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Global assessment of fire risk: using a global fuel map and climatological data to estimate fire behavior with FCCS

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Abstract
The spatial distribution, structure, and environmental conditions of the fuels are key variables in wildland fire behavior and effects. This study developed environmental scenarios, based on global weather information and topography, in order to calculate surface fire behavior parameters using the Fuel Characteristic Classification System and a global fuel map previously developed.
The results show the geographic variation in monthly mean wind speed and fuel moisture content for the months of January and July and for the period 1981-2010. Also, the worst monthly conditions were evaluated, corresponding to the maximum monthly wind speed and minimum fuel moisture content. From these environmental scenarios, the rate of spread for the global fuels was mapped, obtaining more realistic results than in the past.

Keywords: *Fire risk, FCCS, global fuel map, fire behavior, ECMWF*

1. Introduction

Surface fire behavior is dependent on the available fuels and also on the environmental conditions when the fire occurs. Specifically, fuel moisture, slope and wind speed affect the speed in which fire spreads, and the energy released by it (Rothermel 1983). The different fire behavior systems that are currently widely used, such as BehavePlus (Andrews *et al.* 2008), the National Fire Danger Rating System (Cohen and Deeming 1985), the Canadian Fire behavior prediction (Stocks *et al.* 1989), the Fuel Characteristic Classification System (Ottmar *et al.* 2007), etc., include these environmental conditions in the calculation of the surface fire parameters.

The Fuel Characteristic Classification System (FCCS) (Ottmar *et al.* 2007) was designed to represent the structural and geographic diversity in wildland fuels, and combines the fuel properties into "fuelbeds", which include the physical and chemical variables used to model fire behavior and fuel consumption, and predict emissions (Riccardi *et al.* 2007). FCCS uses fuel characteristics (e.g. percentage cover, loading, depth) to calculate and report nine fire potentials, organised into three categories: surface fire behavior potential, crown fire potential and available fuel potential (Sandberg *et al.* 2007a). Also, based on input environmental variables, the FCCS predicts surface fire behavior parameters using a reformulation of the Rothermel (1972) fire behavior model (Sandberg *et al.* 2007b). During previous work developing fuel maps using FCCS (Pettinari *et al.* 2013; Pettinari *et al.* 2014), default environmental parameters were used to estimate fire potentials and surface fire behavior such as rate of spread, flame length, and reaction intensity. The use of a defined set of environmental conditions allowed the comparison of the different fuelbeds based solely on their intrinsic characteristics, but they did not reflect the variations of weather conditions around the world, which influence fire behavior. In this study we focused on improving the fire behavior results by means of applying more realistic environmental conditions to the different regions of the world.

2. Methods

To run FCCS, it is necessary to select the fuelbeds that will be included in the calculations, and also the environmental variables that affect fire behavior. These environmental conditions are: fuel moisture content (FMC) for different fuel classes, wind speed and slope. The required FMCs are: 1-, 10- and 100-hr dead fuel moisture, and live-herb, live-shrub and live-crown moistures. The FMCs can be input as individual FMCs, or a Fuel Moisture Scenario (FMS) can be used. The 16 combinations of the Scott and Burgan (2005) dead and live FMSs are already input as selectable FMSs. Terrain slope is input in units of % slope, and wind speed is input in units of miles per hour (mph).

For the purpose of this study, we selected FMSs from the existing ones in FCCS according to their dead 10-h FMC, and we created slope and wind scenarios to reflect the influence of these variables in surface fire behavior. All the calculations were done using FCCS version 3.0 module inside the Fuel and Fire Tools (http://www.fs.fed.us/pnw/fera/fft/index.shtml, accessed June 2014) version 3.03.203. The climatic data was extracted from the European Centre for Medium-Range Weather Forecast (ECMWF). We used the ERA-Interim Global Reanalysis (Dee *et al.* 2011) because it includes all the climatic variables required to calculate the environmental variables for the FCCS run, and it is the latest release of the ECMWF reanalyses. The data covers a 30-year period, from 1981 until 2010, and was rescaled from the original 0.75º grid to a 0.50º grid covering the whole globe directly at the ECMWF Data Server. ERA-Interim provides daily forecast information for 8 hours UTC (time steps): 0, 3, 6, 9, 12, 15, 18 and 21 hr. Since the lowest fuel moisture content usually occurs at early afternoon, the globe was divided in 8 strips of 45º longitude, each one including information of local solar time (LST) between 12 hr. (in the western part of the strip) and 15 hr. (in the eastern part of the strip). For example, the data of UTC 15:00 was used for the strip extending between 45º and 90º, and that information represents weather conditions at 12 hr for the longitude 45º, 13 hr. for longitude 60º, 14 hr. for longitude 75º and 15 hr. for longitude 90º. Table 1 summarises the climatic variables used for this study and their characteristics.

