Vegetation Fire Smoke:

Nature, Impacts and Policies to Reduce Negative Consequences on Humans and the Environment

A Publication of the Council of Europe
Directorate of Culture and Cultural and Natural Heritage

prepared in the frame of the

European Open Partial Agreement on the Prevention, Protection Against and Organization of Relief in Major Natural and Technological Disasters – EUR-OPA Major Hazards Agreement

as a contribution to the

4th International Wildland Fire Conference
Sevilla, Spain, 13-17 May 2007

Wildfire2007

by

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1. Rationale

Air pollution generated by Vegetation Fire Smoke (VFS) is a phenomenon, which has influenced the global environment in prehistoric and historic time scales. Although historic evidence of the impacts of VFS on societies is rather scarce, there are indications that VFS has been a factor, which influenced society significantly since the Middle Ages. In the recent decades, increasing application of fire as a tool for land-use change, has resulted in more frequent occurrence of extended fire and smoke episodes with consequences on human health and security. Some of these events have been associated with droughts that are attributed to inter-annual climate variability, or possible consequences of regional climate change. In metropolitan or industrial areas, the impacts of VFS may be coupled with the emission burden from fossil fuel burning and other technogenic sources, resulting in increasing vulnerability of humans.

VFS is defined by a number of different topics, such as formation and transportation, composition, environmental, health and infrastructure impacts and by the strategies and tactics to cope with the impacts. The existing limitations regarding better understanding and measuring of the impacts, as well as, the voids in prevention and mitigation are challenges for scientists and organizations. Co-coordinated and joint efforts can increase awareness and prepare new guidelines, recommendations and policies. In the context of climate change, it is important that the state-of-the-art knowledge gained in all topics regarding VFS will be better publicized and dispersed, in the hope of better coping with all its impacts.

This work reviews the character, magnitude and role of pyrogenic gaseous and particle emissions on the composition and functioning of the global atmosphere, human health and security. Special emphasis is given on radioactive emissions generated by fires burning in peatlands and on terrain contaminated by radionuclides. The transboundary effects of VFS pollution are a driving argument for developing international policies; to address the underlying causes for avoiding excessive fire application and to establish sound fire and smoke management practices and protocols of cooperation in wildland fire management at international level.

2. Introduction

Vegetation Fire Smoke Pollution: Prehistoric and Historic Evidence

Prehistoric occurrence of fire smoke emissions and the deposition of fire smoke aerosol in lakes and on ice have been documented by a large number of sediment and ice core studies, which provide with important sources for reconstruction of fire activities [Clark et al., 1997]. Together with biogenic, marine and soil-dust particle, the smoke from vegetation fires has determined the composition and functioning of the natural global atmosphere before the expansion of human populations and industrial age [Andreae, 2007].

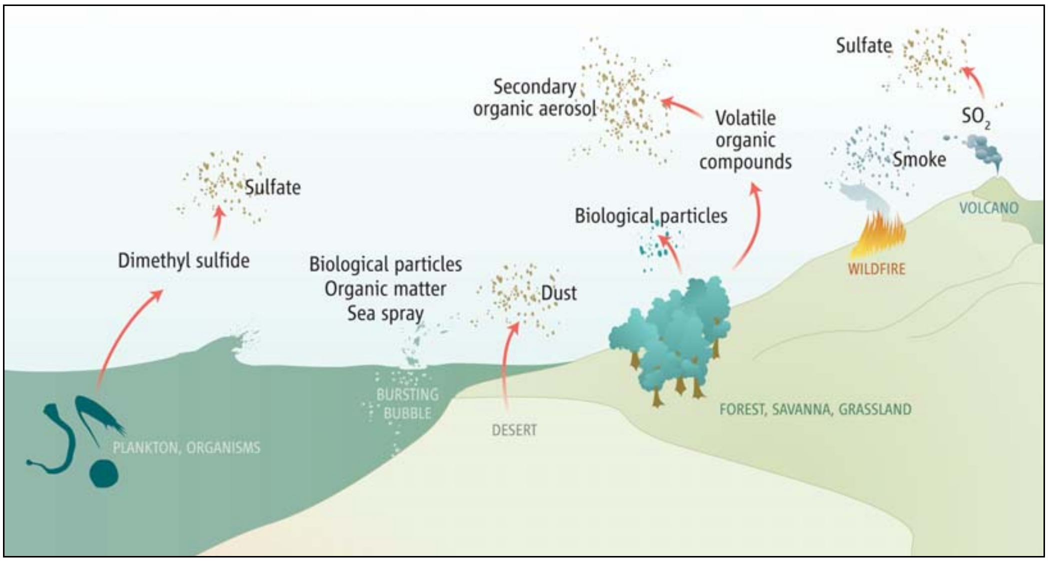

Figure 1. Sources of aerosol particles to the natural atmosphere: Primary particles – such as sea spray, soil dust, smoke from wildfires, and biological particles including pollen, microbes, and plant debris – are emitted directly into the atmosphere. Secondary particles are formed in the atmosphere from gaseous precursors; for example, sulphates that are formed from biogenic dimethyl sulfide and volcanic sulphur dioxide (SO_2), as well as, secondary organic aerosol from biogenic volatile organic compounds. Reprinted with the permission of Andreae 2007. Copyright: 2007 AAAS.

In the history of land-use phenomena and problems, association with vegetation fire smoke has been documented in a few cases. One example is the smoke pollution generated by land-use fires and land-use change in Northern Germany since the 16th Century. At that time, large uncultivated bogs and swamps dominated the region. With the population growth, people were forced to enlarge the area under production and started to cultivate these areas by burning the bogs [Goldammer, 1998].

Figure 2. Moor burning in Friesland (Frisia) around 1900. Sometimes smoke from these land-use fires covered large areas of Europe. Source: Archive, Fire Ecology Research Group / Global Fire Monitoring Center (GFMC).

Burning of bogs began usually in mid-May and ended in June. The drying of the organic material and the heat caused the break up of the normally barely accessible plant nutrients of the bog, enabling the cultivation of oat and buckwheat on the freshly burned fields without fertilization. The burning of bogs was first noted in the year 1583. Smoke pollution from bog burning seemed to have an oppressive effect on the northwest German areas, even in areas far away. This effect, the "smell of burning" was known under the term "High Smoke". First historic evidence of an extended regional European fire smoke episode dates back to the end of the 17th Century. In 1657, the bog burnings began on 6 May in Northern Friesland, carried by strong easterly winds. On the next day, the smoke had reached Utrecht (Netherlands), and a little bit later had changed direction, passing Leeuwarden towards Den Helder, and reaching the sea on 15 May. There, the wind changed northwest and drove the bog smoke back, so that on 16 May it had reached Utrecht and Nijmwegen again. At the same time, the smoke was also noticed in Hanover, Münster, Köln, Bonn, and Frankfurt. On 17 May 1657, the smoke reached Vienna, on 18 May Dresden, and on the 19 May Kraków (Poland).

Other historic evidence is provided by the description of a large-scale fire-smoke pollution in Russia in the year 1915 [Shostakovich, 1925]. There have been reported the effects of a 50-days fire episode between June and August 1915, during which more than 140,000 km^2 of forest lands were affected by fire between Angara River and Nijnya Tunguska. Smoke pollution was reported on a total land area of about 6 million km^2 with extreme pollution, resulting in visibility of less than 20 metres on more than 1.8 million km^2.

Contemporary Trends in Vegetation Fire Smoke Pollution

As a consequence of demographic developments and increasing pressure on vegetation resources in many developing countries, the application of fire as a land-clearing tool in large-scale land-use change projects, increased rapidly over the last three to four decades. In addition to traditional land clearing by smallholders shifting cultivation (slash-and-burn agriculture), the establishment of pastures and sugar cane plantations, e.g. in Brazil, or forest clearing for the establishment of palm oil plantations, or other cash crops in Southeast Asia, and also other tropical regions, involved massive burning of vegetation. During droughts, such as the dry spells associated with the El Niño-Southern Oscillation phenomenon, land-use fires also escaped to large uncontrolled wildfires, reinforcing the fire smoke burden at regional scale.

Other regions that are undergoing a trend of urbanization are experiencing an abandonment of the rural space. The rural exodus often results in an increase of wildfire hazard, due to decreasing land cultivation and utilization of vegetation resources. Increased fuel loads (combustible materials) are resulting in more severe and often uncontrollable fires. Portugal is one of the most impressive examples where land abandonment – coupled with the establishment of highly flammable eucalypt and pine plantations – has resulted in extended fire and smoke pollution episodes [Varela, 2005].

Other regions of the word are suffering an unhealthy combination of socio-economic, political and environmental drivers of ecosystem impoverishment and land degradation. In countries in transition in Eurasia the institutional and political capabilities to practice efficient forest and fire management have declined to an extent that fires are becoming almost uncontrollable. This is especially the case in the Central Asian region [Goldammer, 2006a], where regional droughts associated with illegal forestry activities, arson and negligence have resulted in extended severe fire episodes with smoke pollution affecting neighbouring countries and long-range smoke transport in the Northern hemisphere.

Exploring Vegetation Fire Smoke Characteristics and Impacts

Historically, knowledge regarding vegetation fire smoke has been acquired through observations and measurements on smoke produced in real forest/vegetation fires, as well as from experiments in wind tunnels and prescribed burning. Additionally, studies regarding the pyrolysis of lignicellulosic materials, combustion of wood and pyrolysis/combustion of biofuels provided detailed information on different issues regarding vegetation smoke. All these have established the basic knowledge regarding vegetation fire smoke formation, composition and transportation.

Moreover, recent studies using new approaches, methods and considerations have enhanced relevant knowledge and offered new potentialities. The state-of-the-art knowledge on VFS consists, among others, of better understanding the generation and transport of VFS components, advanced specialized monitoring methods, novel methods for monitoring human exposure, new approaches for toxicity assessment, as well as, novel methods for coping with VFS impacts. More specifically:

- There is a better understanding of the nature and the components of VFS.
- Its complexity has been measured and better recorded (advanced, specialized field monitoring methods, determination of additional hazardous smoke components)

In addition, new methods can be used for evaluating VFS health, environmental and infrastructure impacts (novel methods of monitoring exposure, new biomarkers, synergy with urban pollution, quantification of VFS contribution to the anthropogenic greenhouse effect).

