Taking the Pulse of PyroCumulus Clouds

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Abstract: Forest fires can burn large areas, but can also inject smoke into the upper troposphere/lower stratosphere (UT/LS), where stakes are even higher for climate, because emissions tend to have a longer lifetime, and can produce significant regional and even global climate effects, as is the case with some volcanoes. Large forest fires are now believed to be more common in summer, especially in the boreal regions, where pyrocumulus (pyroCu), and occasionally pyrocumulonimbus (pyroCb) clouds are formed, which can transport emissions into the UT/LS. A major difficulty in developing realistic fire plume models is the lack of observational data within fire plumes that resolves structure at a few 100 m scales, which can be used to validate these models. Here, we report detailed airborne radiation measurements within strong pyroCu taken over boreal forest fires in Saskatchewan, Canada during the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS)

summer field campaign in 2008. We find that the angular distribution of radiance within the pyroCu is closely related to the diffusion domain in water clouds and can be described by very similar simple cosine functions. We demonstrate with Monte Carlo simulations that radiation transport in pyroCu is inherently a 3D phenomenon and must account for particle absorption. However, the simple cosine function promises to offer an easy solution for climate models. The presence of a prominent smoke core, defined by strong extinction in the UV, VIS and NIR, suggests that the core might be an important pathway for emission transport to the upper troposphere and lower stratosphere. We speculate that this plume injection core is generated and sustained by complex processes not yet well understood, but not necessarily related directly to the intense fires that originally initiated the plume rise.

1. Introduction

Forest fires are known to burn vast areas, and also inject smoke into the upper troposphere/lower stratosphere (UT/LS), where the stakes are even higher for climate, because emissions tend to have a longer lifetime, and can cause regional and global climate effects, as is the case with some volcanic eruptions. Fires of this nature are common in summer in the boreal regions of Alaska, Canada, and Russia (Fromm et al., 2010; Soja et al., 2007; Stocks et al., 2003).

Large forest fires release enough energy, both sensible and latent heat, to lift the smoke-laden air beyond the condensation level, resulting in the formation of cumulus clouds. Due to their association with fires, these clouds are commonly referred to as pyrocumulus (pyroCu), or pyrocumulonimbus (pyroCb) when convective storms are sufficiently deep to glaciate and form anvils. The pyroCbs have unique dynamical and microphysical structures, and constitute an important mechanism for troposphere-stratosphere transport of biomass burning emissions such as aerosols and trace gases, thereby contributing to raising their budgets in the UT/LS (Damoah et al., 2006; Luderer et al., 2006; Trentmann et al., 2006; Fromm et al., 2005; Fromm and Servranckx, 2003). There is now growing evidence that wildfires should be considered as additional sources of aerosol and trace gases to the UT/LS region, which was previously thought to be primarily dominated by volcanic eruptions (Fromm et al., 2010; Luderer et al., 2006).

There is still significant uncertainty on how much of the energy released by combustion contributes to local heating of the atmosphere and is available for convection, and how much of the energy is lost due to radiative processes. Commonly found estimates for the radiative energy are between nearly 14% (Wooster et al., 2005) and 50% (McCarter and Broido, 1965; Packham, 1969). These estimates are based on laboratory studies or observations of small-scale fires, and their application to large-scale crown fires resulting in pyroCu or pyroCb convection is subject to considerable uncertainty. The interaction of this radiative energy with atmospheric constituents is also highly uncertain. In the thermal infrared, where most of the fire radiation is emitted (Wooster, 2002), aerosols are rather inefficient absorbers. It is likely that most of the radiative energy from the fire is absorbed by cloud droplets or gaseous absorption at cloud base or in air masses that are entrained into the convective plume. This implies that the radiative energy from the fire is trapped in the lower part of the pyro-convection and therefore contributes to the convective energy. It is therefore important to consider the radiative processes in detail.

A major challenge in developing realistic fire plume models is the lack of observational data within forest fire plumes that can be used for validating these models. This is not a big surprise, because making observations within forest fire plumes is challenging at best, and flying into the "core" of rising smoke can be very risky. The possibility of damaging expensive instrumentation is also high. Here, we report detailed radiation measurements from within a pyroCu core taken onboard the NASA P-3B aircraft during the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) experiment, which took place in Canada in June-July 2008 (Jacob et al., 2010). Such measurements are needed in the investigations of pyro-convection on the spatial scale of individual events, i.e., tens of meters to a few hundred meters. This would contribute to the understanding of the vertical and cross-isentropic transport mechanisms responsible for high-altitude tropospheric and stratospheric injection (Luderer et al., 2006). These radiation measurements are unique; we are not aware of any previous radiation measurements within a forest fire plume at the scales described in the next section.

This study focuses on 2 July 2008 and 6 July 2008, the fourth and sixth flights of the P-3B, respectively, out of Cold Lake, Canada during ARCTAS. These flights provided opportunities for in situ observations of flaming fires, plume evolution and vertical profiles of plumes in homogeneous fire outflow regions. Most importantly, they are the only flights where the P-3B penetrated the pyroCu clouds of active fire plumes. In this study, we emphasize data obtained with a multi-wavelength scanning radiometer, NASA's Cloud Absorption Radiometer (CAR; Gatebe et al., 2003; King et al., 1986), which provides unprecedented detail on pyroCu clouds.

The CAR instrument measures scattered light in 14 spectral bands between 0.34 and 2.30 μm and has a unique scanning geometry and is able to scan a scene of the atmosphere and surface over a 190° scan angle and at high angular resolution (1° instantaneous field of view). When it is flown inside clouds, it is able to provide a side view in the zenith and nadir directions, and all scattering angles in between from an aircraft platform with as much as a 5° roll—assuming no aircraft pitch. Data are sampled simultaneously and continuously on nine individual detectors. Eight of the data channels for spectral bands from 0.34 to 1.27 μm are always registered during the operation, while the ninth data channel is registered for signal selected among six spectral channels (1.55–2.30 μm) on a filter wheel. The filter wheel can either cycle through all six spectral bands at a prescribed interval (usually changing filter every fifth scan line), or lock onto any one of the six spectral bands, mostly 1.656, 2.103, or 2.205 μm, and sample it continuously

2. Observational Assessment of the PyroCu

Some of the biggest Saskatchewan fires during the 2008 summer ARCTAS campaign burned west of Mcintosh Lake and east of Lake Athabaska in Canada. On 2 July (P-3 Flight #18/CAR Flight # 2017) and 6 July (P-3 Flight #20/CAR Flight # 2019) the conditions for fires seemed right, as a cold front moved over the region setting up conditions conducive to sending hot smoke plumes billowing into the upper atmosphere. The P-3B aircraft, with its suite of instruments, was in the air and managed to acquire very good fire data. Below, we provide a general description of the 2 July flight and the primary instruments that were operating during the flight. We will not describe the 6 July flight because of similarities between the two flights, however, full details for this flight can be found on the CAR website (http://car.gsfc.nasa.gov/data/index.php?id=115&mis_id=8&n=ARCTAS). Through these descriptions, we attempt to paint a picture of the nature and character of the fires and in addition, create a preamble for further work on pyroCu and their effects on climate.