Table 1. Climatic variables from the ERA-Interim Reanalysis used for this study

Variable Name	Variable Code	Units	Type of Level	Stream	Other information
10 m Wind Speed	207	m s^{-1}	Surface	Synoptic Monthly Mean	Produced by forecast. Monthly average at time step.
Total Cloud Cover	164	Fraction of cover (0-1)	Surface	Daily	Produced by forecast. Instantaneous at time step.
Snow Depth	141	m of water equivalent	Surface	Daily	Produced by forecast. Instantaneous at time step.
Total Precipitation	228	m of water	Surface	Daily	Produced by forecast. Accumulated from the previous 24 hr.
2 metre Dew Point	168	ºK	Surface	Daily	Produced by forecast. Instantaneous at time step.
2 metre Temperature	167	ºK	Surface	Daily	Produced by forecast. Instantaneous at time step.

2.1. Fuel map

The fuel distribution and their physical and chemical variables related to fire behavior were extracted from the Global Fuelbed Map developed by Pettinari *et al.* (2013). This map is based on vegetation data provided by the GlobCover V2.2 product (Bicheron *et al.* 2008), and has a spatial resolution of 10 arc seconds (~300 m at the Equator). Its legend was defined using the Land Cover Classification System (Di Gregorio 2005). The land cover information was sub-divided using the biomes described in the Map of Terrestrial Ecoregions (Olson *et al.* 2001), in order to account for differences in vegetation characteristics due to the influence of climate. This map (see Fig 1) has a total of 166 Fuelbeds, some of them subdivided according to their percentage of canopy cover. Each fuelbed is

identified by a number, where the thousands value corresponds to the biome, and the following three values identify the land cover type associated with each pixel. For example, fuelbed 13140 is in the Desert and Xeric Shrublands biome: "13", and associated with grass vegetation: "140".