Moreover, new approaches have been proposed and tested in coping with VFS impacts (novel personal protective equipment, specialized transport modelling, state-of-the-art methods of monitoring smoke transportation and dispersion, coping with irregularities in operation of critical infrastructures).

It appears that all these new methods, approaches, and considerations regarding VFS have many advantages but they also create scientific, operational, technical and organizational challenges.

3. Fundamentals

VFS formation

Generally, vegetation fire can be considered as a four-phase process consisting of the pre-ignition, flaming, smouldering and glowing phases. In the first phase (pre-ignition), heat from an ignition source or the flaming front evaporates water and low volatiles from the fuel and the process of pyrolysis begins. In the second phase (flaming), combustion of the pyrolysis products (gases and vapours) with air takes place. Flaming occurs if these products are heated to the ignition point, in contact with heat, e.g., flames from the fire-front. Temperatures in this phase range between 325-350°C [US NWCG, 2001]. The heat from the flaming reaction speeds the rate of pyrolysis and produces greater quantities of combustible gases, which also oxidize, causing increased flaming. The third phase (smouldering) is a very smoky process occurring after the active flaming front has passed. Combustible gases are still produced by the process of pyrolysis, but the rate of release and the temperatures are not high enough to maintain flaming combustion. Smouldering, generally, occurs in fuel beds with fine packed fuels and limited oxygen flow. In the fourth phase (glowing), most of the volatile gases have been burned and oxygen comes into direct contact with the surface of the charred fuel. As the fuel oxidizes, it burns with a characteristic glow, until the temperature is reduced so much that combustion cannot be continued, or until all combustible material is consumed [Johnson, 1999].

A vegetation fire is the result of interaction of three components - fuel, oxygen and heat of combustion. The fuel is in principle the forest, or more generally, the vegetation fuel. However, other types of fuels and/or materials may contribute to the VFS formation and composition, due to the flame-front expansion [Statheropoulos and Karma, 2007].

Vegetation fuels have specific characteristics, such as fuel moisture and fuel temperature, which contribute to the combustion process. The moisture content of the fuel depends on the meteorological conditions, such as the air temperature and relative humidity, as well as the type of vegetation, such as size and shape. Vegetation fuels can be categorized as ground level (1-150 mm), bush level (1.5-2.5 m), low and medium-tree level (3-5 m) and tall-tree level (>5m), depending on their height [Smith et al., 2000; NV, 2007]. Generally, vegetation fuel with high moisture content, such as big branches or tree trunks produces water vapour that lowers the temperature of combustion and hence, favours smouldering. The specific characteristics of the fuel, such as the amount and size burned contribute mainly to the quantity of the smoke produced.

The O_2 to fuel ratio is affected by meteorological conditions (e.g. wind speed and direction) and also vegetation characteristics, such as vegetation density (packing ratio), shape and arrangement (structure). The O_2 to fuel ratio mainly contributes to the type of components in the VFS. For example, evolution of CO and fine particles dominates in incomplete combustion (limited oxygen flow, smouldering phase), whereas in complete combustion (oxygen flow, flaming phase) the emission of CO_2 and H_2O is favoured. However, O_2 flow also affects the amounts of smoke produced, e.g. the amount of particulate emissions generated per mass of fuel consumed during the smouldering phase is more than double of the flaming phase [US NWCG, 2001].

The heat component of the triangle can contribute to the smoke components produced, i.e. it has been found that organic degradation of pine needles commences at 200-250°C, while maximum evolution rate of organic volatiles occurs in the temperature range of 350-450°C [Statheropoulos et al., 1997]; according to another source, peak production of combustible products occurs when the fuels are heated about 316°C [Johnson, 1999].

VFS composition

Generally, Vegetation Fire Smoke (VFS) is an aerosol, which is defined as a colloidal system in which the dispersed phase is composed of either solid or liquid particles in gas, usually air [Johnson, 1999].

VFS, basically, consists of water vapour, permanent gases, VOCs, SVOCs and Particles. Permanent gases include CO_2, CO, NO_x [Radojevic, 2003; Muraleedharan et al., 2000]. SO_x and NH_3 have also been reported. SO_x are usually produced in small quantities, because in general, vegetation fuel sulphur content is low [Ward and Smith, 2001]. Concentrations of SO_2 identified in Brunei Darussalam during the 1998 smoke-haze episode were all below WHO guidelines levels of 100-150 μgm^{-3} [Radojevic, 2003]. However, high amounts of sulphur-based compounds are evolved when sulphur-rich vegetation or soil are burned; e.g. significant quantities of SO_2 and H_2S were produced by forest fires burning in Yellowstone National Park [Reh and Deitchman, 1992]. NH_3 has been determined in savannah fires. The emission ratio of NH_3 relatively to CO_2 has been identified and found to be at low levels; NH_3 mostly emitted during the smouldering than during the flaming phase of combustion [Koppmann et al., 2005; Lacaux, 1995].

Methane [Miranda, 2004; Heil and Goldammer, 2001; Ward, 1999] and various Volatile Organic Compounds (VOCs) have been found in VFS. Hydrocarbons identified were aliphatic, such as alkanes, alkenes and alkynes. Representative compounds included ethane, heptane, decane, propene, 1-nonene, 1-undecene, acetylene [Statheropoulos and Karma, 2007; Shauer et al., 2001; Ward and Smith, 2001; McDonald et al., 2000]. Additionally, aromatic hydrocarbons, such as benzene and alkylbenzenes have been determined; e.g. toluene, xylene, ethyl-Benzene [Statheropoulos and Karma, 2007; Muraleedharan et al., 2000; Reh and Deitchman, 1992]. Moreover, VOCs mixtures included the following oxygenated compounds: alcohols (phenol, m-cresol, p-cresol, guaiacol) [Statheropoulos and Karma, 2007; Shauer et al., 2001; Ward and Smith, 2001; McDonald et al., 2000], aldehydes (formaldehyde, acetaldehyde, furfural, acrolein, crotonaldehyde, benzaldehyde) [Statheropoulos and Karma, 2007; Reinhardt and Ottmar, 2004; Shauer et al., 2001; Reh and Deitchman, 1992; Kelly, 1992], ketones (acetone, 2-butanone) [Statheropoulos and Karma, 2007; McDonald et al., 2000], furans (benzofuran), carboxylic acids (acetic acid), esters (benzoic acid, methyl ester) [Statheropoulos and Karma, 2007; Ward and Smith, 2001; McDonald et al., 2000; Muraleedharan et al., 2000; Reh and Deitchman,1992]. Also, it has been referred that during fire-place pine wood combustion experiments and in a pine forest fire incident, chloro-methane was detected in the smoke produced [Statheropoulos and Karma, 2007; McDonald et al., 2000]. Chloro-methane has been identified as the most abundant halogenated hydrocarbon emitted during biomass burning, mainly consisting of dead and living vegetation (e.g. savannahs, fuel wood, agricultural residues) [Koppmann et al., 2005].

Semivolatile Organic Compounds (SVOCs) found in the VFS were polyaromatic hydrocarbons (PAHs), e.g. benzo (a) Pyrene) [Booze et al., 2004; Muraleedharan 2000; Ward, 1999; Reh and Deitchman, 1992; Kelly, 1992].

Particles in VFS, depending on their size, can be either coarse (>PM_{10}) or fine ($PM_{2.5}$, PM_1, $PM_{1<}$). The particulate matter can be primary released to the atmosphere due to the combustion, or can be formed through physical or chemical transformations (molecular agglomeration of supersaturated vapours, nucleation). Primary particles can be elemental carbon or organic carbon particles.

Inorganic or elemental carbon, also known as graphitic or black carbon (soot), is a product of the incomplete combustion of carbon-based materials and fuels [CEPA, 1999].

Organic carbon can also be produced via secondary gas-to-particle conversion processes. Condensation of hot vapours (VOCs, SVOCs) during combustion processes (tars) and also nucleation of atmospheric species results to formation of new particles, usually below 0.1 μm in diameter. Generally, low-volatility products either nucleate or condense on the surfaces of pre-existing particles, yielding particles in the size range of 0.1-1.0 μm [CEPA, 1999].

Trace elements can also be contained in particles produced from forest fires, such as Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Zn, Rb, Sr, V, Pb, Cu, Ni, Br, Cr [Radojevic 2003; Muraleedharan et al., 2000; Ward and Smith, 2001; Reh and Deitchman 1992]. These species are known to concentrate in the fine fraction.

Particles (PM_{10}, $PM_{2.5}$) have been measured in different forest fires, such as during the Gestosa experimental fires in Portugal [Miranda et al., 2005], during the 1997 haze episode in SE Asia [Muraleedharan et al., 2000; Ward, 1999], in U.S. Montana 2000 wildfire season [Ward and Smith, 2001], in Korea during May 2003 (aerosol impact due to Russian forest fires) [Lee et al., 2005] and also in a forest fire in Greece [Statheropoulos and Karma, 2007].

However, VFS can exist as a more complicated mixture depending on the flame-front expansion. When the flame-front expands due to various reasons, e.g meteorological conditions, other fuels such as wastes can also be burned. In such case VFS can contain not only the components mentioned above, but also other hazardous pollutants, such as Dioxines (Polychlorinated Dibenzo-p-Dioxines/ Polychlorinated Dibenzo-Furans PCDDs/PCDFs), due to the pyrolysis and combustion of wastes. However, other types of fuels and/or materials may contribute to the VFS formation, affecting VFS composition i.e., when vegetation fire is expanding to rural fields, rural/urban constructions or landfills, then wood, plastics, fertilizers, or wastes can also be burned and materials, such as pulverized glass, cement dust, asbestos or plaster and also other chemical compounds can be contained in the smoke produced. Possible scenarios of forest flame-front expansion and the related VFS chemical composition have been integrated in a road map for air-quality assessment [Statheropoulos and Karma, 2007].

It has to be noted that radioactive species can, occasionally, be found in VFS. Their origin can be among others from vegetation fuel radioactively contaminated, e.g. a forest in the site of the Chernobyl Nuclear Power Plant Exclusion Zone [Poyarkov, 2006; Dusha-Gudym, 2005]. It has been reported that in 1992, severe wildfires that burned in the Gomel Region (Belarus) were spread into the 30-km radius zone of the Chernobyl Power Plant and it was found that within the 30-km zone the level of radioactive caesium in aerosols was increased 10 times [WHO/UNEP/WMO, 1999; Dusha-Gudym, 2005]. For more specific information see section 7 “Phenomena”.

