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### **Recommended Citation**

Schuldt, S. J., Nicholson, M. R., Adams II, Y. A., & Delorit, J. D. (2021). Weather-related construction delays in a changing climate: A systematic state-of-the-art review. *Sustainability (Switzerland)*, 13(5), 2861. <https://doi.org/10.3390/su13052861>

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Review

# Weather-Related Construction Delays in a Changing Climate: A Systematic State-of-the-Art Review

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**Abstract:** Adverse weather delays forty-five percent of construction projects worldwide, costing project owners and contractors billions of dollars in additional expenses and lost revenue each year. Additionally, changes in climate are expected to increase the frequency and intensity of weather conditions that cause these construction delays. Researchers have investigated the effect of weather on several aspects of construction. Still, no previous study comprehensively (1) identifies and quantifies the risks weather imposes on construction projects, (2) categorizes modeling and simulation approaches developed, and (3) summarizes mitigation strategies and adaptation techniques to provide best management practices for the construction industry. This paper accomplishes these goals through a systematic state-of-the-art review of 3207 articles published between 1972 and October 2020. This review identified extreme temperatures, precipitation, and high winds as the most impactful weather conditions on construction. Despite the prevalence of climate-focused delay studies, existing research fails to account for future climate in the modeling and identification of delay mitigation strategies. Accordingly, planners and project managers can use this research to identify weather-vulnerable activities, account for changing climate in projects, and build administrative or organizational capacity to assist in mitigating weather delays in construction. The cumulative contribution of this review will enable sustainable construction scheduling that is robust to a changing climate.

**Keywords:** climate change; construction; delay; impact; modeling; productivity; review; weather



**Citation:** Schuldt, S.J.; Nicholson, M.R.; Adams, Y.A., II; Delorit, J.D. Weather-Related Construction Delays in a Changing Climate: A Systematic State-of-the-Art Review. *Sustainability* **2021**, *13*, 2861. <https://doi.org/10.3390/su13052861>

Academic Editors: Sunkuk Kim and Jurgita Antuchevičienė

Received: 4 February 2021  
Accepted: 4 March 2021  
Published: 6 March 2021

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## 1. Introduction

The construction industry is one of the most vulnerable to adverse weather conditions due to its reliance on labor and outdoor activities [1]. Weather events pose major uncertainty factors that negatively impact construction projects' productivity and duration [2]. Forty-five percent of all construction projects are affected, to some degree, by weather, resulting in billions of dollars in additional costs worldwide, on an annual basis [3]. These events can impact project stakeholders through schedule slippage and decreased worker safety, resulting in potential legal repercussions.

This review focuses on the impact of adverse weather events on construction projects, specifically focusing on weather's impact on task feasibility, methods to model delays, and mitigation techniques to counteract these impacts. Weather events directly impact the ability to complete construction tasks, also called task feasibility. Effects on task feasibility range from complete work stoppage to reduced worker productivity and ultimately delays the project schedule. The delay of any project has financial implications, which are shared by the contractor, owner, and external stakeholders. The inclusion of specific language concerning the calculation of permissible delays, based on abnormal or unforeseeable weather, and which weather conditions constitute an excusable delay, have been shown to reduce the number of delay disputes that arise in a project [4–7]. Events like lightning and high winds pose significant threats to workers, slow worker productivity, or require work stoppages, but proper planning and coordination can mitigate risk.

Modeling contributes to understanding weather impacts on construction and can inform construction managers' mitigation and adaptation strategies. As such, decision-makers must model weather events to determine their impact on construction tasks and develop schedules that reduce risk. As it becomes more apparent that climate change increases weather intensity and variability [8], weather prediction improvements will be critical. However, few studies address the influence of climate change on the modeling and mitigating delays. Climate change affects the typical working environment and reduces the validity of current models. Altinsoy and Yildirim (2015) mention the importance of regional climate models in accounting for decreases in worker productivity due to region-specific climate change and suggest the development of more sophisticated models may be crucial for project delay management [9].

With project adjustments and strategies, mitigation of weather-related delays is possible. Mitigation methods can be as simple as observing work-rest cycles and providing weather-appropriate protective gear [10]. Other methods may be more involved, such as planning the project schedule within the proper construction season or ensuring that the construction contract has the right language to prevent ambiguity. Mitigation strategies can help construction managers adapt, avoid, or anticipate delays due to weather.

Despite the significant contributions of the studies mentioned above, none of the studies provide a critical review that holistically explains weather's impact on construction. This systematic state-of-the-art review identified 204 articles covering task feasibility, models, and mitigation techniques of weather's impact on construction. The goal of this review is to (a) identify and quantify the risks weather imposes on construction projects, (b) categorize modeling and simulation approaches that have been developed, and (c) describe the mitigation strategies and adaptation techniques in order to provide best management practices for the construction industry.

## 2. Materials and Methods

### 2.1. Research Methodology

The authors utilized the PRISMA method to conduct a systematic state-of-the-art review (Figure 1). The search was conducted using the following search string in Scopus and Web of Science (WoS) core collection on 27 October 2020: construction AND (weather\* OR climat\*) AND (delay OR impact OR schedul\* OR effect) AND (producti\* OR labor OR labour OR feasib\* OR workability OR safety). The search identified 4337 papers.

After removing 1130 duplicates, the authors performed a two-step screening process using two pre-defined exclusion criteria: (1) only articles focused on the construction industry were considered eligible, and (2) each article had to focus on at least one of the keywords or phrases listed in the search string hierarchy. The first screening reviewed article titles and abstracts and excluded 2982 articles using the pre-defined exclusion criteria. Next, the remaining 225 full-text articles were screened, and an additional 101 articles were removed, resulting in 124 identified eligible records. Additional articles were selected from the references of included texts to expand the systematic review scope, resulting in 80 unique new records. As a result of this methodology, 204 studies were included in the systematic review.

The state-of-the-art component of this paper focused on the inclusion of literature that addressed the role of climate change and construction delays. After each of the 204 articles was read, it was categorized by the degree of focus climate change received as a component of the research. The degree to which climate change is included in the articles is summarized in this paper's climate change section.

### 2.2. Bibliometric Analysis

Figure 2 shows the top producing locations and their associated total number of citations. The United States leads the way in both total publications (42) and total citations (1740), while Australia, the United Kingdom, Canada, and Hong Kong round out the top five producing locations with 23, 23, 15, and 11 publications, respectively. Despite

only publishing 11 papers, Malaysia has the second-most citations (876), followed by Australia (781), Hong Kong (759), and the United Kingdom (573). In total, 51 locations are represented in the 202 papers included in this systematic state-of-the-art review. This collection of papers has a combined h-index of 40, as shown in Figure 3.

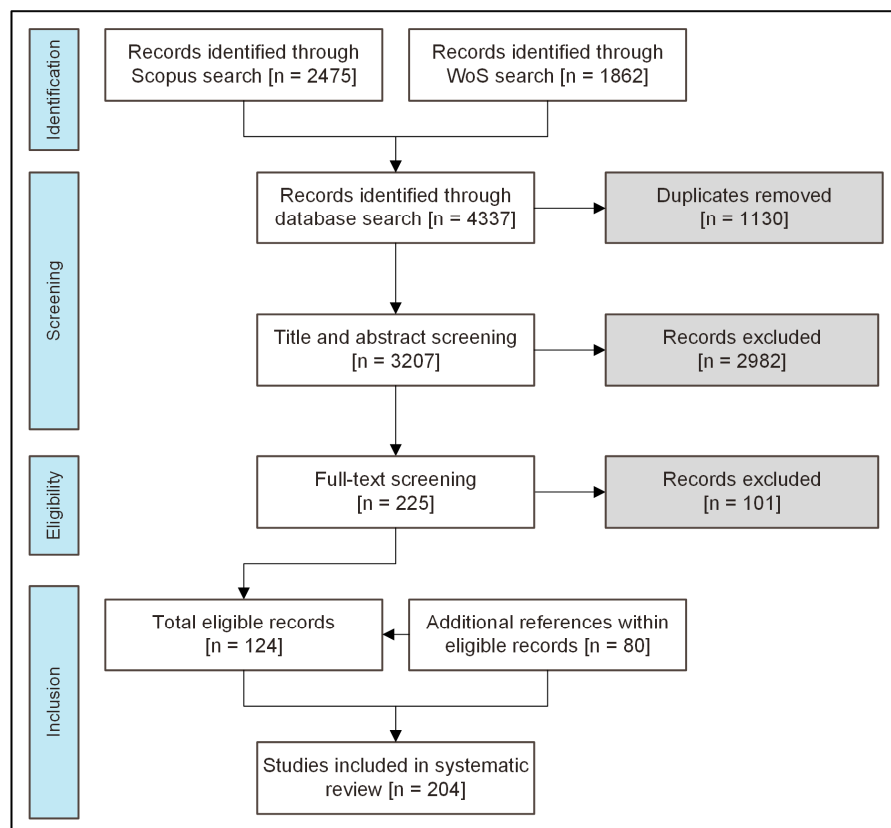


Figure 1. PRISMA Flow Diagram.

