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A SIMPLE MODEL FOR THE STUDY OF THE ALTITUDINAL RAINFALL GRADIENT, APPLIED IN THE TYROLIAN OROGRAPHIC COMPLEX

UN MODÈLE SIMPLE POUR L'ÉTUDE DU GRADIENT OMBRIQUE ALTITUDINAL : APPLICATION AU COMPLEXE OROGRAPHIQUE TYROLIEN

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Summary : The variations of rainfall in a chain of mountains depend on the altitude and also on the sheltered effects inherent in orographic complexes. Gams (1932) has proposed a method which eliminates the effects of altitude in order to allow the comparison of the degree of continentality of stations which are situated at different altitudes. This degree of continentality is expressed by an index which has a cotangent equal to P/A (P = average annual rainfall in mm, A = altitude in meters). This method was applied by Richard (1985) to the whole Alpine chain and allowed a better understanding of the influence of continentality on the distribution of the important alpine forest species.
The domain of validity of this method is nevertheless limited to the mountain belt, that is to say approximately between 900 and 1600 m. Indeed beyond these limits, the increase of rainfall with altitude is no longer linear and the Gams angles diminish at low altitudes and increase at high altitudes. Thus Michalet (1991) has proposed a modified index allowing the application of the method at low altitudes. At high altitude the climatic stations are generally rare over 1600 m. So we have chosen the Tyrolian orographic complex, which is well provided in stations situated at high altitudes, to create a new modified index allowing the generalization of the method at such altitudes. Also this research allows us to propose a model of the altitudinal rainfall gradient and in this way to estimate, with a low and quantified degree of error, the rainfall of the different Tyrolian summits, whatever their degree of continentality should be.
Also a cartographic application of this index is proposed for two seasons in order to separate the real effects of continentality during winter from those of aridity during summer. Finally the biological interest of the method is shown with some examples concerning the main forest species of the area.
Key words: Altitudinal rainfall gradient, continentality, aridity, Alpine chain, Tyrol, mountain trees

Résumé : Dans les massifs montagneux, les variations de pluviométrie dépendent soit de l'altitude, soit des effets d'abris inhérents à tout complexe orographique. Gams (1932) proposa une méthode permettant d'éliminer les effets de l'altitude afin de pouvoir comparer le degré de continentalité de stations situées à des altitudes différentes. Ce degré de continentalité est exprimé par un indice qui a pour cotangente le rapport P/A (P = pluviométrie annuelle en mm et A = altitude en mètres). Cette méthode fut appliquée par Richard (1985) à l'ensemble de la chaine alpine et a permis une meilleur compréhention de l'influence de la continentalité sur la distribution des principales espèces forestières.
Le domaine de validité de cette méthode est néanmoins limité à l'étage montagnard, c'est-à-dire approximativement entre 900 et 1600 m d'altitude. En effet au delà de ces limites, l'accroissement de la pluviométrie avec l'altitude n'est plus linéaire et les angles de Gams diminuent à basse altitude, et augmentent à haute altitude. Michalet (1991) a proposé un indice modifié autorisant l'application de la méthode à basse altitude. Les stations climatiques sont généralement rares au dessus de 1600 m ; aussi nous avons choisi le complexe orographique tyrolien, bien pourvu en stations de haute altitude, pour créer un nouvel indice modifié permettant la généralisation de la méthode à de telles altitudes. Cette recherche nous permet également, de proposer une modélisation du gradient pluviométrique altitudinal et dans cet esprit d'estimer, avec un faible et quantifiable degré d'erreur, la pluviométrie des différents sommets tyroliens.
Par ailleurs une application cartographique de cet indice est proposé pour deux saisons, permettant de différencier les réels effets de la continentalité, durant l'hiver, de ceux de l'aridité, durant l'été. Enfin l'intérêt biologique de la méthode est démontré à l'aide de quelques exemples concernant les principales espèces forestières de la zone.
Mots clès: Gradient ombrique altitudinal, continentalité, aridité, chaine alpine, Tyrol, forêts de montagne