2.1 *General Description of Flight 2017, 2 July 2008*

Our objectives for this flight included flying a segment under the Terra satellite, coordinated with the NASA B-200 carrying the High Spectral Resolution Lidar (HSRL) and the Research Scanning Polarimeter (RSP) instrument) with radiation measurements under clear sky conditions stacked at different altitudes, and in situ observations of flaming fires, showing plume evolution and vertical profiles in homogeneous fire outflow regions. The flight took 6 hours and 20 minutes, with take off at 15:31 UTC (9:31 a.m. local time; see flight log: http://car.gsfc.nasa.gov/data/index.php?id=113&mis_id=8&n=ARCTAS). Fig. 1a shows the flight path from Cold Lake, heading northeast towards Reindeer Lake. We made measurements collocated with the B-200 for about 50 minutes beginning at 16:25 UTC, and observed active fires of different intensities under scattered cloud conditions. We penetrated an active fire plume near Mcintosh Lake at two altitudes, 1303 m (19:18 UTC) and 294 m (19:49 UTC) above the local surface, and flew along the plume axis for about 80 km to study the evolution of aerosol microphysics during downwind transport. Between the two penetrations, we obtained radiation measurements in a vertical profile in the most homogeneous part of the plume and flew across-plume at a low-level. We also sampled outflow from a pyroCu cloud and penetrated the cloud to sample the inside. Fig. 1b shows an image taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) flying aboard the Aqua satellite at 19:35 UTC over the region highlighted in the white box in Fig. 1a. The cloud fields seen in the satellite image are most likely associated with the active fires in the region. Note that the green squares represent fire locations detected by MODIS on the Terra satellite, taken during the overpass earlier that day, at 17:55 UTC. The red squares represent fire locations based on high radiance, relative to background, as seen with the MODIS/Aqua 4-μm channel during the overpass (e.g. Giglio, 2003).

Figs. 1c and 1d show CAR quicklook images selected from a section of the flight where the aircraft went through a pyroCu core during the flight of 2 July (the green line highlights the flight path through the pyroCu, whereas the orange dot in Fig. 1b marks the location of the plume core). A combination of different CAR bands representing red, green, and blue colors helps to differentiate between clouds and smoke and to see through smoke, revealing land surface features such as green vegetation and dark water bodies (see Fig. 1c: false-color RGB(0.47, 0.38, 0.34) μm; Fig 1d: false-color RGB(1.66, 1.04, 0.38) μm). As shown in Fig. 1d, the fire was widespread, covering hundreds of hectares, and it took the aircraft ~15 seconds to cross the core (the core covers a ground area ~2 km, where the measured aircraft groundspeed varied between 127 ms^{-1} and 138 ms^{-1}). The aircraft altitude changed dramatically while traversing the core, rising by 93 m, from 2747 m to 2840 m above mean sea level, an indication of strong updrafts >8 ms^{-1}.

The height of the 2 July PyroCu top above ground was > 3000 m, and the boundary layer (BL) height at the fire location and time of aircraft data acquisition was 1976 m. The BL was obtained by interpolating the values for 12 noon and 3 pm local times from the NASA Goddard Earth Observing System (GEOS-5) data provided by the Global Modelling and Assimilation Office (GMAO). Therefore, the pyroCu extended well above the boundary layer. Recent studies based on digitized plume height analysis from the Multi-angle Imaging SpectroRadiometer (MISR) instrument aboard the Terra satellite have shown that of order 10% of the plumes are injected higher than 0.5 km above the BL; out of eight North American biome types evaluated, fire plumes from boreal forests (which include the study area) are typically injected the highest, with a median injection top height of ~1200 m (as compared to ~800 m for croplands; Kahn et al., 2008; Val Martin et al., 2010). Those studies also found a correlation between the plume injection height and fire radiative power (FRP) measurements from MODIS (Ichoku et al., 2008), indicating that in addition to atmospheric stability structure, fire intensity (represented by FRP) has a strong influence on plume injection height; plume top heights that reached the free troposphere (FT) were produced mainly by high intensity fires having a median FRP of order 500 MW. Table 1 shows the FRP values of the MODIS fire pixels (depicting their relative intensities) from Aqua coinciding with 2 July 2008 flights (in space but not in time). The FRP data record corresponding spatially to the pyroCu plume penetrated by P-3B is shown in boldface characters. However, because of the large difference in time between the FRP measurement from Aqua-MODIS (19:35 UTC) and P-3B penetration of the pyroCu (~21:05 UTC), this FRP value is much less than what would have been required to generate such a high plume and the associated pyroCu. It is probable that the fire became much stronger by the time of the pyroCu measurement. For the P-3B pyroCu penetration on 6 July 2008, no fire pixels were detected by MODIS within a few km of the pyroCu. It is believed that the pyroCu may have moved substantially away from the fire at the time of its penetration, making it impossible to link it to any specific fire detected by MODIS. Therefore, to establish a cause and effect relationship of such transient features as fires and their associated plumes and pyroCu, it is crucial to conduct airborne measurements in synchronicity with satellite overpasses and ground-based measurements whenever possible.

2.2 *NASA P-3B Payload during ARCTAS 2008*

Fig. 2a shows the platform we used in this campaign, the NASA P-3B aircraft. The picture was taken at NASA Ames on 24 June 2008 just before a transit flight to Cold Lake, Canada at the start of the ARCTAS summer campaign. The P-3B payload included 10 primary instruments (see Table 2) for measuring aerosol optical depth, aerosol extinction and scattering, aerosol size distribution (Russell et al., 1999; Clarke et al., 2007), spectral (0.380 – 2.200 μm) and broadband downwelling and upwelling solar (0.2–3.6 μm), and IR irradiance (4.5-42 μm; Pilewskie et al., 2003; Bucholtz personal communication: http://airbornescience.nasa.gov/instrument/BBR), angular distribution of scattered radiation in different directions (Gatebe et al., 2003), cloud condensation nuclei (Roberts and Nenes, 2005; Lance et al., 2006), and NO_2 and carbon monoxide (Strawa et al., 2007; Provencal et al. 2005). The base meteorological and navigational measurements were provided by the Project Data System, which is the primary navigational data system for P-3B investigators.

Fig. 2b shows a schematic of the CAR instrument (Gatebe et al., 2003; King et al., 1986), highlighting its main features. Fig. 2c shows a pyroCu taken onboard the NASA P-3B on 2 July 2008 near Reindeer Lake, Saskatchewan, Canada. The aircraft flew around these fires, sampling clean air upwind and the polluted air downwind. It then flew through the smoke at various altitudes, probing and charting changes in concentration and the "chemical evolution" of the compounds emitted by the fires. The plane also flew into the "core" of the rising fire plumes, where the CAR instrument managed to acquire good data as discussed in this study. These represent the first such measurements in the core of a pyroCb of which we are aware. (See pictures from the 2 July flight on the CAR website at http://car.gsfc.nasa.gov/data/photos.php?mis_id=8&n=ARCTAS&d=2008-07-02&f=2017&l=h and from the 6 July flight at http://car.gsfc.nasa.gov/data/photos.php?mis_id=8&n=ARCTAS&d=2008-07-06&f=2019&l=h.

In the next section, we will present an analysis of the CAR measurements inside pyroCu and results from a Monte Carlo simulation of the radiation field within optically dense media analogous to those observed above.

3. Results and Discussion

3.1 Analysis of CAR Measurements

The core of the pyroCu as seen in Figs. 1c and 1d stands out as a very dark region of the plume, where radiation seems to be uniformly distributed and dominated by strong absorption in all directions. The CAR instrument measured very low spectral radiance values (< 1 $Wm^{-2}\mu m^{-1}sr^{-1}$ in the ultraviolet and visible bands having $\lambda < 0.5$ μm, and at $\lambda = 1.6$ μm, and 2–5 $Wm^{-2}\mu m^{-1}sr^{-1}$ for bands between 0.5 μm and 1.3 μm), independent of direction. The radiance distributions within the core at two zenith angles: 5° and 175° at 0.472 μm, shown in Fig. 3 demonstrate that there is hardly any difference between the downwelling and upwelling radiance within the core region. The a, b and c images in this figures were taken by a forward camera aboard the NASA P-3B at the entry, core, and exit points in the pyroCu. Note the brownish color of the plume inside the core region. The radiance decreases by about two orders of magnitude from outside to the central part of the core, irrespective of the direction and wavelength. We speculate that the core region plays an important role as the main physical pathway through which emissions from fires are transported into the upper troposphere/lower stratosphere (UT/LS), but this observation needs to be validated.

