Impact of climate change on occupational exposure to solar radiation

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Abstract
Occupational exposure to solar radiation may induce both acute and long-term effects on skin and eyes. Personal exposure is very difficult to assess accurately, as it depends on environmental, organisational and individual factors. The ongoing climate change interacting with stratospheric ozone dynamics may affect occupational exposure to solar radiation. In addition, tropospheric levels of environmental pollutants interacting with solar radiation may be altered by climate dynamics, so introducing another variable affecting the overall exposure to solar radiation. Given the uncertainties regarding the direction of changes in exposure to solar radiation due to climate change, compliance of outdoor workers with protective measures and a proper health surveillance are crucial. At the same time, education and training, along with the promotion of healthier lifestyles, are of paramount importance.

INTRODUCTION

In the framework of the impact of climate change on occupational safety and health the exposure to solar radiation (SR) of outdoor workers is a key topic [1]. As a matter of fact the interplay between climate change, stratospheric ozone dynamics and other environmental factors (for instance particulate and gaseous atmospheric pollutants) may significantly affect both acute and long-term occupational exposure to SR, altering over time the total amount of specific spectral bands of SR reaching the earth surface. This in turn may increase or decrease the risk of adverse health effects of SR on skin and eyes, especially the long-term ones, for workers performing their activity outdoors. In addition, environmental factors (*e.g.* microclimate parameters or specific pollutants) potentially modulating several biological effects of SR may be modified by the changing climate. After an overview of factors affecting human exposure to SR and health effects attributed to SR and to its single components, this paper addresses the role of the ongoing climate change and discusses its potential impact on outdoor workers' health, taking into account co-exposures, personal habits and the role of both collective and individual protective measures. In addition, research needs and recommendations are provided.

HUMAN EXPOSURE TO SOLAR RADIATION

SR is mostly optical radiation, spanning from ultraviolet (UV) to infrared (IR) radiation, including visible radiation (light), although ionizing radiation (cosmic rays, gamma rays, X rays) and radiofrequency radiation are also present in the solar spectrum but to a so limited extent at ground level that they do not have health implications. UV radiation (UVR) covers the spectral range between 100 and 400 nm and includes the sub-bands UVC (100-280 nm), UVB (280-315 nm) and UVA (315-400 nm). Visible radiation ranges from 380 to 780 nm, while IR radiation (IRR) covers the spectral window 780 nm-1 mm. IR is subdivided into IRA (780-1400 nm), IRB (1400-3000 nm) and IRC (3000 nm-1 mm). The composition of the solar spectrum out of the atmosphere does not correspond to that at the ground level, as the atmosphere attenuates some spectral components (for instance UVC is completely absorbed by stratospheric ozone, while UVB is only partly blocked). UVR represents about 5-6% of SR at ground level and is composed at noon by 95% of UVA and 5% of UVB, while light and IRR represent, respectively, approximately 45 and 50% of the solar spectrum (IRA alone accounts for over 30% of the solar spectrum) [2-4].

Regarding human exposure to UVR, "dose" is expressed as radiant exposure, measured in J/m^2, representing the UV energy incident on the surface unit of a target like the skin or the eye. Accordingly, UVR "dose rate" is expressed as irradiance (power incident on the surface unit), measured in W/m^2. UVR dose is frequently expressed as "effective" dose, *i.e.* the UVR dose in a given spectral range weighted on an action spectrum representing the efficacy of radiation at different wavelengths in inducing a biological effect, *e.g.* the erythema. In this

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regard, the Minimal Erythemal Dose (MED) is the effective UVR dose able to induce a "just perceptible erythema" on a previously unexposed skin. As MED may be highly variable depending on phototype and other conditions, a Standard Erythemal Dose (SED) was introduced [5]; 1 SED is equal to 100 J/m² of UVR weighted on the standard action spectrum for erythema.

UVR displays a high variability in terms of human exposure being strongly susceptible to the influence of both environmental and individual factors [3, 6, 7]. UVR at the ground depends on time of day (a significant UV exposure occurs between 9:00 a.m. and 3:00 p.m., sun time, with the maximum values between 11:00 a.m. and 1:00 p.m., being UVB much more affected than UVA), season, latitude (3-4% increase for each degree of latitude toward the equator) and altitude (an increase of 300 m in altitude determines a 4% increase of the UVR). Cloudiness is a key factor in determining the amount of UVR reaching the earth surface. For instance, a complete and thick cloud cover blocks almost all the UVB component (while a part of UVA still passes); on the opposite, an incomplete cloud cover or the presence of sparse cloudiness may even increase the UVR reaching ground, with respect to a clear sky, because of scattering and reflections. Moreover, human exposure at ground level is greatly affected by type, extension and spatial orientation of surrounding surfaces. Water surfaces (sea, lakes etc.) and the fresh snow, as well as surfaces of metallic structures, reflect a great proportion (up to 100%) of the incident UVR, determining high exposures. On the opposite, trees and vegetation in general may shield at various degree the UVR. Human exposure is mainly affected by the time spent outdoor and the type of activity. Single parts of the body are differentially exposed to solar UVR, depending on garments worn and on the position with respect to the sun or reflecting surfaces, which, in turn, depends on posture and movements.

UV index is a tool to facilitate the communication of the intensity of solar UVR to the general public [8, 9]. The unit of the UV index is equal to 0.9 SED/h and the UV index value is generally included in the range between 1 (very low) and 10 (very high) sometimes reaching, at low latitudes and/or high altitudes, extreme 11+ values. In the last two decades, UV index has been generally provided daily (or even hourly) worldwide, with a good spatial resolution for an increasing number of locations. A radiative transfer model is applied for UV index calculation taking into account weather conditions; however, UV index is a measure of the direct UVR reaching the ground, not including all reflected or diffused components.

The remaining part of the solar spectrum responds in a similar way to climate change. In particular, IRR, due to important absorption by water, is severely affected by the variability in cloud cover, contributing to the establishment of thermal gradients and exacerbating the intensity of extreme weather events.

HEALTH EFFECTS OF SOLAR RADIATION

As optical radiation does not penetrate deeply biological tissues, skin and eyes are the main biological targets of SR, which however is also responsible of systemic effects. Acute and long-term effects of SR, both deleterious and beneficial, are summarized in *Figure 1*. Effects on wellbeing and circadian rhythms due to both natural and artificial light (see for instance [10]) continue to be poorly characterized. Consequently, their modulation by environmental factors is hard to study and any speculation is currently inappropriate.

