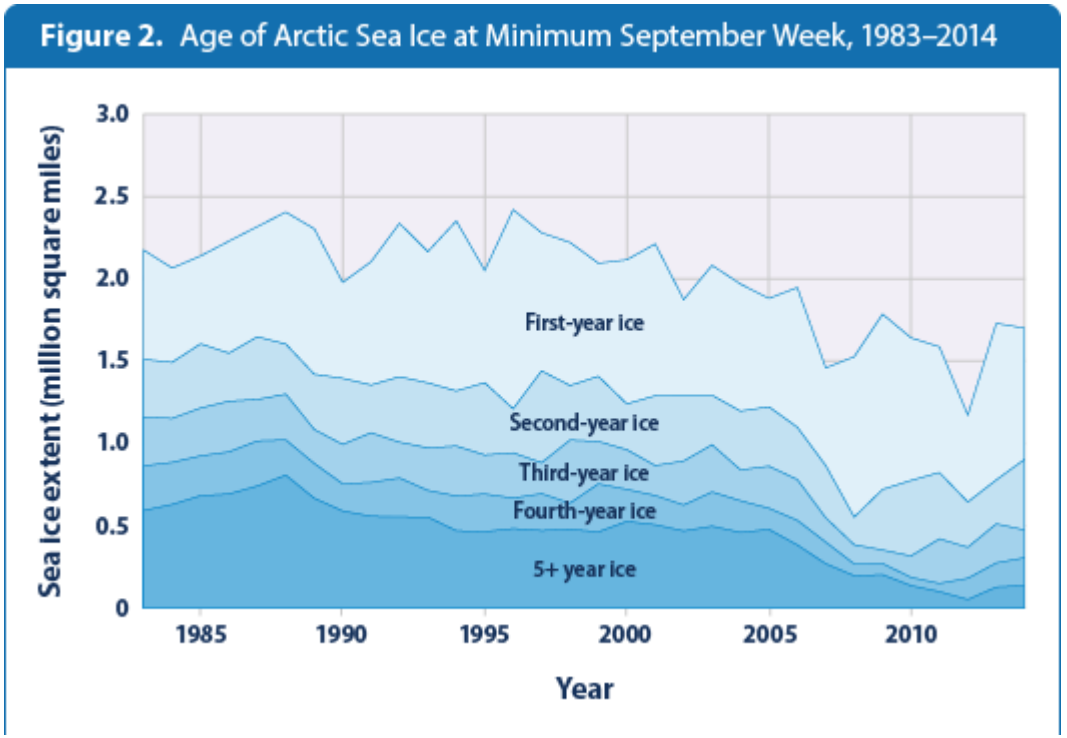
Ozone depletion



Arctic sea ice change







Our society's impressive rapid technological development has come at a significant environmental cost

we should at least
understand how we are changing the planet

Ideally, we should avoid them entirely

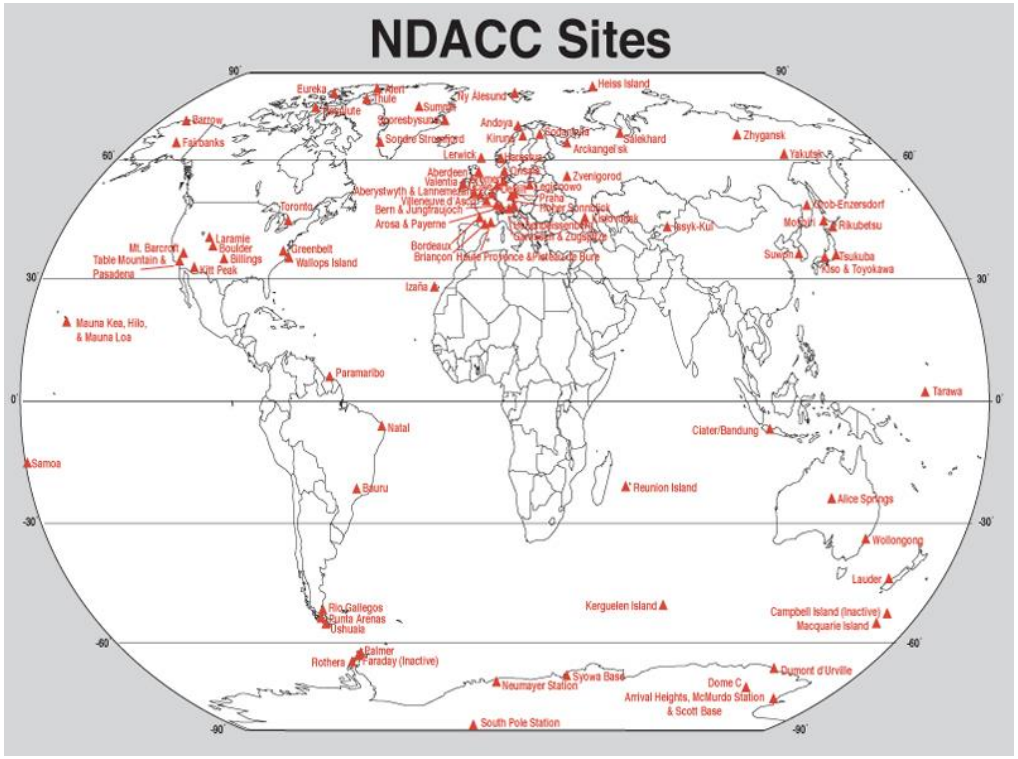
Today's talk

Where is Eureka

PEARL research

Working in the High Arctic

Global context



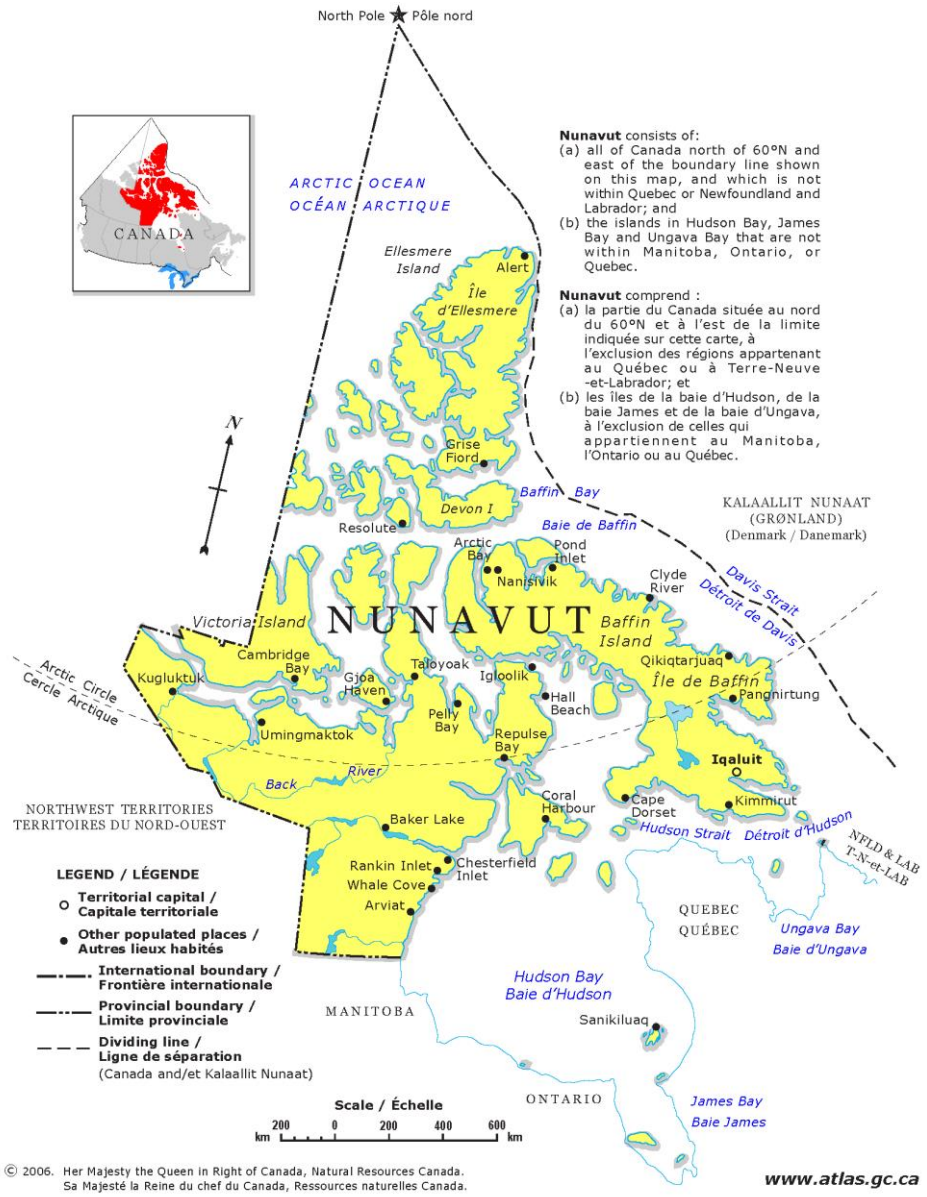
There are atmospheric observatories world-wide

… but there are gaps!

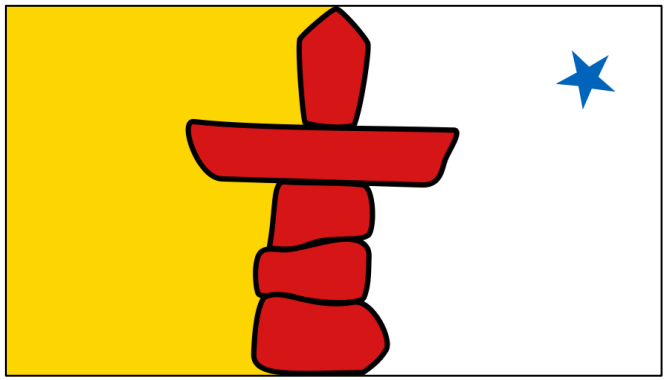
Canadian Arctic

Our Arctic is 40% of Canada's landmass & is home to over 100,000 Canadians.

Nunavut



- Territory created in 1999
- Over 80% Inuit population (total: ~37,000)
- Smallest economy, largest area of all provinces/territories
- Elects a single MP
- Has distinct government system (consensus)
- Unique culture (Inuit)



Eureka, Nunavut is at 80°N, 86.4°W on Ellesmere Island

How far North?!

Where?

Eureka, Nunavut is at 80°N
on Ellesmere Island

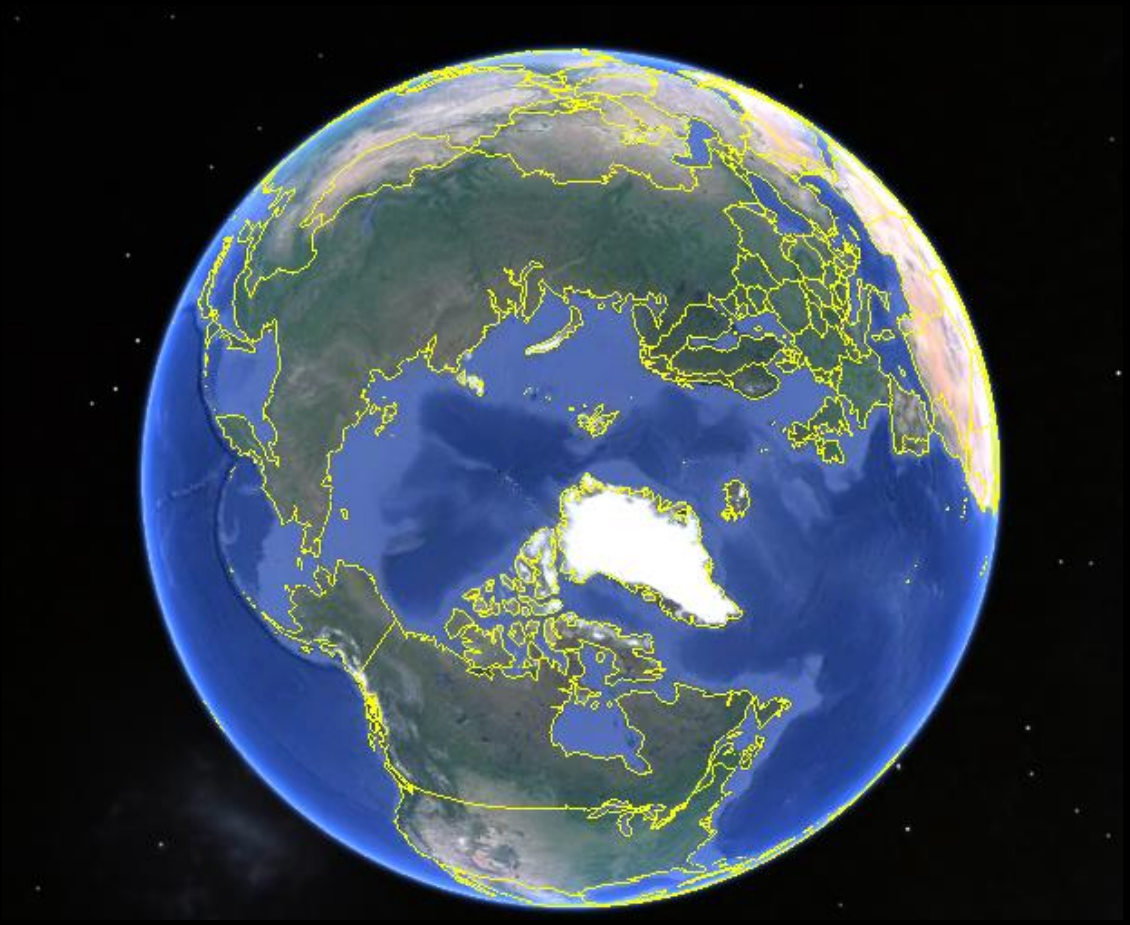
Distances

Eureka/PEARL is over 4000 km north of Toronto!

Yellowknife is ~halfway point

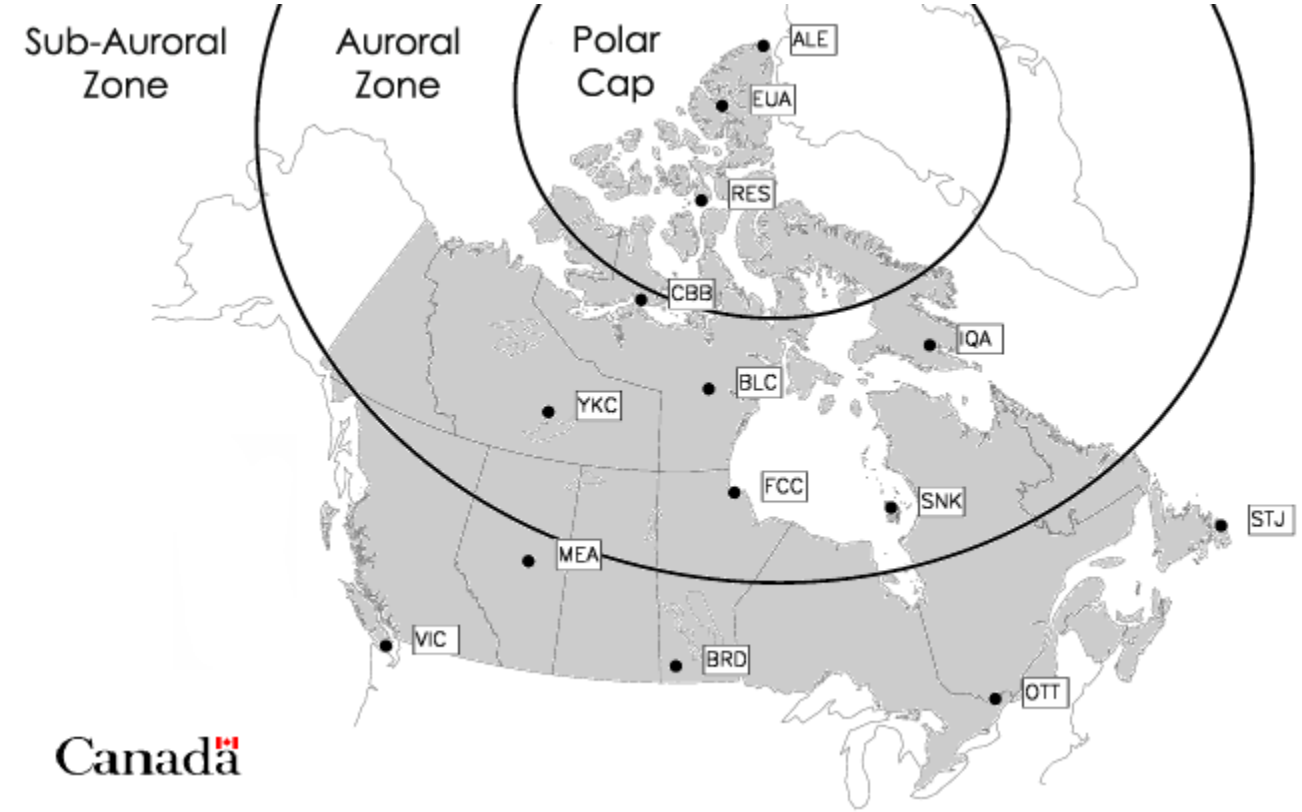
Eureka is closer to:

Stockholm, Sweden
St. Petersburg, Russia
Reykjavik, Iceland
Glasgow, Scotland

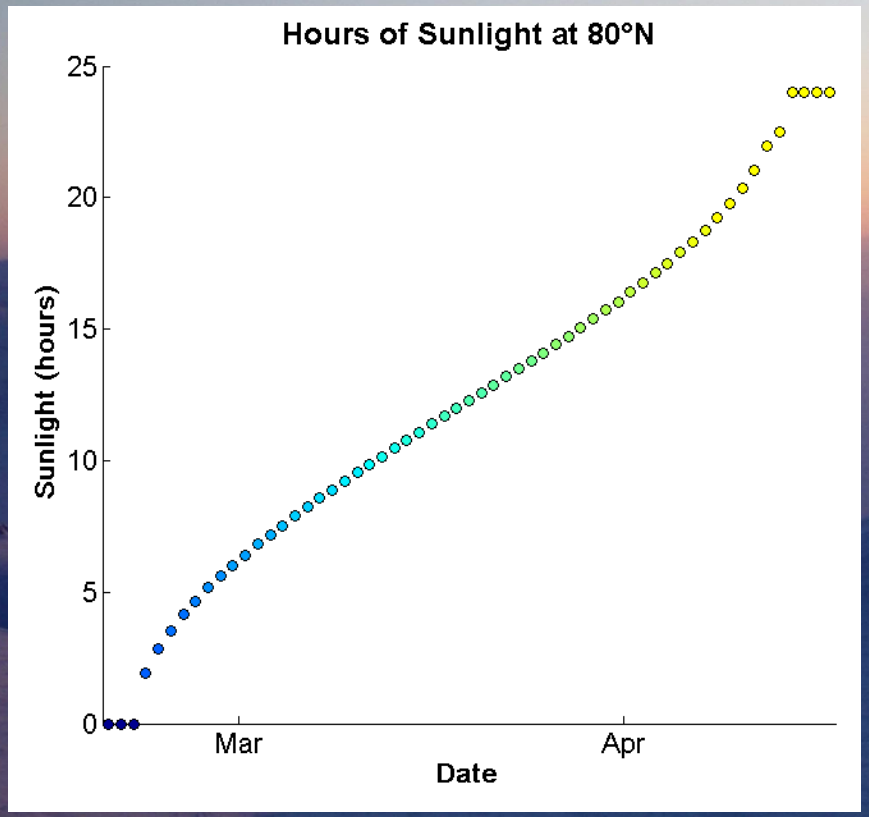


Than to Toronto!

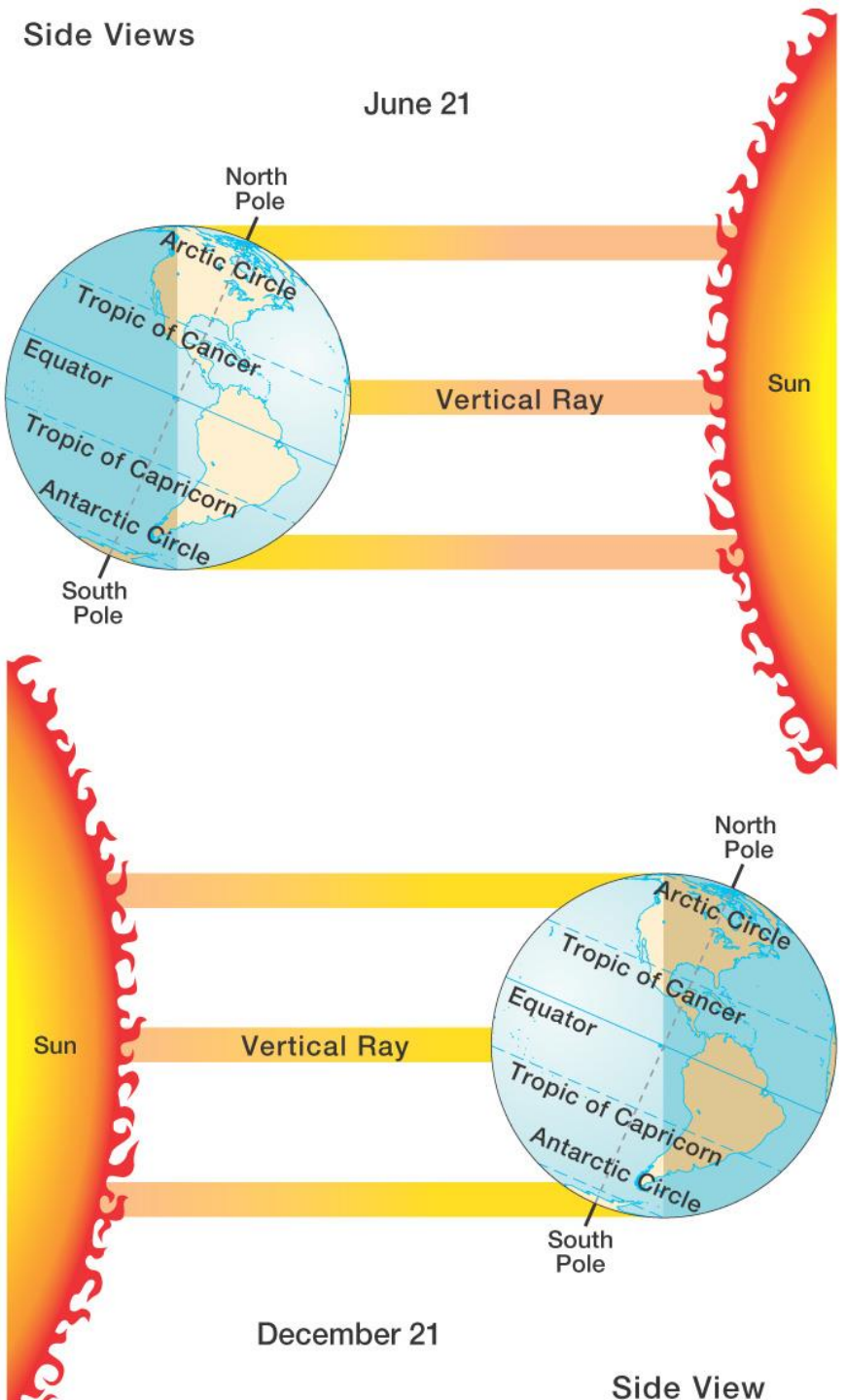
Eureka is farther north than most Northern Lights!

