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学位論文題目	A study of snow optical properties with a multiple scattering radiative transfer model for the atmosphere-snow system and spectral albedo observations
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論文内容の要旨

A multiple scattering radiative transfer model in the shortwave wavelength region has been developed for the atmosphere-snow system in which the absorption and scattering by the realistic gases, aerosols and clouds were included and a radiative interaction between the atmosphere and the snow was simulated. Using this model the atmospheric effects on spectral albedo and radiation budget at the snow surface and the top of the atmosphere were investigated. Furthermore, observations of spectral albedo and bidirectional reflection distribution function (BRDF) with the spectrometer have been made together with the snow pit works on some snowfields. The results of spectral observations were compared to the theoretically calculated ones with a multiple scattering model for the atmosphere-snow system and the effects of snow physical parameters on spectral albedo and BRDF were investigated.

In Chapter 1, the approximation methods for Mie phase function were discussed in calculating the spectral albedo of snow surface by taking account of the multiple scattering by snow particles. The particles such as snow grains which are large compared to the wavelength have a strong forward peak in the phase function of single scattering. It has been known that a large error is led by the calculation of multiple scattering directly using such phase function. Therefore, four types of approximations of Mie phase function were investigated in calculating the multiple scattering by snow particles using the "doubling" method. These involve Hansen's renormalization, Grant's renormalization, the delta-M method and the truncation method. Using these approximations, the spectral albedos of snow surface were calculated under the conditions of effective grain radii of 50, 200 and 1000μm in a wavelength region from 0.3 to 3.0μm, and were compared to that calculated using the delta-Eddington approximation. The reason to compare with the delta-Eddington approximation is that this method does not need a phase function and a behavior of the systematic error is understood. In the Hansen's renormalization, the maximum albedo error exceeded 0.1 for the snow with an effective radius of 1000μm at small solar zenith angles. The delta-M method overestimated the snow albedos at all solar zenith angles at the wavelengths less than 1.4μm for the snow with an effective radius of 1000μm. Reasonable results were obtained by the Grant's renormalization and the truncation method for all three cases of effective grain radii studied. It was also found that these methods save computation time and memory because sufficient accuracy was obtained even with an angle resolution of 0.1° in the forward peak region of phase function. In case of truncation method, the result was not sensitive to the choice of a truncation angle between 5° and 20°.

In Chapter 2, the atmospheric effects on spectral and spectrally integrated snow albedos at the snow surface and the top of the atmosphere were investigated. A multiple scattering radiative transfer model based on the "doubling and adding" method combined with the Mie theory was applied to estimate the effects of absorption and scattering by the atmospheric molecules, absorptive gases, aerosols and clouds. Based on the result of Chapter 1, the truncation method with a truncation angle of 10° was employed to correct the anisotropic Mie phase function. It was shown that the spectral surface albedo was reduced by the atmospheric absorptive gases at large solar zenith angles. The solar zenith angle dependence was weakened at the wavelengths less than $0.5\mu m$ by the Rayleigh scattering and at almost all wavelengths by the atmospheric aerosols and cloud cover. H_2O rich atmosphere decreased the spectral surface albedo at large solar zenith angle in the H_2O bands, while the additional reduction of downward solar flux in the near infrared region by H_2O absorption caused the spectrally integrated surface albedo to increase by several percent. Aerosols increased the spectrally integrated surface albedo at small solar zenith angles and reduced it at large solar zenith angles, however they reduced the spectrally integrated planetary albedo except at large solar zenith angles. Optically-thick cloud cover increased both the spectrally integrated surface and planetary albedos at any solar zenith angle. In the visible region at small solar zenith angles the downward solar flux on the snow surface under cloudy sky could exceed that for clear case, and both further could exceed the extraterrestrial solar flux, resulting from the multiple reflection between snow surface and the atmosphere (cloud cover).

It is concluded, from what has been said above, that the snow surface albedo is affected by the appearances of cloud or aerosols of high concentration. It is also found that the snow surface albedo is affected by the Rayleigh scattering at shorter wavelengths and by the atmospheric absorption at large solar zenith angles. Thus, it is necessary to take the atmospheric effects into account for comparison of the theoretical albedo of snow surface with the measured one, according to the conditions of clouds, aerosols, water vapor and solar zenith angle.

In Chapter 3, the spectral albedo in the wavelength region of $0.35\text{-}2.5\,\mu m$ observed on the snowfield under the cloudy sky at Barrow, Alaska in April, 1997 was discussed. The observed spectral albedo was compared with the theoretical ones calculated by a multiple scattering model for the atmosphere-snow system using the snow physical parameters obtained from the snow pit work. It was found that for new snow consisting of dendrites the optically effective snow grain size was not a crystal size, but of the order of a branch width. The observed spectral albedo was lower than theoretically calculated one for "pure snow" in the visible region and a part of the near infrared region; such reduction was explained by the internal mixture of soot and the external mixture of dust for snow particles. The theoretical spectral albedo calculated for a two-layer snow model that contains impurities agreed well with the measured one at all wavelengths.