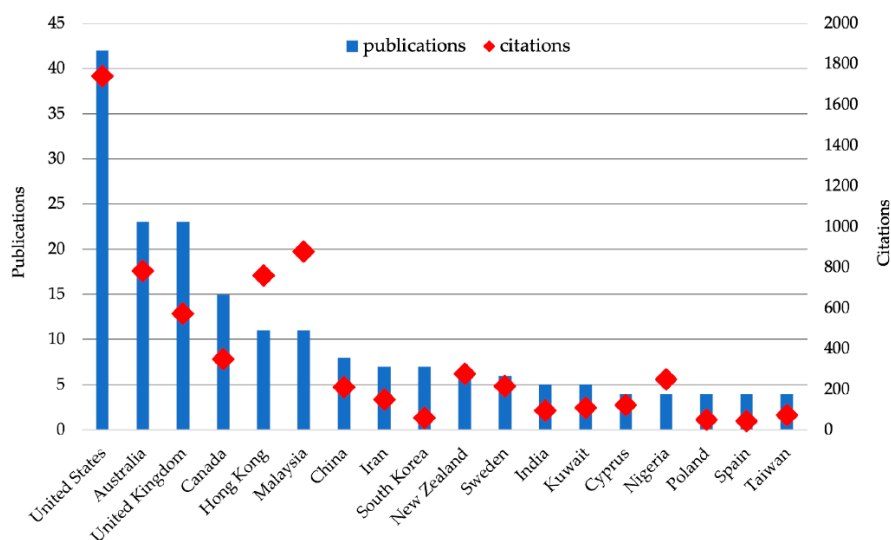
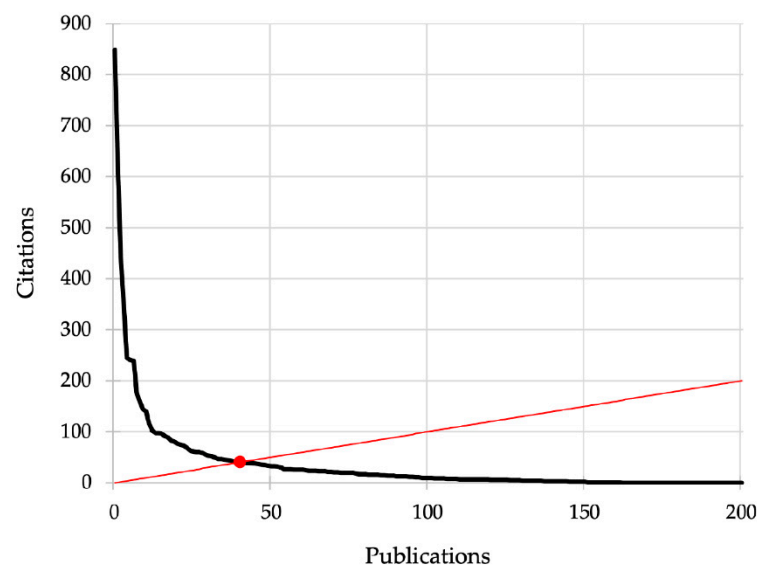
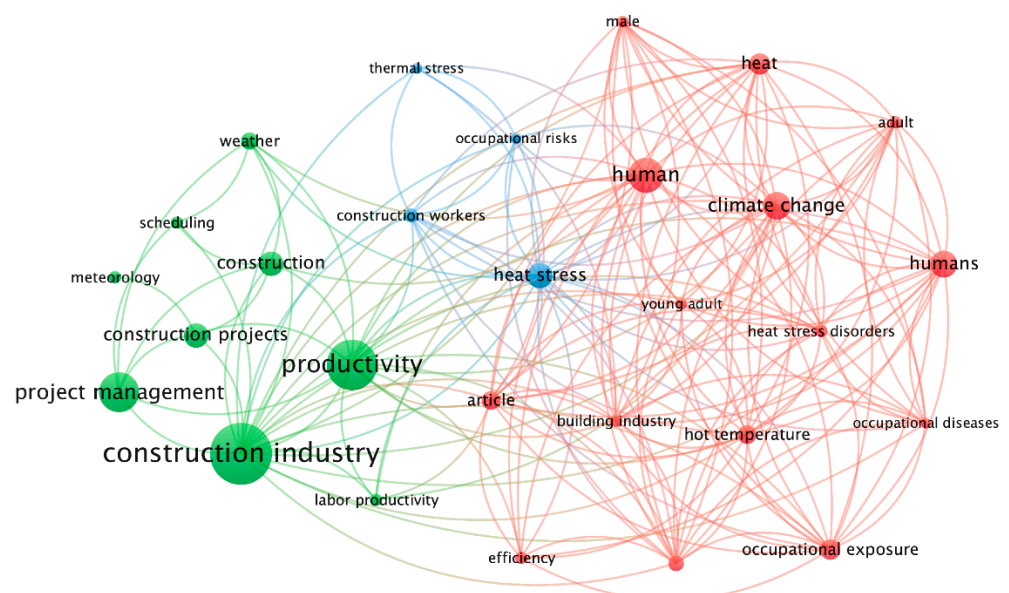


Figure 2. Top producing and highest cited locations.



**Figure 3.** The included publications have an h-index of 40.

A keyword co-occurrence network was constructed for all publications using both author keywords and “keywords plus” provided by the journals. Figure 4 shows the keyword co-occurrence network for the 28 keywords that appeared at least ten times in the included publications. There are three important elements in the keyword co-occurrence diagram. First, circle or node size represents the frequency or number of papers that include the identified keyword. The larger the circle, the more frequently the given keyword appears. Second, the colors represent clusters or related keywords. Finally, the lines represent co-occurrences—the wider the line, the more co-occurrences between the keywords.



**Figure 4.** Keyword co-occurrence showing 28 keywords that appeared in at least ten publications.

These keywords are grouped into three clusters, representing groups of keywords that appeared together in papers at least four times. “Construction Industry” was the most frequently used keyword, appearing in 58 papers, followed by “productivity” (47), “project management” (37), “human” (33), and “climate change” (26).

Table 1 lists the top 10 highest cited papers included in this systematic state-of-the-art review. With 439 citations, Richardson (1981) is the top-cited article [11]. The International

Journal of Project Management accounted for the majority of the highly published papers, including five of the top 10 most cited papers.

**Table 1.** The ten highest cited papers included in the systematic state-of-the-art review.

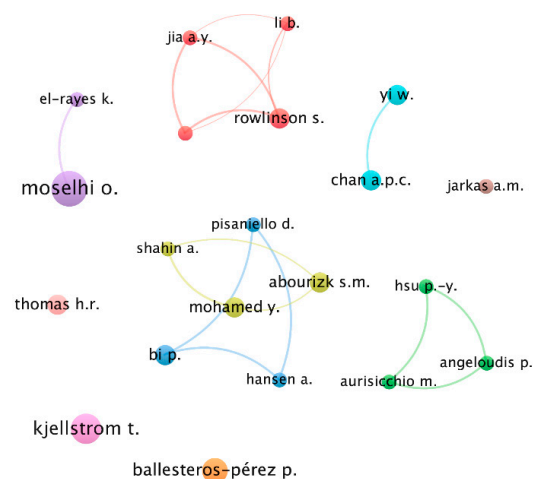
No.	Source Title, Year	Title	Document Type	Times Cited
1	Water Resources Research, 1981	Stochastic simulation of daily precipitation, temperature, and solar radiation	Article	439
2	International Journal of Project Management, 2007	Causes and effects of delays in Malaysian construction industry	Article	398
3	International Journal of Project Management, 1997	A comparative study of causes of time overruns in Hong Kong construction projects	Article	388
4	Ecological Modelling, 1991	A serial approach to local stochastic weather models	Article	311
5	International Journal of Project Management, 2000	Construction delay: A quantitative analysis	Article	298
6	International Journal of Project Management, 2002	The effects of construction delays on project delivery in Nigerian construction industry	Article	290
7	International Journal of Project Management, 2009	Cost escalation and schedule delays in road construction projects in Zambia	Article	268
8	Accident Analysis and Prevention, 2004	The mixed effects of precipitation on traffic crashes	Article	250
9	Archives of Environmental and Occupational Health, 2009	The direct impact of climate change on regional labor productivity	Article	246
10	Structural Survey, 2005	Factors affecting construction labour productivity for Malaysian residential projects	Review	233

Table 2 showcases the nine authors that have published at least four papers included in this systematic review. Notably, while the United States produced by far the most publications included in the review, only one of the top nine most productive authors is affiliated with the United States (Thomas). Professor Moselhi from Concordia University, Montreal, Canada, has the most papers included in this review (seven), and he is followed by authors from New Zealand (Kjellström), Spain (Ballesteros-Pérez), Australia (Peng), Chan (Hong Kong), Mohamed (Canada), Rowlinson (Hong Kong), Thomas (United States), and Yi (New Zealand). Professor Tord Kjellström, the Director of Health and Environmental International Trust, Nelson, New Zealand, has the most citations among the top producing authors (286).

