ANISOTROPY OF SURFACE-EMITTED RADIATION

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ABSTRACT

Surface-emitted thermal radiation plays an important role in the radiation budget of the Earth-atmosphere system. An implicit assumption in most of the modern radiation budget calculations is that the thermal radiance emitted from the surface is isotropic and does not depend on viewing direction. Using data obtained from a specially equipped NASA helicopter and a pair of geostationary satellites, this paper shows that surface-emitted thermal radiation over the forest regions can have a significant angular component during the daytime hours due to effects of differential solar radiative heating. Possible implications of this anisotropy to estimating top-of-atmosphere (TOA) longwave fluxes from satellite radiance measurements are discussed.

1. INTRODUCTION

It has been a common practice in the atmospheric radiation community to assume isotropy when it is working with thermal radiation emitted from the Earth's surface. While this assumption is reasonable for flat and smooth surface (such as ocean, and flat bare land), significant deviations from isotropy in surface-emitted radiation have been reported for vegetated land surfaces. For example, Balick *et al*. (1987) have found some 4 K changes with viewing angle from an oak-hickory forest canopy. Larger variations, up to 8 K, are also found in a study over corn fields and rough soil surfaces (Lagouarde and Kerr, 1993). This type of angular variation in surface-emitted thermal radiation is substantial. It is particularly troublesome for retrieval of TOA longwave fluxes from satellites. Most of the satellite radiation budget data sets have only a simple correction for limb brightening/darkening effects of the sun and atmosphere, but do not take into account of radiance variation with viewing angle. Therefore, significant errors can be built into the final product of these data sets.

In this paper, we examine the thermal anisotropic effect during the daytime hours over various forest regions using clear-sky infrared window data collected from (1) a specially equipped NASA helicopter and (2) a pair of geostationary satellites. Section 2 gives an overview of the type of data collected by the NASA helicopter and the results from one case study. This is followed by a description of the satellite data and their results. Finally, section 4 provides a short summary of our preliminary findings. A discussion is given on the possible implications of these results to estimates of TOA fluxes from satellite radiance measurements.

2. HELICOPTER EXPERIMENT

2.1 Data Description

The first data set used in this study consists of clear-sky narrow-band infrared window radiances collected by the PRT-5 sensor onboard a heavily instrumented NASA helicopter. This helicopter has been used extensively by the NASA Clouds and the Earth's Radiant Energy System (CERES) project to characterize the shortwave and longwave angular radiance distribution patterns over various forest sites in Virginia during different seasons in 1995 and 1996. Utilizing a predefined flight pattern, high quality data have been successfully collected by the helicopter. These data cover the full angular range including a set of viewing zenith (VZ) angle ranging from 0 to 70° and a set of relative azimuth (RAZ) angle ranging from 0 to 360°. The spatial resolution of the data set is about 100 m at nadir. The helicopter usually flew at a constant altitude of 1000 feet and took about 15 to 20 minutes to complete the full set of angular (both viewing zenith and azimuth) measurements. The results presented in this study represent angular radiance data collected over a mixed coniferous and broadleaf forest site during a clear-sky winter afternoon in Virginia. Schematic drawing of the helicopter experiment is outlined in Fig. 1.

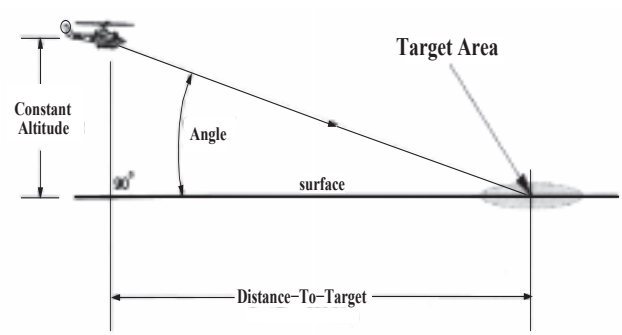

Fig.1: Schematic drawing of the helicopter experiment.

