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ALBEDO OF WHEAT DURING A GROWING SEASON: DIURNAL SYMMETRY AND ASYMMETRY

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1. Introduction

Albedo is an instantaneous, diurnal, seasonal or annual expression of the relationship between solar radiation and the earth-atmosphere interface. It is defined as the ratio between reflected solar radiation and global solar radiation. The albedo plays an integral role in determining the regional climates of surfaces across both spatial and temporal scales. This has led to the inclusion of albedo as a physical parameter in general circulation models (GCMs) (Kondratyev *et al*., 1982; Randall, 1992). GCMs are sensitive to slight changes in albedo because of its significance in determining the net radiation balance of the surface, hence the surface energy balance and the resulting climatology (Hummel and Reck, 1979; Kondratyev *et al*., 1982; Myhre and Myhre, 2003). Several papers have concluded that the accuracy of GCMs may be limited by the paucity of long-term albedo studies over surfaces that are representative of a region (Kondratyev *et al*., 1982; Myhre and Myhre, 2003).

The behaviour of albedo is complex as it is predisposed by both atmospheric and surface controls: solar position, atmospheric transmissivity, surface type and surface condition. There are a number of studies reporting and characterising asymmetrical albedos (Al-Yemeni and Grace, 1995; Arnfield, 1975; Grant *et al*., 2000; Minnis *et al*., 1997; Nkemdirim, 1972; Prata *et al*., 1998; Song, 1998). Minnis *et al*. (1997) suggest that for regions like the southern Great Plains in North America, the albedo tends to be asymmetrical over prairie and pasture surfaces because of variations in sky condition and surface moisture throughout the day. They and others point out that morning dew causes an asymmetrical albedo for bare soil, grass and crop surfaces (Grant *et al*., 2000; Minnis *et al*., 1997; Song, 1998). Other studies have observed an asymmetrical albedo from a reclined canopy in moderate to strong wind, from leaf tracking or from changes in leaf wetness (Al-Yemeni and Grace, 1995; Song, 1998). The studies over grass and crop surfaces observed that forenoon and afternoon albedos were asymmetrical by 2 to 20 percent. Most studies consider the symmetry or asymmetry of the albedo on cloudless days, leaving a paucity of published information about the symmetry or asymmetry of albedo on partly cloudy and overcast days.

In this research, a detailed description of the character of the albedo throughout the day is presented by characterising the symmetry or asymmetry of the albedo for cloudless, partly cloudy and overcast sky conditions throughout the growing season of a wheat crop.

2. Measurement program

2.1 Study site and instrumentation

Research was conducted at the Meteorological Service of Canada's BSRN Bratt's Lake Observatory (BLO), Saskatchewan (50° 12' 10" N, 104° 42' 42" W). The field site at the observatory includes two adjacent fields that share an east-west border. Fields are referred to as the north field and south field. Observations commenced before the crops were planted on April 30 (day of year (DOY) 120) when the north field was covered with a matted lentil material and the south field was covered with flax stubble. Observations were halted from May 12 through May 14 (DOY 132 through 134) so that the field could be harrowed and seeded with hard red spring wheat (*Triticum aestivum L.*). The observations commenced again on May 15 (DOY 135), and continued until harvest on August 25 (DOY 237).

Throughout the 2001 growing season, measurements of global solar, reflected solar, direct beam and diffuse radiation were made. A stand with an adjustable arm was employed to measure reflected solar radiation at 2 m above the surface of each field using ventilated Kipp and Zonen pyranometers. Pre- and post-season calibrations of these pyranometers were conducted at the National Atmospheric Radiation Centre and confirmed that their performance did not change over the growing season. Data was collected with a Campbell Scientific 21X datalogger that measured the sensor signals every second and output a mean, standard deviation, maximum and minimum value every minute.

Global solar radiation, direct beam radiation, diffuse solar radiation, vapour pressure and air temperature were measured at an adjacent

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meteorological compound. Again, measurements were made every second, and every minute, a mean, standard deviation, maximum and minimum value was recorded. Precipitation was measured daily.