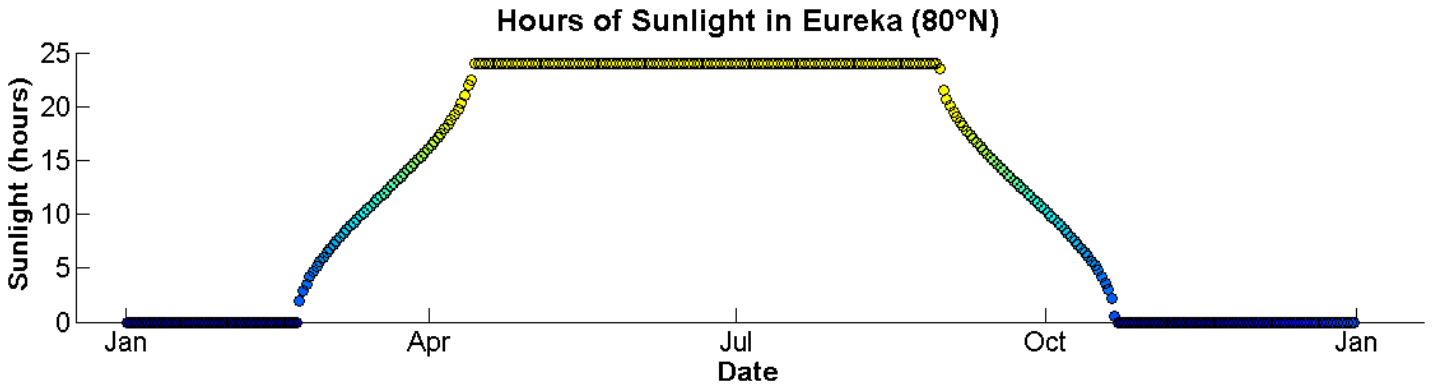


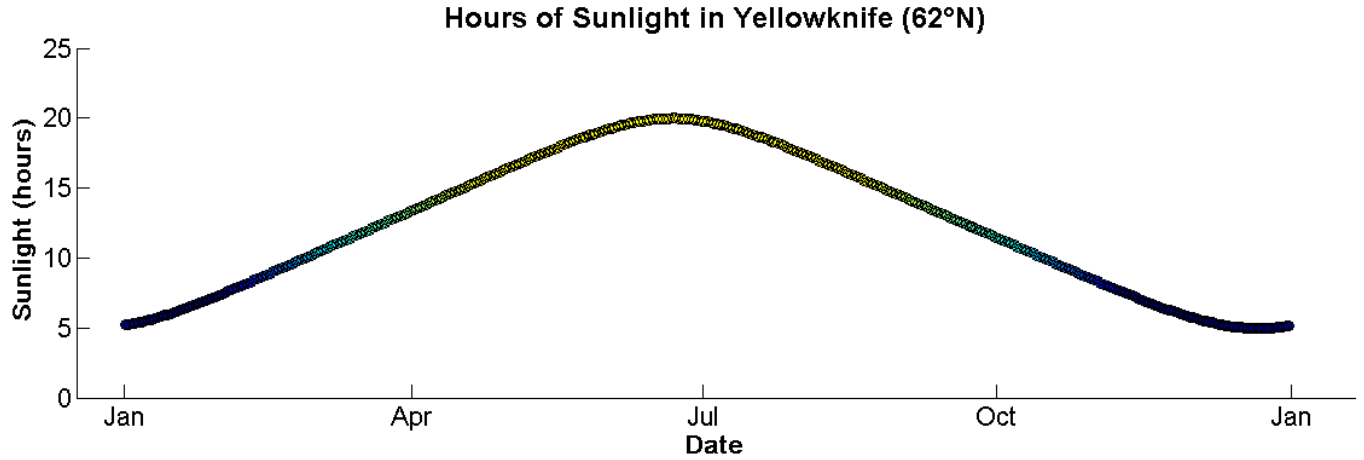
Daylight

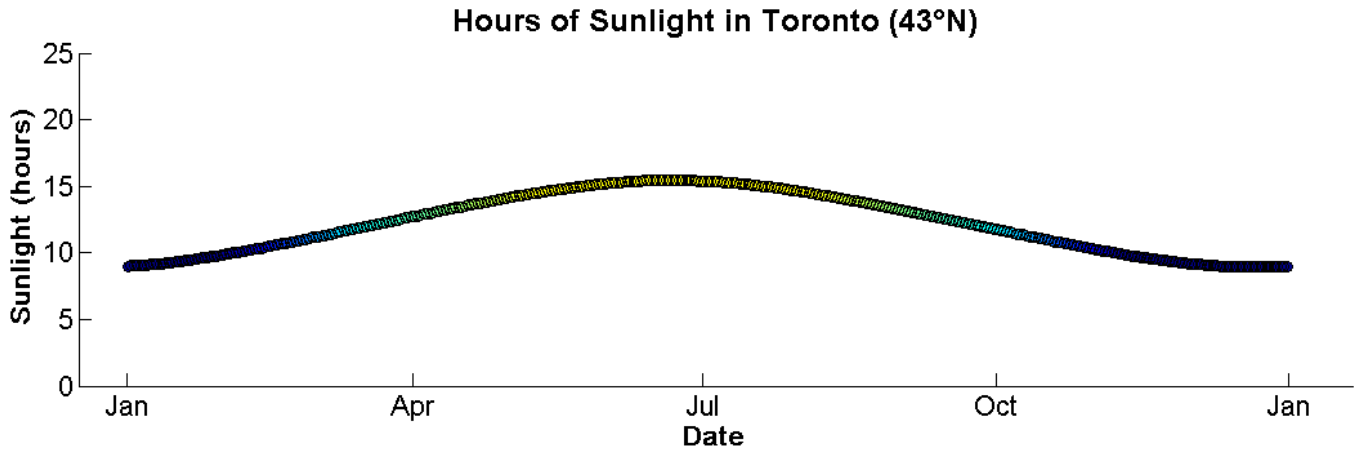


Eureka, Nunavut
18 February – 18 April 2015
Data from the U.S. Naval Observatory



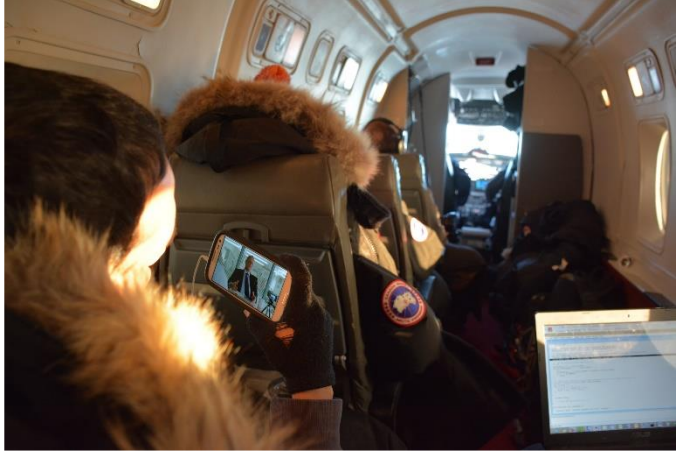

Hours of Sunlight in Eureka (80°N)
Sunlight (hours)
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Jan
Date


Hours of Sunlight in Yellowknife (62°N)
Sunlight (hours)
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Jan
Date


Hours of Sunlight in Toronto (43°N)
Sunlight (hours)
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Jan
Date

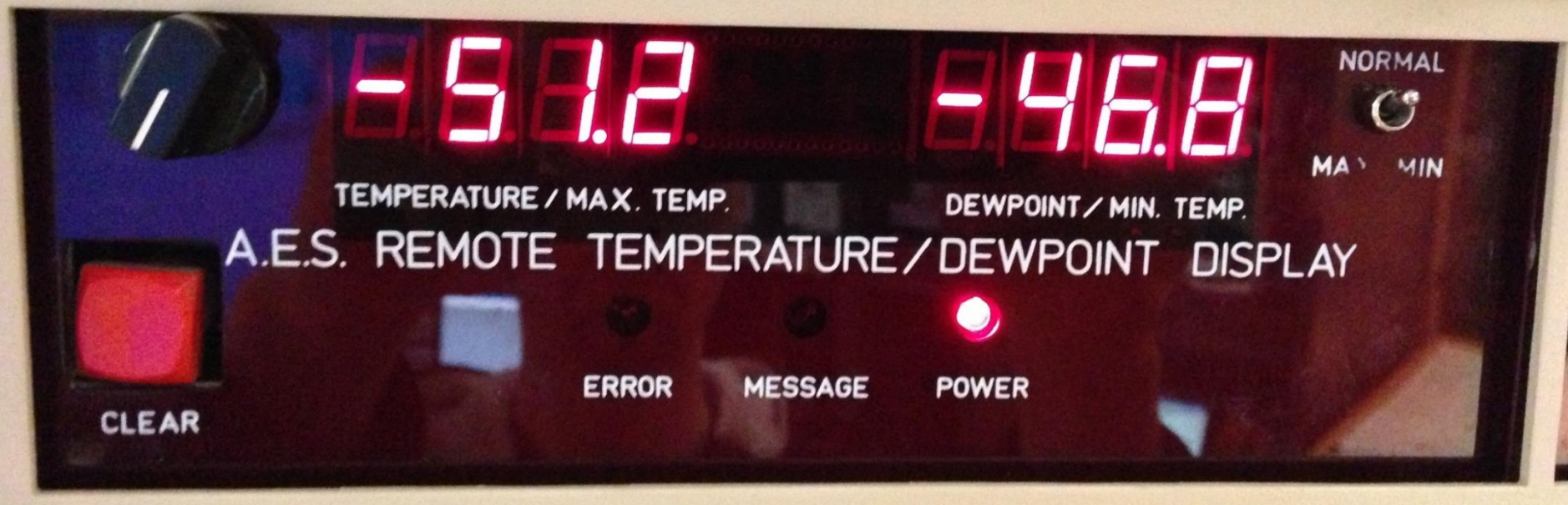
Travelling to PEARL…

Toronto
Edmonton
Yellowknife
Cambridge Bay
Resolute
Eureka



Eureka International Airport

Dress warmly!



Eureka

- Environment Canada facility
- 8 permanent staff
- Short-term research teams

Eureka at twilight

The Eureka Weather Station


WELCOME TO EUREKA
WEATHER STATION
CANADA POSTES
POST CANADA
EUREKA, NU
X0A 0G0
CLARK DOOR

Eureka is the northernmost permanently settled civilian place in the world*

*Nord, Greenland and Alert, Nunavut are further north, but are primarily military

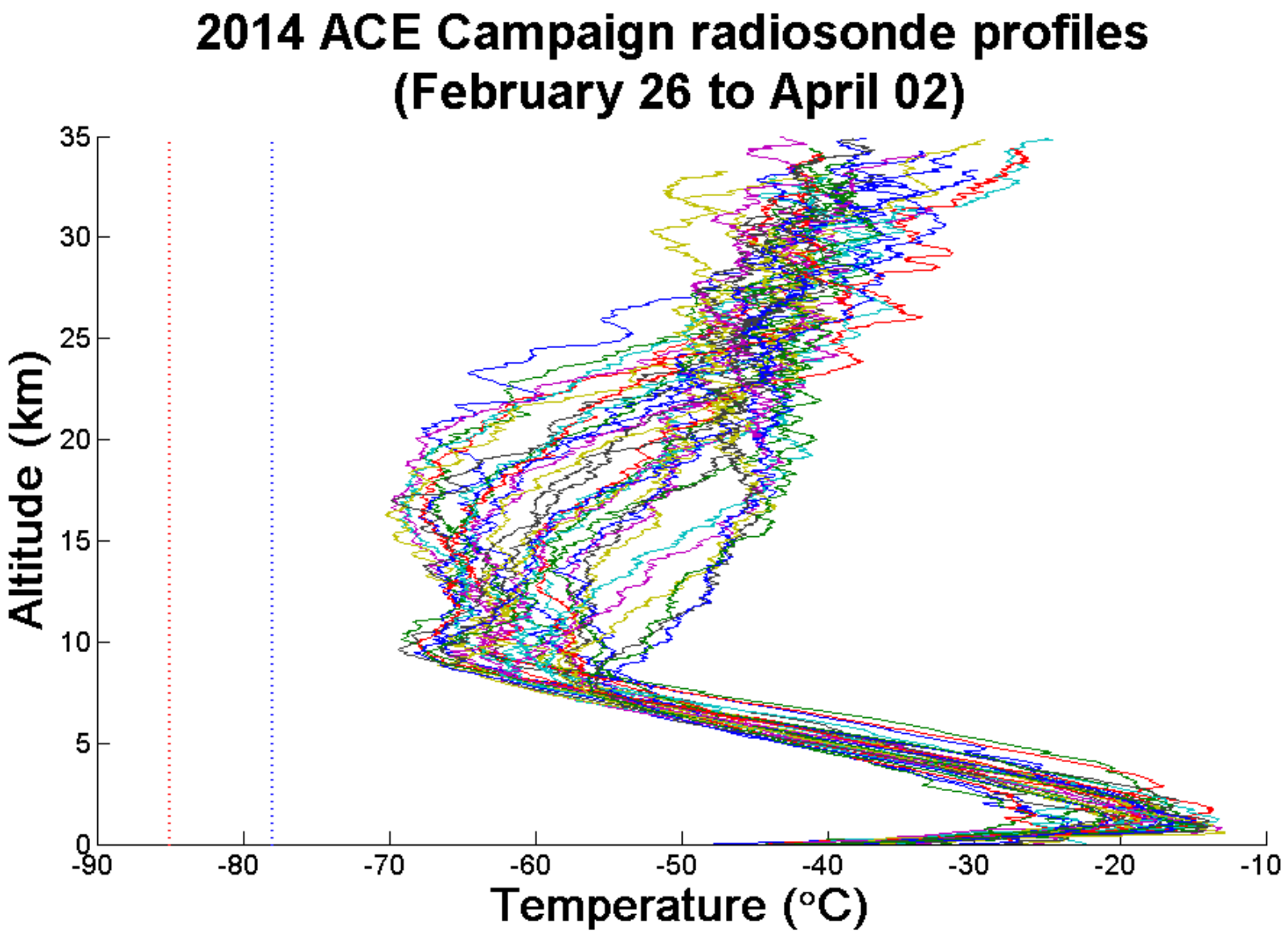
It's like a tiny town. There is:

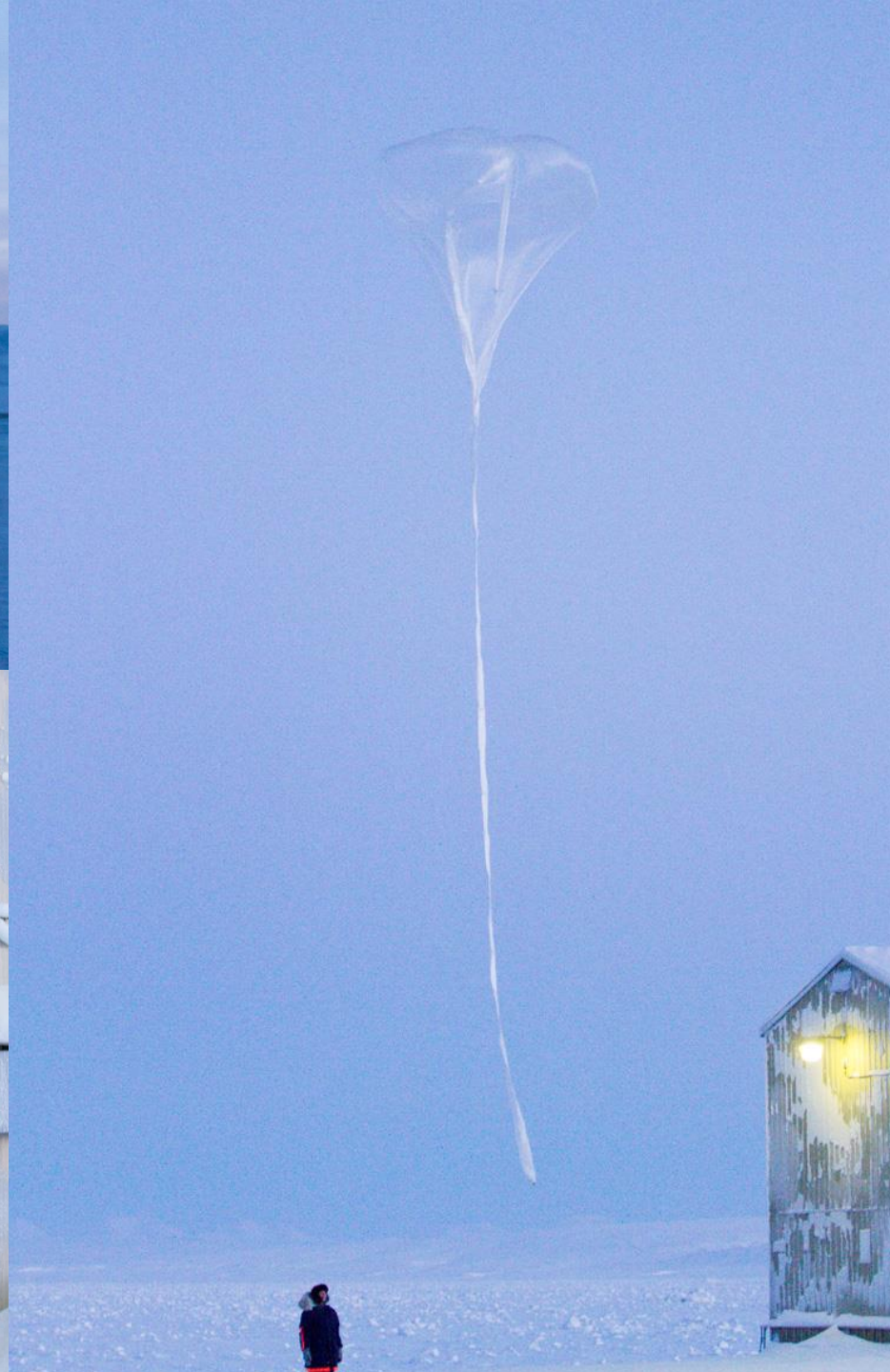
- Post office
- Store
- Bar (BYOB)
- Airport
- Labs
- Guest rooms
- Power facilities
- Sewage facilities
- Water infrastructure
- ~~Hospital/clinic~~

Eureka Weather Station's recreation room

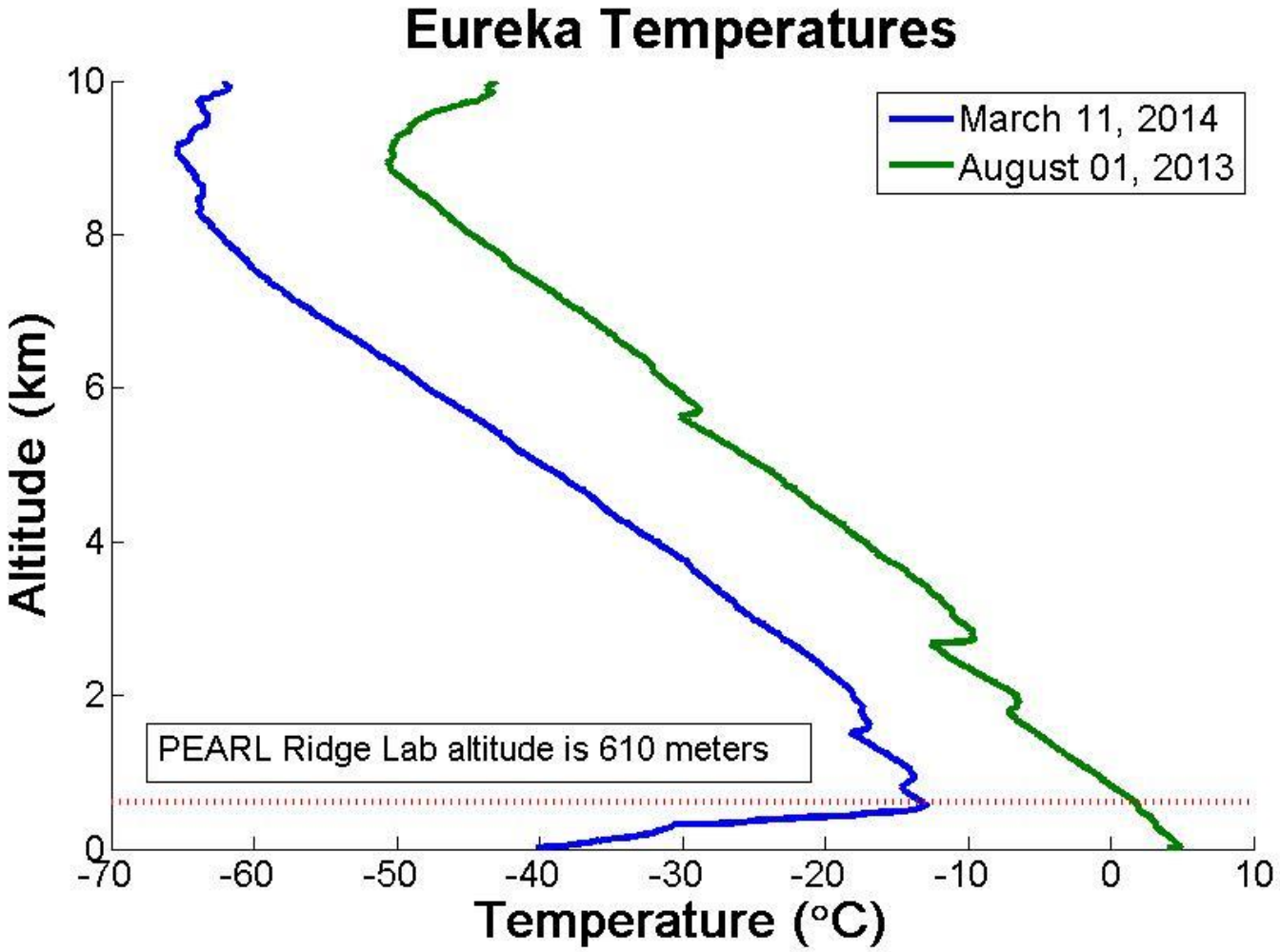
There’s always plenty of food in Eureka

Diesel power generators & temperature inversions


2014 ACE Campaign radiosonde profiles
(February 26 to April 02)
Altitude (km)
0
5
10
15
20
25
30
35
-90
-80
-70
-60
-50
-40
-30
-20
-10
Temperature (°C)



Interesting phenomena: Temperature inversion



Driving to the PEARL Ridge Lab

Be prepared to shovel snow when in the Arctic!

DYK:
Canada's high Arctic is a polar desert.
There is very low humidity!

Figure .: Location of PEARL relative to Eureka.