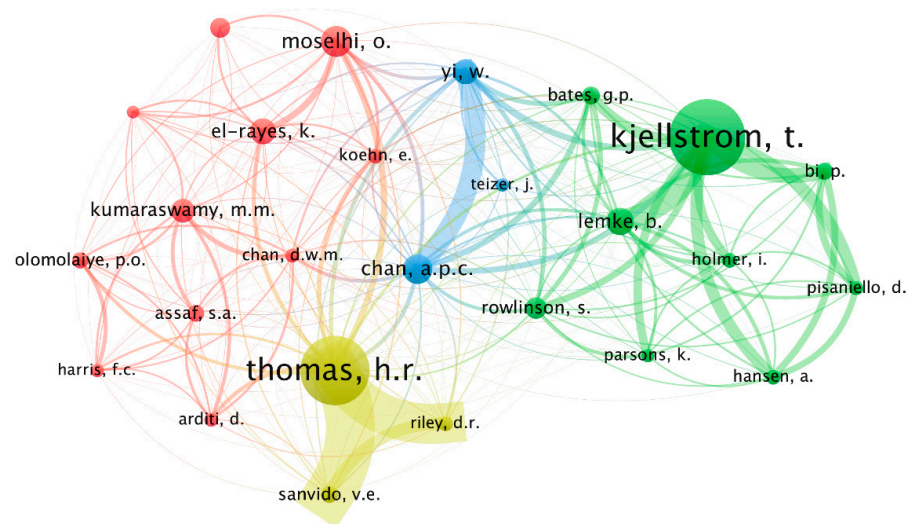
**Table 2.** The top producing authors included in the systematic state-of-the-art review.

Author	Affiliation	Papers	Citations
Moselhi, Osama El Sayed	Concordia University, Montreal, Canada	7	204
Kjellström, Tord E.	Health and Environment International Trust, Nelson, New Zealand	6	286
Ballesteros-Pérez, Pablo	Universidad de Cadiz, Cadiz, Spain	5	58
Bi, Peng	The University of Adelaide, Adelaide, Australia	4	279
Chan, Albert P.C.	Hong Kong Polytechnic University, Kowloon, Hong Kong	4	96
Mohamed, Yasser Abdel Rady I.	University of Alberta, Edmonton, Canada	4	47
Rowlinson, Steve	The University of Hong Kong, Pokfulam, Hong Kong	4	106
Thomas, H. Randolph	Pennsylvania State University, University Park, United States	4	180
Yi, Wen	Massey University Auckland, Albany, New Zealand	4	88

Two additional co-occurrence analysis networks are presented in Figures 5 and 6. Figure 5 visualizes the co-authorship analysis network of authors with three or more publications included in the review. This network shows little interaction or crossover among the top-producing authors. This is to be expected with this systematic review because it draws papers from a wide variety of topics and academic disciplines to holistically determine the impact of weather on construction workers, materials, and tasks. Papers included in this review come from numerous academic disciplines, including engineering, business and management, medicine, environmental science, and decision sciences.



**Figure 5.** Co-authorship analysis network of authors with three or more publications.



**Figure 6.** Co-citation analysis of the 26 authors cited at least 25 times each.

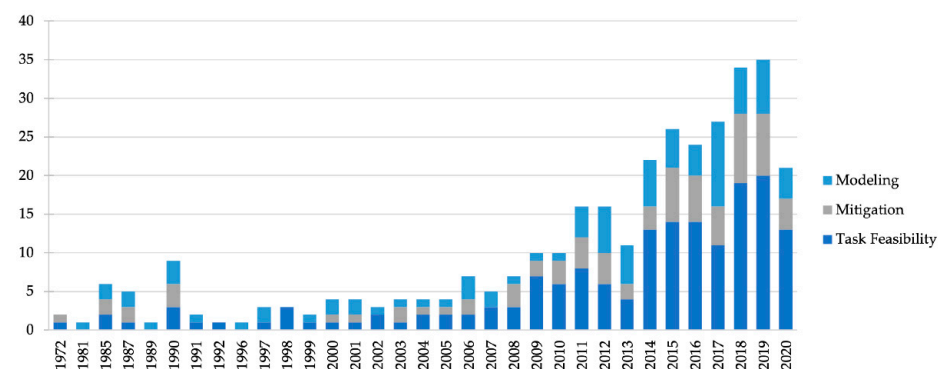
The connectedness of these authors and their research are revealed through the analysis of the author co-citation network shown in Figure 6. The author co-citation network examines whose publications are cited together in the same articles. Twenty-six authors were cited at least 25 times, and they are grouped into four clusters. These clusters represent various research streams of the various aspects of the problem, including the effects of weather on labor productivity and methods to manage heat stress suffered by construction workers. This review agglomerates these disconnected research streams to fully assess the impact of weather on construction.

### 2.3. Classification of Literature

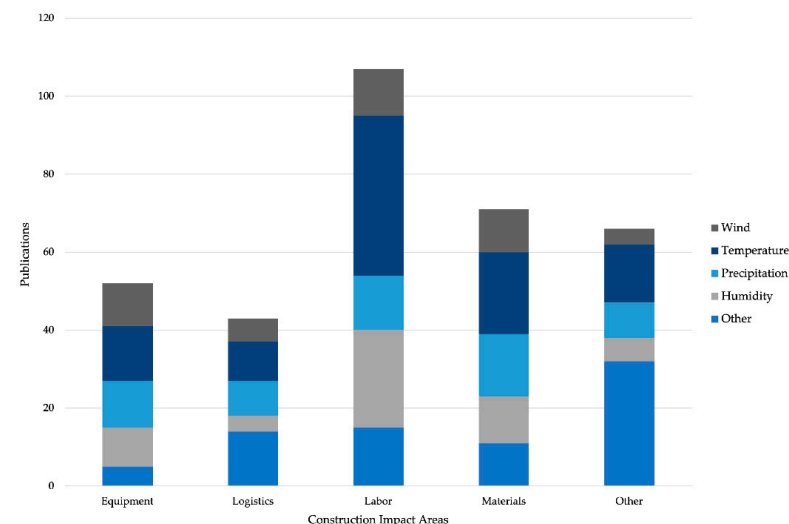
This review includes 204 studies published between 1972 and October 2020. The literature approaches construction weather delays in three main areas: weather attributes that directly cause delays by limiting construction task feasibility; modeling efforts that skillfully predict delays, estimate construction impacts, and optimize scheduling; and techniques implemented to mitigate delays caused by weather. Several areas are most acutely impacted by weather, including labor, equipment, and materials. These types of delays are classified here as task feasibility delays. The review found that mitigative techniques are classified as physical or administrative protocols. Additionally, several climate factors appear in the literature, including temperature, precipitation, humidity, wind, and anomaly weather events. Extreme events, such as tornadoes and hurricanes, are

disruptive to construction and have unexpected, traumatic effects. However, they are not within the primary scope of this review.

An article with multiple focuses is counted in each relevant research area, so the following analysis is not cumulative. Figure 7 provides a non-cumulative, temporal summary of the distribution of paper focus areas. The task feasibility category is the most commonly researched and is featured in 133 of the 204 publications (65.2%) retained in this review. The next most common individual research focuses were modeling (33.3%) and labor productivity (30.9%). Figure 8 summarizes the breakdown of weather attributes by the construction impact area. The impact of temperature is the most common single area studied, accounting for 87 of the 204 publications (42.6%). Humidity (26.0%) and precipitation (20.1%) are the next most commonly researched weather factors. The least common research focus areas include climate change applications (5.9%), physical mitigation techniques (13.2%), and the impact of wind (14.2%).