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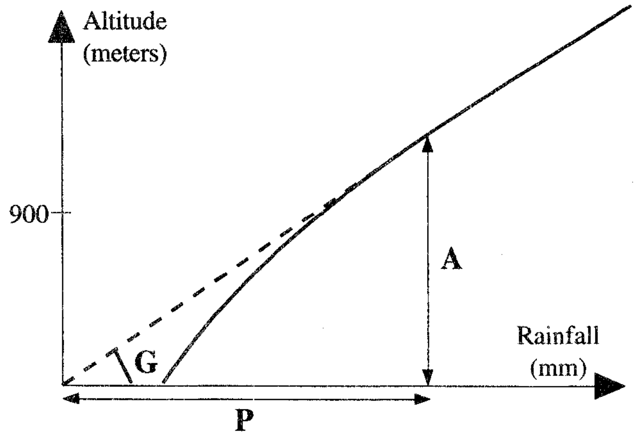
INTRODUCTION

The spatial variations of rainfall are very important in orographic complexes and research on impacts of climatic change on ecosystems needs a good knowledge and explanation of these spatial changes. They can be explained by three facts :

the increase of rainfall with increased altitude.

the sheltering effects which decrease rainfall towards the axis of the massifs.

the geographical position of the massifs conditionning the seasonnal distribution of rainfall.



The full curve shows the real increase of rainfall (with increased altitude) in a certain mountain and the dashed line shows the modified curve which is created under 900 m by the modified index, to make values comparable at all altitudes.
Figure 1 - The index of hygrometric continentality :

if A>900m : cotg G = P/A (Gams 1932)

$$\text{if } A<900\text{m} : \text{cotg } G = \frac{P - \frac{900-A}{100} \cdot \frac{P}{10}}{A} \quad \text{(Michalet 1991)}$$

The two last variations are not dependant on altitude; to follow and explain them, it's important to be independant of the altitudinal effect. Gams (1932) proposed in this way a method which allows the comparison of the rainfall of alpine stations independently of their altitudinal position. The stations are characterized by their altitudinal gradient of rainfall, expressed by an index which cotangent is equal to P/A (figure 1).The method was applied to the whole Alpine chain by Ozenda (1966, 1981) and Richard (1985) and to the Pyrenees by Izard *et al.* (1985). At first the domain of validity of this method was limited to the altitudes of the montane belt, that is to say approximatively between 900 and 1600 m. Due to the fact that the increase in rainfall with increased altitude is only linear between these limits, beyond them Gams indices become lower and lower at low altitudes (under 900 m) and increase at high altitudes (over 1600 m). Michalet (1991a, 1991b, 1993) proposed a modified index allowing the application of the method at low altitudes (figure 1). We have chosen the Tyrolian orographic complex, containing many stations with high altitudes, to propose another modified index, allowing the application of the method over 1600 m.

We will present, in the first part of this paper the results and the climatic applications of the modification of the index, in the second part a cartographic application of seasonnal Gams indices in the Tyrolian massif and finally some biological applications of the method.

THE MODIFICATION OF THE GAMS (1932) INDEX AS A MODEL OF THE ALTITUDINAL RAINFALL GRADIENT

When he modified the Gams index at low altitudes in the Moroccan mountains, Michalet (1991b) showed that the curve of decrease in rainfall with decreased altitude under 900 m diverges from the linear curve proportionally to the rainfall of the station and inversely proportionally to its altitude, as shown on figure 2. So to obtain the equivalent Gams angle for the equivalent altitudinal rainfall gradient, you must subtract from the rainfall of the station a quantity of rainfall which is dependant on both the rainfall and the altitude, as you can see in the modified formula (figure 1).

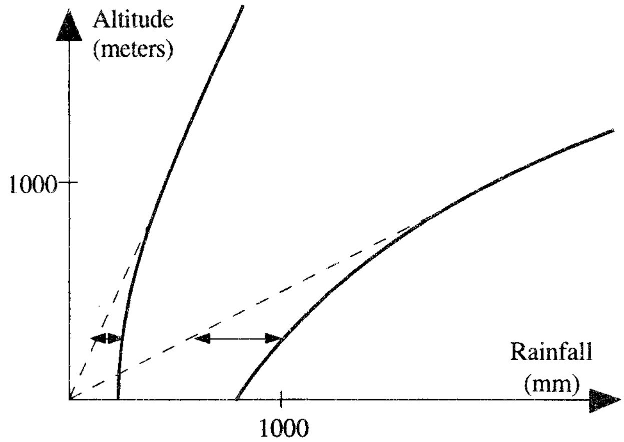


Figure 2 - Importance of the gaps between the two curves (real curves in full line and modified curves in dashed line) for two different gradients of increase of rainfall with increased altitude.

