Mapping the risk of forest fire occurence using NOAA satellite information

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ABSTRACT

The NDVI and the Ts evolution of 21 forest massifs in the South-East of France have been determined from March to October in 1988, 1989 and 1990 by NOAA-AVHRR satellite information. Using the inverse evolution of these 2 parameters, 5 risk classes of forest fire departure in the summer have been determined for 1990. In the Maures massif 5 classes have been mapped for 1990. This showed that periods and areas affected by the highest risk class correspond with those where the largest number of fires appeared in that year.

Key-Words : NOAA satellite data. NDVI. Surface Temperature (Ts). Forest fire risk index. Forest fire risk mapping. Mediterranean forest.

INTRODUCTION

In summer, forest fires represent an important threat to the environment in Mediterranean areas. Every year in the South-East of France, from June to September, a Meteorological Department is constituted; its duties consist of fire risk prediction and fire fighting assistance. To date, soil and vegetation conditions are only estimated from the meteorological station data and the fire departure risk is mapped by extrapolating evapotranspiration and water humidity calculated at each meteorological station. Satellite images have the advantage of covering the whole area, particularly the forests, and allow direct estimation of the condition of vegetation whose electromagnetic behaviour is modified by water stress.

Research on 21 forest massifs in the South-East of France using NOAA-AVHRR satellite images from March to October in 1988, 1989 and 1990 has been conducted. Only results for the Maures massif (divided into 2 parts, South-West and North-East) are presented here (**Figure 1**). NOAA data have a high temporal frequency and the AVHRR channels are well adapted to vegetation monitoring. The spatial resolution of the sensor (1 km^2 at nadir) is suitable for regional scale studies. A vegetation index (NDVI) and the surface temperature (Ts) have been calculated from NOAA-AVHRR data.

1. METHODS FOR CALCULATING THE VEGETATION INDEX AND THE SURFACE TEMPERATURE

1.1. Vegetation index (NDVI)

A vegetation index can be expressed by many different formulae or ratios, but the most commonly used is the Rouse *et al.* (1974) Normalized Difference Vegetation Index (NDVI).

NDVI = (NIR - VIS) / (NIR + VIS)

where NIR: Near Infra-Red and VIS: Visible.

Using the NOAA-AVHRR data

NDVI = (C2 - C1) / (C2 + C1)

where channel 1 is from 0.58 to 0.60 µm and channel 2 is from 0.72 to 1.10 µm.

It has been shown that the NDVI is well correlated with the cover density, the leaf area index (LAI), the above-ground biomass and chlorophyll activity (Tucker 1979, Sellers 1985). The NDVI varies from -1 to +1. The lowest

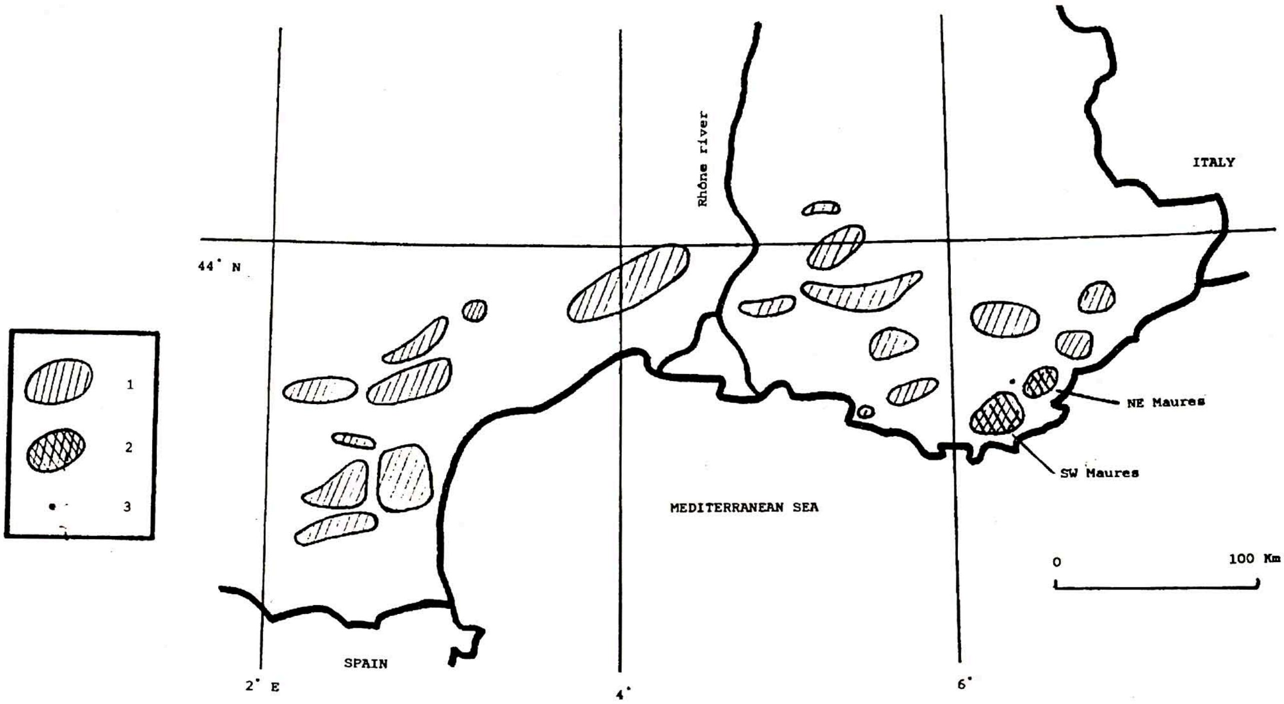


Figure 1 - Location of the Maures massif
1. Massifs studied by satellite information – 2. Maures massif – 3. Meteorological station: Le Luc

values represent either a surface without any vegetation or a senescent vegetation or a cloud. NDVI is negative for water and snow.

