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The development of a remote sensing based technique to predict debris flow triggering conditions in the French Alps

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Abstract. The effects of mass movements, including debris flows, on the inhabitants of mountainous regions can often be catastrophic, causing serious casualties and property damage. These impacts could potentially be reduced with the development of early warning systems. Debris flows are generally initiated by either heavy rainfall or snow melt. In the past, prediction of debris flow events has been limited to the moment of the flow onset and dependant on the accurate description of free flowing water conditions at the time of initiation. This has remained problematic not least because of the high spatial and temporal variabilities of the triggering phenomena, making their accurate measurement by conventional means, such as by raingauges, difficult.

Remote sensing data offers an ideal opportunity to provide information on debris flow triggering conditions, including details of the evolution of triggering rainfall conditions before they initiate a debris flow event. In this paper we outline the development of a remote sensing technique to provide early warning of debris flow triggering conditions using infrared data measured from the Meteosat satellite series, for the Bachelard Valley in the French Alps. The relatively simple relationship and short time interval between the onset of heavy rainfall, and the initiation, movement and deposition of a debris flow allows information on the triggering conditions to be considered as early warning of the actual debris flow event itself, in locations of known debris flow hazard. Predictive information of triggering conditions of a particular hazard is of vital importance to the development of an effective early warning system. The technique outlined in this paper was developed using the debris flow initiation model, of Blijenberg *et al*., linked to automated raingauges over a four year period from 1991 to 1994. Of the six case studies identified warning times of 1–12 hours were given in five of these. A false alarm test over a month period for the region revealed false alarms on two days, only. This paper shows that high temporal resolution remote sensing data can be used to provide early warning of atmospheric conditions likely to initiate debris flow events. This information is of importance to the development of a debris flow hazard early warning system.

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1. Introduction

Debris flows are found worldwide in mountainous environments. A form of gravity induced mass movement; they are intermediate in type between landslides and water flows (Goudie 1995). Generally initiated on steep slopes, they have been described as rapid viscous flows of granular solids, water and air, with a consistency resembling wet concrete (Varnes 1978, Goudie 1995). The initiation of a debris flow is commonly described as occurring in one of two ways. The first considers the initiation of a debris flow as the result of a landslide that steadily transforms itself into a debris flow by dilatancy or liquefaction during its movement (Johnson and Rahn 1970). The second describes the initiation of a debris flow as a sudden failure of coarse debris in a high altitude channel or gully bed (Takahashi 1981). The input, or trigger, for this later mechanism stems from either snowmelt or intense rainstorms.

The effects of debris flows are often catastrophic to the inhabitants of the regions in which they occur, causing serious casualties and property damage (Jan and Shen 1993). For instance, in 1996, a debris flow devastated a campsite in the Spanish Pyrennes killing more than 80 people. The death and economic losses due to debris flow events can be expected to increase with the projected increases in high intensity precipitation events associated with global warming (Zimmermann and Haeberli 1992). These impacts of debris flow activity could potentially be reduced with the development of an early warning system for communities living in hazardous locations. A vital compoment of any hazard early warning system is the accurate prediction of hazard triggering conditions.

Debris flows vary considerably in their size, speed and impact on the environment. Observations of past events have revealed debris flow velocities varying from $0.5\,\mathrm{m\,s^{-1}}$ to over $20\,\mathrm{m\,s^{-1}}$ (Goudie 1995). Rapid debris flows are well-known episodic features in certain parts of the French Alps (van Asch and van Steijn 1991). In this study we focus on debris flows in the Bachelard valley, south of Barcelonnette in the French Alps (figure 1). The debris flows in this area have flow paths up to 1.5 km and widths up to 10 m. Velocity of these flows has been estimated at $7–10\,\mathrm{km\,h^{-1}}$ (van Steijn *et al.* 1988). In general they are initiated by short summer precipitation events. Although presenting only a minimal threat to people in this region they provide a good opportunity to look at the provision of early warnings for debris flows in general. This particular study area was chosen because of the relatively accessible mass movement source areas, and due to the relatively high frequency of debris flows events occurring compared to a number of other debris flow-prone regions.

In the past, debris flow research has focused on developing initiation models (Johnson and Rahn 1970, Takahashi 1978, 1981, Johnson and Rodine 1984) and numerically simulating the movement and deposition processes of the flow (Shieh *et al.* 1996). In both these areas of research, prediction of debris flow events has been limited to the moment of the flow onset and dependant on the accurate description of free flowing water conditions at the time of initiation. The problems associated with this in terms of developing an early warning system for debris flow activity are threefold. First, the potential time for warning of an event is very short due to the relatively instant occurrence of the hazard phenomena upon the onset of triggering conditions. Second, precipitation and snowmelt conditions have large spatial and temporal variability's in mountainous regions and hence the accurate depiction of triggering conditions by ground based measurements such as raingauges is extremely difficult. This means extrapolation of raingauge readings is often highly