Health effects of SR are mostly attributed to UVR, with UVA and UVB differently propagating in and interacting with biological tissues as described hereinafter. UVB may reach the basal layer of the epidermis while UVA, more penetrating, may reach the dermal tissue, which may absorb a significant fraction of the incident UVA [4]. At the eye level, UVR < 290 nm is completely blocked by the corneal tissue while a significant proportion of UVA (60-80%) crosses the cornea and is absorbed by the lens; about 1% of the UVA incident to the eye surface may reach the retinal tissue [11,12].

UVR may be absorbed by macromolecules like DNA and proteins, altering their molecular structures. DNA is regarded as the main target of UVR and DNA lesions (mainly cyclobutane-pyrimidine dimers and 6-4-photoproducts) are produced by both UVB and UVA, although the former is much more efficient. DNA lesions may trigger a lot of molecular events ultimately responsible for both acute and chronic effects, but UVR, especially UVA, is also able to form Reactive Oxygen Species (ROS) in cells and to activate exogenous and endogenous photosensitizing molecules, leading to phototoxic and photoallergic reactions [13, 14]. Finally, UVR exposure may be associated to epigenetic alterations in skin cells [15].

UVR is responsible of both acute and chronic effects on skin and eye, depending on UV dose, dose rate and the susceptibility of the biological targets. At the skin level [2] the best-known acute effect is the erythema, whose severity may span from a just perceptible redding to oedema and blistering depending on the UVR dose. Erythema displays an induction threshold depending on phototype, part of the body and previous exposure, and an action spectrum showing an efficacy of UVB up to 2-3 orders of magnitude higher with respect to UVA. Melanogenesis (the process leading to tanning) is also an acute effect of UVR, displaying the same action spectrum of the erythema and essentially regarded as an adaptive reaction of the skin to the UVR insult. Melanin is a complex molecular structure able to absorb UVR (shielding effect) and to remove ROS: it is produced by melanocytes as granules, which may be transferred to keratinocytes. An immediate pigment darkening (essentially triggered by UVA and acting on the existing melanin) occurs within minutes during exposure, a persistent pigment darkening (triggered by UVA and UVB) takes place within few hours and a delayed tanning (induced mostly by UVB and involving the synthesis of new melanin) arises after days since exposure and may last weeks or even months. Tanning depends critically on the phototype *(Table 1)*. Albinism is a condition of congenital absence of melanin synthesis, with a consequent high photosensitivity. Thickening of the corneal layer (hyperkeratosis) is another adaptive reaction of the skin to UVR exposure.

Table 1
Classification of phototypes regarding features, skin response to UVR, sunburn threshold (in Standard Erythemal Dose – SED. 1 SED = 100 J/m² of UV radiation exposure weigthened on the erythemal action spectrum). Extended and adapted from [9, 33]

Class of individuals	Phototype	Typical features	Skin response to UVR exposure	Sunburn threshold (SED)
Melano-compromised	I	Fair or very fair skin, red or blond hairs, blue or green eyes, freckles; non exposed skin is white	Very sensitive, always sunburns, no tan	< 2
Melano-compromised	II	Fair skin in most cases, red or blond hairs, hazel eyes in most cases	Moderately sensitive, often sunburns, light tan	2-3
Melano-competent	III	Non exposed skin is fair, hairs generally brown or dark, brown or blue eyes	Moderately insensitive, sometimes sunburns, medium tan	3-5
Melano-competent	IV	Non exposed skin is fair or slightly brown, dark hairs and eyes	Insensitive, rarely sunburns, dark tan	5-7
Melano-protected	V	Brown/olive skin, dark hairs and eyes	Insensitive, rarely sunburns, natural dark skin	7-10
Melano-protected	VI	Brown or black skin, dark hairs and eyes	Insensitive, no sunburns, natural dark skin	> 10

An acute effect occurring at the skin level is immuno-suppression, whose action spectrum has a peak at 300 nm and an additional peak in the UVA range (370 nm) [16, 17]. Immunosuppression recognizes several action mechanisms at molecular and cellular level and may be both local and systemic. Immunosuppressive effects of UVR may play a role in the carcinogenic action of SR and it is speculated that they may increase the susceptibility to infections and reduce the effectiveness of vaccines in human populations [17, 18].

Photodermatoses are clinical conditions involving an abnormal skin response to UV and sometimes visible radiation [19-21]. In this regard, outdoor exposure to SR is the most critical scenario for the affected subjects. Photodermatoses display a variety of clinical features and may exhibit various degrees of photosensitivity, with significant individual differences even within the same clinical condition. Photogenodermatoses display a dramatic increase in photosensitivity, with a very strong risk to develop skin cancer in juvenile ages or premature ageing, while for other groups photosensitivity is only slightly increased. Photodermatoses (summarized in *Table 2*) are not confined to fair phototypes but may involve to different extents dark phototypes and

Table 2
Photodermatoses: a profile of the photosensitive disorders involving skin

Group	Subgroup(s)		Single disorder
Autoimmune photodermatoses Abnormal skin response to UV and possibly visible radiation due to immune-mediated mechanisms			Polymorphic Light Eruption (PLE), Chronic Actinic Dermatitis (CAD), *Hydroa Vacciniforme* (HV), Solar Urticaria (SU), Actinic Prurigo (AP)
Photogenodermatoses Diseases with genomic instability due to one or more DNA repair mechanisms impairment	Altered DNA repair		*Xeroderma pigmentosum (XP),* Cockaine Syndrome (CS), Trichothiodystrophy (TD)
	Lack of helicase		Bloom Syndrome (BS), Rothmund-Thomson Syndrome (RTS)
Photoaggravated dermatoses Diseases involving skin or confined to skin which, in terms of clinical features, may be occasionally or usually exacerbated by the exposure to UV radiation in general or may be sometimes associated with photosensitivity			*Lupus erythematosus*, psoriasis, Sjogren syndrome, dermatomyositis, rheumatoid arthritis, bullous dermatitis (pemphigous and pemphigoid), *lichen planus*, atopic dermatitis, seborrheic dermatitis, rosacea, *acne vulgaris*, follicular dyskeratosis (Darier disease), Kindler-Weary syndrome, Smith-Lemli-Opitz syndrome, photosensitivity related to HIV infection
Photosensitization reactions Due to combined exposure to optical radiation and chemical agents	Endogenous (porphyrias)	Hepatic porphyrias	Porphyria cutanea tarda (PCT), Hepatoerythropoietic Porphyria (HEP), Variegate Porphyria (VP), Hereditary Coproporphyria (HCP)
		Erythropoietic porphyrias	Congenital Erythropoietic Porphyria (CEP), Erythropoietic Protoporphyria (EPP)
	Exogenous	Phototoxic reactions	
		Photoallergic reactions	

non-Caucasian individuals [22]. Generally, they are uncommon or very rare conditions, but Polymorphic Light Eruption (PLE) may affect a significant proportion of the population (10-20% of subjects affected at temperate latitudes and up to 6% in Italy) [21, 23]. Moreover, photoaggravated dermatoses as a whole are not infrequent.

