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Occupational and Environmental Chemical Risk Assessment in a Changing Climate: A Critical Analysis of the Current Discourse and Future Perspectives †

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Abstract: Global climate change (GCC) models predict direct changes in region-specific rainfall patterns, floods, sea levels, infectious and heat-related disease patterns. The indirect effects of GCC on chemical risk assessment (CRA) have not received adequate attention. This study presents a synopsis of the implications of GCC on CRA, which forms the basis for both occupational and environmental health. GCC can make organisms more sensitive to chemical stressors, and chemical exposures can make organisms more sensitive to GCC. Consequently, occupational and environmental chemical RA will need mechanistic understanding and analytical tools to predict outcomes of multiple stressors and their combined effects.

Keywords: climate change; greenhouse gases; toxicology; risk assessment; adverse outcome pathways

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1. Introduction

Expanding human activities increase the variety and intensity of stressors, whose effects are exacerbated by accelerating climate change [1–5]. For example, the increase in the concentration of greenhouse gases (GHGs) such as carbon dioxide, methane and dinitrogen oxide is resulting in global warming and climate change [6].

Global climate change (GCC) can make organisms more sensitive to chemical stressors, and chemical exposures can make organisms more sensitive to GCC. Since stressors are heterogeneous and can affect individuals, populations, communities, and their habitats, many disciplines investigate their combined effects, e.g., pharmacology and epidemiology, toxicology, environmental science, conservation biology, and ecology [1]. The common challenge, irrespective of the discipline, is that combined effects cannot be predicted reliably from the individual effect of each stressor, where the way in which each stressor operates in isolation may change or be modified in the presence of other stressors [1,7–9].

This study presents a synopsis of implications of climate change on occupational and environmental chemical risk assessment (CRA). After analysing all the pertinent issues on the topic, the study also makes suggestions for incorporating climate change into occupational and environmental CRA of chemicals.

2. Direct Effects of Climate Change

GCC may influence a variety of environmental variables, including temperature, precipitation, salinity, pH, and insolation of ultraviolet (UV) radiation. Overall, climate change is expected to result in more frequent and intense heat waves, precipitation and storm events. These changes are expected to have an impact on the behaviour and fate of pollutants as well as changes in interactions of pollutants with living organisms, especially thresholds that might trigger adverse events.

2.1. Temperature

Differences in temperatures may alter the physicochemical properties, bioavailability and toxicokinetics of chemicals resulting in different toxicity profiles. Biological rates depend on temperature, where physiological dose–response functions can be used to represent variation (of biological rates) in response to environmental stressors [10]. For example, juvenile *Penaeus semisulcatus* were reported to exhibit significantly higher toxicity to ammonia at 14 °C than at 26 °C [11]. Similarly, the toxicities of two commonly used biocides, chlorothalonil and copper pyrithione (CuPT), to marine copepod *Tigriopus japonicus* and dinoflagellate *Pyrocystis lunulaf*, were highly temperature-dependent, although the temperature dependency varied between the two chemicals [12]. Kwok and Leung [13] also reported temperature-dependent toxicities for tributyltin chloride antifouling biocides to *T japonicas,* while Li et al. [14] reported temperature-dependent toxicities of copper sulphate pentahydrate triphenyltin chloride, dichlorophenyltrichloroethane and copper pyrithione (to marine medaka fish *Oryzias melastigma* and the copepod *T japonicus*).

Temperature has also been shown to affect the toxicity of pollutants to terrestrial organisms. For example, the effect of temperature on the reproductive toxicity of mercury affecting swallows [15] and the effects of temperature on the toxicity of many pollutants affecting herbivores [16] has been reported. Most notably, for several different chemicals, a difference in ambient of 10 °C from 26 to 36 °C produced an effect in rodents that was similar to increasing the dose two- to eight-fold, while the lethal dose of caffeine in mice at 36 °C is one-fifth the lethal dose for mice at 26 or 8 °C [16].

