Arctic Clouds and Radiation

Part 1

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Radiation Transmitted by the Atmosphere

- **Dowgoing Solar Radiation**: 70-75% Transmitted
- **Upgoing Thermal Radiation**: 15-30% Transmitted

**Spectral Intensity**

- **Shortwave**
- **Longwave**

**Wavelength (μm)**

0.2, 1, 10, 70

**Major Components**

- Water Vapor
- Carbon Dioxide
- Oxygen and Ozone
- Methane
- Nitrous Oxide
- Rayleigh Scattering

http://www.globalwarmingart.com/images/7/7c/Atmospheric_Transmission.png
The Arctic receives meridional energy transport which it then radiates to space.
Net Radiation at Top of the Atmosphere averaged for one year

Note: Because of increasing greenhouse gas concentrations there is currently a global averaged net radiative heating of the Earth system of about 0.50 W m$^{-2}$ which is heating the oceans and melting ice.
Streamlines are computed from the advection of total parcel energy plus radiative energy transfer.

Parcel energy is the sum of enthalpy, potential energy, latent energy and kinetic energy.

Notice the role of the oceans in meridional transport.

FIGURE 13.15. Streamlines of the zonal-mean transport of total energy in the atmosphere for annual, DJF, and JJA mean conditions in $10^{15}$ W (from Oort and Peixoto, 1983).
NOAA-19 AVHRR, 11 µm channel   Feb 15, 2010  13:13Z
Arctic Winter Energy Balance

Net IR Up = Conduction + SH + LH

Net IR Up = 160 W m\(^{-2}\)

Infrared Up (Skin Temp)

Infrared Down (Temp and Greenhouse Gases)

Atmospheric Meridional Heat and Moisture Flux

Sea Ice

Freezing releases 20 W m\(^{-2}\)

120 W m\(^{-2}\)

10 W m\(^{-2}\)

Surface Energy Balance

Atmosphere

Clouds (Optical Depth)

Aerosols

Oceanic Meridional Heat and Water Flux

No sun

Ocean
Rough Surface Energy Balance in Winter High Arctic

- Longwave Down
- Longwave Up
- Sensible Heat about 10 W m\(^{-2}\)
- Net Longwave Surface Cooling of about 30 W m\(^{-2}\)
- Heat Conduction about 20 W m\(^{-2}\)

Why is the sensible heat warming the surface?
Sounding – plotted on a SkewT-LogP Diagram

Typical winter sounding at Eureka

Strong surface based temperature inversion

00Z 25 Feb 2010

University of Wyoming
MODIS measurement of skin temperature near Eureka in clear sky conditions. What is the cause of the warm regions?
SHEBA (Surface Heat Budget of the Arctic) was an interdisciplinary program to study the interactions of clouds, atmospheric radiation, and the surface energy balance over the Arctic Ocean. The field phase involved the deployment of numerous measurement systems on board and in the vicinity of the Canadian ice breaker *N.G.C.C. Des Groseilliers*, which was frozen into the Arctic ice pack north of Alaska from October 1997 to October 1998. During this period, Ice Station SHEBA drifted from approximately 75° N, 144° W to 80° N, 166° W.

Similar measurements are available at Eureka with the NOAA SEARCH flux tower.

Persson et al., 2002
Role of water vapour in the Arctic

1. Water vapour is the largest contributor to downward longwave at the surface, even in the dry winter conditions.


3. Changes in meridional transport are important for energy budgets and Arctic amplification.

4. Continued reduction of sea ice area will enhance evaporative fluxes from the ocean.
Contributions to Downward Longwave IR at Surface for Clear Winter Skies at Eureka (computed using SBDART radiation code)

Contributions to Surface IR Forcing

Water vapour dominates even though it is very cold

- H2O: 63%
- CO2: 23%
- O3: 2%
- olap: 4%
- other: 3%
- error: 5%
The Arctic experiences clouds much of the time.

Figure 5. Monthly averaged cloud occurrence percentages from the combined SHEBA lidar-radar data (bold line), surface observations from [Vowinkel and Orvig, 1970] (dashed line) and Warren et al. [1988] (dash-triple-dot), and satellite data from Key et al. [1999] (dash-triple-dot).
Clouds typically warm the surface though very weakly in the summer.
Winter ice clouds reduce surface IR cooling and enhance TOA IR flux.

Optical depth ~ 1.3

Solid Lines – Clear
Dotted Lines – Cloud Layer

Note the increase in downward IR when clouds are added.
The downward longwave irradiance increases rapidly as the cloud thickens.