This modified index was validated for many stations in Morocco (Michalet, 1991a) and in the southern part of France (Pache, 1991). For the higher altitudes it is very difficult to find a new modified index in these countries where stations are very rare over 1600 m. In contrast in the Tyrol (Fliri, 1975) there are around 900 stations, 150 of them situated between 1600 and 2900 m. Also this part of the Alpine chain is very interesting for the study of the sheltering effect because of its thickness which determines important variations of rainfall (figure 3). Furthermore there are many vegetation maps for the study of the biological correlations.

The method used for the modification of the Gams index and thus the modeling of the altitudinal rainfall gradient, is simple and empiric but its validity was at last tested in other massifs. The method of validation consists of finding again the rainfall of real stations at high altitudes using only the altitude of these stations and the average Gams angle of the surrounding lower stations. This validation was carried out for various high altitudes and rainfalls.

At first we carried out for Tyrol a map of the classic Gams index where there are many anomalies for the stations at high altitudes which are characterized by higher indices. The extent of these anomalies is proportional to the altitude

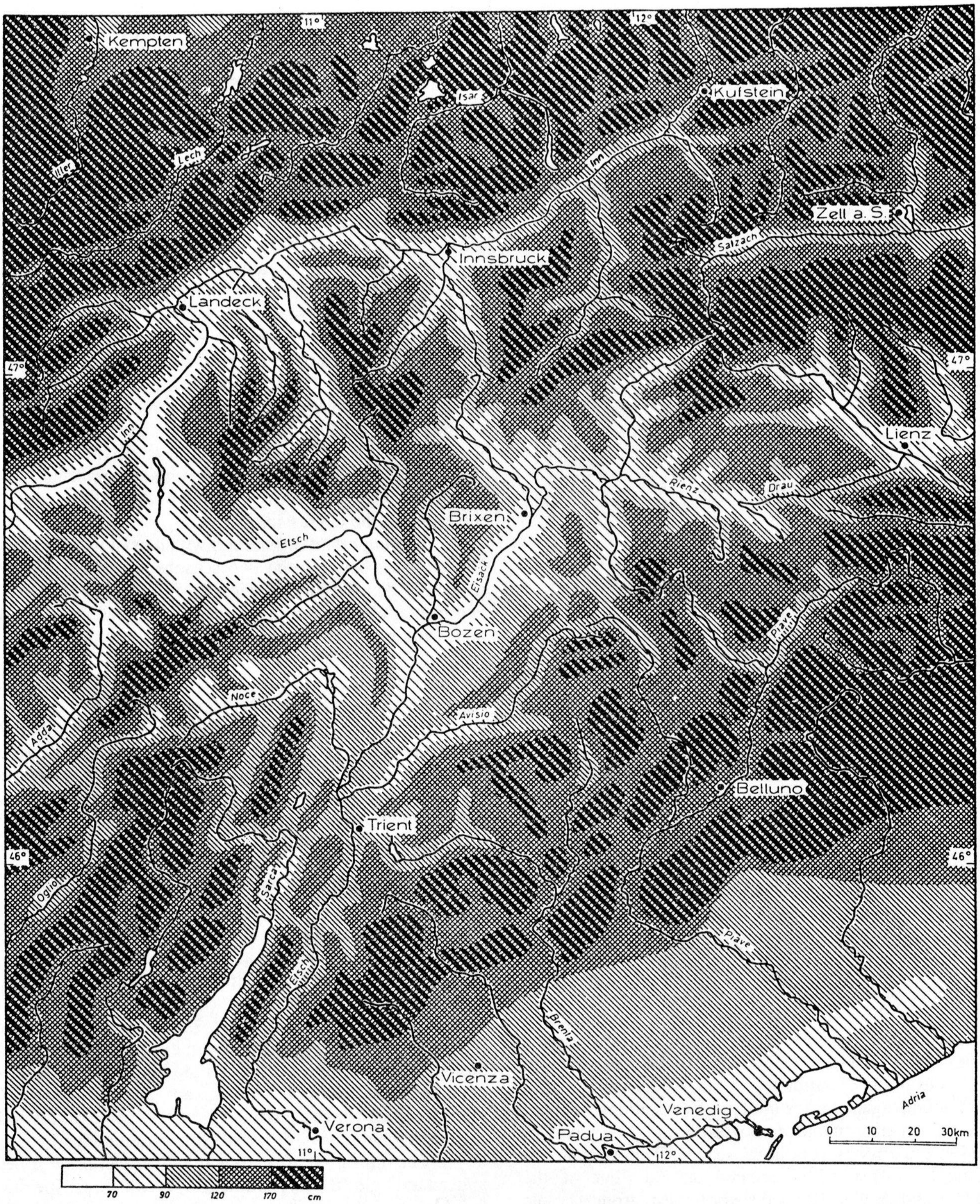


Figure 3 - Annual average of rainfall in Tyrol (from Fliri, 1975).