Phototoxic and photoallergic reactions, which may be included into photodermatoses, may be induced by drugs, industrial chemicals, environmental pollutants, cosmetics, detergents, biocides, plants and plant derivatives *(Table 3)* and involve mainly UVA radiation, followed by UVB and (in some cases) ligth. Phototoxic reactions are not immune-mediated, have a threshold of induction, involve only photoexposed areas, are generally reversible and are regarded as quite frequent in the population (although difficult to quantify). On the opposite, photoallergic reactions are immune mediated, less frequent but potentially more severe than phototoxic reactions, may involve non-photoexposed areas, have low or virtually no threshold of induction by the photoallergen and may lead to the development of a persistent light reaction [24]. Photoallergic reactions are thought to account for 2-10% of patients investigated for a photoexposed site dermatosis [25].

The most important chronic adverse effect of SR on the skin is the induction of cancer: Basal Cell Carcinoma (BCC) and Squamous Cell Carcinoma (SCC), collectively regarded as Non Melanoma Skin Cancer (NMSC), and Cutaneous Malignant Melanoma (CMM). SCC occurs almost exclusively in the photoexposed areas of the skin, displays an action spectrum similar to the erythemal one (as observed in the experimental animals), recognizes the actinic keratosis (AC) as its precancerous lesion and is related to cumulative UVR exposure. BCC and CMM seem to be mostly related to the number and the intensity of sunburns, especially if occurring at juvenile ages [3, 26]. Skin cancer as a whole is absolutely the most frequent type of cancer in humans. BCC accounts for 80-85% of skin cancers, SCC for 10-15% and CMM for about 5%. Epidemiological trends display a strong increase in skin cancer incidence worldwide in the last decades, involving mainly fair phototypes. NMSC in Australia, Europe and USA have an average annual increase of 3-8%, while CMM has an estimated increase of the annual incidence of 3-7% worldwide [26].

Fair phototypes are more susceptible to skin cancer induction, especially for BCC and CMM. Other conditions of increased susceptibility are syndromes with DNA repair impairment (dramatic increase of risk for all skin cancer), congenital giant nevi (for CMM), large scars and burns (SCC), immunosuppression. Human papillomavirus infections (SCC), polycyclic aromatic hydrocarbons and arsenic (NMSC) and ionizing radiation (NMSC and CMM) are recognized to cause skin cancer [26, 27].

SR as a whole is recognized to be carcinogenic to humans by the International Agency for Research on Cancer (IARC) since 1992 (Group 1 of IARC classification of the carcinogenicity evidence) [28]. More recently, SR as a whole, UVR as a whole and the single bands UVC, UVB and UVA have been recognized to be carcinogenic to humans by the IARC [3].

Table 3
A non-exhaustive list of photosensitizers grouped by class/category or origin

Potential photosensitizing agents	Compound and/or single agent
Metabolites	Intermediates of the porphyrin biosynthesis pathway, chlorophyll metabolites
Drugs	Tetracyclines, sulphonamides, nalidixic acid, fluoroquinolones, azoles, griseofulvin, fentichlor, quinine, chloroquine, 5-fluorouracyl, methotrexate, vinblastine, anthracyclines, phenothiazines, tricyclic, alprazolam, chlordiazepoxide, hydrochlorothiazide, furosemide, nifedipine, diltiazem, amiodarone, methyl-dopa, quinidine, propranolol, ibuprofen, ketoprofen, naproxen, piroxicam, diclofenac, celecoxib, sulfonylureas, statins, fenofibrate, clofibrate, buclosamide, isotretinoin, saquinavir, 8-methoxypsoralen, 5-methoxypsoralen, trimethylpsoralen, Photofrin II, cyanines, hypericin
Plants	*H. mantegazzianum* (giant panax), *H. sphondylium, P. sativa, H. lacinatum, A. gigas, L. seseloides, C. officinale, A. arcangelica,* celery, parsley, carrot, fennel, pimpinella, *R. graveolens* (common ruth), *C. bergamia* (bergamot), *D. alba, Z. schinifolium,* cin lemon, orange, mandarin, *F. carica* (fig tree), shamrock, *H. pustulata, H. perforatum* (Hypericum or St. John wort), buckwheat, *A. gramineus, P. ginseng, P. grandiflorum, A. japonica, D. batatas, A. asphodeloides, P. sibiricum rubrum, C. majus var. asiaticum, P. koreana, A. pilosa*
Crude oil and its derivatives, carbon	Polycyclic aromatic hydrocarbons
Dyes	Benzanthrone, methylene blue, toluidine blue, nile blue, eosin, bengal rose, bengal red, fluorescein, rhodamine, acridine orange, acridines in general
Printing inks	Amyl-o-dimethylaminobenzoic acid
Animal food additives	Quinoxalyne-n-dioxide (quindoxin) and its derivatives olaquindox, carbadox and cyadox
Sunscreens	p-aminobenzoic acid (PABA), cinnamates, benzophenones, benzoylmethanes, octocrylene
Antimicrobial agents	Halogenated salicilanylides, esachlorophene, bithionol, chlorhexidine, triclosan
Cosmetics	6-methylcoumarin and 6-ethylcoumarin (contained in essential oils such as the bergamot oil), musk ambrette (aftershave) sandal oil, cedar (citrus) oil, octocrylene
Tattoo formulates	Cadmium sulphide

Occupational exposure to SR is estimated to give a large contribution to overall lifetime UV dose, resulting in an increased risk of SCC [29]. A meta-analysis found a significant increase of SCC risk for occupations with exposure to UVR (essentially outdoor workers), with a pooled OR of 1.77 (95% CI 1.40-2.22) [30], while for BCC another meta-analysis [31] found a pooled OR of 1.43 (95% CI 1.23-1.66), but these values are likely to underestimate the reality. Dose-response relationships and risk coefficients are not established for skin cancers in relation to solar UVR, given the existing uncertainties for a reliable assessment of individual exposure and the crucial role played by the individual susceptibility.

The other skin long lasting effect is photoageing, which is mainly related to cumulative exposure to UVA, involves alterations of dermal fibroblasts and extracellular matrix, as well as of dermal vasculature, and worsens the physiological skin ageing [32]. Epidermal tissue is also involved in skin ageing, characterized by a progressive loss of melanocytes and a slowering of the epidermis turnover, involving UVR long-term action.