<u>VFS lab and field measurements</u>

The determination of the concentration of VFS compounds is quite important for assessing, especially, the health impacts of VFS. It should be noted that in a wildfire incident, dynamic phenomena usually take place (e.g. turbulence is observed compared to laminar flows), very rapid changes of concentration profiles in space and time occur (periodicity is possible but with no constant period) and the environment is considered “heavy” (soot and tars are present, high temperatures and humidity are observed) and hostile, not only for the operator but also for the reliable operation of the measuring instruments. For that reason, the specifications for any type of chemical measurements are highly demanding; i.e., high selectivity, high resolution, ultra low limit of detection, dynamic concentration range. Especially, for carrying out field measurements instrument size and weight, power consumption and maintenance requirements, speed, ruggedness and simplicity of operation are additional specifications. Ideally, field instruments applied on air-quality monitoring in a vegetation fire should have the ability to analyze a broad range of types of compounds and the ability to determine a broad range of concentrations; concentrations may range from low to very high in different sites and hence, dynamic response in concentration changes in space and time is needed. Moreover, instruments should have the ability to measure in non-laminar air conditions (turbulence).

Minimum instrument contamination without any loss of compounds of interest, as well as minimum false alarms and minimum cross sensitivities are required. Instruments should also have the ability to measure human exposure [Statheropoulos et al., 2006].

VFS quantitative analysis

During vegetation fires, high values of peak concentrations of VFS components can be observed, especially, near the flame-front. In Table 1, mean concentrations of VFS components measured in "smoky" conditions in the field (sampling duration 20-30 min) that have been reported in literature are given [Statheropoulos and Karma, 2007; Miranda et al., 2005; Reinhardt et al., 2000; Pinto and Grant, 1999], together with the short-term limits recommended by the National Institute for Occupational Safety and Health (NIOSH).

Concentrations of PM_{10} as high as 47.600 μgm^{-3} have been referred [Reh and Deitchman, 1992], whereas the exposure limit for 24h given by American Conference of Governmental Industrial Hygienists (ACGIH) is 150 μgm^{-3}. Moreover, $PM_{2.5}$ levels measured in the field, at a distance of approximately 70m from the flame-front, were estimated to be 49,500 μgm^{-3} [Statheropoulos and Karma, 2007]; the respective ACGHI 24-h limit is 65 μgm^{-3}. Exposure of the firefighters to CO and formaldehyde can exceed legal and short-term exposure limits, occasionally, in smoky conditions; CO level has been referred exceeding the 200 ppm ceiling set by the NIOSH [Reinhardt et al., 2000].

Table 1. Mean concentrations measured in smoky conditions in the field and Short-Term Occupational Exposure Limits (STELs).

Compound	Concentration	Short term exposure Limits (NIOSH) (U.S.A. 1997)
CO[1]	54 ppm	200 ppm
CO_2[1]	350 ppm	30,000 ppm
Benzene[1]	0.22 ppm	1 ppm
Toluene[1]	0.12 ppm	150 ppm
Xylene [1]	0.08 ppm	150 ppm
Acroleine[2]	0.071ppm	0.3 ppm
Formaldehyde[2]	0.468 ppm	0.1 ppm
BenzoPyrene (BaP)[3]	7.1 ngm^{-3}	-
$PM_{2.5}$ [1,4]	[1]7,000 μgm^{-3}, [4]2,300 μgm^{-3}	[b] 65 μgm^{-3} (24-h)

[1] Statheropoulos and Karma (2007); [2] Reinhardt et al. (2000); [3] Pinto and Grant (1999), [4] Miranda et al. (2005)
[b] ACGIH

Air-quality monitoring in vegetation fires

General

Air-quality monitoring in a vegetation fire can be defined as the ability to, continuously, measure critical components of VFS. Generally, air quality monitoring in the field includes on-site and on-line analysis. Depending on the size, the weight, and the type of motion, field instruments can be categorised as portable instruments (hand-held, back-packed, luggage-carried), mobile labs (units, roving systems) and wearable instruments. Depending on the distance from the flame front, the instruments can be classified as stand-off and point devices (near the flame-front). Depending on the principle used for measuring (if the sample is excited or not), the instruments can be classified as active or passive. Depending on the height-level of monitoring, field methods can be classified as ground-based, aerial and space.

Portable instruments, such as hand-held sensors can be used for measuring CO, CO_2 and other permanent gases. Portable analyzers (hand-held or luggage-carried) can be used for measuring particles. Portable versions of PID analyzers, GC-MS (Gas Chromatography-Mass Spectrometry), GC-IMS (Gas Chromatography- Ion Mobility Spectrometry), GC-GC (Gas Chromatography-Gas Chromatography), and Ion Mobility Spectrometers, can be used for monitoring VOCs. These are mostly point and passive methods.

Mobile labs can use, among others, laser-based instruments, e.g. LIDAR (Light Detection And Ranging technique); a stand-off, active method for air-quality monitoring [NCRST-E, 2001]. LIDAR technique has been has been used for monitoring the impact of the 2002 Canadian forest fires on air quality in Baltimore City [Sapkota et al., 2005; Adam, 2004]. TOF-MS (Time-of-Flight Mass Spectrometry) is another laser based, point, active method that has recently been used for single particle size and composition measurements, in the size range of 30 to 3000 nanometres (Aerosol-TOF-MS) [Filimundi, 2006]. A roving GC-MS system has been used for mapping emissions' concentrations in area [McClennen et al., 1996], which can be also used for air quality measurements in vegetation fires.

Wearable instruments, is new and emerging type of instruments, which is strongly based in micromachining and miniaturization, and can be either "worn" or can be part of the uniform of an operator. This is the case of miniaturized ion mobility spectrometry system (μ-IMS), used as alarm device, as well as for monitoring of human exposure [Vautz, 2006]

Ground based methods

Analytical instruments have been used, mostly, as ground based methods for monitoring smoke and aerosols, generated by vegetation fires [Grant, 1999]. These systems measure meteorological parameters, and do GIS positioning. They also carry out on-site aerosols measurements, monitor visibility and determine molecular species (CO, O_3 and hydrocarbons). However, they do have limitations in samples capacity and concentration ranges when running on-line measurements.

Hand-held sensors and portable instruments can also be used as ground based methods. Additionally, diffusion dosimeters with the principle of gradient analysis, such as the long-term diffusion tubes [Vautz, 2006; Reh and Deitchman, 1992], can be also used as ground based methods to estimate the concentrations of specific pollutants of interest. However, those devices have limitations regarding identification of unknown compounds and may be strongly affected by background interferences (cross-sensitivity), providing thus with false responses.

Field sampling in a fire incident needs fast moving, high-speed separation of the VFS complex mixture and quick and reliable estimation of real-time data, in order to address effective emergency response plans and protective measures for the operational people and the exposed population. Hyphenated instruments referred above, e.g. Gas Chromatography-Mass Spectrometry (GC-MS), for monitoring volatiles and gases, as well as Aerosol Time of Flight Mass Spectrometer (ATOFMS) for the on-line chemical analysis of particles, provide with capabilities for covering the requirements of VFS field monitoring. A hyphenated technique that may also be used for the on-line monitoring of VFS in the field is the Pulsed Sampling/Mass Spectrometry [Tzamtzis et al., 2006]; this method allows for direct sampling of VFS in ambient conditions, in an environment characterized by dynamic phenomena and rapid changes of components concentrations in time and space. Specifications of portable units and devices for monitoring air-quality in a "smoky" environment, such as the one in a vegetation fire, are presented elsewhere [Agapiou, 2005].

Aerial methods

Aerial methods of monitoring air quality include aerial measurements of pollutants in the smoke plume, by using aircrafts [Johnson, 1999]. Field observations by aircraft measurements have shown elevated ozone levels in forest fire smoke plumes (Stith et al, 1981). Moreover, small helium-filled balloons can be used to determine mid-level wind direction, so that to ensure that smoke will not affect any smoke-sensitive areas [Johnson, 1999].

Figure 3. Aerial VFS monitoring in Indonesia in the early 1990s by the Global Fire Monitoring Center (GFMC). Source: GFMC

Figure 4. DC-3 research aircraft of the Max Planck Institute for Chemistry used for aerial VFS measurements during the SAFARI-92 campaign. Source: GFMC

Figure 5. Aerial VFS monitoring during the research campaign AFARI-97, Kenya 1997. Source: GFMC

Space methods

There are satellite systems with aerosol detection capability. The NOAA Polar Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR) and the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) are such examples. The NASA Stratospheric Aerosol and Gas Experiment (SAGE) provides vertical resolution. The Total Ozone Mapping Spectrometer (TOMS) depicts aerosols at coarse resolution. A relationship between MODIS Aerosol Optical Thickness (AOT) and ground based hourly fine particulate ($PM_{2.5}$) has been shown [Hutchison, 2003; Wang and Christopher, 2003]. The MOPITT (Measurement of Pollution in The Troposphere) instrument aboard the NASA Earth Observing System (EOS) Terra satellite is a thermal and near IR gas correlation radiometer, designed specifically to measure CO profiles and total column CH_4.(Figure 7). CO pollutant can also be used as a tracer for other pollutants, such as ozone at or near ground level [Edwards, 2003].