The 1988 images are from NOAA 9 satellite and the 1989 and 1990 images from NOAA 11. Each image, which represents a 5 day composite, has been processed by the CNES (Centre National d'Etudes Spatiales)

Several procedures have been undertaken to calculate the NDVI in 1988 and 1989. In 1989, the sensitivity of the NOAA 11 channels 1 and 2 decreased in the first months after the satellite was launched. To compensate for this degradation, a 0.06 increase in the NDVI is necessary (Holben *et al.* 1990).

The CNES decided to correct for atmospheric effects for 1990 channels 1 and 2 but not for 1988 (NOAA 9) and 1989 (NOAA 11). To compare the 1988 and 1989 NDVI values with the 1990 ones, field radiometric measures made in Crau in 1989 have been used (Santer *et al.* 1990).

$$y' = 1.18\, y + 0.09$$

where y = uncorrected NDVI and y' = corrected NDVI.

Such a correction increases the vegetation index. A similar increase has also been obtained by King *et al.* (1990) but by a different method.

1.2. Surface temperature

Surface temperature (Ts) is calculated using the thermal infra-red (NOAA channels C4 from 10.5 to 11.3 µm and C5 from 11.5 to 12.5 µm), which represents the spectral sphere where vegetation electromagnetic radiation depends on the vegetation temperature. Ts is a good indicator of the water substratum. When the substratum is well supplied with water, the solar radiative energy is partly used for evapotranspiration. Thus the top layer of the vegetation (as seen by the satellite) becomes cooler. If water is lacking, on the other hand, evapotranspiration is reduced and part of the solar energy is not lost by the vegetation. Ts therefore increases with the water stress.

There are several methods for calculating surface temperature with NOAA C4 and C5 channels. The Kerr and Lagouarde formula (1990) is used here:

$$Ts = CV * Tvs + (1 - CV) * Tss$$
$$Tss = 3.1 + 3.2\, T4 - 2.2\, T5$$
$$Tvs = -2.4 + 3.6\, T4 - 2.6\, T5$$

where Tss is temperature of bare soil and Tvs is temperature of a soil covered by vegetation; T4 and T5 are temperature extracted from the C4 and C5 channels, and CV (Vegetation Coefficient) = 2 * NDVI in 1988 and 1989 (no atmospheric corrections on channels 1 and 2).

In 1990, the atmospheric corrections made by the CNES forced us to use another value for CV (CV = 4/3 NDVI according to a personal communication from Lagouarde).

In 1988, the Ts increased by 2°C because the NOAA 9 overpass time is 4 p.m. instead of 2 p.m. for NOAA 11 in 1989 and 1990 (Courault 1991).

The most cloudy scenes have been removed from the time profiles using a simple filter which combines (for each pixel of the studied massifs) a low vegetation index and a low surface temperature.

An average NDVI and an average Ts have been computed for each date in each forest massif (averages of 341 pixels for the South-West Maures and 188 for the North-East Maures).

2. INTERPRETATION OF THE NDVI AND TS FLUCTUATIONS AS A FACTOR OF WATER STRESS

2.1. Evolution of the NDVI

The evolution of the NDVI values from March to October are very similar in the 2 parts of the Maures massif, but they are always a little higher in the South-West **(Figure 2)** than in the North-East **(Figure 3)**: their maximums and minimums are 0.72 and 0.67, 0.38 and 0.36 respectively. In a comparison between the 21 massifs studied in the South-East of France (Prosper-Laget *et al.* 1993), the Maures possess high values of NDVI and present a similar seasonal evolution to all the other massifs.

However, great differences exit between years 1988, 1989 and 1990. In 1988, the values of NDVI are low in spring and increase quickly in late spring. They reach their maximum in June in the NE. They remain high until the beginning of August, the period in which the NDVI decreases suddenly to 0.10 between 2 dates (3 August and 8 August). Its evolution resembles that of a bell-shaped curve with a maximum in early summer. In 1989, the same seasonal evolution is displayed but it happens earlier and all the maximum values are lower than in the previous year. In spring, the NDVI is high; it reaches its maximum as early as the 9th of June, then it suddenly decreases and remains stable afterwards. In 1990 the NDVI shows the same curve as for 1988 but with lower values. The NDVI increases slowly until the end of spring and remains high until the beginning of July, when it begins to decrease irregularly.