Eye structures may be damaged by UVR [11, 33, 34]. The best-known acute effect is photokeratitis, a generally reversible effect with an action spectrum similar to the erythemal one, an induction threshold, and a severity directly proportional to the dose. As suggested by epidemiological studies, the most important chronic effect is cataract [9, 33, 35-37], especially cortical cataract, which may be induced by prolonged exposure to UVR. Cataract is a frequent age-related occurring condition and is the leading cause of blindness worldwide,

especially in developing countries. Another chronic effect mainly attributed to prolonged environmental UVR exposure is *pterygium*, involving an abnormal growth of the corneal *limbus*. It is still debated if UVR may induce macular degeneration or facilitate its occurrence as well as if a causal relationship between UVR exposure and uveal melanoma does exist [11].

As known, UVR may induce beneficial effects (see *Figure 1*), among which the strongest evidence is related to the synthesis in the skin of the precursor of the vitamin D3. Vitamin D3 is not only important for calcium homeostasis, but is involved in an increasing number of physiological and pathological processes, including those related to immune function and cancer induction [38-40]. The question of serum levels of 25-OH-vitamin D3 defining a deficient, an insufficient, an acceptable or an optimal vitamin D status is still debated, as well as the potential interference of photoprotective measures with vitamin D3 synthesis [41-44]. There is an increasing evidence that some postulated beneficial effects of solar UVR, such as lowering the blood pressure or even a reduction of the risk for some internal cancers *(Figure 1)*, are not linked to vitamin D3 synthesis but may recognize other mechanisms of action, such as mobilization of nitric oxide from skin or release of neuroendocrine mediators [45, 46].

In addition to UVR, the shortest wavelengths of visible radiation, *i.e.* blue and violet wavelengths (the so-called "blue light"), may be of concern for exposure to SR. Light is in fact absorbed by biological chromophores like melanin, haemoglobin and those contained
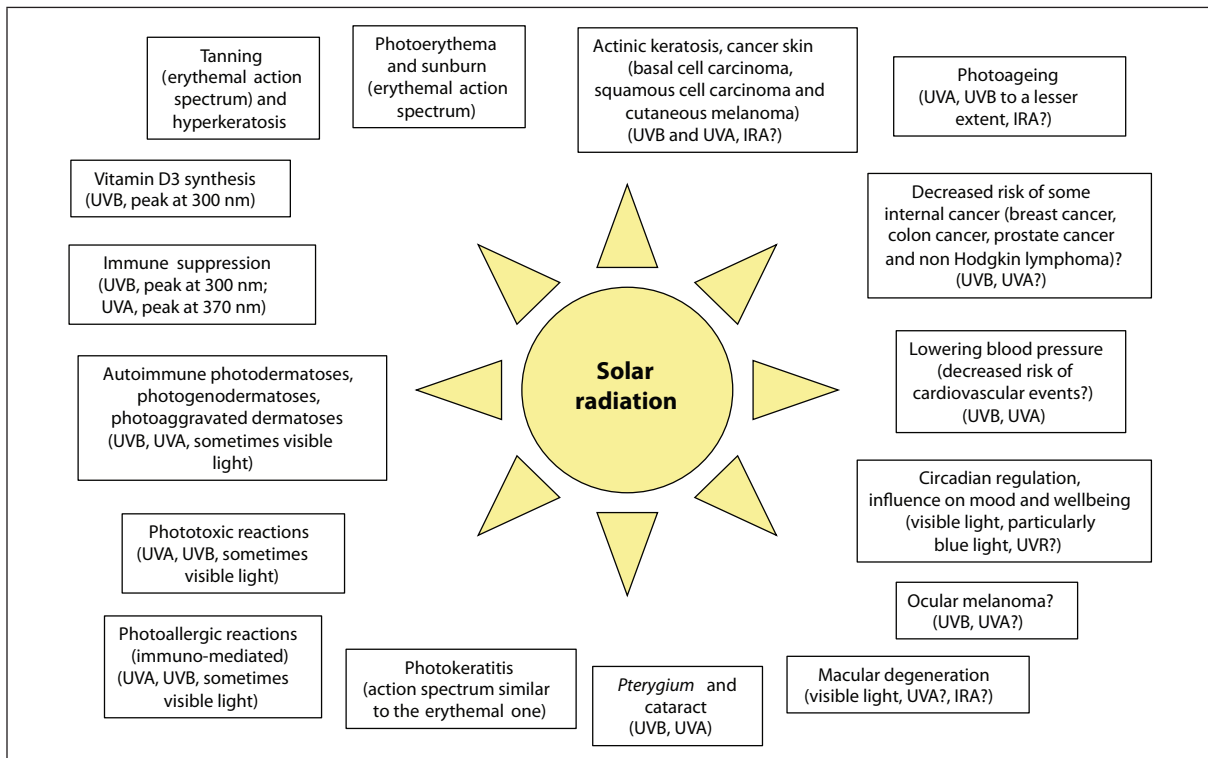

Figure 1
A simplified scheme of the known or suspected adverse and beneficial health effects of solar radiation, with the indication of the spectral band/s involved.

in photoreceptors, then triggering photochemical and thermal reactions. The solar retinopathy, due to an acute and direct exposure of the naked eye to sunlight, may in practice occur only when the sun is fixed during an eclipse or in the case of prolonged exposure without ocular protection to sunlight reflected by a surrounding large and highly reflective surface like snow and ice. Long-term exposure to short-wavelength light (including both direct sunlight and skylight) may contribute to the age-related macular degeneration occurrence [34, 47, 48]. The last one is the leading cause of vision loss in developed countries, accounting for 14% of blindness cases in people over 55 and 37% in people over 75 [48]. It is estimated that more than 1.5% of Caucasians over 70 have and advanced form of age-related macular degeneration, while another 10% is affected by an early form of the same disease [34].