In Chapter 4, the effects of snow physical parameters on spectral albedo and bidirectional reflectance of snow surface were discussed by comparing the observed spectral data with the theoretical ones. The observations of spectral albedo and bidirectional reflectance in the wavelength region of $0.35-2.5\,\mu m$ were made together with snow pit work on a flat snowfield under the clear sky in eastern Hokkaido, Japan in February, 1998. The effects of snow impurities, density, layer structure, and grain size attained by in situ and laboratory measurements were taken into account in snow models for which spectral albedos were calculated using a multiple scattering model for the atmosphere-snow system. Comparisons of these theoretical albedos with measured ones suggest that the snow impurities were concentrated at the snow surface by dry fallout of atmospheric aerosols. The optically equivalent snow grain size was found to be of the order of a branch width of dendrites or of a dimension of narrower portion of broken crystals as was same in Chapter 3. This means that the optical equivalent snow grain size is smaller than the so-called snow grain size measured glaciologically. The observational results for the BRDF normalized by the radiance at the nadir showed that the anisotropic reflection was very significant in the near infrared region especially at the wavelengths longer than 1.4μm, while the visible normalized BRDF (NBRDF) patterns were relatively flat. Comparison of this result with two kinds of theoretical NBRDFs, where one having been calculated using single scattering parameters by the Mie theory and the other using the same parameters except for Henyey-Greenstein (HG) phase function obtained from the same asymmetry factor as in the Mie theory, showed that the observed NBRDF agreed with the theoretical one using HG phase function rather than with that using Mie phase function, while the albedos calculated with both phase functions agreed well with each other. This suggests that the optically effective snow grain shape is neither the sphere nor the ordinary hexagonal column, by which respectively the rainbow or halo appear in the theoretical BRDF pattern, but is the nonspherical particle having the smooth phase function.

論文の審査結果の要旨

本論文は，高緯度・極域のエネルギー収支にとって重要な役割を果たしている雪氷面のアルベード（反射率）について，放射伝達モデルに基づく理論計算と分光観測によって議論したもので，雪氷ー大気系の放射過程を理解するだけでなく，気候変動監視のためのリモートセンシングにも役立つ結果を提供するものである。

本論文の第１章では，積雪内部の放射過程において，個々の積雪粒子によるミー散乱を仮定し，その位相関数の近似法について綿密な検討を加え，ダブリング法によって放射伝達を計算する際の最適な手法を見出した。

第２章では，積雪粒子による多重散乱を考慮した積雪中の放射伝達モデルを開発し，さらに現実的な気体，エアロゾル，雲の吸収や散乱を含む大気を結合し，積雪と大気の間の放射相互作用を考慮した短波長域（0.3 ～ 2.5μm）における大気ー積雪系多重散乱放射伝達モデルを完成した。この大気ー積雪系多重散乱放射伝達モデルによって，地表面アルベードや大気上端アルベード(プラネタリーアルベード)に対する大気の効果を論じた。大気上端のアルベードだけでなく，地表面でのアルベードも大気の影響を強く受けることが確認された。大気がある場合の波長別雪面アルベードは，太陽天頂角が大きい場合，気体による吸収が効くことと直達光に比し散乱光の成分が増加することから，大気がない場合に較べて減少する。また，厚い雲がある場合には波長積分した雪面および大気上端のアルベードは一様に増加すること等を示した。

さらに第３章および４章では，積雪面上において分光器による波長別アルベードおよび双方向反射率(BRDF)の分光観測と同時に積雪断面観測を行い，大気ー積雪系多重散乱放射伝達モデルによる理論計算値と比較することにより，積雪物理量が波長別アルベードやBRDF に与える影響を調べた。そして，実際の積雪観測から得られた積雪中の不純物，積雪密度，層構造，粒径をもとに積雪モデルを作り，放射伝達モデルを用いて波長別アルベードを計算した。これらの比較から，不純物が積雪表面に高濃度で堆積したことを示唆する結果が得られた。また，アルベード観測から推定された積雪粒径については，樹枝状結晶の樹枝部分など，最小部分の大きさの影響が支配的であることなどが明らかになった。測定装置についても，これまで誤差要因として問題となっていた入射角依存性や波長依存性を最小限にする工夫が施され，晴天下でも精密な測定が実現可能となった。

このように，測定された波長別の雪面アルベードを現実の積雪物理パラメータに基づく放射伝達モデルによる理論計算値で精密且つ定量的に説明し得たことは，これまでにない画期的な成果であり，高く評価できる。また，これにより，波長別アルベードの測定から，逆に積雪粒径や積雪中の不純物濃度を推定する可能性が示されたことになる。これらの研究は，今後，衛星を利用した雪氷圏リモートセンシングの理論的背景をより確実なものとし，同時に広域の気候変動研究への道を開くものとして大いに期待される。

以上の審査の結果，本論文は理学博士の学位に値する論文であることが審査員全員一致により認められた。

なお，これらの研究成果は既に学術誌に投稿され，本博士論文の一部はそれら既発表の

論文で構成されている。各論文はいずれも共著の形になっているが，実際にはその大部分が第１著者である青木輝夫氏の業績であることを確認した。本博士論文提出にあたり，各論文の共著者の同意並びに出版社の許諾を得ているものであることを付記する。