Radiative characteristics of the Arctic atmosphere during spring as inferred from ground-based measurements

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Abstract. The radiative characteristics of low-level clouds over the Arctic ice pack in spring are inferred from ground-based broadband flux measurements using a radiative transfer model. An informal comparison of several radiative transfer models is performed for clear-sky conditions observed in April during LEADEX. The broadband longwave and shortwave surface fluxes obtained with Streamer and the broadband longwave surface flux obtained with the Rapid Radiative Transfer Model (RRTM) correlate well with the observations. The Streamer code is chosen to determine cloud optical and microphysical properties based on its performance under clear-sky conditions, its sophisticated treatment of clouds, and its option for calculating fluxes using a discrete ordinate technique. The radiative properties of the Arctic atmosphere are complicated by the presence of clouds. Low clouds occurred 30% of the time during LEADEX. The longwave and shortwave optical depths of clouds based below 2 km are inferred from surface-based measurements of cloud base height and broadband radiative fluxes by matching the observed fluxes with those obtained with the four-stream radiative transfer code available as part of Streamer. The retrieved broadband shortwave and longwave optical depths for low clouds observed during LEADEX ranged between 0.2 and 5. An attempt is made to infer cloud phase and cloud particle size from the ratio of the retrieved broadband shortwave and longwave cloud optical depths. This ratio ranges from 1.33 to 1.75 for ice, from 0.85 to 1.9 for liquid, and from 0.85 to 1.9 for mixed-phase clouds. Although there is much overlap between the ranges, it is shown that liquid-water clouds are characterized by optical depth ratios that are generally smaller than those found in ice clouds. This method for inferring cloud microphysics from surface-based measurements of broadband radiative fluxes and cloud base height may prove useful where more sophisticated observations of cloud microphysics are lacking.

1. Introduction

The most important component of the surface energy budget in the Arctic is the net radiation. Under clear skies the shortwave and longwave surface radiative fluxes are affected by the presence of aerosols and haze that are highly inhomogeneous in both the horizontal and the vertical [Barrie, 1986]. The effect of aerosols or haze over a highly reflective surface has been shown to be quite complex [e.g., McCracken et al., 1986; Blanchet and List, 1987] and dependent on the aerosol/haze optical properties. Large solar zenith angles and surface albedos accentuate the effect aerosols have on the shortwave flux at the surface by increasing the path length through multiple reflections between the highly reflective surface and the atmosphere. The extreme cold complicates the treatment of longwave radiation, since a significant contribution to the longwave flux occurs at the lower-frequency water vapor rotation bands. The very dry conditions typical of the Arctic drastically reduce water vapor absorption, opening a "dirty window" at longer wavelengths that allows radiation to escape to space much more readily in this region (R. G. Ellingson, J. A. Curry, K. Starnes, J. E. Walsh, and B. D. Zak, Overview of north slope of Alaska/adjacent Arctic Ocean (NSA/AAO) science issues and sitting strategies, paper submitted to J. Clim., 1996).

The surface radiative fluxes in the Arctic are strongly modulated by the presence of clouds. Over the Arctic ice pack the effect that clouds have on the surface energy budget is of particular importance because of the sensitivity of sea ice thickness to surface irradiances [e.g., Shupe and Curry, 1984; Curry et al., 1995]. Between mid autumn and mid spring the amount of solar radiation reaching the surface is limited by large solar zenith angles typical of high latitudes, allowing longwave radiation to dominate the radiative energy budget. Clouds increase the emission of longwave radiation by the atmosphere and tend to warm the surface during these months. For a brief period during the summer, when the solar insolation is at a maximum, the presence of clouds results in a cooling at the surface. However, averaged over the year, clouds tend to warm the surface in the Arctic [e.g., Curry and Ebert, 1992], in contrast with what occurs at lower latitudes.

The effect of clouds on both solar and terrestrial irradiances is determined by the microphysical and macrophysical properties of the cloud. These properties include particle phase, size, shape, and concentration; cloud base height and geometric cloud depth;
and cloud fraction. The effect of increasing particle size on the transmitted shortwave flux depends on the compensating effects of increased absorption and forward scattering. The downwelling longwave radiation at the surface depends on the temperature and emissivity of the cloud layer. For optically thin liquid clouds the emissivity decreases with increasing particle size [Curry and Herman, 1985]. The same general relationships have been obtained for ice clouds [Ebert and Curry, 1997], except ice backscatters more in the visible and absorbs more in the near-infrared than liquid water.

The optical and microphysical properties of clouds observed over the Arctic ice pack are summarized by Curry et al. [1996]. In the Arctic, low-level clouds are predominantly crystalline during winter and liquid during summer. Mixed-phase clouds occurring in the lowest 2 km of the troposphere are common during the transition seasons. The effective radii observed in liquid stratus clouds range between 3.6 and 11.4 μm [Herman and Curry, 1984]. Curry and Ebert [1992] estimated an ice particle effective radius of 40 μm from particle size distributions obtained by Witte [1968] in winter.