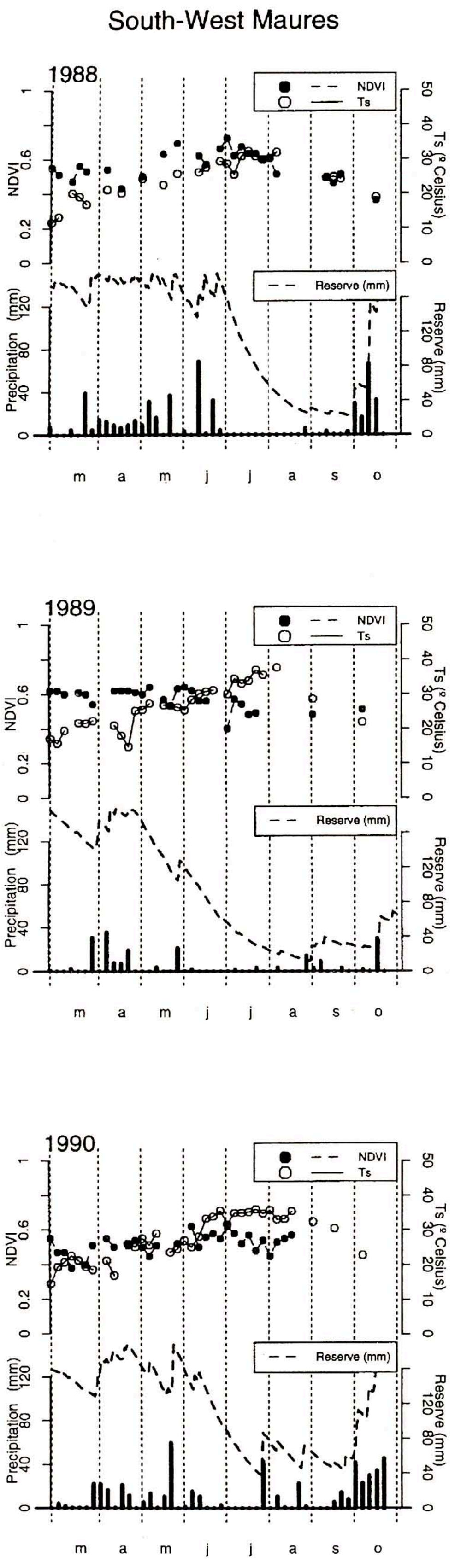
The maximum NDVI values differ depending on the year. They are higher in 1988 (0.72 in the SW and 0.67 in the NE) than in 1989 (0.64) and 1990 (0.62), even if they are, on the whole, slightly higher in the SW than in the NE.

The NDVI depends on the leaf position and expresses the photosynthetic activity of the vegetation (Tucker 1979, Sellers 1985). Low values correspond to weak photosynthetic activity caused by a number of different reasons: e.g. the inadequacy of the solar radiation or of the soil water (hydric stress), parasite attack or mineral deficit. It is known that the photosynthesis of the holm oak (*Quercus ilex* L.), a Mediterranean tree, changes according to the solar radiation and the hydric potential, which illustrates that there is hydric stress at the stomata level (Eckardt *et al.* 1977).

In the Maures, the lowest values of the NDVI which appear in early spring and in summer correspond to two different factors. They indicate the hydric stress in the latter part of the season. These low values are related to the decrease in the soil moisture retention and the length of time passed since the last rainfall. They correspond to the plant reaction which starts restricting its transpiration as early as the first or the second day following the beginning of the soil drying (Humbert 1977).

The precipitation figures used have been collected at the meteorological station of Le Luc **(Figure 2 and 3)**. This station is situated outside the massif, so the figures are not entirely representative for the Maures. In addition, the NOAA images used for the NDVI represent a 5 day synthesis which can explain the lag between rainfall and its consequences on the NDVI: precipitation occuring at the end of the synthesis period may only influence a response in the NDVI value in the following synthesis period and not in the simultaneous one.

The soil moisture retention used here has been calculated daily using Le Luc data by Météo-France (SOL 1992). In 1988, the NDVI values decrease suddenly on the 8th of August (0.51 in the SW Maures and 0.44 in the NE which are the summer minimum for the vegetation index), the corresponding moisture retention being about 35-40 mm **(Figure 2 and 3)**. In 1989, this significant decrease happens on the 4th of July (minimum summer NDVI: 0.40 and 0.37 corresponding to about 40 mm), and on the 3rd of August in 1990 (0.45 and 0.38 with a moisture retention of about 55 mm because of a better temporal distribution of the precipitation in the beginning of summer than in 1988 and 1989). The summer decrease in the NDVI indicates that the hydric stress of the vegetation occurs at dif-