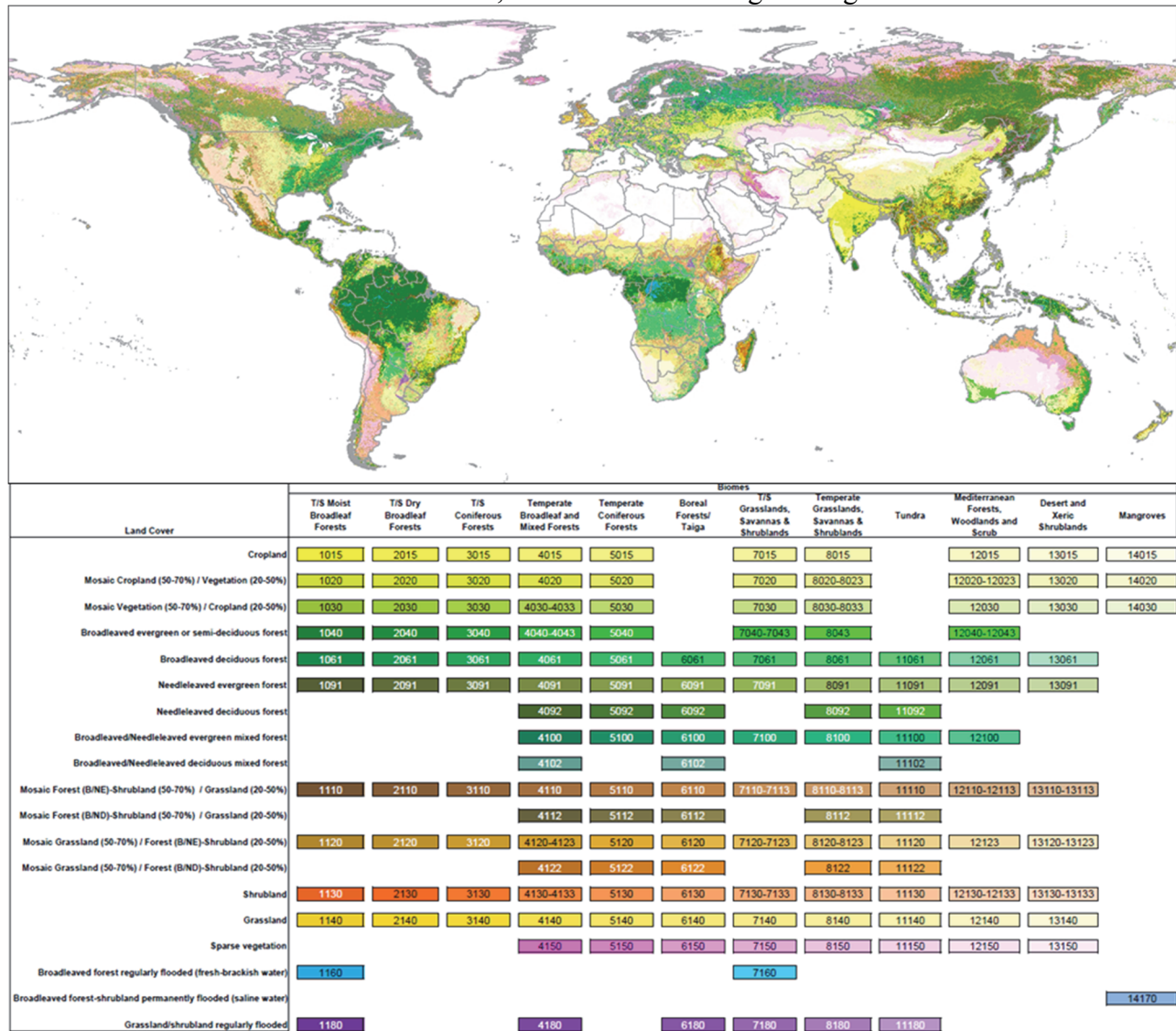| Land Cover	Biomes											
	T/S Moist Broadleaf Forests	T/S Dry Broadleaf Forests	T/S Coniferous Forests	Temperate Broadleaf and Mixed Forests	Temperate Coniferous Forests	Boreal Forests/Taiga	T/S Grasslands, Savannas & Shrublands	Temperate Grasslands, Savannas & Shrublands	Tundra	Mediterranean Forests, Woodlands and Scrub	Desert and Xeric Shrublands	Mangroves
Cropland	1015	2015	3015	4015	5015		7015	8015		12015	13015	14015
Mosaic Cropland (50-70%) / Vegetation (20-50%)	1020	2020	3020	4020	5020		7020	8020-8023		12020-12023	13020	14020
Mosaic Vegetation (50-70%) / Cropland (20-50%)	1030	2030	3030	4030-4033	5030		7030	8030-8033		12030	13030	14030
Broadleaved evergreen or semi-deciduous forest	1040	2040	3040	4040-4043	5040		7040-7043	8043		12040-12043		
Broadleaved deciduous forest	1061	2061	3061	4061	5061	6061	7061	8061	11061	12061	13061	
Needleleaved evergreen forest	1091	2091	3091	4091	5091	6091	7091	8091	11091	12091	13091	
Needleleaved deciduous forest				4092	5092	6092		8092	11092			
Broadleaved/Needleleaved evergreen mixed forest				4100	5100	6100	7100	8100	11100	12100		
Broadleaved/Needleleaved deciduous mixed forest				4102		6102			11102			
Mosaic Forest (B/NE)-Shrubland (50-70%) / Grassland (20-50%)	1110	2110	3110	4110	5110	6110	7110-7113	8110-8113	11110	12110-12113	13110-13113	
Mosaic Forest (B/ND)-Shrubland (50-70%) / Grassland (20-50%)				4112	5112	6112		8112	11112			
Mosaic Grassland (50-70%) / Forest (B/NE)-Shrubland (20-50%)	1120	2120	3120	4120-4123	5120	6120	7120-7123	8120-8123	11120	12123	13120-13123	
Mosaic Grassland (50-70%) / Forest (B/ND)-Shrubland (20-50%)				4122	5122	6122		8122	11122			
Shrubland	1130	2130	3130	4130-4133	5130	6130	7130-7133	8130-8133	11130	12130-12133	13130-13133	
Grassland	1140	2140	3140	4140	5140	6140	7140	8140	11140	12140	13140	
Sparse vegetation				4150	5150	6150	7150	8150	11150	12150	13150	
Broadleaved forest regularly flooded (fresh-brackish water)	1160						7160					
Broadleaved forest-shrubland permanently flooded (saline water)												14170
Grassland/shrubland regularly flooded	1180			4180		6180	7180	8180	11180			

Figure 1. Global fuel map. The table legend lists the 166 fuelbeds developed. B: Broadleaf, NE: Needleleaf Evergreen, ND: Needleleaf Deciduous.