Changes in temperature have an effect on the bioavailability of persistent organic pollutants and their subsequent uptake and bioaccumulation. For example, increased temperatures are expected to reduce the overall bioaccumulation of organic contaminants in the Arctic marine food web [17], but increase the bioavailability of metals (Cd, Pb and Zn) in soil [18].

2.2. Preciptation, Rainfall Patterns, Floods, Sea Levels

GCC will influence water availability and quality. Increased precipitation has been predicted for some regions such as northern Europe, North and South America as well as northern and central Asia, while substantial droughts have been predicted for other regions such as southern Africa, Asia and the Mediterranean, i.e., the impacts are area- or region-specific [19]. Although the mean total quantity of water resources is likely to increase for Africa as a whole, substantial variations are expected for individual sub-basins and countries, along with increases in the drought events and their duration, i.e., variations exist for regions and sub-regions [20]. In that regard, IPCC models predict rainfall increases over most part of West Africa with the exception of the coastline where a little decrease in amount of rainfall was estimated [21]. This stressor does not necessarily act in isolation, where the effects of precipitation and temperature on vegetation index have also been modelled and should be considered [22].

2.3. Water and Soil Salinity

The effects of climate change on water availability and quality will in turn affect water and soil salinity [23,24]. Salinity has been reported to enhance the toxicity of many pollutants to many aquatic organisms, including L-selenomethionine to Japanese medaka (*Oryzias latipes*) embryos [25], polyvinylpyrrolidone (PVP) coated silver nanoparticles to

Tisbe battagliai (Tb) and *Ceramium tenuicorne (Ct)* [26]. Interaction between salinity and pollutants has been reported not only in aquatic organisms, but also terrestrial organisms. For example, salinity increased the toxicity, as indicated in changes in weight and mortality, of Zn^{2+} to the earthworm *Eisenia fetida* [27]. Salinity also increased soil Cd availability and toxicity to microbial organisms, as indicated in the decreased soil microbial respiration rate, microbial biomass and enzyme activity [28]. Similarly, salinity reduced tolerance of conocarpus (*Conocarpus erectus* L.) against Cd stress due to increased uptake of toxic ions and intensification of oxidative stress [29]. In some cases, increasing salinity reduced the toxicity of some pollutants. For example, increased salinity reduced the acute toxicity to *T japonicus* due to precipitation of the dissolved concentrations of the ions [30]. Similarly, salinity was reported to be protective against acute Ni toxicity in the crustacean species *Litopenaeus vannamei* and *Excirolana armata* [31].

3. Indirect Effects of Climate Change

The impacts of GCC are numerous, including changes in human migration as a result of rainfall patterns or sea level rise, heat-related mortality and mutation in infectious disease vectors [32]. Furthermore, predictive models indicate that GCC will affect the geographic distribution and annual number of generations of agricultural pests, which will in turn change pesticide use patterns [33–35]. This will increase the usage and sources of pesticides [36–38].

Following release from primary sources, pollutants are stored on various compartments from where they are subject to various secondary release processes. According to UNEP/AMAP [39], climate change will affect the rate of mobilization from materials and stockpiles, volatilization as well as partitioning between air and soil and air and water. Indeed, changes in climate variables such as temperature, winds, precipitation, currents, and snow will in turn change transport, deposition and fate of contaminants. Soil properties that control pollutants adsorption and mobility such as temperature, moisture, organic matter, mineral fractions, and microbial activities are affected by climate change. Consequently, exposure to contaminants could be increased because of desorption and remobilization of soil contaminants [40]. This is important for both environmental exposure to chemicals (e.g., pesticides) and occupational exposure to chemicals, especially exposure of workers to agricultural pesticides on re-entry.