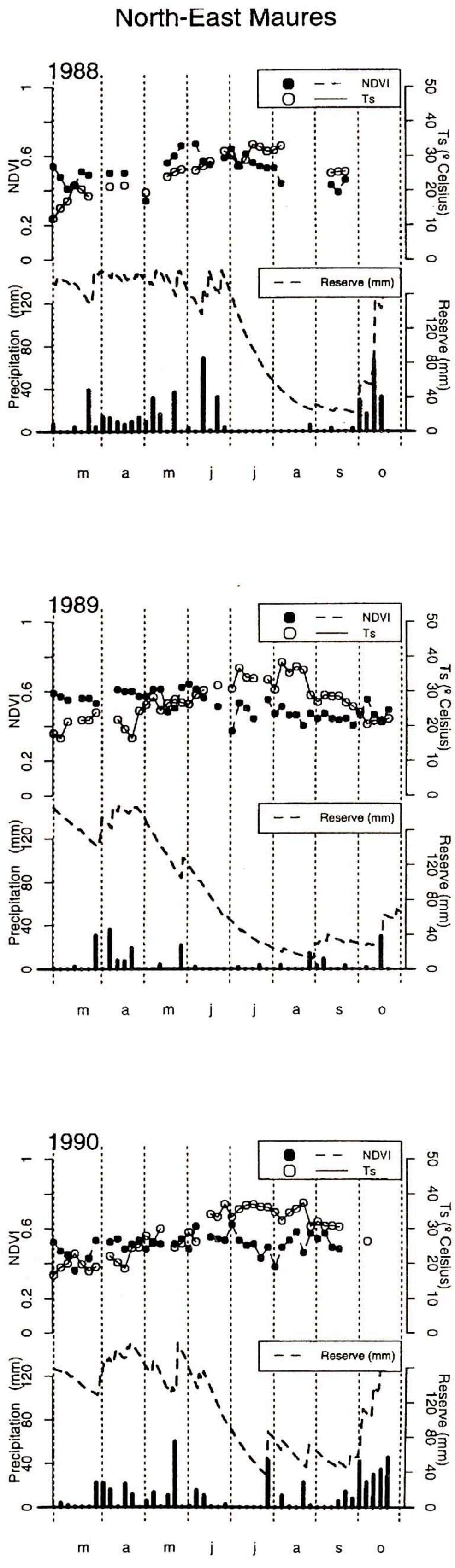


Figure 2 - NDVI and Ts evolution in the South-West Maures (from March to October)
Precipitation (histogramms) and soil moisture retention (dashed-lines) are calculated with the Le Luc meteorological data

Figure 3 - Idem Figure 2, except North-East Maures

ferent times according to the year, but always later than the initial restriction of the soil moisture retention. It only appears when the soil water deficit influences the leaf position. It is linked with interannual variability of soil water which depends on the precipitation. At Le Luc, the year 1987-88 is considered "normal" (934 mm rainfall) when compared with the mean 1951-80 (922 mm), while 1988-89 (402 mm) and 1989-90 (523 mm) are dry years as experienced throughout all Provence (Bidet *et al.* 1991).

The temporal distributions of the precipitations are also different in the 3 years. They are examples of types of summer drought, their duration and the dates of their beginning and end (Douguédroit 1992).

2.2. Evolution of the Ts

The surface temperature curves of the 21 forest massifs display a similar seasonal evolution from March to October for the 3 years from 1988 to 1990. It increases until summer and decreases in autumn (Prosper-Laget *et al.* 1993), but the summer maximums differ according to the massif and to the year. Generally speaking, the massifs with a dense vegetation have relatively low Ts whilst those with a sparse vegetation tend to have a high Ts. The vegetation is fairly dense in the Maures massif but it is thicker in the SW than in the NE where Ts is always higher **(Table 1)**:

Table 1 - Maximum Ts in the Maures in 1988, 1989 and 1990

	1988	1989	1990
SW Maures	32°2	37°6	36°0
NE Maures	33°5	38°2	37°3

However, maximum Ts is generally lower in 1988 than in 1989 and 1990, with a very small difference between the last two years (Table 1). This is connected with the quantity and the seasonal distribution of precipitation throughout the years (see 2.1.). In 1988, the soil moisture retention reaches its maximum (150 mm) in May-June and decreases in July because of the lack of precipitation in the summer. Ts in the Maures increases from 26-28°C in June to 30-33°C in July-August (Figure 2 and 3). In 1989, because of low rainfall, the soil moisture retention only attains 150 mm during a short period and decreases as early as the beginning of May. The Ts which was about 25°C at the end of April reached 29°C at the beginning of June and exceeded 30°C as early as mid-June. In 1990, the soil moisture retention keeps stable at 150 mm until the end of May because of the seasonal distribution of the precipitation which is poor but which lasts until the beginning of summer. Ts evolves as in 1989 but more slowly. Water supply to the soil produces an increase in the actual evapotranspiration (AET) which makes the heating of the soil diminish. On the contrary, without rain, the AET decreases and the soil and the vegetation become warmer.