Each fuelbed has several structural, physical and chemical parameters, necessary to run FCCS. These parameters were extracted from global products based on remote sensing when possible, or from existing databases. The percentage of tree cover was extracted from the MODIS Vegetation Continuous Field, Collection 5, product (Carroll *et al.* 2011), and canopy height was derived from the map developed by Simard *et al.* (2011). For each fuelbed, the mean value of these variables was used. Representative tree, shrub and grass species were assigned based on the description of the ecoregions of the World Wildlife Fund Ecoregions' database (http://worldwildlife.org/science/wildfinder/, accessed June 2014). The remaining variables for each fuelbed (canopy height to live crown (HLC), tree density, diameter at breast height (DBH), the presence or absence of ladder fuels, shrub height, grass height and load, dead woody fuels cover and depth, fuel loads by size class of dead woody fuels, and litter and duff cover and depth) were assigned selecting the most similar fuelbeds from the ones in the FCCS database or from the Natural Fuels Photo Series from Mexico and Brazil (Ottmar *et al.* 2001; Morfín-Ríos *et al.* 2008).

2.2. **Slope**

Percentage slope was calculated using the GTOPO30 product, which is a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometre at the Equator), developed by the United States Geological Survey (USGS) - EROS Data Center (https://lta.cr.usgs.gov/GTOPO30, accessed June 2014).

Three slope classes were established with the following criteria (see Figure 2):
- Slope class 1: 0% slope (for slope ranges between 0 - 5%)
- Slope class 2: 30% slope (for slope ranges between 5 - 45%)
- Slope class 3: 70% slope (for slopes higher than 45%)
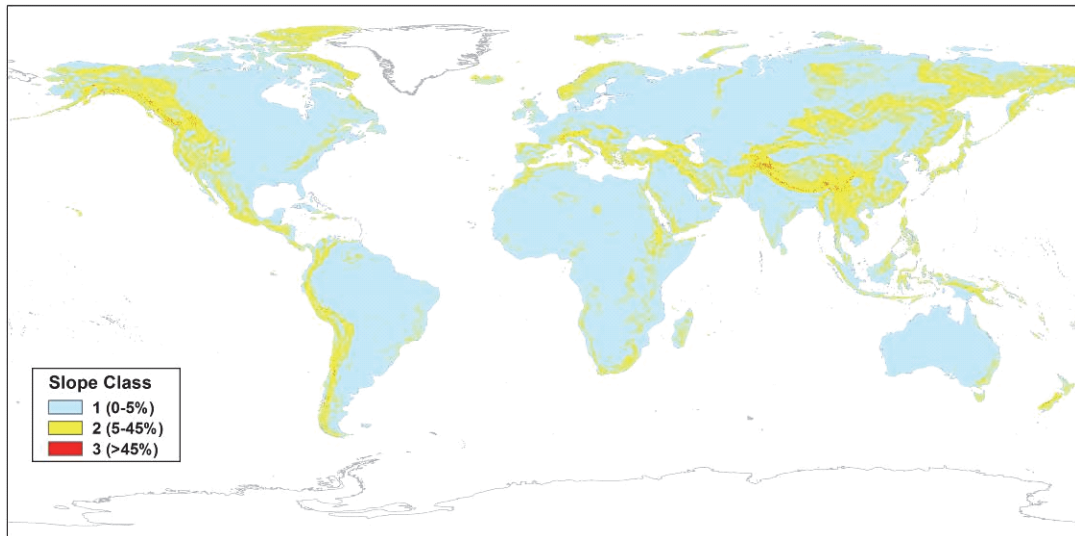
Figure 2. Slope classes derived from GTOPO30.

2.3. **Wind Speed**

The wind speed data was downloaded from the ECMWF Data Server directly as a monthly mean wind speed for each time step. The mean value of wind speed for each month within the 30-year period was calculated, and also the maximum monthly wind speed was identified.

