Spectroscopy Can Address Many of the Un-answered Questions Related to Global Warming & Climate Change
Solar Radiation Interacts With Earth’s Atmosphere in Many Ways

Radiance for a Black Body

\[ B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp \left( \frac{hc}{\lambda kT} \right) - 1} \]

Emissivity of a material will alter magnitude of the wave that gets launched
Earth's Self Emission of Energy to Space Occurs At Infrared Wavelengths via Radiation

High Resolution Broadband Spectrometer Shows Much Structure in the Reflected Solar & Emissive Infrared
Radiation Exchange Between Earth, Sun & Space Is Enormous But Imbalance Driving Climate Change Is Small

Illustration by Trenberth 2010

Net Imbalance 0.9 W/m²

Atmospheric Gases Absorb Solar & Terrestrial Energy (i.e., warm the atmosphere)

99.9% of the Earth’s atmosphere does not absorb significant solar or infrared radiation.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Symbol</th>
<th>Fraction</th>
<th>∆Watt/m²</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N₂</td>
<td>78.084%</td>
<td>≈ 0</td>
<td>Provides Thermal Inertia</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O₂</td>
<td>20.9476%</td>
<td>≈ 0</td>
<td>Provides Thermal Inertia</td>
</tr>
<tr>
<td>Water</td>
<td>H₂O</td>
<td>0.5%</td>
<td>±</td>
<td>Self regulates, Feedback</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>CO₂</td>
<td>0.038%</td>
<td>1.4</td>
<td>Fossil Fuels, Biosphere</td>
</tr>
<tr>
<td>Methane</td>
<td>CH₄</td>
<td>0.00018%</td>
<td>0.7</td>
<td>Agriculture, wetlands, landfills</td>
</tr>
<tr>
<td>Ozone</td>
<td>O₃</td>
<td>0.002%</td>
<td>0.25</td>
<td>Chlorofluorocarbons, pollution</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>N₂O</td>
<td>0.000032%</td>
<td>0.15</td>
<td>Agriculture</td>
</tr>
</tbody>
</table>

These “trace” gases absorb an additional 150 Watts/meter² to increase average temperature 60 F

> Without these trace gases the Earth’s average temperature would be -0.5 F.
> Atmosphere absorbs 2.75 W/m² more in 2003 than in 1880 (Hansen 2005)
Climate Models Have Large Uncertainty in Radiative Forcing Estimates……..Need Satellites to Resolve

Solar Irradiance Reported for Last Three Solar Cycles
(from Fall 2008 AGU Meeting)
However, Satellite Sensors Differ Considerably in Their Reported Observations of Total Solar Irradiance

There is an unexplained 0.37% difference between TIM and VIRGO or ACRIM. Satellite Sensors Differ Considerably in Their Reported Observations of Total Solar Irradiance. Classically Accepted Value 1365.4 W/m². Newest Value 1360.8 W/m². 4.6 W/m².

Solar Radiance & Earth Reflected Radiance Differ Enormously & Measuring this Accurately Is Difficult

How can accurate measurements be made from space to trend climate forcings?
Adjustments to Climate Models (Such as This One) Continue as Better Data Becomes Available

Note: Numbers represent spatial & temporal average over entire globe

Increase of atmospheric CO$_2$ Has Been Accurately Measured for Many Decades

Annual cycle due to photosynthesis and respiration of soils.

Long term trend due to emission of fossil fuels

Charles David Keeling
1928-2005
2002 Nat'l Medal of Science
Atmospheric CO\textsubscript{2} has risen 35% in last 150 years and is projected to rise to 200% in the 21st century.

Increase in atmospheric CO\textsubscript{2} is currently +2.5 ppm/year and rising. That is 4.4 billion tons of carbon added to the atmosphere each year.

8/28/1859
Edwin Drake’s 1\textsuperscript{st} oil well

Solar Cycles Don’t Explain Longer Term Earth Temperature Trend

Solar radiance maxima is approx. every 11 years (2000, 1989, 1981) and has been decreasing since 2002. 20\textsuperscript{th} century warming was 0.75 K/century and is accelerating:

- Solar irradiance cannot explain stratospheric cooling and global tropospheric warming seen in last 30 years (GHG’s can!) Solar irradiance was important in previous centuries

- Recent studies show that the solar cycle drives a ±0.1 K temperature cycle.
- Little ice age and medieval warm periods were redistribution of global energy
- Present day warming is global and monotonic.

The myth survives even though scientists have persuasively discredited the solar contribution to late 20\textsuperscript{th} century warming. Why?
Significant amounts of Siberian and Alaskan permafrost *could* melt within 100 years. *Very likely* in 300 years.

Permafrost is composed of ices that are millions of years old and contain *tremendous* amounts of methane.