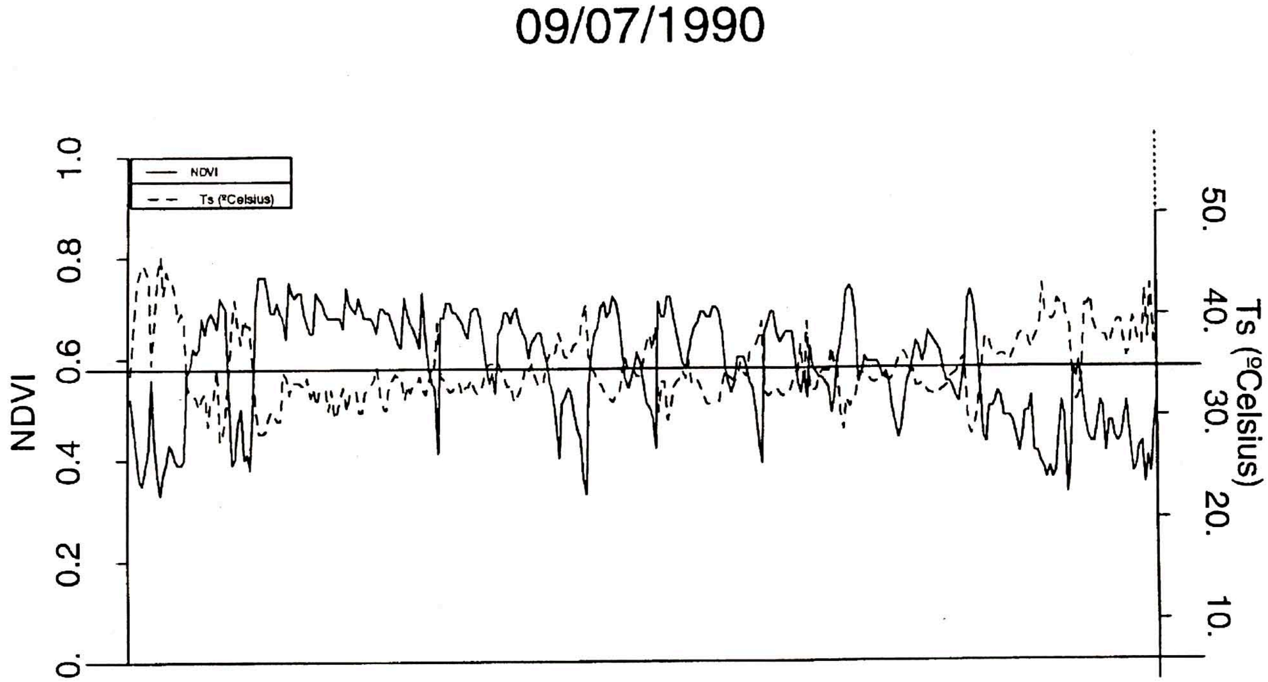
The minimum soil moisture retention appears at the end of summer in September 1988 and earlier in 1989 (August) and in 1990 (July). When rainfall is low and stops at the beginning of spring (as in 1989), the vegetation removes water from the soil earlier in the season and the moisture soil retention dries up earlier. Ts evolves in the opposite way; it increases when the hydric stress intensifies. It can show the level of drought reached by the vegetation in summer, which one can use as an indicator of forest fire risk.

3. FOREST FIRE RISK MAPPING FROM NDVI/TS RELATION

3.1. Compared evolution of NDVI and Ts

Goward *et al.* (1985) have displayed a linear relation between the HCMM (Heat Capacity Mapping Mission) satellite Ts and several vegetation indices calculated from the visible and near infra-red channels of the Landsat MSS satellite. This relation is the best when using the NDVI. King *et al.* (1990) have brought to light from the NOAA satellite data the opposite evolution between NDVI and Ts in Mediterranean forests. When Ts increases at the beginning of the summer, a few days later NDVI decreases. We have been able to check for the 21 massifs that the increase of the Ts is accompanied by a decrease in the vegetation index. The negative relationship between Ts and NDVI only exists during a hydric stress period, that is in summer 1988 and as early as the end of spring (from May) in 1989 and 1990. In a dry period, high Ts means heating of the soil due to a soil moisture deficit, which leads to a decrease in vegetation index, thus indicating that the vegetation activity is reduced.

The average values of NDVI and Ts for a massif only approximate the inverse relationship. A pixel by pixel comparison displays it better **(Figure 4)**. The values of both NDVI and Ts calculated for each pixel and computed in the same order for the 2 scenes of the 9th and 19th of July for the SW Maures illustrate this relationship. When the NDVI (the Ts) is higher (lower) than the massif average, the Ts (the NDVI) is lower (higher) than the same average. In June as in August, the same pixels (which means the same areas) have values higher or lower than the average.



