Polar clouds and aerosol: Key results from CloudSat-CALIPSO

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CLALIPSO-CLOUDSAT
Ten year Progress Assessment and Path Forward
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Plan: A focus on Polar Regions’ atmosphere

• **Processes**: Aerosol – Clouds – Radiation – Precipitation – Circulation.
• **Observations**: Space, ground, aircraft and laboratory experiments.
• **Validation**: From ground-based, via *in-situ* aircraft to satellites.
• **Model simulations**: Microphysics, radiation and climate models.
• **Data assimilation**: Operational forecast and climate models.
• **Future missions**: Active – passive instruments.
Polar Thin Ice Clouds

Sulphate Trend and Seasonal Variation

- Due to anthropogenic emission, sulphate concentration increases by about 50X during polar night with respect to the cleaner summer time.
- The associated sulfuric acid is responsible for TIC modulation and dehydration.
- The cooling process is predicted by model simulations and observed from satellites and ground stations.

Ref. Gong, 2005
Polar night: Indirect IR effect of sulphate (acid)
Aerosol on clouds, precipitation and radiation.

Clear skies spring : Direct solar effect of arctic haze
Sulphate and soot aerosols on solar radiation.
Cloudy summer: Little effects of aerosol with dropping concentration. Possible effect of soot on snow albedo.

Ref: http://lebleupack.blogspot.ca/2013/07/wicked-arctic-skies.html
CALIPSO – CloudSat revealed very extensive TIC associated to sulphate aerosol

Ref.: http://www.touristmaker.com/climate/polar.html
Processes

Aerosol – Clouds – Radiation – Precipitation – Circulation
Background

• Early DGF hypothesis (Blanchet & Girard, Nature, 1994)
Greenhouse Atmospheric Radiation at the ground

- From enhanced precipitation/dehydration a vast spectral cooling window opens up in the far IR range, in the so called « dirty window ».
Generation of Available Potential Energy in the Atmosphere
due to Latent Heat (tropics) and Radiative Cooling (Poles)

- Increasing cooling rates in the Arctic during winter, enhances the heat deficit
- Storm activities are strengthened to transport and fill the energy gap

Radar – Lidar Thin Ice Cloud Types
(Definition)

Thin Ice Cloud type 2
high [aerosols] (acidic),
large ice crystals and fast sedimentation

Thin Ice Cloud type 1
low [aerosol] (pristine),
small crystals slow sedimentation
Radar – Lidar Thin Ice Cloud Types (Definition)

Thin Ice Cloud type 2
- high [aerosols] (acidic),
- large ice crystals
- and fast sedimentation

Thin Ice Cloud type 1
- low [aerosol] (pristine),
- small crystals
- slow sedimentation
Process #1 – Adiabatic Cooling (Dynamics)

Time Scale: ~ 6 – 24 hours
Process #2 – Direct IR Cooling (IR from Ice Clouds)

Time Scale: \(~ 1 – 5 \text{ days}\)

DT \approx -3 \text{ to } -8^\circ \text{C}

DT \approx 0 \text{ to } +2^\circ \text{C}

TIC-2B

TIC-1

High OLR

Low OLR

TIC-1

ocean
topography attenuatin cloud-free TIC-1 TIC-2A TIC-2B TIC-2C mixed-phase
Process #3 – Indirect IR Cooling (Lost Water Vapor GHG)

Time Scale: ~ 1 – 2 weeks

- CALIPSO Cloud Mask
- ECMWF Humidity Analysis
- Cold Low Cycloysis in the Polar Vortex
- Dimond Dust Precipitation
- Cold Dry Anomaly
- Low OLR
- High OLR

DT ≈ -5 to -10°C

PCP-Water ~ 1 mm  Model Bias + 0.3 mm (30%)
Net Heating Rate [°C/day]
Net Heating Rate [°C/day]: TIC vs ITCZ Ci+Cb
Arctic Clouds: TIC-1, TIC-2A, TIC-2B, TIC-2C

CloudSat radar

CALIPSO lidar

Map High Arctic

2200 km trajectory


Russia

Siberia
Observations
Space, ground, aircraft and laboratory experiments
Polar Night Observations: A-Train and PEARL
E-AERI & FIRR at PEARL 2015-16

In preparation for TICFIRE microsat mission, 3 campaigns are planned to test FIRR during winter.