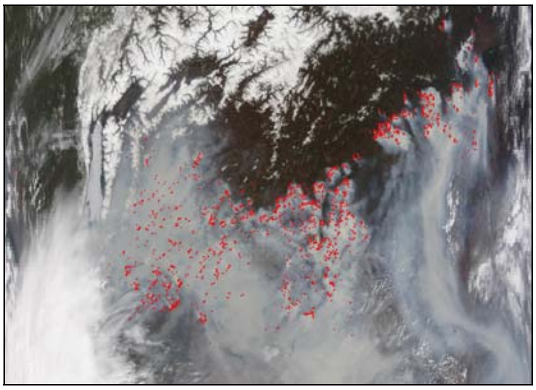

Figure 6

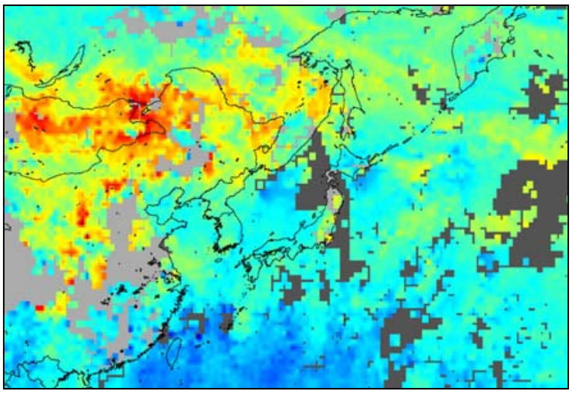

Figure 7

Figure 8

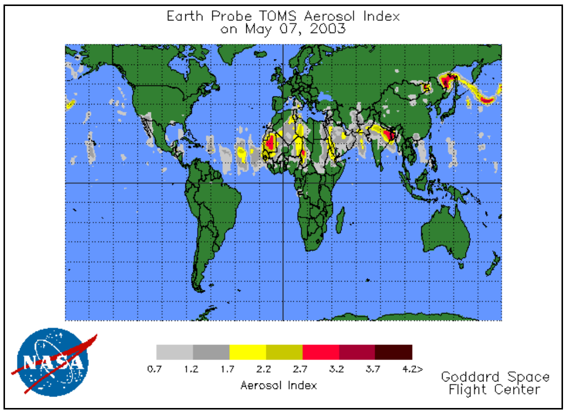

Figure 9

Figure 6. Active fires in the Transbaikal Region (Russian Provinces Chita and Buryatia) depicted by the MODIS instrument on Terra, 8 May 2003 (courtesy: NASA). **Figure 7**. 3-8 May 2003 carbon monoxide concentration originated by VFS in the Transbaikal Region depicted by the MOPPIT instrument on the Terra satellite (courtesy: NASA). **Figure 8**. Smoke plume from fires burning in the Transbaikal Region on 8 May 2003, stretching to Sakhalin and N Japan (MODIS). **Figure 9**. Same situation on 7 May 2003 as depicted by NASA TOMS.

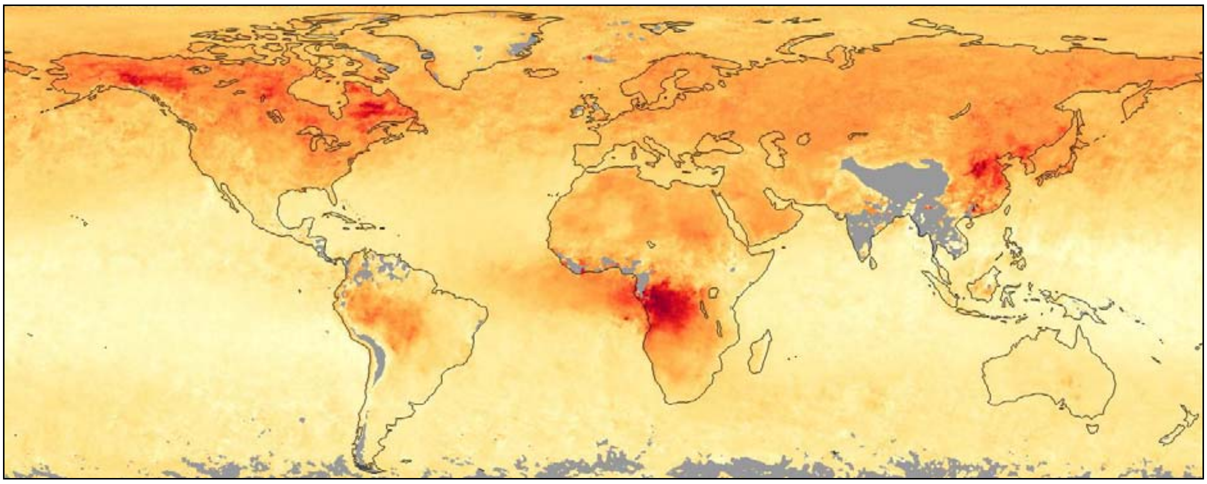

Figure 10. Global carbon monoxide (CO) concentrations in the northern hemispheric summer of 2004 depicted by the MOPITT sensor. A record fire season in Alaska in 2004 spread smoke across the Northern Hemisphere and elevated CO levels across North America and Europe. Red indicates high concentrations, while yellow indicates low concentrations. The high levels over China are caused by industrial and urban pollution. The high CO concentrations in Sub-Saharan Africa are generated by savanna fires. The Alaskan fires released approximately 30 tg (teragrams – 1 tg = 1 million metric tons) of CO (for comparison of global estimates – see section 4 below). Source: NASA Earth Observatory (2006).

4. Magnitude and type of vegetation affected by fire

National statistical databases on the spatio-temporal extent of wildland fires – numbers and size of fires occurring in forests, other wooded lands and other lands – are not only important for fire management planning, but also for environmental; economic and humanitarian impact assessments. In the majority of the countries of the world, the data collected by agencies on the ground or by aerial monitoring are not reflecting the full extent of wildland fires. In most countries the forestry agencies or other services are collecting data only for the protected forests and other protected vegetation under their respective jurisdiction. Only in a few countries data of grassland, steppe and peat bog fires are entering the statistical databases. The fire statistical data provided by the recent survey in the regions of the Global Wildland Fire Network in the frame of the Global Forest Resources Assessment 2005 (FRA 2005) are reflecting this general situation and therefore do not provide a complete picture.

Other datasets on spatial and temporal occurrence of vegetation fires have been produced, based on various spaceborne sensors, such as the NOAA AVHRR, MODIS, MERIS, ASTER and SPOT-Vegetation instruments. These datasets include all vegetation types affected by fire. Active fires and area burned recorded from space include both the ecologically benign fires burning in fire-dependent or adapted ecosystems, and the economically and environmentally detrimental fires burning in fire-sensitive systems. Thus, these satellite-derived data cannot be compared directly with the conventionally collected data of the forest services, which are generally restricted to wildfires occurring in production or protected forests.

One of the global satellite-derived assessments of land areas affected by fire in the year 2000 was conducted by the Global Vegetation Monitoring (GVM) Unit of the Joint Research Center (JRC), in partnership with other six institutions, using the medium-resolution (1 km) satellite imagery provided by the SPOT-Vegetation system [JRC, 2002]. According to the dataset, the global vegetated area affected by fire in the year 2000 was 350 million hectares. Details on the area burned by country can be downloaded at the JRC website [JRC, 2002].

Based on such global satellite-derived datasets and / or published statistics and models, a number of studies have been conducted to estimate total global gaseous and aerosol emissions from vegetation fires, e.g. the most recent Global Wildland Fire Emission Model (GWEM) [Hoelzemann et al., 2004].

Table 2, provides an overview of global emission of selected species annually emitted from vegetation fires in the late 1980s, based on emission factors as summarized by Andreae (2004).

Table 2. Global annual emission of selected pyrogenic species in the late 1990s (in mass of species per year; Tg a^{-1}). Note: 1 Tg = 1 million metric tons; dm = dry matter.

	Savanna and grassland	**Tropical forest**	**Extra-tropical forests**	**Biofuel burning**	**Charcoal making and burning**	**Agricultural residues**	**Total pyrogenic**	**Fossil fuel burning**
Tg dm burned	3160	1330	640	2663	196	1190	9200	---
CO_2	5096	2101	1004	4128	169	1802	14,300	23,100
CO	206	139	68	206	19	110	750	650
CH_4	7.4	9.0	3.0	16.2	1.9	3.2	41	110
NMHC	10.7	10.8	3.6	19.3	0.4	7.6	53	200
Methanol	3.8	2.6	1.3	3.9	0.16	2.1	13.8	---
Formaldehyde	1.1	1.8	1.4	0.4	0.10	1.4	6.3	---
Acetaldehyde	1.6	0.86	0.32	0.36	0.05	0.68	3.9	---
Acetone	1.4	0.83	0.35	0.06	0.05	0.65	3.3	---
Acetonitrile	0.33	0.24	0.12	0.48	0.01	0.21	1.4	---
Formic acid	2.1	1.4	1.8	0.35	0.11	0.3	6.0	---
Acetic acid	4.2	2.8	2.5	2.4	0.30	1.0	13.1	---
NO_x (as NO)	12.2	2.2	1.9	2.9	0.16	3.0	22.3	45
N_2O	0.67	0.27	0.17	0.16	0.01	0.08	1.4	2.0
NH_3	3.4	1.7	0.88	3.5	0.06	1.5	11.0	0.4
SO_2	1.1	0.76	0.64	0.73	0.015	0.48	3.7	228
COS	0.05	0.05	0.02	0.11	0.01	0.07	0.31	---
CH_3Cl	0.24	0.10	0.03	0.14	0.0005	0.28	0.80	---
CH_3Br	0.006	0.010	0.002	0.008	0.00011	0.004	0.031	---
$PM_{2.5}$	16.1	12.0	8.3	19.1	0.34	4.6	60	---
TPM	26.2	11.3	11.3	25.1	1.1	15.5	91	---
TC	11.7	8.7	5.3	13.8	0.24	4.8	45	27
OC	10.6	7.0	5.8	10.5	0.18	3.9	38	20
BC	1.5	0.88	0.36	1.6	0.06	0.82	5.2	6.6
K	1.09	0.39	0.16	0.14	0.02	0.33	2.1	---
CN	1.1E+28	4.5E+27	2.2E+27	9.1E+27	1.3E+26	4.0E+27	3.1E+28	---
CCN (1% SS)	6.3E+27	2.7E+27	1.7E+27	5.3E+27	7.6E+25	2.4E+27	1.8E+28	---
$N_{(>0.12\ \mu m\ dia.)}$	3.7E+27	1.3E+27	6.4E+26	2.7E+27	3.8E+25	1.2E+27	9.6E+27	---

Abbreviations: $PM_{2.5}$: particulate matter <2.5 μm diameter, TPM: total particulate matter, TC: total carbon, BC: black carbon, CN: condensation nuclei, CCN: cloud condensation nuclei at 1% supersaturation, $N_{(>0.12\ \mu m\ dia.)}$: particles >0.12 μm diameter.