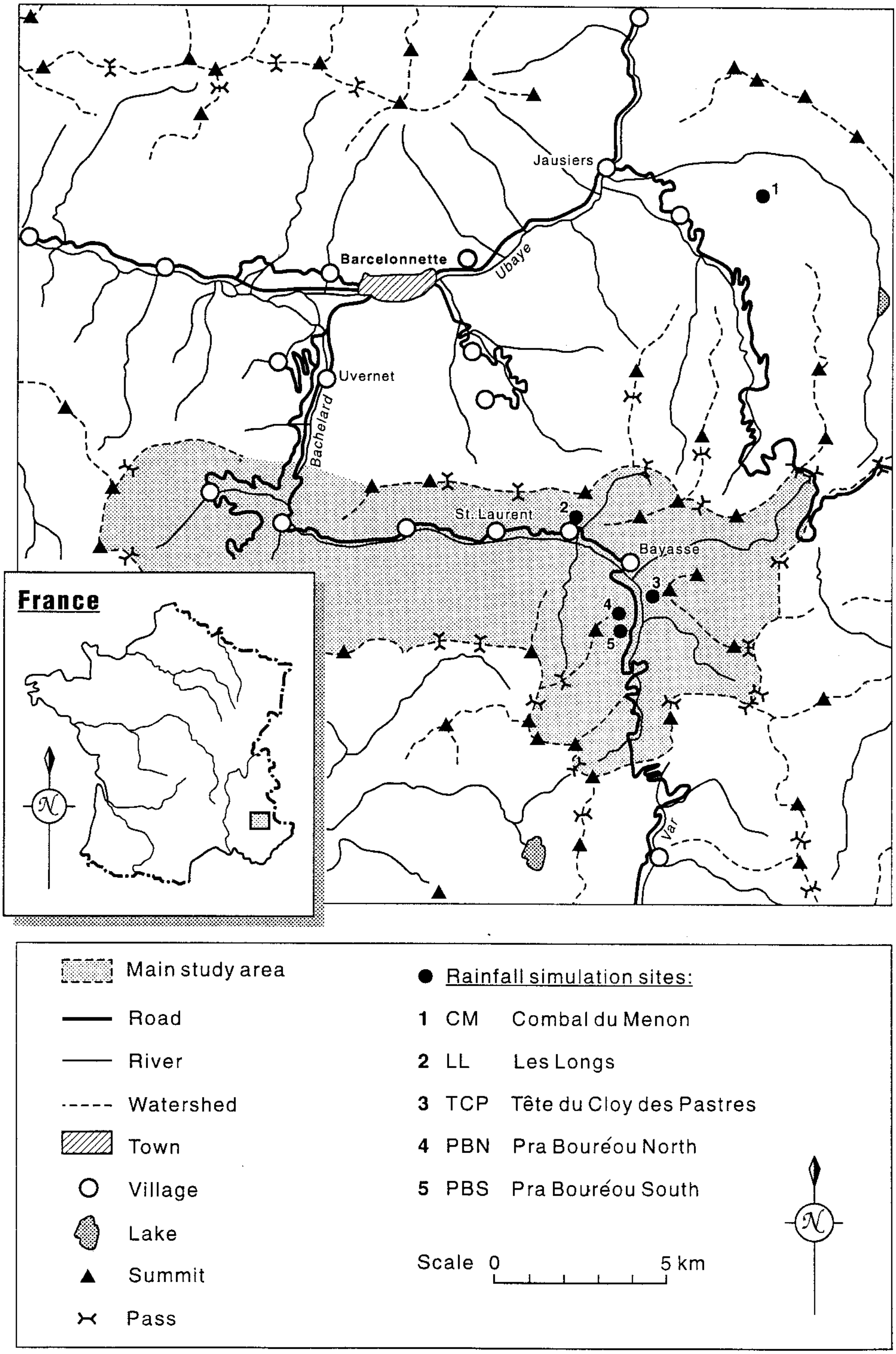

Figure 1. A map of the French Alps showing the location of the Bachelard valley and area over which the debris flow initiation model was developed (based on Blijenberg *et al.* 1996).

error prone. Third, very little is known about the precipitation conditions over mountainous terrain due to the lack of observations and insufficient theoretical attention given to the weather and climate phenomena of such regions (Beniston *et al*. 1994).

Remote sensing data offers an opportunity to provide information on local precipitation over large areas, largely irrespective of geographical location, and importantly, details of the evolution of triggering conditions before they initiate a debris flow event. Precipitation estimates derived using satellite data commonly utilises data from the infrared and/or passive microwave regions of the electromagnetic spectrum. In this paper we look at the use of infrared data measured by the Meteosat satellite series to provide information on the evolution of triggering conditions for debris flow initiation. The relatively simple relationship and short time interval between the onset of heavy rainfall, and the initiation, movement and deposition of a debris flow allows information on the triggering conditions to be considered as early warning of the actual debris flow event itself in locations of known debris flow hazard.

A key point in developing a technique for predicting rapidly evolving triggering conditions, is the identification of the exact times of the various debris flow initiation events. This information is required to assess, adapt and validate the technique and lengths of early warning possible. Not surprisingly, given the remote location of the debris flow initiation sites, or source areas, accurate measurements of these times are rarely available. In this study we obtain this information from a combination of video evidence, a debris flow initiation model linked to two raingauges and field surveys. Video evidence was derived from a video camera mounted in the debris flow source area. Unfortunately restricted to daylight hours, the camera used in this study was also limited to retrieving only the date of the flow event, and not the time. The exact time of the event was therefore obtained using a debris flow initiation model using input data from automated raingauges. Video evidence and field surveys were used to confirm that debris flow events had occurred.

2. Physiographic setting

The Bachelard valley is located 20 km south of Barcelonnette in the Alpes de Haute Provence (figure 1). The valley forms part of the stream system of the river Ubaye. One of the key denudational processes along the valley walls is the initiation of debris flows. Most debris flows originate in source areas situated at altitudes between 1900 and 2600 m. In figure 2 a debris flow source area in the Bachelard valley is shown. The lithology of these areas is of sedimentary origin. Above approximately 2000 m the sandstone of the Gres d'Annot formation is found. Underneath this formation, is an outcrop of marls and chalks from the Cretaceous period. Most source areas are located at the transition of these formations. The sandstones provide the coarse fractions, whereas the chalks and marls deliver the fine fractions for debris flow initiation (van Steijn *et al*. 1988). Vegetation in the source areas is almost entirely absent with the exception of a few grasses. Human influence in these areas is minimal.

