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Respiratory Disorders and Air Pollution: Impact of Climate Change-An Updated Review

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Abstract:

Background: Viral respiratory infections (VRIs) are a leading cause of global morbidity and mortality. Climate change has exacerbated environmental conditions, potentially altering the epidemiology of these infections. The interaction between meteorological factors and VRIs remains inadequately understood, necessitating a comprehensive review.

Aim: This review investigates the impact of climate change on the seasonal distribution, outbreak dynamics, and transmission patterns of VRIs, highlighting the influence of meteorological factors and extreme weather events.

Methods: A systematic synthesis of recent epidemiological, biological, and ecological evidence was undertaken. The review analyzed data on meteorological conditions, extreme weather phenomena, and long-term global warming trends, focusing on their effects on VRIs.

Results: VRIs exhibit distinct seasonal patterns influenced by temperature, humidity, and indoor microclimates. Low temperatures and humidity enhance viral survival and transmission, especially for influenza and RSV. Extreme weather events, such as heatwaves and floods, intensify respiratory health risks by affecting air quality and sanitation. Long-term climate changes have shifted the spatiotemporal dynamics of VRIs, with trends indicating earlier onset and longer epidemic durations in temperate regions.

Conclusion: Climate change is reshaping the epidemiology of VRIs through its effects on meteorological variables and extreme weather events. Enhanced surveillance, interdisciplinary research, and adaptive strategies are crucial for pandemic preparedness in a changing climate.

Keywords: viral respiratory infections, climate change, air pollution, seasonal patterns, extreme weather events, epidemiology, public health.

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Introduction:

Viral respiratory infections (VRIs) constitute the most common type of infectious diseases globally and are significant contributors to morbidity and mortality worldwide [1]. These pathogens trigger periodic seasonal epidemics and possess the capacity to induce catastrophic pandemics. In the 21st century, significant outbreaks and pandemics, such as Severe Acute Respiratory Syndrome (SARS) in 2003, Influenza H1N1 in 2009, Middle East Respiratory Syndrome (MERS) in 2012, and COVID-19 in 2019, have caused considerable human mortality and morbidity, as well as significant economic disruption. The hazards linked to the formation and extensive transmission of VRIs have markedly increased due to fast population expansion, urbanization, worldwide travel, civil upheaval, migration, and human-induced environmental degradation, including climate change. Climate change is considered the foremost health threat of the 21st century. Human actions, chiefly greenhouse gas emissions, have caused unparalleled rises in global temperatures and the occurrence and severity of extreme weather events. These climatic changes endanger human health in various ways. Heat-related mortality is the most immediate effect, but climate change also indirectly impacts health by altering vectors, environmental contaminants, and the availability of food and water, consequently intensifying climate-sensitive infectious and non-communicable diseases. Escalating intensity and frequency of extreme weather events are associated with the rise of vector-borne diseases, attributable to their effects on pathogens, vectors, and hosts [7]. Moreover, climate change undermines socioeconomic health factors, including economic stability and healthcare access, disproportionately affecting vulnerable communities and exacerbating health inequities [8].

The correlation between climate change and vector-borne respiratory infections has been a longstanding issue. Seasonal viral respiratory infections, such as influenza, have traditionally exhibited elevated incidence rates in winter, presumably due to lower temperatures [9]. Recent trends, however, suggest a shift in the seasonal peaks of specific VRIs towards warmer times [10,11]. Numerous vector-borne respiratory infections (VRIs) are categorized as climate-sensitive diseases, with a minimum of one climatic variable affecting their epidemiology [12]. Nonetheless, the exact correlation between climate change and VRIs remains insufficiently comprehended. Inquiries continue on the influence of global warming on the epidemiological trends of viral respiratory infections and the possible future alterations in their epidemic dynamics due to climatic changes. Current research, primarily examining particular climate variables in confined areas, has produced ambiguous results. Furthermore, the mechanisms behind these contradictory connections remain inadequately explained. A thorough and methodical comprehension of the impact of meteorological circumstances, extreme weather phenomena, and long-term climatic trends on the dynamics of VRIs remains insufficient. This review aims to fill existing knowledge gaps by synthesizing recent epidemiological, biological, and ecological evidence regarding the impact of climate change—evidenced by meteorological variations, extreme weather occurrences, and persistent global warming—on the epidemic dynamics of viral respiratory infections (VRIs). It specifically analyzes the spatiotemporal distribution of seasonal epidemics, disease outbreaks, and pandemics. This synthesis seeks to reveal the fundamental mechanistic pathways, promote a collective understanding, and pinpoint essential areas for future research by incorporating findings from several disciplines. These insights are essential for informing pandemic preparedness measures amid a swiftly evolving atmosphere.