5. Smoke Dispersion

VFS produced in an incident of big vegetation fire is usually transported many kilometres away from the flame-front. Distribution of VFS is depended on the meteorological data (wind speed and direction, temperature, relative humidity RH%). Usually, fine particles can be transported to long distances (cross border transfer), whereas the coarse particles deposit on surfaces (e.g. soil, streams). In Table 3, some of the VFS pollutants and their transfer through the environment are presented [Brauer, 1999]. According to Nakajima et al. (1999), during the 1997 episode in Southeast Asia, the smoke-haze layer covered an area up to 10 million km^2. Moreover, during 2002, the Canadian forest fires in a province of Quebec affected the PM levels of Baltimore U.S.A., located hundreds of kilometres from the source [Sapkota et al., 2005]. Fires in Canada were also found to cause high concentrations of carbon monoxide and ozone over a period of two weeks in the Southeastern United States and across the Eastern seaboard during the summer of 1995 [Wotawa, 2000].

Table 3. Indicative VFS compounds and how they are transported from the source [Brauer, 1999].

Compound	Example	Notes
Permanent gases	CO, CO_2	Transported over distances
	O_3	Only present downwind of fire- transported over distances
	NO_2	Reactive concentrations decrease with distance from fire
Hydrocarbons	Benzene	Some transport - also react to form organic aerosols
Particles	PM_{10}	Coarse particles are not transported and contain mostly soil and ash
	$PM_{2.5}$	Fine particles transported over long distances

Specialized modelling of VFS dispersion

Atmospheric transport models (ATMs) can be used for predicting the area that will be affected by VFS and the concentrations of pollutants (gases, VOCs and particles). The movement of the pollutant through the atmosphere, as a result of the mean wind field and turbulent mixing processes, is balanced by the difference between the emission inputs and pollutant losses due to deposition by wet and dry processes. There are two main modelling approaches: Lagrangian models that follow the trajectories of segments or particles and Eulerian models, which solve the diffusion equation at every point on a fixed grid [Tapper and Hess, 1999].

The transport of forest fire emissions (e.g., CO) has been simulated by using the Lagrangian particle dispersion model FLEXPART for the burning seasons of 1997 and 1998; the results of the model simulation were in good agreement with ground-based, as well as satellite-based measurements [Spichtinger et al., 2004]. A numerical system called AIRFIRE has been developed to estimate the effects of vegetation fires on air quality, integrating several components of different modules, such as the mesoscale meteorological model MEMO, the photochemical model MARS, and the Rothermel fire spread model [Rothermel, 1972]. The system was applied to simulate plume dispersion from a wildfire that occurred in a coastal area, close to Lisbon city, at the end of September 1991. Results, namely the obtained pollutants concentration fields, point to a significant impact on the local air quality. Estimated carbon monoxide concentration levels were very high, exceeding the recommended hourly limit value of the World Health Organization, and ozone concentration values pointed to photochemical production [Miranda, 2004].

Dispersion of VFS has been studied using direct-detection LIDAR measurements and a Reynolds-averaged Navier-Stokes fluid dynamics model. Comparison between experimental and theoretical results showed that the model adequately describes the influence of the main factors that affect the dispersion of a hot smoke plume in the presence of wind [Lavrov et al., 2006].

6. Main Environmental Problems

Environmental Impacts

VFS can have impacts on the air, water and soil. The long-term effects of vegetation fire emissions on atmospheric composition and global processes have been presented and discussed [Houghton, 1992]. Short-term effects of forest fires include elevated trace gas, aerosol and CO_2 levels, nitrogen deposition, acid precipitation, and local climatic changes, all of which may have direct negative or positive effects on plant functioning in undisturbed forests [Vitousek et al., 1997; Bazzaz, 1990; Fan et al., 1990]. Environmental impacts of VFS include the increase of the ground level ozone, due to photochemical reactions of VFS components in the presence of NO_2, e.g. CO and VOCs are considered ground-level ozone precursors [Hogue, 2005]. It has been reported that the big wildfires in Alaska and the Canadian Yukon during the summer of 2004, generated huge plums of CO and other pollutants and affected large areas of the Northern Hemisphere by increasing ground-level ozone [Barry, 2005]. Moreover, according to another study there was evidence that Canadian forest fires in 1995 changed the photochemical properties of air masses over Tennessee on days during the fire period [USDA, 2002]. During the 1997-98 SE Asia fire-smoke episode, enhanced concentrations of CO_2, CH_4 were observed throughout the troposphere from eastern Java to the South China Sea [Heil and Goldammer, 2001]. Additionally, it has been reported that photosynthesis of three tree species was reduced by the smoke-haze of 1997 in Indonesia, due to elevated aerosol and atmospheric pollutant levels [Davies and Unam, 1999]. VFS particles can pollute surface water directly, by deposition, or can be part of the soil. In this case and after a rainfall, suspended soil particles, as well as dissolved inorganic nutrients and other materials, can be transferred into adjacent streams and lakes, reducing water quality and disturbing aquatic ecosystems balance. In sandy soils, leaching may also move minerals through the soil layer into the ground water [USDA, 1989].

Recent research reveals that, as a consequence of climate change, mercury reserves once protected in cold northern forests and wetlands, will increasingly become exposed to burning. Mercury is released to the atmosphere with fire smoke. Turetsky et al. (2006) quantified organic soil mercury stocks and burned areas across western boreal Canada; it was assumed that, based on ongoing and projected increases in boreal wildfire activity due to climate change, atmospheric mercury emissions will increase and contribute to the anthropogenic alteration of the global mercury cycle and to the exacerbating mercury toxicities for northern food chains.

Impacts of VFS on Critical Infrastructures

Reduced visibility is the main impact of VFS on critical infrastructures. The following are recorded incidents: In 1994, VFS from fires in Sumatra (Indonesia) reduced initially the average daily minimum horizontal visibility over Singapore to less than 2 km. Later, the visibility in Singapore dropped to 500 m. At the same time, the visibility in Malaysia dropped to 1 km in some parts of the country [WHO/UNEP/WMO, 1999]. Other impacts on infrastructures include the irregularities in operation of airports (reduced or cancelled flights), highways and hospitals, as well as, of army camps. For example the regional airports in Indonesia were closed during the haze period of 1997. In 1982-83, 1991, 1994 and 1997-98, the smog episodes in South East Asia resulted in closing of airports and marine traffic. In addition, accidents in the highways or possible airplane crash and human losses can be the result of reduced visibility. Several smoke-related marine and aircraft accidents occurred during late 1997 [WHO/UNEP/WMO, 1999]. From 1979 to 1988, 28 fatalities and more than 60 serious injuries were attributed to smoke that drifted across roadways in the Southern United States [Mobley, 1990]. According to a study [Muraleedharan et al., 2000], the haze impact on areas, where a school and a hospital were situated, during the 1998 smoke episode in Brunei Darussalam was significant. Limited data and case studies exist regarding VFS impacts on critical infrastructures for risk management.

Figure 11: People exposed to VFS in East Kalimantan, Indonesia, during the 1997-98 fire-smoke episode. Source: A. Hoffmann (GFMC).

Figure 12: VFS pollution in Khabarovsk, Far East of the Russian Federation caused by forest and peat fires in NE China / Far East of Russia (18 October 2004). Source: L. Kondrashov, Pacific Forest Forum

7. Phenomena

Peatland fires

The above-cited and well-investigated recurring regional VFS pollution in South East Asia, a phenomenon largely resulting from application of fire in land-use change and extended wildfires, are observed since the 1980s. Despite the ASEAN Agreement on Transboundary Haze Pollution, signed by the ASEAN member states in 2001, which aimed at reducing regional smoke-haze caused by VFS, the inappropriate and illegal use of fire land vegetation conversion, especially on drained peatlands, is still practiced [Goldammer, 2006b]. The recent public interest on emissions from peatland conversion fires is fuelled by the controversial debate on the increasing conversion of peatlands to establish oil palm plantations as source of “bio energy”.

While much public attention has been given to regional VFS pollution in Southeast Asia, there is limited scientific and public coverage on the transboundary transport and impacts of peat fire smoke on human health and security in the northern hemisphere.

Fact of the matter is that fires burning in drained or desiccated peatlands are an important source of extended fire smoke pollution in formerly cultivated and nowadays abandoned regions of Northern Eurasia. In Western Russia, peatlands have been drained and used for agricultural purposes since the early 19th Century. The fen Peatlands were used as agricultural fields but are out of use now. According to the Wetlands International Russia Programme, peatland fires are a common phenomenon in the Russian Federation [Minaeva, 2002] and may contribute to about 10% of the total area burned [Shvidenko and Nilsson, 2000]. In most cases, the fires started outside the peatlands, caused by forest visitors, hunters, tourists, or by agricultural burning and burning activities along roads.

In September 2002, the VFS from peat and forest fires in Moscow Region reduced the visibility to less than 100 meters in Moscow, where the concentration of carbon monoxide exceeded the permissible values by more than three times (European Water Management News, 2002). The smoke pollution did not only cause a dramatic reduction of visibility but also had detrimental impacts on the health of the Muscovite population, and resulted in an increase of hospital admissions. In spring 2006, smoke from peat and forest fires in Western Russia was noted in the United Kingdom. In summer 2006, VFS from fires burning in Russia persisted over Finland for weeks [GFMC, 2006].

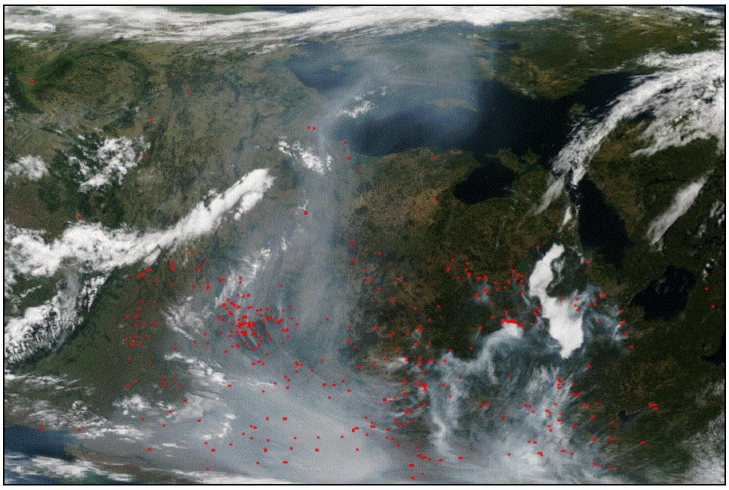

Figure 13

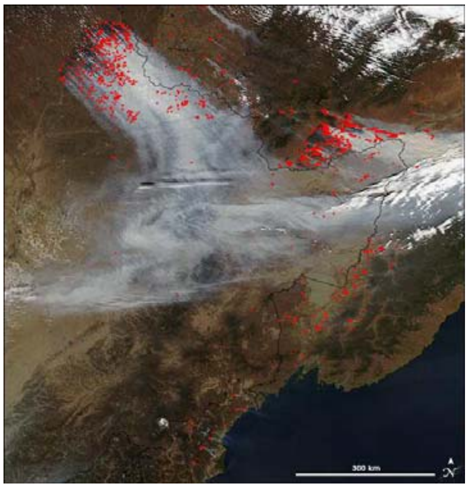

Figure 14

Figure 13 (left): Satellite scene of Western Russia on 4 September 2002. The heat signatures of the peat and forest fires are given in red colour. The smoke plumes (light blue haze) stretch from Western Russia to Belarus, Poland and the Baltic Sea. **Figure 14 (right):** Smoke transport from fires (marked in red) in northern China (top left) and south-eastern Russia (right) on 15 October 2004. Source: True colour image by Moderate-Resolution Imaging Spectroradiometer (MODIS), resolution 2 km.

