SPATIAL AND TEMPORAL PATTERNS OF THE STABILITY AND HUMIDITY TERMS IN THE HAINES INDEX TO IMPROVE THE ESTIMATE OF FOREST FIRE RISK IN THE VALENCIA REGION OF SPAIN

Maria Jesús BARBERÀ BISBAL[1], María José ESTRELA NAVARRO[2], Raquel NICLÒS CORTS[1], José Antonio VALIENTE PARDO[3]

[1] *University of Valencia, Faculty of Physics, Earth Physics and Thermodynamics Department, Spain*

[2] *University of Valencia, Faculty of Geography and History, Spain*

[3] *Instituto Universitario Centro de Estudios Ambientales del Mediterráneo – CEAM-UMH, Spain*

m.jesus.barbera@uv.es, raquel.niclos@uv.es, majoesna@uv.es, josean@ceam.es

ABSTRACT

The assessment of risk index in the propagation and evolution of a hypothetical forest fire is commonly based on stability and moisture content at different atmospheric levels. The Haines Index combines these terms to determine the environmental potential for wildfire growth. In this study the environmental stability and humidity associated with the lower atmospheric layers in the Western Mediterranean Basin are investigated by analysing Haines Index calculations over a 29 year period. The Haines Index climatology can be applied to the study of plume-dominated forest fires. These fires tend to present very erratic propagation behaviour and create highly dangerous situations for fire brigades. Thus the knowledge of the typical index values and the meteorological situations that generate them could be extremely useful for minimizing the fire risk and planning specific fire-fighting activities. In the present study we carry out a spatial and temporal analysis of the Index and its terms in the Valencia region on the basis of NCEP/NCAR reanalysis data from 1980 to 2008, obtaining a detailed climatological analysis of the HI in the Valencia region for each variant of elevation, which can be used as a reference tool. Moreover, using NCEP reanalysis maps at 500 and 850 hPa, we also perform a daily synoptic analysis for the studied period which is finally associated to the different values that the Index can show in this area. As a result three dominant synoptic weather situations have been defined in this region: continental, maritime and convective. A direct proportionality has been found between increases in the Haines Index and convective situations.

Studies in relation to forest fires are required, given that climate change scenarios forecast that extreme risk situations will increase in intensity, frequency and extension.

Key words: Haines Index, climatology, stability, humidity, plume-dominated fires

RESUMEN

La evaluación del índice de riesgo en la propagación y evolución de un hipotético incendio forestal está basada habitualmente en la estabilidad y el contenido de humedad en los diferentes niveles atmosféricos. El Índice de Haines combina estos términos para determinar el potencial ambiental en el desarrollo de un incendio forestal. En este estudio la estabilidad ambiental y la humedad asociada a las capas atmosféricas más bajas de la cuenca del Mediterráneo occidental se investigan mediante el análisis del cálculo del Índice de Haines durante un período de 29 años. La climatología del Índice de Haines puede aplicarse al estudio de los incendios forestales dominados por columna. Estos incendios tienden a presentar un comportamiento de propagación muy errático y crear situaciones altamente peligrosas para las brigadas de extinción. Así, el conocimiento de los valores típicos del índice y las situaciones meteorológicas que los generan, pueden ser muy útiles para minimizar el riesgo de incendios y planificar las actividades específicas para combatir los incendios. En el presente estudio se realiza un análisis espacial y temporal del índice y sus términos en la Comunidad Valenciana haciendo uso de la base de datos de reanálisis NCEP / NCAR desde 1980 hasta 2008. Se obtiene un análisis climatológico detallado del HI en la región Valenciana para cada variante de elevación, que se puede utilizar como una herramienta de referencia. Por otra parte, haciendo uso de los mapas de reanálisis NCEP a 500 y 850 hPa, también realizamos un análisis sinóptico diario durante el período de estudio que finalmente se asocia con los diferentes valores que el índice puede tomar en este área. Como resultado se han definido tres situaciones meteorológicas sinópticas predominantes en esta región: continental, marítima y convectiva. Se ha encontrado una relación directa entre el aumento del Índice de Haines y situaciones convectivas.