2.2 Data Analysis

The angular data collected from the helicopter were processed at NASA langley Research Center and the results for this case study are summarized in Fig. 2 for a solar zenith angle SZ=53°. For a given viewing zenith angle, the PRT-5 measurements show a strong dependence on relative viewing azimuth angle. Specifically, the data indicate that the surface-emitted thermal radiation tends to be (1) higher over the sun-illuminated side of the forest (i.e., viewing the target in the direction toward the backward scattering plane of the sun with RAZ=180°) and (2) lower over the shadowed side of the forest (such as viewing the target in the direction toward the forward scattering plane of the sun with RAZ=0°). The brightness temperature differences between the two azimuthal directions can be as large as 4.5 K for VZ=60° (i.e., dotted line Fig. 2). These results are very similar to those of earlier studies as noted in the introduction. The magnitude of these bidirectional effects also decrease with decreasing viewing zenith angle. For the overhead case with VZ=0° (such as solid line in Fig. 2), variations in PRT-5 brightness temperature with respect to relative azimuth angle are reduced to zero. These observed bidirectional patterns in the surface-emitted thermal radiation are consistent with the effects caused by differential solar radiative heating between the sun-illuminated side and the shadowed side of the forest. Specifically, the side of forest that is heated by the sun tends to have a higher skin temperature than the shadowed side of the forest. Therefore, the sun-illuminated side tends to emit at a higher radiance level than the shadowed side of the forest.

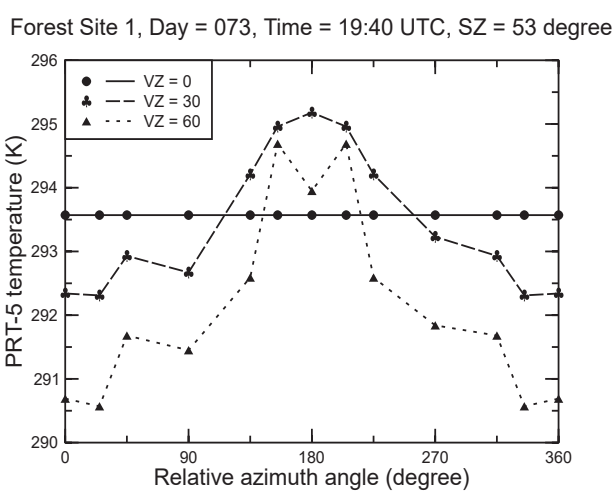

Fig. 2: Angular PRT-5 radiation data collected by the NASA helicopter over a forest site in Virginia during a winter afternoon with solar zenith angle of 53° (solid line for viewing zenith of 0°, dashed line for 30°, and dotted line for 60°).

3. SATELLITE EXPERIMENT

3.1 Data Description

The second data set comes from clear-sky narrow-band infrared window radiances collected from GOES-7 (or GOES-WEST) and GOES-8 (or GOES-EAST) geostationary satellites over the central United States on October 14, 1995. The resolution of these satellite data set is 4 km at nadir. During this period, GOES-7 is located at 135° west longitude and GOES-8 is located at 75° west. These satellite data are organized into radiance pairs (shown in Fig. 3) for analysis. Since the two GOES satellites are viewing the central United States from different locations in space, analyzing the satellite data in a paired fashion will allow one to effectively explore the angular dependence (i.e., viewing zenith and azimuth angle) of thermal radiation emitted from Earth. In order to further minimize the effects due to differences in atmospheric thermal structures (both temperature and moisture) as viewed from the two different satellites, areas with relatively dry and cold atmosphere after cold frontal passage during the data period were chosen. Specifically, data from three different clear-sky forest regions over the United States (outlined in table 1) are examined in details. Region I includes forest over a sloping mountain area. Regions II and III contain low-elevation forests. Each of these regions represents an area roughly 100 km by 100 km on the Earth's surface.

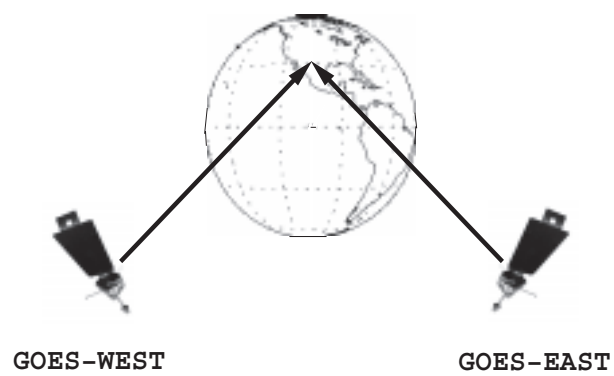

Fig. 3: Schematic of the paired satellite data collected from GOES-EAST and GOES-WEST geostationary satellites over central United States.