and the rainfall. Consequently we tested a preliminary new formula which uses the exact opposite modification to the one used at low altitudes. The validation trials revealed that the modification was too strong, showing that the gap between the real curve of increase in rainfall with increased altitude and the linear curve was smaller than the gap between the curves at low altitudes. Finally we find this new index:

$$\text{cotg } G = \frac{P + \dfrac{A-1600}{100} \cdot \dfrac{P}{20}}{A}$$

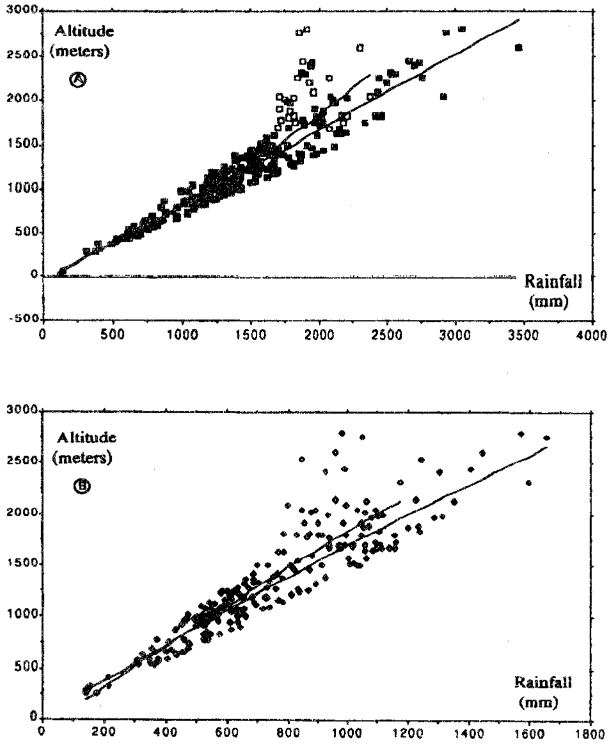


Figure 4 - Polynomial regressions showing the increase of rainfall with increased altitude in Tyrol for two categories of Gams indices (A : 35-45°, B : 55-65°). The real rainfall is in black and the modified one in white).

The figure 4 shows in polynomial regressions the extent of the gaps which exist between the two curves for two categories of Gams indices (35-45 and 55-65) and the figures 5 and 6 show in linear regressions the influence of the modification on the linearity of the curves for the same categories (see the different R-squared). We also give in figure 7 an example of validation in the Valese valley where we have found again the rainfall of five stations at high altitude with an error included between 2 and 8 % ; but for one station the error is very high : 35 %. This station, col du Grand Saint-Bernard is situated on the ridge of the Valese alps and receives from the north-west strong oceanic influences along the range ridge between France and Switzerland. So the reference stations should not be nearest ones situated in deep and sheltered valleys (58°) but those situated in the same flux as Martigny (45°).

We can conclude that our modification is valid (until around 3000 m) but the connected modelisation (using the formulae of the curves in figure 5 and 6) must be used with care in complex massifs like the western ridge of the Valese Alps.

THE CLIMATIC MAPS

We have realized two seasonnal maps of the Gams indices :

- a summer map (figure 8) which could emphasize the aridity of a climate for important indices.
- a winter map (figure 9) which could individualize stations characterized by an important hygrometric continentality (low winter rainfall) or by an hygrometric oceanity (important winter rainfall).

On these two maps you can see the influence of the sheltering effects which cause a strong decrease in rainfall towards the axis of the chain, independantly of the altitude of the stations. Generally the altitudinal rainfall gradient appears quite homogenous for each massif but there are some complex areas like in the Otzaler Alpen between the Inn and Etsch valleys ; in this massif, as in the Valese Alps, the gradients are very different inside the deep valleys and on the ridge of the mountains. On the contrary in the midle Etsch valley, between Bozen and Meran, the gradient is higher than the one of the surrounding summits. These differences are due to the orientation of the valleys regarding the origin of the depressions.