CANADA

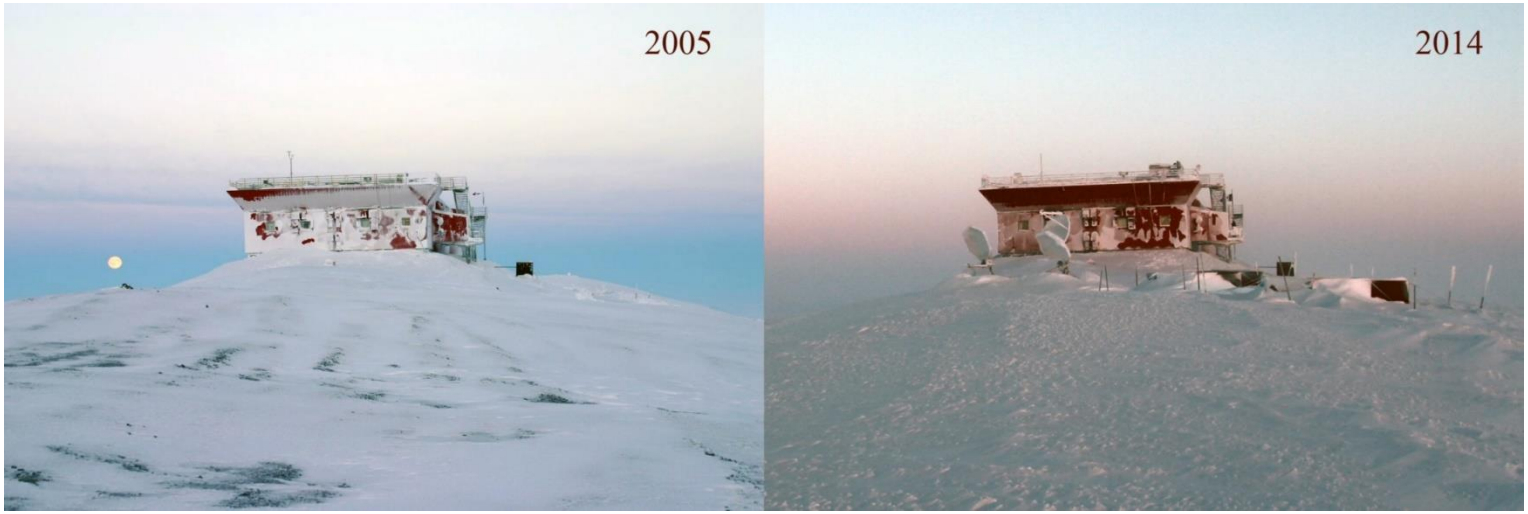
EC has a variety of specialized vehicles…

Along the road to the PEARL Ridge Lab

PEARL

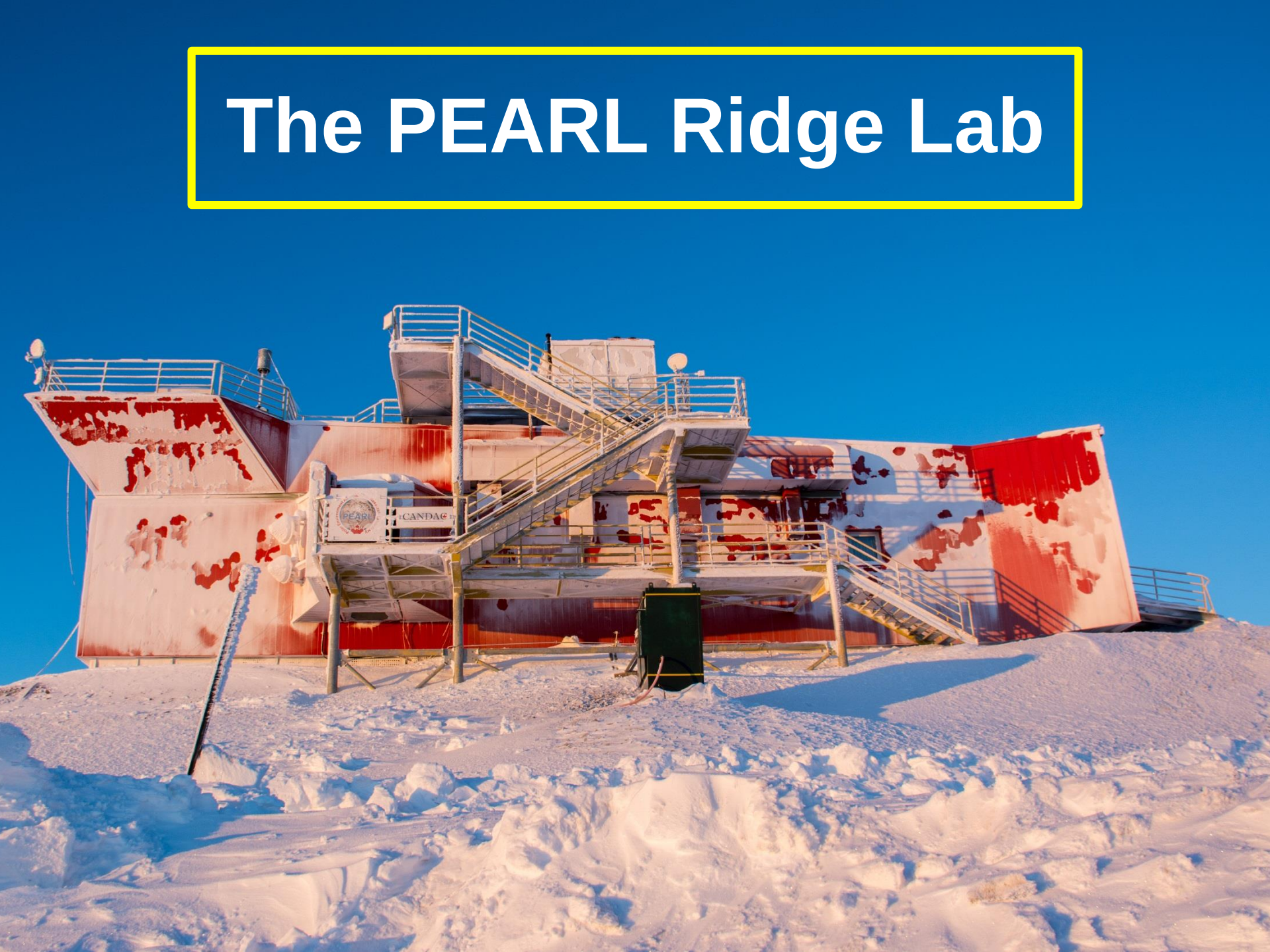
- Ideally situated to study the high Arctic atmosphere
- Run by CANDAC since 2006
- Originally built as an Environment Canada facility, AStrO, in the 1990s

(Arctic Stratospheric Ozone Observatory)



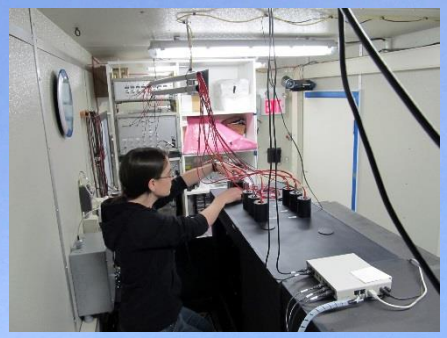
- 80.05° North, 86.4° West
- 610 meters a.s.l.
- ~15 km from Environment Canada's Eureka Weather Station

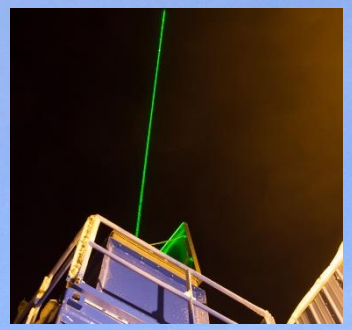
The PEARL Ridge Lab



It’s not easy to get here, but it’s beautiful!

Zero-altitude PEARL Auxiliary Lab (0PAL)





SAFIRE

(Surface and Atmospheric Flux, Irradiance and Radiation Extension)

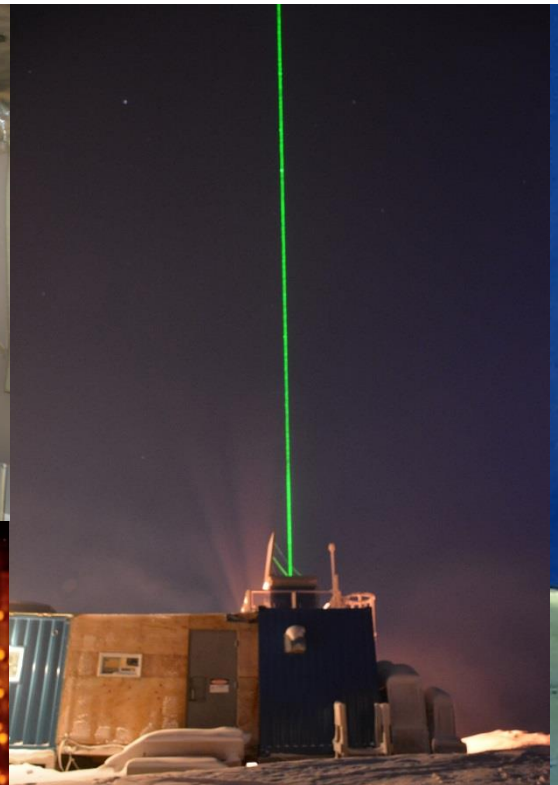
The flux tower


Research at PEARL?
Ozone Depletion
Climate Change
Pollution

How do we measure the atmosphere?

Ground-based spectrometers

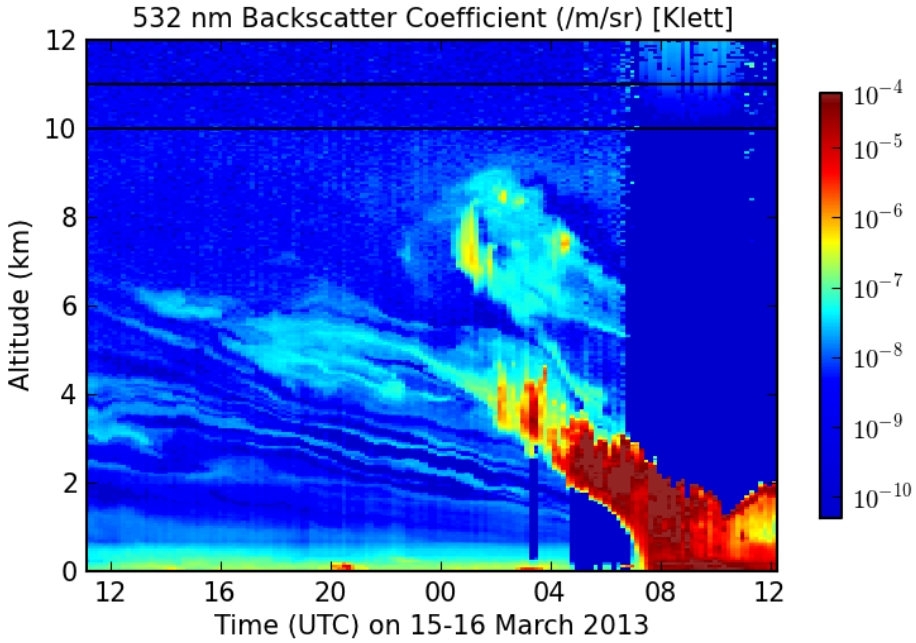
Ground-based lidars



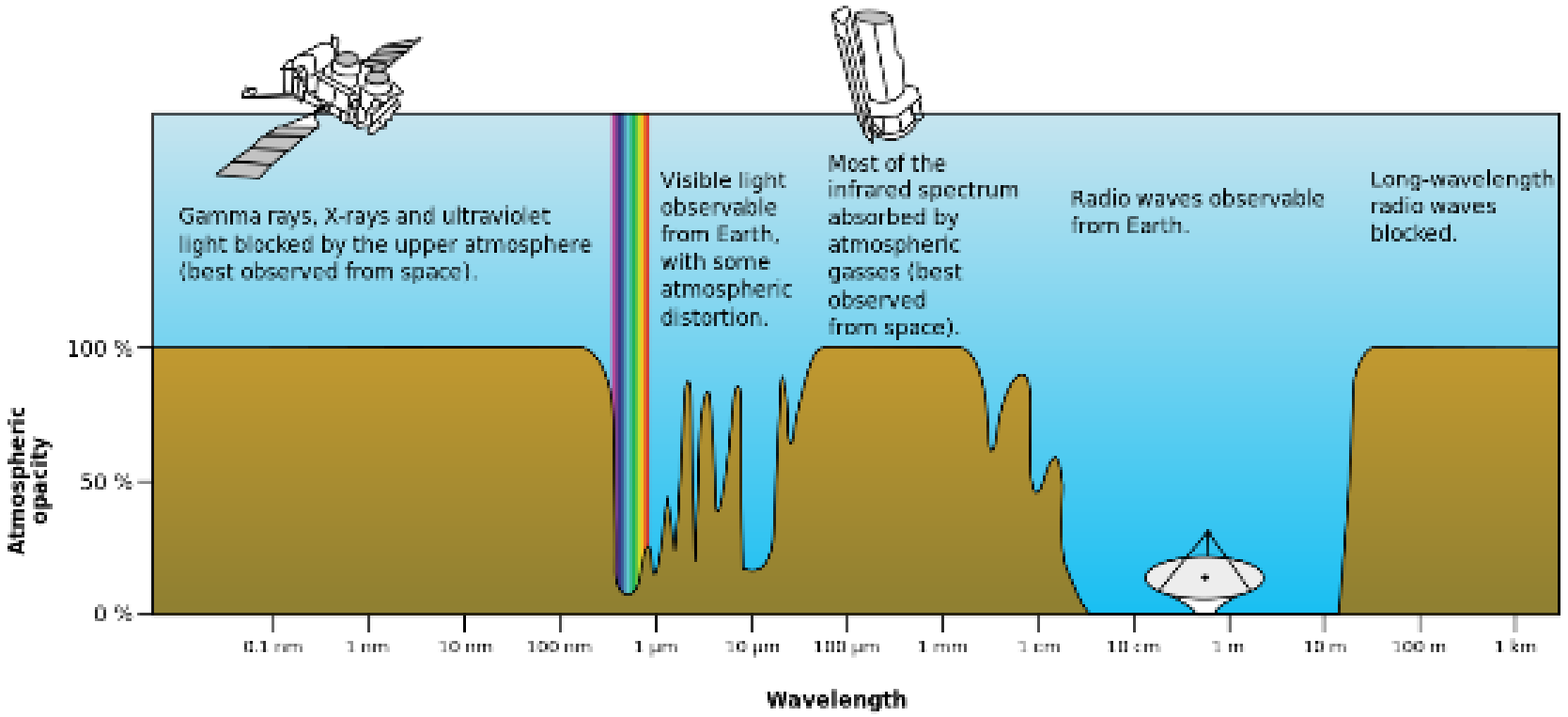
Balloon measurements

LIDARs

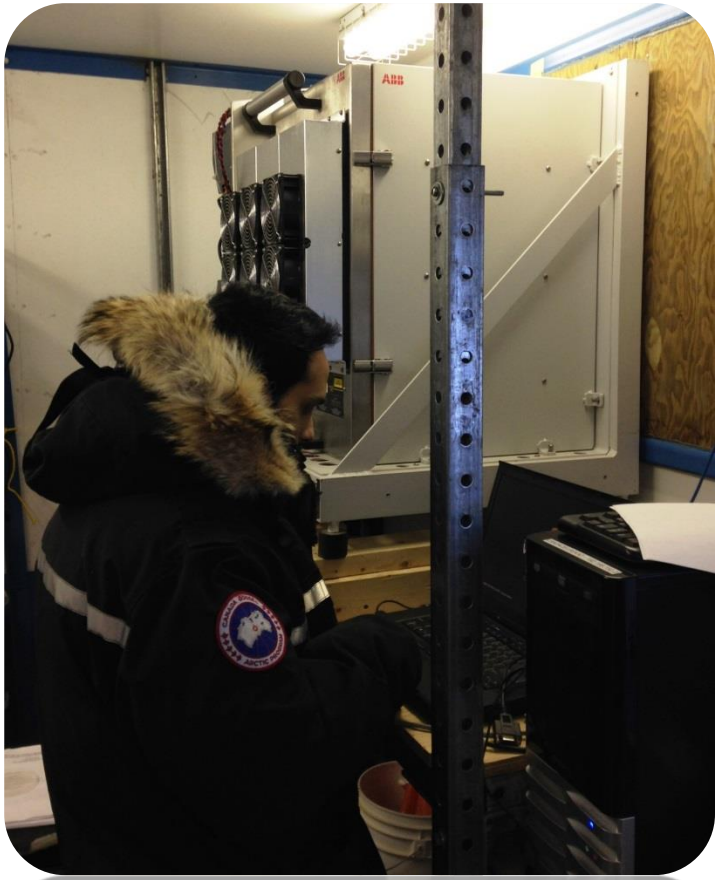
Light detection and ranging



PEARL's instruments mostly observe the atmosphere in the UV, visible, infrared and microwave regions of the EM spectrum



E-AERI: an emission FTIR



UV-Vis Lab

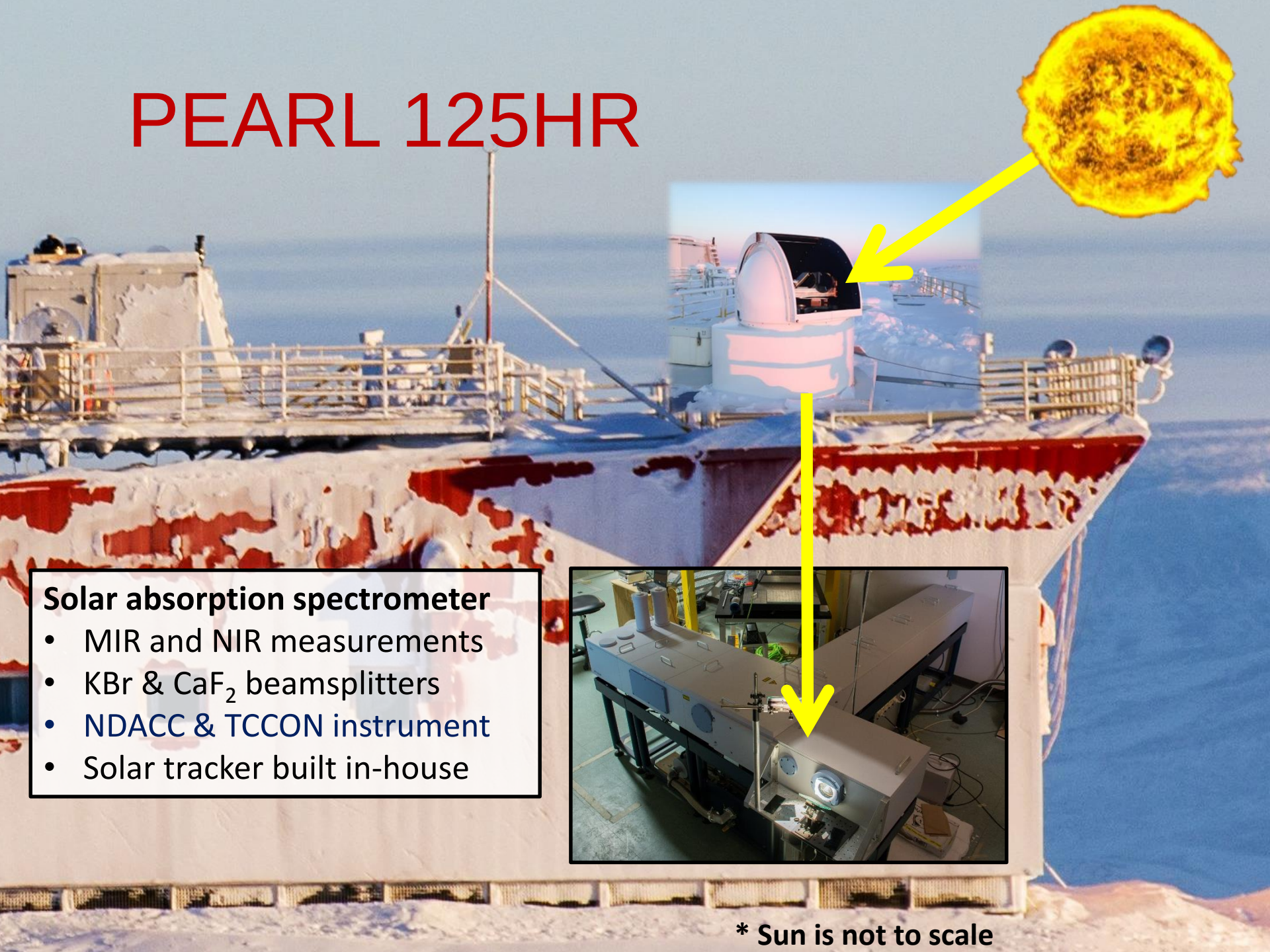

© Dan Weaver


DANGER
CONFINED SPACE
AUTHORIZED PERSONNEL ONLY

PEARL 125HR

Uses sunlight to create “maps” of the atmosphere

PEARL 125HR



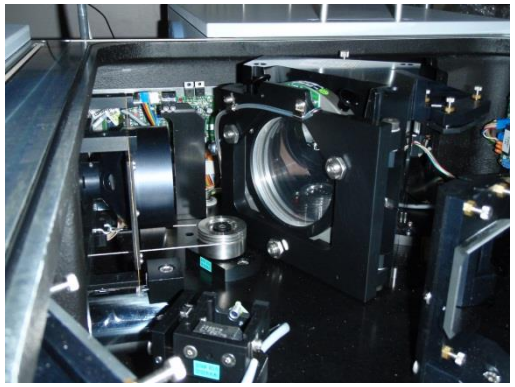
Solar absorption spectrometer

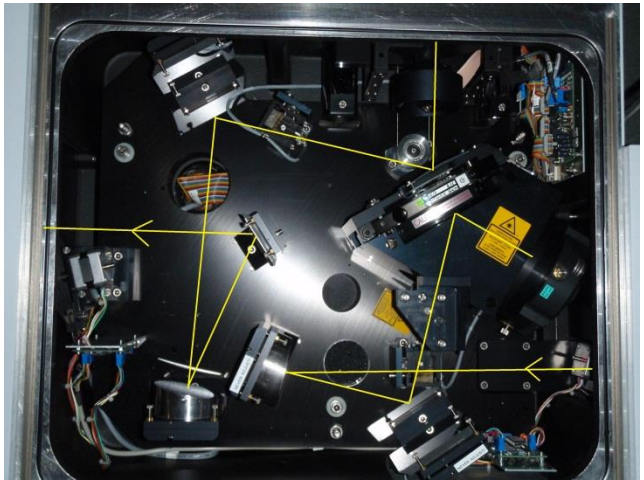
- MIR and NIR measurements
- KBr & CaF_2 beamsplitters
- NDACC & TCCON instrument
- Solar tracker built in-house

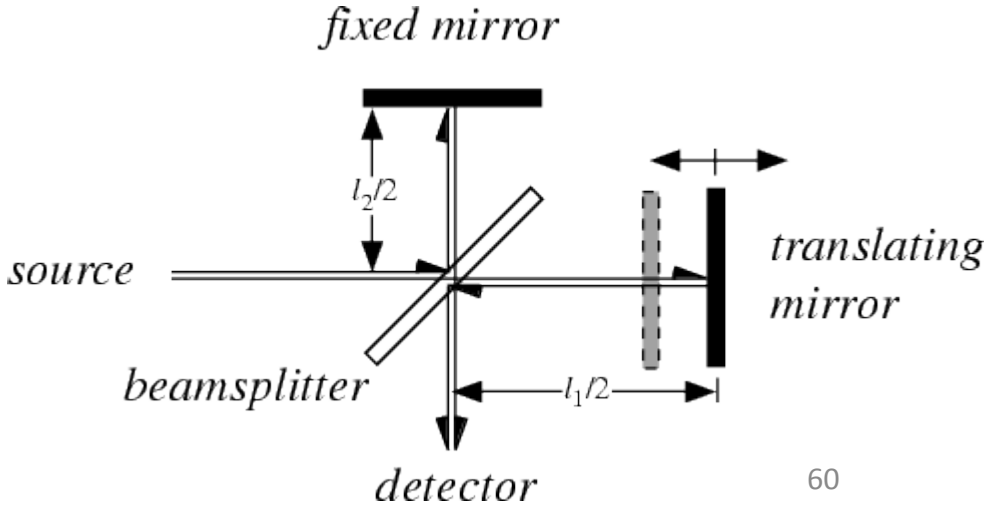
*** Sun is not to scale**

Fourier transform spectroscopy

- Light is passed through a beam splitter
- Two beams of light travel different path lengths
- Detector measures an interference pattern
- As the moving mirror changes position, different frequencies of light peak at different times. The result of a scan is an interferogram.
- The Fourier transform of the interferogram is the observed spectrum, which can be analyzed to retrieve gas abundances and distribution.
- The spectral resolution of an FTS is directly related to the maximum optical path difference





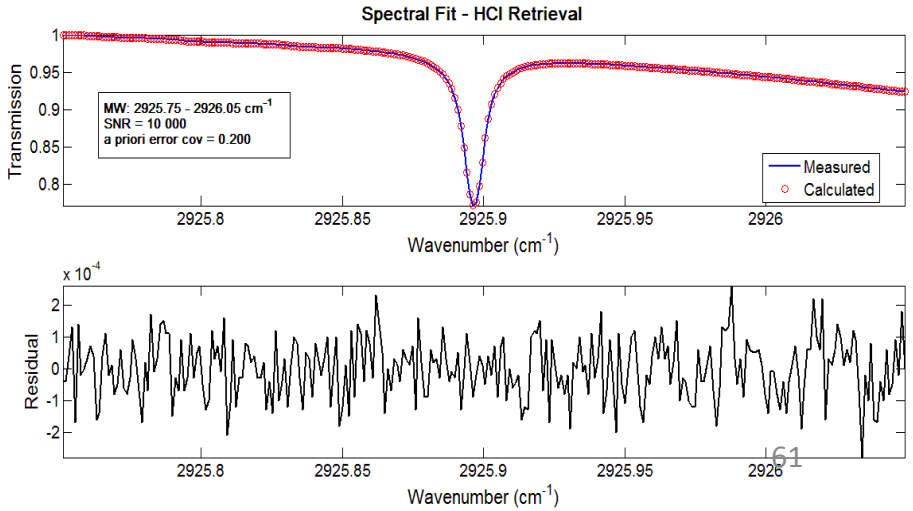


Spectral features

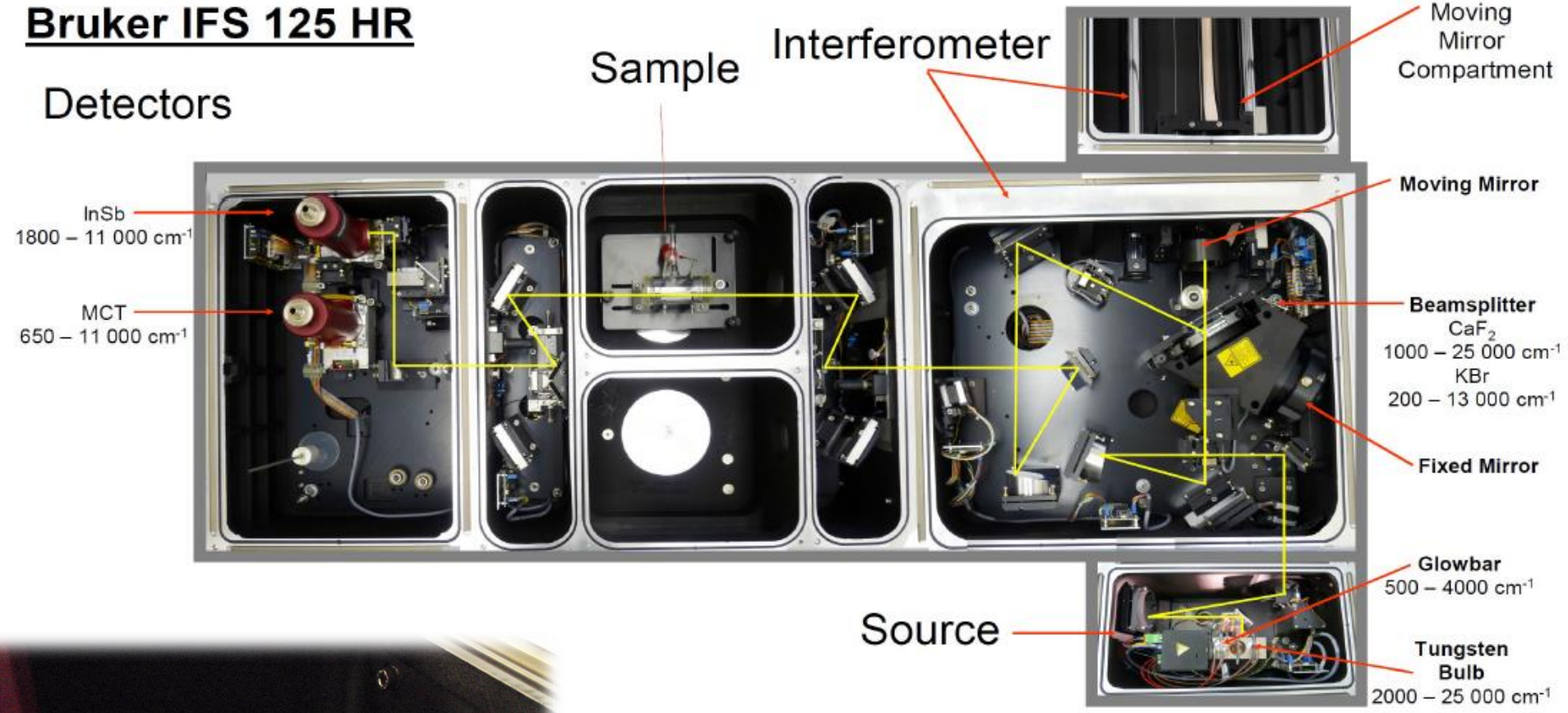
- Extensive lab tests provide a database of spectral features for atmospheric gases.
  - There are 64 000 water vapour lines!
- This knowledge enables us to select appropriate features to examine.
- Inferring abundances and vertical distribution relies on the shape of the observed spectral line.
  - The line strength is directly related to the abundance.
  - The shape is related to the distribution.