2.2 Supplemental measurements

Daily volumetric soil moisture measurements were made throughout the growing season. Soil sampling (between 7:00 and 9:00 CST) commenced on DOY 120 and continued until DOY 237. The samples were taken from the upper 10 mm of soil and five layers from 0 to 250 mm. Volumetric soil moisture was characterised daily by averaging five sample locations for each depth interval from each field.

Plant sampling was conducted throughout the growing season to assess the phenological stage of the wheat, plant height and above ground biomass. Every two or three days, at ten fixed locations in each field, the standing and extended heights of the crop were recorded. The standing height is the height of the plant from the ground to its highest point. The extended height is the height of the plant from the ground to the highest standing point when all parts of the plant are manually extended upwards.

Above ground biomass was determined by manually harvesting the crop from ten randomly selected quadrants (250 x 500 mm) in each field. At each location, the surface was first photographed and five plant heights recorded (one in each corner of the quadrant and one in the center). The vegetation was then harvested at ground level. Fresh and dry weights for nine of the ten sample locations in each field were obtained by weighing the samples and then drying the samples for 72 hours at 70˚C. The remaining sample had its plant components (leaves, stems and heads) separated and weighed.

The sample that had its plant components separated was also used to determine the leaf area and leaf area index (LAI). The fresh leaves were laid flat on a white bristol board, covered with plexiglas and photographed (Bailey and Stewart, 1982). The leaf area was determined from the photographs with a density slice function. The relationship between leaf area (LA) to leaf dry weight (l_{dw}) was found to be:

$$LA = 0.0166\, l_{dw} + 0.0135,\ r^2 = 0.85. \quad (1)$$

A leaf area for each sample date was then determined by applying Equation 1 to the average leaf dry weight. The leaf area was then divided by the sampling area to produce LAI.

The growing season was divided into seven stages based on surface and crop conditions. These divisions, except pre-seeding, are based on the phenological stages of wheat as outlined by Robertson (1968) and the Agrometeorological Centre of Excellence (ACE, 2002).

2.3 Data analysis

To examine the diurnal symmetry, half-hour forenoon and afternoon albedos, at the same zenith angle, were compared

$$\Delta\alpha_z = \frac{\alpha_{AM} - \alpha_{PM}}{\overline{\alpha}} * 100 \qquad (2)$$

where $\Delta\alpha_z$ is the percent difference of the forenoon and afternoon albedo, α_{AM} is the forenoon albedo at a particular zenith angle, α_{PM} is the afternoon albedo at a particular zenith angle and $\overline{\alpha}$ is the mean of the forenoon and afternoon albedo at a particular zenith angle. Initially, the $\Delta\alpha_z$ data was graphed for each day against the zenith angle, and thereafter re-occurring trends were grouped for analysis.

Both atmospheric and surface conditions were employed to investigate $\Delta\alpha_z$ behaviour. Differences in forenoon and afternoon sky conditions were compared by examining the difference in transmissivity and surface soil moisture. The differences in the available surface moisture condition were examined using the vapour pressure deficit (vpd) .

3. Results and Discussion

Diurnal albedo trends were influenced by both atmospheric and surface conditions. However, the diurnal symmetry of the albedo was found to be predominately related to transmissivity. During cloudless or nearly cloudless conditions, the albedo was inversely related to transmissivity (Figure 1), and is similar to the observations of others (Arnfield, 1975; Nkemdirim, 1972). Days 187 and 218 illustrate the inverse nature of albedo with transmissivity. As zenith angle increases, the solar beam travels through more atmosphere, resulting in greater beam attenuation and a lower transmissivity. In terms of reflected solar radiation, as the zenith angle increases, less solar radiation is back-scattered and/or absorbed by the surface because the ground is more characteristic of a smooth surface. Therefore, the albedo increases with the zenith angle.