Fig. 4 compares relative spectral radiance as a function of zenith angle for internally scattered radiation measured deep inside an optically thick water cloud, pyroCu and a thick "pure" smoke, which is defined by lack of reflectance sensitivity in the near-infrared bands ($\lambda \geq 0.87$ μm), at selected CAR wavelengths. According to King et al. (1990), radiance measurements from an individual scan of the CAR are considered to be in the diffusion domain, if three conditions are satisfied: (i) the zenith radiance exceeds the nadir radiance, (ii) the maximum deviation from the theoretical cosine curve is less than or equal to 5% of the mean amplitude, and (iii) the number of times the deviations from a cosine distribution changes sign is greater than or equal to 4, which helps to assure that fluctuations are random, and not systematic drifts. These criteria pertain to the diffusion domain of an optically thick media if the scattering is conservative (no absorption), and thus are to be expected for liquid water clouds at wavelengths around 0.67 μm (as seen in Fig. 4a). The theoretical curve is generated from measured zenith and nadir radiances using the following cosine relationship

$$I(\tau,\cos\theta) = a + b\cos\theta \tag{1}$$

where

$$a = \frac{1}{2}(I_0(\tau,1) + I_{180}(\tau,-1)),$$
$$b = \frac{1}{2}(I_0(\tau,1) - I_{180}(\tau,-1)) \tag{1a}$$

and I_0 and I_{180} are the zenith and nadir radiances at $\theta = 0°$ and $\theta = 180°$, respectively. From Eq. 1a, we came up with a general equation for any two downward and upward viewing angles in the form

$$a = \frac{1}{2}(I_{\theta'}(\tau,\cos\theta') + I_{180-\theta'}(\tau,-\cos\theta')),$$
$$b = \frac{1}{2\cos\theta'}(I_{\theta'}(\tau,\cos\theta') - I_{180-\theta'}(\tau,-\cos\theta')) \tag{1b}$$

As such, Eq. 1b is not restricted to using zenith ($\theta = \theta' = 0°$) and nadir ($\theta = \theta' = 180°$) input radiances, unlike Eq. 1a, and can be used to describe the radiation field in optically thick media given any two downward and upward viewing directions, or $\theta' = 90°$ (where b $= I_{90}(\tau)$) and any other direction. This general formula can be applied to CAR observations away from the zenith and nadir directions, and therefore can accommodate the realities of data acquisition on an airborne platform that has a nonzero pitch and/or roll angle.

For the liquid water cloud case, obtained on 29 June 2008 (20:00 UTC) in Canada, the angular radiance field at the shortest wavelengths can be described by a cosine function expected for conservative scattering in the diffusion domain (King, 1981; King et al., 1990), where the cloud is expected to have a small to negligible amount of absorption. This is demonstrated in Fig. 5 (liquid water cloud case), where the angular distribution of the radiation field obtained from measurements (continuous curve, abstracted from Fig. 4a) is compared to that expected in the diffusion domain for conservative scattering (dotted curve) at $\lambda = 0.472$ μm. We note that the angular radiance field becomes increasingly anisotropic as absorption increases in the CAR bands at wavelengths exceeding 1 μm (Fig. 4a), because stronger absorption implies that a smaller portion of downwelling solar radiation can be reflected back up from below. In this case, the three conditions for the diffusion domain at a conservative scattering wavelength were met. King et al., (1990) show that when the three conditions are assured, quantitative information about cloud absorption properties from the angular distribution of scattered radiation can be derived, dependent only on the optical properties of the medium and possibly on the reflectivity of the underlying surface, but independent of the solar zenith angle and solar irradiance.

The problem now is to describe the radiation pattern inside an optically thick pyroCu, the core of a pyrcoCu, and smoke, which seem to be increasingly anisotropic as absorption tends to dominate at the shorter wavelength and is not negligible. However, the diffusion domain theory for optically thick clouds with modified a and b (Eq. 1b; Fig 4b), can also describe the angular radiance distribution in a pyroCu as shown in Fig. 5 (blue solid curve represents measurements, green dotted line represents the fit), but b must assume a negative value, because in this case, the relative radiance is highest at nadir rather than at zenith. The cosine function can also represent the pyroCu core case (Fig. 4c), but an additional $\sin\theta$ term is needed (Eq. 2) to reproduce the bow shaped curves in Figs. 4c and 5 (note that the solid lines represent observations, while dotted lines represent fit to the observations).

$$I(\tau,\cos\theta) = (a + b\cos\theta) + (c + d\sin\theta) \qquad (2)$$

which requires only the knowledge of the zenith angle, θ, and some constants. The parameters a and b are easily determined from Eq. 1a & 1b. The last two terms represent a mathematical ansatz, where the term c is obtained from zenith and nadir radiances following Eq. 1b, and d was determined through trial and error until the best fit was found (d = -0.1). It is interesting to see that radiation transport in an optically thick pyroCu core can be described by simple geometrical functions, whereby the first two terms represent scattering processes, while the third and fourth terms represent absorption processes. To gain better understanding of radiation transport in a pyroCu, we next attempt to reproduce the radiation pattern observed by the CAR instrument using 1D and 3D Monte Carlo simulations.

3.2 *Monte Carlo Simulation*

We now explore the optical characteristics of pyroCu using 1D and 3D Monte Carlo radiative transfer simulations. The Monte Carlo model is an appropriately modified version of the code used in several earlier studies, including Várnai and Marshak (2001), and was also tested in the Intercomparison of 3D Radiation Codes (I3RC) project (Cahalan et al., 2005). The actual code used in this paper was also tested through comparisons with DISORT (Discrete Ordinates Radiative Transfer) model (Stamnes et al. 1988) runs for absorbing, plane-parallel clouds. To keep simulation uncertainties below 0.5%, each result is based on 4 million photon trajectories in backward Monte Carlo simulations.

Because the purpose of these Monte Carlo simulations is to understand the basic behaviours in Fig. 4 (and not to simulate the exact values observed by CAR), the simulations use a simple setup (Fig. 6). The calculations assume a 2D slab cloud that is infinite in the cross-sun (Y) direction, lies between 1 km and 2 km altitudes, and is 1 km wide ($\Delta Z = \Delta X = 1$ km). The extinction coefficient is 100 km^{-1}, so the cloud optical thickness is 100 in both Z and X directions. Because we simulate radiances deep inside the cloud, where multiple scattering minimizes the details of the scattering phase function, we assume the cloud particles have a Henyey-Greenstein phase function with an asymmetry parameter of $g = 0.85$. The solar zenith angle is taken as 30° and the surface albedo as 0.2. For simplicity, no atmospheric effects—Rayleigh scattering or gaseous absorption—are considered.

Fig. 7 shows simulation results that can shed light onto the behaviours in Figs. 4a, 4b, and 4c. (At this stage we do not attempt to simulate the complex behaviours in Fig. 4d.) The black dashed line displays a qualitatively similar behaviour to the clean cloud in Fig. 4a and shows the general behaviour of 1D radiation calculations, which assume horizontally homogeneous and infinite (plane-parallel) clouds. The line illustrates that in 1D cases, the radiance of the highly diffuse radiation deep inside clouds is always greater looking up than looking down regardless of the amount of particle absorption. This is because the conservation of energy and the lack of light sources below imply that the upwelling flux can never exceed the downwelling flux. This particular simulation was based on a single scattering albedo of 0.975, representing stronger absorption than typically occur in liquid water clouds in the visible near-infrared (cf. Fig. 4a), but with a shape typical of what occurs in absorbing liquid water clouds.