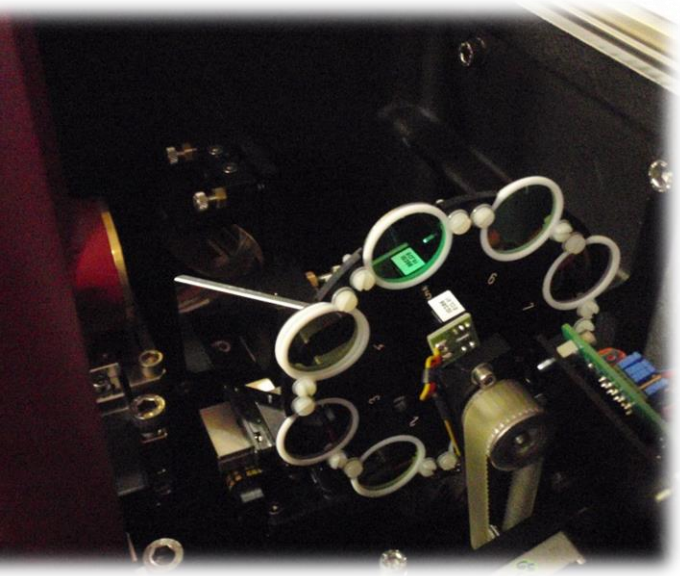
$$S = \int_{-\infty}^{\infty} k_\nu \, d\nu$$

where k_ν is the absorption coefficient of the molecule being studied



Bruker IFS 125 HR



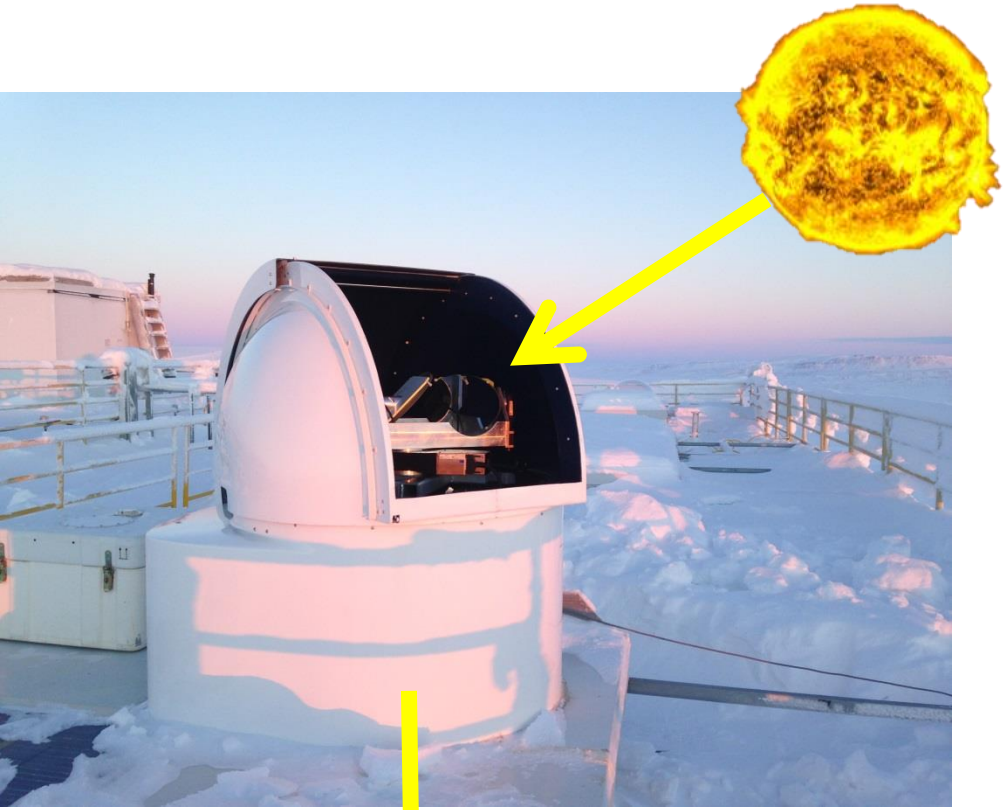


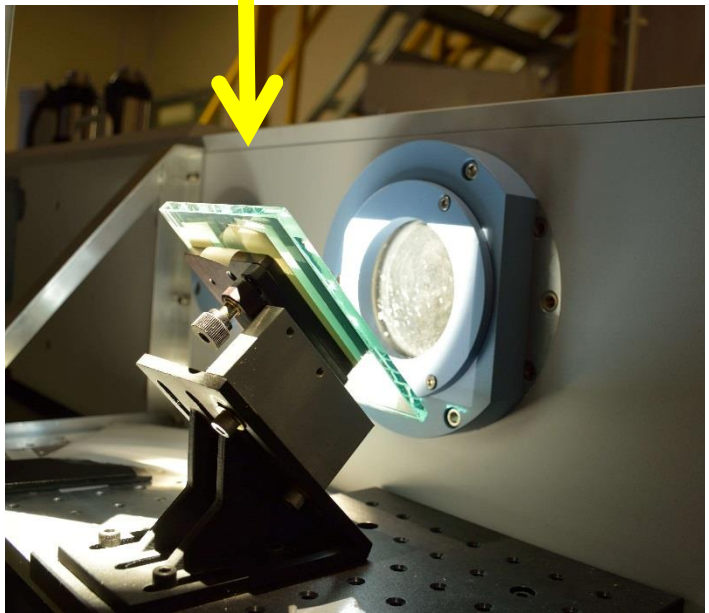
NDACC narrow bandpass filters used at Eureka

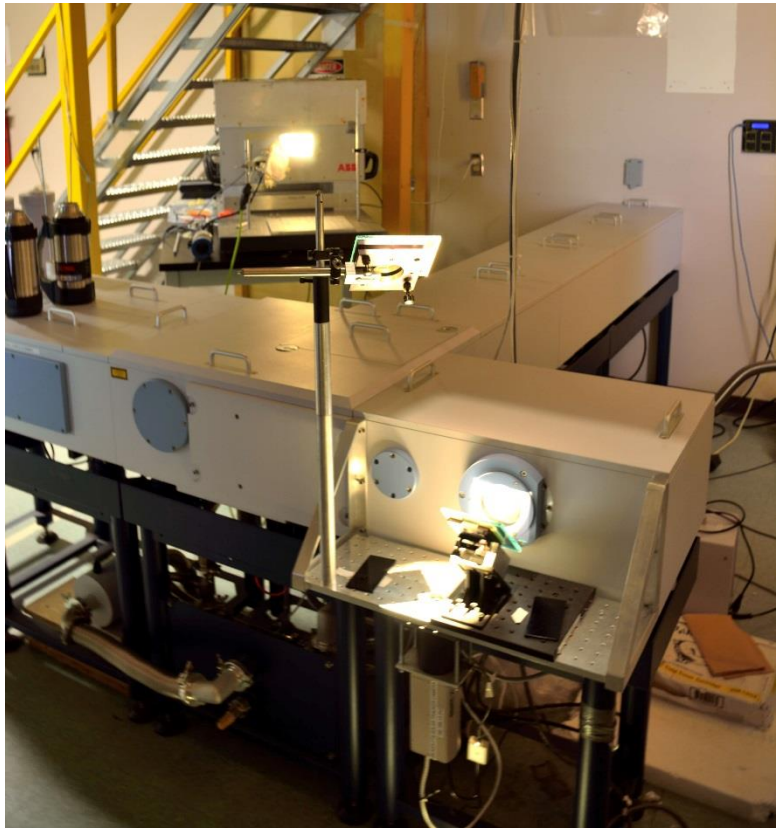
Filter number	Wavenumber range (cm^{-1})	Wavelength range (μm)
1	3950 – 4300	2.32 – 2.53
2	2700 – 3500	2.85 – 3.70
3	2420 – 3080	3.25 – 4.13
4	1950 – 2700	3.70 – 5.13
5	1800 – 2200	4.55 – 5.55
6	700 – 1350	7.40 – 14.28
7*	700 – 1000	10.00 – 14.28
8*	1000 – 1400	7.14 – 10.00

* these filters were installed in August 2007.

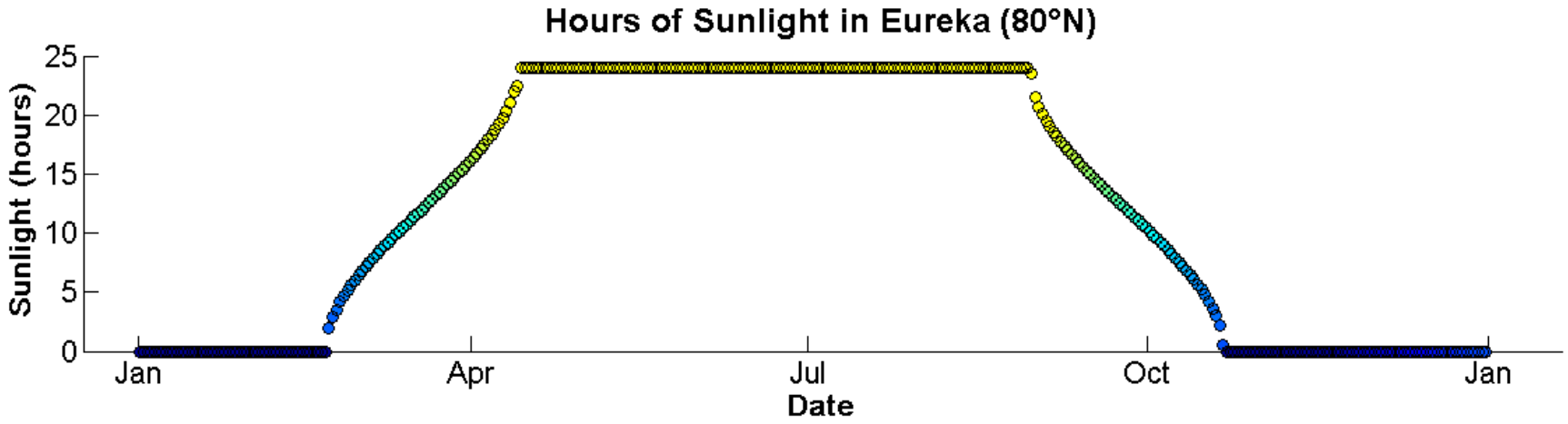
Table from Lindenmaier (2012)







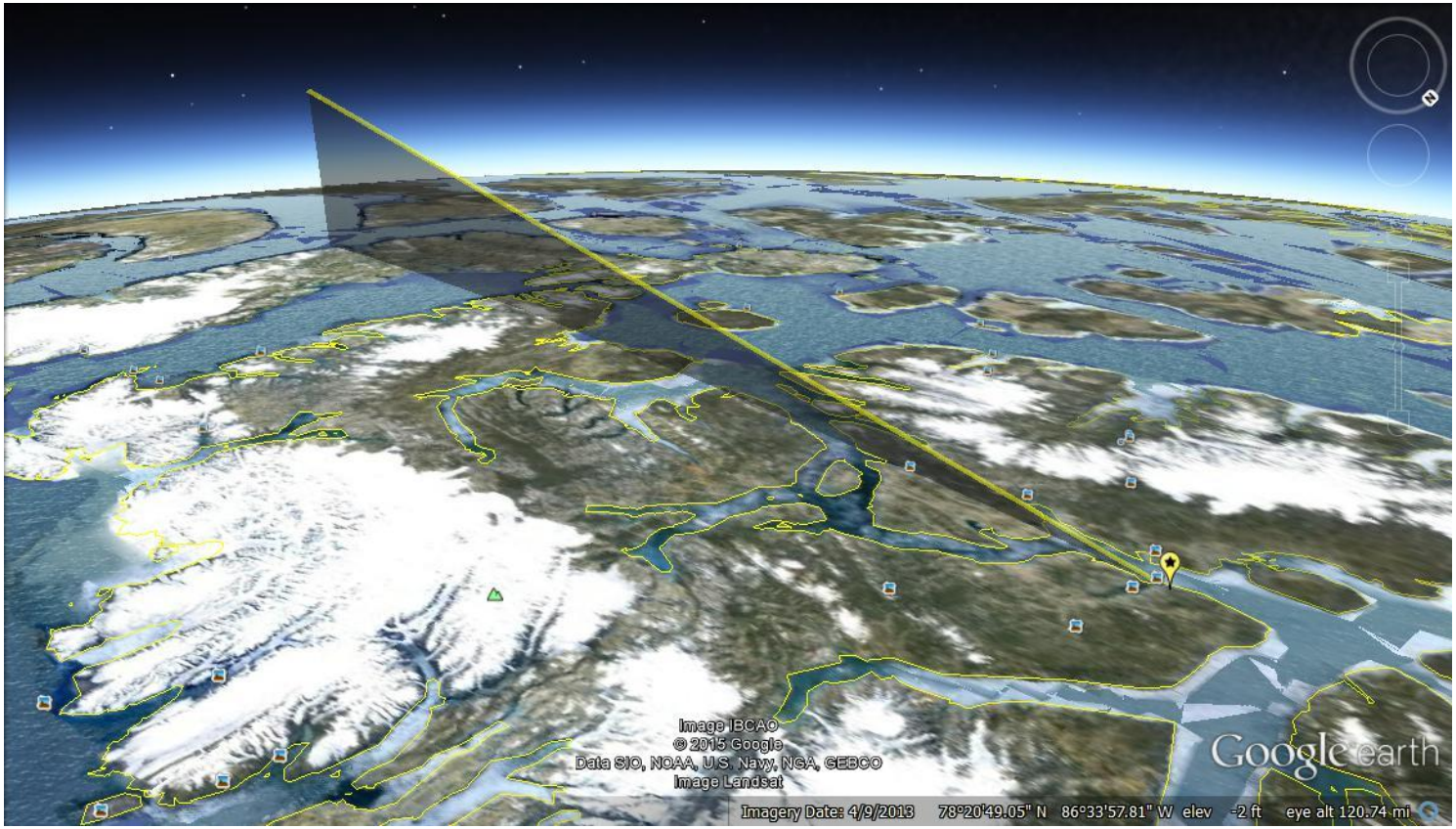
While a powerful technique,
FTIRs are limited to
clear weather, sunny conditions.



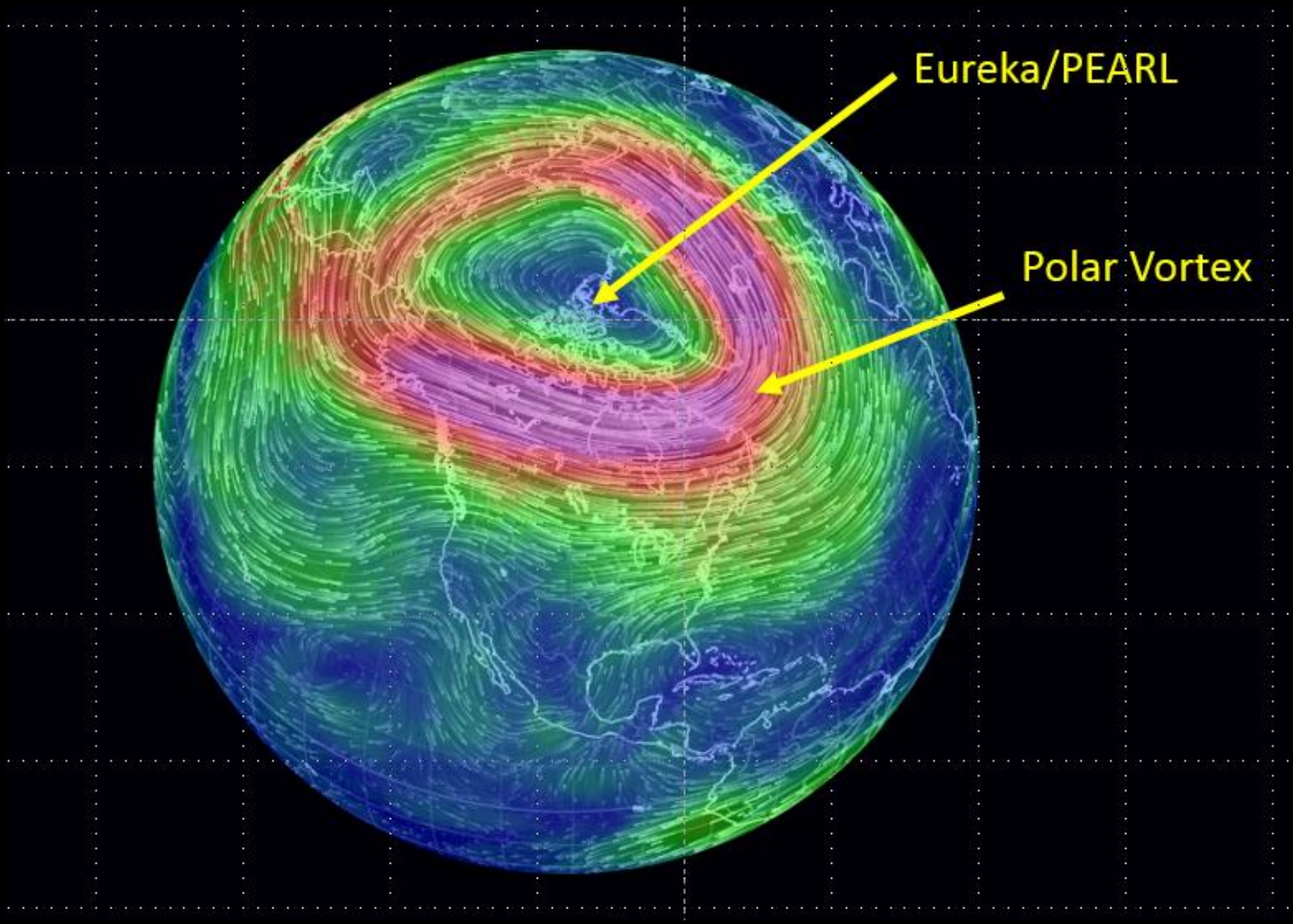
We are currently experimenting with using the moon as a light source…

Because the FTIR is looking at the Sun from a high latitude, we're actually looking south

Measurement at 2 pm, March 10, 2014

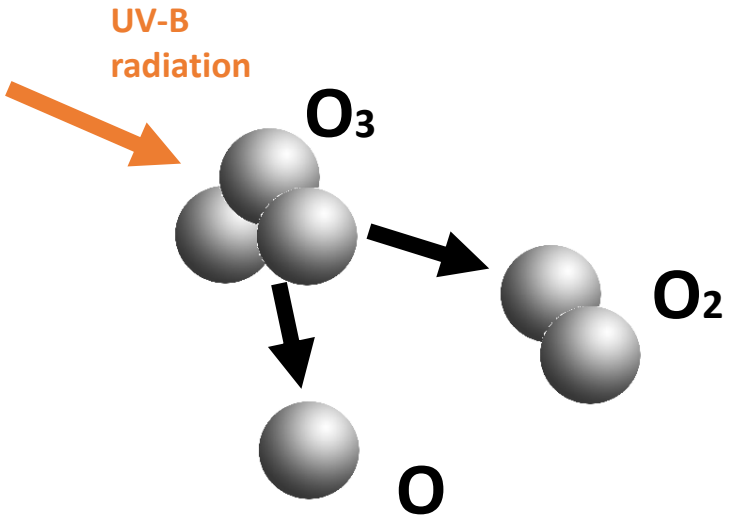


At 8 km altitude, we're measuring ~ 70km away
At 20 km altitude, we're measuring ~150 km away
At 35 km altitude, we're measuring ~250 km away
At 50 km altitude, we're measuring ~350 km away
At 100 km altitude, we're measuring ~600 km away

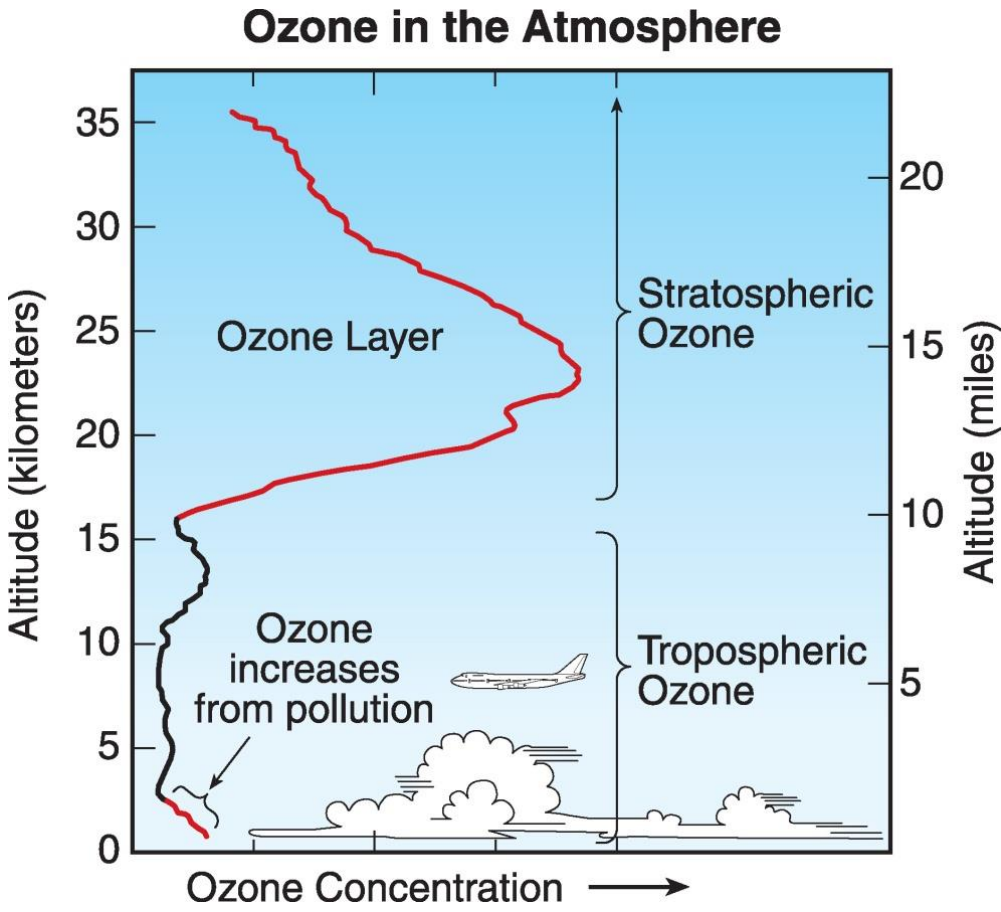

Eureka/PEARL
Polar Vortex

What are we using these measurements to study?

