A Space-borne Forest Fire Observation System

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1. Introduction

Forest fires have significant social, economical and environmental impacts. Fire is a major disturbance to the boreal ecosystem, and it is particularly vulnerable to climate change induced by increasing trace gases. In general, fires occur under hot and dry weather, which is the trend of climate change in boreal forest regions as projected by many climate models (Henderson-Sellers et al., 1995). Such a trend of climate change appear to coincide with the trend of fire activity in the boreal forest regions where fires have increased since the 1950s [Stocks, 1991]. For example, five of the Canada's most serious fire years in this century occurred after 1980, and the top three years occurred after 1989. Whether the coincidence is an indication of climate change remains an open question, since fire activities are dictated by many factors. Nevertheless, it is certain that climate change will have a major impact on fire. In return, climate is also affected by the release of particulate and greenhouse gases (GHGs) into the atmosphere (Crutzen et al., 1979). Smoke aerosols exert a cooling effect on climate, while GHGs have a warming effect. Understanding the interaction between fire activities and climate change requires acquisition of extensive and long-term monitoring of fire and climate. In addition to the far-reaching influence on climate, fire activities may have tremendous immediate impact on the economy and the well-being of forest sector. Early detection of fires and close monitoring of their development are essential to fire management agencies. Operational fire monitoring over large areas is only feasible through satellite remote sensing. Unfortunately, a suitable satellite-based observation system does not exist in Canada.

The central goal of this study is to develop a satellite-based fire monitoring system. Using this system, we can detect and monitor fire activities and assess their effects, both during and at the end of the fire season. Such information is critical for sustainable forest development and for making decisions as to whether, when and which fires are to be suppressed. Ground-based fire observations are employed for validation purpose. The ground data has been extracted from individual wildfire reports prepared by the forest fire management agencies in the Provinces of Saskatchewan and Manitoba. Wildfire reports represent the best information available for each individual fire. The data include fire number, location, size and burning period. The fire location represents the point of ignition for each fire. The total burned area of each fire was estimated primarily from aerial sketch maps which may or may not include unburned islands. Ignition dates are the date of discovery and while it is quite common for fires to smolder or "hold over" for one, or more days prior to discovery, the fire size at the time of discovery is typically less than one hectare.

2. Algorithm

Many algorithms have been developed to detect active fires using AVHRR measurements. Most of them were designed for applications in the tropics [Kaufman et al., 1990; Arino and Mellnotte, 1995] and few were applied to boreal forest [Flannigan and Vonder Haar, 1986]. In general, the algorithms that take advantage of the multi-channel measurements from AVHRR in order to increase the confidence of detection and information content of a fire are similar in concept. For example, the method of Kaufman et al. [1990b] consists of three steps on the basis of channel 3 and 4 data. We tested the method and found that the essential information is contained in channel 3. The second and third test of Kaufman et al., designed to remove the effect of warm surface and clouds, did not play a significant role in the relatively colder environment of the BOREAS region but were used nevertheless since they did not seem to have any adverse effect.

AVHRR channel 3 is most sensitive to active fires because it tends to become saturated with the presence of small fires (fraction of a pixel). Depending on the sensor, calculated saturation brightness temperature in channel 3 ranges from 322 K to 331 K [Robinson, 1991b]. Following an examination of burning areas (indicated by smoke in channel 1), we chose 316 K as the threshold, coincident with that used by Kaufman et al. [1990]. As mentioned above, we also used the two other tests suggested by Kaufman et al.: difference of brightness temperature between channel 3 and 4 larger than 10 K and brightness temperature in channel 4 larger than 245 K. The most prominent problem encountered in using these three tests, is the false alarm due to sun glitter. Sun glitter arises from specular reflection of the incoming solar radiation over many objects such as water bodies, snow, ice, swamp, bare soil and clouds. There are several hundreds of lakes of various sizes, numerous rivers and swamps located across the BOREAS study region that are strong specular reflectors. In addition to saturation in channel 3, such pixels have high reflectance in channel 1 and 2 and low NDVI, which are all similar to the spectral characteristics of smoke. Therefore, fire information in these channels is limited. For a flat object such as the calm water surface, sun glitter occurs at a view zenith angle similar to the solar zenith and a relative azimuth angle around 180^o, i.e., forward scattering. However, in reality, the phenomenon is often observed in many forward scattering directions near the principal plane, presumably due to the rough surface of a natural reflector. Therefore, we simply discard all forward scattering measurements (the geometry is known for each pixel acquired). This may eliminate some fires but this omission can be compensated to some extent by the overlapping of sun-synchronous orbits at such high latitudes as the BOREAS region and by visual inspection. We have tried other methods proposed to cope with this problem but without much success. While they may eliminate some false alarms, they also remove many real fires. Changing the threshold values does not seem to result in significant improvement.