Se requieren estudios relacionados con los incendios forestales, dado que los escenarios de cambio climático pronostican que las situaciones de riesgo extremo aumentarán en intensidad, frecuencia y extensión.

Palabras clave: Índice de Haines, climatología, estabilidad, humedad, incendios forestales dominados por columna.

1. INTRODUCTION

Current fire-risk forecasting schemes are mainly based on meteorological variables. The most commonly used fire-risk indexes are calculated from surface weather variables (McArthur, 1967; Deeming *et al.*, 1977; Turner and Lawson, 1978; Velez, 1982); however, these variables are not the only ones that influence fire spread. Atmospheric instability and dryness have been associated with large wildfires for many years (Brotak and Reifsnyder, 1977; Potter, 1996; Choi *et al.*, 2006; Winkler *et al.*, 2007). Haines (1988) was the first to develop a fire risk index, the Haines Index (HI), based on the stability and moisture content of the lower atmospheric layers. The HI is an indicator of the potential risk of forest fires when the vertical convective plume is more important than horizontal winds, i.e., the so-called plume-dominated fires (Haines, 1988).

Application of the HI in EEUU, Australia, Croatia and Korea (Winkler *et al.*, 2007; Trouet *et al.*, 2009; Choi et al., 2006; Long, 2006; Mokoric and Kalin, 2006; Weber and Dold, 2006; McCaw. *et al.*, 2007) has resulted in good overall correlations between the HI and large forest fire development. Nevertheless, the HI has not been applied in the Western Mediterranean Basin, despite the identified presence of plume-dominated fires in several experimental campaigns within various European research projects that were implemented mainly in the Valencia region (Land use changes interactions with fire in Mediterranean landscapes (LUCIFER), 1996-2000; Forest fire spread prevention and mitigation (SPREAD), 2002-2004; Euro-Mediterranean Wildland Fire Laboratory: A "wall-less" Laboratory for Wildland Fire Sciences and Technologies in the Euro-Mediterranean Region (EUROFIRELAB), 2003-2006).

The study region is located on the East coast of the Iberian Peninsula (Western Mediterranean Basin, Fig. 1), with about 500 km of coastline and an average width of 80 km. This area is characterized by a complex orography (with elevations from sea level up to 1800m) and a wide range of environments and landscapes (Niclos et al., 2014). The main features are its abrupt interior zone, crossed by the Betic and Pre-Betic mountain systems in the South and the Iberian mountain system in the North (Estrela et al., 2000). The Mediterranean Basin is one of the five Mediterranean-climate regions on the Earth where there are relatively cold and wet winters alternated with long, hot, and dry summers. Spring and autumn seasons are ephemeral and highly variable.