Ozone



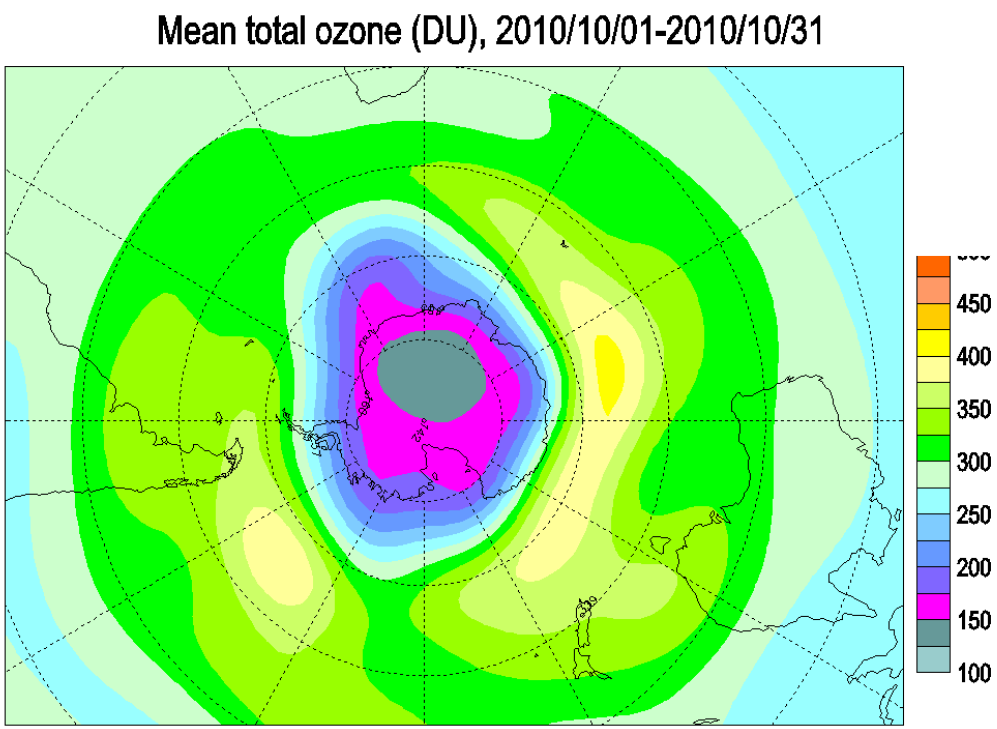
- Ozone in the stratosphere protects us from harmful UV radiation (good!)
- Ozone in the troposphere is a pollutant and harmful to breath! (bad!)



UNEP/WMO, 2006: Fig. Q1-2

"Space isn't remote at all. It's only an hour's drive away if your car could go straight upwards." – Sir Frederick Hoyle

Ozone ‘Hole’ in Antarctic: First Discovered in 1985



What is an Ozone ‘Hole’?

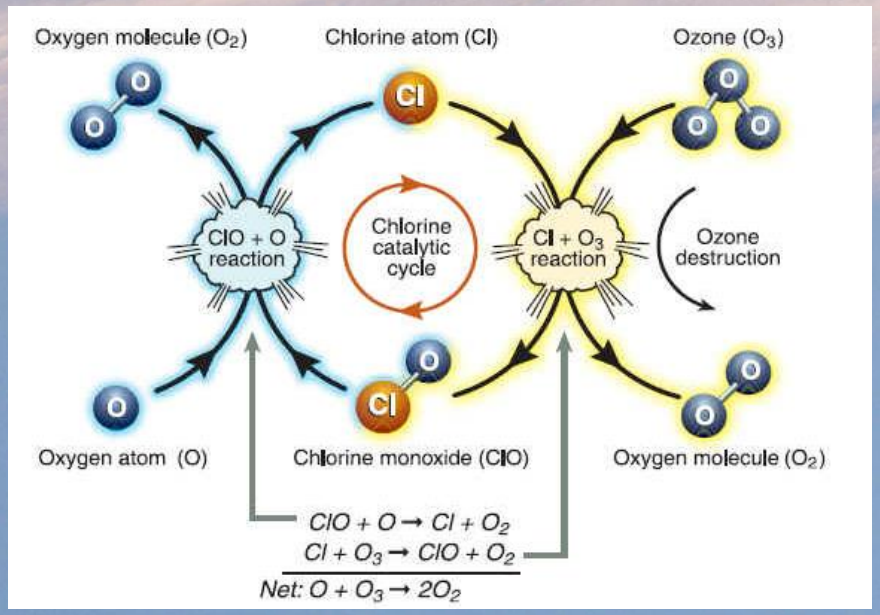
- When there is very *little* ozone
- ~ 1/3 (or less) than usual
- Puts plants and animals at greater risk of UV radiation exposure.
- Too much UV radiation can damage skin cells, which can lead to skin cancer and strong UV radiation can damage the cell structure of plant material.

http://exp-studies.tor.ec.gc.ca/cgi-bin/selectMap?lang=e&type1=du&day1=mm&month1=10&year1=2010&howmany1=1&interval1=1&intervalunit1=m&hem1=s&type2=no&day2=23&month2=02&year2=2010&howmany2=1&interval2=1&intervalunit2=d&hem2=n&mapsize=100

How CFCs destroy ozone

- When CFCs reach the ozone layer, ultraviolet sunlight breaks them apart to form atomic chlorine.

$$CF_2Cl_2 + \text{sunlight} \text{----->} CF_2Cl + Cl$$



One chlorine atom can destroy thousands of ozone molecules, because it is "recycled" through catalytic cycles.

http://www.theozonehole.com/ozonedestruction.htm

Ending Ozone Destruction

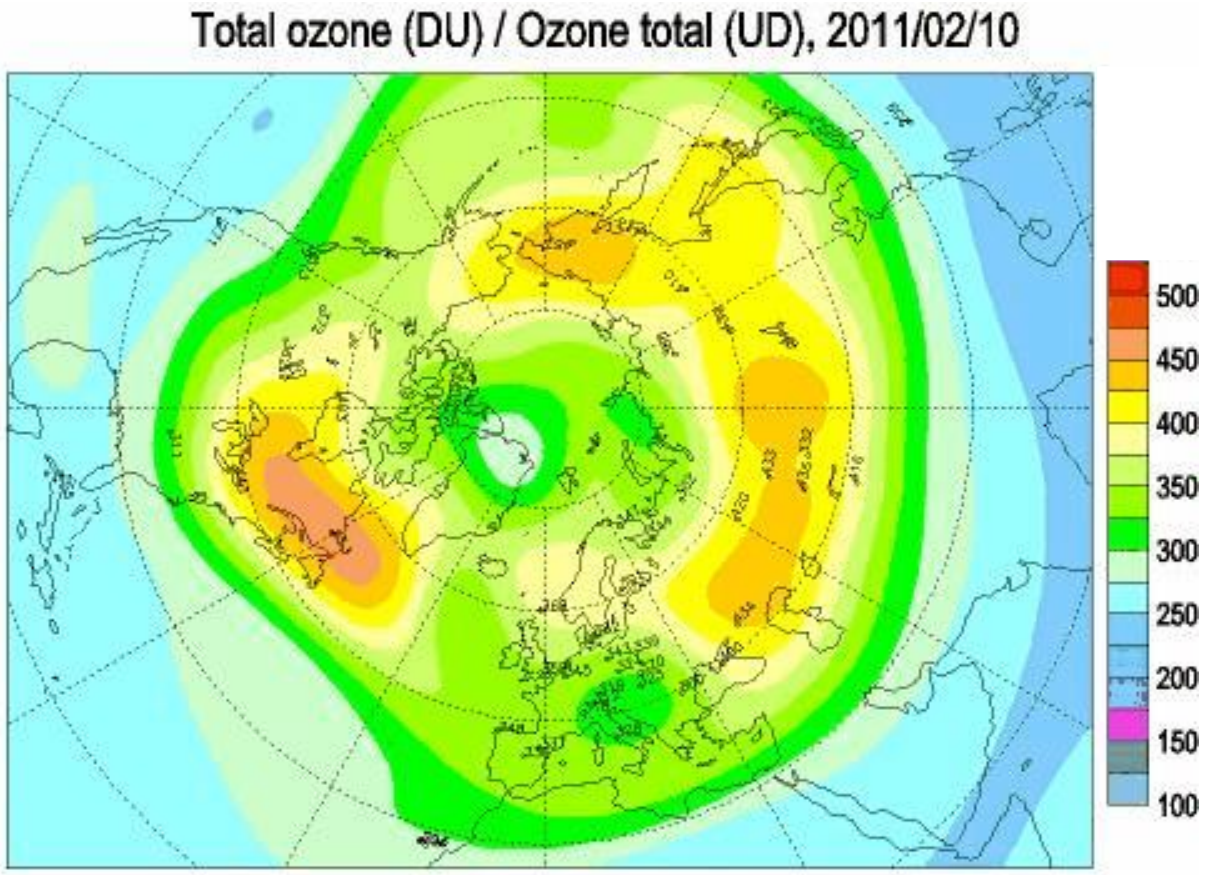
How does this stop?

- When Cl encounters methane, CH_4 or when ClO encounters NO_2, the cycle terminates

$$Cl + CH_4 \text{ ----> } HCl + CH_3$$

$$ClO + NO_2 \text{ ----> } ClNO_3$$

A Big Surprise: 2011 Arctic Ozone Hole

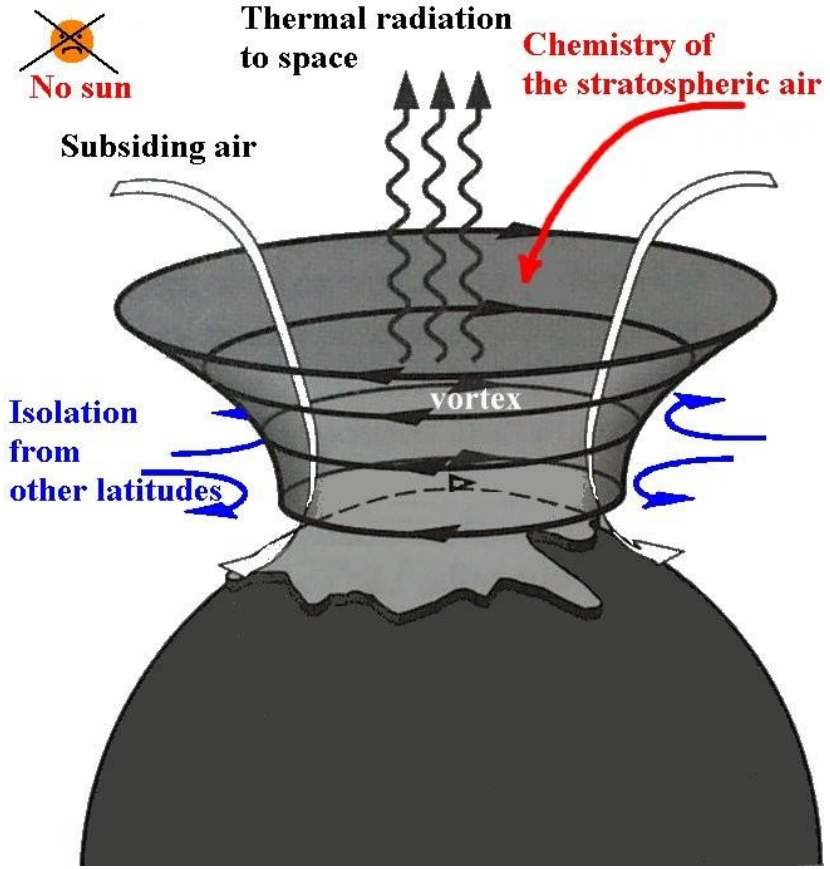


Colder than usual temperatures in the Arctic stratosphere caused the largest ozone depletion event yet observed. Debate surrounds use of the term 'hole'.

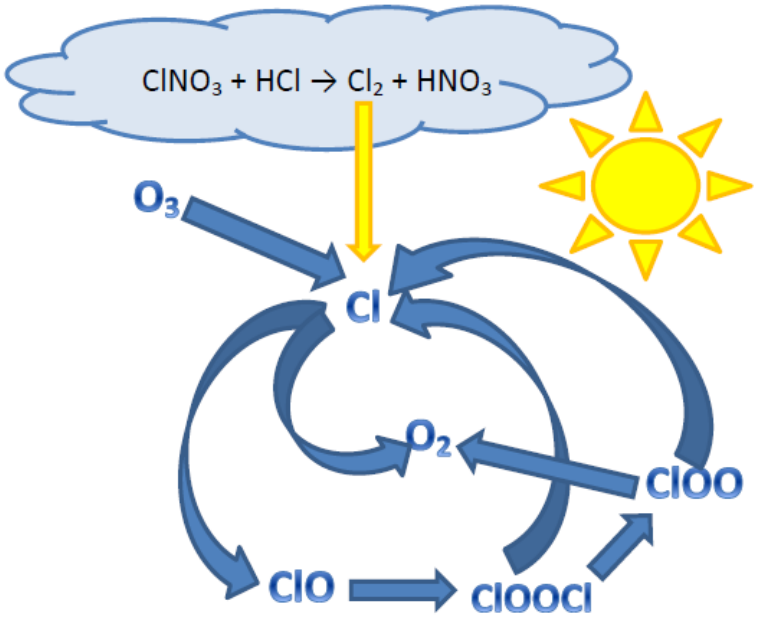
Why Ozone Holes in the polar regions?

The Polar Vortex enables the stratosphere to reach very low temperatures (< 78ºC), allowing Polar Stratospheric Clouds to form.

PSCs provide a surface for ozone-destroying chemical reactions to happen.



PSC chemistry

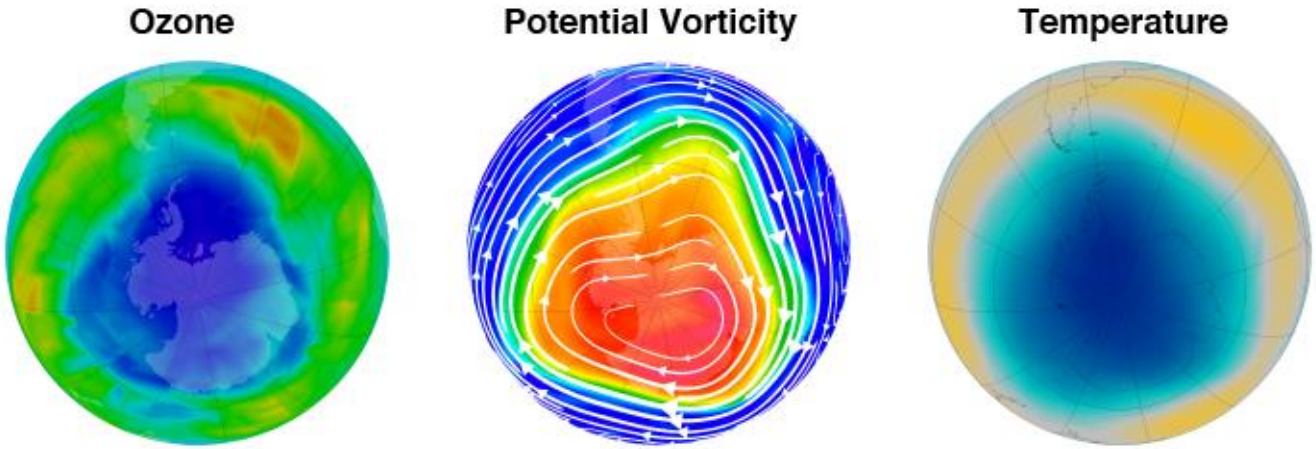


$ClONO_2 + HCl \rightarrow Cl_2 + HNO_3$

$Cl_2 + sunlight \rightarrow 2\ Cl$

$Cl + O_3 \rightarrow O_2 + ClO$

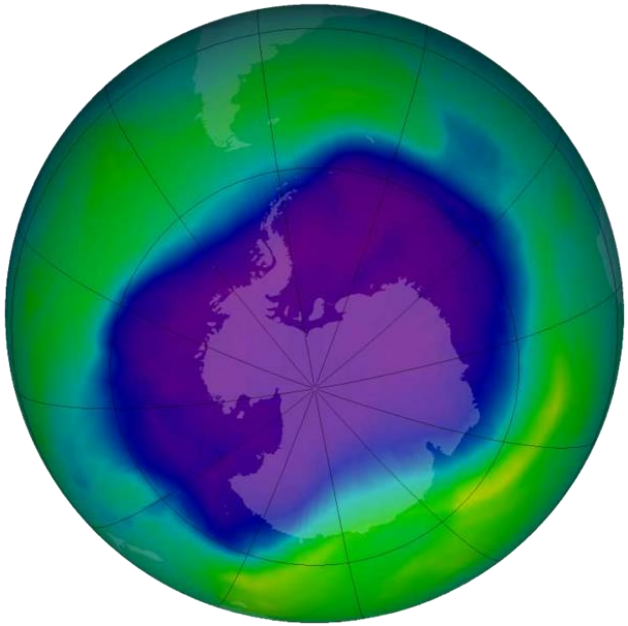
Without PSCs, $ClONO_2$ and HCl would not generate active chlorine, but instead would remain in a reservoir until eventually deposited to the ground.



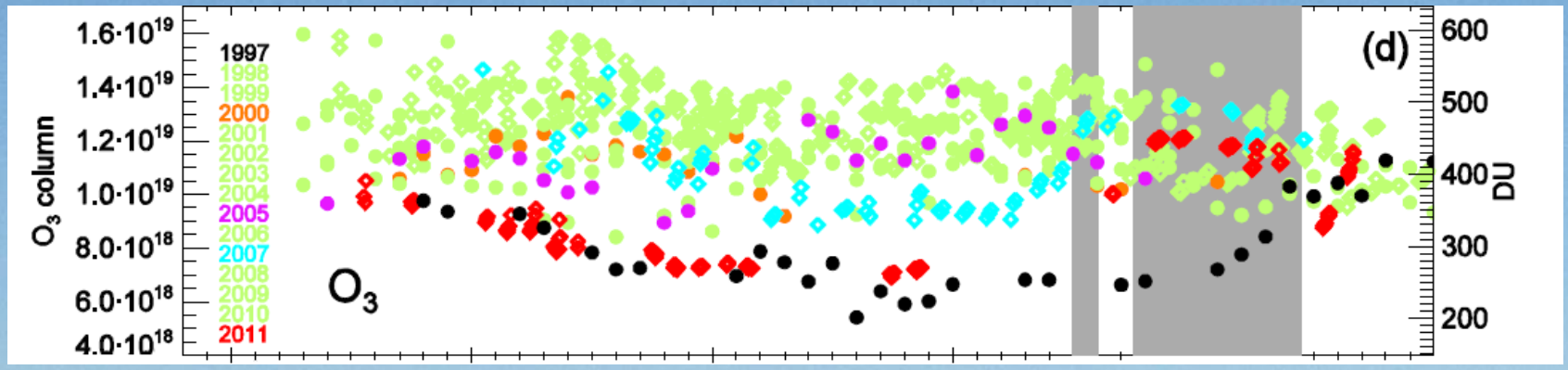
Why is ozone depletion *still* a problem?

- CFCs have a long lifetime.
- It will take at least another 50 years for a full recovery
- This should be a warning for us to be cautious about modifying the Earth's atmosphere...

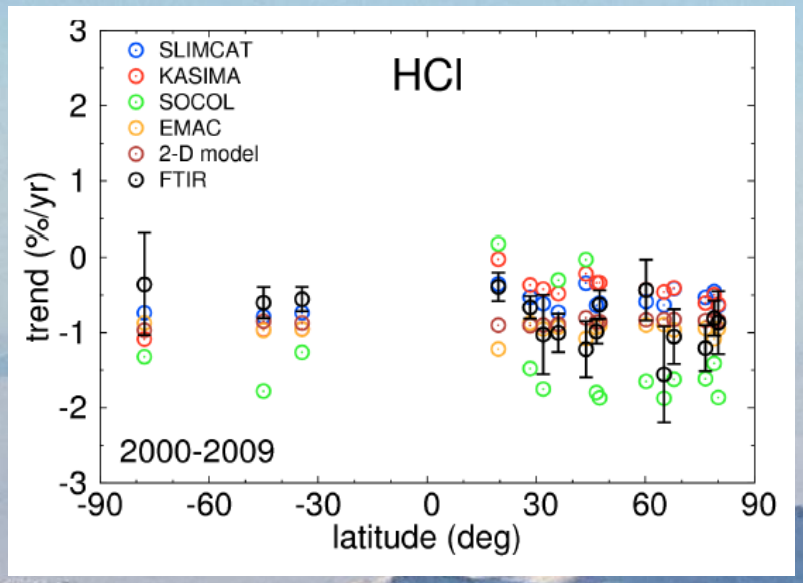
2006's Antarctic ozone hole:



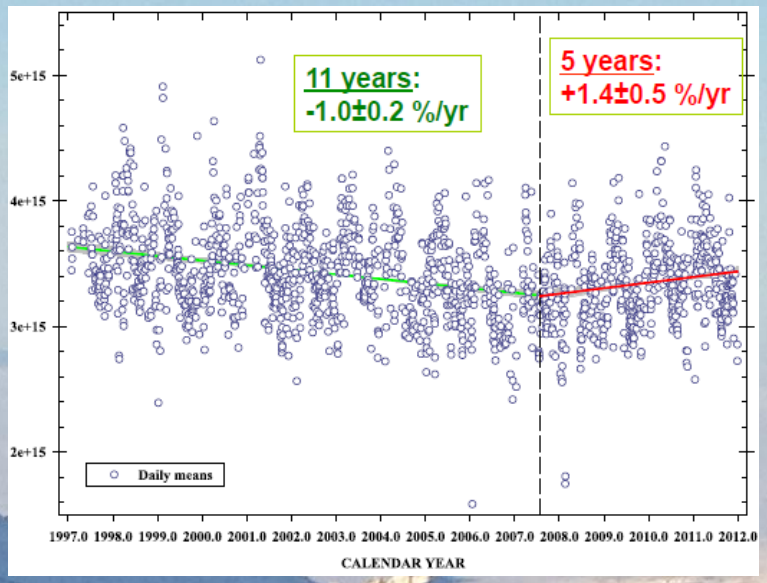
Current research into trends



PEARL O_3 timeseries from Lindenmaier (2012)



Global HCl trends from Kohlhepp (2012)



Jungfraujoch HCl from Mahieu (2012)

FTIRs have a useful advantage

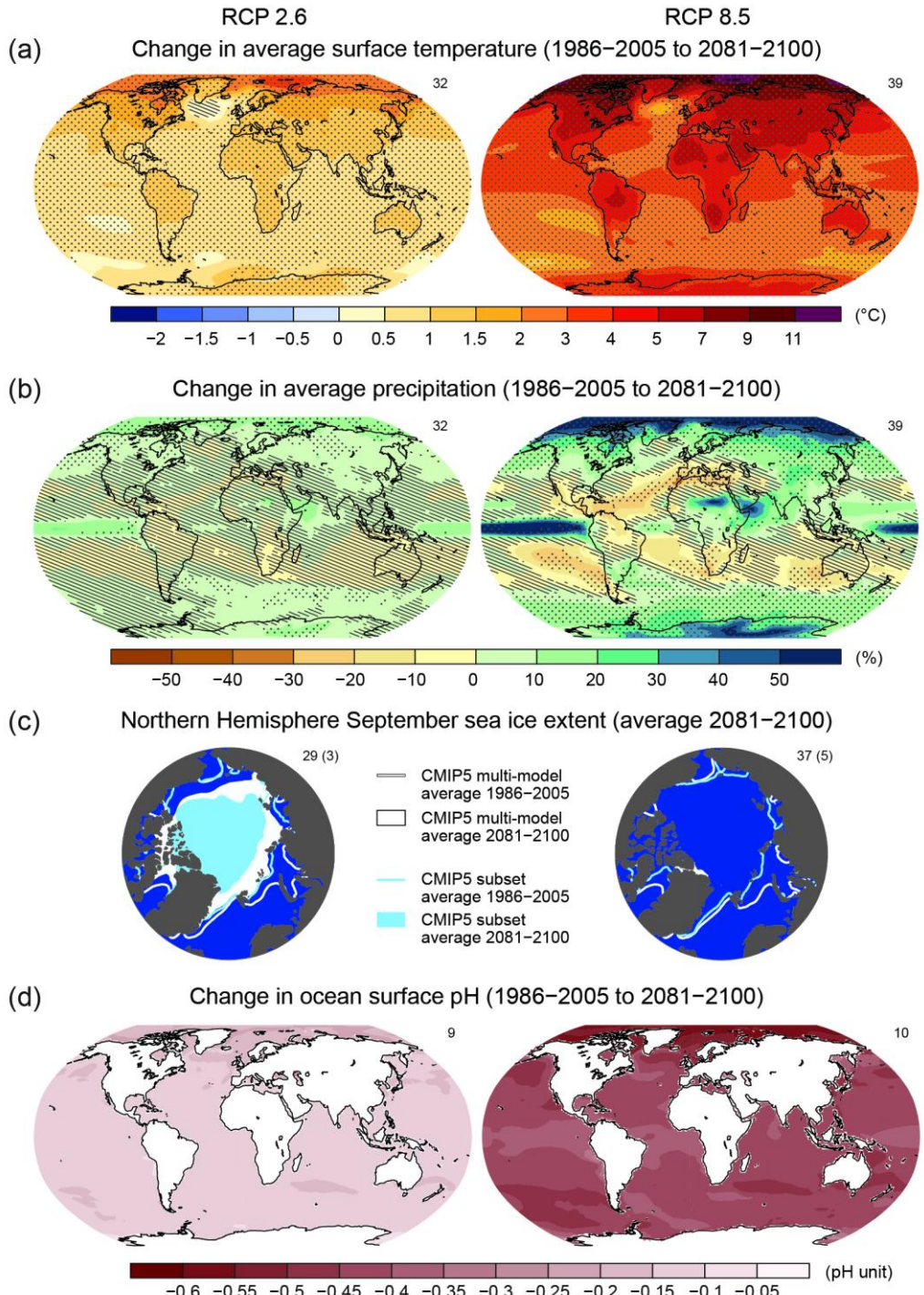
- They can take large spectra from which *many* atmospheric gases can be measured simultaneously
- This is a powerful means of observing chemistry.
- PEARL's FTIR measurements are being used to investigate conversions between active and reservoir forms of Chlorine, and the relationships with nitrogen chemistry