Surface-based remote sensing of the optical properties of liquid clouds occurring in the Arctic has been attempted by Francis et al. [1991] and Leontyeva and Stamnes [1994]. Francis et al. [1991] obtained cloud optical depth by comparing broadband shortwave and longwave flux measurements obtained during the Marginal Ice Zone Experiment (MIZEX) with results from the δ2-stream solution of Liou [1974]. By adjusting the cloud base height and the visible cloud optical depth until the observed and modeled broadband shortwave and longwave irradiances matched, the visible cloud optical depth was obtained for an assumed cloud phase, effective radius, and geometric cloud depth. Leontyeva and Stamnes [1994] determined the total column broadband shortwave cloud optical depth by varying it until the observed broadband solar irradiance matched to within 10 W m⁻² of that obtained with a two-stream δ-Eddington radiative transfer model [Joseph et al., 1976]. They determined that the cloud optical depth is sensitive to the surface albedo and the assumed aerosol/ haze optical depth. For solar zenith angles greater than 60° and a broadband surface albedo greater than 0.6 they have shown that the broadband solar irradiance received at the surface is insensitive to effective radius.

Previous attempts to retrieve Arctic cloud optical properties from ground-based measurements have assumed the clouds were comprised of liquid droplets. This assumption is not be valid during spring and autumn, when mixed-phase clouds are often present in the lowest 2 km of the atmosphere. Curry et al. [1990] have shown that the transition from liquid to ice phase during April occurs over a range of temperatures (i.e., 253-266 K), which presumably depends on the quantity and type of ice-forming nuclei present and the age of the cloud.

We infer the radiative characteristics of the Arctic atmosphere in spring using ground-based measurements obtained during the 1992 Arctic Leads Experiment (LEADEX). The radiative properties of clear-sky conditions and low-level clouds are examined. Broadband longwave and shortwave cloud optical depths are determined by comparing the observed surface fluxes with those obtained with a detailed radiative transfer model for a varied cloud optical depth. An attempt at deriving cloud microphysical characteristics from the retrieved longwave and shortwave cloud optical depths is made by extending the method of Twomey and Cocks [1982] to transmitted broadband solar and terrestrial flux measurements.

2. Data

The surface energy budget over the Arctic ice pack was examined in spring (March 20 to April 20, 1992) as part of LEADEX [Ruffieux et al., 1995]. Measurements were taken on the permanent ice pack at a drifting base camp located near 73°N, 145°W, or about 240 km northeast of Prudhoe Bay, Alaska. The base camp included the following relevant instrumentation: two to four rawinsonde launches per day, an upward pointing laser ceilometer, and upward and downward looking pyranometers and pygeometers [Wolfe et al., 1992]. The upward pointing laser ceilometer provides a continuous record of cloud base height for clouds based below 3.5 km. In addition, the ceilometer is used to detect the presence of multiple cloud layers and to provide information on

<table>
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<th>Table 1. LEADEX Cloud Events</th>
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fractional cloud cover. Ceilometer data were collected every 30 s to obtain a 5-min average cloud fraction. Downwelling broadband solar (0.283–2.8 μm) and terrestrial (4.0–50.0 μm) irradiances were measured at the surface with an Eppley pyranometer and an Eppley pygeometer, respectively. These fluxes are corrected by the manufacturer to provide broadband fluxes over the wavelength ranges 0.285–4.0 μm and 4.0–200.0 μm. Surface fluxes were measured at a sampling rate of 0.1 Hz and averaged over 15-min intervals. The longwave and shortwave flux measurements are accurate to within ±2% as discussed by Raffieux et al. [1995].

Cloud events are chosen to be as nearly compatible with the plane-parallel approximation as possible. These conditions are most closely satisfied when the sky is overcast (i.e., ceilometer reporting cloud fraction greater than or equal to 9/10) and the solar zenith angle is less than 75°. The data set is further limited by the requirement that there be no mid- or high clouds present as determined by satellite imagery and the relative humidity profile.

To fulfill the zenith angle requirement, only cloud events occurring during the last three weeks of LEADEX are considered. Table 1 lists the characteristics of each cloud event examined in this study. The duration of the cloud event is determined by the period of time the ceilometer registers 9/10 cloud cover or greater (including obscuration) for each 5-min period. These cases also have a well-defined cloud base and are not precipitating.

The effect that clouds have on the surface radiative fluxes is demonstrated in Figure 1. Two quite different cloud events are illustrated: one with a tenuous base near 1000 m and one with a solid base at 200–300 m. The second cloud event increases the downward longwave flux at the surface by nearly 70 W m⁻² while reducing the downward shortwave flux by 90 W m⁻² at solar noon. Breaks in the cloud cover are clearly seen as negative spikes in the longwave flux time series.

3. Clear-Sky Radiative Transfer

The ceilometer indicated that the lowest 3.5 km of the atmosphere was free of clouds approximately 70% of the time. Available advanced very high resolution radiometer satellite imagery is used to determine when clear skies extend through the entire troposphere. It was determined that completely clear skis occurred for an extended period of time on several days. The observed clear-sky downwelling broadband fluxes at the surface are compared with the fluxes obtained by using a two-stream radiative transfer code. The comparison is done to assess the validity of the clear-sky determination made from ceilometer and ancillary satellite data. Positive biases in the modeled clear-sky shortwave flux coupled with negative biases in the modeled clear-sky longwave flux indicate the potential presence of clouds or haze. Errors in the water vapor measurements or the assumed climatological ozone profile will show up as biases in the clear-sky shortwave flux calculations. Time variation in aerosol concentrations may be inferred by comparing calculated clear-sky shortwave fluxes with observation on consecutive days.