The climate in the area of interest is characterised by both Mediterranean and oceanic influences. In terms of debris flow initiation the former is of most interest. The Mediterranean influence results in the occurrence of relatively isolated rainstorms, mainly at the end of spring and during autumn (van Steijn *et al*. 1988). According to field observations (de Graaf *et al*. 1993, Blijenberg *et al*. 1996), most

Figure 2. Debris flow source area in Bachelard valley. The dashed line delineates the source area.

debris flows are initiated during the heaviest of these rain storms in summer and early autumn. Rainfall data recorded in the valley shows a yearly precipitation of 977 mm at a height of 1660 m. As a result of orographic instability, rainfall varies significantly in the valley with an increase of precipitation expected with height.

3. The debris flow initiation model

A number of studies have linked rainfall intensity and duration with the onset of debris flows (Caine 1980, van Asch *et al*. 1991, van Steijn 1996). For this study it was decided to utilise a debris flow initiation model with the variables of slope angle and rainfall intensity (Blijenberg *et al*. 1996). This model was developed after field observations of the initiation process in the test site revealed these two factors to be the most important in describing debris flow initiation (Blijenberg *et al*. 1996). During these field observations it was noted that the initiation process commenced with the formation of microscale mudflows or microslumps. These microslumps are formed under intense rainfall conditions and provide the coarse debris material in the gully bed with the necessary amounts of fine material and water, to move. In order to investigate the complete initiation mechanism a number of rainfall simulations were carried out in the debris flow source area and an empirical initiation model developed (Blijenberg *et al*. 1996).

Rainfall simulation results from these observations are shown in figure 3. From this figure it can be deduced that a critical combination of slope angle and rainfall intensity is essential for the initiation of microslumps and debris flows. Rainfall intensities and slope angles greater than the line drawn in the diagram are taken to indicate that the conditions exist for debris flow initiation. Rainfall intensity below

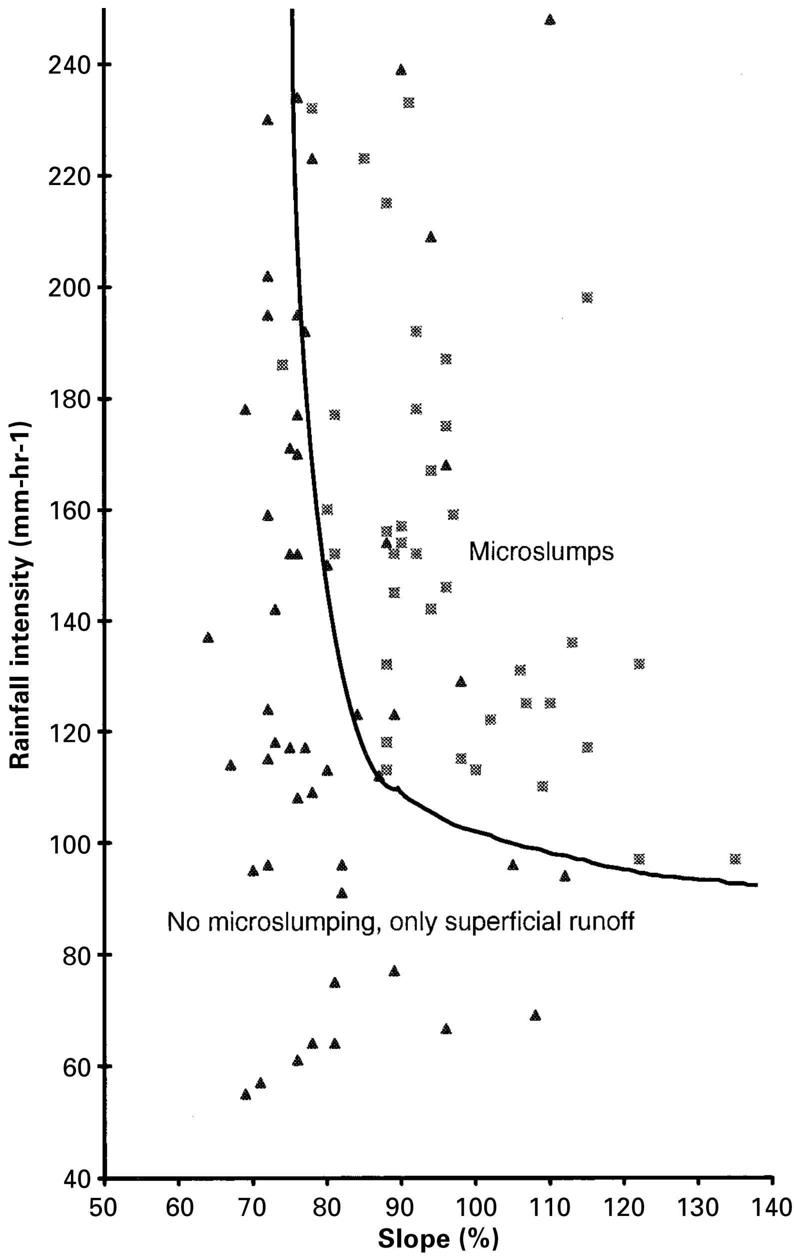

Figure 3. Rainfall simulation results from the Bachelard valley showing the occurrence of microslumps as a function of slope angle and rainfall intensity (Blijenberg *et al.* 1996).

the critical intensities needed to initiate microslumps result in either the infiltration of water into the surface or superficial runoff.