Climate change

- Over the last 50 years, the Arctic has warmed by 5°C

  (Lesins et al. 2010)

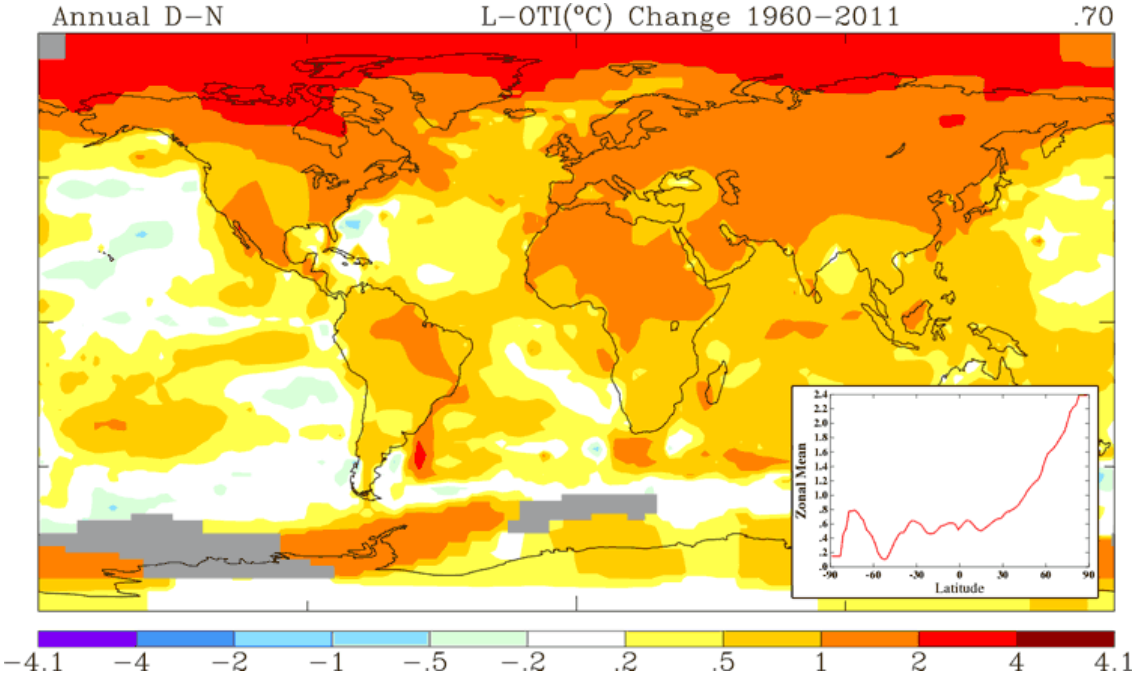
- The Arctic is expected to warm more than & faster than any other area of the world. (IPCC, 2014)

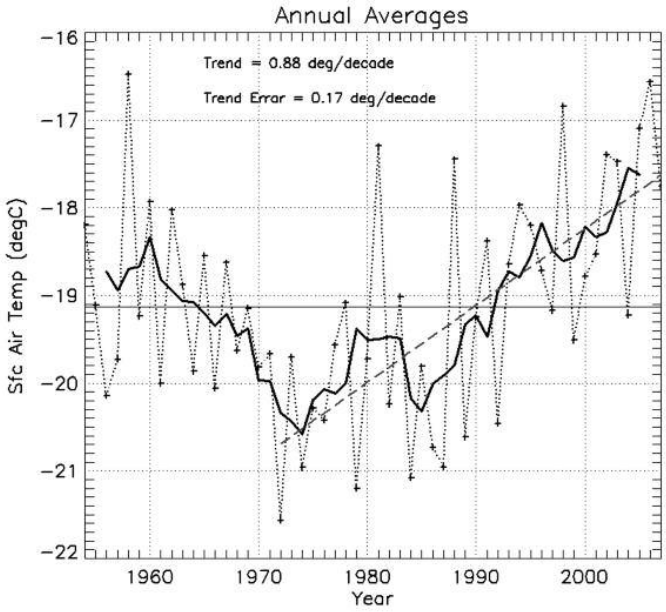


Arctic temperature change

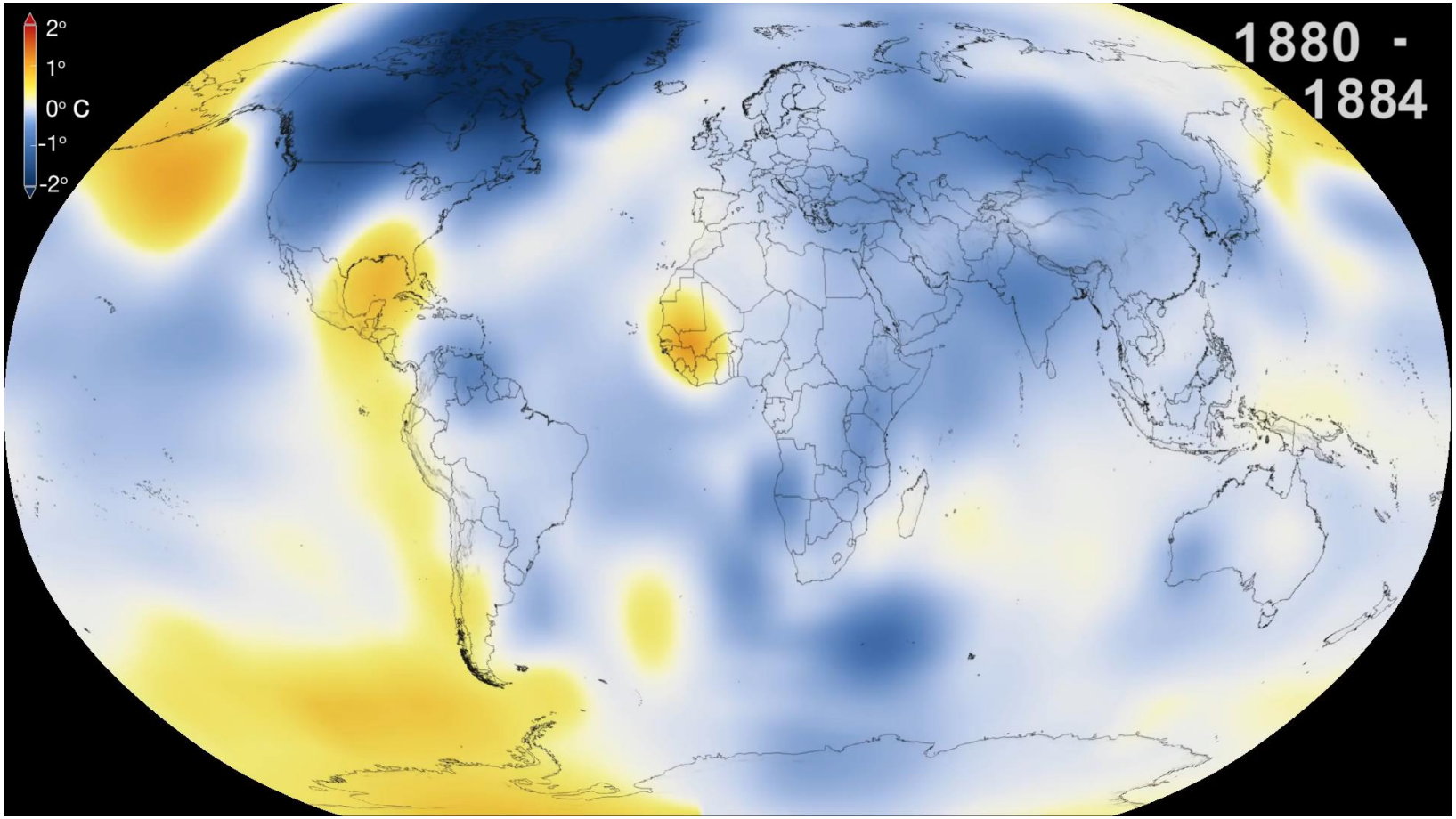
Eureka temperature trend:
0.88°C/decade since 1972
(Lesins et al. 2010)

Total warming:
- 1.5°C summer (least)
- 4.5°C autumn (most)





Global temperature change



Total Carbon Column Observing Network (TCCON)

Arctic climate & water vapour

Mid-latitudes

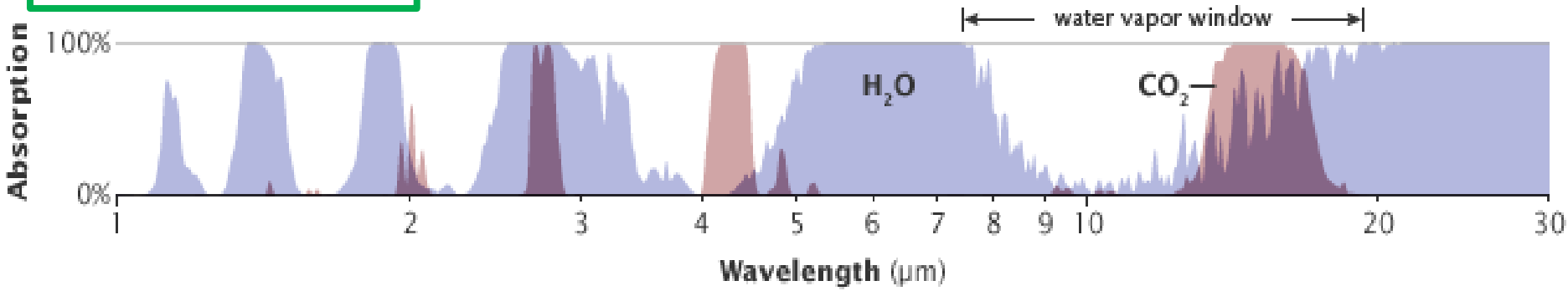


Image credit: http://earthobservatory.nasa.gov/Features/EnergyBalance/page7.php

Arctic

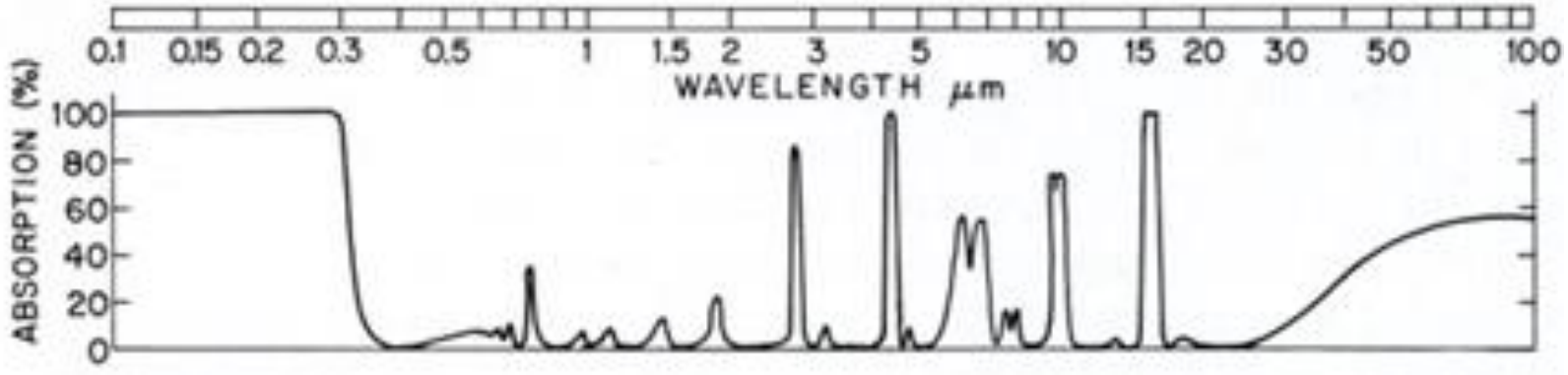
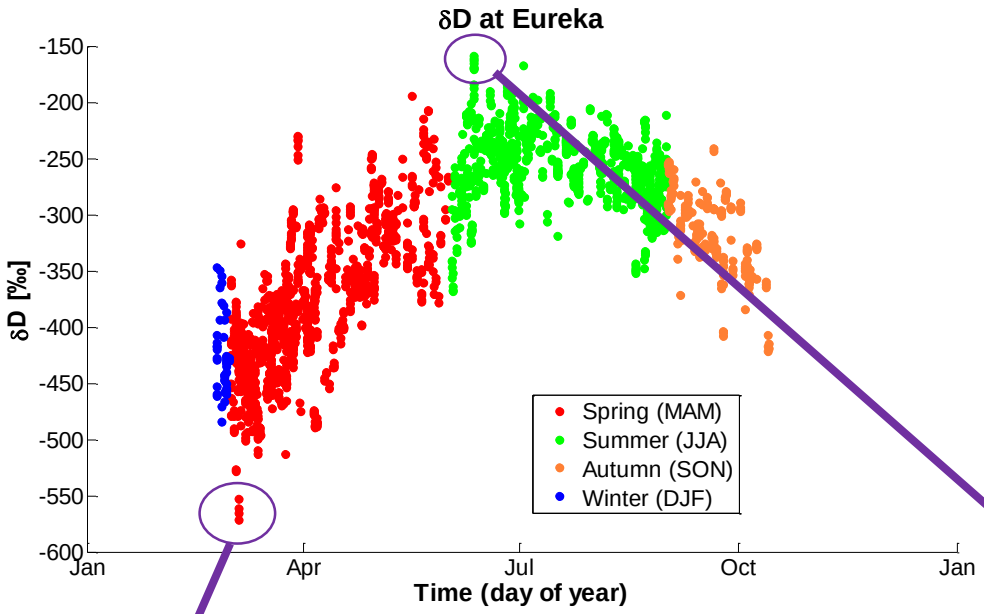
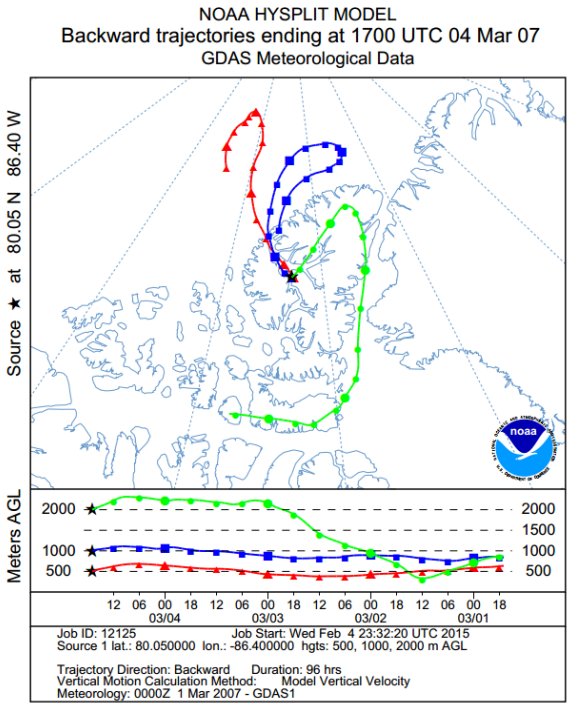
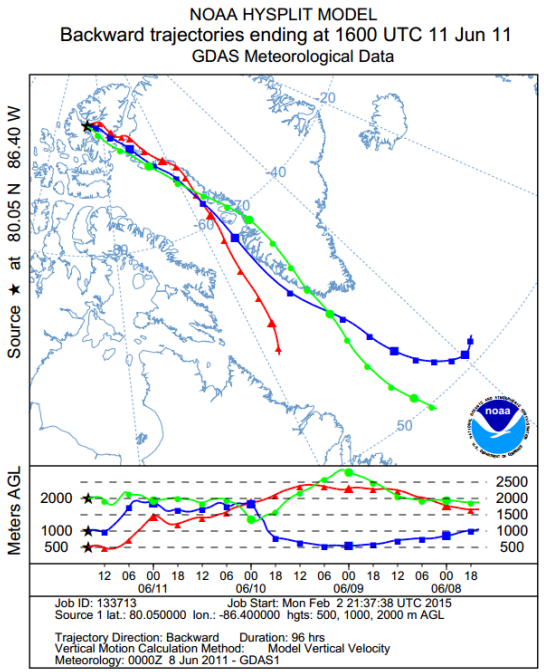


Image credit: Zak, B. and K. Stamnes (1997): ARM Science Meeting – Session Papers. 19-25


δD at Eureka
δD [‰]
-150
-200
-250
-300
-350
-400
-450
-500
-550
-600
Jan
Apr
Jul
Oct
Jan
Time (day of year)
Spring (MAM)
Summer (JJA)
Autumn (SON)
Winter (DJF)


NOAA HYSPLIT MODEL
Backward trajectories ending at 1700 UTC 04 Mar 07
GDAS Meteorological Data
Source ★ at 80.05 N 86.40 W
Meters AGL
2000
1000
500
12 06 00 18 12 06 00 18 12 06 00 18 12 06 00 18
03/04 03/03 03/02 03/01
Job ID: 12125 Job Start: Wed Feb 4 23:32:20 UTC 2015
Source 1 lat.: 80.050000 lon.: -86.400000 hgts: 500, 1000, 2000 m AGL
Trajectory Direction: Backward Duration: 96 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Mar 2007 - GDAS1


NOAA HYSPLIT MODEL
Backward trajectories ending at 1600 UTC 11 Jun 11
GDAS Meteorological Data
Source ★ at 80.05 N 86.40 W
Meters AGL
2000
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1500
1000
500
12 06 00 18 12 06 00 18 12 06 00 18 12 06 00 18
06/11 06/10 06/09 06/08
Job ID: 133713 Job Start: Mon Feb 2 21:37:38 UTC 2015
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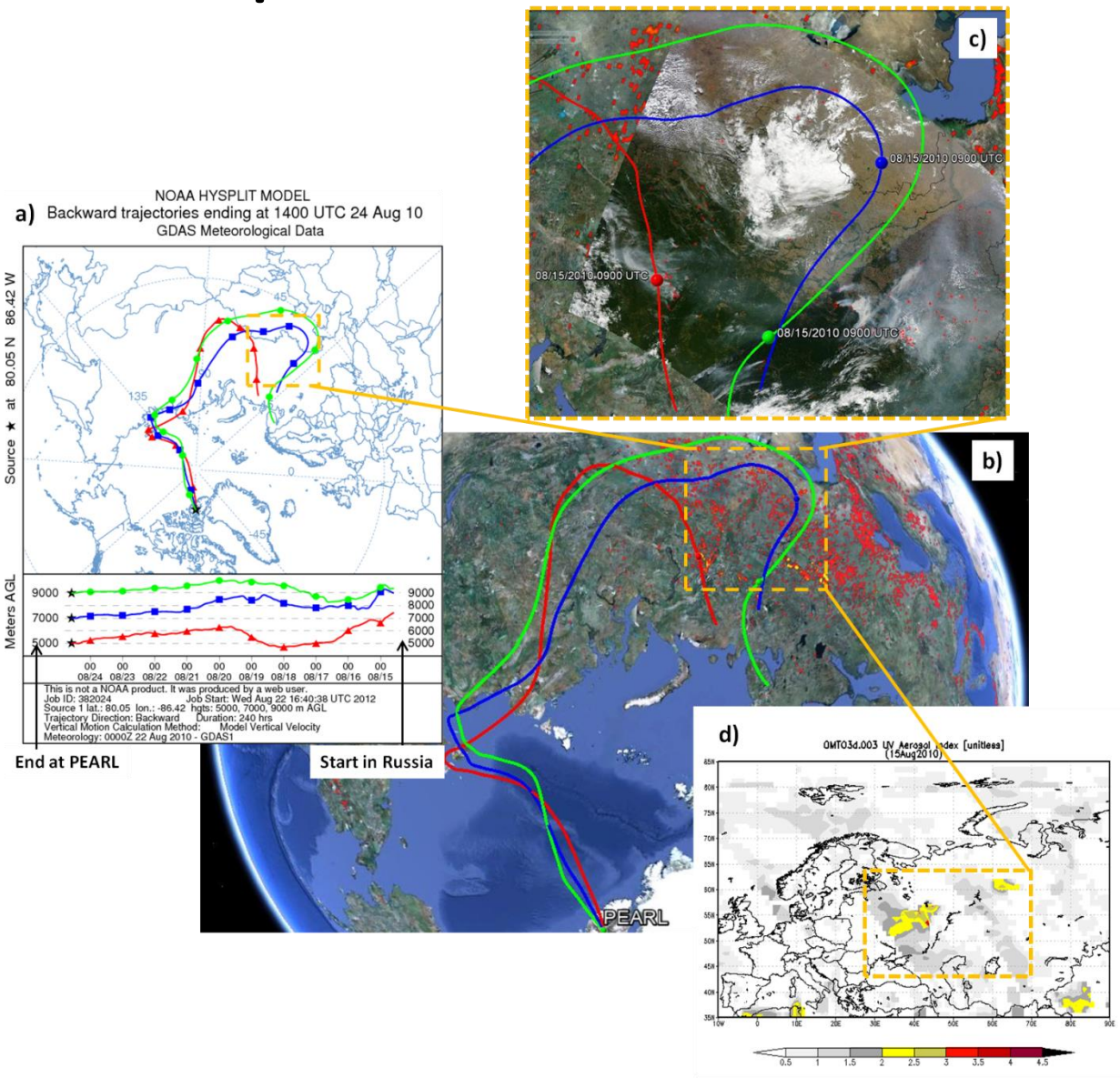
Trajectory Direction: Backward Duration: 96 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 8 Jun 2011 - GDAS1

Pollution transport



One more science objective…

Satellite validation

Eureka is easy to get to …for a satellite!