3. Results

A large volume of NOAA-11 AVHRR data were employed for this study. Hundreds of single-day AVHRR images received in 1994 were processed and fire pixels on each image were identified. Figure 5 shows the distribution of fires detected by satellite (red spots) and observed at the surface (yellow signs) in a region of 800 X 700 km^2 located across the provinces of Saskatchewan and Manitoba in Canada during the summer of 1994. The background is an image of land cover types and water bodies. Note that the fire locations reported at the surface correspond to where the fires were first spotted. The total burned area over this region was estimated to be 1.82 and 1.97 million hectares according surface and satellite observations, respectively. Except for some scattered small fires, the agreement is fairly good, given that many uncertainties associated with satellite-based detection. On one hand, the algorithm tends to overestimate the area as a result of the saturation of channel 3, the degree of overestimation depending on the burned area and the flame temperature. On the other hand, the method could underestimate the burned area as it only sees the fires that are active when the satellite overpasses. The degree of underestimation is variable, depending on fire duration and movement. The low sampling rate of the sun-synchronous satellite could miss some short-lived fires. It is probably because of the two offset factors that lead to a reasonable estimate of burning area.

In addition to the spatial distribution of fires, the evolution of fires can be closely monitored, as is shown in Figure 2 in which fire locations detected by AVHRR channel 3 and the associated smokes visible from channel 1 reflectance are displayed. The burning took place south of the Southern Indian Lake. The first fire was detected by satellite on June 6. Two days later, another fire was spotted in the south. The two fires expand rapidly in the next few days. Afterwards, fires become less obvious as clouds moved in. By the end of July or beginning of August, the fire activities in the region reach peak and the two groups of fires approach to each other. The composite of total area of burning during this period is displayed on the last panel, which compares very well with ground report. However, the fire starting date reported at the surface is a few days later than that detected by satellite. Despite of cloud cover that may obscured some fires, the comparison of fire starting dates for all the fires as shown in Figure 1 shows that the majority of satellite-based dates are generally earlier than surface observed ones. There are about eight cases whose starting dates differ by more than one month. This might be due to two factors: 1) fires usually occur under dry weather conditions with few clouds, and 2) the amount of burning at the beginning of a fire is so small or in such remote areas that it may not draw the attention of surface observers. Conversely, AVHRR channel 3 can detect a fire as small as 10X10 m^2 [Kaufman et al. 1990a]. Thus, satellite monitoring is indispensable to earlier fire detection, even if a ground-based fire monitoring system is in place.