Short- to long-distance transport of smoke has also been noted within Central and East Asia during the last years. The fire episodes of 1998 (Far East), 2003 (Transbaikal region) and 2004 (North-East China, Jewish Autonomous Region) caused severe smoke pollution in the Far East of Russia. The consequences of regional smoke pollution in 2004 were recorded in Khabarovsk and revealed that both aerosol and carbon monoxide concentrations exceeded the maximum permissible concentrations [Goldammer et al., 2004].

Transport of Radionuclides in Vegetation Fire Smoke

As a result of failure on the Chernobyl nuclear power plant, a total of 6 million ha of forest lands were polluted by radionuclides. The most polluted forest area covers over 2 million ha in Gomel and Mogilev regions of Belarus, in Kiev region of Ukraine and in Bryansk region of the Russian Federation. The main contaminator is caesium-137 (^{137}Cs); in the core zones of contamination strontium-90 (^{90}Sr) and plutonium-239 (^{239}Pu) are found in high concentrations. This region constitutes the largest area in the world with the highest contamination by radionuclides and is located in a fire-prone forest environment in the centre of Europe.

Every year, hundreds of wildfires are occurring in the contaminated forests, peatlands and former agricultural sites. Between 1993 and 2001 a total of 770 wildfires in the closed zone of Ukraine affected 2,482 ha. In the period 1993-2000, 186 wildfires occurred in the closed zone of Belarus and affected an area of 3,136 ha including 1,458 ha of forest. The above-cited report from Ukraine reveals that in 2002 alone, a total area of 98,000 ha of wildland was burned in the contaminated region of Polissya.

Under average dry conditions the surface fuels contaminated by radionuclides – the grass layer and the surface layer of peatlands – are consumed by fire. Most critical is the situation in peat layers, where the radionuclides are deposited. The long-range transport of radionuclides lifted in the smoke plumes of wildfires and their fallout on large areas were investigated in detail in 1992. Radioactive smoke plumes, containing caesium-137, were monitored several hundred kilometres downwind from the sites where fires occurred in May and August 1992 [Dusha-Gudym, 2005].

This risk of radioactive contamination has not decreased substantially and is particularly threatening the population living in the immediate environment of the accident site (4.5 million people). Radioactive emissions are also a high risk for firefighters. In addition, populations are affected by radioactive smoke particles transported over long distances [Dusha Gudym, 2005; Poyarkov, 2006].

A similar situation is found on the territory of Kazakhstan. At the Semipalatinsk Nuclear Weapons Test Site, more than 450 nuclear tests, including ca. 100 atmospheric tests, were conducted for a period of 40 years between 1949 and 1989. Radioactive contamination is highest in Eastern Kazakhstan, including the fire-prone pine-strip forests along the Irtysh River at the border to the Russian Federation (Gorno-Altay). A recent report reveals that radioactive emissions from fires burning in Central Asia in 2003 were recorded in Canada [Wotawa et al., 2006].

8. Human health impacts of FVS

Toxicity of the VFS

Generally, toxicity is defined as the deleterious or adverse biological effects caused by a chemical, physical, or biological agent. Toxicity can be acute, defined as any poisonous effect produced within a short period of time, or chronic, defined as the capacity of a substance to cause adverse human health effects as a result of chronic exposure. For evaluating acute toxicity, toxicity indicators can be used, such as the LC_{50} (concentration of a substance at which 50% of the tested population is killed), or the EC_{50} (concentration of a substance at which 50% of the tested population are affected [ContamSites, 2007]. For evaluating chronic toxicity the LOEC (lowest observable effect concentration) can be used. The toxicity of chemicals is also related to the duration of the exposure. Generally, exposure is defined as the contact made between a chemical, physical, or biological agent and the outer boundary of an organism. Acute, is the exposure by the oral, dermal, or inhalation route for 24 hours or less. Chronic, is the repeated exposure by the oral, dermal, or inhalation route for more than approximately 10% of the life span in humans. Exposure Assessment is defined as the identification and evaluation of the human population exposed to a toxic agent, describing its composition and size, as well as the type, magnitude, frequency, route and duration of exposure [EPA, IRIS].

Toxicity of the Vegetation Fire Smoke mixture is the additive or the synergistic result of all the possible hazardous smoke components, depending on the fuel types burned and the possible materials contained in the VFS. Additive toxicity is defined as the toxicity of a mixture of contaminants that is equal to the summation of the toxicities of the individual components. Synergistic toxicity is defined as the toxicity of a mixture of contaminants that may result to a total toxicity far greater than the summation of the toxicities of the individual components [ContamSites, 2007].

Vegetation Fire Smoke can contain toxic compounds such as:

- ***Respiratory irritants:*** Irritants can cause inflammation of mucous membranes. Ammonia and nitrogen dioxide are indicative examples. Irritants can also cause changes in respiration and lung function, such as sulfur dioxide, formaldehyde and acrolein [MSU, 2005]. According to specific studies, formaldehyde and acroleine were found suspected for causing respiratory problems to the exposed fire-fighters [Reinhardt et al., 2000; Reinhardt and Ottmar, 2004].

- ***Asphyxiates:*** They prevent or interfere with the uptake and transformation of oxygen. Examples include carbon monoxide, which in high concentrations can result in immediate collapse and death [MSU, 2005]. Methane and Carbon dioxide are also considered asphyxiates. A 17% inhaled oxygen content is the safe limit for prolonged exposure. A 5% oxygen content is the minimum compatible with life. Concentrations of 1% produce stupor and memory loss [Stefanidou-Loutsidou, 2005].

- ***Carcinogens:*** A carcinogen is a chemical, known or believed to cause cancer in humans. The number of proven carcinogens is comparatively small, but many more chemicals are suspected to be carcinogenic [PTCL, 2007]. Weight-of-Evidence (WOE) for carcinogenicity is a system (U.S. EPA) for characterizing the extent to which the available data (human or animal data) support the hypothesis that an agent can cause cancer to humans. WOE descriptors are classified from A to E; group A are known human carcinogens, whereas group E are compounds with evidence of non-carcinogenicity [EPA, IRIS]. Carcinogens can be of three categories: Category 1, are substances known to be carcinogenic to humans, for which there is sufficient evidence to cause cancer development; Category 2, are substances for which there is sufficient evidence of causing cancer to humans, based on long-term animal studies and other relevant information; Category 3, are substances that can possibly have carcinogenic effects but for which available information is not adequate to make satisfactory assessments [UB, 2007]. According to the above, benzene is considered as A (human carcinogen), formaldehyde as B1 (probable human carcinogen), acetaldehyde as B2 (probable human carcinogen), crotonaldehyde as C (possible human carcinogen), toluene and phenol as D (not classifiable as human carcinogens) [EPA, IRIS].

- ***Mutagens:*** A mutagen is an agent that changes the hereditary genetic material. Such a mutation is probably an early step to the development of cancer, e.g. formaldehyde, acroleine [PTCL, 2007]. Teratogens may cause non-heritable genetic mutations or malformations in the developing foetus, e.g. toluene [PTCL, 2007].

- ***Systemic Toxins:*** They are chemicals, which can cause toxic effects, as a result of their absorption and distribution to a site distant from their entry point [EPA, IRIS]. An example is the heavy metals e.g. lead, mercury and cadmium [Stefanidou-Loutsidou, 2005], which may be contained in the VFS particles, especially when the flame-front expands to waste disposals (landfills) [Statheropoulos and Karma, 2007].

- ***Toxic effect of particles:*** Fine particles, known as respirable, are more aggressive than coarse; they aren't stopped by the cells of the respiratory tracts and can penetrate the lungs. In this way, hazardous compounds absorbed by the fine particles can reach the air cells [Cesti, 2004; Fowler, 2003; Dawud, 1998; Malilay, 1998]. Toxic effect of particles is related to the quantity of toxic substances that maybe absorbed and the affinity for site of action (enzyme, membrane). In general, biological absorption of particles by human body can take place by filtration through pores of membranes, simple diffusion, facilitated diffusion, active transport (against concentration gradient) or endocytose (pinocytose – phagocytose). Biological absorption can be oral (mouth, stomach, intestine, colon), pulmonary, cutaneous (skin), ocular (eyes) or parenteral. Some of the health effects due to particles can be acute toxicity, skin corrosion/irritation, serious eye damage/eye irritation, sensitisation (allergy), germ cell mutagenicity, carcinogenicity, specific target organ systemic toxicity (TOST), respiratory irritation etc. [Seyenaeve, 2006].

Exposure to VFS

Exposure to vegetation fire smoke (VFS) can be quantified as the concentration of the smoke components in the subject in contact, integrated over the time duration of that contact. In order to have a more representative assessment of VFS health impacts, it should be considered that exposure to VFS is simultaneous exposure to multiple substances, such as gases, liquids, solids (mixed exposure). A potential synergism may exist among various VFS components.
Exposure can be characterized as point, area/surface or network; such exposure characteristics should be taken into account for addressing exposure limits. Temporal/averaged, discrete/sporadic or continuous/cumulative exposure has to be taken into account in order to calculate an averaged, sporadic or cumulative exposure, respectively [Seyenaeve, 2006].