3.1. Model Description

Version 2.04p of Streamer [Key, 1995] is employed. Streamer has its roots in the STRATS/DisORT code of Tsay et al. [1989]. This radiation package has several features that are advantageous for this study, including high spectral resolution, a detailed treatment of surface radiative properties, the availability of several aerosol models and profiles, and an option to use either the two-stream code of Toon et al. [1989] or the discrete ordinates solver developed by Stammes et al. [1988], which allows for 4 to 48 streams.

For clear-sky conditions the shortwave irradiances are computed with the two-stream model using 24 bands from 0.28 to 4.0 μm. Rayleigh scattering by the atmosphere and solar absorption by CO₂, O₂, O₃, and H₂O are accounted for as well as scattering and absorption by aerosol particles. The clear-sky broadband surface albedo is determined assuming a deep layer of fresh snow and is a function of the solar zenith angle.

The longwave irradiances are computed by using the two-stream model with 104 spectral intervals from 4.03 to 250 μm. The extension of the modeled longwave spectrum to 50 μm beyond the observed spectral range results in an overestimation of the longwave surface flux relative to the surface observations by less than 0.5 W m⁻². Gaseous absorption by CO₂, H₂O, and O₃ is parameterized with an exponential sum fitting of the transmissions method [Wiscombe and Evans, 1977]. The absorber amounts are scaled empirically with pressure and temperature dependence according to Kneizys et al. [1980].

The model accepts vertical profiles of temperature, water vapor, ozone, and aerosol as well as concentrations of well-mixed gaseous constituents. A climatological profile of ozone characteristic of sub-Arctic winter conditions is assumed [Ellingson et al., 1991]. Aerosol profiles and radiative properties are chosen from Shettle and Fenn [1979] to be representative of conditions observed during LEADEX with background tropospheric aerosols and high stratospheric loading to emulate the effect of the Mt.
Pinatubo eruption in June 1991. Stone et al. [1993] reported a visible optical depth for stratospheric aerosols of 0.2. A visible aerosol optical depth of 0.29 is used to account for the contribution from tropospheric aerosols. Carbon dioxide is uniformly mixed through the atmosphere at a concentration of 350 parts per million. Vertical profiles of temperature, moisture, and ozone are extended above the top of the sounding to 100 km with climatological mean values.

3.2. Clear-Sky Irradiances

The observed clear-sky broadband solar fluxes at the surface are compared with those obtained with Streamer in Figure 2a. Comparisons are made with the plane parallel assumption is valid. The downward solar flux (direct plus diffuse) at the surface, computed at 30-min intervals, is compared with 15-min measured solar flux. There is significant scatter around the line of 1:1 correspondence, although the best fit line nearly overlays this line. The scatter can be attributed to time variations in the aerosol profiles. Biases that would indicate systematic errors in the assumed ozone profile or the observed water vapor profile are not present.

The modeled and observed downwelling broadband longwave irradiances for clear sky are compared in Figure 2b. There are fewer data points, because the longwave flux mainly depends on the temperature and moisture profile, which were only observed two to four times per day. The data points have been divided into day and night observations to demonstrate the lack of diurnal biases in the data. A systematic negative bias of about 3 W m\(^{-2}\) is evident. This discrepancy can be attributed to emission by trace gases (e.g., CH\(_4\) and N\(_2\)O) not treated by the model. These trace gases may contribute more than 2 W m\(^{-2}\) to the observed downwelling longwave flux at the surface. Leonard and Stammes [1994] have noted that water vapor amounts may be underestimated under extreme cold conditions. The presence of haze may also contribute to underestimates in the modeled clear-sky longwave flux at the surface.

3.3. Clear-Sky Model Intercomparison

To determine the utility of radiative transfer models in the Arctic, an informal intercomparison is conducted for two clear-sky cases observed during LEADEX. The Intercomparison of Radiation Codes Used in Climate Models (ICRCCM) [Ellingson et al., 1991] was undertaken to determine discrepancies among climate

<table>
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<th>Acronym</th>
<th>Model</th>
<th>Source</th>
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<td>Key [1995b]</td>
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<tr>
<td>MM5</td>
<td>NCAR/PSI Mesoscale Model</td>
<td>Dudhia [1989]</td>
</tr>
<tr>
<td>CCM2</td>
<td>NCAR Community Climate Model, version 2</td>
<td>Briegleb [1992a, b]</td>
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<tr>
<td>EC3</td>
<td>European Centre for Medium-Range Weather Forecasts, version 3</td>
<td>Morcrette [1991]</td>
</tr>
<tr>
<td>HAR</td>
<td>Colorado State GCM</td>
<td>Harshvardhan et al. [1987]</td>
</tr>
<tr>
<td>RRTM</td>
<td>Rapid Radiative Transfer Model, (longwave only)</td>
<td>Mlawer et al. [1995]</td>
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The modeled broadband downward longwave and shortwave radiative fluxes at the surface are intercompared in Figure 4. The models tend to underestimate the downwelling longwave radiation in both cases. The radiative transfer codes underestimate the observed downwelling longwave flux by between 1.5 and 25 W m\(^{-2}\). The longwave fluxes obtained for case 1061 are slightly greater, as the temperature profile has warmed. The large negative bias in CCM2 has been attributed to inadequate treatment of absorption by water vapor likely in the rotational bands at the far end of the longwave spectrum (J. Kiehl, personal communication, 1997). The RRTM includes contributions by trace gases that the other models do not include. The lack of trace gases is partially responsible for the larger negative biases seen in the other models. The presence of aerosols or haze may also have contributed to this bias.