Clouds dampen the zenith angle control and, when cloud cover increases, both transmissivity and the albedo decrease (Figure 1).

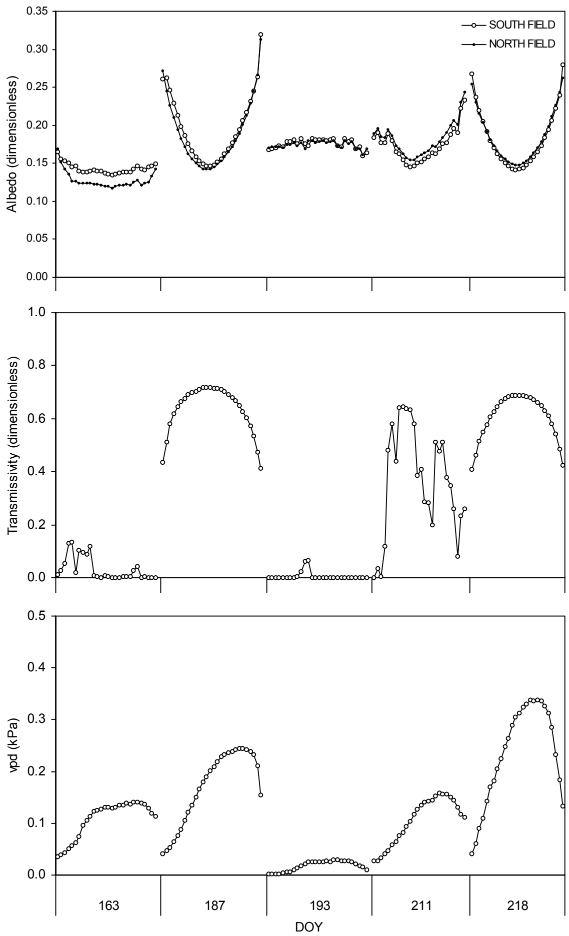

Figure 1. The diurnal trend of albedo for two wheat fields, transmissivity and vapour pressure deficit (vpd) on five selected days during the 2001 growing season.

During overcast days, small variations in the albedo were attributed to changes in cloud type and thickness. For example, on DOY 163, the albedo decreased slightly over the day as the cloud cover changed from altostratus and altocumulus in the morning, to altostratus and cumulus in the afternoon. On DOY 163, the albedo also varied slightly from one half-hour period to the next in response to changes in cloud thickness. During partly cloudy conditions, the albedo also increased or decreased from one half-hour to the next in response to transmissivity increasing or decreasing.

The diurnal variation in albedo was also controlled by changes in the surface condition. During the pre-seeding, bare soil and emergence stages, surface soil moisture decreased during the morning on cloudless and partly cloudless days and this resulted in the albedo being asymmetrical. During these stages, the minimum albedo was observed between 7:30 and 10:30 LAT. The study of the relationship between the albedo and surface moisture availability was aided through a comparison of the albedo to the vapour pressure deficit (vpd) (Figure 1). With higher surface soil moisture, more moisture is available for evaporation, and the vpd will exhibit lower values. DOY 142 is a good example of the early morning drying trend that occurred throughout the pre-seeding, bare soil and emergence stages (Figure 2). The vapour pressure and the vpd increased from dawn until 7:30 LAT. This suggests that dew, which provided water for ready evaporation, was decreasing. The surface soil moisture evaporated as the morning progressed because there was more potential energy for vaporizing surface dew. In response to the declining surface soil moisture, the forenoon albedo decreased until 7:30 LAT ($\alpha = 0.088$). After 7:30 LAT, the vapour pressure declined and the vpd increased sharply because the dew, which provided surface moisture, was now fully evaporated and the surface temperature was rising. Hence, the albedo increased as the zenith angle increased.