Fire fighters' exposure to VFS is characterized mostly by a standard periodicity (every summer) and high frequency (e.g. long-lasting fires). Hence, the ability to measure on-line their exposure is considered critical. Exposure of population to VFS is not a continuous situation. However, susceptibility of the receptors should also be taken into consideration during exposure assessment, as long as sensitive groups, such as children, pregnant women, people with respiratory problems and the elderly are considered more vulnerable [USEPA, 2001].

Exposure limits

Various Health Organizations and relevant services have established exposure limits for compounds that are characterized "suspected for causing health implications". The most well known health organizations and the respective limits are the ACGIH-TLV (American Conference of Governmental Industrial Hygienists-Threshold Limit Value), the Occupational Safety and Health Administration - Permissible Exposure Limit (OSHA-PEL) and the National Institute for Occupational Safety and Health-Recommended Exposure Limit (NIOSH-REL). These limits have been established for occupational exposure of 8h or 24h. In addition, for some compounds are given the Short Term Exposure Limits (STEL).

However, these Occupational Exposure Limits (OELs) have limitations. For example, hyper-susceptibility is not taken into consideration. In addition, Threshold Limit Values assumptions take place for a young and healthy worker that might not be representative, especially for the exposed population. Moreover, inhalation is considered the main route of exposure and the exposure pattern is 8 hours/day / 5 days/week [Seyenaeve, 2006]. Though, in emergency situations work-shifts of the firefighters are often extended.

For unusual schedules, adjustments of these limits to the extended work-shifts need to take place [Kelly, 1992; Reh and Deitchman, 1992]. Threshold limits for the fire-fighters exposure to VFS is an issue that needs further study. The time duration of the shifts varies, depending on the extension of the fire. In addition, the distance of the shift camping from the fire-front is usually not enough so that the firefighter to recover from smoke inhalation. Camping in a distance from the fire and smoke front is a problem, especially in the case of forest fires in small islands, where dispatching means and personnel is difficult [Statheropoulos, 2005].

Especially for the exposure to particles, during a vegetation fire very high concentrations of particles at short time duration may be observed; that short-term peaks may cause some of the most significant health implications. Hence, the 24-h assumption of particles for OELs might not be efficient for short-term risk assessment in a vegetation fire. It should be emphasized that official exposure limits of particles in the front-line are not exist. However, there was an effort to provide with some criteria, in order to assess the severity of the situation in a forest fire [USEPA, 2001]. Adjustment of the existing exposure limits to the hostile conditions of vegetation fires has to be taken into consideration, not only for the exposed population, e.g. for the sensitive groups, but also for the fire-fighters of the front-line. In addition, exposure limits to VFS components should be addressed considering that VFS exposure is taking place in the field, compared to occupational indoor exposure.

Exposure assessment of VFS

A number of methods have been used for monitoring personal exposure. The “Personal Exposure briefcase” and the “Micro- Environmental (ME) box” [Vardoulakis, 2006] are among them; they use air-samples collecting cartridges for later analysis in the lab. Long-term diffusion tubes (Draeger) have been used for measuring exposure in personal breathing zone of the firefighters [Reh and Deitchman, 1992]. Diffusive sampling of BTEX by a SPME method has also been reported [AIHA, 2004]. A method that is based on breath air analysis has been preliminary tested [Statheropoulos et al, 2006].The method is using Tedlar bags for collection of expired air samples of the subjects, who were exposed to VFS; samples were transferred into multi-bed sorbent tubes and analyzed by a TDU-GC-MS (Thermal Desorption- Gas Chromatography-Mass Spectrometry) instrument. The Volatile Organic Compounds (VOCs) determined consisted of products of several metabolic pathways (endogenous compounds) and the inhaled contaminants (exogenous compounds).

In general, exposure assessment to VFS hazardous compounds can be carried out by using:

- Compounds in urine samples for wood smoke exposure, (e.g. family of methoxylated phenols, levoglucosan) [USEPA NW, 2003; USEPA NW, 2002].
- VOCs analysis in expired air, for the determination of compounds such as BTX, styrene or other, as indicators of fire-fighters exposure [Statheropoulos et al., 2006]
- VOCs analysis in the air to determine compounds that are characterized as potential carcinogens (e.g. Butadiene-1,3; Benzopyrene) [Vardoulakis, 2006].
- Exposure models that are using various physicochemical properties as a tool for VFS impacts assessment. VFS physical and chemical properties affect its duration as a stressor in human and also the environment. The size and shape of particles in VFS are critical, as long as fine ($PM_{2.5}$, $PM_{<1\mu m}$) and aerodynamic particles can be transferred in long distances and also can penetrate more easily the respiratory system, causing more severe health effects. Among the chemical properties, alkalinity and acidity are important; alkaline pH of particles is known to cause nose and chest irritation. In addition, vapour pressure of VFS components is correlated with their ability to persist in the environment. Another factor of interest is Henry’s low constant, which provides with additional information regarding how compounds are distributed between gas and liquid phase; high value means that the compound tends to remain in gas phase. Moreover, chemical’s octanol-water partition coefficient gives information regarding compound absorption efficiency from human body and organic carbon sorption coefficient of compounds characterizes the ability of special filters to retain a compound [Hogue, 2006].

- Numerical approaches

Various numerical approaches have been proposed in the literature:

a) Calculating the assessment criterion Em for mixed exposure
According to the equation (1), the mixed exposure assessment of fire-fighters due to their exposure to VFS complex mixture, has been done by calculating the assessment criterion Em:

$$Em = C_1/T_1 + C_2/T_2 + ... + C_i/T_i .... + C_n/T_n \quad (1),$$

where, Ci represents concentrations of the respective substances and Ti represents the threshold limit value of the respective substances (American Conference of Governmental Industrial Hygienists, ACGIH). Values of Em more that 1 are considered critical [Morioka et al., 1999]. Em values have been estimated for acroleine, formaldehyde and respirable particulate ($PM_{3.5}$), during fire-fighters work-shifts [Reinhardt et al., 2000].

b) CFK equation for estimating Carboxy-hemoglobin (COHb) in blood

Another numerical approach is the use of CFK (Coburn, Foster, Kane) equation. Inhalation of CO increases production of Carboxy-hemoglobin (COHb) in blood. If concentration level of COHb exceeds 5%, then various symptoms can be recorded (tissues hypoxia that causes headache, dizziness, nausea) [Reh and Deitchman, 1992].

c) *Calculation of exposure limit reduction factor in non-traditional work-shifts*

To evaluate compliance of non-traditional work-shifts with 8-hour PELs, OSHA uses simple formulas to calculate an exposure limit reduction factor. Equation (2), is used to calculate CO exposure during an extended work-shift:

$$\text{Adjusted CO exposure limit} = \text{PEL} \times \frac{8}{\text{Duration}} \quad (2)$$

where, Adjusted CO exposure limit = the revised exposure limit to account for the extended work-shift, PEL = the permissible exposure limit (or other exposure limit, such as the TLV) and Duration = the duration of the extended work-shift (hours) [Reinhardt et al., 2000].

d) Calculation of Time-Weighted Average (TWA) exposures

In order to estimate the Time-Weighted Average (TWA) exposures of fire fighters over the duration of a work-shift and while on the front-line, another numerical model has been proposed:

$$\text{TWA} = \frac{C_1 \times T_1 + C_2 \times T_2 + ... + C_n \times T_n \text{ TWA}}{T_1 + T_2 + ... + T_n}, \quad (3)$$

where, Tn = the time in minutes of period n, and Cn = the pollutant concentration during period n [Reinhardt et al., 2000].

9. Conclusions

VFS is a complicated mixture with serious impacts on the environment and human health, as well as the national economy (Rittmaster et al., 2006). Strategies and tactics exist to cope with its impacts. However, a number of issues are still open for further elaboration and decision making. The Health Guidelines for Vegetation Fire Events prepared by the WHO-UNEP-WMO (2000) in dealing with potential risks to public health of emissions from vegetation fires are still valid by recommending the need to investigate:

- Characterization of the magnitude and composition of the emissions and their transformations during transport;
- Quantification of resulting concentrations of ambient air pollutants in populated areas;
- Evaluation of likely exposure scenarios for affected populations (both indoors and outdoors);
- Assessment of consequent health risks posed by such human exposures.

More generally speaking, the Guidelines recommend a number of research and development topics, including:

- Development of dedicated space-borne remote sensing technologies for improving decision support in fire management, including technologies for fire detection and early warning;
- Impact of climate change on fire regimes and fire severity;
- Implementation of a global vegetation fire inventory, and the implementation of a centre to monitor, archive, and disseminate global fire information, as well as forecast fire and related hazards;
- Special attention to fire-generated radioactive emissions;
- Development of source information for fires in different ecosystems;
- Physical/chemical factors contributing to the changes that occur over time and space during transport;
- Compilation of information pertaining to levels of exposure and fire activity, in conjunction with past fire and smoke episodes;
- Mitigation approaches;
- Health impacts of air pollution due to biomass burning within the general population.

In addition, a “catalogue of ideas” was prepared in a teleconference entitled “Short and long term health impacts of forest fire smoke on the fire-fighters and the exposed population” [FFNet 3, 2005], organized by the European Center for Forest Fires (ECFF) (a Center which operates in the framework of the European Open Partial Agreement on the Prevention, Protection Against and Organization of Relief in Major Natural and Technological Disasters - EUR-OPA Major Hazards Agreement). This catalogue includes the following:

- Forest fire smoke is a complex mixture of chemical compounds produced from combustion of forest fuel. However, as fire expands, it may burn constructions, landfills or crops. Asbestos, glass cement and combustion products of plastics, pesticides, insecticides can potentially be found in forest fire smoke. Data need to be collected regarding this concept.
- Forest fire front is characterized by dynamic phenomena. Very rapid changes in compounds concentration profiles in space and time are observed. Temporarily, extremely high concentrations of chemical compounds and particles can be measured near the flame-front (e.g. $PM_{2.5}$ as high as 50,000 μg/m^3, CO at 44 and benzene at 700 μg/m^3). Firemen have to be well aware of this situation. On-line monitoring is possible with small, portable devices, e.g. for particles (μg/m^3) and CO.
- Forest fire smoke plumes can travel very big distances (even continents) and cross borders. In big forest fire incidents, the air quality of areas situated in long distance from the incident can be disturbed. Trans-border management may be needed.
- Surveillance and monitoring the air quality in the fire front, as well as, in a distance from the forest fire is necessary. However, present generation of sensors (mainly for monitoring light gases), of instruments (for monitoring VOCs and SVOCs) and of particle analyzers are not designed for surveying a heavy, hostile (for humans and devices) environment and for measuring on-line in the field. More research is needed towards this direction.
- Prioritization of forest fire smoke components is needed in regard to safety and health impacts to firemen and population. Studies and workshops can be the potential framework for deciding on these issues.
- The synergism of various compounds and materials found in forest fire smoke and the possible photochemical reactions, which may occur and can be responsible for surface level ozone increase, need to be investigated.
- Exposure limits for the fire-fighters need to be established, taking into consideration the complexity of smoke, the dynamic phenomena which occur during a forest fire, the nature of firemen's work, the duration of work-shifts and the site of the shift camping. Research and studies, with strong operational components, might be the way for providing solutions.
- Existing PPE (Personal Protective Equipment), as simple as a surgical mask and as complicated as operational masks needs to be benchmarked with careful experimentation.
- Exposure limits of population and especially for infants, elderly people, pregnant women, and people with pre-existing cardiovascular and respiratory diseases have to be set and criteria of evacuation need to be considered. Evaluation of existing or similar studies needs to be carried out.