**Figure 7.** Non-cumulative, primary research areas by year; many of the papers address multiple research areas resulting in what appears as a greater number of papers than were published in each year.

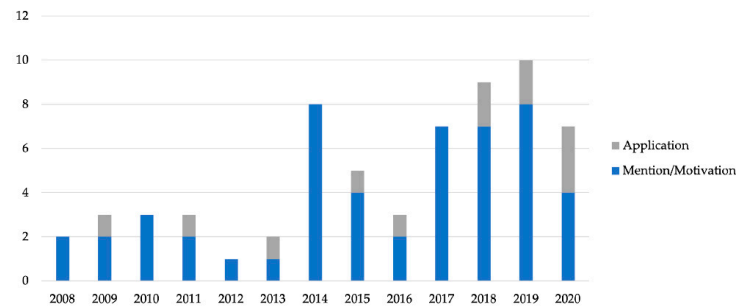


**Figure 8.** Weather factors by construction impact areas/task feasibility research area; one study may include multiple weather factors; therefore, this figure is not cumulative.

The papers are also classified by whether the effects of changing climate are addressed. Sixty-four of the studies reviewed consider climate change in some form, where 12 of those 63 papers directly address climate change through the use of projections in modeling or analysis, while 51 simply mention climate change as a motivation, limiting factor, or future research opportunity, without using projections in their analysis. Thirty-seven of the 63 papers that meaningfully address climate change consider temperature changes. Figure 9

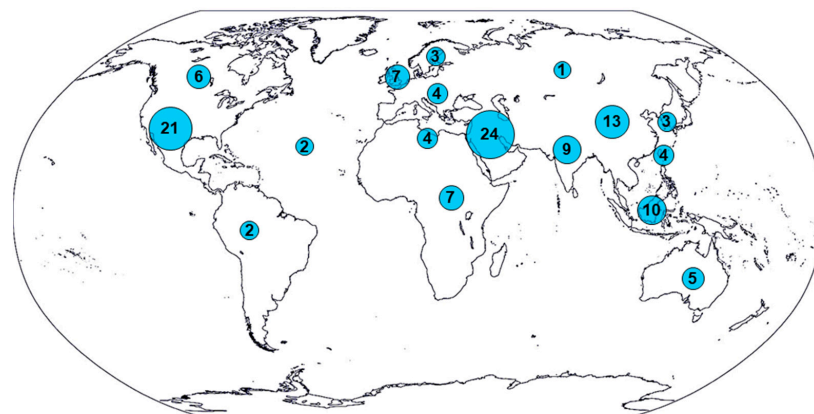


depicts the progression of climate change as a focus in the papers reviewed, with the first publication occurring in 2008. Superficial allusions to climate change have increased steadily since its first mention, though only limited and sporadic modeling applications have been completed. Clearly, there is a demand for the inclusion of climate change projections in construction scheduling and delay modeling that is not being satiated.



**Figure 9.** The number of studies considering climate change. Those that mention climate change or use climate change as a motivation without applying projections in their analysis are categorized as “Mention/Motivation.” In contrast, those that apply climate change (e.g., through climate projections) are categorized as “Application.”

Geographic trends exist in the literature for case study-based papers. Figure 10 below displays scaled circles corresponding to the number of studies emanating from each applied to that region, of a total of 128 case studies identified from the 204 studies retained. One example of regionalization is the prevalence of worker/labor productivity studies in the Middle East [12–17] and East Asian Countries near the Tropic of Cancer [10,18–22]. The prevalence of worker productivity studies in these regions could be due to the vast number and density of the labor forces in nations like India and China or the recent increase in development in these countries. The Arabian Peninsula’s high temperatures draw many researchers to study laborer conditions and worker health. Fewer case studies exist in colder regions and the African continent. Those studies collected for colder regions include Sweden [23], Finland [24], Denmark [25], Norway [24], Canada [26,27], Nepal [19], Russia [28], and offshore construction [29,30]. The studies of the African continent were conducted in Nigeria [31–33], Libya [34], Egypt [35,36], Zambia [37], or across several countries [8,38]. There are no regional, standardized modeling techniques for incorporating weather delays in construction. The likely reasons include a regional variation of climate impacts, available data, and goals [3,9]. Overall, the spatial analysis of case studies retained by the PRISMA search indicates that a greater quantity of publications came from countries with larger populations, advanced construction industries, and a large number of research universities.



**Figure 10.** World map of case study locations with scaled bubbles correlating to the number of studies in that region. Two case studies were applied to offshore construction and are represented here in the Atlantic Ocean.

### 3. Results and Discussion

#### 3.1. Overview Source of Delays

While weather conditions during many days allow for meaningful construction progress, suboptimal temperatures, precipitation, and winds challenge task feasibility. Ultimately, the weather creates delays, which can drive schedule slippage and cost. Schedulers must account for likely delays in their planning. The addition of climate change considerations increases complexity to the problem facing construction planners and managers. Examining the influence of climate change and its impact on adverse weather conditions will help depict a holistic view of its present and future implications on construction work. As such, the following sections discuss the impact of adverse weather conditions on construction project efficiency. The effects of adverse weather conditions are separated into sections related to worker productivity, construction materials, and equipment use. Additionally, modeling techniques used in research to create preventative strategies for negative consequences to weather are discussed.

#### 3.2. Impact of Weather on Task Feasibility

Studies investigating construction delays find weather as a contributing factor. The most frequent weather factors studied consist of temperature, humidity, precipitation, and wind [19,20,39–42]. These weather factors affect labor, materials, and equipment, each in unique ways. Temperature changes generally affect the length that laborers can work outside, in addition to putting limitations on equipment if conditions prove unsafe for operations. Humidity poses a threat to material placement, specifically concrete, which can be negatively affected by even slight additions of water beyond its water-cement ratio. This effect is doubly negative in precipitation conditions, which can negatively affect labor and equipment operations, especially if that precipitation combines with other weather effects such as lightning or snow, heavy snow accumulation, and material freezing. Finally, winds can affect materials and labor through the need for restraints for unconstructed materials, and debris knocked around by winds can threaten personnel. Even high-strength winds can threaten equipment operations. All three aspects of task feasibility can be affected by these weather conditions. As such, the following sections describe in detail the scope of these threats.

##### 3.2.1. Labor

The workforce is the most critical resource regarding task feasibility [43]. Worker productivity is an uncertain factor that can be affected by exogenous variables, including weather. As previously stated, the most frequent weather factors studied are temperature [19,20,23,39–42,44], humidity [19,20,23,39–42,44], precipitation [23,44], and wind [20,23,39–42,44].

Temperature variation is negatively correlated to worker productivity, causing 64% of productivity variability [42]. For every 1 °C rise in temperature above 28 °C, worker productivity can decrease by up to 57%, and temperature rise increases the risk of heat-related injuries, including heat rash, heat cramps, heat exhaustion, and heatstroke [42]. Prolonged, unmitigated exposure to heat can adversely affect the human body [1,45,46]. An individual working under heat stress conditions is four times more likely to experience heat-related illness [47]. Moreover, exposure to cold temperatures affects the skin, muscles, and internal organs [20]. Low temperatures reduce the power and performance of workers [20]. However, the adverse labor productivity effects caused by cold temperatures can be reduced by wearing appropriate clothing [41].

Each country is affected differently by temperature variations. Countries with high poverty rates, lower labor standards, and informal employment arrangements, which are given government protection, experience higher costs than developed countries [48]. For example, the United States shows a loss of work capacity of 0.17% under moderate work conditions, while India shows a 2% loss under the same conditions [49]. The effects of the increased temperatures also produce ordered results outside of illness. These effects are

psychological and caused by the stress of prolonged exposure to hot environments [48]. The effects of heat lead to slower work, more mistakes, and create an atmosphere of increased risks of accidental injuries [21,42,49].

In addition to temperature and humidity, precipitation and wind speed affect worker productivity. Rain and snow slow or stop productivity and divert worker attention to covering or protecting materials and work areas [23]. If work areas are not protected in adverse weather conditions, workers have to spend time shoveling and cleaning in the aftermath (Jung et al. 2016). While large weather events are often considered most disruptive, even low magnitude events can affect construction. Precipitation occurring as light rain (less than 4 mm per 12 h) can reduce labor productivity by up to 40% [23]. Jung et al. (2016) found that even moderate precipitation (at least 5 mm per hour) can result in a work stoppage. Precipitation can also have latent effects on construction. Heavy snowfall can affect worker productivity regardless of whether it occurs on the day of the scheduled work tasks and can reduce crew efficiency by 35% [50].