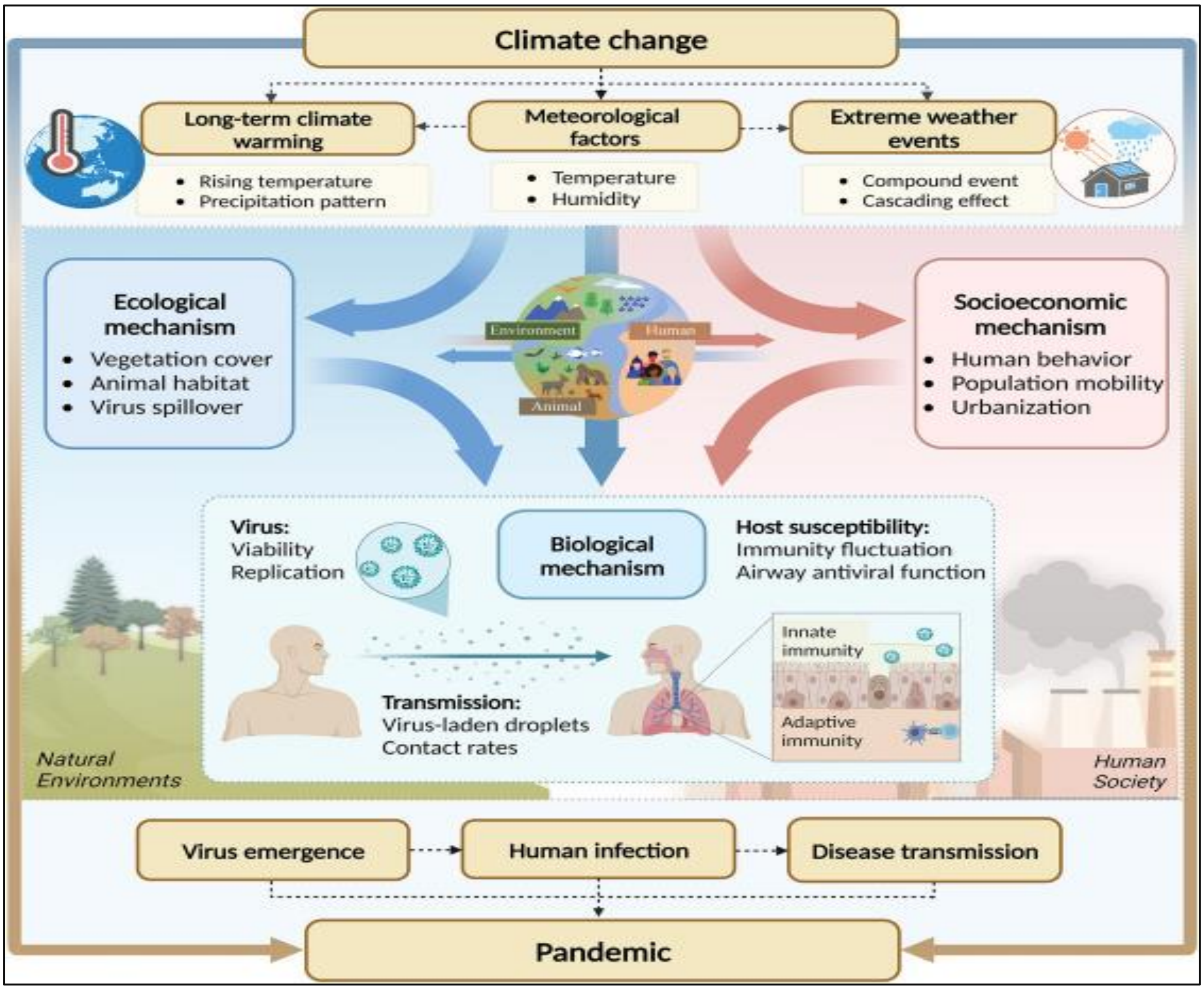

Figure 1: Climate Change and Respiratory Disorders.