Following the emergence stage, during cloudless and most partly cloudy conditions, the

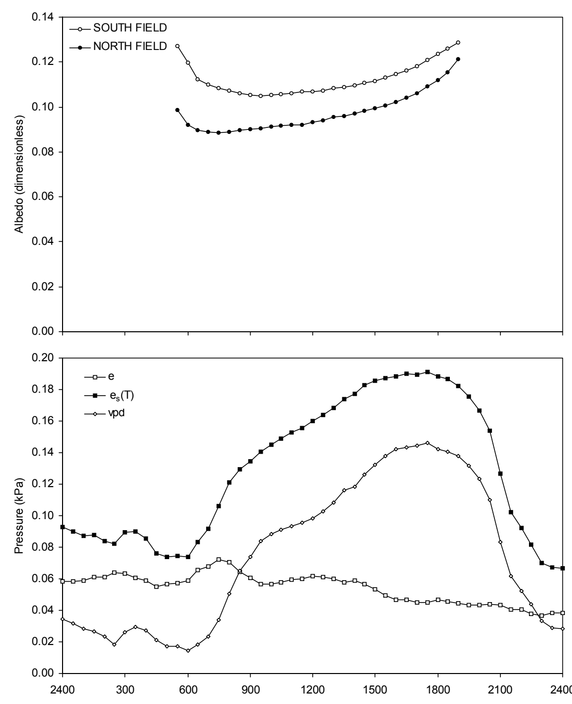

Figure 2. The albedo, vapour pressure deficit (vpd), vapour pressure (e) and saturation vapour pressure ($e_s(T)$) for DOY 142.

albedo did not demonstrate a relationship with soil moisture or vpd. During nearly overcast and overcast conditions with a period of precipitation, the albedo was related to the vpd (but to a lesser extent than during pre-seeding, bare soil and emergence stages) with the albedo decreasing as surface moisture increased.

Several patterns emerged when the symmetry of the daily albedo was described by the percent difference between the forenoon and afternoon albedos (Equation 2). For most days during the growing season, the diurnal albedo demonstrated some degree of asymmetry. Commonly, the asymmetry was in response to changes in transmissivity. However, the albedo was symmetrical ($\pm$10%) for overcast, nearly overcast, cloudless and nearly cloudless days when the surface condition was unvarying.

Throughout the pre-seeding, bare soil and emergence stages, the albedo was asymmetrical. This was linked to decreasing surface soil moisture throughout the day (Figure 3a). The $\Delta\alpha_z$ curves are skewed to the right because the surface soil moisture was greater at the beginning of the day. This trend was only present for the pre-seeding, bare soil and emergence stages because this is when changes in surface moisture most strongly affected the albedo. Once the surface was vegetated, the decreasing moisture no longer resulted in asymmetrical albedos. The albedo was solely that of the vegetated canopy.

Slopes of the $\Delta\alpha_z$ trends were found to be both negative and positive. On four occasions $\Delta\alpha_z$ had a positive slope because the transmissivity was greater in the morning than the afternoon. On numerous occasions, $\Delta\alpha_z$ had a negative slope and this was most prevalent during the jointing stage (Figure 3b). In most cases, the asymmetry occurred because the transmissivity increased throughout the day. On several occasions, the slope was negative when it rained in the morning and the skies cleared in the afternoon. On other days, such as DOY 179, $\Delta\alpha_z$ was positive around midday and dropped to negative values at the end of the day, as transmissivity was greater in the afternoon (Figure 3c). DOY 179 provides an interesting example where the morning was foggy until approximately 8:30 LAT (zenith angle, Z = 51°), and overcast until 12:00 LAT (Z = 27°). Thereafter, cloud cover began to decrease until 13:00 LAT (Z = 28°) and then remained steady with 0.5 cumulus cloud. In response, $\Delta\alpha_z$ was negative when the morning was foggy, and $\Delta\alpha_z$ decreased as the fog lifted. After the fog lifted, $\Delta\alpha_z$ was $\pm$1 percent (Z = 46°)