Although precipitation and high wind speeds may render construction tasks unfeasible, the primary factor causing the worker productivity delay is the risk to workers' safety. High wind speeds increase the risk of worker accidents [23]. For example, workers governed by safety standards legislation are generally prohibited from completing construction tasks on scaffolding during high winds or electrical storms due to falling or electrocution safety risks [51]. Snow coupled with cold temperatures can also cause falling hazards as workers can slip on ice [52]. Moreover, painting in high winds presents a 'struck-by' hazard as buckets can be blown over and fall onto workers on lower levels [51].

### 3.2.2. Materials

Though weather-related construction delays are most commonly associated with worker productivity, weather conditions can negatively impact the behavior of construction materials. The scope of this analysis is limited to materials used in major outdoor construction activities since the weather has minimal impact on indoor construction. Therefore, the materials investigated are concrete, asphalt, brick, steel, and soils. Numerous climatic factors exist that could potentially damage these materials. However, this paper's scope will focus on the impact the previously identified aspects of climate—temperature, humidity, precipitation, and wind have on each of the materials listed above.

Low temperatures, high winds, and precipitation are consistently critical factors that affect concrete placement productivity rates [53]. Concrete pour activities are limited to temperatures between 0 °C and 40 °C, and maximum wind speeds less than 30 knots. Due to the freezing point of water, exceeding these thresholds degrade the concrete's final strength [54]. Cold weather concrete mixtures have been developed with a non-chloride accelerator that protects against freezing at ambient temperatures as low as −7 °C [55]. The use of heated enclosures and insulated blankets can overcome this threshold, and so a complete work stoppage threshold is redefined at −15 °C [52]. The effects of hot weather on concrete were shown to be minimized with the use of water reducing and retarding admixtures [56]. Water evaporation can occur in hot weather, changing the water to cement ratio and decreasing compressive strength [57]. Heavy rainfall can also impact productivity for concrete operations. Increasing the water content of a concrete mix will have negative results. Asphalt paving operations have similar temperature thresholds but are more susceptible to small amounts of precipitation in the form of rain, snow, or hail [58]. Spreading an aggregate mix under wet conditions is difficult, and freezing temperatures can increase viscosity too quickly [54]. The base must be dry, and temperatures cannot be between 0 °C and 10 °C [59].

Masonry is another construction task that can be impacted by weather, and predominantly temperature. A normal temperature range for masonry work is between 4.4 °C and 37.8 °C. Laying bricks should not occur if temperatures are below 4.4 °C before construction begins. If temperatures drop below 4.4 °C during construction, the mortar will need to be heated to maintain a minimum of 4.4 °C. In hot conditions, mortar needs to be kept below

48.9 °C for it to be effective [60]. Cold weather was seen to cause a 3 to 5-h delay in mortar mixing [61]. The majority of literature is focused on masonry labor-productivity under certain weather conditions instead of the effect on the material [62,63].

Steel is another frequently used material in construction projects [51,52,64]. It is most often associated with structural reinforcement, including columns, foundations, or footers, and structural support in vertical construction [51,52]. In addition to its prevalence within the industry, activities that use steel are generally found on the project's critical path and can affect the scheduled duration when delayed [65,66]. Therefore, it is crucial to account for weather risks when planning projects containing steelwork due to its exposed nature [4,67].

When using steel in construction, planners should consider wind, temperature, and precipitation in their scheduling. Wind speed is the most frequently cited aspect of weather impacting steel construction [9,52,68]. Wind speeds exceeding approximately 56.33 km/h were unsafe for lifting operations because these efforts involved the use of cranes [52,54,68]. Visibility, as affected by precipitation, also prevented the assembly of steel structures [50,69]. Rain intensity rather than total rainfall affects steel construction, although work stopped when the area's average reached 1.04 cm [70]. Joining methods like welding and steel detailing is also affected by precipitation [54]. Extreme temperatures tend to impair the labor force's ability to use steel before the material is adversely affected [66,71]. However, at sufficiently cold temperatures, typically below  $-51.1$  °C, certain types of steel become more brittle, which should be put at high consideration if building in arctic conditions or if freezing temperatures of this magnitude are expected [64].

Additionally, extreme cold weather plays a role in the type of steel selected. Traditional carbon steel frequently shatters when exposed to repeated shock loading, necessitating the use of steel alloys [64]. Research surrounding extreme hot temperatures focused on steel construction's labor productivity rather than how the material was affected.

Earthwork operations and site preparations can be heavily impacted by precipitation and low temperatures. Rainfall can hinder performance and increases soil humidity [54]. Runoff can quickly flood a worksite without proper sealing. Permanent and temporary drainage facilities should be put in place early to prevent delays [61]. A common precipitation threshold set for mass excavations is between 6.35 mm and 12.7 mm [59]. Excavations in freezing temperatures can be especially challenging. Frost penetration can create frozen soils that can be very difficult to remove, refill, and compact [72]. A gas-operated ground thawing device may be required in some cases [64].

### 3.2.3. Equipment

An essential component to task feasibility is the use of construction equipment and how weather conditions may affect operational limits. For this study, the definition of equipment is limited to construction vehicles. Construction vehicles include tracked and wheeled vehicles as well as temporary construction cranes.

Weather conditions that affect construction equipment are primarily cold temperatures, high winds, and heavy rain. The environmental limitations for equipment are examined below through an analysis of these three weather conditions. Construction vehicles, independent of type, are affected by cold weather, defined as  $-17$  °C to  $-29$  °C [64]. Anything below  $-29$  °C is considered arctic conditions, and special winterization measures are needed to protect equipment.

In cold conditions, a problem of primary concern is cold-starting engines. As temperature drops, engine oil becomes more viscous, making engines harder to crank. At low-temperatures, batteries also put out less power. The engine must reach a temperature that the components and oils can function normally to overcome cold conditions. Using engine heaters is a way to achieve operational engine heat [64]. Engine heaters require an investment in additional equipment to plug engine heaters into. An additional solution is to build heated garages to store equipment. Construction equipment makes extensive use of hydraulics, especially in earth moving equipment. Hydraulics require unique win-

terization to ensure that hoses and O-rings can withstand low temperatures [73]. Typical construction equipment is not capable of operating in extremely low temperatures without proper winterization upgrades.

Wind speeds have a considerable effect on cranes. High winds can make using cranes unsafe. From 2000 to 2010, 1125 tower crane accidents caused over 780 fatalities [74]. Generally speaking, it is dangerous to operate a tower crane in winds over 72.42 km/h. Many countries have regulations that significantly restrict crane operations in high winds [75].

The crane manufacturer's recommendations for wind speed limitations closely adhered to the construction industry safety standards. Weather conditions that exceed the allowed crane wind speed will cause a shut down in operation. As loads increase, the maximum allowable wind speeds decrease. Modern weather forecasting and on-site anemometers allow for more efficient lift planning schedules and increase project safety.

Precipitation can have a significant impact on construction vehicle operations. Muddy conditions caused by wet weather can stop operations entirely depending on the type of vehicle and the soil conditions. In extreme cases, a site may become inaccessible due to flooding.

Muddy conditions on-site will limit the type of vehicles that can be operated. Tracked vehicles are ideal for muddy conditions, but they are more costly to maintain and slower. Treads reduce vehicle ground pressure and allow it to traverse a broader range of terrain [76]. Although tracked vehicles can operate better in wet conditions, wheeled vehicles are better for on-road transport due to their increased speed and fuel efficiency [76]. Construction vehicles that need to regularly leave the site, like dump trucks, concrete trucks, and other transport vehicles, must be wheeled. However, wheeled vehicles cannot navigate heavy mud. In wet conditions, these wheeled vehicles are confined to roads or other improved surfaces. This restriction can increase delays because materials coming on-site will need to be cross-loaded from over the road transport to a vehicle capable of navigating the muddy conditions.

Precipitation is the most significant weather predictor of on-road motor vehicle crashes [77]. Vehicle transport will be slowed during precipitation events, along with an increased risk of accidents and injuries. These delays frequently impact the flow of workers and material to the site. Additionally, the frequency of rain events has a significant impact on the risk of traffic accidents. There are several percent increases in the risk of an accident if there have been two days between rain events vs. 20 days [78]. This is due to the accumulation of oils on the road surfaces. More frequent rains tend to wash away oils before they can accumulate.