Etiologic and Epidemiological Characteristics of VRIs

Viral respiratory infections (VRIs) are well recognized as the most prevalent infectious diseases and a major cause of morbidity and mortality. They encompass a wide range of viruses, from established, human-adapted endemic diseases to emerging, extremely virulent zoonotic viruses with pandemic potential [13]. Commonly linked viral illnesses include influenza viruses, respiratory syncytial viruses (RSV), parainfluenza viruses (PIV), human metapneumoviruses (HMPV), human coronaviruses (HCoV), rhinoviruses (RV), adenoviruses (ADV), human bocaviruses (HBoV), and enteroviruses (EV). These viruses circulate annually in human populations. VRIs are characterized by a range of genetic and physical traits. Influenza viruses belong to the Orthomyxoviridae family, while RSV is classed under the Paramyxoviridae family; both are enclosed with single-stranded RNA viruses. Their primary mechanisms of transmission encompass droplets, aerosols, and direct touch. Influenza viruses peak in winter in temperate regions, but RSV exhibits activity during both winter and early spring [15,10]. Similarly, HMPV and HCoV, both enveloped RNA viruses, demonstrate seasonal peaks in late winter and spring or winter, respectively [14,16]. PIV exhibits subtypespecific seasonality; PIV-1 and PIV-2 peak in fall and winter, while PIV-3 is prevalent in warmer months, and PIV-4 circulates sporadically year-round [14]. Rhinoviruses and HBoV exhibit year-round activity, peaking in autumn and spring or summer, respectively, whereas ADV and EV, both non-enveloped viruses, are predominantly active throughout the year or primarily in summer and fall. The clinical manifestations of viral respiratory infections (VRIs) range from mild upper respiratory symptoms, like the common cold, to severe lower respiratory tract infections, such as pneumonia requiring hospitalization. The severity of these infections is influenced by various factors, including physiological condition, nutritional status, hygiene practices, and environmental conditions that affect the respiratory mucosa, respiratory function, and immune response [13]. Vulnerable populations include young children (under 5 years), elderly individuals (65 years and older), pregnant women, immunocompromised patients, and individuals with pre-existing heart conditions [19]. Transmission of viral respiratory infections (VRIs) occurs mainly through three primary routes: direct or indirect contact with contaminated surfaces (fomites), droplet transmission over short distances, and aerosol transmission over longer distances. Infected individuals expel virus-laden droplets during speech, coughing, or sneezing, with their deposition and evaporation influenced by environmental and climatic conditions [20,21].

Seasonality and Transmission Dynamics

Seasonality is a fundamental attribute of VRIs, particularly in temperate regions. Influenza viruses, RSV, HMPV, and HCoV predominantly peak in winter or early spring, while EV activity is most pronounced in summer and autumn. Latitude significantly influences transmission dynamics, with lower latitudes exhibiting earlier peak timings, shorter seasonal durations, and less seasonal variability for viruses like RSV and influenza [25,26]. In contrast, viruses such as ADV, RV, and HBoV exhibit sporadic activity throughout the year [27]. The seasonality of PIV is complex due to the varied patterns displayed by its subtypes [15]. Understanding these spatiotemporal patterns provides critical insights for developing more effective preventive strategies. The determinants of VRI seasonality have been thoroughly examined. Seasonal fluctuations in viral activity may reflect inherent viral characteristics, including differences between enveloped and non-enveloped viruses, with host physiological responses influenced by climatic factors, including immune modulation and nutritional availability [28]. Behavioral changes, including increased indoor activity during colder months, significantly intensify this seasonality [29]. Climatic conditions are the primary external factors affecting VRI seasonality, underscoring the need for interdisciplinary research to elucidate the complex interactions among viruses, hosts, and the environment.

Influence of Meteorological Factors on Seasonal Epidemics of VRIs

Seasonal outbreaks of viral respiratory infections (VRIs) are closely associated with variations in meteorological conditions. Comprehensive studies have investigated this association, emphasizing temperature, humidity, precipitation, sun radiation, and wind speed as key factors influencing VRI incidence. In the Northern Hemisphere, low temperatures, decreased humidity, and lower sun radiation are commonly linked to winter epidemics, while heightened precipitation characterizes VRI peaks in tropical and subtropical areas [30,31]. Although wind speed has both positive and negative correlations with VRIs, these relationships are probably affected by additional climatic variables [32–35]. Research mostly emphasizes RSV and influenza because to their high infection rates and existing surveillance frameworks [36].

Temperature and Humidity

Temperature and humidity are acknowledged as essential climatic variables influencing seasonal VRI epidemics [37]. Laboratory tests have shown that low temperature and humidity increase viral survival and transmission, especially for influenza, while weakening host airway defenses [38–40]. Epidemiological data from temperate regions, including Canada, China, Greece, and the United States, support these findings, demonstrating an inverse correlation between these characteristics and the incidence of VRI [41–44]. Global studies indicate that "cold-dry" and "warm-humid" circumstances serve as catalysts for epidemics in temperate and tropical regions, respectively [9]. The regional variability in these findings may indicate behavioral adaptations to local climates that influence virus transmission patterns. Recent study highlights the intricate, nonlinear connections between temperature and humidity in influencing VRI dynamics, demonstrating J-shaped, U-shaped, and bimodal exposure-response relationships as a result of advancements in statistical modeling and viral detection techniques [11,27,45–47]. Moreover, absolute humidity (AH) has proven to be a more dependable predictor than relative humidity (RH) for seasonal VRI patterns, exhibiting a U-shaped correlation with influenza transmissibility in research conducted in China and Hong Kong [50]. Notwithstanding these insights, quantifying the exact influence of climatic conditions on VRI seasonality remains difficult [51].

Indoor Microclimate

The influence of indoor settings on the effects of outdoor weather conditions on VRIs merits consideration. Indoor heating and air cooling can substantially change indoor climates, frequently decreasing relative humidity and altering absolute humidity. Research indicates that increased indoor relative humidity via heating systems diminishes virus survival and infection rates, but inadequately ventilated, air-conditioned environments promote virus transmission [29,53]. These findings underscore the necessity for caution in interpreting results from research dependent on external meteorological data, since they may insufficiently reflect inside exposure circumstances [15].