Measurements from 1991 to 1994, taken from two automated raingauges in the source area and applied to the above model, revealed the likely occurrence of nine 'very likely' debris flow events. As stated earlier, the video camera, unlike the raingauges, had no timer. In order to verify the model-derived estimations of debris flow initiation times, the readings of the raingauges had to be matched with those of the video; both sources of data recorded chronologically. The precise matching of raingauge readings with video evidence proved difficult, due to the numbers of rainfall events. However some of the cases were successfully matched and the model assumed to accurately identify initiation conditions. Of the nine events identified by the model, two cases were actually witnessed by field surveys and these were labelled 'certain' debris flow events. Footage from the video camera showed that seconds after the rainfall started, superficial runoff took place. When rainfall intensities exceeded 50 mm h^{-1} for several minutes, small pebbles were detached from the valley walls. At higher intensities, microslumps on the valley walls were observed and in the most extreme cases a debris flow was initiated. In this paper six case studies were chosen for further examination, including the two certain cases. The omission of the three other cases were made purely on the grounds of the availability of satellite data at the authors' disposal.

4. Remote sensing technique

With the exact times of debris flow initiation estimated the next step in developing the prediction technique was the application of satellite data prior to these times to identify potentially triggering rainfall conditions. For the purposes of this study infrared data from the satellite series, Meteosat was used. Data from Meteosat has a maximum spatial resolution of 5 km by 5 km at sub satellite point and samples the same Earth location once every 30 min. The data available for this study had a sampling rate of once every 3 h for 1991, and once every 2 h for the rest of the study period and a spatial resolution of approximately 8–10 km over the region concerned.

Satellite-based rainfall retrievals using infrared data rely on the indirect relationship between the cloud top temperature and surface rainfall (Rasmusson and Arkin 1992). In the past infrared-based rainfall algorithms have been used successfully to provide information on tropical and sub-tropical rainfall totals over daily and monthly time scales (Barrett 1993). At higher latitudes (poleward of latitude 45°), the use of infrared data has been generally restricted to convective meteorological conditions and occasions when the temperature of the Earth's surface is sufficiently different to that of the cloud tops. As stated in the introduction, the rationale behind using satellite data in contrast to raingauge data, was because such data can provide information on developing rainfall and cloud conditions likely to trigger a debris flow, so enabling a longer early warning time till hazard event onset.

Remote sensing data has been previously shown to be capable potentially of providing early warning information of flooding events (Barrett and Cheng 1996, Scofield and Achutuni 1996). These flood-warning techniques have concentrated on identifying relatively large rainfall events capable of delivering considerable amounts of water to areas susceptible to flooding. By contrast, debris flows in the Bachelard Valley are initiated by relatively small, intense rainfall events. The cloud conditions responsible for these rainfall events were observed to develop rapidly, with explosive growths in size and height. In developing a technique using remote sensing data to provide early warning of debris flow triggering conditions it was decided to target this rapid cloud growth stage. It was also decided that warning of potential debris flow triggering conditions would be given if target clouds were identified not just over the Bachelard Valley itself, but also around it, to allow for advection of clouds and to provide information on meteorological conditions in the region as a whole. The basis for this latter point is that some potentially triggering cloud clusters were felt to be sub pixel in size (and thus not visible in the satellite data) in the early stages of their development, but were associated with other larger cloud clusters in the area. The technique developed for this study is shown in figure 4.

The structure of the early warning technique loosely follows that of the Hierarchical Operational Procedure (HOP) of Barrett and Cheng (1996) with the above conceptual differences and associated changes in conditions. The area chosen to provide information on cloud conditions in the Bachelard Valley was denoted as