### *3.3. Methods to Model or Predict Delays*

Mathematical models are algorithms used to calculate outputs based on input data and specified parameters and constraints to find solutions to set objectives. These tools help decision-makers identify optimal or near-optimal solutions for problems with large search spaces [16]. Weather is modeled to determine the impacts on workers, equipment, and schedule [34,52]. Weather modeling consists of three overarching types: weather generation models, construction impact models, and project scheduling models, as shown in Table 3.

Weather generation models utilize site-specific weather data, historical weather, geographical extrapolation, or some combination of the datasets mentioned above to simulate or predict delay-causing events in a construction area [9]. Most construction-related weather models use historical weather to predict delay-causing events, but extrapolation is used when historical data is unavailable. Weather events of interest include factors such as temperature, precipitation, wind, humidity, and frost [9,52,68]. Weather generation models can be adjusted based on the data used to produce a wide range of probabilistic and deterministic scenarios at a specific site, which improves project planning capabilities [72]. These types of models work to predict the weather and intensity of weather during a project timeline.

A stochastic weather generator that can compute a series of weather sequences of the most influential weather parameters affecting construction is a vital requirement of the proposed framework [9]. Classification of weather-generation methods is based on the historical weather data treatment: parametric [9,11,79,80] and non-parametric approaches [51,81,82]. Parametric weather generators are numerical models that reproduce synthetic weather data as a daily time-series of weather variables with the same statistical properties as historical weather data [11,79]. Parametric models excel when a construction period is not applied [83].

**Table 3.** Modeling literature characterization.

Author	Model Type	Objectives	Data Used
Ballesteros et al. 2016 Wilks 2009 Racsko et al. 1991 Richardson 1981	Weather	Weather prediction	Parametric weather data
Caraway et al. 2013 Lee et al. 2012	Weather	Weather prediction	Non-parametric weather data
Chan et al. 2012 Choi and Ryu 2014 El-Rayes and Moselhi 2001 Risikko et al. 2003 Gatti et al. 2014	Impact	Weather effects Impacts on workers	localized weather data
Chan et al. 2012 Choi and Ryu 2014 Risikko et al. 2003 El-Rayes and Moselhi 2001	Impact	Weather effects impacts on materials	localized weather data
Yaseen et al. 2020 Xiang et al. 2013 Moselhi et al. 2012 Yi et al. 2015 Moohialdin et al. 2019 Boateng et al. 2012 Wei 2017 Ghani et al. 2020	Impact	Weather prediction Impacts on construction	Parametric and/or non-parametric weather data
Jung et al. 2016 Senouci et al. 2018 Thomas et al. 1999 Yi et al. 2017 Muqeem et al. 2011b Shahin et al. 2011 Shahin et al. 2014 Shahin et al. 2007 Dytczak et al. 2013 Hassanein and Moselhi 2004 Wales and AbouRizk 1995 Moselhi et al. 1990 Pan 2004 Senouci et al. 2017 Shan and Goodrum 2014 Al-alawi et al. 2017	Construction Scheduling	Weather prediction Impacts on construction Optimized schedule/worker productivity	Parametric and/or non-parametric weather data
Muqeem et al., 2011a Alfakhri et al. 2017 Kholy 2013 Gunduz et al. 2015 Taha et al. 2016 Sheng et al. 2018 Castro and Dawood. 2006	Construction Scheduling	Schedule Optimization Cost Optimization Worker Productivity Weather is not the focus of research	Determined delays on equipment, materials, and personnel

While models that do not utilize weather data have been developed [34,36,43,84–86], construction impact models use weather-generation data to model critical weather effects test task sensitivity. Task sensitivities are used to develop construction delay estimates,

which can be transformed into outcomes of interest such as cost, schedule, and worker productivity [42,68,72,87].

Construction impact models use stochastic weather model results to determine impacts on many construction factors, such as worker productivity. One notable model is the WEATHER model, which analyzes the impact of weather-related events on worker productivity [58]. Hot and humid climates produce a significant delay stemming from the change in weather [42]. The effects of cold weather on worker productivity are not as commonly studied as hot and humid climates; however, extreme weather events, both hot and cold, when modeled, show impacts on productivity, safety, and health [20].

Construction impact models viewing the effect of weather-related events on worker productivity [24,58,88–90], construction materials [24,58,88,89], and construction processes [20,38,42,91–95]. Construction impact models that focus on worker productivity are regression-based and only consider single weather factors [23,57,88–90]. These models are criticized as too simplistic concerning their ability to accurately represent weather impacts on worker productivity [42]. These model types are also used to gauge worker productivity based on physiological responses at the individual level: heart rate, resting heart rate, and breathing rate [90] as well as recovery rate [88]. Major criticisms of single factor regression models rest on the fact that such models use simple weather parameters [42]. While these models are used to predict worker productivity, some do not include confounding factors such as mental and physiological factors and individual worker capabilities [42]. These confounding factors are improved by gathering data through worker-mounted cameras and computer vision analysis technology to quantify worker time and produce activity quantities [42]. Another issue with modeling construction site impacts is the lack of a standard definition for worker productivity under various weather conditions [42].

Project scheduling models are used to generate efficient schedules based on construction site conditions, weather impacts, and worker productivity [15,42,49,51,64,67,71,87,96–101]. A multi-objective optimization model can generate optimal or near-optimal schedules that minimize construction projects' time and cost in extreme weather regions [16]. Building information models are primarily used as a simulation tool to integrate construction information into productivity rates used for scheduling [65]. Optimizing scheduling to account for weather impacts on construction sites can also be subject to prioritized variables: minimizing time, cost, and maximizing quality of profit [16,83].

### 3.4. Mitigation Techniques/Adaptation Strategies

Weather delays can be mitigated with physical and administrative project adjustments and strategies. The reviewed literature indicates that 14% of papers included physical mitigation methods, and 30% had administrative mitigation strategies. Mitigation strategies are validated by comparing the results of the weather and construction models highlighted in the literature. Physical mitigation techniques are primarily used in the execution phase of construction, while administrative mitigation techniques are used in the construction planning phase. Understanding weather variations and planning uncertainty in task feasibility required a more precise decision-making tool for contractors and owners [85]. Predicting an accurate construction duration will create better control of a project's budget [102]. Research and utilization of these mitigation strategies can help construction managers adapt, avoid, or anticipate delays due to weather.

#### 3.4.1. Physical

Physical mitigation techniques found in the literature primarily focused on strategies to improve worker productivity due to temperature [10,48,54,103–107]. For example, productivity losses due to heat exposure for labor workers can be combated with regulated physical work breaks, increased fluid intake of workers, and personal protective devices such as sun reflecting hats or more breathable fabric for personal clothing items [10]. Chan et al. researched 30 identified fabrics and their effect on worker productivity, resulting in preferred prototype uniforms for construction workers [103]. Additionally, humidity

sensors have been designed to weave into fabrics to sense relative humidity surrounding workers [108,109]. These sensors display the environmental humidity and effects from the individual wearing the fabric by indicating increased humidity in the fabric from sweat [110]. Biosensing chips can push this monitoring further. Developed for the elderly and disabled, these sensing chips monitor body heat, heartbeat, and pulse oximetry. This information can be transmitted to necessary personnel for monitoring and necessary intervention [111]. Air conditioners are currently used for indoor construction to avoid or reduce the effects of heat exposure on workers and equipment [48]. Additive construction, or 3D printing, research shows a reduction in conventional construction tasks and the number of construction workers intended for them [112]. The reduction in labor consequently improved safety through reduced injuries, including those resulting from hot and cold temperatures [113]. Automation and mechanization of work reduce laborers' physical effort in construction, increasing productivity and offset environmental impacts such as high temperature and humidity [48]. Regarding extreme cold temperatures, Havers and Morgan (1972) believed, with the help of technological advances, construction workers will be allowed to continue to work longer into the cold season [64].

In addition to labor productivity, physical mitigation strategies for construction are applied to methods [48,107] and materials [54,56,57]. Modular construction and manufacturing opportunities can help construction managers avoid weather impacts like temperature, humidity, wind, and precipitation by allowing project work to continue in controlled, off-site environments [48,107]. Materials that are vulnerable to climatic elements, such as concrete, can be mitigated by adding physical barriers between the materials and weather, such as using plastic tarps or changing the mix design additives [54]. Avoiding or adapting to the weather during project execution can help project managers mitigate overall project delays.