Arctic ice clouds are often in this regime of low to moderate optical depths.
The E-AERI (Extended Atmospheric Emitted Radiance Interferometer) measures zenith radiance at 1 cm$^{-1}$ spectral resolution from 400 to 3300 cm$^{-1}$ or 25 to 3 µm (Kim Strong, UofT)

Compare FLBL and EAERI Oct 21, 2008

Red: FLBL (QZ sounding)
Black: EAERI (23.4+Z obs)

Mariani et al., 2012
Particle Backscatter Cross-section (High Spectral Resolution Lidar)

Infrared Spectrum of Downwelling Longwave (AERI)

Cloud is blocking the IR window
Thin Ice Clouds (TIC-1) visible by lidar but not by radar (type 1)
Consists of very small but likely numerous ice crystals

Aerosol backscatter cross section 12-Jan-2009

MMCR Backscatter Cross Section 12-Jan-2009

http://lidar.ssec.wisc.edu/cgi-bin/archive/month?site=2&type=all
Deep Precipitating Ice Systems

Aerosol backscatter cross section  07-Mar-2009

MMCR Backscatter Cross Section  07-Mar-2009
Deep Non-Precipitating Ice Systems

Aerosol backscatter cross section 13-Feb-2009

MMCR Backscatter Cross Section 13-Feb-2009
Supercooled liquid water layer

Precipitating ice crystals (TIC-2c)

Lidar (532 nm)

Cloud Radar (8.7 mm)
Snow precipitating from shallow supercooled liquid cloud layer or from deep ice clouds.

Ice crystals have a higher depolarization ratio compared to liquid cloud droplets.

Figure 1. (a) Time-height plot of the lidar depolarization ratio field, (b) corresponding time series of the layer-average depolarization ratio values for the low level water cloud (asterisks) and ice crystal precipitation (diamonds), and (c) time series of microwave radiometer column liquid water amount (mg/m²) for 6 May 1998.

Intieri, et al., 2002
**Mixed-Phase Cloud Statistics During SHEBA**

**Fig. 3.** Monthly and annual mixed-phase cloud statistics of (a) occurrence fraction, (b) cloud-base height, (c) cloud thickness, and (d) cloud temperature. The box-and-whisker plots provide the 5th, 25th, 50th, 75th, and 95th percentiles of the data, and the mean is given as a symbol.
Mixed phase clouds can persist for many hours and days. This is not the case in mid-latitudes.

Possible Factors:
- Few ice nuclei
- Weaker dynamics

**Figure 4.** Probability distribution function of mixed-phase cloud lifetime. Bin sizes are 1 h, and cloud layers with gaps of less than 1 h in duration were considered to be continuous. A total of 284 cloud layers were identified, and the most persistent cloud layer lasted for 153 h or 6.4 days. The box-and-whisker plots provide the 5th, 25th, 50th, 75th, and 95th percentiles of the data, and the mean is given as a symbol.

Shupe et al., 2006
Mixed Phase Clouds can be found at very cold temperatures

**Fig. 5.** Probability distribution functions of mixed-phase cloud temperature in 1°C bins.

Shupe et al., 2006
Thank you
Extra Slides
Eureka is losing about 160 W m\(^{-2}\) of IR radiation to space during the winter.
Jan Carbon dioxide
360 to 385 ppm

Jan Methane
1838 to 1872 ppb

Jan Nitrous oxide
303 to 319 ppb

Carbon monoxide
(not used)

http://www.esrl.noaa.gov/gmd/ccgg/iadv/
NOAA-19 AVHRR
11 μm channel
Feb 23, 2010  10:12Z
Fig. 2. Comparison of IWC derived from aircraft measurements (asterisks) and radar retrievals (diamonds). Aircraft data are directly from Zuidema et al. (2005). Radar retrievals are given as the mean (diamonds) and standard deviation (horizontal lines) of results for a 20-min time period surrounding the aircraft measurements at a given height.
TABLE 1. Annual mean and range of observations for mixed-phase cloud properties. The range covers the 5th to 95th percentiles of the data for all parameters except $A_c$, where the range is for monthly averages.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_c$</td>
<td>41%</td>
<td>10%–70%</td>
</tr>
<tr>
<td>$h_{base}$</td>
<td>0.9 km</td>
<td>0–3.5 km</td>
</tr>
<tr>
<td>$\Delta h_{cld}$</td>
<td>1.9 km</td>
<td>0.4–4.4 km</td>
</tr>
<tr>
<td>$T_{cld}$</td>
<td>$-14^\circ C$</td>
<td>$-27^\circ C$ to $-2.3^\circ C$</td>
</tr>
<tr>
<td>$D_{mean}$</td>
<td>93 $\mu m$</td>
<td>27–200 $\mu m$</td>
</tr>
<tr>
<td>IWC</td>
<td>0.027 g m$^{-3}$</td>
<td>$10^{-4}$–0.11 g m$^{-3}$</td>
</tr>
<tr>
<td>IWP</td>
<td>42 g m$^{-2}$</td>
<td>0.1–200 g m$^{-2}$</td>
</tr>
<tr>
<td>LWP</td>
<td>61 g m$^{-2}$</td>
<td>2.2–180 g m$^{-2}$</td>
</tr>
</tbody>
</table>
Figure 9. Ratio of broadband shortwave to broadband longwave optical depth determined from model parameterizations for liquid- and ice-phase clouds.