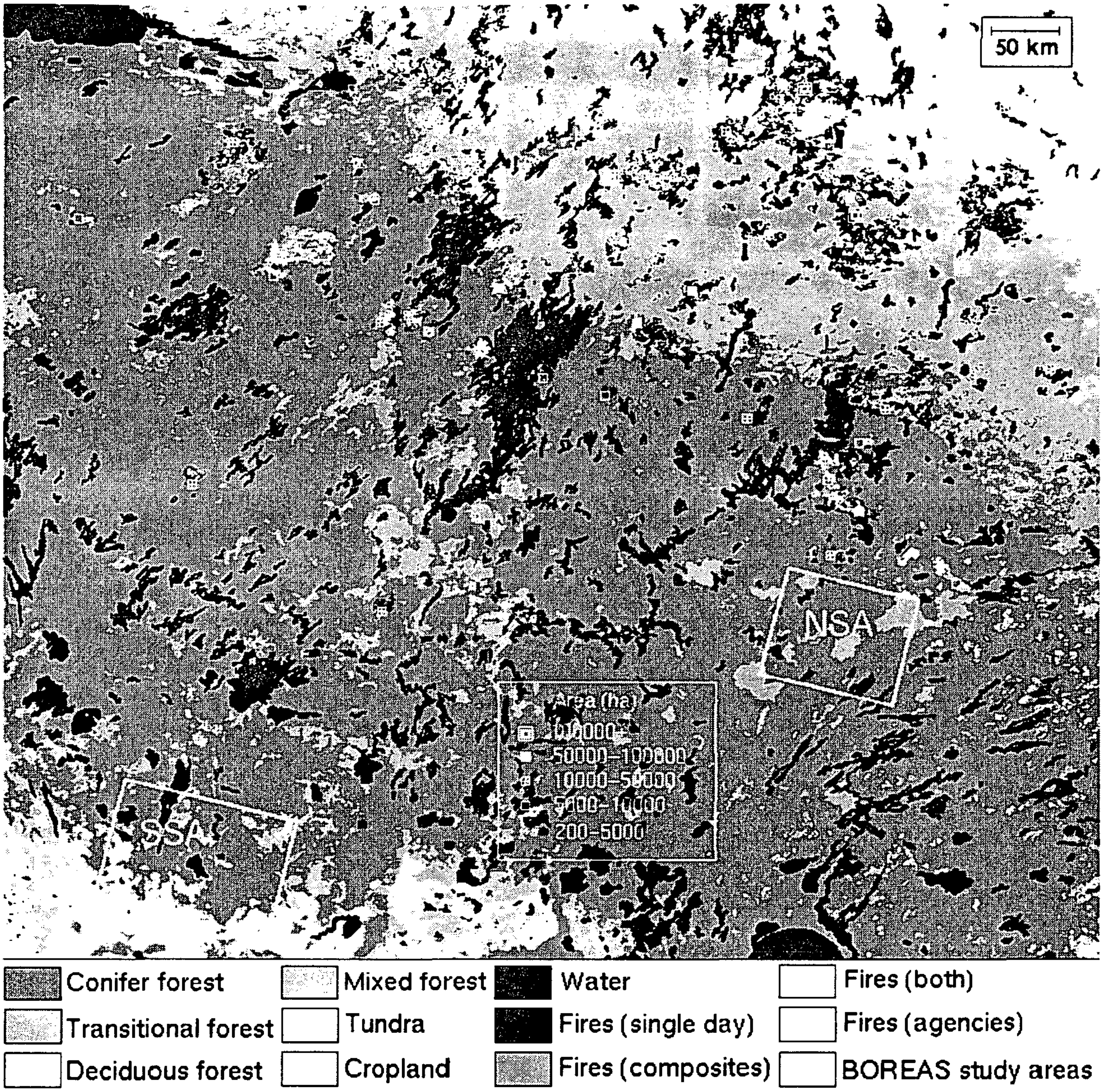

Fig. 1 Distribution of fires detected by NOAA/AVHRR satellite (red spots) and observed at the surface (yellow signs) in a region of 800X700 km^2 located across the provinces of Saskatchewan and Manitoba in Canada during the summer of 1994. The background is an image of land cover types and water bodies.