Eureka, NU (80°N, 86°W)
TIC-2B from PEARL and CALIPSO Simultaneously

7 January 2007, 14h (Ref.: Ed Eloranta, OPAL at Eureka NU)

Ref.: eloranta@lidar.ssec.wisc.edu
TIC Type Amount: CloudSat-CALIPSO vs PEARL
January 2007

From Space: CALIPSO-CloudSat

From Ground Base: Lidar-Radar @ Eureka

TIC formation in the lower stratosphere
TIC Clouds and PRECIPITATION initiated in the UTLS region
CALIPSO Dataset (Jan 2010)

Ref.: Yacine Bouzid
Validation
From ground-based, via *in-situ* aircraft to satellites
April 14, 2008
ISDAC Flight 20-21

Natural (volcanoes & DMS) + Anthropogenic sulfate

TIC & precipitation forming in sulphate plumes

Veniaminof
Cleaveland
Asian Aerosols
Evidence of Acid Aerosol – Cloud – Precipitation Interactions

From CALIPSO during ISDAC April 2008
ISDAC Aircraft Campaign – March April 2008: Sources of IFN-SO$_2$

Examination of the CALIPSO satellite tracks, which intersects the back trajectories in the region away from the airborne measurements.
ISDAC Aircraft Campaign – March April 2008: Cloud Microphysics

ISDAC (April 2008)
- Ice and mixed-phase arctic clouds
- Barrow-Fairbanks (Alaska)
- Aircraft Convair-580 from NRC (Canada)
- Probes: 2-DS, 2-DC, 2-DP, Rosemount Icing Detector, PCASP...

High [small ice crystals] looks like a **TIC-1/2A**

April 15, 2008 00:55:40 – 01:17:24
Low [large ice crystals] looks like **TIC-2B**

Ref.: JOUAN C. - Remote sensing of Arctic clouds and aerosol acidification effects - March 28, 2011 - ASR Meeting
ISDAC Aircraft Campaign – March-April 2008: IFN-Size vs RH-T

Acid Coated IFN
Ice Forming Nuclei

Flow cell coupled to microscope

Particles before ice nucleation

$\text{RH}_i < 135\%$

$200 \mu\text{m}$

Particles after ice nucleation

$\text{RH}_i = 135\%$
Arctic Winter

In Laboratory

Allan Bertram UBC

High Supersaturation
Low nucleation rate
Explosive growth
Few Ice Crystals
Easy Precipitation

Low Supersaturation
High nucleation rate
Slow growth
Many Ice Crystals
Low Precipitation

RH(%) vs. T_{cell}(K)

Arctic Winter

(NH_4)_2SO_4 DRH

uncoated kaolinite
coated, (NH_4)_2SO_4
coated, H_2SO_4

Immersion Freezing
Deposition Freezing
Ground Campaign, Eureka – Winter 2015-16
Far IR Spectral Radiometer (FIRR)
Far IR Spectral Radiometer (FIRR)

- Far-infrared
- No observation from space yet!

**8-14 µm Window**

**15 µm CO₂**

**8-50 µm Far IR**

**Profiling Capability**

- 7.9-9.5 µm
- 10-12 µm
- 12-14 µm
- 17-18.5 µm
- 18.5-20.5 µm
- 17.25-19.75 µm
- 20.5-22.5 µm
- 22.5-27.5 µm
- 30-50 µm
B1: 7.9 µm to 9.5 µm
B2: 10.0 µm to 12.0 µm
B3: 12.0 µm to 14.0 µm
B4: 17.0 µm to 18.5 µm
B5: 18.5 µm to 20.5 µm
B6: 20.5 µm to 22.5 µm
B7: 22.5 µm to 27.5 µm
B8: 30.0 µm to 50.0 µm