A great deal of scatter among is evident in downwelling shortwave surface flux calculations. Excluding the MM5 results, these flux calculations vary by as much as 60 W m\(^{-2}\). The flux obtained with MM5 are much less than the observed values and those obtained with the other models due to extinction from scattering by the atmosphere which has been remedied in version 2 of MM5 (J. Dudhia, personal communication, 1996). The results also indicate the importance of aerosols, as the models without aerosols show significant positive biases in the downwelling shortwave flux at the surface. Time variations in aerosol properties is seen by comparing model biases in the two cases. In case 1001, both EC3 and STR3 underestimate the downward shortwave flux, while in case 1061, both models overestimate the observed flux. This finding is indicative of an increase in the aerosol optical depth from case 1001 to case 1061, which is consistent with sun photometer measurements collected during LEADEX [Stone et al., 1993].

4. Radiative Transfer in Cloudy Conditions

Low-level clouds were observed by the ceilometer about 30% of the time. This cloud fraction includes instances in which the ceilometer was totally obscured by either precipitation or fog, which occurred about 8% of the time. The shortwave radiative properties of clouds are determined with the discrete ordinate solver for 4 streams in Streamer. The model cloud radiative properties are a function of cloud depth: particle phase, size, and water content, and spectral wavelength, as described below.

4.1. Liquid Water Clouds

The radiative properties of liquid water clouds depend on the liquid water path, \(LWP\), and the mean particle size. If the liquid water content, \(q_l\), within the cloud is assumed to be vertically homogeneous, then the liquid water path can be defined as

\[
LWP = q_l \Delta z,
\]

where \(\Delta z\) is the depth of the cloud.

The radiative properties of clouds are parameterized after Hu and Stamnes [1993] and are given by

\[
\tau = LWP \left( a_1 r_c^{b_1} + c_1 \right),
\]

\[
1 - \omega = a_2 r_c^{b_2} + c_2,
\]

\[
g = a_3 r_c^{b_3} + c_3,
\]

where \(\tau\) is the cloud optical depth, \(\omega\) is the single-scattering albedo, \(g\) is the asymmetry parameter, \(r_c\) is the mean particle size or effective radius, given by the ratio of the third to second...
moments of a drop size distribution, and $a_i$, $b_i$, $c_i$ ($i = 1, 2, 3$) are empirical coefficients that are functions of wavelength and effective radius. Values for the coefficients are given in tabular form by [Hu and Stammes [1993]].

4.2. Crystalline Clouds

The optical properties of crystalline clouds are complicated by variations in particle shape and orientation as well as the density of the ice. Uncertainties in the theory of scattering by nonspherical ice particles are noted as well. Although the complex interaction between radiation and nonspherical ice crystals is not well understood, general relationships between ice particle size, ice water path and cloud optical properties have been developed [Ebert and Curry, 1992]. This approximation may not be bad for randomly oriented irregularly shaped ice crystals that are commonly observed in the Arctic [Curry et al., 1990].

In Streamer, crystalline clouds are parameterized in terms of an equivalent sphere effective radius, $r_e$, and ice water path, IWP. The effective radius is determined assuming a polydisperse ice crystal size distribution composed of randomly oriented hexagonal cylinders. Shortwave single-scattering properties for ice crystals have been parameterized by Ebert and Curry [1992] following the formalism set forth by Stingo [1989] for liquid water clouds and are given here for completeness. The optical depth, $\tau$, single-scattering albedo, $\omega$, and asymmetry factor, $g$, are given by

$$\tau = IWP \left( a + \frac{b}{r_e} \right), \quad (5)$$

$$1 - \omega = c + dr_e, \quad (6)$$

where $IWP$ is the ice water path defined following (1) and $a$, $b$, $c$, $d$ are wavelength-dependent coefficients given by Ebert and Curry [1992].

The parameterization of ice cloud optical properties in the longwave follows the method of [Hu and Stammes [1993]] in which Mie calculations are made assuming equivalent sphere effective radii. The equations for optical depth, single-scattering albedo, and asymmetry parameter are identical to (1)-(4) except the values of $a$, $b$, and $c$ are for ice and depend only on wavelength [Key, 1995].

4.3. Model Sensitivity

Potential errors in the modeled surface fluxes for a cloudy situation are examined by varying the uncertain model parameters and inputs through their range of possible values. Some inputs (e.g., cloud base height and temperature profile) affect only the longwave irradiances, others (e.g., surface albedo) affect only the shortwave irradiances, and still others (e.g., microphysical characteristics and water vapor profile) affect both. Unless otherwise noted, the following conditions are assumed for each sensitivity study. The temperature and moisture profiles observed during LEADEX on April 12, 1992 at 0000 UTC (Figure 5) arc used. A 300-m deep cloud layer based at 1 km is assumed to be present. The cloud is assumed to be composed of liquid drops with an effective radius of 7 microns. The liquid water content is varied between 0.01 g m$^{-3}$ and 0.5 g m$^{-3}$, so that by using (1) and (2) the cloud broadband shortwave optical depth ranges between 0.7 and 15.

Microphysical properties are assumed to be constant with height.
through the cloud. Shortwave computations are made assuming a solar zenith angle of 67.3° and a broadband surface albedo of 0.8, typical of sea ice covered with fresh snow.