The other three curves in Fig. 7 are from 3D simulations. Energy conservation requires the scene average net radiation to flow downward even in 3D situations. However, this trend can reverse locally inside clouds in 3D situations because large amounts of radiation can reach the surface easily in clear areas between clouds and, after reflection from the surface, can enter through the cloud base and create an upwelling flow of radiation inside the cloud. In addition, sunlight entering through a sunlit cloud side can create a horizontal net flow toward the shadowy side (Fig. 6).

The blue squares in Fig. 7 show that the downward flow entering through the cloud top still dominates our 3D case if there is no absorption. The red circles, however, show that absorption can drastically change the radiation pattern by depleting much of the downwelling radiation wending its way through the cloud. As a result, the upwelling flow of radiation reflected from the surface can match the weakened downwelling flow, creating comparable intensity peaks looking up ($\theta = 0°$) and down ($\theta = 180°$). This is similar to the behaviour in Fig. 4c (pyroCu core). Lastly, the green dashed curve in Fig. 7 shows that for a lower altitude cloud absorption reduces the downwelling (upwelling) radiation more (less), and so upwelling radiation can fully dominate and create a trend similar to that in Figure 4b (pyroCu).

Finally, Fig. 8 more explicitly explores the role of absorption and scattering properties in shaping radiation patterns. Fig.8a shows that even relatively weak absorption (SSA $\leq$ 0.99) can allow upwelling radiation to match or even exceed the downwelling flow in a 3D situation. In turn, Fig. 8b shows that increasing the number of particles (i.e., the extinction coefficient) yields similar effects to increasing their absorptivity, as both changes make it harder for radiation to reach an instrument deep inside the cloud. This implies that radiation patterns similar to those observed in pyroCu and pyroCu core (Figs. 4b and 4c) can arise in thick clouds even if absorption is relatively weak, although stronger absorption is required in thin clouds. The interplay between scattering and absorption can also allow upwelling radiation to dominate even in the upper parts of clouds if particles are distributed unevenly. For example, if the cloud extinction coefficient increases with altitude (e.g., Raga and Jonas, 1993)—e.g., as ascending droplets grow through condensation—strong absorption or scattering above can greatly reduce the downwelling radiation and allow the upwelling radiation reflected from the ground to dominate even at high altitudes.

4. Conclusions

This study provides an analysis of airborne radiation measurements with the CAR instrument within strong pyroCu over boreal forest fires in Saskatchewan, Canada during the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) summer field campaign in 2008.

We found the pyroCu core to be very interesting having very low light levels from the UV to near IR regions of the electromagnetic spectrum, and very uniform radiance field in all directions. Spectral radiances measured within the core were very small < 1 $Wm^{-2}\mu m^{-1}sr^{-1}$ in the ultraviolet and visible bands, $\lambda < 0.5$ μm, and at λ=1.6 μm, but substantially larger (2–5 $Wm^{-2}\mu m^{-1}sr^{-1}$) for 0.5 μm $< \lambda <$ 1.3 μm, independent of direction. We found the angular distribution of radiance within the pyroCu to be related to the diffusion domain in water clouds that can be described by very similar cosine functions with an additional sine term. We demonstrate with Monte Carlo simulation that radiation transport in pyroCu is inherently a 3D problem and must account for strong particle absorption. The proposed simple description of the radiation distribution within the pyroCu or pyroCu core may lead to better understanding of these cloud systems and provide a simpler solution for their inclusion in climate models. Based on the low radiation values measured in the core of the pyroCu, we speculate that the formation of the dark core is an important feature for establishment of a possible pathway for transportation of fire emissions to the upper troposphere and lower stratosphere, but this remains to be validated.

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Table 1

Locations and FRP values of fire pixels detected by Aqua-MODIS on 2 July 2008 at 19:35 UTC in the vicinity of the measured pyroCu, as indicated in Fig. 1b

Latitude (°N)	Longitude (°W)	Fire Radiative Power (MW)
55.685	105.283	108.273
55.682	105.299	112.081
55.677	105.331	37.455
55.688	105.320	84.818
55.706	**105.320**	**105.710**
55.733	105.334	20.674
55.778	105.235	24.367
55.773	105.267	18.737
55.803	105.197	84.151
55.838	105.150	25.296
55.835	105.166	17.619

Table 2

P-3B Aircraft Instrumentation for ARCTAS

Instrument Name	Data Products	Technique	Principal Investigator	Detection limit (Nominal accuracy)
AERO3X	Aerosol optical properties, NO_2 mixing ratio	Cavity ring-down extinction; Sample rate: 2 sec. (Strawa et al., 2007).	A. Strawa, NASA ARC	Extinction and scattering – 2 σ sensitivity ≈ 0.2 Mm^{-1}, Extinction and scattering – 2 σ precision ≈ 0.1 Mm^{-1}, NO_2 mixing ratio – 2 σ sensitivity better than 1 ppb
Ames Airborne Tracking Sunphotometer (AATS)	Aerosol optical depth and extinction, water vapor column and profile	Tracking Sun photometer, 0.354-2.138 µm (Russell et al. 1999)	J. Redemann, BAERI/NASA ARC	Slant OD ~0.002 (±0.01) Slant WV ~0.0005 to 0.006 gcm^{-2} (±8%)
Broad Band Radiometers (BBR)	Radiation fluxes (solar: 0.2-3.6 µm & IR: 4.5-42 µm)	Radiometer	A. Bucholtz, NRL	Estimated Accuracy: 3–5%
Cloud Absorption Radiometer (CAR)	Radiance, aerosol, cloud & Earth surface properties	Angular (cross-track zenith to nadir) scanning radiometer, 0.340-2.301 µm	C. Gatebe, USRA/NASA GSFC	Radiance absolute accuracy <5%
Continuous-Flow Streamwise Thermal Gradient Cloud Condensation Nuclei	Cloud Condensation Nuclei (CCN)	Supersaturation generated by relative diffusion of water vapour and heat (Roberts and Nenes, 2005)	A. Nenes, Georgia Tech	SS Range: 0.20 – 0.60%, ±0.05%

(CCN) Counter (CFSTGC)				
Carbon monoxide By Attenuated Laser Transmission (COBALT)	CO mixing ratio (mole fraction) at a 1-Hz rate based on measured absorption, gas temperature, and pressure using Beer's Law	off-axis integrated cavity output spectroscopy – TLAS (Provencal et al. 2005)	J. Podolske, NASA/ARC	Precision: 0.2 ppbv (1-s averaging time), uncertainty <1.0%
Hawaii Group for Environmental Aerosol Research (HiGEAR)	aerosols (Aerosol number, size, composition, volatility, optical properties; Clarke et al., 2007; Shinozuka et al., 2011, Howell et al., 2006)	OPC, PSAP, TDMA, CN counter, ToF-AMS, SP2, nephelometer	A. Clarke, U. Hawaii	See references: Shinozuka et al., (2011).
Project Data System (PDS)	base meteorological (P, T, RH) and navigational measurements	See reference: Barrick	John Barrick NASA/LaRC	See references: Barrick
Solar Spectral Flux Radiometer (SSFR)	Solar spectral flux	Spectrometer (380-1700 nm) with nadir and zenith hemispheric collectors	S. Schmidt, U. Colorado	Absolute accuracy 3-5%. Precision 1%