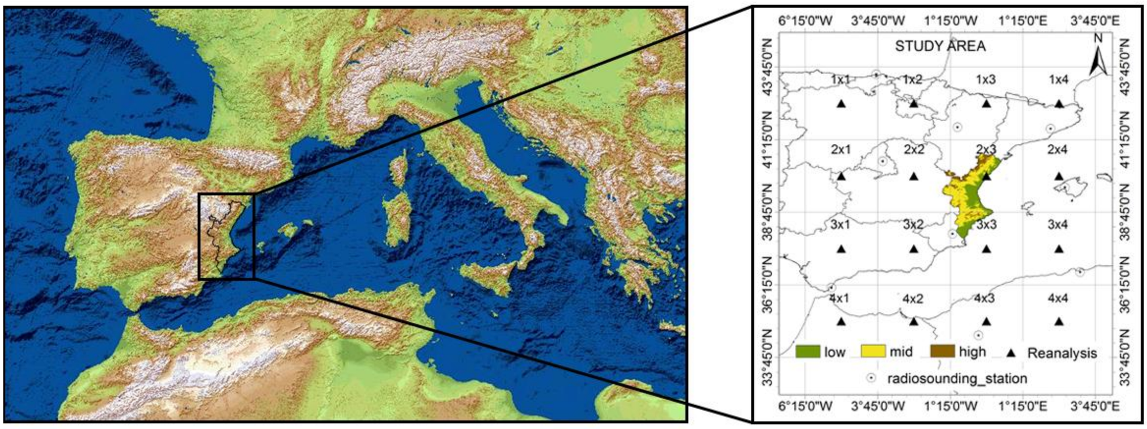

Fig. 1: Location of the study area (Valencia region, Eastern Spain). Valencia region topography reclassified for the three HI variant elevations, the cells in which NCEP/NCAR reanalysis data are available and the radiosounding station distribution.

During the last decade, the Firefighters of the Valencia region (Eastern Spain) have noted an increase in plume dominated fires in this zone. They have asked for reliable information to be able to predict and identify this kind of fires, since extinguishing them is complicated by their erratic behaviour (Quilez, 2007; Barberà *et al.*, 2009, 2010a,b, 2014). The ability to provide adequate spatial and temporal forecasts of the risk of forest fire ignition and spread is crucial in fire-extension planning and fire-risk minimization. Therefore, the aim of this work is to analyse the HI - and especially its two main terms, humidity and stability - in the Valencia region in the Western Mediterranean Basin (Fig. 1). For this region, HI spatial and temporal patterns for the period 1980-2008 were determined, and a synoptic classification of the different HI values found during this period was described.

2. DATA AND METHODS

The HI (Haines, 1988) is calculated as the sum of two terms, A and B:

HI = A + B

where A = (TP1 - TP2) is related to the lower atmosphere stability, and B = (TP3 - TdP3) to the humidity. TPi and TdPi are the air temperature and the dew point temperature at pressure level Pi, thus both terms A and B are expressed in temperature units.

Depending on the surface elevation above sea level (h) of the region of interest, there are three possible atmospheric layers used for computing the HI, and they provide what are known as the low (h < 1000 feet, lower than 305m), mid (1000 < h < 3000 feet, or 305 and 914m respectively) and high (h >3000 feet, higher than 914m) elevation HI variants (Table 1; Haines, 1988; Choi *et al.*, 2006; Potter *et al.*, 2008). The low elevation variant was originally developed for the P1=950hPa pressure level; however, the fact that this atmospheric level is not included in numerous atmospheric profile databases led Potter *et al.*, (2008) to suggest using P1=925hPa as the standard pressure level. Table 1 shows the values used for this level (Choi *et al.*, 2006).

Surface Elevations	Pressure Level	Stability (*TP1 – TP2*)	*A*	Humidity (*TP3 – TdP3*)	*B*	*HI=A+B*
< 305 m (low)	P1=950 hPa (925 hPa) P2=850 hPa P3=850 hPa	< 4ºC (2,7ºC)	1	< 6ºC	1	Potential for large fires 2-3: very low 4: low 5: mid 6: high
		≥ 4ºC (2,7ºC) < 8ºC (6,7ºC)	2	≥ 6ºC <10ºC	2	
		≥ 8ºC (6,7ºC)	3	≥ 10ºC	3	
305 – 914 m (mid)	P1=850 hPa P2=700 hPa P3=850 hPa	<6ºC	1	< 6ºC	1	
		≥ 6ºC < 11 ºC	2	≥ 6 ºC <13ºC	2	
		≥ 11ºC	3	≥ 13ºC	3	
> 914 m (high)	P1=700 hPa P2=500 hPa P3=700 hPa	< 18ºC	1	< 15ºC	1	
		≥ 18 ºC < 22ºC	2	≥ 15ºC < 21ºC	2	
		≥ 22ºC	3	≥ 21ºC	3	