Pinto et al., 1997
The High Arctic is losing about 160 W m$^{-2}$ of IR radiation to space during the winter.

Dec, Jan, Feb Top of Atmosphere Longwave Radiation (W m$^{-2}$)

http://www-pcmdi.llnl.gov/obs/pods/mo/plt/rlut.cpc_olr.mo.sc.7901.8812.djf.htm
Fu – Liou Radiative Transfer Code

Correlated-k plane-parallel calculation.

2-stream in short-wave and 2- or 4-stream in long-wave.

6 short-wave bands, 12 long-wave bands.

Absorption by O$_3$, H$_2$O, CO$_2$, CH$_4$, N$_2$O and water continuum.

Rayleigh molecular scattering.

Can input aerosol and water and ice cloud profiles.

Agrees with line by line to within 1 W m$^{-2}$

Very fast.
Figure 2.22 Mean annual cycle of cloud cover (total cloud and low cloud, in %) for the central Arctic Ocean based on COADS data through 1995 (by the authors).

Serreze & Barry, 2009
Figure 6. Monthly averaged cloud base height and cloud top height from the combined lidar-radar data set.
Figure 12. Scatterplot of lidar depolarization ratio versus height (km) from 1 November 1997 through 8 August 1998.
Mixed-phase clouds occurred 41% of the time during the SHEBA annual cycle, and 59% of the time that clouds were observed. The annual minimum monthly fraction was 10% in December and the maximum was 70% in September. The majority of mixed-phase clouds occurred in the spring and fall transition seasons. About half of the mixed-phase clouds observed at SHEBA consisted of a single shallow, cloud-top liquid layer from which ice particles formed and fell.  

Shupe et al., 2006

On average, mixed-phase cloud layers persisted for 12 h. However, many mixed-phase cloud systems persisted for multiple days with only minor intermediate breaks in mixed-phase cloudiness.

Mixed-phase clouds occurred at temperatures ranging from 40° to 0°C, with most observations from 25° to 5°C. These clouds were typically 1–3 km thick with a cloud base near the surface.

Annual mean mixed-phase microphysical properties are $D_{\text{mean}}$ 93 m, $IWC$ 0.027 g m$^{-3}$, $IWP$ 42 g m$^2$, and $LWP$ 61 g m$^2$. These are all larger than the equivalent single-phase cloud properties from SHEBA presented by Shupe et al. (2005).

Ice particle sizes and IWC reach a broad maximum in the upper-middle portion of the average single-layer mixed-phase cloud, somewhat higher within the cloud than for single-phase ice clouds. This profile shape, and its difference from single-phase ice clouds, is likely associated with the liquid water source near the cloud top.

The liquid fraction, or the ratio of liquid water to total condensed water, generally increases with temperature. The annual average relationship transitions from full glaciation at 24°C to complete liquid water at 14°C, although at any given liquid fraction there is a 25°C range of observed temperatures. The temperature range over which this phase transition occurs may change moderately with season.
Fig. 1. (a) Lidar depolarization ratio, (b) radar Doppler spectrum width, (c) MWR-derived liquid water path, and (d) dry-bulb and dewpoint temperature soundings at 0515 UTC during a mixed-phase cloud case on 6 May 1998. The heights of the liquid cloud layer at the time of the sounding are indicated in (d).
Fig. 6. Monthly and annual statistics of cloud (a) $D_{\text{mean}}$, (b) ice water content, (c) ice water path, and (d) hours of occurrence for mixed-phase (star) and all-ice clouds (diamond). The all-ice cloud results are from Shupe et al. (2005). The box-and-whisker plots provide the 5th, 25th, 50th, 75th, and 95th percentiles of the data, and the mean is given as a symbol.
FIG. 8. Monthly and annual statistics of cloud (a) liquid water path and (b) hours of occurrence for single-layer mixed-phase (star) and all-liquid (diamond) clouds. These data are a subset of the full dataset that contained only one liquid-containing cloud type in the vertical column such that the microwave radiometer–derived LWP could be differentiated between mixed-phase and all-liquid clouds. The box-and-whisker plots provide the 5th, 25th, 50th, 75th, and 95th percentiles, and the mean is given as a symbol. MWR data prior to December are not available due to an instrument calibration error.
Fig. 10. (a) Scatterplot of the liquid fraction \([\text{LWP}/(\text{LWP} + \text{IWP})]\) vs cloud-top temperature for mixed-phase clouds. Also plotted are the annual and seasonal average relationships. (b) Box-and-whisker plots summarizing the same data used in (a). The 5th, 25th, 50th, 75th, and 95th percentiles and mean value are provided.
Fig. 11. The relative probabilities of four distinct ranges of the liquid fraction \([\text{LWP}/(\text{LWP} + \text{IWP})]\) given a cloud-top temperature. For each column, the sum of probabilities for the four possible categories equals 100\%.