As stated above, visible radiation may induce photosensitization reactions in the skin: compounds like certain dyes and porphyrins are activated by wavelengths in the visible range and visible radiation, especially at the longest wavelengths, is able to penetrate deeply the skin. IRR is a major part of the solar spectrum, but there is no direct thermal hazard for the skin exposed to the IRR component of SR, even for prolonged exposure. However, a growing number of *in vitro* studies shows that IRA photons may interfere with the electron transport chain in the mitochondria, resulting in ROS production and in signalling cascades, ultimately leading to a change in gene expression [49, 50]. It is speculated that IRA, which is deeply penetrating and reaches the subcutaneous tissues, may contribute to skin ageing and may synergize with UV in terms of biological effects. The temperature increase *per se* is a source of ROS and may change gene expression profile, with synthesis of heat shock proteins (HSP) and metalloproteinases (MMPs, responsible of the extracellular matrix remodelling and ultimately involved in photoageing). If skin temperature exceeds 39 °C these effects are marked and may lead to pathological changes. Some authors (for instance [51]) speculate that in experimental animals the carcinogenic effectiveness of UVR increases of 3-7% for each additional degree of ambient temperature. On the other hand, there is a clear epidemiological indication that chronic exposure to heat may induce cancer; in fact, SCC may arise from lesions of *erythema ab igne* [52]. Elevated temperatures could interfere with DNA repair mechanisms or allow mutated or premalignant cells to escape apoptosis favoring the carcinogenic process of the skin [51, 53-55].

Incidence rates of NMSC in 10 US regions are significantly correlated not only with environmental UV levels but also with the mean values of the daily maximum temperatures recorded during the summer period, suggesting an increase of UV carcinogenic effectiveness (higher for SCC) of about 2% for each degree in temperature increase [56].

THE ROLE OF STRATOSPHERIC OZONE AND CLIMATE CHANGE

Global factors affecting the exposure to SR are alterations of the stratospheric ozone layer and the ongoing climate changes, both having a potential serious impact on human health [57, 58]. Erythemal UVR may increase because of the stratospheric ozone depletion [59], which occurred mainly at high latitudes and Polar Regions (Antarctica in particular) since the 1970s following a seasonal trend, with a more marked effect in the southern hemisphere. The implementation of the Montreal Protocol with the ban of the CFCs depleting ozone is expected to restore during the 21th century, beyond the year-to-year variability due to atmospheric circulation and solar activity, the stratospheric ozone levels existing in the 1970s, especially in circumpolar regions. The trend of recovery is expected to be different for mid- and tropical latitudes versus high latitudes/ Polar Regions. Data indicate that for latitudes included between 60° S – 60° N the total ozone increased by about 1% since 2000 [60]. A direct assessment of the health impact of stratospheric ozone depletion is very difficult at mid latitudes in highly populated regions, especially for long lasting effects, due to the slighter and more complex oscillations of the ozone layer and to a lot of confounding factors. At higher latitudes, studies are difficult because of the lack of densely populated areas, especially in the southern hemisphere. However, there is a well-documented case of health outcomes directly linked to stratospheric ozone depletion. In Punta Arenas, the city of Chile closest to the Antarctic continent, in parallel with an over 50% decrease in ozone (with a concomitant increase in UVB levels), a 56% increase of CMM and a 46% increase of NMSC were reported for the period 1987-2000 [61]; notably, almost half of the cases did not belong to phototypes I and II.

For each 1% sustained decrease in stratospheric ozone, a 1.7% and 3% increase in the annual incidence of respectively BCC and SCC is expected in faired-skinned subjects [26], but great uncertainty remains in risk calculations. It has been speculated that the implementation of the Montreal Protocol will prevent two million cases of skin cancer yearly worldwide by the year 2030 (a reduction of 14% per year) [62].

Projections on stratospheric ozone dynamics are affected by uncertainties due to the model used, the natural year-by-year oscillations, the differences among high latitudes, mid latitudes and tropics, the trend related to types, amounts and kinetics of pollutants and aerosols released into the atmosphere. In addition, a changing climate may affect stratospheric ozone and, conversely, ozone depletion may affect climate change [58]. For instance, the alterations in temporal/geographical patterns of cloudiness may induce a warming of the troposphere and a cooling of the stratosphere, so altering the rate of ozone formation (which occurs mainly at low latitudes), transportation and degradation (the last one occurring mostly at Polar Regions). The direction of the net effect on the stratospheric ozone levels (and consequently on the ground levels of erythemal UVR) is difficult to predict, especially at the regional level, but it is not excluded that the time to restore the past ozone levels may be longer than expected and that the ozone depletion may involve to a greater extent mid- and low latitudes. However, the latest revisions on this topic state that future changes in UVR outside the Polar Regions will be likely due to factors other than stratospheric ozone [60].

Moreover, climate change and stratospheric ozone may mutually interact indirectly, as some substances (and their breakdown products) replacing the ozone depleting chemicals, according to the Montreal protocol, have a greenhouse effect. Therefore, they may contribute to global climate change if their atmospheric concentrations rise above current levels [63], for instance due to an increasing practice of air conditioning worldwide, with a potential higher environmental dispersion of refrigerating chemicals.

Regarding climate change itself, the last assessment report of the Intergovernmental Panel on Climate Change [64] states that an average temperature increase well over 2 °C is projected to occur worldwide by the end of the 21th century, with a change in the pattern of rains and a strong increase of both frequency and intensity of extreme weather events. The temperature increase may be contained within 2 °C relative to pre-industrial levels if the Kyoto protocol on the control of greenhouse emissions will be fully implemented by all countries.

Climate change potentially affects human exposure to SR, and consequently the type, frequency and severity of induced health effects, both directly and indirectly. An example of the former is a modification of the patterns of cloud cover [58]. Changes may involve the total number of sunny days, their distribution over the year and the type of cloudiness, with a not predictable net effect in terms of exposure to SR. UVB is the spectral band most affected by cloudiness, while exposure to UVA is expected to change less. In the case of subjects usually protecting themselves, changes in cloud cover may induce people to change frequency and level of personal protection, even in the presence of comparable levels of environmental UVR.

An indirect effect of climate change on exposure to SR is the following: higher temperatures, especially during the summer, may induce people to spend more time outdoors and to expose a greater skin surface to the sun [65, 66]. On the other hand, more severe microclimatic conditions may induce subjects usually staying outdoors to spend more time (if possible) indoor or in shaded areas. Again, the net direction of the effect is not predictable in absolute terms. It is dependent on factors like personal habits and type of job. The use of sunscreens or other means of personal protection may or may not vary in response to changes in microclimatic parameters, but in the last case it may lead to a decreased protection (for instance the frequency of application of sunscreens may be unchanged, while there may be need for a more frequent application given intense sweating).

Therefore, behavioral modifications in response to climate change and a proper implementation of sun protection strategies are likely to be the main determinants of exposure to SR [67].

Another indirect effect of climate change may involve alterations in the concentrations of environmental pollutants in the troposphere, because of regional/local alterations in temperature, humidity etc. Consequently, modifications in UVR levels may occur, since particulate matter and some volatile pollutants strongly absorb UVR [68]. In developed countries and in the northern hemisphere in general, the continuous improvement of air quality, with a progressive reduction in airborne concentrations of different class of pollutants, is expected to result in 10-20% increase in erythemal UVR exposure over the most populated areas, except for China [60].