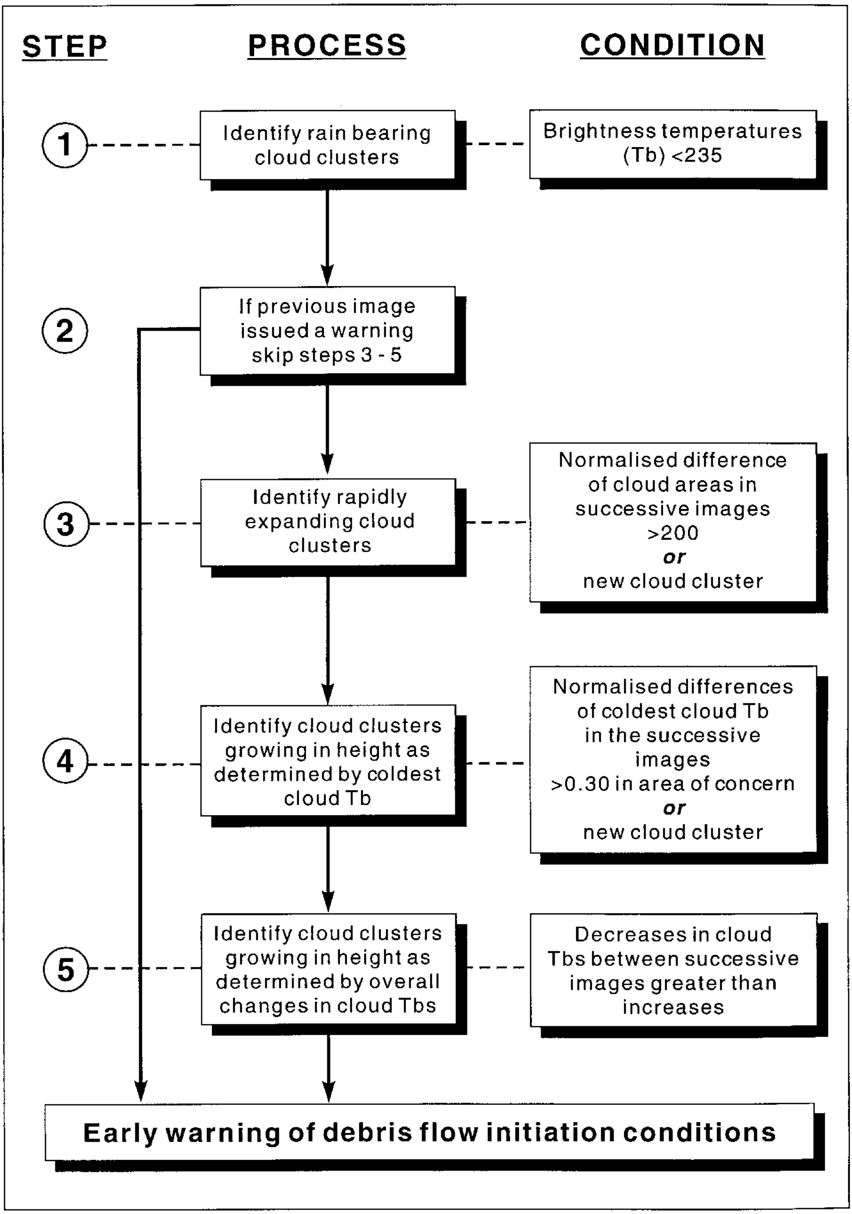

Figure 4. Outline of the remote sensing data based early warning technique for debris flow initiation conditions.

a being four Meteosat pixels either side of that centred on the Bachelard Valley. The first step in the procedure is to identify cloud clusters using a brightness temperature threshold of 235 K. The next step is activated only when a warning had been given from a previous image (i.e. potentially debris flow triggering conditions had been identified earlier), and simply by-passed steps three to five. In step three rapidly expanding cloud clusters are identified using a normalised difference of cloud cluster areas between successive images and a threshold of only accepting cloud clusters with a normalised difference of area over 200, or new cloud clusters. In step four the height of the cloud clusters are analysed and the coldest cloud cluster brightness temperature compared to that of the same cloud in the temporally previous image. Likewise, in step five the technique tries to identify changes in the height of the cloud by comparing the cloud cluster temperatures as a whole to those of the same cloud cluster in a previous images. The rationale behind developing steps three to five was that, as stated above, in the area of interest the triggering cloud types were noted from field observations to undergo extreme rapid expansion in both size and height. Warning of potential debris flow triggering conditions is assumed on the occurrence of cloud clusters fulfilling the above requirements in the area of interest.

The tracking of cloud clusters using temporal sequences of data is a complex issue, dependant on the dynamics of the cloud clusters and the time interval between samples. In this study the comparison of cloud cluster area and height occurred when cloud clusters overlapped in successive images. When such a situation didn't occur it was assumed that the cloud had evolved in the time period between images.

5. Case studies

Debris flows, although relatively common in this particular location, are still rare events. During the four years studied, the model, raingauges, video evidence and field survey revealed only nine events. Of these only the initiation times of two could be defined with total confidence. The early warning times possible from the technique developed in this paper are given for the six case studies in table 1. The initiation times of the debris flow events are taken from the raingauges and model. From this table it can be seen that the remote sensing technique provided early warning in five of the six cases. The longest warning was one of 12 h 28 min on 26 June 1994. Unfortunately, the technique failed to provide any warning for one of the cases on 5 August 1993. This was thought to be due to the temporal resolution of the satellite data used. The duration of the rain initiating the debris flow on this day was only 19 min, the lowest duration of all cases. Also shown in table 1 are the lengths of time over which the technique warns of triggering conditions (by step 2). The original

Table 1. Debris flows initiation and early warning times (in GMT).

Certain events		Very likely events		Warning start time (hours)	Warning end time (hours)	Warning length (hours)
Date	Time	Date	Time			
12 July 1991	14:07			12:33	21:33	01:34
		9 Aug 1991	05:03	21:33	12:33	07:30
		5 Aug 1993	14:15	none	none	none
		15 Aug 1993	13:38	12:33	18:33	01:05
26 June 1994	15:01			02:33	18:33	12:28
		27 Jul 1994	18:43	16:33	19:33	02:10

Meteosat image and steps one, three, four and five of the remote sensing technique for the case studies on 8 August 1991 at 21:33 GMT, and 15 August 1993 at 12:33 GMT are shown in figures 5 and 6 respectively. The target area is shown by the box. In these case studies it can be noted that, on the whole, the technique uniquely identifies cloud clusters in the area concerned before the debris flows were initiated. Cloud clusters outside this area have been largely eliminated by the various stages of the technique. In these images cloud clusters outside the area of concern have been treated the same as those inside the area. There has been no removal of cloud clusters other than indicated by the technique.

In addition to the six case studies, a month-long period from 8 August to 8 September 1993 was chosen in order to assess the number of false alarms produced by the technique. This particular period was chosen because of satellite data availability and to avoid fresh snowfall. Results from running the technique every two hours show that there were false alarms on only two days, 13 and 27 August. During the month period rainfall occurred at the test site raingauge, on seven occasions. Rainfall is likely to have occurred even more frequently in the whole region monitored, including other areas susceptible to debris flows. No note was kept of the number of cloudy days. Figure 7 shows the false alarm at 14:33 GMT on 13 August 1993.

6. Discussion

The ability of a community to live in proximity to a natural hazard, without loss of life, is dependent, in part, on the length of warning that can be given until the onset of the hazardous phenomena. Preliminary results in this paper show that remote sensing data can be used to provide early warning of triggering conditions for debris flow events in the French Alps. Of the six cases examined in this study the triggering conditions for five were correctly identified with approximately 1–12 h warning. Given the location of potentially hazardous slope conditions, derived from information on slope angle and regolith availability, this early warning information could be used to close roads and evacuate local inhabitants in locations at risk from debris flow activity. A number of methods exist for the mapping of landslide hazard zones, which would help delineate areas at risk from debris flow activity, including: the creation of landslide inventory maps (Wright and Nilsen 1974); applied geomorphological hazard mapping using aerial photo-interpretation and fieldwork (Brunsden *et al.* 1975); slope instability hazard mapping using terrain classifications (Carrara *et al.* 1977); and slope instability hazard mapping by correlation of slope inventory maps with parameter maps (Yin and Yan 1988, van Westen 1992). The choice of mapping methodology is often dependant on the availability of data and the scale of mapping required, varying from synoptic or regional scale (1:100000 to 1:250000), to large scale (1:5000 to 1:15000). In the Bachelard valley the limiting factor in terms of mapping debris flow hazard zonation are the availability of terrain data.