Table 1: VARIABLES AND SCALES FOR CALCULATING THE HI ACCORDING TO THE TERRAIN ELEVATION (Haines 1988; Choi *et al.*, 2006 and Potter *et al.*, 2008)

Each of the three variants has the two components: the stability term (A) and the humidity term (B). Values from 1 to 3 are assigned to each of these terms depending on the magnitude of the temperature differences. The more unstable the atmosphere aloft is, the higher the A term will be and the higher the probability of convective plume-dominated wildfires. Analogously, drier atmospheric conditions imply larger B values which are favourable for the spread of wildfires. Thus, the HI varies between 2 and 6 for each of the three variants, with values equal to or greater than 5 indicating critical conditions for the formation of plume-dominated wildfires.

The synoptic network of upper-air observing stations, http://weather.uwyo.edu/upperair/sounding.html, has no radiosounding stations in the Valencia area Fig. 1, so we have worked with reanalysis data provided by NCEP/NCAR (National Centers for Environmental Prediction/ National Center for Atmospheric Research, Kalnay *et al.*, 1996).

The NCEP/NCAR reanalysis spatial resolution of 2.5x2.5 degree was used due to the fact that the 1x1 degree database was more limited temporally (beginning on July 30, 1999) and thus was not considered extensive enough to carry out a climatological study. Also, radiosounding station distribution close to the study area is shown in Fig. 1 and it is observed that the nearest stations are spaced greater distances than 2.5 degrees.

Data from 1980 to 2008 were used because the earlier NCEP/NCAR reanalysis data presented inconsistent quality as a result of the implementation of satellite data in 1979 (Kalnay *et al.*, 1996). 00 UTC data were selected, as this was the time slot in which the HI was originally developed by working with the temperature and relative humidity variables to determine the dew-point temperature (Lawrence, 2005) at the 925, 850, 700 and 500 hPa pressure levels.

Fig. 1 shows also the grid distribution of the Digital Elevation Model (DEM) for the Valencia region with a 50 m resolution, as reclassified for the three elevations that give rise to the three HI variants. Thus, there are 16 gridpoints over the Eastern part of the Iberian Peninsula at a 2.5º resolution but 3 of them (2x2, 2x3 and 3x3) covers the Valencia region. The GrADS (Grid Analysis and Display System) software was used to process the data (Doty, 1995) .The database for the statistical analysis was generated by calculating the climatological averages, for the HI, A and B during the study period (1980-2008) for each of the three elevations.

The spatial data processing was carried out with ArcGIS software by using a kriging method (Oliver, 1990) for the NCEP/NCAR data interpolations over the 16 gridpoints abovementioned and different spatial analysis tools of the geostatistical and spatial analyst toolboxes.

Climatological values for the whole period, calculated as the average of the complete database, i.e., mean daily values (00:00 UTC) from 1980 to 2008 (see in Fig. 3) and annual means, as the average of values during a specific year, were calculated at 00:00 UTC from 1980 to 2008. With respect to the temporal analysis, we represented the interannual, evolution of the A and B terms and the HI in each of the NCEP/NCAR grids that contain any part of the Valencia region and for each variant of the HI (see in Fig. 4).

A synoptic analysis was developed with the NCEP synoptic daily charts at 500 and 850 hPa for the period 1980 to 2008 (http://www.wetterzentrale.de/). The methodology applied was the same as used in Millan *et al.*, 2005 and a daily dataset was obtained where each day was classify depending on its synoptic situation in one of the following three dominant types (Fig. 2):

a) Continental flows, in this case the air mass source provides no extra moisture; generally speaking, these are Westerly flows

b) Maritime or Easterly, the air mass source does provide extra moisture due its trajectory over the Mediterranean Sea.

c) Convective situations are those with predominance of vertical movements instead of horizontal (advection) displacements of air masses.

The three dominant types of synoptic situations were also distinguished both at surface level and aloft taking into account the source of air masses at the surface (lines on a Mean Sea Level pressure map) and aloft (maps at both 500 and 850 hPa).