Very little discrimination of clouds-surface contrast and height location

Profiling discrimination capability

Cut off from surface dependency

Ref.: S.A. Clough and M. J. Iacono, JGR, 1995
Atmospheric and Environmental Research Inc
NETCARE Campaign – April 2015
NETCARE Campaign – April 2015
NETCARE/FIRR/TICFIRE Campaign – April 2015

Clear Sky April 11, 2015
Cloudy Sky April 13, 2015

MODIS 11 µm channel

CloudSat

April 14, 2015
Spectral Radiance vs Simulations: Clear Sky

- MODTRAN V5.4
- Clear sky
- April 11, 2015
- Two altitudes

![Graph showing spectral radiance vs simulations.

- Measurements at 2.7 km and 5.6 km.
- Simulations at 2.7 km and 5.6 km.
- Brightness temperature (°C) vs Wavelength (µm).]
• Spectral radiance profiles in cold atmosphere regions
• April 7, 2015 (left)
• April 11, 2015 (right)
Cloudy Skies Measured vs Simulated Radiance Profile

- Complex profile
- Short wave and longwave features correlate
- Spectrally resolved
Cloud-Radiation Closure Experiments

Cloud $\tau = 2$
Validation of IR Cooling Rates

Simulated by MODTRAN V5.4

Clear Sky: April 11, 2015

Cloudy Sky: April 13, 2015

Observed
Ground Campaign, Eureka – Winter 2015-16

© Dan Weaver
Ground Campaign, Eureka – Winter 2015-16

Validation against reference E-AERI at PEARL, Eureka
Clear Sky Observed FIRR vs Simulation

Validation against a radiative transfer model: MODTRAN
Retrieved Total Precipitable Water
Raman Lidar Profile: April 7, 2016 (21.5h)

FIRR Spectral Profile: April 7, 2016 (24h)
Model simulations
Microphysics, radiation and climate models
Monthly Mean Aerosol – Observed vs Simulated
Data assimilation
Operational forecast and climate models
Planck Function and Channel Ranges
Jacobian AIRS and FIRR/TICFIRE - Humidity

Room for improvement with more FIR bands
Analysis Error Variance – AIRS vs FIRR/TICFIRE

Temperature

Moisture

Laurence Coursol
Pierre Gauthier
Future missions
Active – passive instruments
Combining Limb & Nadir 3D Views
Coverage Analysis – Orbit Altitude, 650 km

Daily coverage, based on 20° half-angle:

- 70% coverage from 60° to 70° lat
- 90% coverage from 70° to 76° lat
- 100% coverage from 76° to 84° lat
- (~40% coverage of P3 region)
To monitor TIC, atmospheric water and cold anomalies formation, a new microsatellite is being developed.
Conclusion

• Spectral Radiance is a fundamental quantity to constrain models.

• Sidetracking via “evaluation” of aerosols and cloud microphysics add uncontrollable errors and model biases ($R_{\text{eff}}, N, \text{types… do not exists!}$).

• Direct and accurate measurement of radiation energy everywhere and all the time is the ultimate and least biased constrain.

• It can be directly assimilated into forecast models.

• The combination of active and passive instruments is the way to go!
Summary

• Coordinated observations from space, ground and aircraft are essential.

• CloudSat and CALIPSO have permitted to close many of the gaps in the complex interaction between aerosol, clouds, precipitation and radiation in the Arctic during the polar night.

• The involved feedback processes are powerful modulators of the atmospheric circulation and regional climate.

• Future mission should involve active instruments together with radiometric measurements, especially in the far IR and sub-mm range.
Thanks!
Two Coupled Planetary Scales Feedback Loops

**Vertical Branch**: Time scale ~ 1 – 5 days (indirect IR-Cloud)
- Aerosol
- Cloud
- Precipitation
- Radiation

**Horizontal Branch**: Time scale ~ 1 – 2 weeks (DGF)
- Circulation
- Aerosol transport
- Radiation