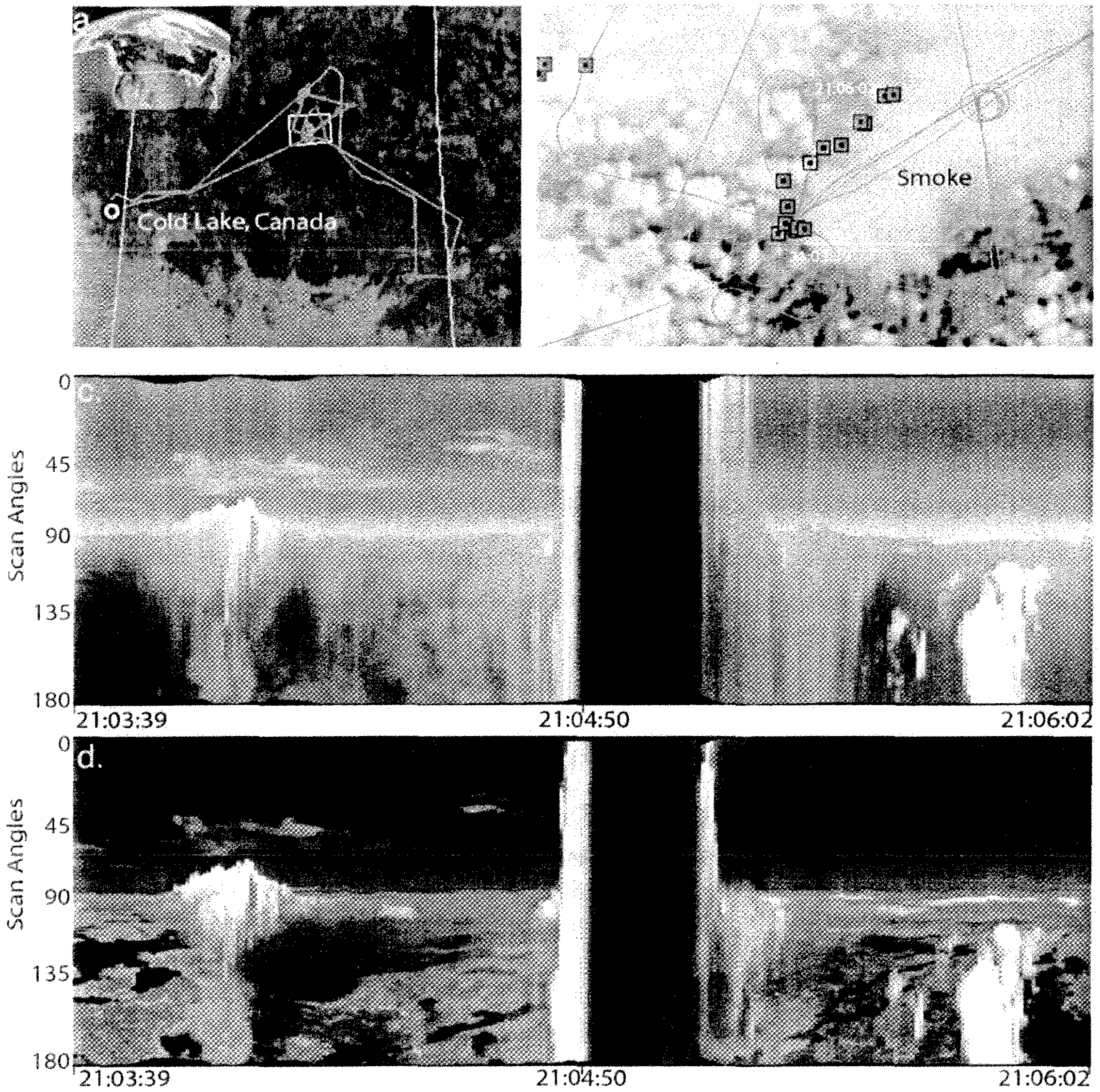
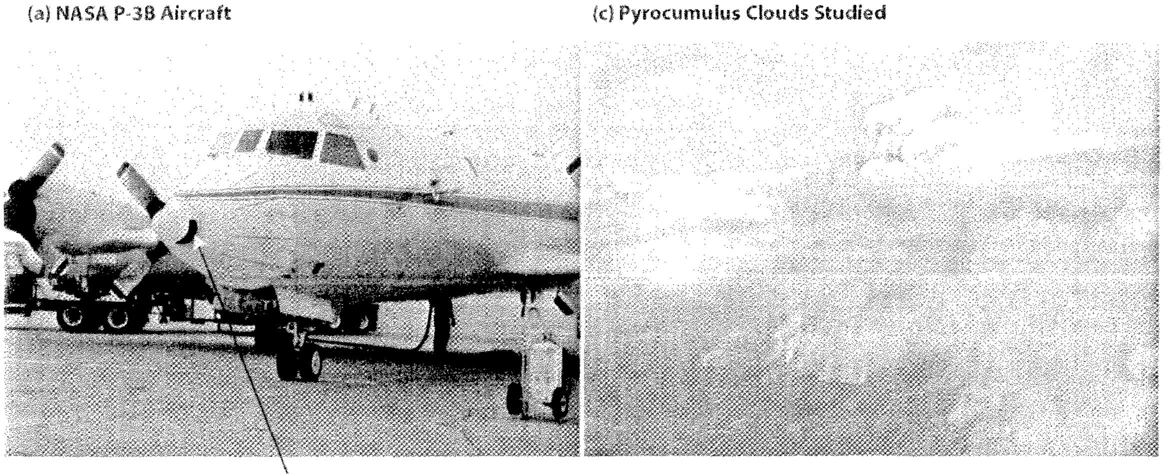


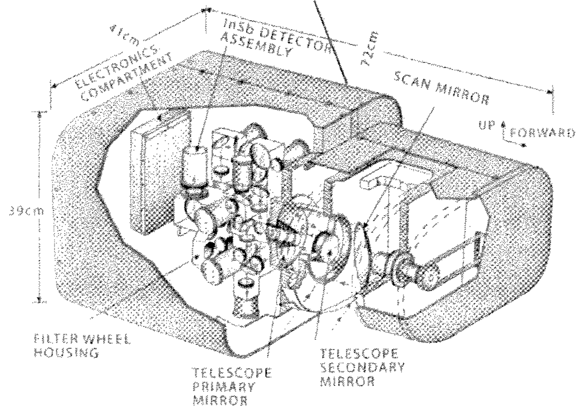
Fig. 1. (a) NASA P-3B flight track 2 July 2008 during the ARCTAS 2008 summer campaign. (b) MODIS/Aqua image taken on 2 July 2008 over the area marked by the rectangle in (a). The red (green) squares are fire locations during Terra (Aqua) overpass at 19:35 UTC (17:55 UTC), and the orange square marks the location of the fire plume that was penetrated by the P-3B. (c)-(d) CAR quick-look images of the fires taken aboard the NASA P-3B over the flight section highlighted in green in (b). A combination of red, green, and blue colors using different CAR bands helps differentiate cloud from smoke, and to see through smoke and identify land surface features such as green vegetation and dark water bodies. The red, green, and blue color assignments in (c) are 0.47, 0.38, 0.34 μm and for (d) 1.66, 1.04, 0.38 μm.



