Monitoring Aerosol, Clouds and Water in the Polar Atmosphere

part III

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Canadian Regional Climate Modeling and Diagnostics Network

Summer School
NSERC CREATE Training Program in Arctic Atmospheric Science

Alliston, ON, July 23-27, 2012
Cloud – Radiation Feedback
Winter (IR dominated)

#1
- Greenhouse
  - Surface and TOA radiation flux
    - Surface Temperature
      - Atmospheric temperature and water
        - Precipitation
          - Acid
            - No
              - Aerosols
              - Yes
                - Dehydration
        - Large scale advection and vertical motion
      - DGF Process
        - TIC-2
          - TIC-1
            - Dehydration

#2
- Cloud fraction
- Cloud optical depth
Plan

- A 360° cloud view around the Pole
- Polar GHG & DGF versus NAO activity
- Simulating atmospheric moisture in cold climates
- Measuring cold anomalies and water budget
- TICFIRE project

Ref.: CALIPSO Web site
Frequent Arctic Overpass
Compact Time Sampling and near 3D Horizon View
« Tour d’horizon » around the Pole
January 19, 2007

532 nm Total Attenuated Backscatter, /km /sr

Begin UTC: 2007-01-19 00:11:10.7732
End UTC: 2007-01-19 00:24:29.7492
Version: 01.10
Image Date: 01/25/2007
« Tour d’horizon » around the Pole
January 19, 2007

532 nm Total Attenuated Backscatter, km/sr

Begin UTC: 2007-01-19 01:50:03.5802
End UTC: 2007-01-19 02:03:22.5552
Version: 01.10
Image Date: 01/25/2007
« Tour d’horizon » around the Pole
January 19, 2007
« Tour d’horizon » around the Pole
January 19, 2007
« Tour d’horizon » around the Pole
January 19, 2007
« Tour d’horizon » around the Pole

January 19, 2007

532 nm Total Attenuated Backscatter, km $^2$/sr

End UTC: 2007-01-19 13:35:36.6662
Version: 01.10 Image Date: 01/25/2007
« Tour d’horizon » around the Pole
January 19, 2007
« Tour d’horizon » around the Pole
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January 19, 2007
« Tour d’horizon » around the Pole
January 19, 2007
« Tour d’horizon » around the Pole
January 19, 2007

532 nm Total Attenuated Backscatter, /km/sr

Begin UTC: 2007-01-19 08:25:37.7822
End UTC: 2007-01-19 08:38:56.7582
Version: 01.10
Image Date: 01/25/2007

Legend:
- 1.0 × 10⁻¹
- 9.0
- 8.0
- 7.0
- 6.0
- 5.0
- 4.0
- 3.0
- 2.0
- 1.0 × 10⁻²
- 8.0
- 7.5
- 7.0
- 6.5
- 6.0
- 5.5
- 5.0
- 4.5
- 4.0
- 3.5
- 3.0
- 2.5
- 2.0
- 1.5
- 1.0 × 10⁻³
- 9.0
- 8.0
- 7.0
- 6.0
- 5.0
- 4.0
- 3.0
- 2.0
- 1.0 × 10⁻⁴

Map and data from [source].
« Tour d’horizon » around the Pole
January 19, 2007
« Tour d’horizon » around the Pole
January 19, 2007
« Tour d’horizon » around the Pole

January 19, 2007
Frequent Arctic Overpass
Compact Time Sampling and near 3D Horizon View
Loop #3 : The big circulation
**Lorenz Energy Cycle**

PM: mean available potential energy  
PE: eddy available potential energy, which is composed of PSE and PTE  
PSE: stationary eddy available potential energy  
PTE: transient eddy available potential energy  
KM: mean kinetic energy  
KE: eddy kinetic energy, which is composed of KTE and KSE  
KTE: transient eddy kinetic energy  
KSE: stationary eddy kinetic energy  

\[
\begin{align*}
\frac{\partial K_M}{\partial t} &= C(P_M, K_M) + C(K_E, K_M) - D(K_M), \\
\frac{\partial K_E}{\partial t} &= C(P_E, K_E) - C(K_E, K_M) - D(K_E), \\
\frac{\partial P_M}{\partial t} &= G(P_M) - C(P_M, K_M) - C(P_M, P_E), \\
\frac{\partial P_E}{\partial t} &= G(P_E) - C(P_E, K_E) + C(P_M, P_E).
\end{align*}
\]

http://wmolc.org/multi_model/energetics.php
Lorenz’s Energy Cycle (Lorenz, 1967; Boer, 1975)