Extreme Weather Events and Climate Anomalies

The intensification of extreme weather events due to climate change has profound implications for VRI outbreaks. Prolonged heatwaves, wildfires, and heavy rainfall events are becoming more frequent and severe, influencing air quality, hydrological systems, and health determinants, thereby increasing infection susceptibility and disease risk [54,55].

Heatwaves and Compound Events

Heatwaves exacerbate respiratory health risks by increasing air pollution levels through high-pressure conditions, sunlight, and stagnant air, which intensify particulate matter concentrations. These conditions can impair lung function and exacerbate pre-existing respiratory illnesses, such as asthma and COPD [56–60]. Studies indicate that heatwaves significantly increase the risk of acute respiratory infections, with synergistic effects from droughts and wildfires further elevating VRI susceptibility [56–58].

Heavy Rainfall and Floods

Heavy rainfall and associated flooding are predicted to increase globally, particularly affecting resource-limited tropical and subtropical regions [5,61–63]. Flood events often lead to overcrowding and poor sanitation, amplifying VRI risks [68]. Studies show heightened hospital admissions for acute respiratory infections following heavy rainfall, with direct floodwater exposure linked to a 2.75-fold increase in influenza-like illnesses [64–70].

El Niño and Seasonal Variability

El Niño events, characterized by abnormally warm sea surface temperatures in the tropical eastern Pacific, have been linked to increased influenza outbreaks [52,71]. Wintertime temperature anomalies during El Niño events have been associated with earlier and more severe influenza epidemics in subsequent years. Notably, major influenza outbreaks between 1957 and 2009 coincided with such climatic anomalies, underscoring the influence of El Niño as a predictive factor for influenza outbreaks [71,72]. As climate change progresses, these meteorological and climatic phenomena are expected to play an increasingly significant role in shaping the patterns and severity of VRI epidemics.

Long-Term Climate Changes:

Prolonged climatic warming has led to a about 1.2 °C increase in world average temperatures relative to pre-industrial levels, predominantly due to anthropogenic influences. This warming trend has caused significant issues in the atmosphere, hydrosphere, and biosphere, including changes in climate zones, modified vegetation cover, melting glacial permafrost, and loss of biodiversity. If prevailing rates continue, global temperatures are anticipated to surpass the key 1.5 °C threshold by mid-century, resulting in catastrophic and potentially irreversible effects on ecosystems and human cultures. Epidemiological surveillance in temperate countries has recorded a change in the seasonal onset of respiratory syncytial virus (RSV) activity towards warmer months, accompanied by a reduction in epidemic durations in recent decades. These patterns are postulated to arise from global temperature elevations and the subsequent expansion of tropical climatic zones [10,74,75]. Nevertheless, empirical validation of these findings is constrained by the lack of long-term, continuous monitoring data. Modeling studies offer further insights; for example, Baker et al. forecasted that future RSV outbreaks will migrate geographically northward, accompanied by prolonged epidemic durations. Simultaneously, elevated humidity associated with rising temperatures may diminish outbreak intensity, however areas subjected to heavy rainfall could see increasing epidemic severity [76]. Liu et al. predicted considerable intra-season temperature fluctuations in highly populated northern mid-latitude regions under Representative Concentration Pathways (RCP) scenarios, which might increase influenza morbidity risks by as much as 50% by the end of the century [77].

Respiratory viruses range from endemic human-adapted diseases to zoonotic organisms with the potential for pandemic emergence. RNA viruses from the Orthomyxoviridae, Coronaviridae, and Paramyxoviridae families, such as influenza viruses, human coronaviruses, RSV, parainfluenza virus, and human metapneumovirus, often traverse species barriers. Disease emergence often follows a three-stage process: (1) infections remain in natural reservoirs; (2) spillover events facilitate localized human transmission; and (3) sustained human-to-human transmission develops with insufficient population immunity, potentially leading to pandemics. Global networking intensifies this advancement [79]. Climate change markedly exacerbates spillover hazards via ecological and societal disturbances. Increasing temperatures, modified precipitation patterns, and habitat degradation induce changes in animal distributions, facilitating interspecies virus transmission. Modeling studies indicate that spillover hazards would escalate by 2070 as species interactions amplify due to altered environmental conditions [80]. A research analyzing Arctic samples supports this, indicating increased spillover potential associated with glacier melt runoff, a sign of climate change [81]. These findings highlight the relationship between environmental changes and the emergence of new disease risks, requiring strong surveillance and mitigation methods.