Sun-synchronous orbits provide global coverage, and frequently pass over the poles

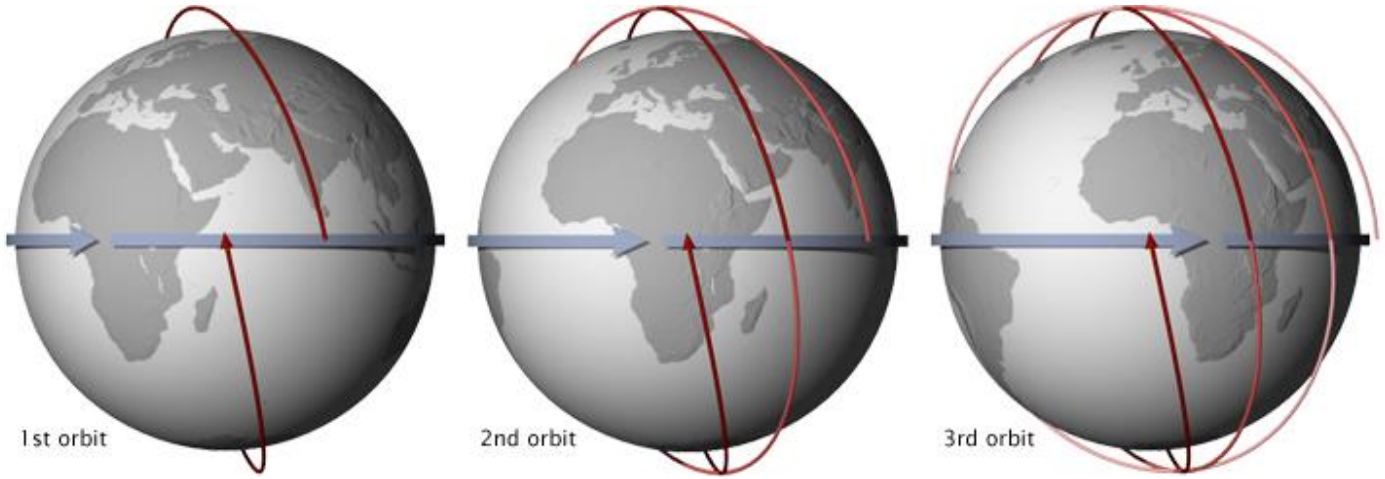
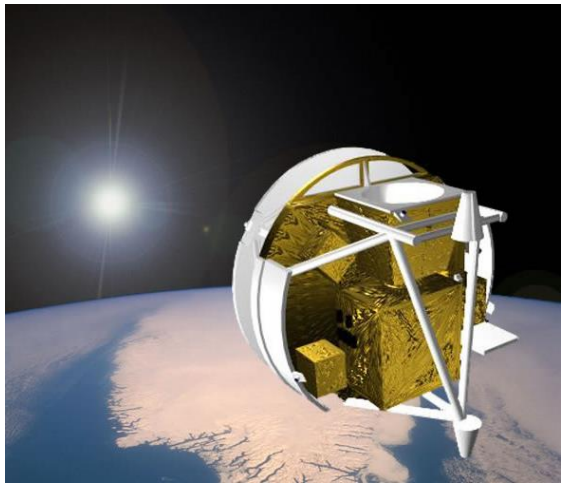


Figure from http://earthobservatory.nasa.gov/Features/OrbitsCatalog/page2.php

ACE (Canada)

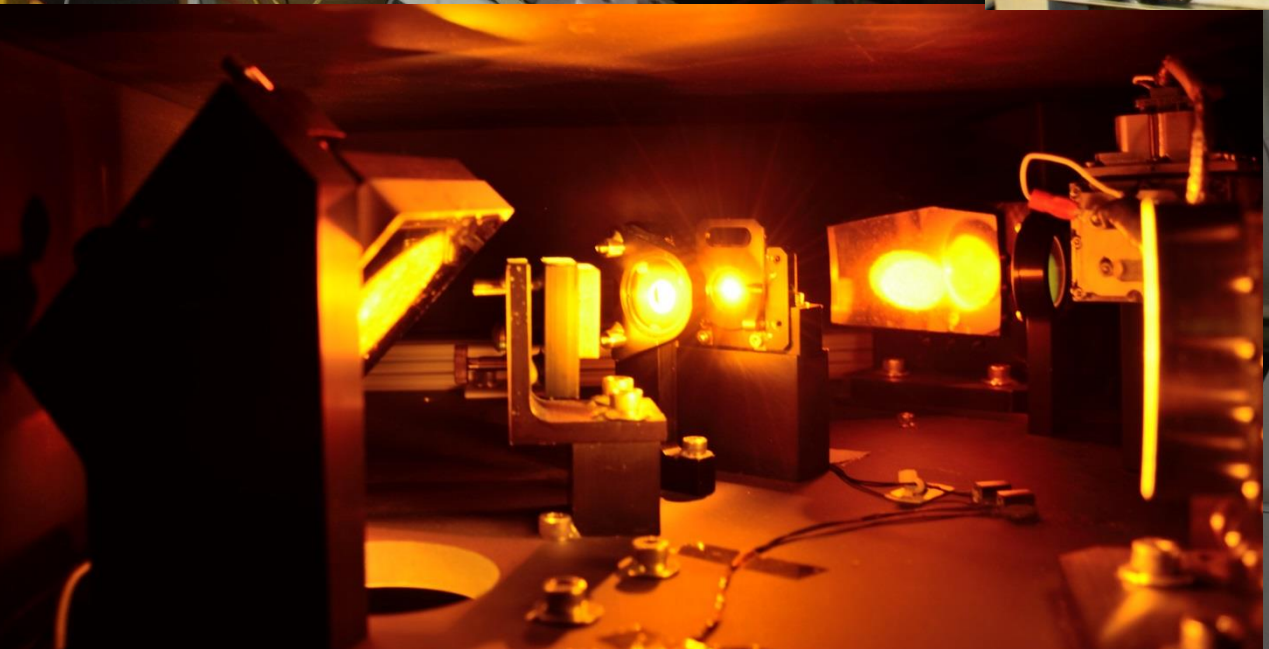


OCO-2 (U.S. NASA)

Odin (Sweden & Canada)

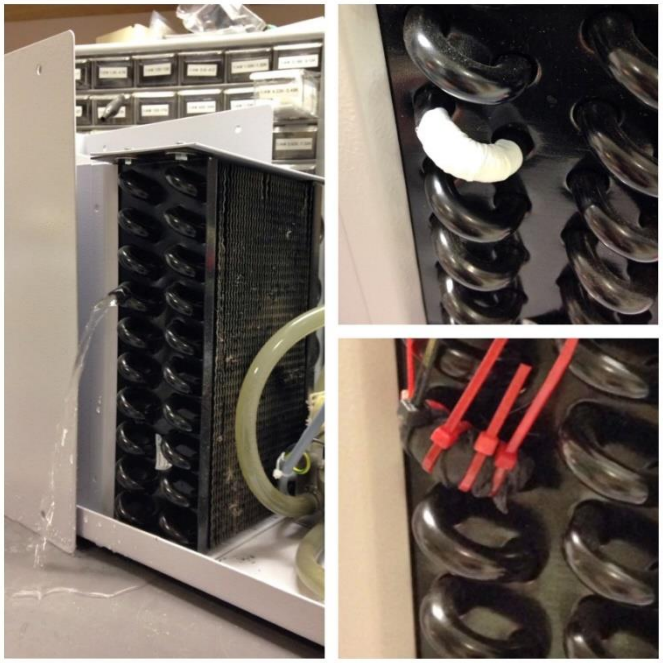
GOSAT (Japan)

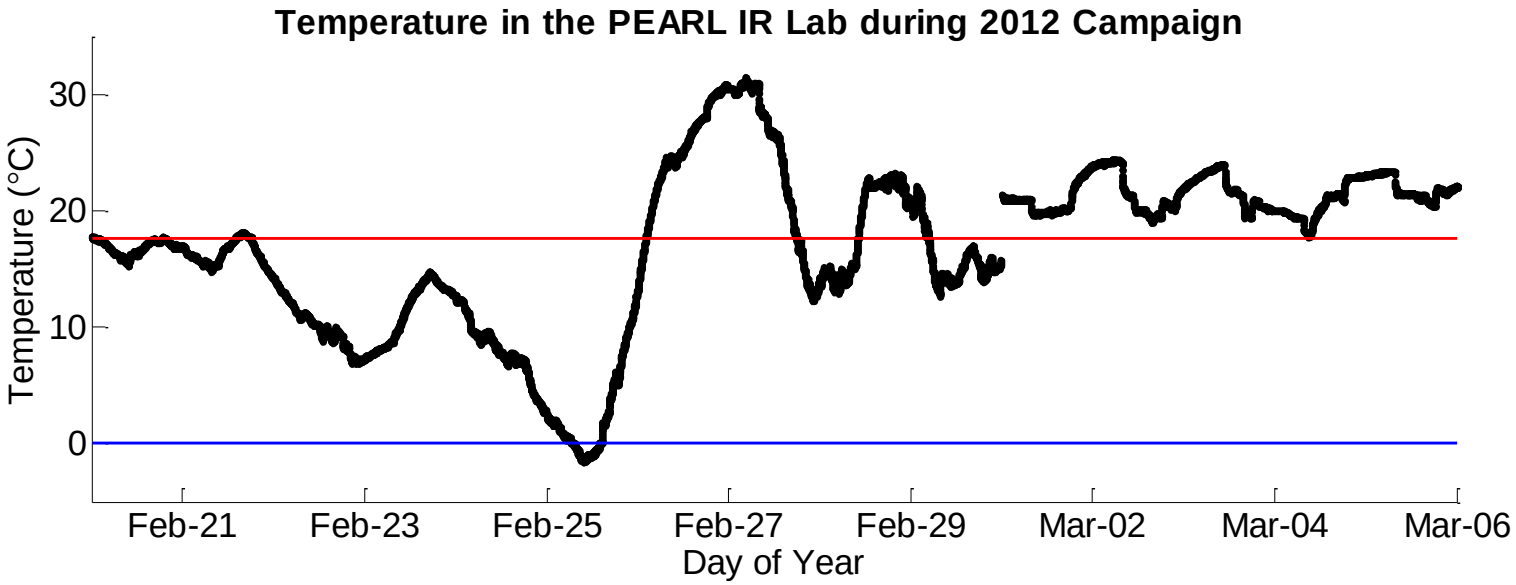
PARIS



Working in the extreme cold is challenging, for people & equipment

Operational challenges abound



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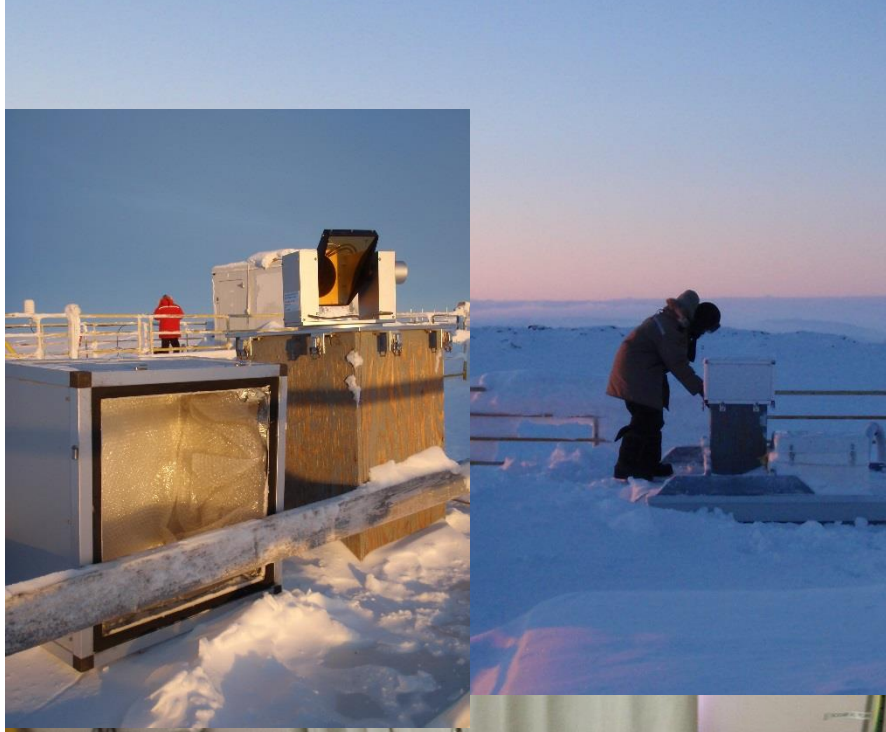
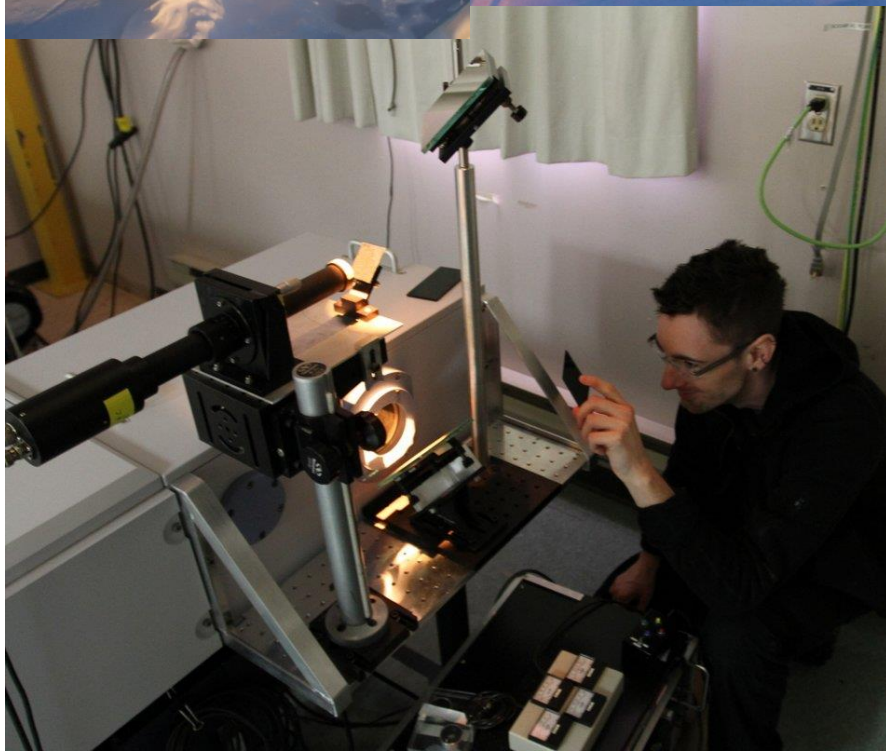
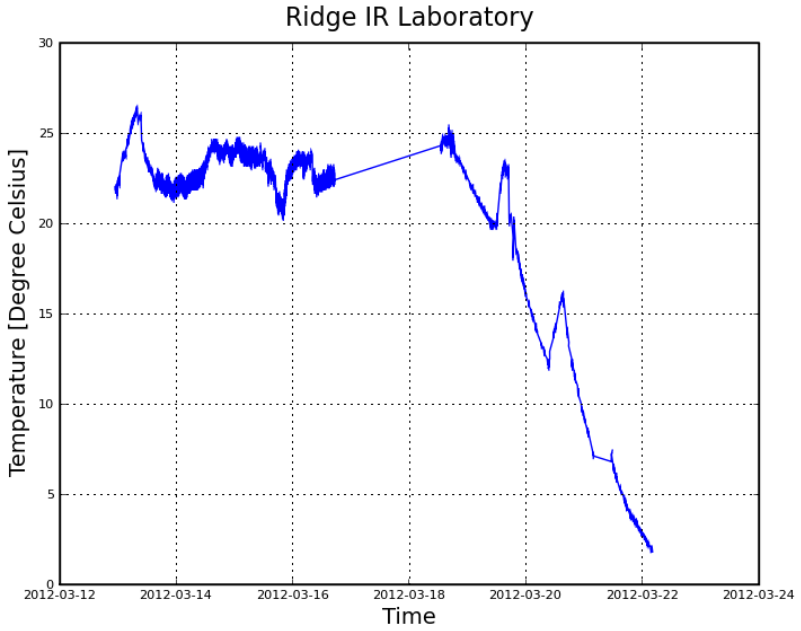
Upgrades





Heat & Cooling

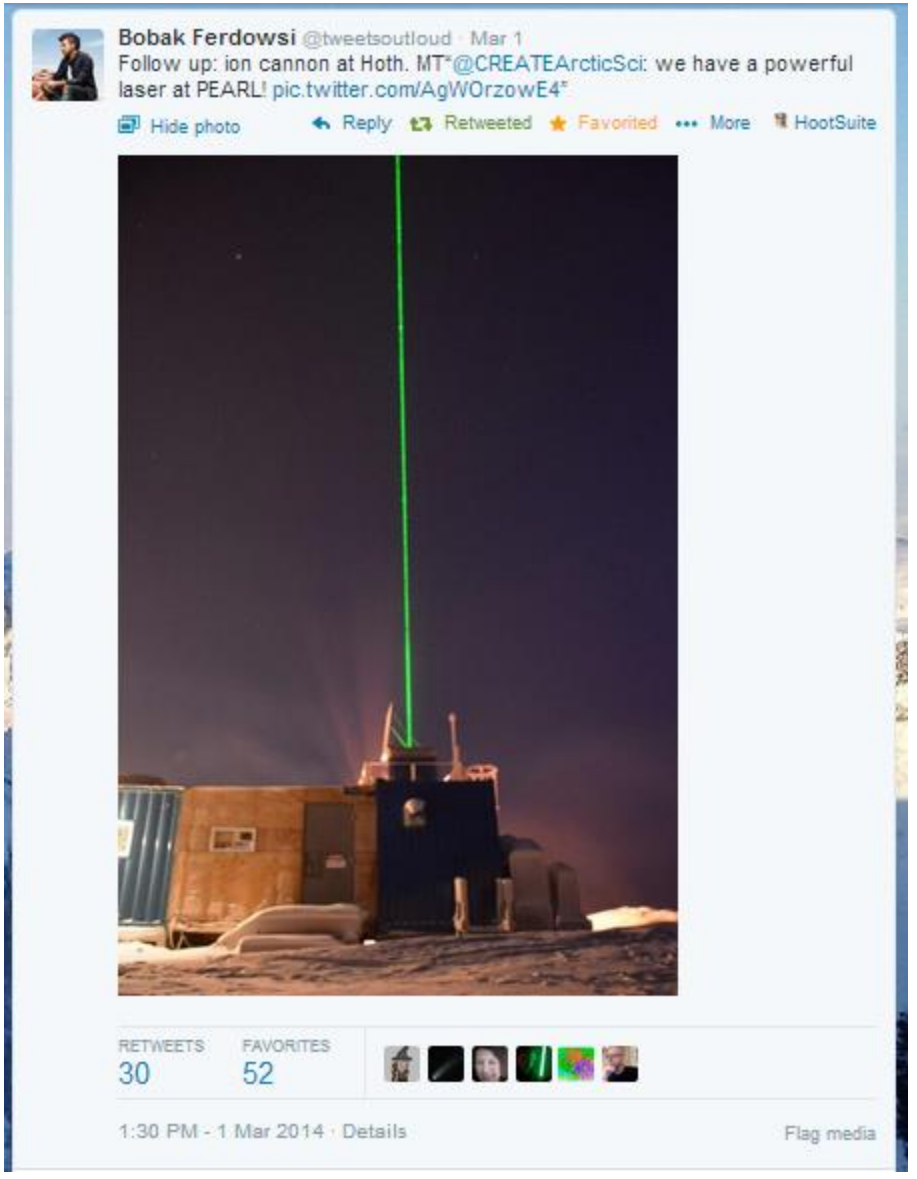
Arctic challenges



Internet

- Website for CANDAC, which runs PEARL
- Campaign website
- Social media
  - Twitter
  - Instagram
  - blog

Twitter: jokes with NASA engineer & former internet meme



& more fun

Thank you.

More information

www.twitter.com/CREATEarcticsci

www.instagram.com/CREATEarcticsci

http://createarcticscience.wordpress.com/

http://acebox.uwaterloo.ca/eureka/

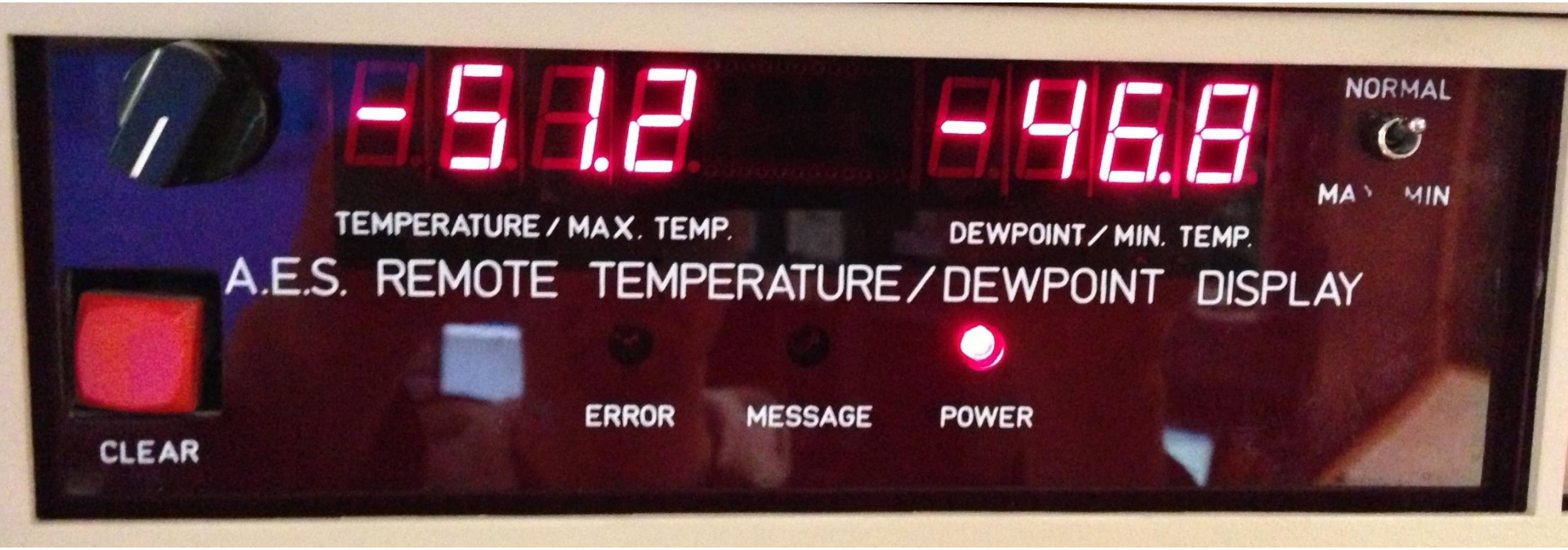
CANDAC.ca

Contact me

dweaver@atmosp.physics.utoronto.ca

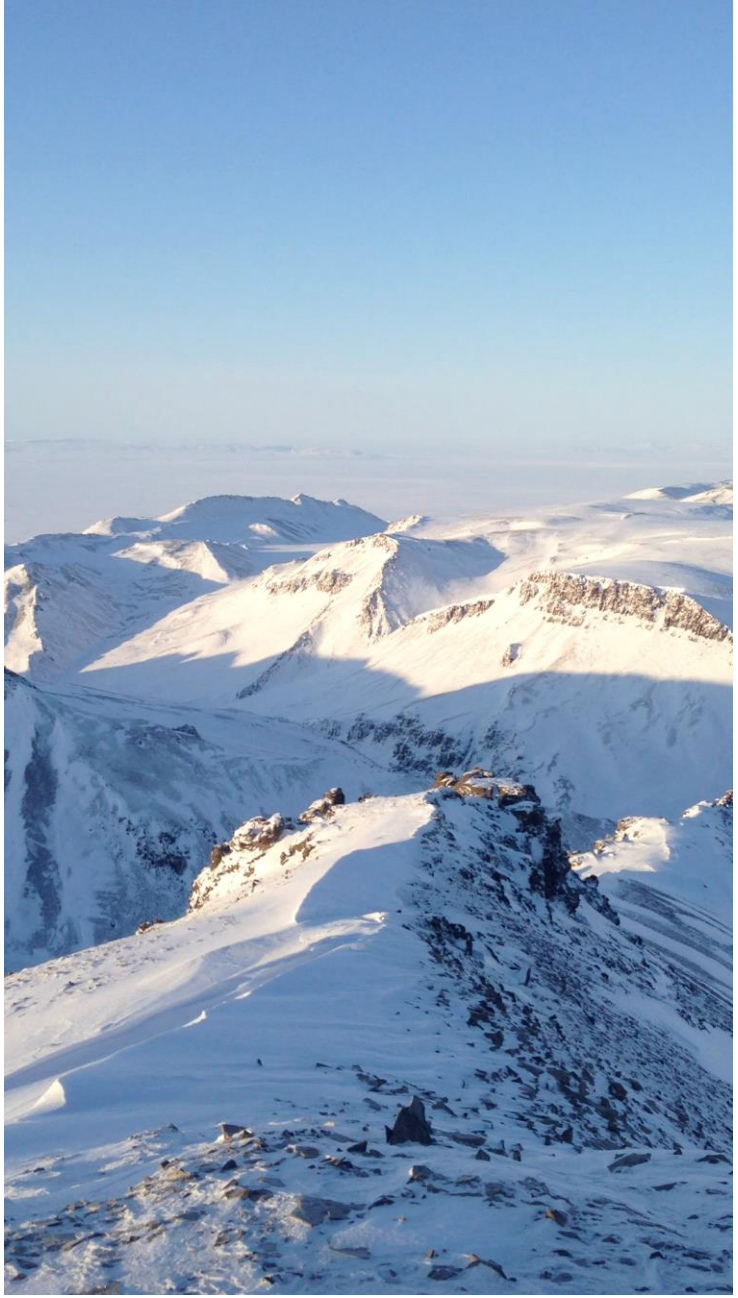

Exploring
Eureka

Temperature



Dress warmly!