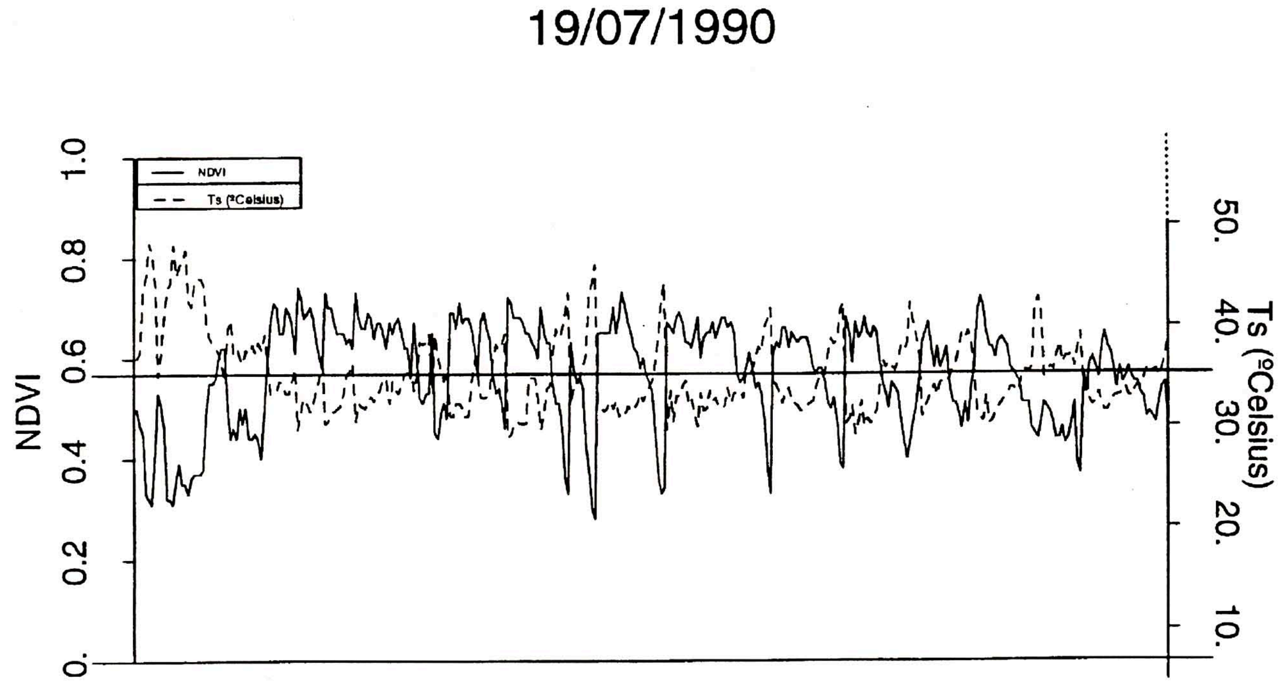


Figure 4 - Comparison between the NDVI and the Ts values of all the pixels in the SW Maures on the 9 and 19 July 1990 The horizontal line represents the NDVI and Ts averages of each day.

3.2. Elaboration and interpretation of the map of summer fire departure risk

Using 10 cloudless images for the 21 massifs from April to September 1990 (1990 being the only year without any correction of the satellite NDVI and Ts), a scatter plot made of Ts scaled values of each pixel in X axis and of the corresponding NDVI scaled values in Y axis has been computed (**Figure 5**). The NDVI and Ts values or the scaled values (SV) of NDVI and Ts are computed from the following formulae:

$NDVI = (2/255 * SV) - 1$ and $SV = (NDVI + 1) * 255/2$
$Ts = (65/255 * SV) - 10$ and $SV = (Ts + 10) * 255/65$

The scatter plot includes 28610 pixels. An orthogonal regression applied to the plot presents 80 % of explained variance on the first axis. The pixel population has been divided into 5 equal population classes (quintiles) along this axis.

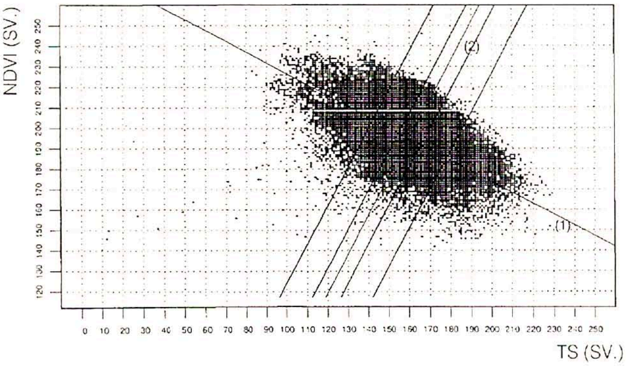


Figure 5 - Five classes of the forest fire departure risk in summer
The scatter plot is computed with all the pixels of 10 scenes from April to September 1990 for 21 massifs in South-East France (Each pixel is defined by its NDVI and Ts scaled values SV)
(1, $y = -0.528x + 279.3$ and, 2, $y = 1.892x - 107.4$

We have shown before (2.1., 2.2. and 3.1.) that an increase in Ts was the signal of the ET diminishing because of the decreasing water supply to the vegetation, and that the decrease in NDVI was the signal of the modification of leaf position due to a low water supply. The high correlation between them (80 % of explained variance) illustrates the inverse relationship. All the values of each pixel of the 10 scenes for the 21 massifs have been divided into 5 classes corresponding to the 5 quintiles. The first class (first quintile) links the lowest Ts values to the highest NDVI ones. The fifth class (quintile n°5) links the highest Ts values to the lowest NDVI ones. That classification from 1 to 5 represents classes of increasing water deficit of the vegetation and increasing soil moisture deficit. Therefore it can be considered as a classification of the risk of summer forest fire departure in the Mediterranean areas.

Ten maps of the 5 classes in the Maures massif between April and September 1990 show the spatial and the temporal evolution of fire risk (**Figure 6**). The first class is well represented at the beginning of spring but is less significant in May and in September. The fifth class is not important before July. It can be seen that the spatial distribution of the classes has the same relative order on the 10 scenes. The NE is always represented by lower risk classes compared to the SW. In the SW the West and the