The daily synoptic classification was merged with the different values that the HI can take in each of the elevations. Statistics were computed for the probability of occurrence for each of the abovementioned synoptic situations depending on the value taken by the HI (Fig. 5).

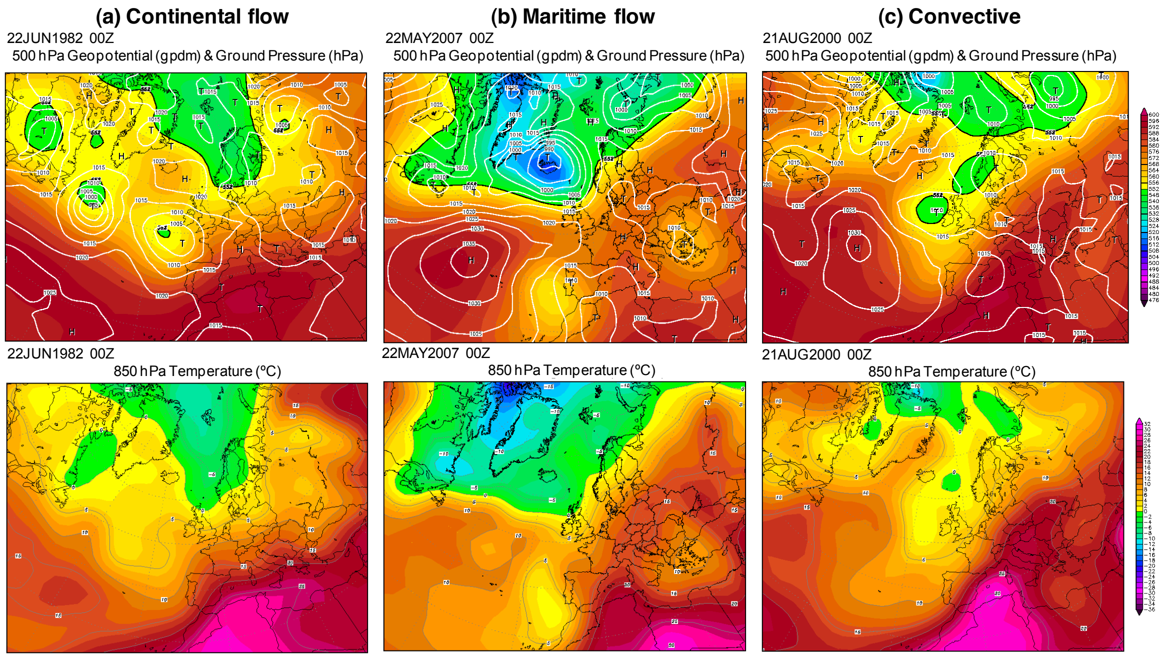

Fig. 2: Examples of the classified synoptic situations: (a) continental flow, (b) maritime flow and (c) convective situation. 500 hPa geopotential and ground pressure (top), and 850 hPa Temperature (bottom) reanalysis data from NCEP (data provided online at www.wetterzentrale.de). In the top panels T represents a low pressure system.

3. RESULTS AND DISCUSSION

3.1. HI spatial patterns

Figure 3 shows climatological averages ranged from 2 to 6 (according with Table 1) for each of the HI variants (low, medium and high elevations).