The important differences which exist in the values of Gams indices between the two seasons are connected to the seasonnal distribution of rainfall of the Central Alps; in continental climate the inner areas are charaterized by very high winter Gams indices (65-85°) while summer is still relatively wet, with Gams indices around 50°. On the contrary in oceanic and submediterranean climates like in the south part of the western Alps (French Alps) the inner areas are characterized by important summer Gams indices (60-70°) while winter is not too dry with Gams indices around 50° (Pache, 1991). These differences do not appear in the classic maps of annual Gams indices (Richard, 1985) where all the inner Alps seem homogenous with indices around 60°.

THE BIOLOGICAL APPLICATIONS

The annual Gams index has been used for many biological correlations such as the absence of beech-forest in the inner Alps or on the contrary the abundance of larch or scots pine-forests in the same "continental valleys" (Gams, 1932, 0zenda, 1985). We have shown in previous work (Pache *et al.*, 1995) the difficulty in explaining the complex biological composition of the whole Alps with only a few climatic correlations based on an annual index. The precedent maps have shown that a certain value of this index can correspond to very different climatic situations.

The utilisation of seasonnal indices can bring a better understanding of the distribution of several forest species in the Alpine chain. We have shown (Pache *et al.*, 1995) the importance of the degree of hygrometric continentality for two species. Fir is absent from the poles of continentality (winter index above 65°) and on the contrary larch is absent from the most oceanic massifs (winter index less than 45°).The degree of summer aridity can explain the ditribution of spruce which is very rare and only located at

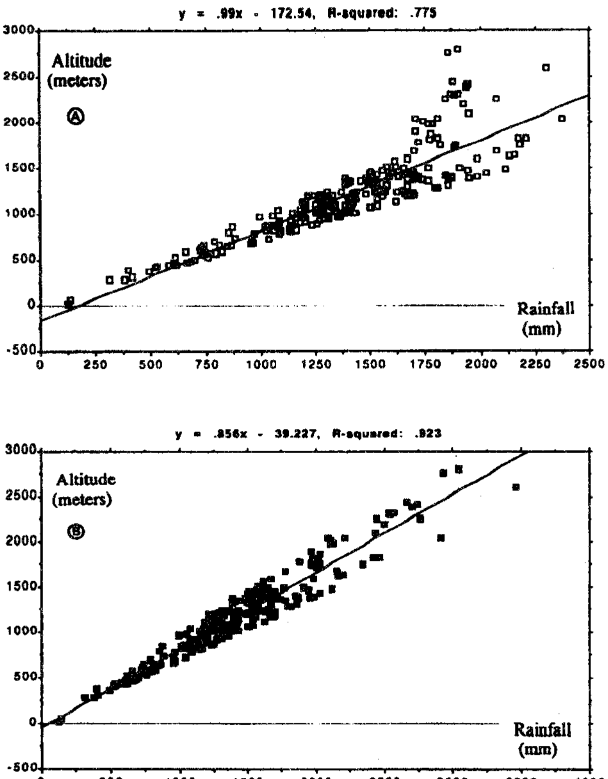


Figure 5 - Influence of the modification of the Gams index on the linearity of the curves of increase of rainfall with increased altitude for the 35-45° Gams domain (A : real rainfall, B : modified rainfall).

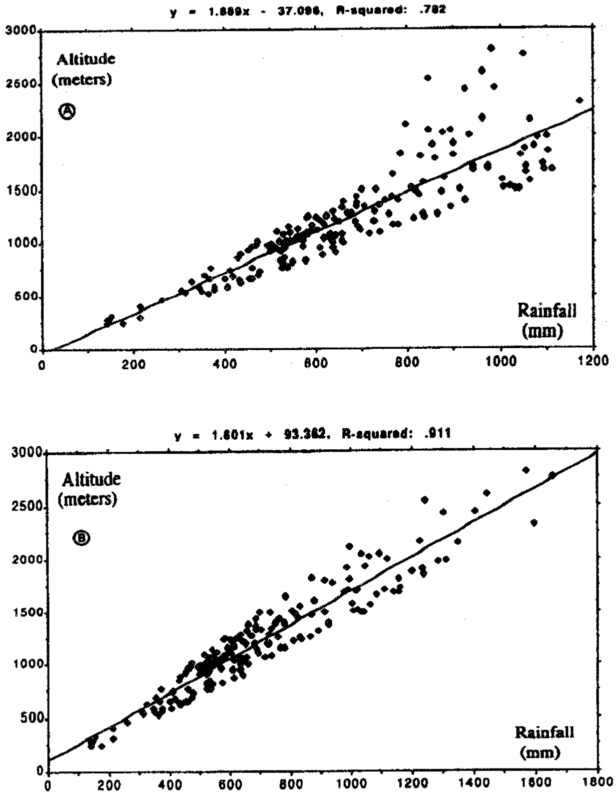


Figure 6 - Influence of the modification of the Gams index on the linearity of the curves of increase of rainfall with increased altitude for the 55-65° Gams domain (A : real rainfall, B : modified rainfall).