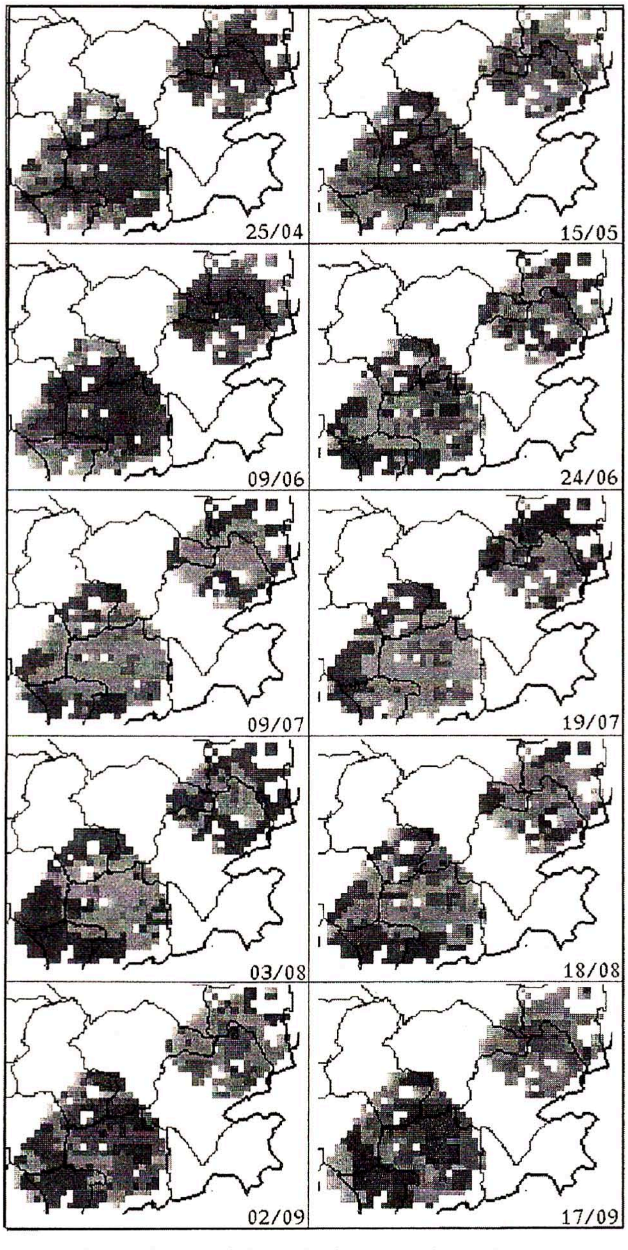


Figure 6 - Evolution of the risk of summer forest fire departure in the Maures from April to September 1990
The date on each map indicates the first day of the 5 day NOAA synthesis.
class 1, blue, no risk; class 2, dark green, low risk; class 3, light green, medium risk; class 4, orange, high risk; class 5, red, very high risk.

South higher risk classes are always present – generally higher than the rest of the massif.

3.3. Validation of the mapping: Study of the fires in the Maures in 1990

The stocklist of the fires for each district of the Maures in 1990 (number of departures and burnt surfaces) has been established by the Centre de Traitement de l'Information of the Conseil Général of the Bouches-du-Rhône, which has conducted since 1973 a statistical inventory of all the fires in the South-East of France (Opération PROMETHEE).

The Maures massif, as it has been delimited on NOAA images, is divided into 14 districts. In 1990, fire departures happened in the outlying districts where the risk appears important on the maps of the NDVI-Ts correlation **(Figure 6)**. In April, a lot of fire departures happen but no important fire has expanded (12 departures in SW and W districts, but only 4.8 ha burnt). As in the "departement" of Alpes Maritimes, the "departement" of Var in which the Maures massif is located, a relatively high number of winter fires occur but they do not spread to large surfaces in the spring because of the high soil moisture content. We can see on the maps that the high risk classes (4 and 5) are not represented in April. The NDVI-Ts index is suitable only for the summer months which is the period when NDVI and Ts have the strongest inverse relationship.

The surface of the high risk classes increases unequally after April. On the 9th of June, it occupies a smaller surface than on the 15th of May. The fire risk has diminished as 87 mm of precipitation fell at Le Luc between these 2 dates. As a consequence, Ts is cooler in the beginning of June than in mid-May because AET has increased as has the NDVI due to the development of photosynthetic activity. The high risk classes (4 and 5) occupy their most important surface from the end of June to the end of August. The fifth class is most developed by the end of June and in August, which corresponds to the largest numbers of fires **(Table 2)**.

It can be seen that fires began in the outlying districts of the Maures where the highest risk has been computed and at the dates when the class 5 (highest risk) occupies large surfaces **(Table 2)**. Mapping therefore identifies fire risk locations and dates. The number of fire departures reveals the importance of vegetation drought and therefore the fire risk. It only depends on the previous climatic conditions. As for the burnt surfaces, they vary according to the actual climatic conditions (such as the wind speed) but also to the action of humans and fire fighting equipment. The risk of fire spread is better predicted by a special index which is linked more to the instantaneous climatic and fire fighting conditions and to the ability of vegetation to burn.

The large fire which began on the 21st of August in Collobrières district spread towards the South and West and burnt 9600 ha **(Table 2)**. The burnt area can be identified on the maps **(Figure 6)** because another study has delimited its location using a SPOT image (Puech *et al.* 1991). In September, the diagonal NW-SE of class 5 in the SW Maures massif does not represent an area of the highest risk but the scar of the fire. Ts are high on black soils and the NDVI is low because there is no vegetation. The trace of the large fire starting from the Vidauban district in the NE of the Maures on the 21st of September **(Table 2)** does not appear on the maps which stop at this date.