Table 1: Forest Classification for the Three Regions of United States.

Region	Location	Type of Forest
I	New Mexico	Coniferous over Sloping Mountain
II	Arkansas	Broadleaf
III	Texas	Mixed Coniferous and Broadleaf

3.2 Data Analysis

Satellite data collected from GOES-7 and GOES-8 over the three specific forest regions were processed and area averages for each region were calculated using McIDAS system. Furthermore, limb brightening/darkening effect is also removed using empirical model of Minnis and Harrison (1984).

3.2.1 Cross-calibration

The narrow-band infrared window instruments onboard the GOES-7 (10.4 to 12.1 micron) and GOES-8 (10.2 to 11.2 micron) satellites have a small difference in spectral coverage (Menzel and Purdom, 1994). In order to remove this mismatch, cross-calibration of the two instruments is performed using both clear-sky and total overcast radiances collected at local noon at regions located at 105° west, the mid-point between the two satellites location. A least-squares fit to the data was computed and used to convert all GOES-7 radiances into equivalent GOES-8 infrared data. The results of this cross-calibration are given in Fig. 4. In general, the temperature corrections are small and vary from -0.3 K at 260 K to 0.4 K at 300 K. These corrections are very close to the noise level of the GOES-8 infrared instrument, which is 0.2 K at 300 K and 0.4 K at 230 K.

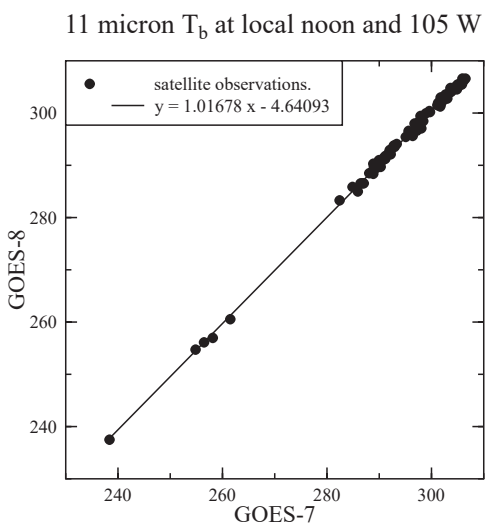

Fig. 4: Cross-calibration of GOES-7 and GOES-8 data.

3.2.2 Radiance Pairs Results

The results of the satellite radiance pairs analysis are given in Fig. 5 in the form of a scatter diagram of GOES-7 versus GOES-8 brightness temperature for all three regions of interest during the daytime hours on October 14, 1995. For isotropic radiation field, the thermal radiances received by the two satellites should be exactly the same and all the data points should lie on the straight line that runs diagonally across the diagram. However, this is not the case in Fig. 5. Instead, significant deviations from the straight line are observed for all three regions; suggesting strong anisotropic effects in the thermal infrared wavelength over these forest areas. The largest brightness temperature difference between the two satellite measurements is found in the coniferous forest (Region I) over the mountains in New Mexico (i.e., up to 5 K).

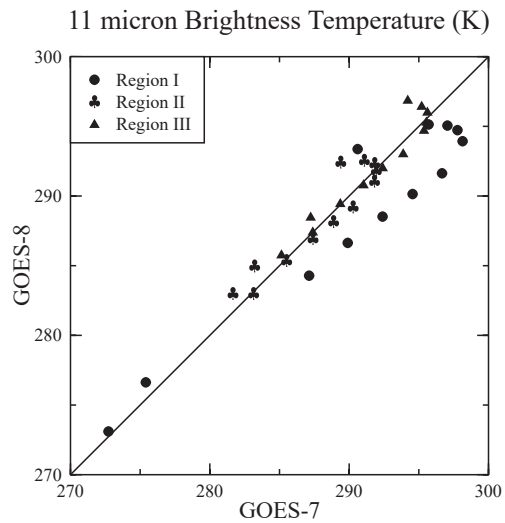

Fig. 5: Scatter diagram of GOES-7 to GOES-8 brightness temperature for the three forest regions in United States.