Climate Change-Viral Respiratory Interplay:

The interplay between climate change and viral respiratory infections (VRIs) operates through complex mechanistic pathways that encompass biological, social, and environmental dimensions. While substantial research has sought to elucidate these pathways, inconsistencies remain, necessitating further exploration to comprehensively understand the mechanisms by which climate impacts VRIs. Key pathways include the following: Meteorological factors significantly influence virus viability and transmission, as demonstrated by laboratory studies. Low temperatures enhance the stability of lipid-enveloped viruses, such as influenza and RSV, while exposure to ultraviolet radiation deactivates viruses [21]. Relative humidity (RH) modifies virus-laden droplet dynamics by altering sedimentation and evaporation, influencing transmission modes under varying conditions [82]. Animal studies indicate that influenza virus survival follows a U-shaped curve relative to RH, with reduced efficiency at moderate levels [18,21,39,83]. These findings provide a biological basis for seasonal VRIs, often exacerbated under "cold-dry" or "warm-humid" conditions [40,53]. Furthermore, in vitro studies reveal that lower temperatures optimize viral replication in the upper respiratory tract, supported by the temperature-dependent viral tropism (TDVT) hypothesis, which suggests viral adaptation to temperatures conducive to organ-specific replication [40,84].

Fluctuations in temperature and humidity influence airway antiviral functions, affecting both innate and adaptive immunity. Cold, dry air impairs epithelial barriers, mucociliary function, and tissue repair mechanisms in the respiratory tract. Moreover, recent evidence highlights a cold-air-induced suppression of innate antiviral defenses in nasal tissues [85–88]. Seasonal variations, including sunlight exposure, regulate immune responses, such as vitamin D synthesis, critical for combating respiratory infections [89]. However, heatwaves present a unique challenge, with experimental data showing suppressed CD8+ T-cell responses and antibody production under extreme temperatures (≥36 °C) [15]. Wildfires and heightened air pollution during heatwaves further exacerbate respiratory tract irritation and inflammation, reducing lung function and increasing vulnerability to VRIs [59,60]. Human behavior, shaped by climatic conditions, directly affects virus transmission. For instance, household crowding has been shown to amplify VRI risks during rainy seasons [64]. Similarly, behavioral shifts, such as increased indoor activities during extreme weather, foster conditions conducive to viral spread, explaining seasonal VRI patterns in both temperate and tropical climates [53]. Extreme weather events, such as floods and heavy rainfall, disrupt housing and healthcare systems, forcing displaced populations into crowded shelters with inadequate ventilation, thereby elevating viral transmission risks [65]. Climate-induced migration, exacerbated by rising sea levels and environmental degradation, further facilitates cross-regional disease spread, heightening epidemic and pandemic risks [5].

Climate change-induced droughts and land degradation undermine agricultural productivity, particularly in vulnerable tropical regions, worsening food insecurity and impairing host immunity [90,91]. Moreover, intensified agricultural practices and deforestation amplify zoonotic disease risks by increasing wildlife-livestock-human interfaces, enabling pathogen spillover [92,93]. Urban systems, often strained by cascading climate impacts such as rising sea levels and heavy rainfall, face increased susceptibility to respiratory illnesses due to damp and poorly ventilated housing [94,95]. Climate stressors disrupt public health efforts by impairing transportation, supply chains, and healthcare personnel mobility, compromising disease prevention and control measures [70]. Changes in natural environments, including shifts in climate belts, ocean acidification, and biodiversity loss, exacerbate ecological vulnerabilities. The geographic ranges of animal species are shifting as habitats shrink, increasing the risk of zoonotic spillovers. Studies have identified tropical forests with high mammalian biodiversity as hotspots for disease emergence, particularly in areas affected by agricultural expansion and land-use changes [75,78,96,97]. These pathways underscore the multifaceted impacts of climate change on VRIs, necessitating targeted strategies that integrate biological, ecological, and socio-environmental considerations to mitigate future health risks.

Data Analysis:

This review consolidates current interdisciplinary information to clarify the connection between viral respiratory infections (VRIs) and climate change across three key dimensions: meteorological parameters, extreme weather events, and long-term warming. The investigation investigates the biological, social, and environmental mechanisms through which climate affects VRIs, with the objective of promoting interdisciplinary comprehension of these intricate relationships. The research examines nine viral pathogens linked to viral respiratory infections, especially those that can cause recurrent seasonal outbreaks and severe pandemics. Although comprehensive epidemiological studies have investigated the relationships between meteorological variables and VRI seasonality, notable regional variability remains. In contrast, minimal emphasis has been directed towards the effects of extreme weather occurrences, with the majority of evidence stemming from single case studies. Fewer studies examine the effects of prolonged climatic warming on VRI dynamics in human populations.