#### 3.4.2. Administrative

Two standard tools used for administrative project adjustments are contract specifications [4,5,114] and project schedule management [83,101]. These tools are used to anticipate and avoid potential delays due to weather during the planning phase. Weather-related provisions generally have been insufficiently and equivocally stipulated in contract specifications [114]. Incorporation of model results and by-activity weather thresholds are possible in contract specifications. As suggested by Ibbs et al. (2018), four categories are critical for consideration: (1) definition of inclement weather, (2) counting of contract time by considering weather conditions, (3) indirect consequences of inclement weather, and (4) time extension for weather delays. Claims and disputes based on delays are reduced by adequately analyzing region-specific weather, including these results in construction contracts and project schedule duration. Additionally, the inclusion of specific language on how to calculate the amount of delay based on abnormal or unforeseeable weather, as well as what weather conditions constitute an excusable delay, have been shown to reduce the number of delay disputes that arise in a project [4–7,9].

Weather can produce project duration deviations of approximately 10 percent, and as project duration increases in length, seasonal weather changes become more difficult to avoid [54]. Instead, these weather delays should be anticipated and accounted for in the project schedule. Both parametric and non-parametric models have been utilized and accompany various tradeoffs in construction schedule modeling based on the definition of parameters [83]. Optimized models for scheduling are used to determine the best construction schedule when factoring in weather data such as external air temperature, wind velocity, precipitation, and ice and snow cover [9,96]. When used appropriately, scheduling models show an increase in productivity by 10% while resulting in a large decrease in production cost [101].

Advances in sustainable technologies and prefabricated construction have proved beneficial in improving logistics and supply management capabilities, notwithstanding adverse weather conditions. When properly implemented, modular integrated construction



(MiC) [115] and Building Information Modeling (BIM) [116] offer considerable benefits in alleviating the amount of on-site construction work, which further reduces the impact of extreme weather disruptions on project scheduling and productivity [117,118]. Shahtaheri et al. (2017) conducted a study analyzing the development of various MiC modular production technologies, specifically 3D fixturing and jig systems, laser cutting, and robotic assembly [119]. Despite MiC's associated benefits, there are challenges associated with the use of MiC, including its inflexibility towards modifications in design and reworks during construction [120]. In contrast, recent studies concerning the integration of BIM-GIS in architecture, engineering, and construction highlighted numerous advantages that improve efficiency and productivity during administrative planning [116,121]. Effective 4D BIM modeling requires high information technology (IT) skills and intelligence, both of which are not easily accessible in every region or market [122].

### 3.5. Climate Change Considerations

While most studies of weather-driven construction delays focus on historical precedents and retrospective analyses, they fail to account for future projections of climate. More accurate prediction measures, including those based on climate change, will enable construction projects and activities to meet planned schedules better and reduce the impact of costly overruns. Climate change has the potential to impact various aspects of weather in the future. For example, more extreme climate change projections show a global temperature change of 2.7 °C by the end of the century, which could decrease worker productivity by as much as 52% [49,123]. The newest research reports that the frequency, intensity, and duration of heatwaves increase with global warming [48]. As such, projections show a likely increase in maintenance costs from between \$785 million to \$2.8 billion annually for the US highway system by 2050 due to rutting and cracking from freeze–thaw and higher temperatures [124]. Additionally, increases in precipitation and flooding can impact construction in various ways, including logistically and financially [37,125]. The most impacted of the identified research area is labor productivity, which can be attributed to human exposure to hot and humid working conditions, which can cause heatstroke and other debilitating injuries [104,126]

The papers in this research are recategorized to investigate how climate change is addressed, whether the climate change space is thoroughly explored in the literature, and what, if any, significant trends exist in modeling approaches. As identified in the “Classification of Literature” section, climate change research falls into two general categories: (1) papers that indirectly address climate change through mention, motivation, or limitation without application; and (2) those that directly apply climate change impacts on construction in some way, e.g., by using predictions to predict delays. A majority of papers that consider climate change do so as a motivation for their research or future research. Alshebani and Wedawatta (2014) explore the impacts of temperature and humidity on construction in the United Kingdom because climate projection models suggest summer heatwaves and humidity will increase in and around the British Isles. Similarly, Moda et al. (2019) study temperature rise and worker productivity in Sub-Saharan Africa and suggest that future research prioritize incorporating climate change into construction policies and considerations. Some research was motivated by finding mitigation for foreseeable changes caused by climate change spanning from the resilience of small business construction companies [127,128] to adapting construction contract language [129] and transferring the risk of delay using weather index-based financial instruments [130].

The publications that focus on climate change application do so by considering how weather factor changes may influence construction in the future. Climate change applications are commonly accomplished by applying climate projections to researched relationships between construction and weather factors. Kim and Lee (2020) analyzed spatial clusters of occupational structures to determine the types of construction activities that will be at higher risk due to increased temperatures and perceived temperatures (wet bulb) in the Korean Peninsula. They found a need for spatial diversification of occupational

structures so that geographic areas of extreme heat rise will not cripple an entire industry [131]. Kjellstrom et al. (2018) used representative concentration pathway (RCP)-based predictions to model the interaction of worker productivity and high-temperature environments. The authors find that daylight working-hour output may decrease in tropical areas between 2–6% by the end of the century. Altinsoy and Yildirim (2015) study the direct and indirect impacts of temperature change on construction labor productivity using EU ENSEMBLES project projections. Bastidas-Arteaga and Stewart (2016) apply RCP projections to the relationship between climate change factors and the corrosion and degradation of infrastructure to understand the long-term implications to infrastructure construction and maintenance [132]. Chavaillaz et al. (2019) showed that high heat periods are robustly linked to cumulative CO<sub>2</sub> emissions and determined that the loss of labor productivity from increased heat exposure is directly related to anthropogenic CO<sub>2</sub> emissions [133].

Consideration of climate change in construction delay-related papers has increased over the past decade. This increase is likely due to the increasing amount, accessibility, and accuracy of climate parameter projections, which, coupled with established relationships to specific construction areas, enable projections of construction impacts. Though climate change considerations in this field are increasing, those papers with climate change considerations only comprise a fraction of the total articles reviewed (30.8%). Those that apply climate change analyses or projections account for 3.9% of papers reviewed. With climate change models, projections, and study results more available than ever, researchers should include the application of projected climate impacts on construction in their work. Application is particularly important because changes in climate trends could make policies and models based solely on historical climate data less reliable in the future.

#### 4. Discussion

The global construction industry accounts for 12% of the world's gross domestic product [39]. As global urbanization and population increase, the construction industry is expected to grow in size [39]. Despite the importance and steady growth of the industry, the negative impacts on construction workers and tasks due to climate change and weather fluctuations are given little attention [8,39,134]. Weather factors can cause unpredictable effects on construction projects, leading to delays, increased costs, or legal repercussions [1]. These negative consequences from the unpredictability of weather manifest themselves as risks to project success. Some weather factors can be anticipated through planning or site preparation, while others are unanticipated. Forecasts may predict delay-generating temperatures, precipitation events, and extreme weather events; however, predictions are not always accurate in terms of time and magnitude [70]. Still, some weather events may occur with little warning, or forecasts may change suddenly, impacting a construction site's feasibility and productivity. There are three primary weather-related sources of delays for construction projects identified in literature: extreme temperatures [8,19,20,39,49], precipitation [50,70,135], and high winds [23,68].

##### 4.1. Extreme Temperatures

Amid yearly changes in climate, construction workers' health is continuously at high risk within their work environment due to extreme temperature effects [8,39,49]. Greenhouse gas emissions have contributed to the steady rise in global temperatures, leading researchers to project increases in extreme hot weather intensity and frequency [39]. As temperatures rise, construction workers become more vulnerable to heat-related illnesses and heat stress [39,45,134]. Acharya et al. (2018) mention that construction workers are 13 times more likely to suffer from consequences related to heat-related illnesses compared to workers from other industries [39]. Wet-bulb temperature has high practicality in predicting the effects of heat stress on construction workers [94].

Like extreme heat, extreme cold weather can significantly impact construction workers' health and productivity and task feasibility for outdoor work [19]. Budhathoki and Zander (2019) mention a study by Gasparrini et al. (2015) within their analysis that stated extremely

cold conditions kill 20 times more people than extreme heat. Although the literature primarily focuses on extreme temperature impacts on laborers, extreme temperatures can also significantly affect task feasibility through delays concerning material and equipment use. For example, productivity for concrete pouring decreases while working in cold temperatures [54]. Additionally, specifications recommend avoiding bricklaying operations during extreme cold temperatures (Brick Industry Association, 2018). To prevent delays resulting from these negative consequences on construction sites, adequately defining cold weather construction expectations is important [64]. Havers and Morgan (1972) mentioned studies on thresholds for cold temperature construction work. These thresholds helped create effective procedures, regulations, and measures to determine when and how construction can commence effectively. The construction season can be extended in many locations due to the warming climate considering the increase in global temperatures due to climate change. Regardless, more research is needed to determine effective procedures for cold weather construction for areas that will continue to experience extreme winter seasons.