The sensitivity of downwelling fluxes at the surface to changes in vertical profiles of temperature and moisture is examined. Surface fluxes are computed for the two soundings depicted in Figure 5 assuming the cloud layer described above is present. The cloud has a broadband shortwave optical depth of 5.6. The modeled longwave radiative flux at the surface is 7 W m⁻² greater for the 0000 UTC profile, while the modeled shortwave fluxes are quite similar. The radiative effect of water vapor is isolated by varying the precipitable water in the 0000 UTC sounding. A 50% reduction in the precipitable water results in a decrease in the downwelling longwave flux at the surface by more than 3 W m⁻² and an increase in the downwelling shortwave flux of 4.7 W m⁻² for optically thin clouds. The impact of variations in the moisture profile on the surface fluxes is reduced as the cloud optical depth increases.

The longwave flux at the surface is sensitive to changes in the macrophysical properties of a cloud layer. The modeled longwave flux is plotted as a function of the broadband longwave optical depth and cloud base height in Figure 6. For optical depths less than 4 the longwave flux at the surface is strongly related to the longwave cloud optical depth. For large optical depths the cloud acts as a blackbody such that increases in optical depth have little impact on the longwave flux at the surface. Variations in the cloud base height affect the modeled surface flux if the temperature profile deviates significantly from isothermal. For the temperature profile used here, a change in the cloud base height of 250 m alters the modeled downward longwave flux by as much as 3 W m⁻². This effect increases with increasing optical depth and is larger for a decrease in cloud base height for this particular case. The effect of varying the geometric cloud depth on the modeled longwave flux at the surface is found to be of second-order importance.

The modeled surface irradiances are affected by vertical variations in the cloud microphysical properties. A simple test was done to determine the sensitivity of surface fluxes to vertical inhomogeneities in cloud microphysical properties whereby the base-line, single cloud layer has been divided into two cloud layers of equal depth. Cloud microphysical properties are then varied in the two layers while their vertically averaged values remain constant. Assuming a vertically averaged liquid water content of 0.2 g m⁻³, we find that vertical variations in liquid water content change the downwelling longwave flux at the surface by less than 1 W m⁻² and have little effect on the downwelling shortwave flux. Vertical variations in effective radius have a significant effect on the modeled shortwave flux at the surface. For a liquid water content of 0.1 g m⁻³ a change in the vertical structure of effective radius from a constant value of 1 μm to two layers of equal depth with effective radii of 5 μm and 9 μm results in a decrease in downward shortwave radiation at the surface by about 5 W m⁻². This effect increases with increasing liquid water path or optical depth. The longwave flux at the surface is insensitive to vertical variations in effective radius.

The modeled downwelling shortwave flux at the surface is a strong function of the broadband surface albedo under cloudy sky conditions. Surface fluxes are calculated as a function of broadband shortwave cloud optical depth for broadband surface albedos of 0.4, 0.55, and 0.8, representing bare ice covered with melt ponds, bare ice, and ice covered with fresh snow, respectively. It is seen in Figure 7 that the downwelling shortwave flux is extremely sensitive to surface albedo and the sensitivity increases with increasing cloud optical depth. The importance of properly specifying surface type is evident. For example, assuming a broadband optical depth of 5, a change in the albedo from 0.4 to 0.55 results in an increase in the downwelling shortwave radiation at the surface of 20 W m⁻².  

![Figure 5](image1.png)  
**Figure 5.** Temperature and moisture profiles obtained by two successive radiosonde launches of a drifting ice camp at 0000 UTC (solid line) and 0600 UTC (dotted line) on April 12, 1992, during LEADEX.

![Figure 6](image2.png)  
**Figure 6.** Sensitivity of modeled downward longwave irradiance at the surface to variations in cloud base height as a function of broadband longwave optical depth, $\tau_{\text{LW}}$.

![Figure 7](image3.png)  
**Figure 7.** Sensitivity of modeled downward shortwave irradiance at the surface to variations in the surface albedo as a function of broadband shortwave optical depth, $\tau_{\text{SW}}$. 
Table 3. Potential Error in Modeled Broadband Surface Fluxes

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The results of these sensitivity analyses are summarized in Table 3. Both fluxes are somewhat sensitive to changes in the moisture profile, especially for optically thin cloud layers. The modeled surface longwave flux is most sensitive to changes in the cloud base height, while the modeled shortwave surface flux is strongly dependent on the surface albedo, particularly for optically thick clouds. The modeled downwelling longwave flux is insensitive to vertical variations in cloud microphysical properties, while modeled shortwave fluxes are particularly sensitive to vertical variations in particle size.

5. Retrieval of Broadband Optical Depths

The broadband longwave and shortwave cloud optical depths are derived for several cloud events occurring during LEADEX. The method of retrieval of the broadband optical depths from surface-based flux measurements is similar to that employed by Francis et al. [1991] and Leontyeva and Stammes [1994]. However, since the cloud phase is unknown, separate calculations are performed assuming liquid- and ice phase cloud optical properties for each case. The liquid and ice cloud optical depths are varied until the modeled and observed fluxes agree to within 5% to account for uncertainties in observations and model assumptions. This criterion is similar to that used by Leontyeva and Stammes [1994] to obtain shortwave cloud optical depths. The broadband optical depth for solar radiation (0.28–4.0 μm) is obtained through a weighted average based on the spectral partitioning of solar radiation [Tsay et al., 1989]. Similarly, the broadband longwave optical depth (4.0–200 μm) is a spectrally weighted average based on the Planck function for the mean temperature within the cloud layer. The geometric cloud depth, which has been shown in section 4 to be of second-order importance, is held constant at 300 m for each case. Only cases with a well-defined cloud base are examined.