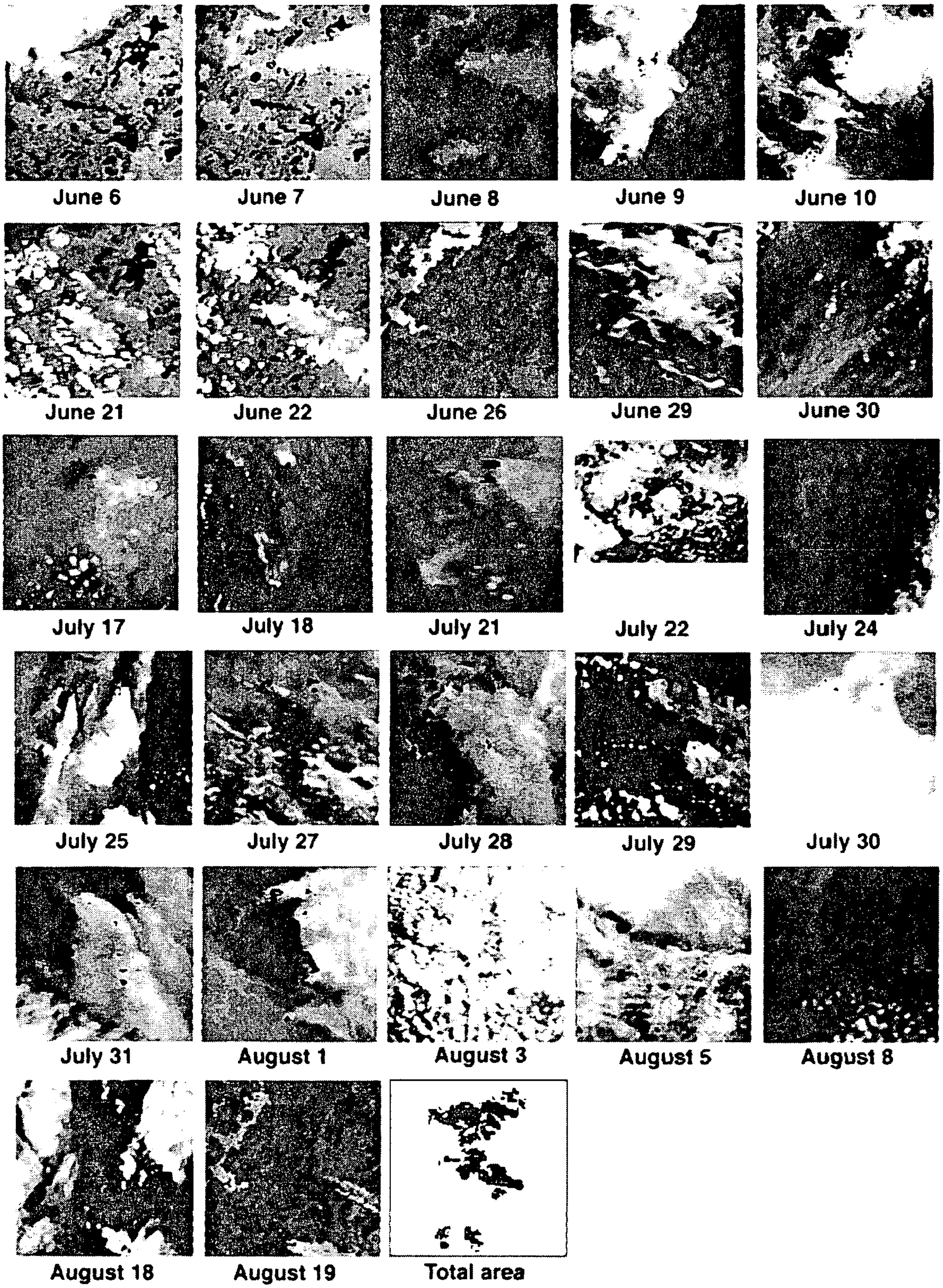
June 6
June 7
June 8
June 9
June 10
June 21
June 22
June 26
June 29
June 30
July 17
July 18
July 21
July 22
July 24
July 25
July 27
July 28
July 29
July 30
July 31
August 1
August 3
August 5
August 8
August 18
August 19
Total area

Fig. 2 Evolution of fire locations detected by AVHRR channel 3 (red spots) with a background denoting channel 1 reflectance. The image is about 100 km × 100 km.

4. Summary

Forest fire is a major disturbance to the boreal ecosystem and interact with climate change. This study investigates the extent and dynamics of the forest fires occurred in and around the BOREAS region during the summer in 1994, an active fire season on record. The statistics of fire activities were obtained from AVHRR (aboard NOAA-11) data employing a satellite-based remote sensing technique that was designed particularly for monitoring boreal forest fires. Active fires and burned area are estimated. Such basic fire attributes as the area and period of burning extracted from the satellite data are compared against the ground reports made by the fire management agencies in Saskatchewan and Manitoba, Canada. The total burning area over an area of 800X700 km^2 around the study region is approximately 2 million hectares in the summer of 1994 according to both satellite and surface observations. The majority (87%) of the ground reported fires were detected by satellite that also identified some fires missed by the ground observers. Most fires in 1994 occurred in the transitional forest to the north and northwest of the BOREAS region. Regarding to the monitoring of fire evolution, the daily satellite detection approach is as effective as, or even more effective than ground observation, provided that cloud cover does not occur persistently.

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