We also speculate that in the long period, climate changes may extend altitude and latitude of some productive activities (agriculture), with a potential higher exposure to solar UVR for a high number of subjects.

OCCUPATIONAL EXPOSURE TO SOLAR RADIATION AND PROTECTION OF OUTDOOR WORKERS

Several working activities are conducted outdoors and outdoor workers are potentially exposed to levels of SR significantly higher than those of indoor workers and/or the general public. The definition of a worker as an "outdoor worker" is not univocal. Some jobs or activities are undoubtedly conducted outdoors, some are borderline and a lot of others are mostly indoors. Moreover, some indoor activities may involve exposure to SR through unshielded windows or other glass/plastic transparent barriers (which completely block UVB, but only partially UVA). For the scope of the present paper an outdoor worker is defined as a worker spending most or a significant proportion of his/her working time outdoors. It is difficult to identify all outdoor workers or activities, but an indicative list includes farmers, forestry workers, green areas maintenance workers, open sky miners, construction workers, asphalt workers, railway workers, power lines and water pipes workers, fishing activities, beach workers, offshore workers, ski instructors and other outdoor winter workers, outdoor sport instructors, professional sport practitioners, outdoor security activities, drivers, fuel station workers, postmen, workers engaged in outdoor loading and unloading activities, street vendors.

It is even more difficult to quantify the number of employees for each sector/category, as national and international job classifications often meet different criteria. However, for a given country they represent a significant part of the entire workforce.

Photoprotective measures are discussed in several guidelines, statements, positions papers, recommendations and informative materials worldwide, produced by international or national bodies, scientific society or single authors (see for instance [9, 21, 69, 70]). They are primarily oriented to the protection of the general public, but some of them contain indications for the photoprotection of workers exposed to SR. The aim of skin protection is not only the prevention of sunburn episodes, but also the reduction of cumulative suberythemal exposure to UVR [71], more subtle than the erythemal one as it induces photoadaptation in non photosensitive individuals, so lowering the risk perception and relaxing the adoption of protective measures. Regarding protection of eye against SR, its aim is essentially to prevent long-term effects on periorbital skin, cornea, lens and retinal tissue.

In Europe, natural optical radiation (essentially sunlight and skylight) is not included in the field of appli-

cation of the directive 2006/25/EC [72], which covers only the protection of workers against artificial optical radiation. However, the employer has the duty to assess all risks for workers' health and safety, as stated by the framework directive 89/391/EEC [73], and to adopt appropriate preventive and protective measures. Therefore, SR is an occupational hazard to be assessed.

Risk assessment and implementation of environmental, organisational and individual measures aimed at reducing workers' exposure to SR have to be addressed depending on:
• level of exposure (occasional *vs* intermittent *vs* continuous outdoor permanence, central hours *vs* rest of the day, season, availability of shaded areas etc.);
• surrounding environment (high albedo surfaces may increase individual exposure, adding the reflected and diffused radiation to the direct one);
• co-exposures (to irritants, sensitizing substances, photosensitizers etc.);
• individual biological features and medical conditions of the worker.

An important step in risk assessment is the exposure assessment, for which no standardized methods to readily quantify the exposure of eyes and skin areas of an individual to different spectral components of SR are recognized since now, despite the availability of approaches based on direct measurements, questionnaires, predictive models etc. Only UV dosimeters may be worn by the worker to assess personal exposure [6, 74], but their use may be difficult in some situations, may be a source of discomfort and does not reflect the exposure of all photoexposed body areas.

In any case, compliance with exposure limits established by the ICNIRP guidelines for UVR [33] is very difficult in several outdoor settings. For instance, the limit value of 30 J/m^2 for both skin and eye effective exposure to UVR may be easily exceeded (even in few minutes) at mid latitudes during the summer in the central hours of the day.

Therefore, it is of paramount importance to obtain a substantial reduction of the overall exposure to the solar UVR, especially for the most exposed workers, jointly with workers' training about short- and long-term health risks associated with exposure as well as about tools to reduce it. Risk management is based on environmental shielding of SR, individual protection, organizational measures, information, training and health surveillance. Measures for protection of workers against SR have to be compatible with other ones for protection against different risk factors (*e.g.* chemical agents, dusts etc.), not impairing the thermal comfort as far as possible.

If feasible, rotation of workers between indoor and outdoor jobs reduces the overall individual exposure to SR. For outdoor workers the availability of shadow provided by trees, curtains, gazebos etc. is of the greatest importance, as well as spending lunchtime and breaks in shaded areas. When high albedo surfaces are present in the workplace (water, fresh snow/ice, sand, metals etc.) shadow may not be sufficient for a proper reduction of the exposure and additional shielding barriers may be requested.

Adequate clothing represents the most important individual protection. It is recommended to wear long sleeved shirts and trousers. The Ultraviolet Protection Factor (UPF, a parameter to express the shielding capacity of a textile determined in standardized conditions and measured in integers: a UPF 20 means that only a 1/20 of the incident radiation is transmitted across the textile) varies widely among garments, up to 1,000 and even over. A UPF at least 50 is recommended for outdoor workers [75]. In general, dark coloured, thick and tight woven fabrics protect more than light coloured, thin and loose woven fabrics. In addition, protection is generally higher for dry than for wet tissues, as well as for new versus stretched and aged ones. Wool, polyester and other artificial fibres display the highest UPFs, while cotton and silk have lover UPFs.

The use of large brimmed hats is important for protection of the scalp (especially in bald individuals), the forehead, the ears and the neck. In alternative, a legionnaire-style hat may be used.