The landslides examined in this study have flow paths up to 1.5 km and widths up to 10 m. They are rapidly moving, reaching speeds of 7–10 km h^{-1}. The Meteosat data, by contrast, in the French Alps, have a spatial resolution of 5–6 km in an east–west direction and 8–10 km in the north–south direction, and a temporal resolution of once every 30 min. The data used in this study has a temporal resolution of once every two and three hours. In the past, remote sensing data, and in particular Earth observation data, has been restricted to the monitoring of massive landslides or the zonation of regions vulnerable to landsliding (Astaras *et al.* 1997, de Graaf

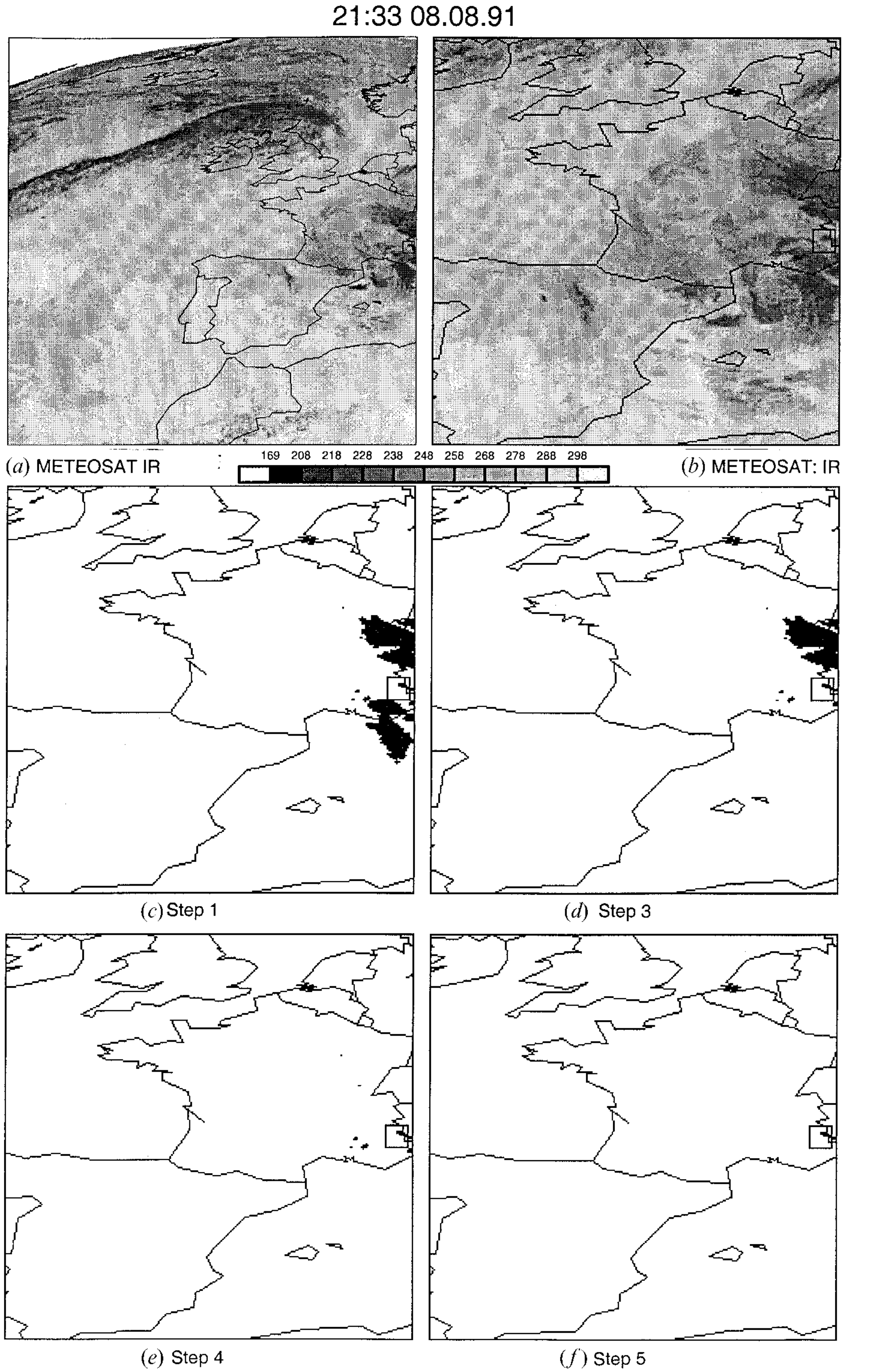

Figure 5. (*a*) Meteosat image, (*b*) subsampled Meteosat image and early warning technique results for: (*c*) step 1, (*d*) step 3, (*e*) step 4 and (*f*) step 5 for 8 August 1991, 21:33 GMT. The box highlights the area of interest.