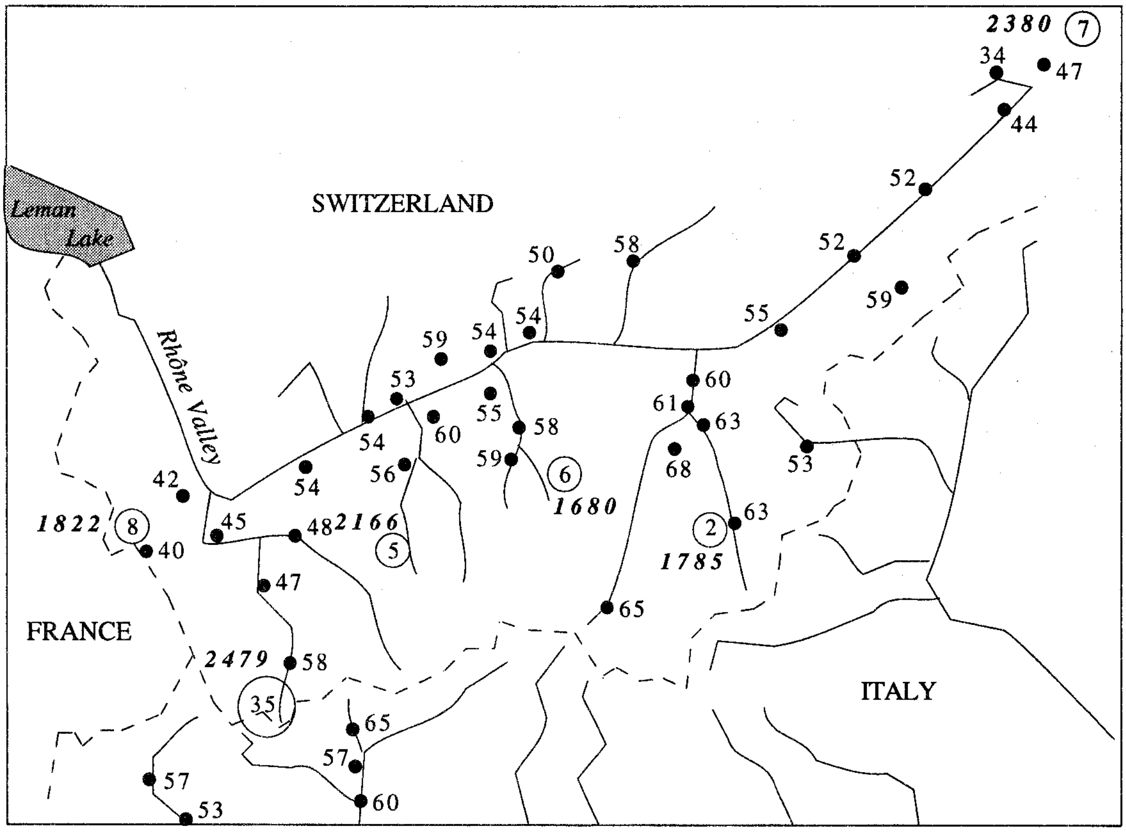


Figure 7 - Validation of the modification for six stations in the Valese Alps. The circled values are the error in % of rainfall and the underlined values are the altitude of the station. For the lower stations (<1600m) the value is the Gams index