Our thorough integration of interdisciplinary research demonstrates that climate change has both direct and indirect impacts on the incidence and proliferation of VRIs. Biological and epidemiological data highlight the essential roles of temperature and humidity as key meteorological factors affecting VRI seasonality. Increasing global temperatures and irregular precipitation patterns, resulting from climate change, are expected to alter the spatial and temporal dynamics of seasonal epidemics. Moreover, extreme weather events intensify transmission risks by enhancing host proximity and exposure, especially in resource-limited areas where climate threats worsen vulnerabilities like displacement and food shortages. In the long term, these climate changes increase the probability of VRIs in previously unexposed regions and periods. The rise of zoonotic infections and the risk of pandemics mostly result from ecological and socioeconomic changes induced by climate change and increased interactions among humans, animals, and the environment. The examination of biological, social, and environmental pathways underscores critical ramifications for the progression of VRI transmission, ranging from localized seasonal outbreaks to worldwide pandemics. While numerous mechanisms are not well comprehended, certain ones offer essential insights. If seasonal viral respiratory infections are regulated by intrinsic oscillation cycles affected by weather-dependent behavioral and physiological components, as suggested by some studies [29], climate change may disrupt these cycles, making seasonal patterns more unpredictable. This volatility in weather patterns may exacerbate the effects of climate change on VRI seasonality.

Emerging VRIs with pandemic potential, arising at human-animal interfaces, are affected by climate change via intricate interplay of ecological, social, and environmental factors. Human actions, such as urbanization and habitat encroachment, modify interaction patterns between humans and animal reservoirs [12]. The enhancement of global connection, notwithstanding the transient disruption from COVID-19, accelerates the swift transboundary dissemination of VRIs via travel, trade, and population displacement. The interrelated aspects emphasize the necessity of implementing a One Health approach, which amalgamates human, animal, and environmental health issues to tackle regional and global health threats stemming from climate change [98]. This strategy improves interdisciplinary collaboration, fortifies disease surveillance, and guides pandemic preparedness efforts. Notwithstanding advancements, contradictory results continue to exist about the mechanisms that connect climatic causes to VRIs. Discrepancies frequently emerge due to variations in study design, statistical approaches, data comparability, virus species, and diagnostic techniques [51]. Furthermore, the mediating influences of ecological and socioeconomic variables on population vulnerability are yet little examined. In vitro and animal studies offer limited understanding of the molecular mechanisms behind these relationships, although they do not encompass the intricate interconnections of environmental and social variables. There is an urgent need for research to elucidate these complex systems and examine the interaction of many climatic and non-climatic elements. The occurrence of compound climatic occurrences, arising from the intersection of many climatic factors and risks, is under heightened scrutiny. These occurrences, frequently aggravated by environmental contamination, can amplify health hazards and increase the prevalence of VRIs [4][5]. Conventional assessments, which generally concentrate on individual factors, may undervalue these cumulative hazards. It is vital to do advanced research that includes chemical exposures, such as precise temperature and humidity ranges linked to increased VRI incidence.

Early warning systems are essential instruments for proactive disease prevention, resource distribution, and outbreak management. Combining multisource data with sophisticated predictive methods can improve the promptness and precision of disease forecasts. Nonetheless, the applicability of conventional epidemiological models is frequently limited by regional climate heterogeneity. Advanced models integrating climate data and forecasting methodologies could markedly enhance predictive accuracy, allowing for the early identification of climate-induced VRI epidemics and supporting focused prevention measures. Connecting epidemiologists and atmospheric scientists is crucial for creating sophisticated predictive frameworks, thereby assuring a holistic strategy for addressing the health effects of climate change on VRIs. The intricate interaction of climatic, biological, social, and environmental elements highlights the complex impact of climate change on VRIs. The ramifications are significant, ranging from seasonal variations in transmission patterns to an increased chance of pandemics. Confronting these difficulties requires an interdisciplinary strategy that integrates creative research approaches, effective early warning systems, and international cooperation. This analysis highlights the necessity of incorporating climatic factors into public health efforts to address the increasing risk of VRIs amid swift environmental changes.

Challenges Facing Respiratory Health in the Era of Climate Change

The era of climate change has introduced multifaceted challenges to respiratory health, driven by both direct and indirect environmental transformations. These challenges emerge from complex interactions between changing meteorological conditions, increasing air pollution, and the expanding prevalence of respiratory infections. While global initiatives to combat climate change focus on mitigation and adaptation strategies, the effects on respiratory health demand critical attention. This discussion examines the primary challenges to respiratory health in the context of climate change, emphasizing the roles of environmental pollutants, altered disease dynamics, and socioeconomic vulnerabilities.