Northeast US climate impact assessment
(all values are changes from 1961-1990)

<table>
<thead>
<tr>
<th></th>
<th>Low Emission</th>
<th>High Emission (track we are on)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric CO2 in 2100</td>
<td>550 ppmv</td>
<td>940 ppmv</td>
</tr>
<tr>
<td>2040 Winter Temperature</td>
<td>2.5 to 4.0 F</td>
<td>2.4 to 4.0 F</td>
</tr>
<tr>
<td>2070</td>
<td>4.0 to 5.0 F</td>
<td>4.0 to 7.0 F</td>
</tr>
<tr>
<td>2100</td>
<td>5.0 to 8.0 F</td>
<td>8.0 to 12 F</td>
</tr>
<tr>
<td>2040, Summer Temperature</td>
<td>1.5 to 3.5 F</td>
<td>1.5 to 3.5 F</td>
</tr>
<tr>
<td>2070</td>
<td>2.0 to 5.0 F</td>
<td>4.0 to 8.0 F</td>
</tr>
<tr>
<td>2100</td>
<td>3.0 to 7.0 F</td>
<td>6.0 to 14 F</td>
</tr>
<tr>
<td>Number of Days &gt; 100 F</td>
<td>3 to 9</td>
<td>14 to 28</td>
</tr>
<tr>
<td>Sea Level Rise</td>
<td>7 to 14 inches</td>
<td>10 to 23 inches</td>
</tr>
<tr>
<td># heavy rains (&gt;2” in 48h)</td>
<td>+8%</td>
<td>+12 to +13%</td>
</tr>
<tr>
<td>Length of growing season</td>
<td>2 to 4 weeks</td>
<td>2 to 6 weeks</td>
</tr>
<tr>
<td>First leaf bloom date</td>
<td>1 day/decade earlier</td>
<td>2 day/decade earlier</td>
</tr>
</tbody>
</table>
Even if we stabilize at 550 ppm, a significant amount of Greenland will ultimately melt.

Greenland glacier is 3-km thick at center: as ice melts, elevation is lowered, air is warmer. But, melting will take many centuries if the glacial models are correct.

65 Million Year Temperature Reconstruction

Temperature derived from sediment cores from Deep Sea Drilling Project and Ocean Drilling Program.

30 Mya: Drake passage, uplift of Himalaya’s, Andean Mountains (increase weathering, draw down CO2)

25 Mya: Expansion of grassland habitats, draw down of CO2.

15 Mya: Columbia River volcanism (increase CO2)

5.5 Mya: closure of Panama 3 Mya, NOTE change from 41 ky to 100 ky cycles

1.0 Mya: transition from 41 Kyr(tilt) to 23+100 ky (precession) cycles.
Satellite Spectroscopy Will Provide Many Answers to Help Quantify How Fast Climate is Changing

It Will Also Help to Better Predict What the Weather Will Be Like Locally in the Next 5 Days

Our Goal Is to Profile the Temperature of the Atmosphere at Various Altitudes Using Spectroscopy
Measuring Atmospheric Temperature Not Possible at Solar Wavelengths Due to High Solar Reflection

**TABLE 3.3.** Albedo (%) of Various Surfaces Integrated over Solar Wavelengths

<table>
<thead>
<tr>
<th>Surface</th>
<th>Albedo (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare soil</td>
<td>10–25</td>
</tr>
<tr>
<td>Sand, desert</td>
<td>25–40</td>
</tr>
<tr>
<td>Grass</td>
<td>15–25</td>
</tr>
<tr>
<td>Forest</td>
<td>10–20</td>
</tr>
<tr>
<td>Snow (clean, dry)</td>
<td>75–95</td>
</tr>
<tr>
<td>Snow (wet and/or dirty)</td>
<td>25–75</td>
</tr>
<tr>
<td>Sea surface (sun &gt; 25° above horizon)</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Sea surface (low sun angle)</td>
<td>10–70</td>
</tr>
</tbody>
</table>

Scattering of Solar Energy by Clouds Prevents Use of Other Spectroscopic Wavelengths

**Calculated Radiative Properties of a 2-km-thick Stratus Cloud**

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Absorbed (%)</th>
<th>Scattered (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Out top</td>
</tr>
<tr>
<td>0.55</td>
<td>0.2</td>
<td>79.8</td>
</tr>
<tr>
<td>0.765</td>
<td>0.5</td>
<td>80.6</td>
</tr>
<tr>
<td>0.95</td>
<td>8.1</td>
<td>76.3</td>
</tr>
<tr>
<td>1.15</td>
<td>17.9</td>
<td>70.4</td>
</tr>
<tr>
<td>1.4</td>
<td>47.4</td>
<td>49.9</td>
</tr>
<tr>
<td>1.8</td>
<td>61.9</td>
<td>37.6</td>
</tr>
<tr>
<td>2.8</td>
<td>99.6</td>
<td>0.4</td>
</tr>
<tr>
<td>3.35</td>
<td>99.4</td>
<td>0.6</td>
</tr>
<tr>
<td>6.6</td>
<td>99.05</td>
<td>0.95</td>
</tr>
<tr>
<td>Total</td>
<td>10.0</td>
<td>73.8</td>
</tr>
</tbody>
</table>
Most Promising Range of Wavenumbers for Atmospheric Temperature & Moisture Observation