Potential Energy:
\[
\frac{da}{dt} = NQ + \alpha \omega
\]

Kinetic Energy:
\[
\frac{db}{dt} + \alpha \frac{\partial}{\partial x_j} \left( pv_j + \pi_{i,j} v_i \right) = -\alpha \omega - \varepsilon
\]

Lorenz Efficiency Factor:
\[
a \equiv N c_p T + P
\]

\[
b \equiv k + \Phi - p\alpha
\]

\[
N \equiv 1 - \left( \frac{p_r}{p} \right)^{R_a/c_p}
\]

Potential Energy:
\[
Q = T \frac{ds}{dt} = c_p \frac{dT}{dt} - \alpha \omega
\]

Kinetic Energy:
\[
STORMS
\]

Molecular Momentum Flux

Local Dissipation

Geopotential

Work

Potential Energy

Kinetic Energy

Heating Rate

Vertical Motion

Specific Volume

STORMS

Barotropic Reference Pressure

Lorenz Efficiency Factor

Molecular Momentum Flux
Cooling processes

Total Cooling \approx -30 \text{ to } -50^\circ C

\[ Q = T \frac{ds}{dt} = c_p \frac{dT}{dt} - \alpha \omega \]

**Process #1: Dynamics**
\[ \Delta T \approx -10^\circ \text{ to } -20^\circ C \]
Air is lifted along with aerosols

**Process #2: Direct IR**
\[ \Delta T \approx -16^\circ \text{ to } +10^\circ C \]
Cooling over the total column in TIC-2

**Process #3: Indirect IR**
\[ \Delta T \approx -5^\circ \text{ to } -10^\circ C \]
Dehydration and opening of the grey far-IR window
North Atlantic Oscillation
NAO

Ref.: Jim Hurrell, NCAR
http://www.cgd.ucar.edu/cas/jhurrell/indices.html
http://earthobservatory.nasa.gov/Study/NAO/NAO_2.html
Northeastern Canada – River Bassin Hydrology
M. Slivitzky – Ouranos – Brown – CFLCo

Magpie

Moisie

Natashquan

Réservoir de Churchill Falls (1961-1999)
Equivalent Liquid Water (surface accumulation)
Sulphur Dioxide Emission Trend
Steve Smith of the Pacific Northwest National Laboratory

Sulphur Dioxide Emission Trend
1990 - 2006

Ref.: http://www.eea.europa.eu/
North Atlantic Oscillation – NAO

Positive Phase : High NAO
(a) Storm activity anomalies (%)  (b) Precipitation anomalies (mm/month)  (c) Sea level pressure anomalies (mb)  (d) Temperature anomalies (degrees C)

Negative Phase : Low NAO
(a) Storm activity anomalies (%)  (b) Precipitation anomalies (mm/month)  (c) Sea level pressure anomalies (mb)  (d) Temperature anomalies (degrees C)

Ref.: Osborn, T. @ http://www.cru.uea.ac.uk/cru/info/nao/
Average Strong East Coast Winter Storms (ECWS)
Winds Exceeding 52 mph
(US Northeast Regional Climate Center)
Observed Winter Storm Trend
Northern Hemisphere

Number of intense (< 970hPa) winter cyclones per year in the Northern Hemisphere. The red line represents a 5 year running mean. Ref.: Lambert, S. J. (1996).
Anthropogenic Forcing of NAO

Ensemble GCM Simulations for 2 Scenarios A2 and B2

(C. Cassou, 2004: La Météorologie, 45, 21-33)

Control: Present Climate
Exp.1: Pessimistic Case A2
Exp.2: Moderate Case B2

Greenhouse Gases
Sulphate Aerosols (solar only)

Our question: What about IR?