(a) NASA P-3B Aircraft

(c) Pyrocumulus Clouds Studied

(b) CAR Schematic

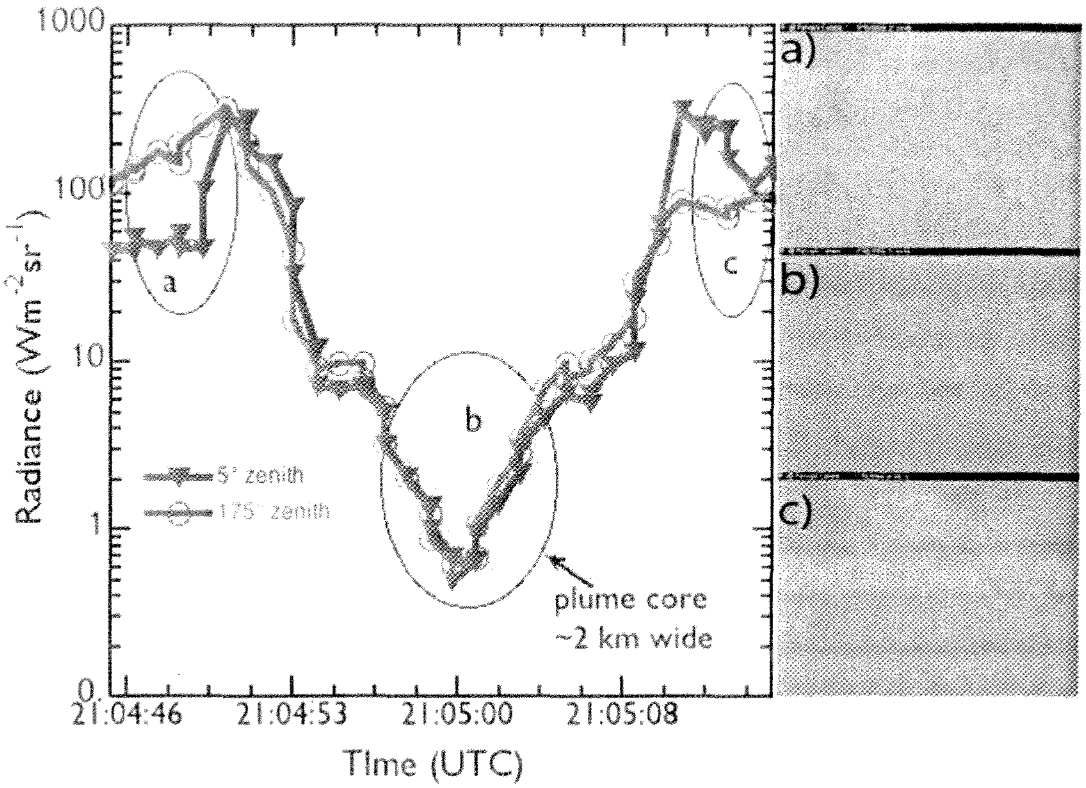


(d) Cloud Absorption Radiometer (CAR) Parameters

Angular Scan Range	190°
Instantaneous field of view	17.5 mrad (1°)
Pixels per scan line	382
Scan rate	1.67 lines per second (100 rpm)
Spectral channels (μm)	14^{a} (8 continuously sampled and last six in filter wheel)
bandwidth (FWHM)	0.340(0.009), 0.381(0.006), 0.473(0.021), 0.683(0.021), 0.871(0.022), 1.037(0.021), 1.222(0.023), 1.275(0.023), 1.564(0.032), 1.657(0.042), 1.738(0.040), 2.105(0.045), 2.202(0.043), 2.303(0.044)

Fig. 2. (a). The NASA P-3B at NASA Ames Research Center, California, USA in June 2008 during the ARCTAS field experiment. (b) Schematic of NASA's Cloud Absorption Radiometer (CAR), which is mounted in the nose of the NASA P-3B aircraft. (c) Picture of the fire plume that the P-3 penetrated on 2 July during ARCTAS. (d) Specifications for the CAR, which contains 14 narrow spectral bands between 0.34 and 2.30 μm. The CAR flew nine fire missions aboard P-3B in Canada between 28 June and 10 July 2008.

Fig. 3. Zenith and nadir radiances at 0.472 μm, on a flight through a pyroCu, between 21:04:45 and 21:05:29 UTC, on 02 July 2008. Pictures a, b and c are from a forward camera aboard the NASA P-3B, and coincide with entry, core penetration, and exit points of the pyroCu, respectively. The core was very dark, and brownish in color. The distance from the core to the edge of the pyroCu is about 318 m (assuming average aircraft speed of 132.5 m/s).



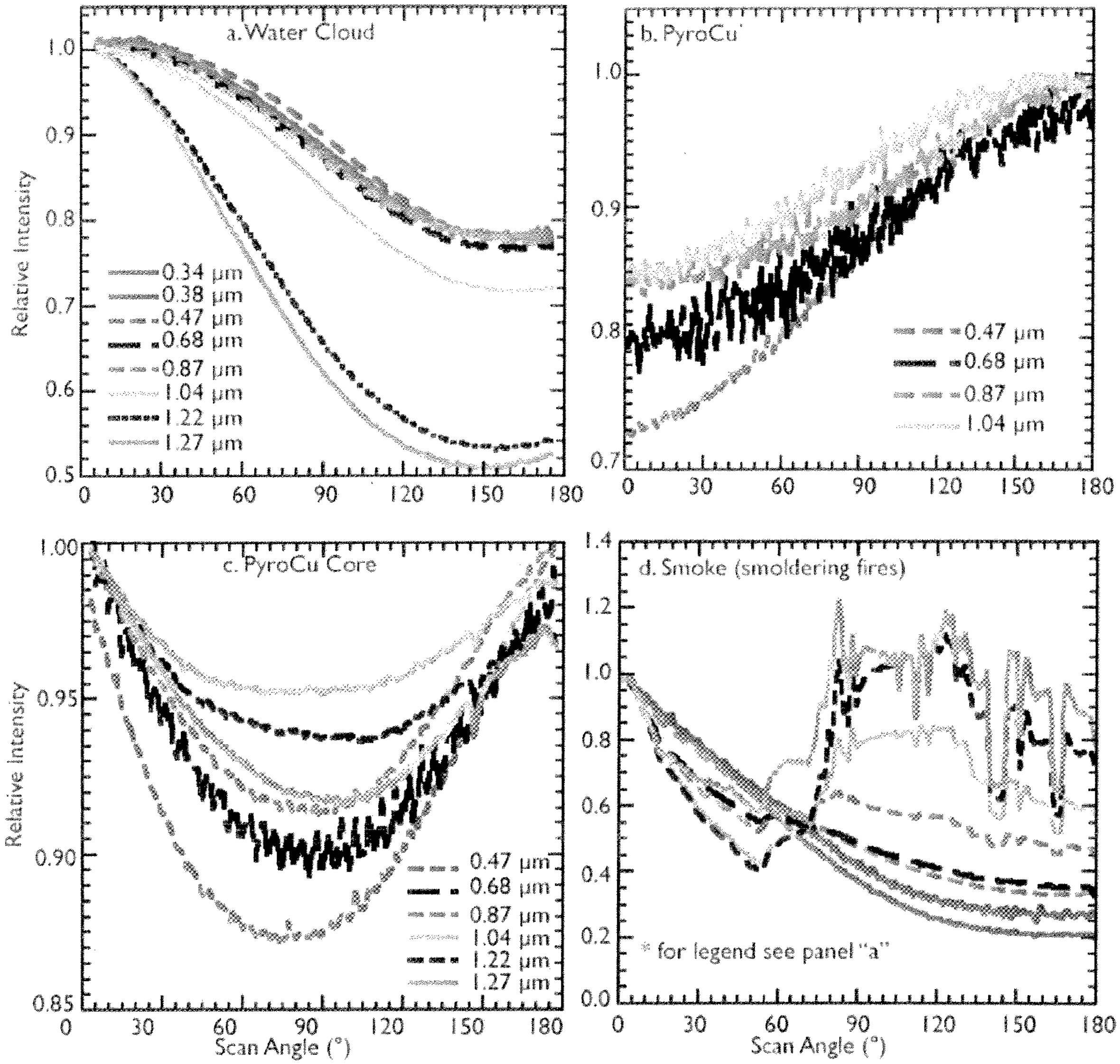


Fig. 4. Relative spectral intensities from CAR as a function of zenith angle for internally scattered radiation measured inside (a) liquid water cloud, (b) pyroCu, (c) core of pyroCu, and (d) thick smoke from smoldering fires with no cloud present. The UV channels are not included in (b) and (c) because of low values of signal-to-noise values. The effects of surface reflectance are clearly seen in the "pure smoke" case (d) at wavelengths, $\lambda \geq 0.68$ μm.