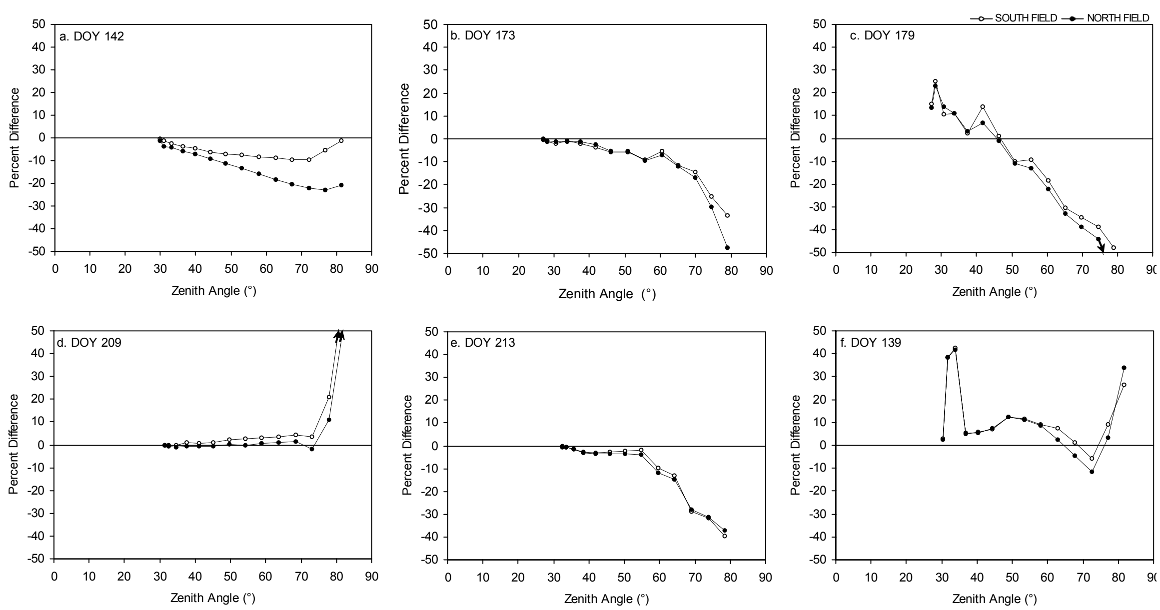

Figure 3. The percent difference between the forenoon and afternoon albedo on six selected days. The percent difference is the forenoon albedo subtracted from the afternoon albedo and divided by the average of the forenoon and afternoon albedo.

and, after which, $\Delta\alpha_z$ increased as the zenith angle decreased. The $\Delta\alpha_z$ increased because the afternoon albedo was influenced by the zenith angle and clearer sky conditions. When all solar radiation is diffuse, the albedo has an effective zenith angle of approximately 45° (Piggin and Schwerdtfeger, 1973).

Throughout the day $\Delta\alpha_z$ tended to increase as the zenith angle increased. This was a function of the sky condition where forenoon and afternoon transmissivities were more alike at smaller zenith angles than at larger zenith angles. This trend is not unexpected because as the zenith angle increases, the time between the morning and corresponding afternoon albedo is greater, and the sky condition maybe very different. In contrast, $\Delta\alpha_z$ at smaller zenith angles are closer in time, and therefore there is a greater likelihood that the sky condition remained the same.

Several days were symmetrical ($\pm 10\%$) at lower zenith angles, but became asymmetrical at higher zenith angles as the sky and surface conditions changed (Figure 3d and 3e). Again, changes in transmissivity are often related to these differences. However, on a few occasions, the albedo decreased because a rain event at the beginning or end of the day increased soil moisture. DOY 209 is an example of how a change in transmissivity can influence the symmetry of the albedo (Figure 3d). The day was nearly cloudless ($\leq 0.5\%$ cloud cover) until approximately 18:00 LAT when the transmissivity decreased as cloud cover increased. In response, the albedo was greater in the morning than the afternoon for Z > 73°. On DOY 213, the opposite is true (Figure 3.3e). The morning was nearly overcast until Z $\approx$ 55°, and was partly cloudy for the rest of the day. The sky condition did not vary greatly after Z $\approx$ 55°, and thus the albedo was symmetrical for most of the day. On DOY 213, the asymmetry increased negatively at higher zenith angles because the morning had a lower transmissivity.