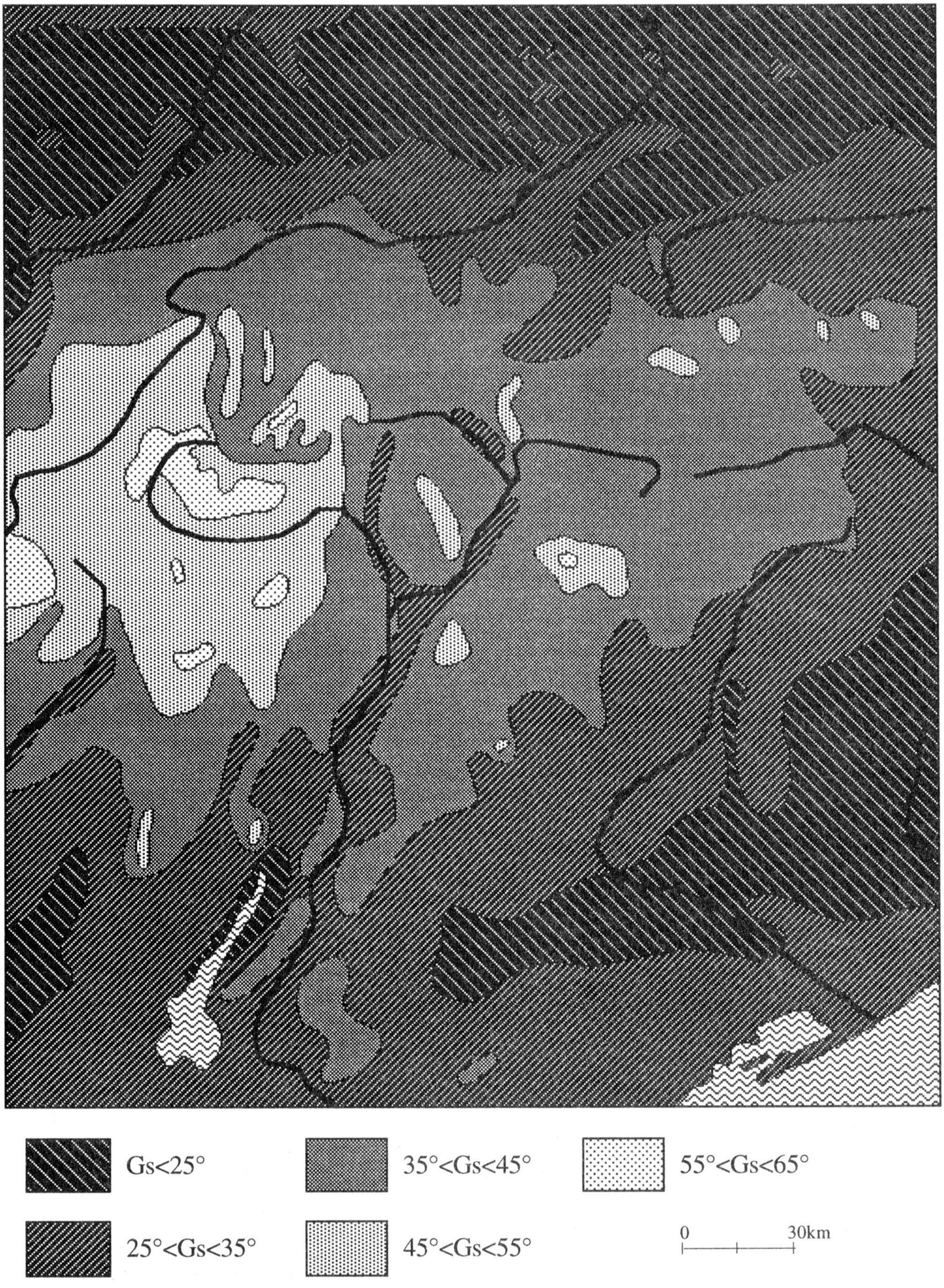


Figure 8 - The map of the summer Gams index.