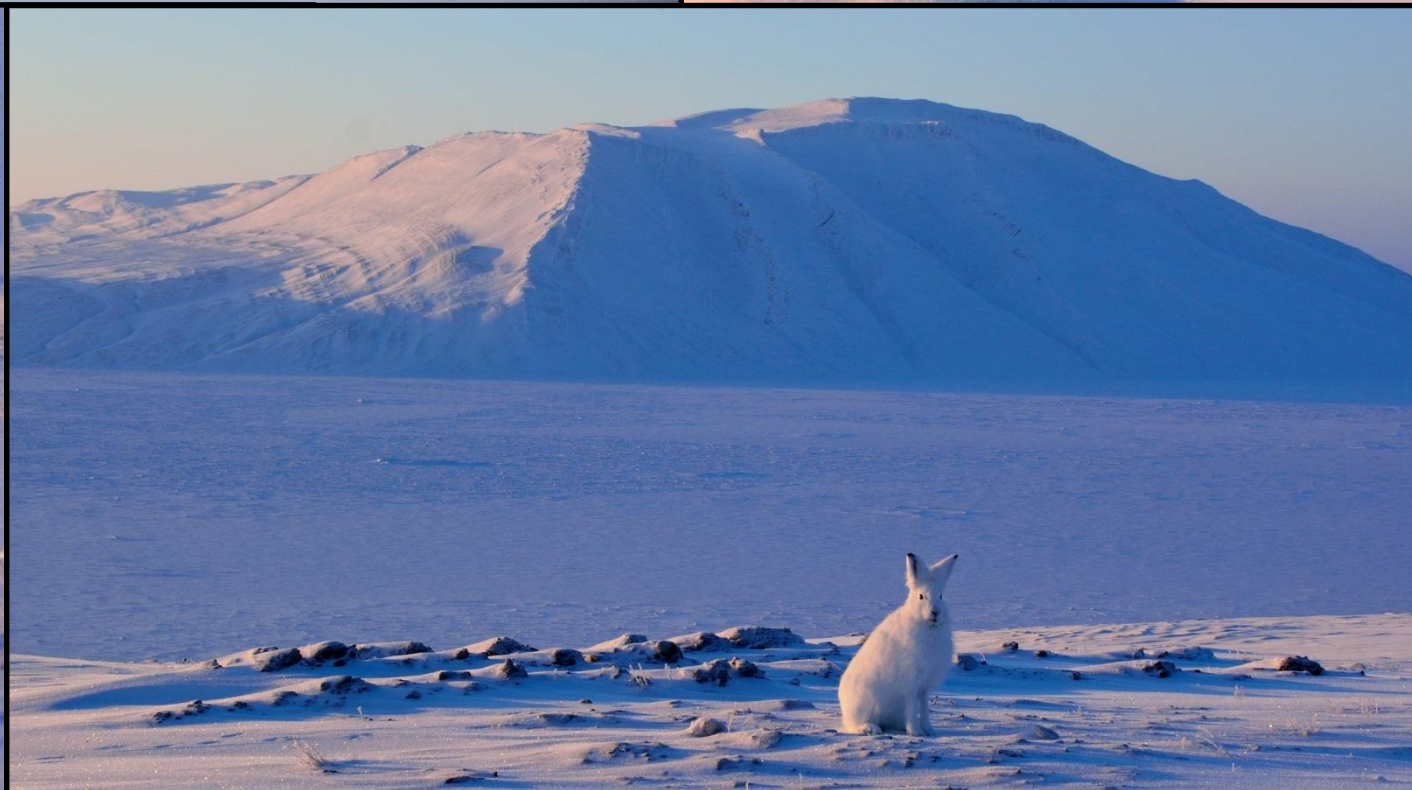

Bring a sense of adventure & curiosity



Night hikes

Arctic Wildlife


© Dan Weaver

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Scenery


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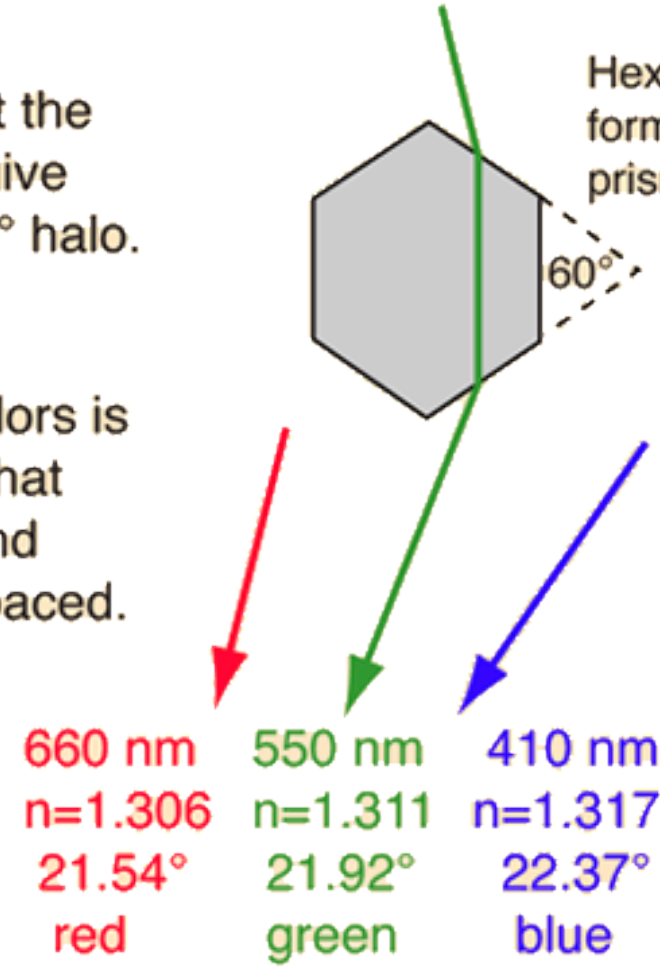
Parhelia, or “sun dogs”
(parhelion is singular)

Halo & sundog explanation

Hexagonal ice crystals refract the sun's rays to give the familiar 22° halo.

The order of colors is reversed from that of diffraction, and more closely spaced.



Source: http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/halo22.html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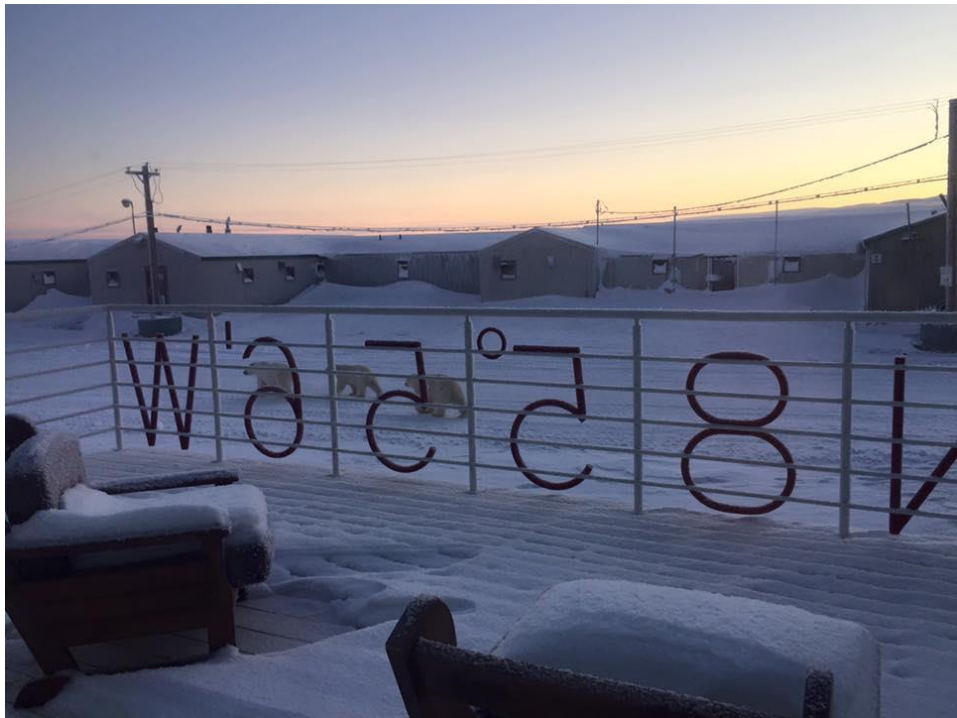
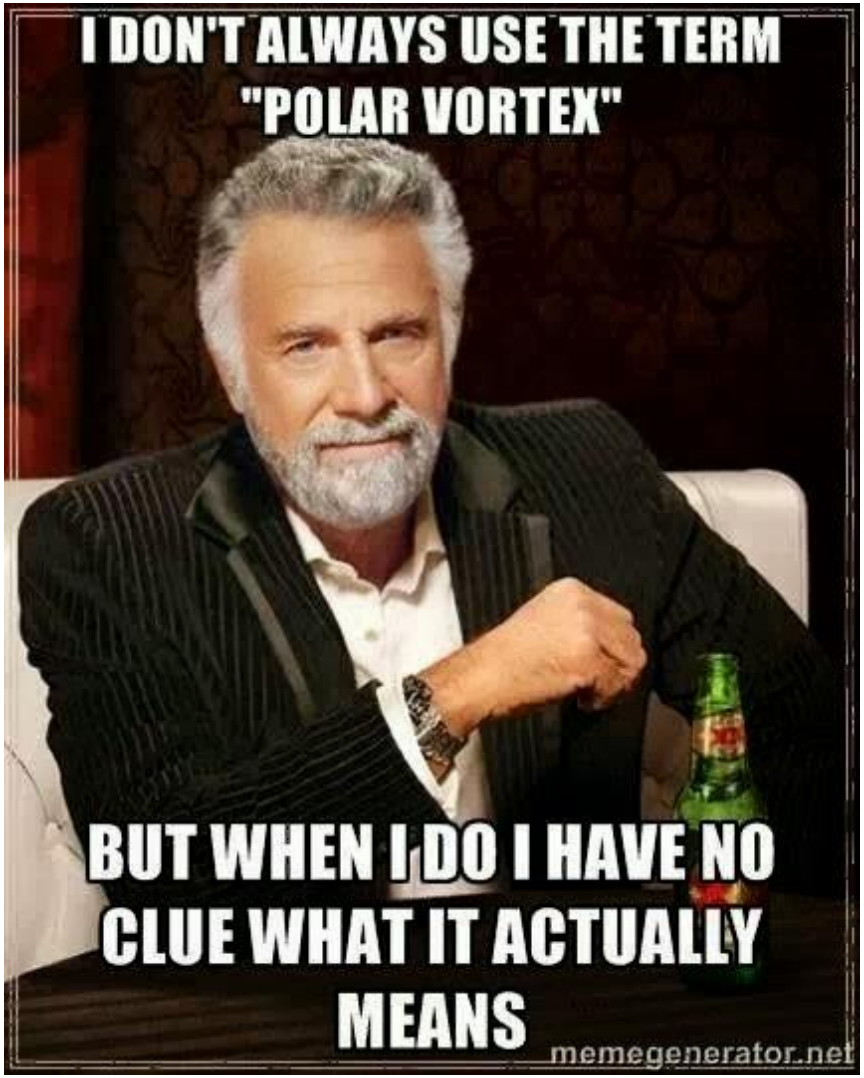
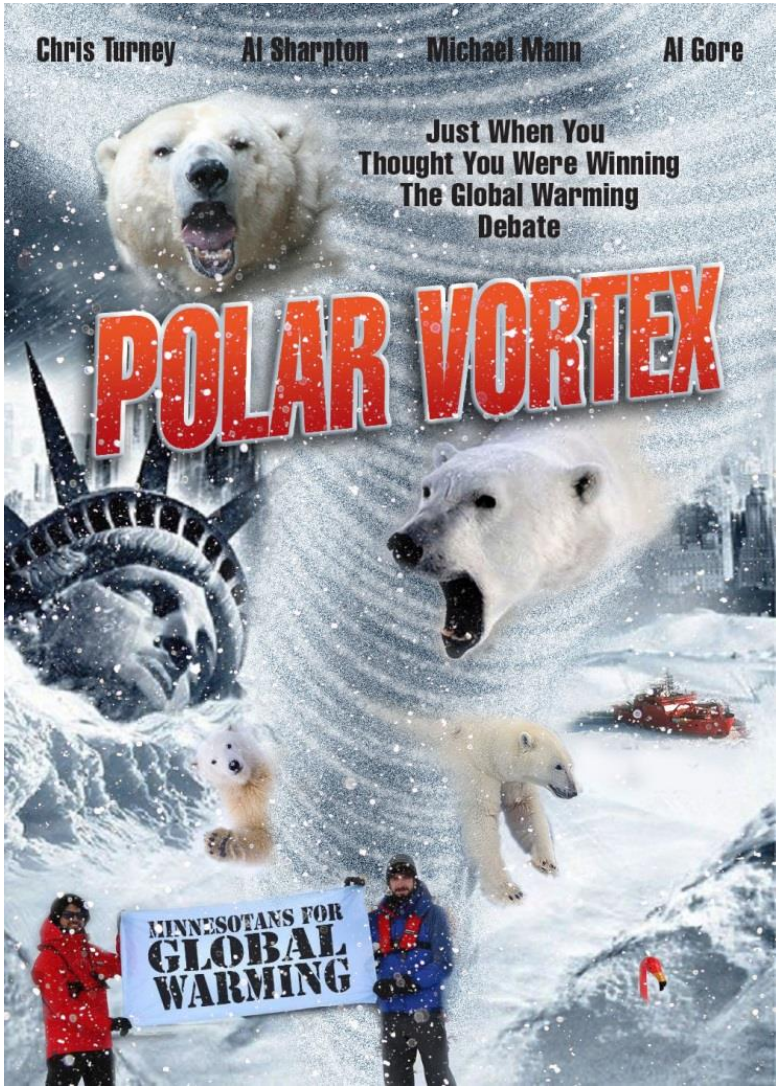
Polar Bears

(all photos from Jay Roberts)

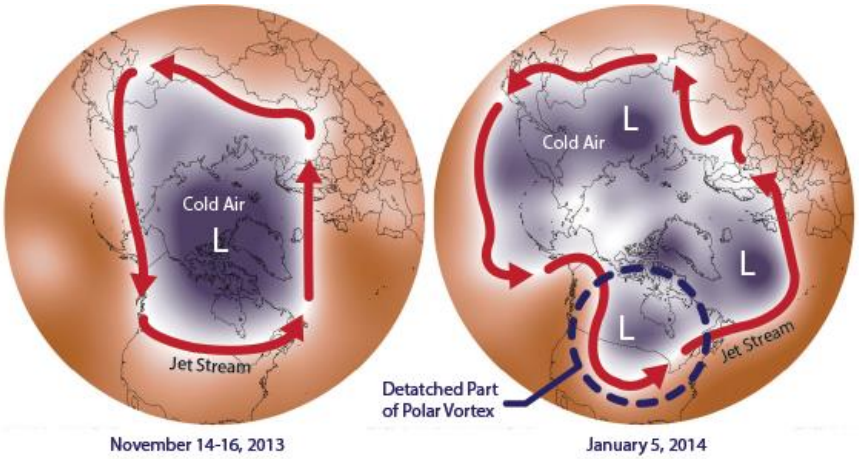


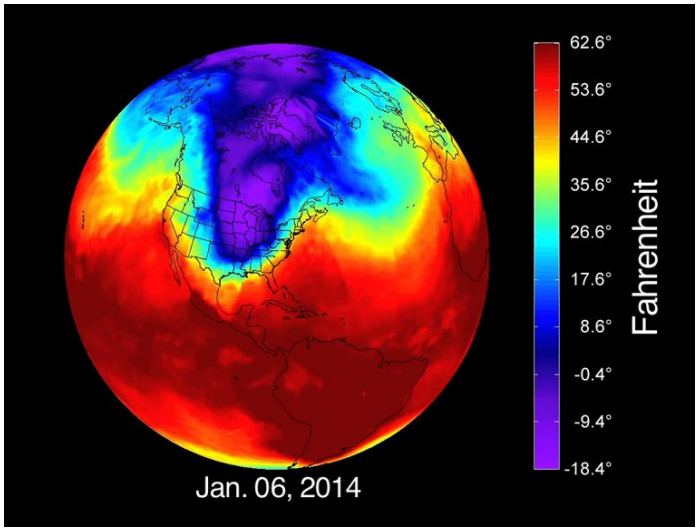
2014 Polar Vortex visits the south

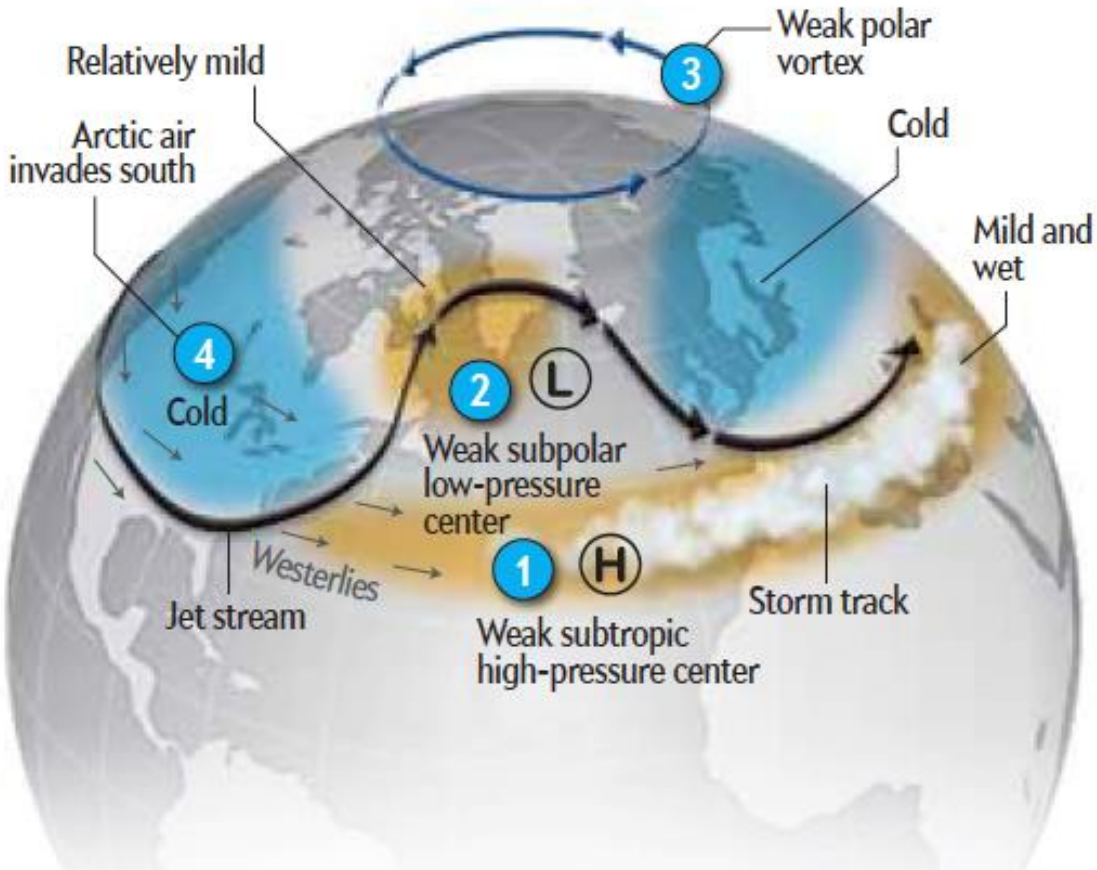




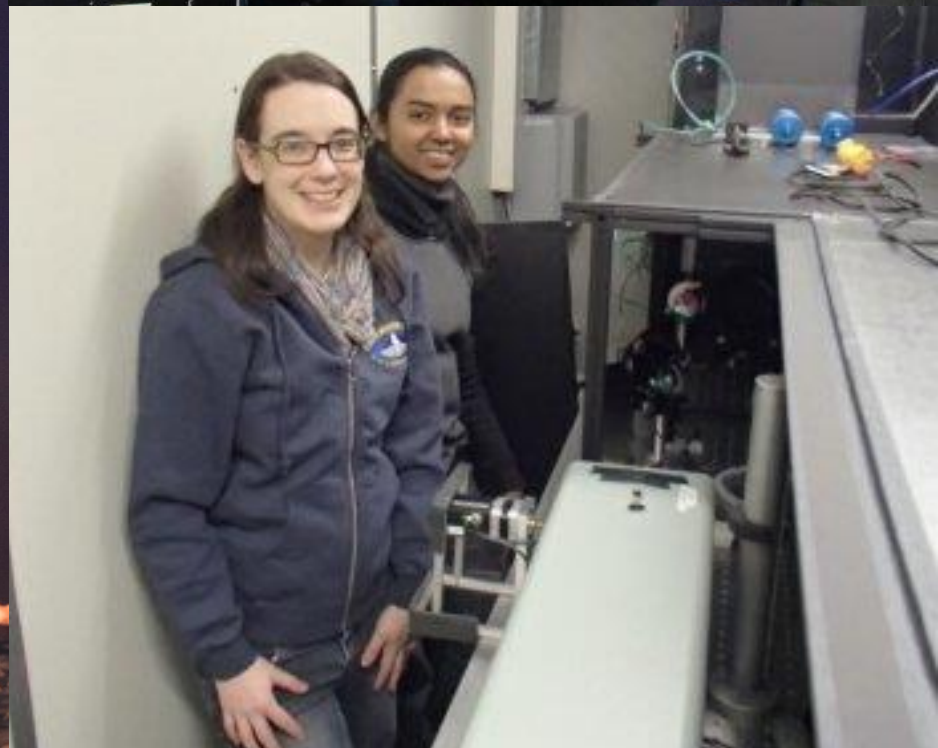
Polar Vortex







CRL



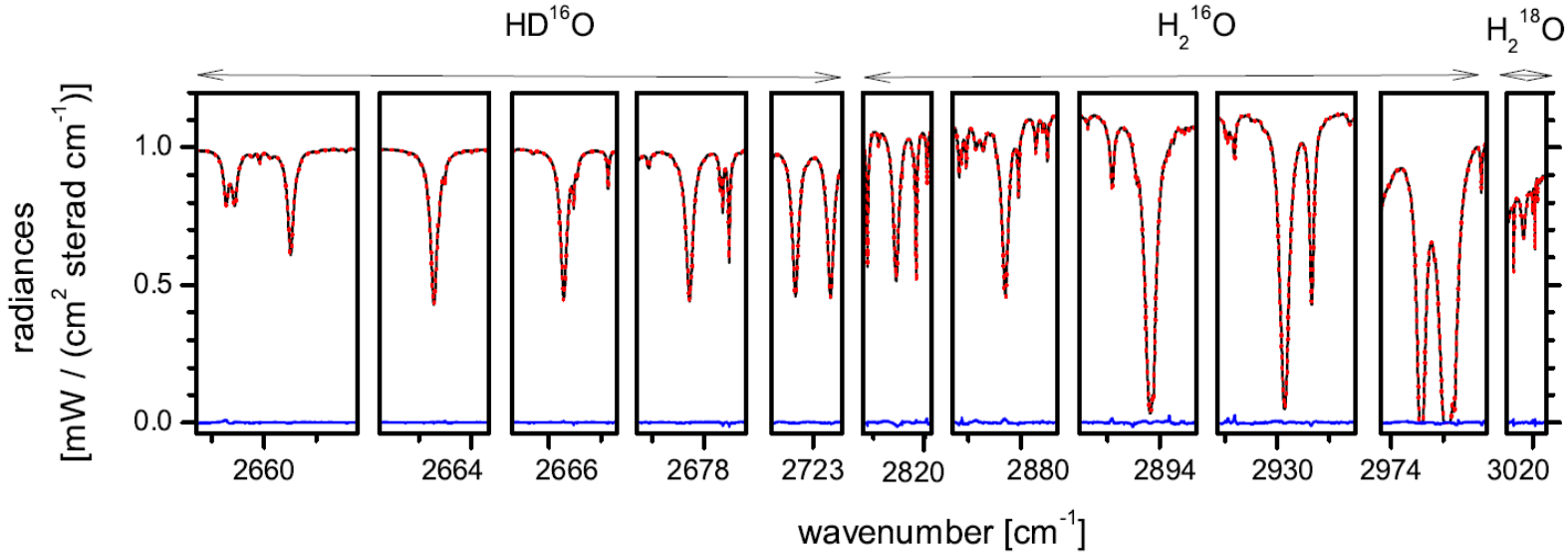
Upper Paradise

Line shapes

- Intrinsically, a spectral line should correspond to one unique energy value
- There are three primary causes of line broadening:
  - Natural broadening (molecule's energy uncertainty)
    - Has a negligible effect on the observed line shapes. .
  - Pressure broadening (caused by molecular collisions)
    - Dominant effect on the wings of spectra lines for molecules below ~20 km in altitude since it is a pressure-dependent phenomenon (Wallace & Hobbs, 2006).
  - Doppler broadening (caused by motion)
    - Dominant effect on line shapes for molecules above ~ 50 km, but is significant throughout the atmosphere, and is stronger in the center of a spectral line.
- This provides the ability to recover information about the distribution of gases in the atmosphere.
- Often, Pressure and Doppler broadening are combined to be described as a Voigt line shape.

MUSICA microwindows

- Cover a range of weak and strong absorption lines to gain sensitivity to the significant range of abundances.
- These microwindows have four interfering species: O_3, CO_2, N_2O, CH_4.
  - Retrieval of CO_2 is used as a quality control test, as abundances are well-known.



MUSICA microwindows for ground based FTIR water vapour retrievals (Fig. 2, Schneider et al., 2012).