Concerning the protection of fire fighters, it should be taken into consideration that Personal Protective Equipment (PPE) has to be effective, easy to use and flexible. A number of specific tactics have been referred in the literature by various organisations and researchers [Johnson, 1999]. According to the NIOSH investigators, it is recommended that the use of bandannas should be prohibited. The firefighters should be provided with single-use filter respirators, designed to remove dusts and mists. These masks should have filters 99% efficient in removing particles with a geometric mean diameter of 0.4 to 0.6 microns and a standard geometric mean deviation no greater than 2 Moreover, they should consist of exhalation valves, increasing the level of comfort to the user. Such respirators will provide the firefighter with better protection than bandannas, provided that they are worn properly and they are fit-tested [Reh et al., 1994].

A novel method for protection of the firefighters is called “the escape mask”, which is used in the South of France (department Bouches du Rhone) in order to reach a survival area (note: that mask must not be used during regular fire fighting) [Raffalli, 2006].

Until now, there is no available mean that protects from all the hazards of smoke [Johnson, 1999]. For example, although respiratory protection exists for irritants, such as aldehydes and particulate matter, it is not currently possible for carbon monoxide [Reinhardt and Ottmar, 2004]. However, selfcontained breathing apparatus (SCBA) respirators or full-face respirators could provide with a better protection against VFS, but generally they are not considered very practical because they encounter problems, such as difficulty to be carried, heat load and fogging [Reinhardt and Ottmar, 2004].

Masks can also be used for the protection of the exposed population, e.g. during the Hoopa Valley forest fires in California 1999, filtered (N95) and non-filtered masks (paper/surgical masks, or bandanas) were distributed [Mott et al., 2002]. However, mask use (filtered or not) might not be proved ineffective; this can be associated with hours of outdoor exposure, not fit-testing and the variability in filtration effectiveness of the masks.

A question is raised regarding the appropriateness of recommending masks to the general population in severe smoke episodes, taking also into consideration that such a recommendation could encourage outdoor exposure [Mott et al., 2002].

A number of recommended actions for public health are presented in the following, in order to decide on evacuation in hazardous smoke conditions [USEPA, 2001]. The actions are based on monitoring particles concentration levels (Table 4).

Table 4. Recommended actions for coping with smoke impacts based on the particulate concentration levels [USEPA, 2001].

Categories	**$PM_{2.5}$ or PM_{10} Levels (μg/m^3 1-hr to 3-hr)**	**Recommended Actions**
Good	0-40	If smoke event forecast, implement communication plan
Moderate	41-80	- Issue public service announcements (PSAs) advising public about health effects/symptoms and ways to reduce exposure - Distribute information about exposure avoidance
Unhealthy for sensitive groups	81-175	- If smoke event projected to be prolonged, evaluate and notify possible sites for clean air shelters - If smoke event projected to be prolonged, prepare evacuation plans
Unhealthy	176-300	- Close schools (possibly based on school environment and travel considerations) - Consider cancelling public events, based on public health and travel considerations
Very unhealthy	301-500	-Close schools -Cancel outdoor events (e.g. concerts and competitive sports)
Hazardous	> 500	-Close schools -Cancel outdoor events (e.g. concerts and competitive sports) -Consider closing workplaces not essential to public health -If PM level projected to continue to remain high for prolonged time, consider evacuation of sensitive populations

It should be noted that evacuation of an area might not be always proved effective. According to a study in Hoopa Valley forest fires (California 1999), evacuation did not reduce self-reported lower respiratory health effects. Various considerations exist regarding evacuation for an extended period of time [Mott et al., 2002].

In regard to reduced visibility, particulate matter in wood smoke has a size range near the wavelength of visible light (0.4-0.7 micrometers) and hence, smoke particles efficiently scatter light and reduce visibility. Initial air quality estimation is possible by assessing visibility impairment, as shown in Table 5 [USEPA, 2001].

Table 5. Air quality assessment based on visibility impairment

Categories	Visibility in Miles	PM Levels (1hour average, µg/m^3 $PM_{2.5}$ or PM_{10}
Good	10+	0-40
Moderate	6 to 9	41-80
Unhealthy for sensitive groups	3 to 5	81-175
Unhealthy	1.5 to 2.5	176-300
Very unhealthy	1 to 1.25	301-500
Hazardous	0.75 or less	> 500

Due to the direct and indirect health and environmental impacts of VFS early identification of the situation is necessary for effective copying with the impacts. Early warning systems may provide effective tools for fire and smoke management in local, regional, and global applications. Information on current weather and vegetation dryness conditions provides with the starting point of any predictive assessment. From this information, the probability of the risk that a wildfire will start and the prediction of the possibility of current fire behaviour and fire impacts can be derived. Short- to long-range fire weather forecasts allow assessing the fire risk and severity within the forecasting period. Advanced space-borne remote sensing technologies allow for fire weather forecasts and vegetation dryness assessment, covering large areas (local to global) at economic levels and with accuracy that otherwise cannot be met by ground-based collection, and dissemination of information. Remote sensing also provides with capabilities for detecting new fires, monitoring ongoing active wildfires and land-use fires, and in conjunction with fire weather forecasts, an early warning tool for assessing extreme wildfire events.

10. Challenges ahead: Public policies addressing wildland fire smoke

The primary aim of this paper was to provide a state-of-the-art report on the nature of vegetation fire smoke emissions. Exposure and vulnerability of humans to fire emissions, however, are demanding for information on options for limiting smoke impacts on human health and security. A number of recent vegetation fire smoke pollution episodes have caused public concerns and alerted policy makers. Some responses such as calls or laws for eliminating the use of fire in land management have resulted in conflicts, contradicting effects, or are difficult – if not impossible – to enforce. Examples include the fire use ban in Indonesia, which is in force since the mid-1990s and has been proven to be ineffective. As stated above, the ASEAN Agreement on Transboundary Haze Pollution, signed by the ASEAN member states in 2001 and aimed at reducing regional smoke-haze caused by VFS, has proven to be inefficient – largely because Indonesia was not willing and able to reduce inappropriate and illegal use of fire in land-use change, especially on drained peatlands (Goldammer, 2006).

An example of contradicting effects is the reduction of prescribed burning in the U.S.A. due to limitations imposed by the U.S. Environmental Protection Agency standards. These limitations have resulted in a reduction of application of prescribed fire for various land management objectives in the 1980s and 1990s. Clearly, smoke products from prescribed fire are basically identical with those emitted from uncontrolled wildfires (Ward et al., 1993). The application of prescribed fire, however, includes smoke management options, which will reduce smoke impacts on humans. The reduction of prescribed burning resulted in the build-up of fuels, which – in turn – contributes to the risk of large, high-intensity and high-severity fires that are difficult to control, including uncontrollable and comparatively more severe impacts of smoke.

Besides the implications of fire bans on potentially uncontrolled fires and smoke production, it must be reminded that fire exclusion from fire-adapted or fire-dependent ecosystems, which require a regular influence of fire, would result in dramatic changes of structure, biodiversity, stability and productivity. A complete exclusion of fire from land-use systems would affect livelihoods of hundreds of millions of people worldwide.

However, the transboundary transport of vegetation fire smoke from one country to another country is increasingly subject of public and political debates. Three recent cases may highlight this issue. In May 2006 Western Europe including the United Kingdom were affected by fire smoke pollution generated and transported from vegetation burning in Western Russia. As a consequence of the high concentration of PM_{10} monitored in the United Kingdom the UK Department for Environment, Food and Rural Affairs (DEFRA) announced that the UK government was going to push for a revision of the United Nations Convention on Long Range Transboundary Air Pollution to prevent similar occurrences in the future (GFMC, 2006).

In August 2006 the VFS emissions from Western Russia, Ukraine, and Belarus was transported to the Nordic countries. Smoke exposure was particularly severe in Finland where the air pollution exceeded the limits of the maximum permissible amount of airborne dust in city air of 50 micrograms per cubic metre of air for almost two weeks. In order to deal with this transboundary process a joint Russian-Finnish wildland fire exercise was held in Karelia (Finland) soon after these events (GFMC, 2006).

In March-April 2007 the fire smoke generated by numerous land-use fires in Northern Thailand, Myanmar, Lao, China and Cambodia caused an extremely severe regional smoke pollution. The situation was aggravated by an extraordinary meteorological phenomenon, which trapped the smoke close to the ground. This resulted in a situation similar to the close-to-ground pollution in Southern Malaysia and Singapore as a consequence of Indonesia's land-use fires. Tensions and international discussions on defining common solutions were reported from the region (GFMC, 2007).

These examples reveal the transboundary and international nature of vegetation fire smoke emissions, and that there is a problem in an increasingly vulnerable global society, which we need to address cooperatively and collectively. Bilateral and multilateral agreements are necessary to address thee issues. An international agreement – legally binding or voluntary – could be helpful to set standards for prevention and response to vegetation fire smoke pollution. The use of the WHO/UNEP/WMO Health Guidelines for Vegetation Fire Events (WHO/UNEP/WMO, 1999), the Voluntary Fire Management Guidelines (FAO, 2006), the Global Fire Monitoring Center (GFMC) and the mechanism of the UNISDR Global Wildland Fire Network (UNISDR, 2007) are available to facilitate such an international approach.

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