CONCLUSION

The inverse correlation between the summer satellite-derived NDVI and Ts of a lot of Mediterranean forests in France, and the division of the scatter plot into 5 classes allow mapping of the forest fire departure risk in summer which can be considered as fitting the risk after an *a posteriori* control. The areas and dates computed as belonging to the highest class risk in the Maures massif in 1990 correspond with those of the most important numbers of fire departures in that year. A similar study will be carried for other years in the Maures and in 21 other massifs of the South-East of France to test the robustness of the NDVI-Ts inverse relation in summer and of the fire risk reparti-

Table 2 - Fire departure numbers and burnt surfaces in the Maures districts from April to September 1990. (Totals are carried to the end of each synthesis)

	from/ to:	01/04 29/04	30/04 19/05	20/05 13/06	14/06 28/06	29/06 13/07	14/07 23/07	24/07 07/08	08/08 22/08	23/08 06/09	07/09 21/09
departures	fires < 100 ha	12	6	5	2	7	2	8	9	8	5
	fires > 100 ha	0	0	0	1	2	0	0	1	0	2
burnt surface (ha)	fires < 100 ha	4,8	0,7	41,7	3,6	55,5	3	5,1	8,1	0,8	70,8
	fires > 100 ha	0	0	0	150	904	0	0	9600	0	11812

tion. It is the first step towards a possible use of such risk mapping for monitoring forest fire risk.

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REFERENCES

Bidet, Choisnel, de Neuville, Giorgetti, Grigner, Jacq, Martin, Navarre & Soude, 1991, *2 années de sécheresse en région Sud-Est et Corse*. SMIR/SE Météo France, n.p.

Courault D. & Fischer A., 1991, *Développement des actions visant à approfondir les possibilités d'application opérationnelle des satellites NOAA-AVHRR au suivi agroclimatique des cultures à l'échelle de la CEE.* Contrat INRA-CCR n°4223-9D-12 ED ISP F, Rapport Intermédiaire, n.p.

Douguedroit A., 1992, Sécheresse et incendies de forêts en région méditerranéenne française. *Analyse spatiale quantitative et appliquée*, **32**, 169-176.

Eckardt E., Berger A., Methy M., Heim G. & Sauvezon R., 1977, Interception de l'énergie rayonnante, échanges de CO2, régime hydrique et production chez différents types de végétation sous climat méditerranéen. *Les processus de la production végétale primaire*, MOYSE A. ed., 1-75.

Goward SN., Cruickshanks GD. & Hope AS., 1985, Observed relation between thermal emission and reflected spectral radiance of a complex vegetated landscape. *Remote Sensing of Environment*, **18**, 137-146.

Holben BN., Kaufman YJ. & Kendall J.D., 1990, NOAA 11 visible and near infra-red inflight calibration. *International Journal of Remote Sensing*, **11** (8), 1511-1519.

Humbert J., 1977, *Contribution à l'étude des transferts hydriques dans le système sol-plante-atmosphère*. Thèse de 3[e] cycle, mention Ecologie, Université L. Pasteur, Strasbourg, 194 p.

Kerry Y., Lagouarde J.P., Imbernon J. & Bègue A., 1990, *Suivi agroclimatique des cultures en zone sahélienne à partir des données NOAA de Mas Palomas*. Rapport final du projet CEE "Désertification", Commission des Communautés Européennes, n.p.

King C., Gouyet JF., Julien JP., Legleau H., Malon JF., Phulpin T. & Valette JC., 1990, *Apport des données satellitaires NOAA-AVHRR dans le suivi de la végétation forestière*. BRGM, INRA, METEO FRANCE, R30903: 40 p. et annexes, R35517: 51 p.

Puech C., Lavabre J. & Martin C., 1991, *Les feux de forêts de l'été 1990 dans le massif des Maures: Cartographie à l'aide de l'imagerie satellitaire, Premières conséquences sur le cycle hydrologique, Recherches sur les phénomènes d'érosion.* Groupement d'intérêt scientifique Réal Collobrier, CEMAGREF, CNRS, 12 p. + cartes et figures.

Prosper-Laget V., Douguedroit A. & Guinot JP., 1993, Evaluation par télédétection satellitaire de la sécheresse du sol en région forestière méditerranéenne. *Publications de l'Association Internationale de Climatologie*, **6**, pp. 141-150.

Rouse, Haas, Schell, Deering & Harlan, 1974, *Monitoring the vernal advancement of retrogradation of natural vegetation.* NASA/GSFC Type III, Final Report. Greenbelt MD. 371 p.

Santer R., Deuze J.L., Devaux C., Vermote E., Guyot G., Gu X.F., VerbruggheE M. & Leroy M., 1990, SPOT calibration on the test site "La Crau", France). *5[e] Colloque International ESA, "Mesures physiques et Signatures en télédétection", Courchevel*, pp. 77-80.

Sellers, 1985, Canopy reflectance, photosynthesis and transpiration. *International Journal of Remote Sensing*, **6** (8), 1335-1372.

Sol B., 1992, Incendies de forêts dans le Sud-Est de la France: le point sur l'estimation de la sécheresse du sol. *Note de travail SMIR/SE* n°9, 29 p.

Tucker CJ., 1979, Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sensing of Environment*, **8**, 127-150.