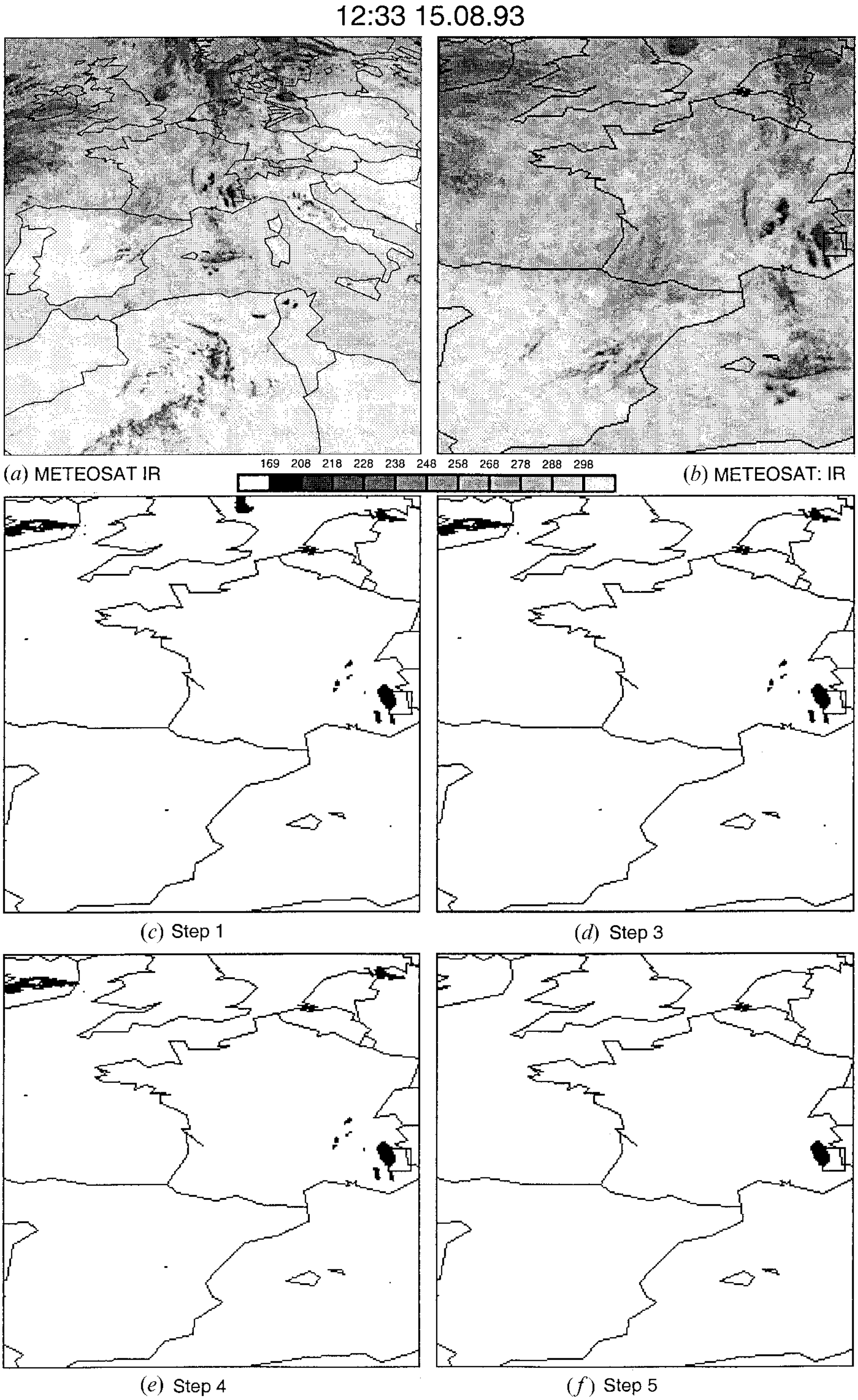

Figure 6. (*a*) Meteosat image, (*b*) subsampled Meteosat image and early warning technique results for: (*c*) step 1, (*d*) step 3, (*e*) step 4 and (*f*) step 5 for 15 August 1993, 12:33 GMT. The box highlights the area of interest.