The longwave and shortwave optical depths obtained assuming liquid and ice radiative properties are listed in Table 4 for each case. It is seen that the retrieved liquid-phase shortwave cloud optical depths are 20–40% greater than those retrieved assuming ice radiative properties. The retrieved longwave cloud optical depth is relatively insensitive to the assumed cloud phase. Differences in the retrieved shortwave cloud optical depths as a function of particle phase are caused by enhanced backscattering in the visible and absorption in the near infrared by ice clouds relative to liquid clouds. Thus, to attenuate a given amount of shortwave radiation an ice cloud will have a smaller optical depth than a liquid cloud.

The sum of errors in modeled longwave and shortwave flux at the surface resulting from uncertainties in model inputs and assumptions (see Table 3) are used to perform an error analysis on the retrieved broadband optical depths listed in Table 4. Since surface albedo and cloud base height were observed during LEADEX, the total uncertainty in the modeled shortwave and longwave surface fluxes is 10 W m⁻² and 5 W m⁻², respectively. The error bars obtained assuming liquid and ice radiative proper-

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* L, liquid; M, mixed phase; I, ice.
† "Best guess" at particle phase.
ties are shown in Figure 8 for each case. The ice error bars for shortwave optical depths extend below the liquid error bars, thus broadening the range of retrieved shortwave optical depths. The largest range of shortwave optical depths coincides with the case with the largest solar zenith angle (e.g., case 1). Excluding case 6, the error bars for the long-wave optical depths are fairly uniform in size, are nearly independent of assumed particle phase, and are generally smaller than those obtained for the shortwave optical depths. In case 6 the cloud layer emits as a blackbody, resulting in a large uncertainty in the retrieved longwave optical depth.

Comparison with observations cannot be made directly because valid in situ measurements of cloud properties were not made during LEADEX. If we assume we have a perfect retrieval with the exception of cloud phase, then the retrieved broadband shortwave optical depth ranges from 0.2 to 3.0. The range of values includes the uncertainty associated with unknown cloud particle phase. The shortwave optical depth of 0.2 to 0.4 obtained for cases 9 and 10 are likely crystalline, given the temperature for each case is less than 253 K. The retrieved ice optical depth of 0.23 for each case is similar in magnitude to values obtained for low level ice crystal clouds observed in April, which ranged from 0.076 to 0.7 (Curry et al., 1990). The largest cloud optical depths are expected in summer in the Arctic; however, even during the peak season, shortwave cloud optical depths obtained by Herman and Curry (1984) for low stratus clouds were often less than 5. Shortwave optical depths obtained by ground-based measurements of Leontyeva and Staines (1994) near Barrow, Alaska, in April are generally greater (mean optical depth of 8) than those obtained here; however, these values are for the entire atmospheric column, which may include multiple cloud layers. Further, we would expect clouds near Barrow to have microphysical properties vastly different from those observed over the ice pack because of its proximity to open water, coastal influences, raised topography and differing synoptic activity.

The retrieved broadband longwave optical depths (excluding case 6 because of potential saturation) are nearly independent of assumed particle phase and range between 0.18 and 2.2. The grey flux emittances obtained by Curry and Herman (1985) for low-level summertime stratus clouds correspond to broadband longwave optical depths ranging from 0.8 to 6.2. These values may serve as an upper limit on the retrieved longwave optical depth for low clouds. It is noted that to our knowledge broadband longwave cloud optical depths have not been previously derived from ground-based measurements.

### 6. Retrieval of Microphysical Characteristics

The longwave and shortwave broadband optical depths, derived assuming liquid- and ice-phase optics, are used in the retrieval of cloud microphysics. The potential for inferring cloud particle size from two narrow bands in the near infrared with different absorption characteristics has been known for some time (e.g., Twomey and Cocks, 1982). This concept is extended in an attempt to retrieve estimates of particle phase and size from information contained in the broadband solar transmittance and terrestrial emittance. The spectral variation of single-scattering albedo and asymmetry parameter, which gives the relative amount of backscatter by cloud particles, differs for liquid and ice. Differences in these broadband shortwave and longwave parameters may be used to retrieve particle phase from transmitted broadband fluxes. Solar radiation is mainly scattered by cloud particles in the visible, while absorption becomes important in the near infrared. This near-infrared absorption is enhanced for large liquid drops and ice crystals of all sizes. Absorption by ice crystals occurs in several bands (e.g., 1.1, 1.6, 2.1, and 3–4 μm) not present in the absorption spectrum of liquid water. Comparing the spectral distribution of the asymmetry parameter for liquid and ice reveals additional differences between the two cloud phases. The asymmetry parameter is greater for liquid at solar wavelengths between 0.3 and 1.0 μm, while it becomes greater for ice in the infrared (i.e., between 1 and 4 μm). Since most of the solar energy is in the visible and near infrared portion of the spectrum, spectral weighting results in a larger asymmetry parameter for liquid (i.e., ice particles backscatter solar radiation more efficiently than liquid drops). The enhanced near-infrared absorption and backscattering by ice clouds allows for more efficient attenuation of solar radiation than that by liquid clouds. Differences in the longwave
radiative properties of liquid and ice are less significant, although clouds composed of small liquid drops will emit more effectively than clouds composed of large ice crystals.