Use of sunscreens is another important measure to reduce over time the exposure to solar UVR, as the regular sunscreen use may reduce frequency and severity of sunburn episodes. A limited evidence of protection with regard to long-term effects of SR is also provided by existing epidemiological data, more consistent for actinic keratosis and NMSC than for CMM and photoageing [76]. For the UVB band the protective effectiveness is given by the Sun Protection Factor (SPF, defined as the ratio between the MED of protected and unprotected skin in a group of volunteers under standardized conditions), expressed in integers and ranging from 2 to over 50 (values over 50 are all indicated as 50+). For instance, a SPF 30 means that the 3.3% of the effective incident UVB reaches the epidermal tissue. UVA protection is tested assessing the ability of a standard application of the sunscreen to prevent the immediate pigment darkening in volunteers. Organic sunscreens are molecules like benzophenones, cinnamates, octocrilene etc. absorbing in the UV spectrum, while inorganic sunscreens are nanoparticles of zinc oxide or titanium dioxide, able to absorb, reflect and scatter UVR. A combination of organic and inorganic sunscreens extends the spectral range of protection, covering UVB and the majority of the UVA spectrum. Commercial sunscreens are formulations where the active component(s) is (are) mixed with vehicles, excipients, emollients and other components in a suitable water or oily phase. Sunscreen effectiveness, potential adverse effects, formulations and compliance are still a matter of debate [77-79]. The choice of a sunscreen has to take into account the following indications:
• a broadband (UVB + UVA) protective sunscreen is requested to confer protection against the whole UVR spectrum and products with a high photostability are preferred if a prolonged outdoor permanence is expected;
• a product with a SPF at least 30 is recommended. In case of photosensitive individuals the ideal is a SPF 50 or 50+;
• sunscreens have to be applied covering all photoexposed skin areas and in sufficient amount. For creams

and other solid formulations a quantity of 2 mg/cm² is regarded as sufficient;
• the cosmetic formulation may vary: creams, lotions, oils, sprays etc. are currently available. Each formulation has advantages and disadvantages. For instance, creams are easily spreadable and do not need frequent reapplication. Moreover, if labelled "water resistant" they resist to water contact or sweat. However, each application is time consuming and the product has to be reapplied at least every 2 hours. In presence of a very hot or a dusty environment a cream layer on the skin may worsen the sense of discomfort. On the opposite, sprays are easy to use, give a sense of freshness but need to be reapplied very frequently. In addition, their resistance to both water and sweat is poor;
• protection of lip skin is very important for prolonged exposures to sunlight, in which case it needs a frequent application of sunscreens in stick or balm formulations;
• the adverse effects associated to sunscreens use are likely to be limited, although this is still a matter of debate. A possible risk linked to systemic absorption of ZnO or TiO₂ nanoparticles is unlikely, as they are almost entirely retained by the corneal layer of the skin. The possible endocrine disrupting activity of some sunscreen active ingredients (like benzophenones) is also debated, but high dosages and systemic absorption seem to be required to observe some effects in the experimental animals. A risk of sensitization against one or more sunscreen components, including active components, may not be completely avoided, but with the current formulations is low. For subjects affected by a photodermatosis the choice of a suitable formulation is crucial and they should better use products labelled "for sensitive skin".

The use of eyeglasses is essential not only to shield eye against UVR, but also to protect the periorbital skin, especially in photosensitive individuals. Cost and brand are not related to photoprotective properties of a sunglass as an expensive one does not necessarily protect better than a cheaper one. A general rule is to choice sunglasses with complete or almost complete UVR blocking properties (99-100% of the incident UVR). In addition, the sunglass has to confer a good side protection in order to prevent laterally incident UVR entering the eye and focusing on specific areas of the corneal or lens tissues. In the case of visible radiation, sunglasses contribute to reduce eye exposure to blue and violet light, the most dangerous for retinal tissues.

UVR adverse effects may be worsened by co-exposures to chemical agents, e.g. photosensitizers. It is necessary to reduce as much as possible the occupational exposure to photosensitizers by means of personal protective devices or, by the judgment of the occupational physician, excluding workers under treatment with photoactive drugs from duties involving exposure to SR. Exposure to chemical irritants could synergize with UVR lowering the threshold of erythema or worsening inflammatory outcomes in photosensitive individuals. In this case is imperative to reduce or avoid exposure to such chemicals. Generally, skin reactions induced by allergens and sensitizing agents may add to and exacerbate the inflammatory response of the tissue to UVR. Conse-

quently, the contact of the skin with these agents has to be strongly reduced or avoided. The prolonged contact with detergents results in an alteration of the hydro-lipidic film and may facilitate the action of both irritants and sensitizers of the skin as well as of photosensitizers. The same is true in the case of prolonged contact of hands with wet surfaces or materials, typical of several jobs/activities [80], that may induce maceration of the skin. As a consequence, the contact of skin (usually of the hands) with detergents or wet matrices has to be avoided or strongly reduced whenever possible.

Health surveillance is a part of the preventive framework in occupational health and is implemented by the Member States of the European Union following national regulation and practice as stated by the directive 89/391/EEC [73]. However, in several European countries SR is not included in the list of the occupational risk factors for which the health surveillance is compulsory. In any case, several outdoor workers are additionally exposed to risk factors for which health surveillance is instead compulsory. Moreover, health surveillance may be applied on worker's request, if the occupational physician states that the request itself is related to occupational hazards. Consequently, many outdoor workers undergo, or should undergo, health surveillance in practice.

Health surveillance is aimed at establishing the job fitness of the worker as well as to identify early signs of diseases, especially the chronic ones. In the case of skin cancer a proper health surveillance may allow early diagnosis of the disease. Conditions making the worker particularly sensitive to the risk have to be taken into account: fair phototypes (I and II), skin cancer prone conditions, previous skin neoplasms, presence of a photodermatosis, compromised immune status, eye diseases, exposure to photosensitizers etc. In addition, non occupational exposure to SR or to other sources of UVR (e.g. tanning devices) has to be assessed, too. While working activities involving prolonged or even "normal" exposures to solar radiation are not compatible with disorders implying a dramatic increase in photosensitivity (such as photogenodermatoses), they may be nevertheless compatible with most conditions of increased photosensitivity if the affected workers are adequately protected and surveyed.

DISCUSSION AND CONCLUDING REMARKS

The balance between adverse and beneficial effects of exposure to SR for outdoor workers is not easy to address, because it depends on several variables: amount of exposure, phototype, medical conditions, therapeutic treatments, co-exposure to physical and chemical agents etc. Exposure scenarios due to climate change/ozone depletion add complexity in this regard, taking into account the uncertainties of the available risk models [60, 62]. However, given the frequency, intensity and duration of exposure to SR for a lot of outdoor activities, adverse effects are expected to prevail on beneficial ones, not only for photosensitive individuals but for the generality of workers. In addition, little is known on the interaction between different spectral components of SR with regard to biological effects on skin and eye, but

a synergism related to some biological endpoints may not be excluded. To assess the contribution of climate change with regard to several adverse effects of SR, especially those occurring after a long latency period and/or a prolonged exposure, local and global time trends of diseases due to, or associated with, exposure to SR need to be strictly followed, matching them with environmental outdoor parameters such as temperature, humidity, UV index, level of selected pollutants etc. For outdoor workers, multicentric epidemiological studies are required, taking into account variables due to different behavioural and cultural profiles of the different populations the workers belong to. A crucial step in this regard is the assessment, as carefully as feasible, of the individual past exposure of the workers, in both cumulative terms and regarding the frequency and intensity of overexposures (sunburns), including non occupational exposures since childhood (for instance leisure time, vacations and artificial tanning): an ongoing research activity attempts to address this topic [81]. In addition, exposure patterns to SR and co-exposures to chemical and physical agents have to be fully determined.