Air Pollution and Respiratory Health

One of the most direct pathways through which climate change impacts respiratory health is via air pollution. Rising temperatures, coupled with urbanization and industrial activities, exacerbate the concentration of ground-level ozone and particulate matter (PM), particularly fine PM2.5. Exposure to these pollutants is strongly associated with a spectrum of respiratory conditions, including asthma, chronic obstructive pulmonary disease (COPD), and lung cancer. Ground-level ozone, formed by chemical reactions between volatile organic compounds and nitrogen oxides in the presence of sunlight, irritates the respiratory tract, leading to exacerbations of asthma and other pre-existing conditions. Wildfires, increasingly frequent and intense due to prolonged droughts and higher temperatures, further contribute to the deterioration of air quality. Smoke from wildfires contains a mixture of fine particles and toxic gases, which are linked to both acute respiratory symptoms and long-term health consequences. Studies have demonstrated a surge in emergency hospital admissions for respiratory diseases during and after wildfire events, with vulnerable populations, such as children, the elderly, and individuals with pre-existing conditions, being disproportionately affected. Moreover, the interaction between air pollution and allergens, including pollen, presents a dual threat. Climate change extends the growing seasons of allergenic plants and increases pollen production. This, combined with the oxidative stress caused by airborne pollutants, amplifies the severity of allergic respiratory diseases such as hay fever and allergic asthma.

Climate Change and Respiratory Infections

Climate change has also altered the epidemiology of respiratory infections, both in terms of seasonal patterns and geographic distribution. Changes in temperature, humidity, and precipitation significantly influence the transmission dynamics of viral respiratory infections (VRIs). For instance, influenza and other respiratory viruses exhibit seasonality governed by meteorological factors, with warmer temperatures and increased humidity potentially extending transmission periods or shifting outbreaks to previously unaffected regions. Extreme weather events, such as hurricanes, floods, and heatwaves, create conditions conducive to outbreaks of respiratory infections. Flooding, for example, can lead to overcrowded living conditions in shelters, which facilitates the spread of infectious agents. The stagnant water left in the aftermath of floods also fosters the proliferation of pathogens, increasing the likelihood of respiratory illnesses caused by mold exposure and waterborne bacteria. Long-term warming poses an additional threat by influencing zoonotic diseases with respiratory manifestations. Climate-driven habitat changes increase human-wildlife interactions, raising the risk of spillover events. The COVID-19 pandemic serves as a stark reminder of how quickly zoonotic respiratory infections can escalate into global public health emergencies. Climate change, coupled with globalization and urbanization, accelerates these dynamics, making early detection and control measures increasingly critical.

Socioeconomic and Demographic Vulnerabilities

The impacts of climate change on respiratory health are not evenly distributed; socioeconomic and demographic factors play pivotal roles in determining individual and community-level vulnerabilities. Low- and middle-income countries (LMICs) are disproportionately affected due to limited healthcare resources, inadequate infrastructure, and higher baseline exposure to environmental hazards. In these regions, respiratory diseases often coincide with other health burdens, creating compounded risks. Within countries, marginalized populations face heightened risks. People living in urban slums or near industrial zones are more likely to experience prolonged exposure to air pollutants. Similarly, individuals with limited access to healthcare services may delay seeking treatment for respiratory conditions, leading to worse outcomes. Climate change exacerbates these disparities by disproportionately increasing the frequency and severity of respiratory health threats in already vulnerable populations. Children and the elderly are particularly susceptible. Pediatric populations are more vulnerable to the harmful effects of air pollution due to their developing respiratory systems and higher breathing rates relative to body weight. In older adults, climate change-induced stressors often exacerbate pre-existing respiratory and cardiovascular conditions, leading to increased morbidity and mortality.

Challenges in Disease Management and Policy Implementation

The evolving landscape of respiratory health in the context of climate change presents significant challenges for healthcare systems and policymakers. Effective management requires a multidisciplinary approach that incorporates climate science, public health, and clinical medicine. However, gaps in data and predictive models often hinder comprehensive planning. Traditional epidemiological models may fail to account for the complex interactions between climatic variables and respiratory health outcomes, necessitating the development of more sophisticated, climate-informed disease prediction tools. Policy implementation is further complicated by competing priorities in climate change mitigation and adaptation strategies. While reducing greenhouse gas emissions and transitioning to cleaner energy sources are essential for addressing the root causes of climate change, these measures must be balanced with investments in healthcare infrastructure to address its immediate health impacts. Furthermore, global health policies often overlook the interconnected nature of climate change and respiratory health, resulting in fragmented efforts that fail to address the problem holistically.

Future Directions and Recommendations

Addressing the challenges of respiratory health in the era of climate change requires coordinated, evidence-based strategies. Policymakers must prioritize reducing air pollution through stricter emission standards and the promotion of renewable energy sources. Enhancing early warning systems for respiratory disease outbreaks, particularly those linked to extreme weather events, is equally important. These systems should integrate meteorological, environmental, and healthcare data to provide timely and accurate predictions. Healthcare systems must also strengthen their capacity to respond to climate-related respiratory health crises. This includes increasing access to care for vulnerable populations, investing in research to understand the interplay between climate change and respiratory health, and training healthcare professionals to recognize and manage climate-related respiratory conditions. On a global scale, the adoption of the *One Health* approach, which emphasizes the interconnectedness of human, animal, and environmental health, is critical. Collaborative efforts across disciplines and borders can facilitate the development of comprehensive strategies to mitigate the respiratory health impacts of climate change while addressing its underlying drivers. The era of climate change poses profound challenges to respiratory health, driven by a combination of environmental, biological, and socioeconomic factors. From worsening air pollution and shifting patterns of respiratory infections to the disproportionate impact on vulnerable populations, the consequences are both widespread and deeply inequitable. Addressing these challenges requires a multidisciplinary approach that integrates public health, climate science, and social equity. By prioritizing research, policy innovation, and global collaboration, the international community can work toward safeguarding respiratory health in the face of an ever-changing climate.