The wind data correspond to 10 m winds, but the FCCS input requires the midflame wind speed, which is the average wind velocity that affects surface fire spread, and is usually referred as to the velocity of the wind taken at the mid-height of the flames. To convert from 10 m to midflame wind speed, a wind adjustment factor (WAF) is used. This WAF is dependent on the sheltering from overstory vegetation above the fire, and takes values from 0.6 (for unsheltered fuels) to 0.1 (for sheltered fuels), based on 6.01 m (20-ft) wind speeds (Andrews 2012). For this study, a general intermediate WAF of 0.4 for 20-ft winds was used, which corresponds to 0.348 for 10-m winds (Turner and Lawson 1978). As with the slope, three wind speed classes were established, to account for the contribution of wind speeds to fire spread:
- Class 1: 0 – 1.0 m/seg (0 – 2.24 mph). Assigned to 1.0 mph in FCCS.
- Class 2: 1.0 – 2.5 m/seg (2.24 – 5.59 mph). Assigned to 4 mph in FCCS.
- Class 3: 2.5 – 5 m/seg (5.59 – 11.18 mph). Assigned to 7 mph in FCCS.

2.4. **Fuel Moisture Content**

Four FMSs were selected to represent different moisture conditions, based on their 10-hr fuel moisture content. They combine Scott and Burgan's Dead Fuel Moisture Scenario (DFMS) and Live Fuel Moisture Scenario (LFMS). Their FMCs are described in Table 2.

Table 2. FMCs of different fuel classed assigned to each FMS. Extracted from the FMS table inside FFT

FMS Code	FMS description	Herb	Shrub	Crown	1-hr	10-hr	100-hr
D1L1	Very low dead, fully cured herb	30	60	60	3	4	5
D2L2	Low dead, 2/3 cured herb	60	90	60	6	7	8
D3L3	Moderate dead, 1/3 cured herb	90	120	120	9	10	11
D4L4	High dead, fully green herb	120	150	150	12	13	14

The 10-hr FMC was calculated using the equations formulated for the National Fire-Danger Rating System (Cohen and Deeming 1985). Relative humidity was calculated from temperature and dew point using the formulas described in Wanielista *et al*. (1997), because there were not data for relative humidity in ERA-Interim for the 8 time steps. Cloud cover data was converted to the State of Weather code (SoW), which was in turn used to adjust the temperature and humidity values. The 10-hr FMC was calculated daily for each month and for the 30-year period. Wet fuel conditions were assigned for a day when the snow depth was higher than 0 m of water equivalent, or if the total precipitation in the previous 24 hr was higher than 0.01 m. In that case, the 10-hr FMC was assigned to 35%.

From the daily 10-hr FMC, monthly mean values were computed, and from those, the monthly mean value for the 30-year period was obtained, and also the minimum monthly mean value was identified. 10-hr FMC was converted to FMS according to the following classification:

- D1L1: 10-hr FMC < 5.5%.
- D2L2: 5.5% < 10-hr FMC < 8.5%.
- D3L3: 8.5% < 10-hr FMC < 11.5%.
- D4L4: 10-hr FMC > 11.5%.