Sulphate – Clouds – Precipitation via IR in the Arctic Polar Night Dehydration Greenhouse Feedback (DGF)?
Surface Pressure Anomalies (hPa) due to acid aerosol + TIC-2B (DGF)

Cold Anomalies

- The generation of cold air (blue-purple geopotential color contours versus warm yellow-orange subtropical) create gradients of geopotential where big winter storms are forming. **Cold anomalies produce intense storm and severe weather.**
- Thus it is important to monitor the formation of cold air in the Arctic through TIC formation, precipitation and radiation.
- Ice clouds particles specific properties and atmospheric water amounts near detection limit suggest remote sensing applications in far-IR ➔ **TICFIRE mission**
WATER
the cornerstone
Total Precipitable Water Errors over Antarctica in Summer

Ref.: Ye and Fetzer, 2006
Percentage Difference with Elevation – Antarctica Summer
Percentage Difference with Elevation – Greenland Summer
Error Variances: Model and Observations

PREMIER mission and others

Ref.: ESA SP-1313/5 Candidate Earth Explorer Core Missions – Reports for Assessment: Premier – Process Exploration through Measurements of Infrared and millimetre-wave Radiation
Source: A. Waterfall
Measurement Gap in a Critical Spectral Range

In Space Instruments  
Microwaves

Absorption

Wavelength

FIR  Sub-mm

Black Body

TICFIRE

Mid-Upper Troposphere
Sensitivity of the FIR to Water Vapour Concentration for Arctic Air

The diagram illustrates the transmittance of different wavelengths (µm) for various water vapour concentrations and altitudes. The x-axis represents the wavelength in micrometers (µm), while the y-axis shows the transmittance.

Key points:
- **Window**: This region shows a high transmittance, allowing more passage of light.
- **CO₂ and FIR**: These regions are shown in different colors to distinguish them.

For example, at an altitude of 0 km (red line), the transmittance is high across the spectrum, indicating minimal absorption. As the altitude increases to 2 km (green line), the transmittance decreases, particularly in the FIR region, indicating increased absorption of water vapour.

- **2 km**: The transmittance is significantly reduced in the FIR region compared to the CO₂ region.
- **5 km**: The transmittance continues to decrease, with the FIR region being more affected than the CO₂ region.
- **10 km**: The transmittance is almost negligible in both regions, indicating a significant absorption of water vapour at high altitudes.

The diagram helps in understanding how water vapour concentration affects the transmittance of light at different wavelengths and altitudes.
TICFIRE
Payload Concepts
UQÀM-INO-USher
1- Monitor the formation of cold anomalies in Polar Regions and globally near the tropopause from far IR emissions

2- Fill an important gap in the far infrared range where most of the Earth’s atmosphere thermal cooling originate and yet unobserved from satellites.

3- Determine sub-visible cloud types and properties in extreme cold regions.

4- Improve measurements of water-vapour concentration in the low limit (< 5mm columnar) where cold climate is most sensitive.
TICFIRE: Concept and Key Requirements

- **Parameter Requirement**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Bands</td>
<td>#1: 7.9 – 9.5 µm</td>
</tr>
<tr>
<td></td>
<td>#2: 10 – 12 µm</td>
</tr>
<tr>
<td></td>
<td>#3: 12 – 14 µm</td>
</tr>
<tr>
<td></td>
<td>#4: 17.25 – 19.75 µm</td>
</tr>
<tr>
<td></td>
<td>#5: 22.5 – 27.5 µm</td>
</tr>
<tr>
<td></td>
<td>#6: 30 – 50 µm</td>
</tr>
<tr>
<td>Spectral Response</td>
<td>Flat within the each band</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>0 – 45 W m⁻² sr⁻¹</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 W m⁻² sr⁻¹</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1.5 K for a reference temperature of 300 K</td>
</tr>
<tr>
<td>Vertical limb forward sampling</td>
<td>30 pixels in vertical x 1 km</td>
</tr>
<tr>
<td></td>
<td>640 pixels across track x 1 km</td>
</tr>
<tr>
<td></td>
<td>(averaged to 10 km to match)</td>
</tr>
<tr>
<td>Geolocation</td>
<td>Horizontal: Better than 2 km</td>
</tr>
<tr>
<td></td>
<td>Vertical: Better than</td>
</tr>
<tr>
<td>Footprint size</td>
<td>Horizontal: 10 km (GSD)</td>
</tr>
<tr>
<td></td>
<td>Vertical: 1 km</td>
</tr>
<tr>
<td>Swath</td>
<td>Horizontal: 640 km</td>
</tr>
<tr>
<td></td>
<td>Vertical: 30 km</td>
</tr>
</tbody>
</table>

- **Mass:** 30 kg
- **Power Consumption:** 29 W
- **Data rate:** 185 Mb per orbit
- **Volume:** 430 x 430 x 220 mm³
TICFIRE payload: Limb instrument

- NEP < 33 pW
- Resolution in radiance ~0.15 W/(m² sr) for a 1 km x 1 km pixel
- Radiometric resolution better than 0.05 W/(m² sr) if 10 horizontal pixels are averaged