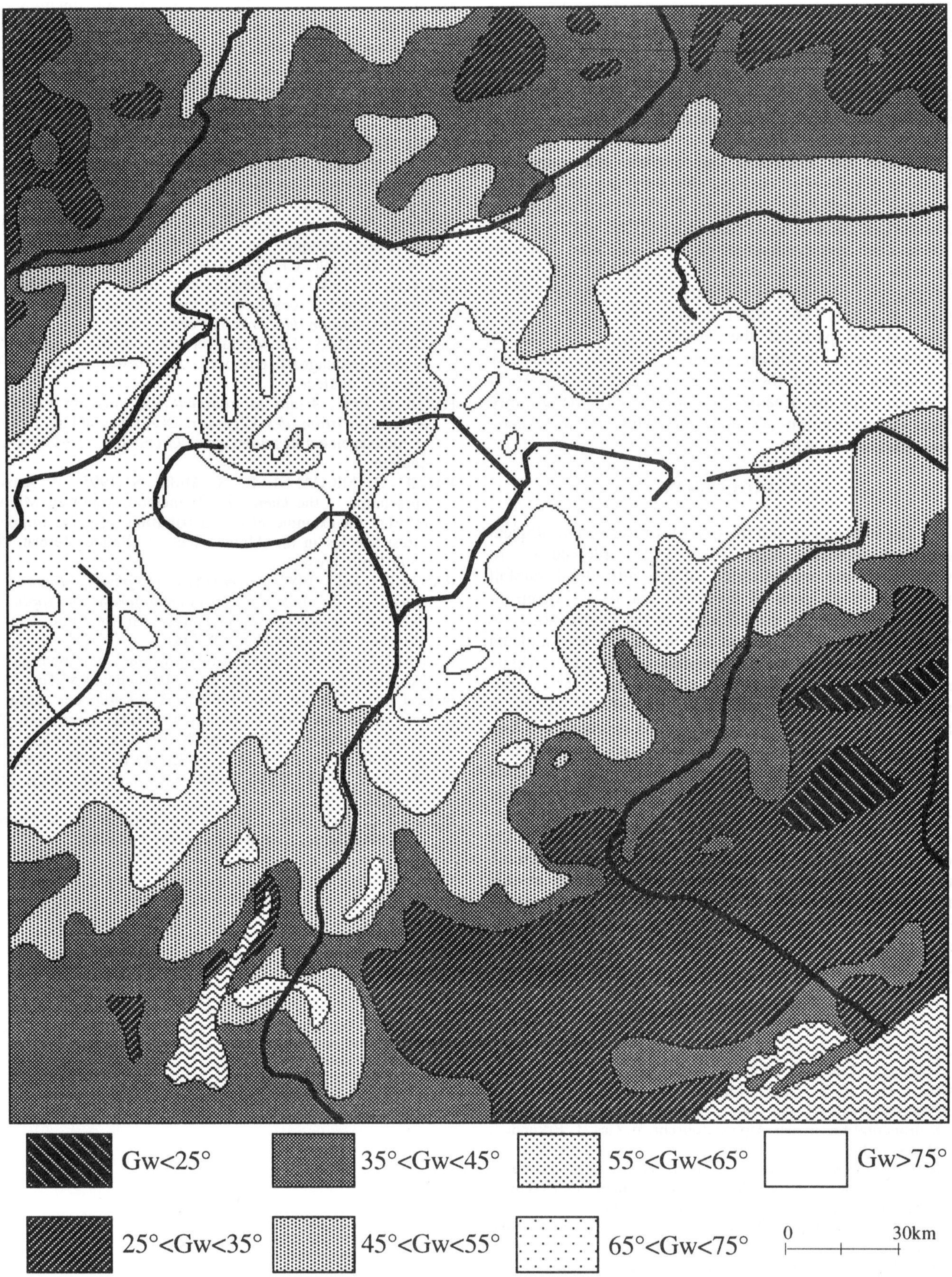


Figure 9 - The map of the winter Gams index.

the subalpine belt for summer indices over 60°. For other species these indices are insufficient when thermic explications are preponderent as it is in the case of beech. Finally the presence and abundance of scots pine is often better explained by the human activities (Rameau, 1987) rather than by climatic factors, although the summer aridity has its importance.

These few examples can explain the important differences which exist between the very dry but weakly continental French Alps, with inner fir-forest without spruce and important climatic scots pine forests (Oberlinkels *et al.*, 1990) and the very continental but still wet inner Tyrolian Alps with inner spruce-forests without fir and edaphic or anthropic scots pine-forests (Schmid, 1950 ; Mayer, 1974 ; Schichtl & Stern, 1967-1988). Also the abundance of larch in the external parts of the Tyrolian Alps and of the Piemontese Alps is clearly connected to high values of winter Gams indices in these continental areas (figure 9). In the French Alps the oceanity (low winter indices) strongly reduces its distribution over the inner Alps and some parts of the intermediate Alps.

CONCLUSION

The importance and the quality of the meteorological datas from Tyrolian Alps (Fliri, 1975) allowed us to develop a simple modelisation of the altitudinal rainfall gradient up to its zone of linearity, that is to say up to 1600 m. Based on the modification of the Gams index we have used an empirical method but the results are validated in others massifs where the rainfall of different Alpine summits has been estimated with around 5% error. Nevertheless without an exact knowledge of the depression paths and of the sheltering effects, such an approach can lead to important errors in very complex orographic situations.

The cartographic representation of the altitudinal rainfall gradients in Tyrolian Alps brought also another validation of this modelisation because the cartographic variations are independant of altitude and governed by the sheltering effects and the seasonal distribution of rainfall. The seasonal approach of the Gams method allows in this way the differenciation of continentality from summer aridity. The few examples of bioclimatic correlations which are given show the biological interests and also the limits of the method.

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