The uncertainties regarding the direction of changing exposure levels to SR (as shown in *Figure 2*) stress the importance of a suitable individual protection and health surveillance for outdoor workers, extended to all exposed subjects, not only to photosensitive ones. Regarding exposure to SR, low risk perception and inadequate sun-protective behaviours persist [82]. In addition, "recreational exposures" and artificial tanning are increasing worldwide.

In the authors' opinion, to manage the occupational exposure to SR in a changing climate the following considerations should be taken into account:
• individual protective measures have to be complementary each other. They may be differently combined with regard to the level of exposure, individual photosensitivity and potential co-exposures;

• protective measures have to be "accepted" by workers [83] and in this regard a proper information and training is crucial;
• garments providing UV protection must not impair thermal comfort of the worker: this is even more important in a changing climate, for instance in the case of more frequent and intense heatwaves occurring in the summer at mid latitudes. As an example, clothes for sportswear manufactured in recent years have an excellent level of UV protection and, at the same time, optimize the thermal comfort [84];
• as previously stated, a synergism in skin cancer induction and/or in photoageing between UV and IR and/or between UV and ambient temperature is supported by experimental data. Moreover, the carcinogenic action of SR on the skin may combine with that of other known skin carcinogens like polycyclic aromatic hydrocarbons (PAHs), a class of widespread environmental pollutants having also photosensitizing properties. As climate change may alter the tropospheric concentration of pollutants like PAHs and may provoke more frequent and intense heatwaves during the summer season at mid latitudes, workers have to be strictly surveyed by the occupational physician with regard to skin cancer prevention;
• since UVR has an immunomodulating action, and being the impact of climate change on UVR environmental levels at local scale unpredictable, the health surveillance of the worker has to include the assessment of the immune status. An immunosuppressive effect could be beneficial in some conditions [17], such as those involving subjects affected by autoimmune diseases or immune-mediated diseases like multiple sclerosis, type 1 diabetes mellitus, rheumatoid arthritis, asthma etc., but not in the case of systemic *lupus erythematosus*, where solar UVR may exacerbate clinical features. Also, UV-induced immunosuppression may worsen the effect of the immunosuppressive treatments in transplanted
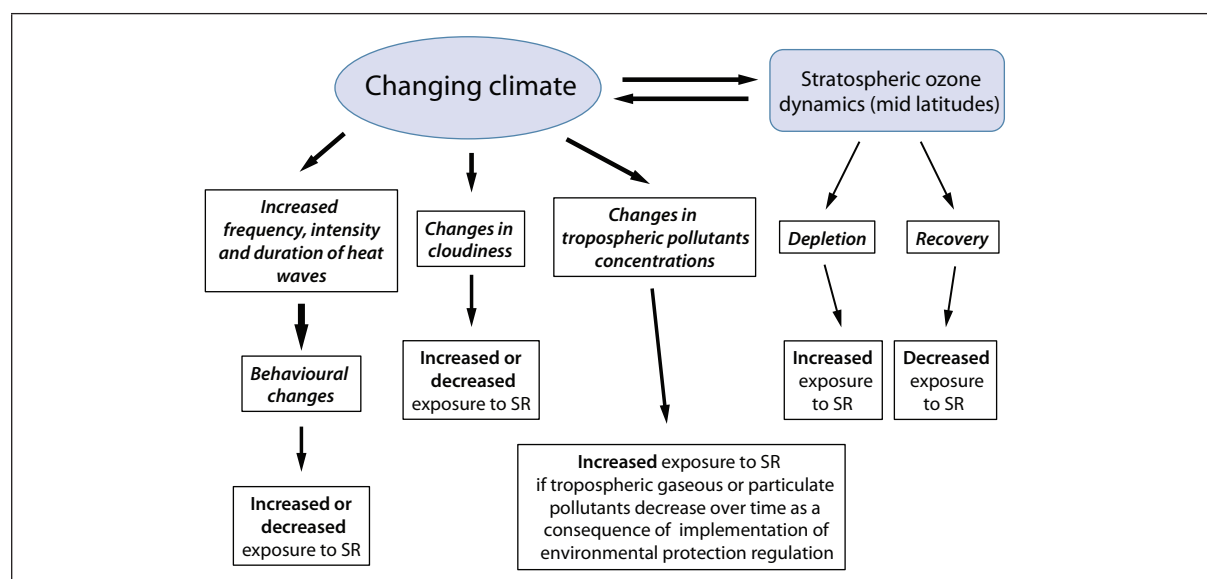

Figure 2
Impact of climate change on occupational exposure to solar radiation (SR).

subjects or in patients affected by autoimmune or other medical conditions. In addition, the changing pattern of infectious agents and vectors due to climate change may increase the infectious risk for the worker, making the periodic evaluation of the immune parameters even more important;

• emerging photoprotective approaches focus on the development of sunscreens covering the spectrum of optical radiation ranging from UV to IRA as well as on active forms of photoprotection based on chemio-prevention. The last ones include topical and systemic administration of antioxidants (like vitamin C and E) or compounds (mostly derived by vegetables, like carotenoids, cathechins, poliphenols etc.) able to modulate gene expression, immune response or ROS metabolism [85-87]. Some formulations of sunscreens containing one or more bioactive compounds are now available on the market. However, questions related to the choice of active principles and dosage are unanswered and uncertainties about metabolism, individual responsiveness, interaction with food or pharmacological treatments are still unsolved. In addition, the current lack of adequate human studies assessing the effectiveness of single compounds or combinations of compounds in preventing both acute and long-term effects of SR on the skin and the eye, as well as their potential adverse effects, does not allow these approaches to become routinary photoprotective measures;

• the occupational physician plays a crucial role in education and training of workers, including those not displaying traits of photosensitivity, also for the sake of establishing a correct risk perception.

In conclusion, health issues related to occupational exposure to SR, if properly addressed, may trigger or improve workers' awareness of the importance of healthier lifestyles, not only as regards diet, physical exercise, smoking and drinking habits, but also avoiding or reducing unnecessary "recreational" exposures, so contributing to their health promotion. This is, in authors' opinion, the best "adaptive" response to live in a world with a changing climate.

Conflict of interest statement

There are no potential conflicts of interest or any financial or personal relationships with other people or organizations that could inappropriately bias conduct and findings of this study.

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