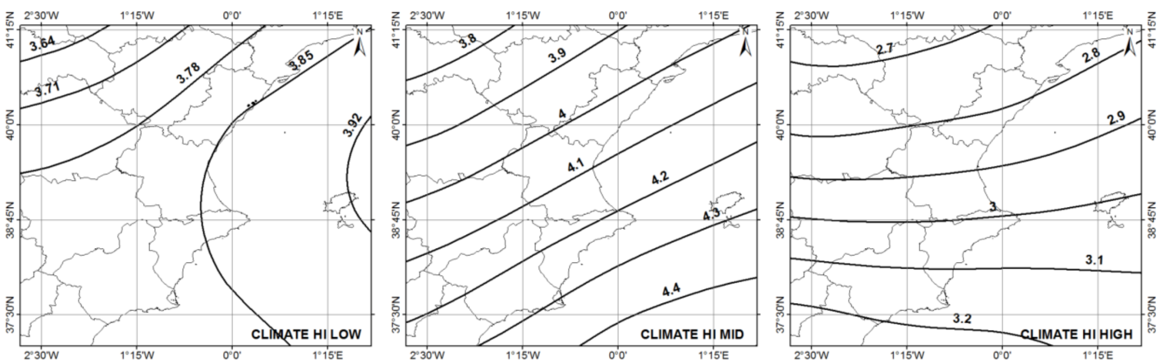

Fig. 3: Spatial distribution of the climatological averages for each variant of the HI calculated for the whole period.

The HI variability for low elevations (left figure) is very low in the Valencian region, with a mean value around 3.8. For mid elevations (center figure) the HIs are higher, with values from 4 in the North of the region to 4.3 in the South. For the high elevation variant (right figure) the lowest climatological HI values were obtained, with HI increasing from North to South (averages around 2.8 in the North and lower than 3.2 in the South). The highest values for the HI climate means are found mainly in the prelittoral and interior zones of the Southern third, and they correspond to the mid elevation variant. Meanwhile, the areas with the lowest HI are found in mountainous zones in the interior North of the region.

3.2. HI temporal patterns

The interannual evolution is analysed for the HI and for the A and B components in the NCEP/NCAR reanalysis data cells that contain information about the Valencia region (2x2, 2x3 and 3x3, see Fig. 1).