In order to examine these angular variations in detail, time series of the ratio of GOES-7 to GOES-8 brightness temperature for each of the three regions is plotted in Fig. 6. The advantage of using the ratio is that it allows one to remove effects due to regional thermal variations between the three target areas and to concentrate only on variations due to satellite viewing differences. For example, GOES-8, at 75° W, views all three regions in the direction toward the backward scattering plane of the sun (i.e., viewing the sun-illuminated side of the forest) during the morning while GOES-7, at 135° W, views the same three regions in the forward scattering hemisphere (such as viewing the shadowed side of the forest). Thus the ratio of GOES-7 to GOES-8 brightness temperature represents the ratio of radiance emitted from the shadowed side of the forest to the radiance emitted from the sun-illuminated side of the forest. During the afternoon, the sun moves to the opposite side of the solar plan and the viewing geometry for the three regions is now reversed. The ratio now represents the ratio of the radiance emitted from the sun-illuminated side of the forest to radiance emitted from the shadowed side of the forest. Furthermore, if the thermal radiation emitted from the Earth is completely isotropic, this ratio will have a constant unity value through out the day. This is, however, not the case in Fig. 6. Instead, a striking anisotropic pattern is observed. Specifically, the ratio of the brightness tempera-

tures shows a sine wave-like oscillation with respect to time. This sine wave-like feature can not be explained by the difference in atmospheric structures between the two satellite's viewing slant paths since these atmospheric effects will only create a constant offset in the time series. Therefore, it is concluded that this feature is caused by the differences in surface skin temperature between the two viewing directions. The ratio is less than unity in the morning for all three regions (i.e., radiance emitted from shadowed side of the forest is cooler than radiance emitted from sun-illuminated side of the forest) and greater than one in the afternoon for all three regions (such as radiance emitted from the sun-illuminated side of the forest is warmer than radiance emitted from the shadowed side of the forest). This thermal angular distribution pattern is consistent with our results obtained from the helicopter experiments. The geostationary views do not include the direct forward scattering angles (i.e., RAZ=0 to 10) at low viewing zenith where shadowing is at maximum. Therefore, the temperature variations are probably even greatly than those seen here.

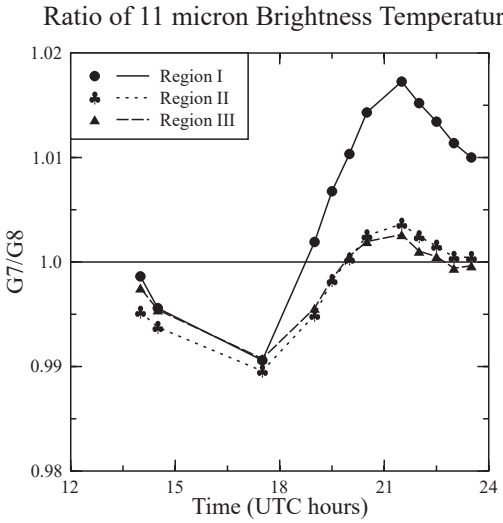

Fig. 6: Time series of the ratio of GOES-7 to GOES-8 brightness temperature for the three forest regions.

4. SUMMARY AND DISCUSSION

Surface-emitted thermal radiation during the daytime hours over various forest regions in United States is examined using data collected from a special NASA helicopter and a pair of geostationary satellites. Significant bidirectional effects are noted in both data sets. These angular radiance patterns are consistent with effects caused by differential solar radiative heating between the sun-illuminated and shadowed sides of the forest. The side of the forest that is heated by the sun tends to have higher skin temperature than the shadowed side of the forest. Therefore, the sun-illuminated side emits at a higher radiance level.

This bidirectional effect in surface-emitted thermal radiation can introduce significant errors into the conventional estimates of TOA clear-sky longwave flux over forest regions and likely over any land surface having enough structure to cast shadows. Conventional longwave estimates are computed using only limb-darkening models to correct for atmospheric absorption. For example, for a background temperature of 295 K, a 4 K variation in the measured brightness temperature due solely to differences in viewing geometry can translate into an uncertainty of 20 Wm^{-2} in retrieved TOA longwave flux. In order to minimize these flux errors, special longwave angular distribution models should be developed for land surfaces in the future to account for this bidirectional effect during radiance to flux conversion process.

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