The retrieval of particle phase and size from broadband transmitted shortwave and emitted longwave fluxes is based on the relationship discussed by Platt and Harshvardhan [1988]. They have shown that the extinction and/or absorption optical depths \( \tau_{i,2} \) for any two narrow bands centered at wavelengths of \( \lambda_{1,2} \) follow

\[
\frac{\tau_i}{\tau_2} = \frac{Q_i(r_i)}{Q_2(r_2)} = \zeta(r_i),
\]

where \( Q \) is the effective extinction or absorption efficiency that is a function of particle phase and effective radius, \( r_e \). The term “effective” indicates that the mean particle size and efficiency parameters have been weighted by the particle size distribution. Thus the ratio of optical depths at any two wavelengths can potentially be used to determine the cloud particle size and phase.

The relationship between the broadband optical depth ratio \( \zeta \), particle size \( r_e \), and phase is determined following the parameterizations of cloud optical depth for liquid and ice as described in sections 4.1 and 4.2. The functional dependence of the broadband optical depth ratio on phase and size is shown in Figure 9. The liquid optical depth ratio, \( \zeta_l \), ranges from 0.85 to 2.0, while the ice optical depth ratio, \( \zeta_i \), ranges from 1.33 to 1.7. The range of liquid effective radii shown in Figure 9 has been constrained by limited observations of microphysical properties of Arctic clouds and by the range of sizes over which the model parameterizations are valid. It is seen that the liquid optical depth ratio is a much stronger function of effective radius than the ice optical depth ratio for liquid radii less than 10 \( \mu \text{m} \). The sensitivity of the ice-phase optical depth ratio to particle size is much smaller but increases with increasing particle size. It is noted that the optical depth ratio for a mixed-phase cloud can be obtained by

\[
\zeta_{ml} = \frac{\tau_{i1} + \tau_{l1}}{\tau_{i2} + \tau_{l2}},
\]

where subscripts \( i \) and \( l \) denote ice and liquid phase, respectively. Figure 10 gives the mixed-phase optical depth ratio as a function of liquid and ice effective radii for a cloud with equal masses of liquid and ice. The mixed-phase optical depth ratio ranges from a minimum of 1.01 for a liquid effective radius of 13 \( \mu \text{m} \) and an ice effective radius of 115 \( \mu \text{m} \) to over 1.9 for liquid effective radii of 4 \( \mu \text{m} \). It is seen that a broad region exists in which

<table>
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<th>Ice</th>
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<tr>
<td>( b )</td>
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<td>-0.003</td>
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<tr>
<td>( c )</td>
<td>0.865</td>
<td>4.139</td>
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Table 5. Coefficients for \( \zeta \) Equations

The retrieved liquid and ice optical depth ratios listed in Table 4 produce a range of potential optical depth ratios, which are limited by the theoretical range of optical depth ratios seen as maxima and minima in Figures 9 and 10. Ratios for both phases are listed for each case in which \( r_{s1W} > 0.5 \), the solar zenith angle is less than 75°, and the retrieved longwave optical depth does not suffer from saturation (e.g., case 6). The retrieved, phase-dependent (i.e., liquid or ice) optical depth ratios for each case are assumed to be valid when they are within the range of theoretical values shown in Figure 9. In most of the cases the retrieved liquid optical depth ratio is valid, while the retrieved ice optical depth ratio is not. The exception is case 8 in which only the retrieved ice optical depth ratio is valid. This case is most likely composed of ice. The rest of the cases may be either liquid or mixed phase (see Figure 10), but not ice, because the ice-phase optical depth ratios are much smaller than the minimum theoretical value possible (\( \zeta_i = 1.33 \)). A “best guess” cloud phase may be obtained by eliminating phase retrievals that require unrealistic particle sizes as compared to previously observed cloud properties. Choosing between liquid and mixed phase is done by setting the lower limit liquid effective radius to 5.5 \( \mu \text{m} \) (\( \zeta_i = 1.3 \)) as observed by Herman and Curry [1984]. The “best guess” cloud phase is listed in Table 4 for each case in which optical depth ratios have been obtained. The in-cloud temperatures listed in Table 1 for likely mixed-phase cases (i.e., cases 2, 7, 11, 12, and 13) range from 247 K to 254 K. These low temperatures suggest that at least some ice is likely present, a finding that would seem to corroborate the mixed-phase retrieval for these cases. Case 4 is characterized by slightly warmer in-cloud temperatures of between 253 K and 258 K and may have been composed almost entirely of supercooled water droplets as suggested by the retrieval. The in-cloud temperature for case 8 was around 252 K, cold enough to support a pure ice cloud as was retrieved. The phase retrievals seem plausible given the range of temperatures for each case; however, the observed temperature cannot be used to unambiguously determine particle phase.