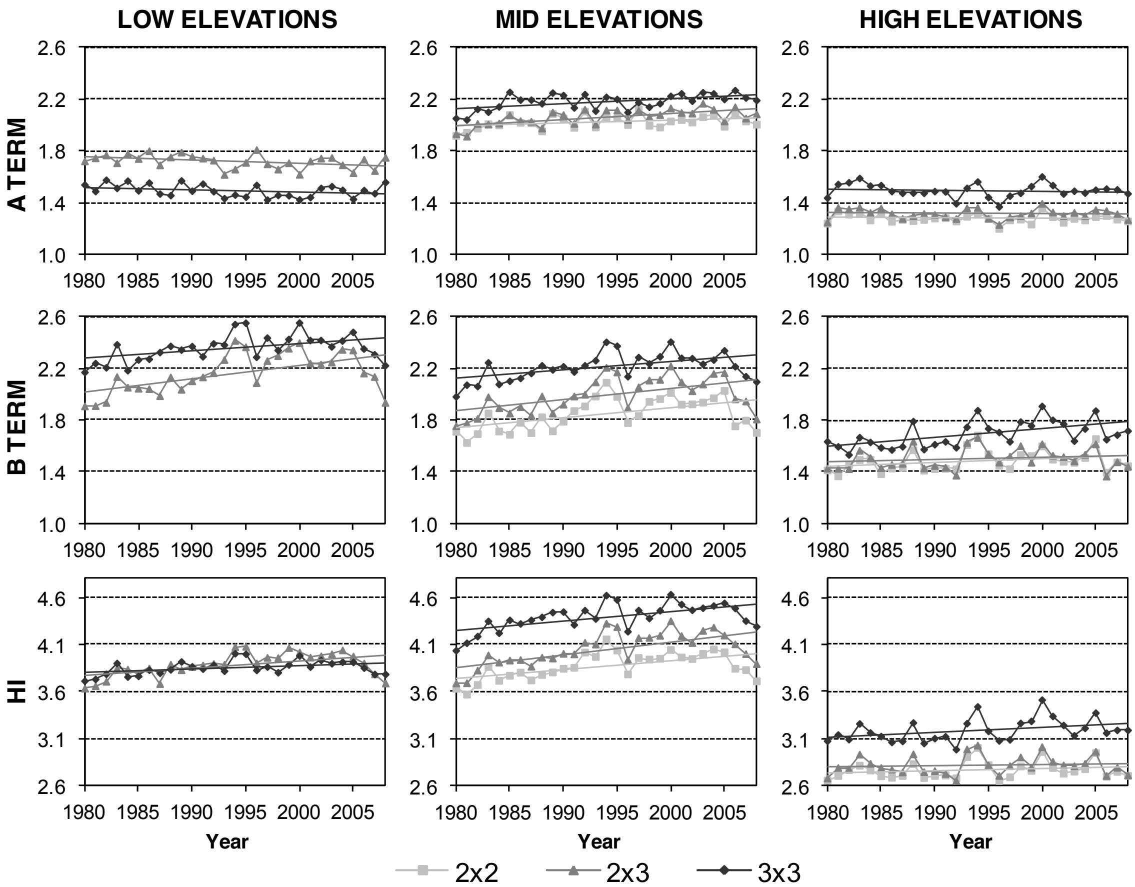

Fig. 4: Interannual evolution of terms A and B and of the HI for the three elevations studied.

Fig. 4 presents the results of the interannual evolution of annual-means and the linear regression of these data at the three elevations studied. As cell 2x2 does not contain topographical altitudes under 305 m, it was eliminated from the low level variant analysis. The figure shows a general trend towards increasing the HI in the whole study period (29 years). Moreover, as in the spatial study, it can be seen that during the whole period analysed, the cell 3x3 which corresponds to the South of the region contains always larger annual-means for the mid and high elevation variants than the other two cells. Values in cell 3x3 are followed by those in cell 2x3, with the smallest annual-means contained in cell 2x2 which covers a very small portion of the region and corresponds to the West part. The HI annual-means at low elevations are then similar in cells 2x3 and 3x3, with slightly higher values observed in cell 3x3 up to 1990 and in cell 2x3 from 1990 on. Both for low and at high elevations, term A shows a very slight interannual tendency to decrease or remain more or less constant; thus, the interannual increase in the HI is determined by the increase in the B term, indicating a decrease in the humidity during the time period analysed. The mid elevation variant of the HI is the one in which the trend towards higher HI values is seen more clearly since the interannual evolution for these regions tends to show an increase both in the stability and in the humidity term, although slightly less so for the stability term.

3.3. Synoptic analysis associated with HI values

Synoptic weather charts are split into two levels: surface and aloft, in order to perform a pattern analysis for their classification into the three dominant types of synoptic situations: maritime, continental and convective. Surface pattern analysis is performed on the surface isobar lines contained in a typical Mean Sea Level Pressure weather chart, while the aloft pattern analysis takes a combination of geopotential heights in a 500 hPa weather chart and the temperature isotherms in a 850 hPa weather chart. The surface and aloft synoptic weather patterns for each value of the HI in all its variants were analysed because of the considerable differences – determined by altitude - in the HI values in our study and in other studies (Choi *et al.*, 2006; Winkler *et al.*, 2007). Therefore if synoptic weather patterns were analysed from HI daily values for the three variants together, the resulting patterns would not be representative due to the differences between the HI variants.