3. Results and discussion

Figure 3 shows the wind speed classes for January and July, for both the mean monthly conditions and the worst monthly conditions, corresponding to the maximum monthly wind speeds in the 30-year period. The highest mean monthly wind speed values during July are found in the Horn of Africa, where the maximum value is 4.6 m/seg for the mean monthly values, and 5.6 m/seg for the worst year. During January, the highest mean monthly wind values are found in the coast of southern Argentina and Chile, the Great Lakes, the coasts of the United Kingdom, a region in northern Siberia and the Borkou region in Chad. The maximum mean monthly value is 4.15 m/seg, and during the worst monthly conditions the maximum value is 5.18 m/seg.
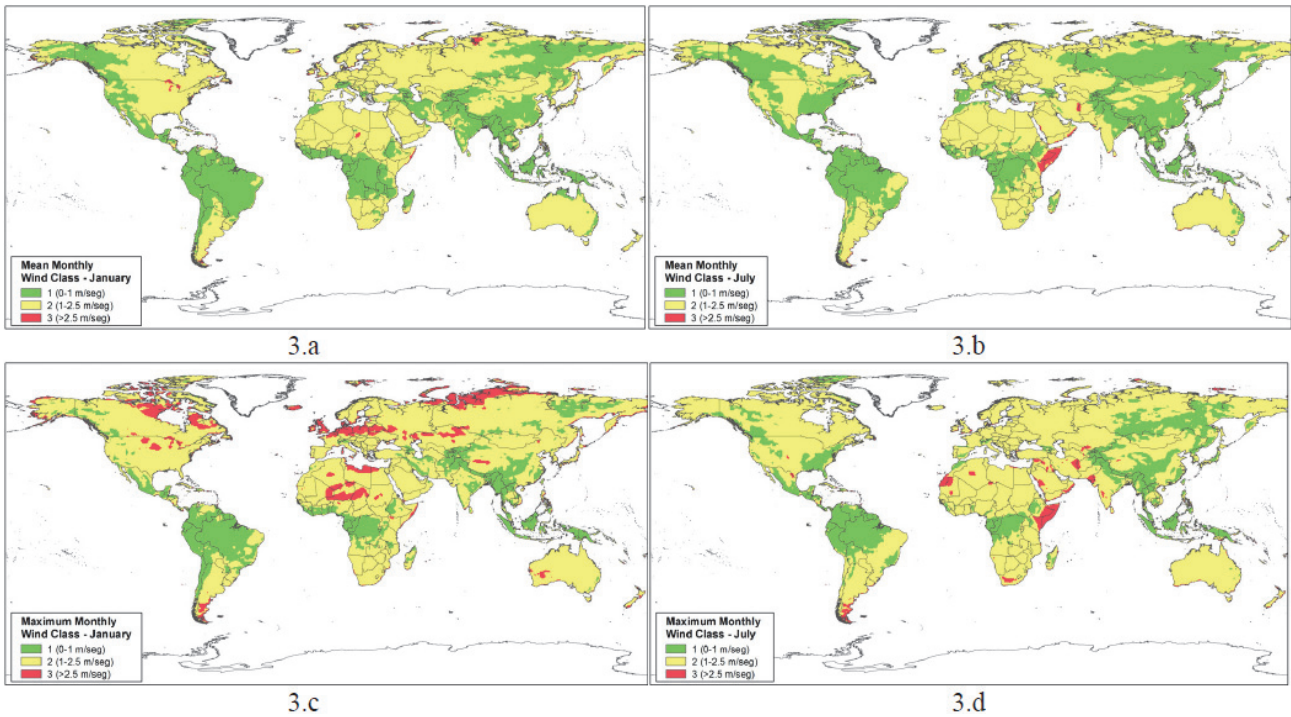
Figure 3. Wind classes calculated for the 1981-2010 period. 3.a: Mean January wind class; 3.b: Mean July wind class; 3.c: Maximum January wind class; 3.d: Maximum July wind class.

Wind speed varies greatly, even at very short time scales (seconds to minutes), and is also influenced by topography, vegetative sheltering, local heating or cooling, and surface friction (Rothermel 1983). The use of different wind classes does not intend to predict wind conditions for a particular moment or point in space, but to identify general regions and time periods where and when faster winds could occur compared with other parts of the world or seasons, and hence more severe surface fire behavior could be expected.
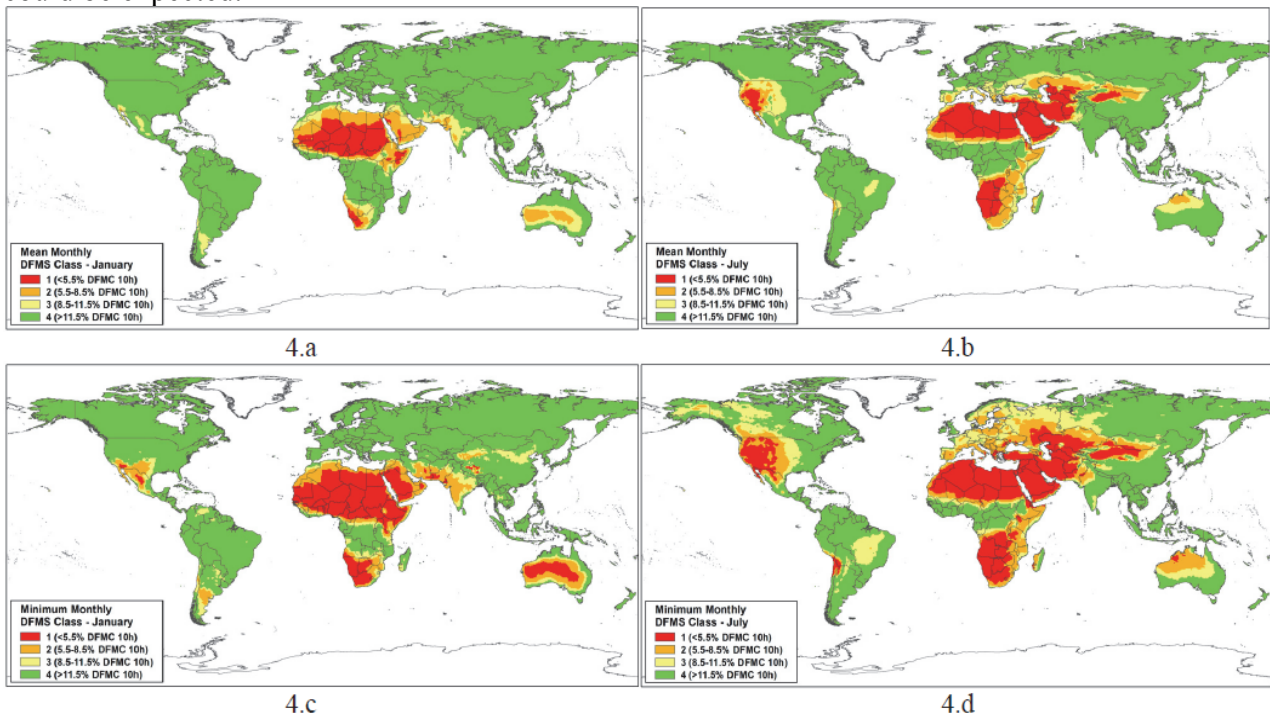
Figure 4. Dead Fuel Moisture Scenario calculated for the 1981-2010 period. 4.a: Mean January DFMS; 4.b: Mean July DFMS; 4.c: Minimum January DFMS; 4.d: Minimum July DFMS.