The effective radii of the cloud layer can be obtained from Figure 9 for liquid- and ice-only cases. Separate equations for liquid and ice are fitted to the curves by performing a nonlinear least squares fit. The relationships for liquid and ice optical depth ratios as a function of liquid and ice effective radii are given by

\[
\zeta_l = a_1 \exp \left( b_1 r_{e1} \right) + c_1
\]

\[
\zeta_i = a_2 r_{e2}^2 + b_2 r_{e2} + c_2
\]

Figure 10. Mixed-phase optical depth ratios for a cloud with equal amounts of liquid and ice present for a range of liquid and ice effective radii.
liquid optical depth ratio of 0.89 results in an effective radius of 12.2 μm, is slightly larger than the maximum value reported by Herman and Curry [1984] for summertime Arctic stratus. This value must be treated with caution, as some ice may be present within or beneath the cloud layer. For case 8 the ice optical depth ratio of 1.51 results in an effective radius of 100 μm.

By using the inferred phase, effective radius, \( r_e \), and phase-dependent broadband shortwave optical depth, \( \tau_{SW} \), the liquid or ice water path can be obtained using the following relation which is valid assuming geometric optics

\[
W = \frac{\tau_{SW}}{3} \frac{2 \rho_r r_e}{\tau_{SW}}, \tag{12}
\]

where the subscript \( x \) denotes the cloud phase. The densities of liquid water and ice are 1 and 0.5 g cm\(^{-3}\), respectively. The effective radius is assumed to be constant with height, and ice particles are assumed to be spherical. For case 4 the inferred liquid water path is 10.7 g m\(^{-2}\), while for case 8 an ice water path of 29.3 g m\(^{-2}\) is obtained.

The retrieved microphysical properties are affected significantly by errors in the retrieved optical depth ratio. For example, by using the optical depth error bars in Figure 8 for case 4 an uncertainty in the optical depth ratio of over ±30% is obtained. This translates to an error in retrieved particle size and water path of nearly 70%. If the optical depth ratio is decreased by 30%, the optical depth ratio falls outside the range of plausible values, so that no microphysical information can be obtained.

Since most of the cases appear to be mixed phase, the retrieved optical depths must be given by a range. The optical depth range is given by the liquid only and ice only optical depths listed in Table 4. For the five likely mixed-phase clouds the broadband shortwave optical depth ranges between 0.5 and 3.0, while the broadband longwave optical depth ranges between 0.6 and 2.2. To our knowledge the retrieval or calculation of an optical depth for mixed-phase clouds has not been previously attempted. This study indicates their potential prominence over the Arctic ice pack in spring. The retrieved liquid and ice effective radii and water paths retrieved for cases 4 and 8 are not unrealistic; however, there are no in situ observations for comparison.

7. Summary and Conclusions

The radiative properties of the atmosphere over the Arctic ice pack during LEADLEX have been described in detail. Clear-sky conditions occurred about 70% of the time. Comparisons of the observed surface fluxes with model results for clear-sky cases reveal that the observed water vapor profile and assumed climatological ozone profile adequately represent the actual conditions present in the Arctic. Temporal variation in aerosol optical depth were documented over periods of less than 1 week.

An intercomparison of radiative transfer models currently employed in or developed for global climate models indicates problems in the treatment of both shortwave and longwave radiation under clear sky conditions during the Arctic spring. Discrepancies among the models in the computation of surface shortwave radiative fluxes are attributed to uncertainties in the aerosol optical depth and variations in the treatment of the surface albedo, which determines the contribution to downwelling shortwave radiation due to multiple reflections. Both problems are accentuated by the large path lengths associated with the large solar zenith angles typical of spring in the Arctic. The models tended to underpredict the downward longwave flux, in part because of the neglect of contributions by trace gases and in part because of inadequacies in the treatment of water vapor emission in the "dirty window" region, which is present at extreme cold temperatures and dry conditions. The surface longwave fluxes obtained with RRTM most closely matched the observations for the extreme conditions typical of the Arctic in spring.

A retrieval technique for obtaining cloud optical and microphysical properties from ground-based measurements has been introduced. This technique is particularly suited for low-level Arctic clouds of unknown particle phase, when more sophisticated observations are lacking. Broadband shortwave and longwave cloud optical depths are determined by individually varying the longwave and shortwave cloud optical depths, separately for liquid and ice, until the modeled and observed surface radiative fluxes matched to within ±5%. An attempt is made to infer cloud microphysical properties from the ratio of broadband shortwave to longwave cloud optical depths. The retrieval of cloud microphysics is limited by the longwave optical depth which must be relatively small and by the potential presence of mixed-phase clouds.

The retrieved mixed-phase cloud optical depths ranged between 0.5 and 3.0 in the shortwave and between 0.6 and 2.2 in the longwave. The cloud phase was unambiguously determined for only one case (i.e., case 8), which was retrieved as an ice cloud with 100-μm particles. Case 4 was most likely liquid; however, the presence of ice could not be completely ruled out. Most of the cases were likely mixed phase for which no cloud microphysical parameters could be derived. It is noted here that in situ observations of cloud particle size and phase coincident with surface radiative flux measurements would help in the interpretation of the optical depth ratios.

The cloud microphysics/optical depth retrieval method employed in this study may be useful for developing a climatology of cloud properties using the Soviet Ice Island data set that includes broadband irradiance measurements, an estimate of cloud fraction and cloud type over a 50-year period. Such a long, continuous record of cloud optical/ microphysical properties is unprecedented for this region and could be used to determine trends in Arctic cloud properties related to the anthropogenic emission of aerosols. In addition, this methodology can be used to supplement more sophisticated cloud remote sensing techniques (e.g., cloud radar) where an a priori determination of cloud phase is needed for the retrieval.

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References

Curry, J. A., and E. E. Ebert, Annual cycle of radiation fluxes over


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