4. Influence on (Toxic) Action or Interactions between Chemicals and Target Molecules

GCC can influence physiochemical properties of chemicals (toxicokinetics), i.e., absorption, distribution, metabolism, and excretion (ADME), or mode of action or interactions between chemicals and target molecules (toxicodymanics), e.g., various transport, degradation, dissipation and fate processes which can in turn influence the internal dose. Chemical, biological and ecological information is used to define the pathways that link stressor exposure to potential adverse outcomes at different organisational levels [41], e.g., adverse outcome pathways (AOPs) in ecotoxicology [42]. AOPs have been used to predict that toxicants may alter the ability of organisms to respond to climate change and, in turn, climate stressors may affect chemical toxicity [43]. AOPs depict links starting from a mechanism-based molecular initiating event (MIE), followed by biological key events (KE) that are connected via key event relationships (KER) and result in an adverse outcome (AO). Chemical and climate-specific stressors can influence the MIE, KE, or KER and ultimately change the AO.

5. Implications on the Validity of Occupational and Environmental Chemical Risk Assessment

GCC may cause more frequent and intense heat waves, precipitation and storm events where these changes impact on the behaviour and fate of pollutants, interactions of pollutants with living organisms, and thresholds that trigger adverse events. The impacts of climate change on the transport, fate and exposure to pollutants have been thoroughly examined and discussed [19,40,44–50]. Occupational and environmental CRA requires an understanding of these kinds of relationships between exposure and effects.

The exposure to chemicals in occupational and environmental settings depends on the dissipation, fate and behaviour of the chemical, which are in turn affected by a number of physical, biological, and ecological processes in the environment that include microbial degradation, volatilization, adsorption, uptake by plants and animals, surface runoff, and leaching [51,52]. These processes are interrelated, where the governing factors for each of these processes are complicated. Hence, it is difficult to interrogate each process in isolation.

The dependencies of toxicity of many pollutants on temperature and salinity are crucial for toxicology and RA. It is predicted that anthropogenically-driven GCC may increase salinity and incidents of extreme temperature events, which may have significant effects on the toxicity of chemical pollutants and lead to adverse effects [43]. Occupational and environmental CRA are based on toxicity data on model organisms obtained under standard test conditions, which may not reflect actual environmental conditions that may change how organisms respond to chemical insults. Indeed, after exposing larval and adult grass shrimp to the fungicide chlorothalonil and the insecticide Scourge under various test conditions of (i) standard toxicity test conditions, (ii) a 10 °C increase in temperature, (iii) a 10 ppt increase in salinity, and (iv) a combined increased temperature and salinity exposure, DeLorenzo et al. [53] reported that standard toxicity bioassays may not be predictive of actual pesticide toxicity under variable environmental conditions.

For ecological CRA, Landis et al. [54] proposed critical changes that involve use of conceptual cause–effect diagrams that include both direct and indirect effects of climate change. In order to consider effects of climate change in standard toxicity testing of pollutants, DeLorenzo et al. [53] recommended toxicity testing under a wider range of exposure conditions to improve the accuracy of CRA.

GCC will trigger multiple stressors and impact a myriad of contaminants in different ways. Under these circumstances, CRA, which often assesses effects of one stressor at time, will have to concomitantly consider interactions among contaminant and non-contaminant stressors. This will include new temperature and precipitation regimes, new ecosystems and hydrologic processes that are likely to result in new responses to lethal and sub-lethal doses of pollutants [54]. Hooper et al. [43] proposed the use of mechanistic toxicological tools such as AOPs in assessing climate change risks.

6. Conclusions

Rapid modifications occur in the environment resulting from climate change and encroachment of human activities on all ecosystems. However, some stressors cannot be mitigated rapidly. GCC will have implications on the validity of occupational and environmental CRA through space and time. Consequently, occupational and environmental CRA will need mechanistic understanding and analytical tools to predict outcomes of multiple stressors and their combined effects. For example, conceptual cause–effect diagrams at spatial and temporal scales can be used in order to account for both direct and indirect effects of climate change, whose magnitude will depend on the extent to which current conditions are altered.

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