The result of the calculation of the 10-hr FMC, which determined the assignation of a Dead Fuel Moisture Scenario (DFMS), is shown in Figure 4. This figure includes the DFMS for January and July, for both the mean monthly conditions and the worst monthly conditions, corresponding to the minimum monthly FMC found in the 30-year period. During January, the highest latitudes of the northern hemisphere are covered in snow, and hence are considered to have wet fuels, and a FMS of D4L4. On the other hand, January means summer for the southern hemisphere, and higher temperatures determine lower FMCs in regions such as Australia and Patagonia. During July, the tropical rain belt is located in the northern hemisphere, and the tropics below the Equator have a dry season, which causes the fuel moisture content to be lower compared to January. This process is particularly noticeable in the southern African savannahs and in the Brazilian cerrados. On the contrary, during January the savannahs above the Equator are drier than during July, due to the shift of the tropical rain belt to the southern hemisphere.

The use of longitude strips derived in brusque changes in weather conditions along the borders of the strips, where at the west of the border the weather data corresponds to 15 hr. LST, while at the east it corresponds to 12 hr. LST. Although in most of the borders that situation did not produce differences in the wind or DFMS classes, it did in some cases, most prominently at longitude 0º in Northern Africa. But since that region is mostly desert, and has few vegetation, it did not cause an important effect in the resulting fire behavior results.

The combination of the 4 possible FMSs, the 3 wind classes, and the 3 slope classes, produced a total of 36 different environmental scenarios, which were used to run FCCS with the exiting fuelbeds. The environmental scenarios are classified as D(a)L(a)W(b)S(c), being a the FMS, b the wind class, and c the slope class. As an example, an environmental scenario of D2L2W1S3 would mean a FMS of 2, a wind class of 1 and a slope class of 3.