This discussion of $\Delta\alpha_z$ has primarily focused on how $\Delta\alpha_z$ increased as the zenith angle increased, and how the albedo is predominately symmetrical around solar noon. However, for several days, the middle of the day had differing forenoon and afternoon sky conditions. For example, on DOY 139, the highest $\Delta\alpha_z$ occurred at Z = 34° because the transmissivity decreased in the afternoon (Figure 3f). When Z > 34°, the transmissivity in the afternoon increased once again and, in response, $\Delta\alpha_z$ decreased to previous levels. The $\Delta\alpha_z$ was negative when Z = 72° because the transmissivity in the morning was lower then the transmissivity in the afternoon. The $\Delta\alpha_z$ increased after Z = 72° because the transmissivity in the morning was lower than the transmissivity in the afternoon.

The days that do not conform to the above $\Delta\alpha_z$ trends have irregular shapes. In every case, the asymmetry was related to different forenoon and afternoon transmissivities. Only during the pre-seeding, bare soil and emergence stages and during periods of precipitation did the surface exhibit a role in determining the diurnal symmetry of the albedo.

The asymmetry of the albedo was similar for the north and south fields, except when the surface was predominately a bare soil and during DOY 183-190. The difference in the asymmetry was a consequence of the difference between the two surfaces. Throughout the pre-seeding, bare soil and emergence stages, $\Delta\alpha_z$ was different for each field because the soil dried at slightly different rates (Figure 3a). When both fields were vegetated, the two surfaces were almost identical, and the differences in $\Delta\alpha_z$ between the two fields were negligible. However, from DOY 183 to 190, $\Delta\alpha_z$ trend was slightly different in each field, and arose because the wheat in the south field was three days more mature than the north field. During this period, the boots were forming ($\approx$ DOY 183 to 186) and heads were emerging from the boot ($\approx$ DOY 186 to 190) at different rates.

The diurnal symmetry in the albedo was sensitive to changes in transmissivity and surface condition. From the pre-seeding stage to the end of the emergence stage, the albedo was primarily controlled by the zenith angle, transmissivity and soil moisture. When the surface was vegetated, the albedo was primarily controlled by the zenith angle and transmissivity.

4. Conclusions

This study has demonstrated that the diurnal albedo is dependant on atmospheric controls (such as zenith angle and transmissivity) and surface controls (such as soil moisture and vegetation cover). As only a handful of published studies have examined the asymmetry of diurnal albedos (Grant *et al*., 2000; Minnis *et al*., 1997; Nkemdirim, 1972; Song, 1998), this study has provided a more comprehensive examination of this characteristic in diurnal albedo regimes.

A number of studies have only focused on the albedo of cloudless days, which are usually symmetrical around solar noon. However, most days are partly cloudy in character. This research has extended the finding of many studies found in the literature as it has characterised the symmetry of the albedo for various atmospheric conditions. Generally, the albedo was symmetrical for cloudless, near cloudless days, overcast and nearly overcast days. Conversely, the albedo was asymmetrical for partly cloudy days.

The study has also characterised the symmetry of the albedo for various surface conditions. Up to the end of the emergence stage, the forenoon albedo was lower than the afternoon albedo because the surface was moist from dew in the morning hours. This was also observed by others (Grant *et al*., 2000; Song, 1998).

There is still a paucity of information on how the albedo changes over a day and additional insight is needed to confirm the findings in this and other studies. The diurnal variation of the albedo needs to be examined over many types of surfaces to provide a better understanding of controls on the symmetrical trends. This is important as albedo studies may serve to confirm satellite measurements, and are employed in climate modeling over a range of spatial and temporal scales.

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