- Sahara Dessert
- Mediterranean
- Antarctic

Spectroscopic Satellite Observations Can Determine Earth Surface Temperature
Atmospheric Gas Absorption Line has Narrow Width at Low Pressure............Dominated by “Doppler Broadening”

\[ \Delta \lambda = \frac{2 \lambda}{c} \sqrt{\frac{2kT}{m}} \]

Mechanism of Doppler Broadening

In thermal equilibrium, the atoms in a gas, each of mass m, are moving randomly about with a distribution of speeds that is described by the Maxwell-Boltzmann distribution function, with the most probable speed given as

\[ \nu_p = \sqrt{2kT/m} \]

The wavelengths of light absorbed or emitted by the atoms in the gas are Doppler-shifted according to (nonrelativistic)

\[ \frac{\Delta \nu}{\nu} = \frac{\nu}{c} \]

Shape of Gas Absorption Lines Can Be Changed By “Pressure Broadening & Temperature”

\[ \Delta \lambda = \frac{2 \lambda}{c} \frac{n \sigma}{\pi} \sqrt{\frac{2kT}{m}} \]

Mechanism of Pressure Broadening

An estimate of pressure broadening due to collisions with atoms of a single element can be obtained by taking the value of \( \nu_p \) to be the average time between collisions. This time is approximately equal to the mean free path between collisions divided by the average speed of the atoms. The mean free path is

\[ \frac{1}{v} = \frac{1}{c} \frac{1}{\Delta T} \]

and the speed is given by

\[ \nu_p = \sqrt{2kT/m} \]

So we find that

\[ \Delta \nu = \frac{1}{c} \frac{1}{\Delta T} \sqrt{\frac{2kT}{m}} \]

where \( m \) is the mass of an atom, \( \sigma \) is its collision cross section, and \( n \) is the number density of the atoms. Thus the width of a spectral line due to pressure broadening is on the order of

\[ \Delta \lambda = \frac{2 \lambda}{c} \frac{1}{\pi} \frac{1}{\Delta T} \frac{1}{\sigma} \frac{1}{\pi} \sqrt{\frac{2kT}{m}} \]

The width of the line is proportional to the number density \( n \) of the atoms.
Pressure Broadened Line Absorption Will Dominate for Altitudes of Greatest Interest

Variation of typical weak Lorentz and Doppler broadened lines through the Earth's atmosphere.

Many Discrete Vibration Modes Exist for CO2

CO₂ Energy level diagram for two vibration states illustrates that large number of discrete transitions possible.
Satellite Observation
When High Resolution Spectrometer Is Used
(0.1 wavenumber resolution)

Example of How Atmospheric Temperature Changes
Atmospheric Transmittance (750 cm\(^{-1}\) - 790 cm\(^{-1}\))

"Broadened" absorption lines begin to merge together

Figure 3.7. Example of the temperature dependence of a rotation–vibration band of carbon dioxide (CO\(_2\)). The gas abundance is the same in both cases; only the temperatures differ: upper, 200 K; lower, 300 K. Note also the strong Q branch in the middle of the figure.
How We Measure & Profile Atmospheric Temperature

1) Absorption line properties
2) High Resolution Spectroscopy

Sensitivity to Temperature Will Vary for Different Observation Wavelengths

Figure 1 — Atmospheric transmission functions pertaining to the SIRS spectral intervals of observation for two different atmospheres.

Derivative of Transmission with respect to ln(p)

One curve for each spectral channel of instrument.
Can Spectroscopic Satellite Observations Improve Our Response to These Types of Severe Weather Events?