For the purpose of showing the differences in fire behavior due to changing environmental conditions, Figure 5 shows the rate of spread values obtained for January and July, during the mean and worst monthly conditions.
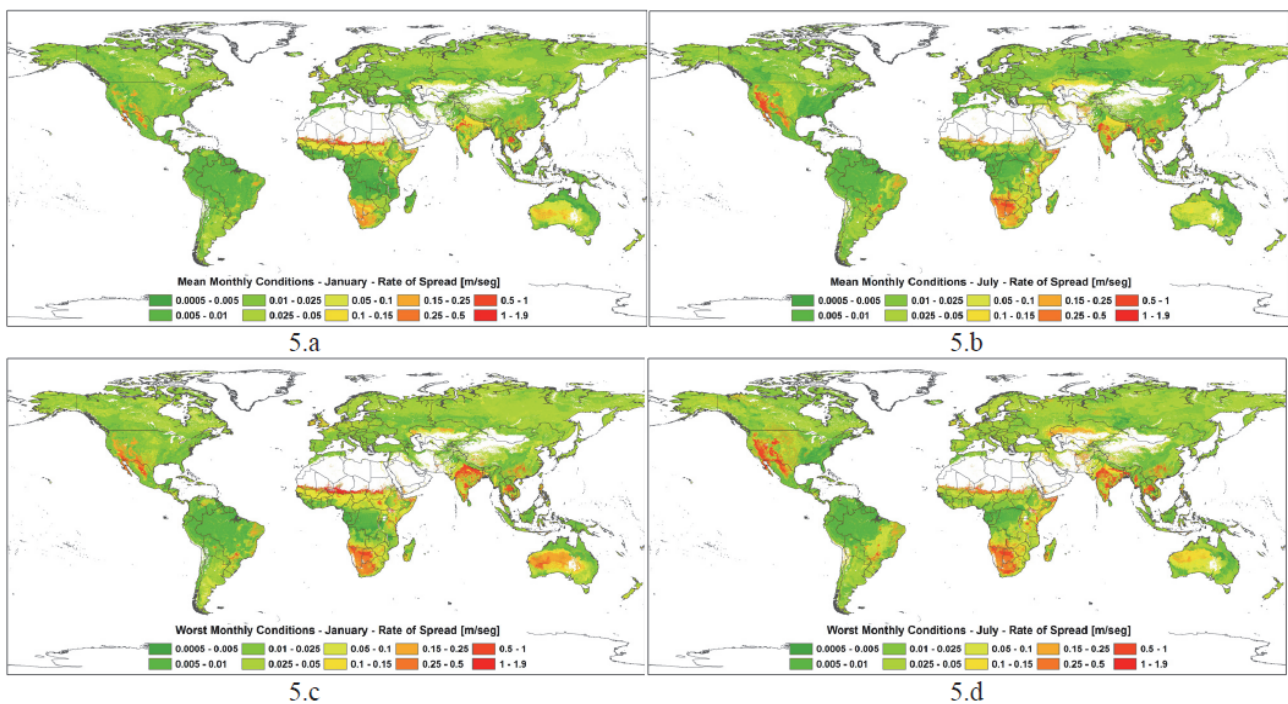

Figure 5. Rate of spread calculated for the global fuelbeds using the environmental conditions detailed in the legend of the maps.

The highest ROS values in Figure 5 (higher than 1 m/seg) belong to fuelbeds associated with grasslands (fuelbed numbers finishing in 140 or 180) and croplands (fuelbeds finishing in 015). The highest ROS correspond to rice croplands in tropical regions (fuelbeds 1015, 2015 and 14015), and vary in their value depending on the environmental conditions. The highest mean value for January is 1.63 m/seg, obtained for an environmental scenario D4L4W3S3. For the mean conditions in July, as well as the worst conditions in January, the highest value is 1.83 m/seg, for an environmental scenario D1L1W2S3. In the worst July conditions, the highest ROS value is 1.88 m/seg, but with an environmental scenario D2L2W3S2. These results indicate the prominent influence of wind on the rate of spread, as specified by the Rothermel's (1972) equations used in FCCS and in other fire behavior systems such as BehavePlus (Andrews *et al.* 2008) or FARSITE (Finney 2004).

The results of the rate of spread show the variation with the different environmental conditions in different seasons, as exemplified for January and July. This is particularly evident in the North American and Australian deserts, as well as in the African savannahs. The comparisons between the mean and worst monthly conditions also reflect the inter-year variability of the weather conditions, and should be taken into account when evaluating possible fire behavior results. The existence of extreme weather seasons can significantly increase the surface fire behavior, as shown in Figs 5.b and 5.d regarding the Brazilian Cerrado, or Figs. 5.a and 5.c in Africa.

4. Conclusion

This study developed environmental scenarios, based on global weather information and topography, in order to calculate the surface rate of spread using the Fuel Characteristic Classification System and a global fuel map previously developed. The results shown correspond to the months of January and July, in order to illustrate the temporal variability of the environmental conditions in different geographic regions. These results allowed obtaining more realistic results than in the past, where only one set of environmental conditions had been used for the whole globe.

 Still, these are preliminary results, and further refinement is needed. Future research will focus on improving the weather data to eliminate brusque changes in weather conditions along some longitudes, incorporating live fuel moisture scenarios to increase the environmental variability, and calculating other fire behavior parameters.

5. Acknowledgements

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