#### 4.2. Precipitation

Precipitation, in all phases, influences construction delays in many regions. Heavy snowfall can affect worker productivity beyond the event's data, provided accumulation hampers access or requires removal [50]. Wind and rain, including extreme weather events such as hurricanes, thunderstorms, and blizzards, can cause damage and unexpected delays during any time of the year [1]. These extreme weather events may shut down entire construction sites for an unknown amount of time. As a result, extreme weather events often end in site cleaning paired with a possible rework from damages.

Regarding the impact of precipitation on task feasibility, rainfall directly impacts the use of specific types of materials and equipment. For example, it is difficult to use certain construction vehicles or steel when rain intensity is high due to unfavorable soil quality [54,64]. The rain has lasting impacts due to runoff and pooling that can make haul routes inaccessible, decrease soil stability, raise groundwater tables, and erode the construction site causing hazards for personnel and vehicles [59]. The literature on precipitation discussed direct effects from most precipitation events. However, the literature lacked information regarding data metrics and ranges showing acceptable work conditions during snowfall. While the literature discussed potential physical and mental negative consequences, there were no cases of specific productivity losses on account of snow. Despite the impact of climate change on increasing yearly temperatures, many regions worldwide receive large amounts of snow. Additional detail and research conducted on the impact of snowfall are needed to enhance the field of study.

#### 4.3. Wind

High winds can affect construction worker productivity and task feasibility mainly due to adverse impacts on worksite safety. Larrison defined the effects of wind on the lifting capabilities and determined that the work stoppage (at least as it relates to crane work) occurs with wind speeds greater than 14 m/s (31.32 mph) [23]. Similarly, Shahin et al. (2014) determined that crane work would stop when wind speeds were higher than 50 km/h (31.07 mph). Jung's 2016 research on high-rise construction projects notes that ground wind speed measurements may not accurately measure the winds experienced by workers and equipment, therefore, requiring a modified civil work weather risk model [52]. The literature concerning wind primarily focused on the adverse effects of wind on construction equipment. However, second and third-order effects on personnel were not captured. Further research is needed to examine the impact of wind on worker performance aside from equipment functionality and material attributes.

#### 4.4. Materials

The primary materials examined in the literature concerning adverse weather conditions are asphalt, brick, steel, and soils. The literature lacked adequate information on the

wood construction industry; therefore, wood was excluded from this analysis. In terms of steel construction, the effects of extreme temperatures on steel have minimal coverage. The literature on steel construction processes was mainly concerned with the challenges of lifting operations during strong wind conditions. This is logical considering the material's strength; however, more attention and consideration should be given toward adaptation strategies for scheduling concerns in areas prone to strong winds, extreme cold, heavy rain, and lightning storms. Creating adaptation strategies to counteract negative consequences of weather events in scheduling will enhance workers' safety and help provide satisfactory work in a timely manner. Surprisingly, the literature on brick construction mainly contained information on weather's impact on worker productivity instead of impacts on the condition of physical material. When physical characteristics of bricklaying operations were addressed, the area of concern was the negative consequences of weather on mortar instead of bricks.

#### *4.5. Equipment*

The literature on construction equipment is somewhat limited. It is mainly focused on vehicles and does not consider things such as hand-held equipment or tools used by individual workers. For temperature, the literature is limited to analyzing vehicle winterization in cold weather. The impacts of wind are only mainly discussed in the context of cranes. It is difficult to quantify the impact of precipitation on equipment, and the literature looks at the effects of muddy conditions and general over the road transport. Looking at transportation on and off the construction site starts to venture into the realm of logistics. Over-the-road logistics start to leave the realm of construction and venture into other fields. However, it is important to note that weather impacts on the supply chain can significantly affect a construction schedule. An area for future study should examine how weather can affect the construction supply chain.

#### *4.6. Climate Change*

The majority of the articles that include climate projections solely focus on temperature projections and their impact on the labor force. There are few mentions of how climate change affects wind or precipitation patterns. This lack of exploration may be attributed to the difficulty in providing projections for wind and precipitation, which further negates its use in real-world applications. Additionally, the impact of climate change on materials and equipment has been given little attention in the literature. This research shows that fewer studies exist on the impact of weather on materials and equipment overall; therefore, it is reasonable that few climate change applications exist. Concerning climate change, the direction for future research must expand beyond the effects of temperature on worker productivity and focus more on the impact of second and third-order effects for other climatic variables.

### **5. Conclusions**

There are few application areas for weather-related sources of delays with a more diverse history than in construction; however, the construction industry is extremely vulnerable to delays caused by weather incidents due to the unpredictable nature of outdoor work in the field [8,39,49]. The construction industry's vulnerability to weather-related delays has become an important topic within the last decade due to climate change influences. Accounting for future projections of weather events in construction processes, logistics, and modeling is crucial for success in the coming years. This study highlighted the impacts of adverse weather on construction projects focusing on worker productivity, task feasibility, models used to predict delays best and optimize planning, and mitigation strategies to overcome delays using 204 publications spanning from 1972 to 2020. The literature is rich in information on the methods and regulations incorporated into construction processes to mitigate weather-related delays for various materials and equipment. Additionally, the literature on worker productivity presents opportunities for a plethora of real-world

applications; however, actual implementations remain limited due to the lack of adequate procedures, regulations, and measures [64].

The effects of adverse weather vary depending on geographic location; therefore, mitigation measures will vary depending on the type of weather incidents under consideration. Many weather effects on task feasibility are related to equipment and materials, including cranes and concrete. In contrast, the examples of weather impact on worker productivity primarily stem from extreme temperatures and humidity. When considering weather variability, the mitigation of negative consequences or perceived process failures is the goal. Mitigating the ramifications of weather will improve efficiency in all domains of construction. Two primary types of mitigation strategies are apparent in the literature, physical and administrative. Physical methods focus on bolstering efficiency in logistics and organization, whereas organizational methods focused on improving contract specifications and project schedule management.

Models can aid in reducing uncertainty connected to weather-related events. Three specific weather modeling methods for diminishing uncertainty in construction are evident in the literature: weather generation models, construction impact models, and project scheduling models [9,42,68,72,114]. To utilize these modeling methods, obtaining historical weather pattern information is crucial as it aids in determining mitigation and adaptation strategies. The importance of accurate weather data cannot be overstated as models are both coupled and sequential. Weather simulation models inform weather impact models, which inform construction schedule models. Additionally, models must not assume that weather factors are stationary, as commonly found in previous studies. Stationary weather assumptions must be reworked to include climate change predictions.

This paper's synthesis of relevant literature will benefit a broad spectrum of professionals to both further research and support construction managers in the field. The three research areas presented in this paper provide a better understanding of the topics covered in this area and identified gaps in the existing literature. Understanding the influences of weather on construction delays can contribute to better project planning, increasing construction productivity, and reducing delay costs due to adverse and changing weather effects.

While the impact of weather on individual construction activities have been widely studied, especially in warmer climates, this systematic state-of-the-art review identified voids in the body of knowledge centering on the conglomeration of weather effects on the global construction industry. Filling these gaps in the existing body of knowledge could help mitigate weather delays for projects exposed to the elements. More in-depth investigations are needed to analyze the limits of construction materials, equipment, and practices currently utilized to capture a construction task's feasibility accurately. Ultimately these limitations need to be combined with the current findings on labor productivity to more precisely capture the actual limits of task feasibility in adverse weather conditions.

**Author Contributions:** Conceptualization, J.D.D. and S.J.S.; methodology, S.J.S.; validation, J.D.D. and S.J.S.; formal analysis, M.R.N. and Y.A.A.II; investigation, J.D.D., M.R.N., S.J.S., and Y.A.A.II; resources, J.D.D. and S.J.S.; data curation, S.J.S.; writing—original draft preparation, Y.A.A.II and M.R.N.; writing—review and editing, J.D.D. and S.J.S.; visualization, M.R.N. and S.J.S.; supervision, J.D.D. and S.J.S.; project administration, Y.A.A.II and M.R.N.; funding acquisition, J.D.D. and S.J.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** The authors wish to thank the 21M AFIT Construction Management students for their support and dedication. The views expressed in this study are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense,

Department of Veteran Affairs, or the United States Government. This material is declared a work of the U.S. Government and is not subject to copyright protection in the USA.

**Conflicts of Interest:** The authors declare no conflict of interest.

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