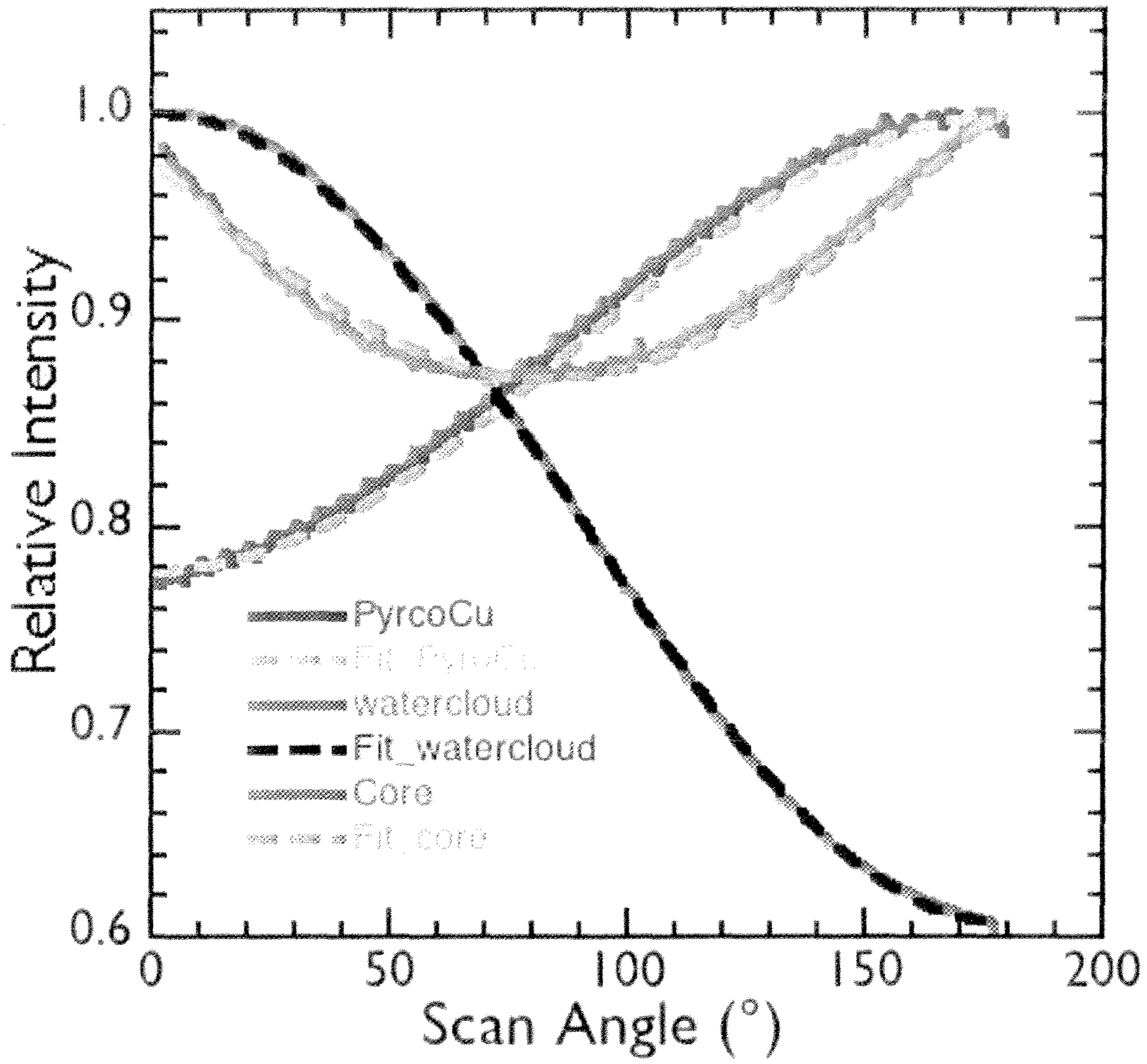


Fig. 5. Observed and fitted relative intensities at 0.472 μm represented by solid and dashed lines, respectively, for water cloud, pyroCu and the pyroCu core. The fitted lines for water cloud and pyroCu were generated by a cosine function given in Eq. 1b, with parameter "b" assuming a negative value for the pyroCu case. The pyroCu core was fitted by Eq. 2.

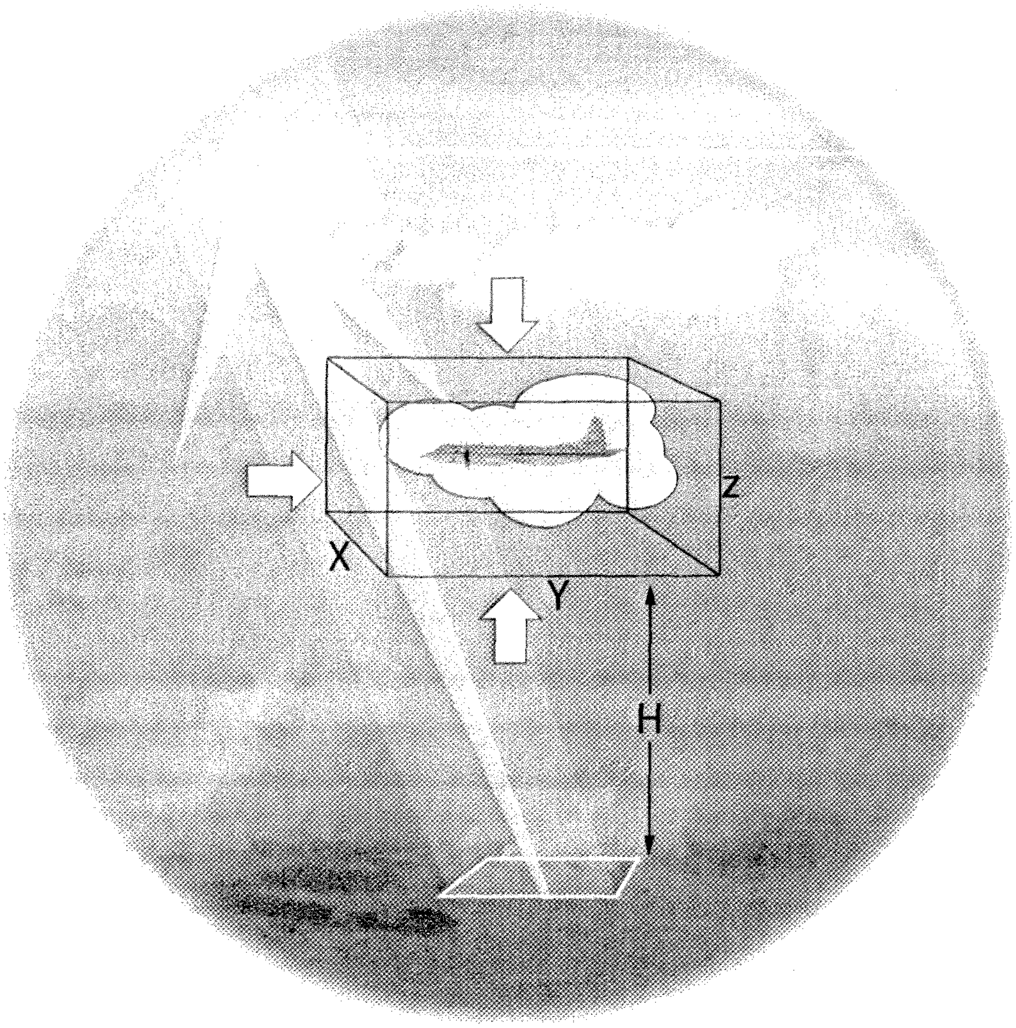


Fig. 6. Illustration of solar illumination paths responsible for the observed radiation patterns in Figs. 4a-c.