Models need to be improved and observations need to be improved to better predict

- Hurricane landfall
- Expected changes of hurricane intensity

Spectroscopy introduces a new dimension to these observations that better tracks wind patterns above and around severe weather

Katrina, Aug 28, 2005
Severe Weather Prediction from Four Perspectives

Jun Li, Jinlong Li, Jason Otkin, and Tim Schmit

True 1200 UTC

GIFTS/HES/IRS 06-12-2002 1200 UTC
Lifted Index [°C]

Red = extreme instability

Simulated Radar

ABI/GOES Sounder like

Beginning of Wide Area Instability Is Recognized by Hyperspectral Satellite Sensor

True 1300 UTC

GIFTS/HES/IRS 06-12-2002 1300 UTC
Lifted Index [°C]

Extreme instability indicated

Simulated Radar

ABI/GOES Sounder like
1 Hour Later

1400 UTC

True
06-12-2002, 1400 UTC
Lifted Index [°C]

GIFTS/HES/IRS
06-12-2002, 1400 UTC
Lifted Index [°C]

Simulated Radar

ABI/GOES Sounder like

2 Hours Later

1500 UTC

True
06-12-2002, 1500 UTC
Lifted Index [°C]

GIFTS/HES/IRS
06-12-2002, 1500 UTC
Lifted Index [°C]

06-12-2002, 1500 UTC
Radar reflectivity [dBZ]

Simulated Radar

ABI/GOES Sounder like
3 Hours Later

Start to See Extreme Instability 4 Hours Later
Extreme Instability Clearly Shown 5 Hours Later
but Note False Alarms with Current Technology

1800 UTC

True
06-12-2002, 1800 UTC
Lifted Index [°C]

GIFTS/HES/IRS
06-12-2002, 1800 UTC
Lifted Index [°C]

Simulated Radar

6 Hours Later

1900 UTC

True
06-12-2002, 1900 UTC
Lifted Index [°C]

GIFTS/HES/IRS
06-12-2002, 1900 UTC
Lifted Index [°C]

Simulated Radar

ABI/GOES Sounder like
Hyperspectral Technology Improves Reliability of Storm Warnings Over Current Technology

Rain Line Shows in Doppler Radar 8 hours Later
Hyperspectral Sensors Can Improve Severe Weather Prediction by 4 - 5 hours over Current Space Technology & by 8 hours over Doppler Radar

Precision Hyperspectral Satellite Cameras Are Being Developed to Better Trend Climate and Provide Better Weather Forecasting Capability
Fourier Transform Spectrometer Built By ITT Exelis in Fort Wayne, Indiana........Now on-orbit to Improve NASA/NOAA Long Range Weather Forecasting

1305 Spectral Channels Covering the Infrared Spectrum with High Radiometric Sensitivity and Accuracy

- Large 8 cm Clear Aperture
- Three Spectral Bands
  - LWIR: 650-1095 cm\(^{-1}\)
  - MWIR: 1210-1750 cm\(^{-1}\)
  - SWIR: 2155-2550 cm\(^{-1}\)
- 1305 Total Spectral Channels
- 0.625 cm\(^{-1}\) spectral resolution
- 3x3 FOVs at 14 km Diameter
- Photovoltaic Detectors in All 3 Bands
- 4-Stage Passive Detector Cooler
- Plane-Mirror Interferometer With DA
- Internal Laser Wavelength Calibration
- Deep-Cavity Internal Calibration Target
- Passive Vibration Isolation System Allows Robust Operation in 50 mG Environment
3 x 3 Hyperspectral Detector Array Step Scanned Across Earth Surface
Ground Algorithms then Calibrate Observations & Convert to Science

3x3 Pixel Hyperspectral Array
Used to Scan Earth Surface

Single CrIS Scan Line
(full sweep, 30 FORs)

Three Successive
CrIS Scan Lines
(nadir to edge sweep)
Partially Unfolded CrIS Optical System Shows Flow of Signal Radiance to Detectors

Scene Radiance

Detector Optics

Cooler

Aft Optics

Telescope

Interferometer

SSM

Optics are Uncooled From Telescope Forward

Interferograms Are Generated Using a Moving Mirror

Change in Optical Path Difference

Types of Interferograms
Example of Compact Optics Packaging for Spaceflight Interferometer

Sample scene (three different types)
ES: Earth Scene
DS: Deep Space
ICT: Internal Calibration Target

Satellite Collects Interferogram Data for Transmission to Ground

Only Processing of Science Data Shown
Typical Spectrum with 20,736 DFT Bins

255 Tap Digital Filter & Optical Filter Eliminates Out of Band Artifacts Prior to Data Compression

LW Band: $650 \text{ cm}^{-1}$ to $1095 \text{ cm}^{-1}$

- Nonlinearity
- Nonlinearity & Double Pass Interferogram
- Metrology up/down sample asymmetry
- Suppression noise floor further
- FPGA clock spurs
- Image needing rejection
- Retain pass band
- Achieve stop band to prevent decimated alias
- DC signal needing rejection (off chart)

FIR Filter Passband Ripple
Cascaded Optical Filter Response
FIR Filter Stopband Ripple
Filtering and Decimation Reduces Downlink Data Rates

CrIS Interferogram Measurements

Double Sided IGMs

Typical Brightness Temperature Map of Earth from Hyperspectral Weather Satellite