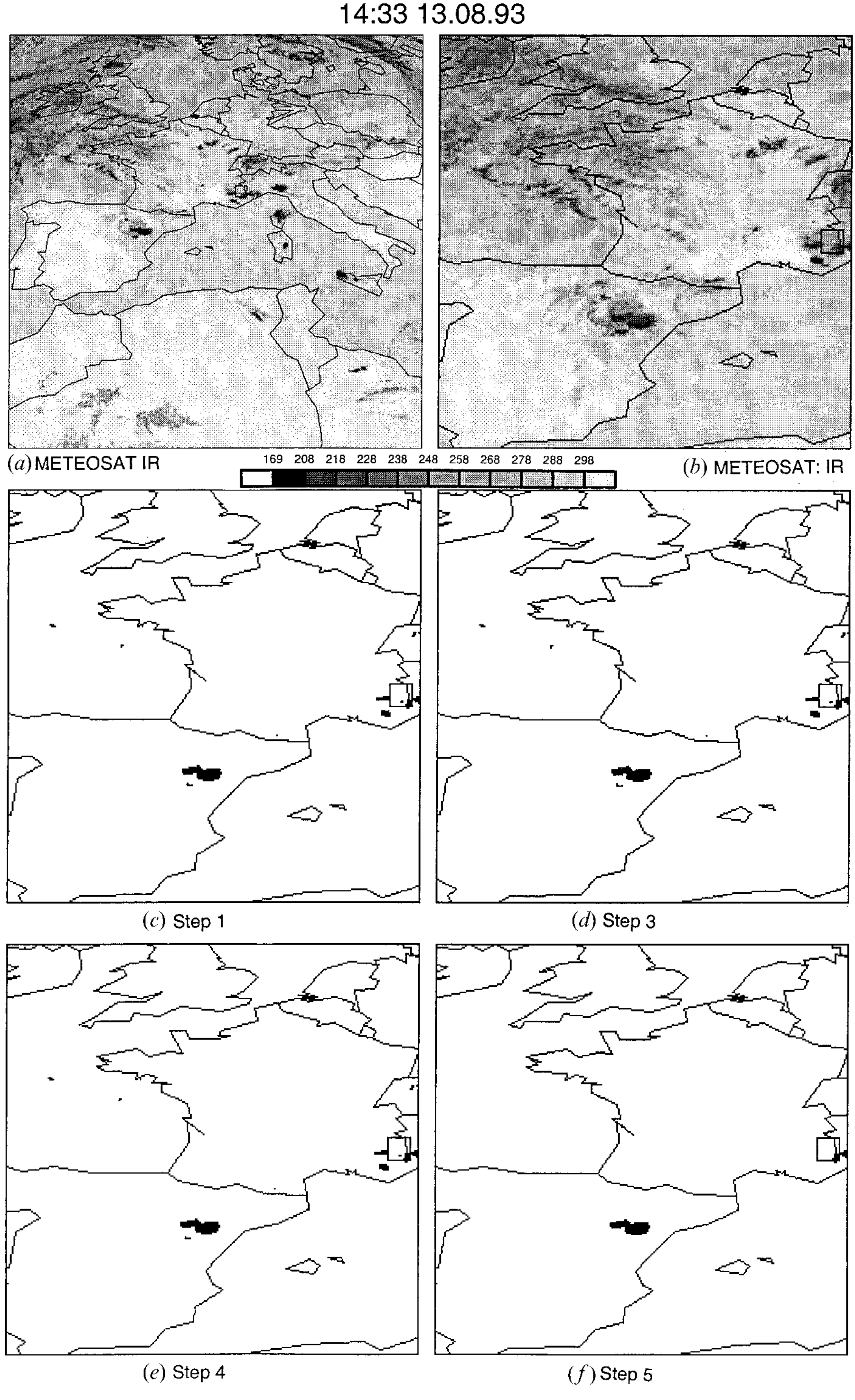

Figure 7. (*a*) Meteosat image, (*b*) subsampled Meteosat image and early warning technique results for: (*c*) step 1, (*d*) step 3, (*e*) step 4 and (*f*) step 5 for 13 August 1993, 14:33 GMT. The box highlights the area of interest.

et al. 1999). However in this study, it is the debris flow triggering conditions that are being monitored. These have lower time and space scales compared to the actual debris flows and are relatively compatible with the scales of remote sensing data used. In this technique the information provided by the satellite data on potential triggering events is derived from a vast area, some hundreds of kilometres squared, and has been related to an individual source area of less than hundreds of metres squared. The case studies have shown that the meteorological conditions necessary for the initiation of debris flows can be derived from satellite data. However, no indication can be made from this information of whether debris flow source areas in the Bachelard valley, other than the test site, also produced debris flows on these occasions. With such a technique it is therefore impossible to say which debris flow source areas will produce movements, only that the triggering conditions exist for some to occur. An increase in temporal frequency of the Meteosat data in further studies, is hoped to allow the reduction in the box size used to denote the area of interest and help differentiate which slopes might produce a debris flow at a particular time.

The use of cloud parameters to determine debris flow triggering conditions rather than rainfall estimates, although reducing the errors associated with retrieving rainfall estimates from satellite measurements, incurs errors associated with correctly and uniquely identifying the clouds that will develop heavy rainfall, over the region concerned. An indication of this error is shown by the failure of the technique to provide early warning in one of the case studies and by the false alarms in the false alarm trial run. An increase in the accuracy of this technique would be expected given higher temporal frequency remote sensing data, especially in the single case where the technique failed to identify a triggering situation and the duration of the rain event was only 19 min. Further investigations might also look at varying the size of the window considered as providing cloud information for the early warning of triggering conditions in the Bachelard valley. For instance in figure 7 it can be seen that a false alarm would have been avoided on 13 August 1993, if the western extent of the box denoting the area of interest had been restricted. It should also be noted that the use of this technique is restricted to summer time. The appearance of fresh snow might produce false alarms. Fortunately field observations have shown that the debris flow events in the Bachelard Valley are generally initiated during summer.

A number of studies have indicated that the combination of passive microwave and infrared data would improve the retrieval of rainfall parameters for flood forecasting (Boni *et al.* 1996, Barrett and Cheng 1996, Scofield and Achutuni 1996). This study has only looked at the use of infrared data due to the speed of development of debris flow triggering clouds and their small size relative to the temporal and spatial resolutions of passive microwave data.

7. Conclusion

In this paper it has been shown that remote sensing data can be used to provide early warning of debris flow triggering conditions in the French Alps. This information is vital for the development of an effective early warning system for debris flow hazards. High temporal frequency remote sensing data from the Meteosat series of satellites allows the identification of cloud clusters likely to develop intense rainfall which in turn are likely to initiate debris flow activity.

Video evidence, field observations and an empirical debris flow model linked to an instantaneous raingauge were used to ascertain the exact times of debris flow initiation. The high spatial and temporal variability of rainfall in mountainous regions and the large areas vulnerable to debris flows compared to the coverages of video and field observations means there are severe restrictions on the use of conventional surface data to provide early warning of debris flow events, over a large region. Additionally the length of early warning possible using such observations is restricted to the relatively short interval between the onset of the triggering phenomena and the hazard event. By contrast, the remote sensing technique outlined above, allows warning of potential debris flow triggering events, over large areas, to be derived before the triggering phenomenon occurs, by attempting to recognise the evolution of intense rain bearing clouds. In this role the remote sensing data is not being used to retrieve rainfall amounts but instead is used to derive raining cloud properties that produce debris flow triggering conditions.

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