Commercial version for technology demonstration (INO)
Simulation in Limb View

**Profiles**

-**H₂O (< 2mm PCPW)**
  - Height (ΔH = 1 km)
  - Sensitive to upper layers
  - Sensitive to lower layers

-**TIC-2**
  - TIC Top altitude
  - TIC Type
  - COD (< 5)

**Clear Sky**
Supported by the Canadian Space Agency (Contract 9F063-100359/002/MTB- Project PT-7)

STDP-4 TECHNOLOGIES FOR FUTURE MISSIONS
PRIORITY TECHNOLOGY 7: FAR IR COATINGS AND FOCAL PLANE ARRAY DEVELOPMENT FOR THE TICFIRE MISSION

Sensor for TICFIRE nadir instrument:
3 x 32 microbolometer matrix

Far-IR coatings:
TICFIRE filters
Microbolometer Infrared Detector Technology

Characteristics of INO Uncooled Microbolometer Technology:

- no cryogenic cooling required: micro and nanosatellite compatible
- broadband sensitivity
  - MWIR (3-5 µm)
  - LWIR (8-12.5 µm) ➔ TICFIRE
  - VLWIR (14-27 µm) ➔ TICFIRE
  - THz (> 35 µm, 100 µm) ➔ TICFIRE
  - Broadband (0.2->50 µm) ➔ BBR
- NEP* on order 5 pW/root Hz
- detector pitch 25 to 100 µm
- space qualifiable
- ROIC formats 256x1, 512x3, 160x120, custom

IRL512 prototypes in test packages
LWIR line-scan image (256x1)
THz image
Gold Black for Broadband Detectors

- **Gold black** is the only absorber film suitable for integration with fast MEMS thermal sensors.

- The only other fully operational gold black facility is at NASA Goddard; it is not generally available to third parties.

- Integration with microbolometer detectors has been demonstrated:
  - Measured pixel level absorption to above 90% from visible to far infrared.
  - Detector thermal capacity increased by less than 50%.

- INO gold black film was integrated with custom linear detector array for EarthCARE BBR.
Optical coatings: Equipment

Thin film box coater key issues:
- FAR-IR thin film evaporation by thermal evaporator
- Evaporation rate control
- Film stoichiometry control
- Densification improvement (Temperature and IAD options)
- Cryogenic pumping for efficient vapor water removal
- Optical thickness measurement accuracy
- Preliminary filter design required to answer questions!

Typical BAK-760 unequipped chamber layout

INO’s BAK-760 Ion-Assisted Deposition (IAD)
# TICFIRE Data Products

<table>
<thead>
<tr>
<th>Spectral Bands</th>
<th>Radiance (BT)</th>
<th>Cloud Top (Limb)</th>
<th>Part. Size (TIC Type)</th>
<th>Water Vapor (Low Range)</th>
<th>COD</th>
<th>Ts</th>
<th>Ice Shape</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>X ↔</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
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<tr>
<td>#2</td>
<td>X ↔ ↑</td>
<td>X</td>
<td>X</td>
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<td>X</td>
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<td>#3</td>
<td>X ↔</td>
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<td>X</td>
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<td>#4</td>
<td>X ↔</td>
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<td>X</td>
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<td>#5</td>
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</tr>
</tbody>
</table>

↔ : Nadir view
↑ : Limb view

Level 1

Level 2a

Level 2b
Summary

- TICFIRE Mission Concept proposes new spectral bands for Earth observation to monitor the **formation of cold anomalies** and **water vapour measurements**

- Covers a important and **unexplored spectral range** for space-borne applications

- Aims at **polar and cold regions** globally (and tropopause)

- Key data for **severe storm** generation medium range forecasting and climate

- Despite the fact that TICFIRE was defined as a standalone mission, its instruments would be a nice **secondary payload** for other **cloud-aerosol oriented missions** as well as for **precipitation oriented missions** involving **microwave radar/radiometer or polarized radar**

- **Technology developments** are initiated to support TICFIRE mission (**far-IR sensor and filters**)
Summary

- Thin ice clouds are dominant feature of the polar night
- Atmospheric models generally overestimate water vapour in cold air by as much as 30 to 40%
- Lacking effective light precipitation (TIC-2) physics parameterization
- Both GHG and aerosol sulphate favours the + NAO phase.
- Take home message: pay attention to atmospheric WATER