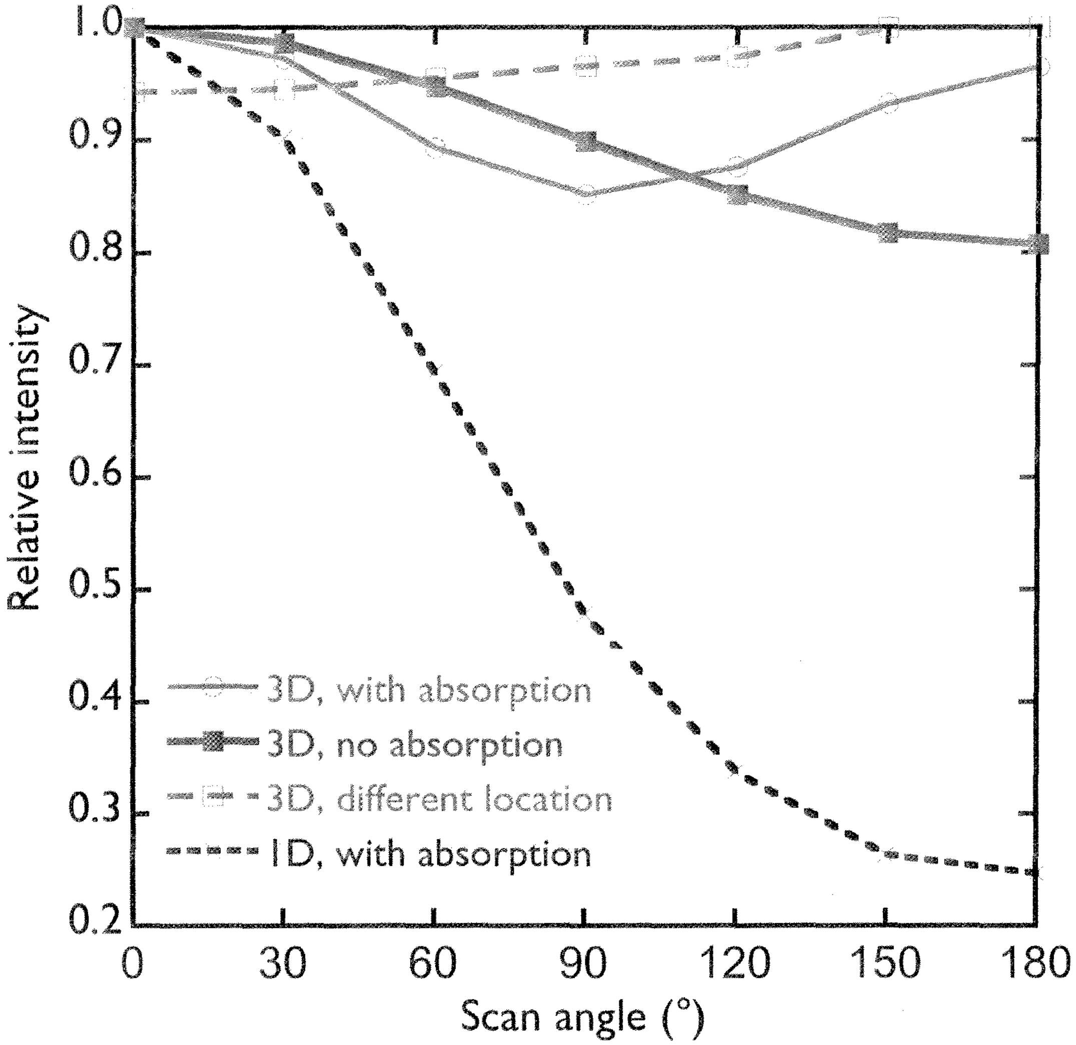


Fig. 7. Simulated CAR data used for understanding the observed behaviors in Fig. 4. The figure shows simulated CAR data for an azimuth perpendicular to the sun (90° relative azimuth). The black, red, and blue curves are for the horizontal center of the cloud at 1.4 km altitude. The green curve, simulating behaviors observed at a different (pyroCu) segment of the flight path, is for a point 200 m away from the sunlit cloud edge at 1.3 km altitude.

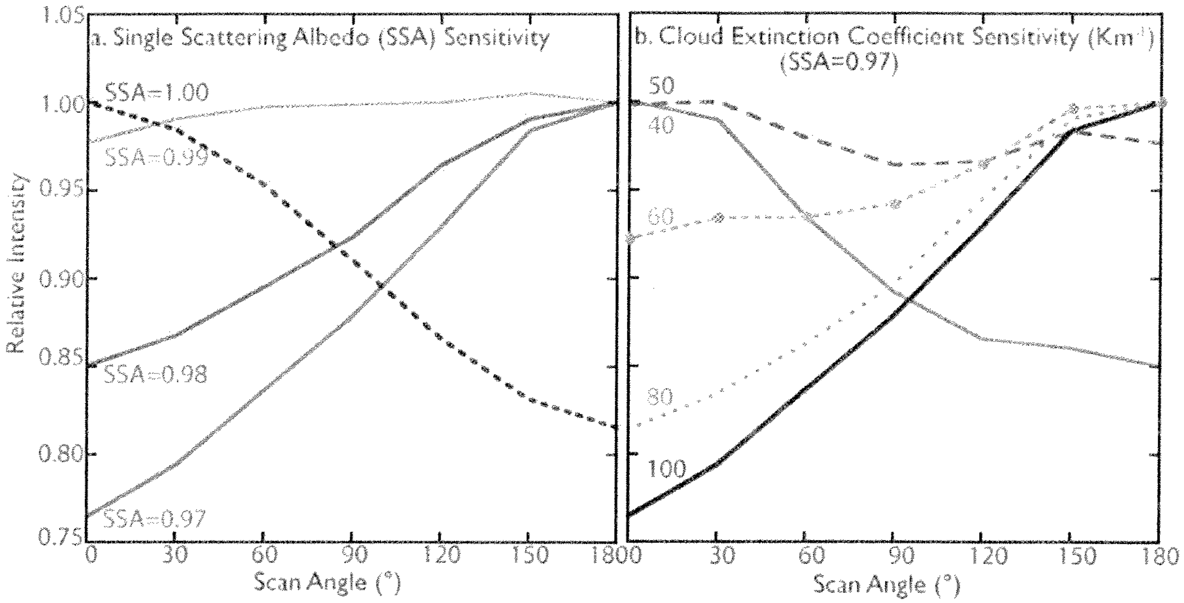


Fig. 8. Impact of (a) variations in single scattering albedo (SSA) at a constant cloud extinction coefficient (100 km^{-1}); and (b) variations in cloud extinction coefficient at a constant SSA (0.97). The simulations are for 85° relative azimuth at a point 300 m away from the sunlit cloud edge at 1.3 km altitude.