Conclusion:

Climate change is redefining the epidemiological landscape of viral respiratory infections (VRIs), posing significant public health challenges. The intricate interplay between meteorological conditions and VRIs underscores the urgency of addressing this evolving threat. Low temperature and humidity are key factors that enhance viral survival and transmission, with evidence suggesting that indoor microclimates and behaviors amplify these effects. Furthermore, extreme weather events, such as heatwaves and floods, exacerbate respiratory health risks by deteriorating air quality and sanitation, disproportionately affecting vulnerable populations in resource-limited settings. Long-term global warming has shifted the seasonal onset and dynamics of VRIs, particularly in temperate regions, where earlier peaks and prolonged epidemic durations are observed. These changes highlight the complex and region-specific nature of climate-sensitive disease patterns. Moreover, the intensification of events like El Niño demonstrates the predictive potential of climatic anomalies in shaping VRI outbreaks. This review emphasizes the need for enhanced surveillance systems that integrate meteorological and epidemiological data to better predict and mitigate VRI outbreaks. Interdisciplinary research is critical to unraveling the mechanistic pathways linking climate variables with viral dynamics. Public health preparedness must also evolve, incorporating adaptive measures to address the heightened risks posed by climate change. Strategies such as improving indoor air quality, ensuring equitable access to healthcare, and bolstering community resilience against extreme weather events are pivotal. In conclusion, the interplay between climate change and VRIs demands a paradigm shift in global health strategies. Addressing this multifaceted issue requires a coordinated effort among policymakers, researchers, and public health practitioners to mitigate the impacts of climate change on respiratory health. By fostering resilience and preparedness, we can safeguard communities against the escalating threats posed by a rapidly changing environment.

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اضطرابات الجهاز التنفسي وتلوث الهواء: تأثير التغير المناخي - مراجعة محدثة

الملخص:

الخلفية: تُعد العدوى التنفسية الفيروسية (VRIs) من الأسباب الرئيسية للمراضة والوفيات على مستوى العالم. لقد أدى التغير المناخي إلى تفاقم الظروف البيئية، مما قد يغير وبائيات هذه العدوى. لا يزال التفاعل بين العوامل الجوية والعدوى التنفسية الفيروسية غير مفهوم بشكل كافٍ، مما يستدعي مراجعة شاملة.

الهدف: تهدف هذه المراجعة إلى دراسة تأثير التغير المناخي على التوزيع الموسمي، وديناميكيات التفشي، وأنماط انتقال العدوى التنفسية الفيروسية، مع تسليط الضوء على تأثير العوامل الجوية والأحداث المناخية المتطرفة. الطرق: تم إجراء

تحليل منهجي لأدلة وبائية وبيولوجية وبيئية حديثة. حللت المراجعة بيانات حول الظروف الجوية، والظواهر الجوية المتطرفة، واتجاهات الاحترار العالمي على المدى الطويل، مع التركيز على تأثيراتها على العدوى التنفسية الفيروسية.

النتائج: تظهر العدوى التنفسية الفيروسية أنماطًا موسمية مميزة تتأثر بدرجة الحرارة والرطوبة والميكروكليما الداخلية. تعزز درجات الحرارة المنخفضة والرطوبة بقاء الفيروس وانتقاله، خاصة في حالات الإنفلونزا وفيروس الجهاز التنفسي المخلوي .(RSV) تؤدي الأحداث المناخية المتطرفة، مثل موجات الحر والفيضانات، إلى تفاقم المخاطر الصحية التنفسية من خلال تأثيرها على جودة الهواء والصرف الصحي. كما أن التغيرات المناخية طويلة المدى قد غيرت الديناميكيات الزمانية والمكانية للعدوى التنفسية الفيروسية، مع اتجاهات تشير إلى بداية مبكرة وفترات وبائية أطول في المناطق المعتدلة.

الخلاصة: يقوم التغير المناخي بإعادة تشكيل وبائيات العدوى التنفسية الفيروسية من خلال تأثيراته على المتغيرات الجوية والأحداث المناخية المتطرفة. إن تعزيز المراقبة، والبحث بين التخصصات، واستراتيجيات التكيف أمر بالغ الأهمية للاستعداد للوباء في مناخ متغير.

الكلمات المفتاحية: العدوى التنفسية الفيروسية، التغير المناخي، تلوث الهواء، الأنماط الموسمية، الأحداث المناخية المتطرفة، الوبائيات، الصحة العامة.