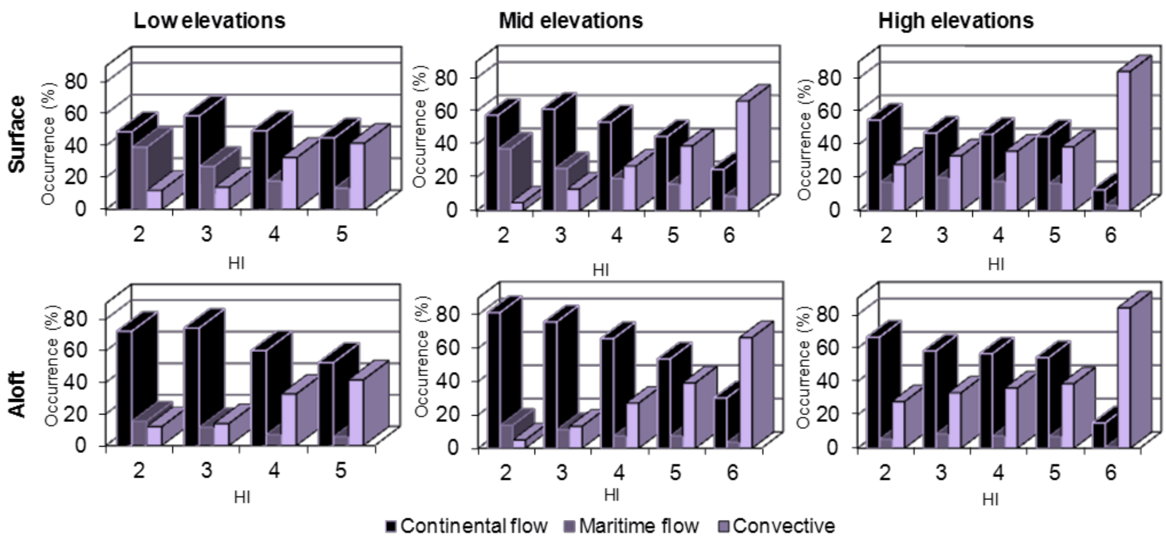

Fig. 5: Synoptic classification at the surface (top) and aloft (bottom) of HI values for the three elevations studied.

The graphs in fig. 5 all show a similar trend, with direct proportionality between increases in the HI value and increases in convective situations. Thus, as the HI value increases, there is a decline of the number of cases for which the synoptic situation is determined by either continental or maritime flows. Moreover, it can be seen that the distribution of the synoptic patterns aloft is quite similar to that found at the surface level, except for the maritime flows which are smaller in number.

In general, synoptic situations involving continental flows show the greatest decrease as the HI value increases. The most pronounced decreases are seen for mid and high elevations between HI values 5 and 6. To better explain these results we have analyzed the stability (A) and the humidity (B) components separately, finding that only 17% of the days with moderate HI present the maximum A term value of 3, which generally reflects that the rest of the days correspond to a maximum dryness, B=3, which is associated with continental airmass circulations in our study region.

4. CONCLUSIONS

A detailed climatological analysis of the HI in the Valencia region (Western Mediterranean Basin) has been carried out using NCEP/NCAR 00 UTC reanalysis data for the last three decades (1980-2008). The resulting information provides an overview of the climatological values at each of the elevations studied for the whole period, and it can be used as a reference tool to interpret and evaluate HI observations and predictions in the study area. This climatological study contributes important details on the operational use of the HI and, most significantly, it identifies the spatial and temporal patterns present at, and between, the different elevations. The fact that these spatial patterns correspond to differences in elevation signifies that a lot of care should be taken when interpreting the different values. A possible user should asses the HI corresponding to the elevation variant of the location of interest and compare it with the climatological values to interpret the potential fire risk.

The main conclusions of the climatological study are listed below:

• At both low and mid elevations, the HI climatological values in the Valencia region are around 4, although HI can be a little higher (4.3) at some points in the Southern third of the region and a little lower (≅3) at high elevations.

• During the study period, the mean interannual HI values show an increasing trend. The highest HI values are registered for mid elevations.

• The synoptic analysis of the different HI values found in our region reveals a direct proportionality between increases in the HI value and convective situations.

The climatology shown in this study could be a useful tool to improve the forest fire risk prediction system. In this sense, studies in relation to forest fires are required, given that climate change scenarios forecast that extreme risk situations will increase in intensity, frequency and extension (IPCC, 2007). The knowledge of the current climate and the difference with the situation in the recent past can help to plan for the future (Obasi, 2001).

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