

# When Weather Disrupts the Vaccine Cold-Chain: Shipping Delays and Storage Risks in Illinois

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## Abstract

**Background:** Severe weather, including heatwaves, winter storms, floods, and associated power outages, poses persistent risks to the vaccine cold chain across the United States, including Illinois by causing storage-unit failures and shipping delays that can lead to temperature excursions - instances when vaccines are exposed to conditions outside the recommended temperature range, compromise vaccine potency, with public-health and economic consequences.

**Methods:** We conducted a scoping review (Arksey & O'Malley; PRISMA-ScR) of publicly accessible evidence (2000-2025) on weather-related disruptions to vaccine storage and shipping, with emphasis on Illinois. Sources included peer-reviewed studies, CDC/IDPH guidance, national datasets (e.g., EAGLE-I, OpenFEMA), and grey literature on monitoring technologies. **Results:** Laboratory studies show pharmaceutical-grade refrigerators can cross 8°C within ~45 - 140 minutes after power loss. Public datasets report exposure (outages, storm events), and Illinois experienced weather-related shipping delays during Winter Storm Uri; Illinois drew on strategic stock to buffer operations. However, Illinois-specific, publicly accessible, cause-coded statewide aggregated data linking weather/power exposure to dose-level outcomes (e.g., excursion counts, doses affected) were not identified. Standard incident protocols are clear, but statewide performance descriptions (coverage, timeliness, equity, especially in high-outage or rural areas) were not found in public sources. Emerging tools (AI-enabled monitoring, cloud connectivity, predictive alerts) are described, yet we did not identify peer-reviewed evaluations or publicly accessible Illinois program documentation showing provider deployment of pre-threshold, predictive alerts or weather-linked excursion prediction. **Conclusions & Public Health Implications:** Given short warming intervals and outages that often last hours, planning in Illinois may be better calibrated to plan-

sible local outage windows, emphasizing continuous digital monitoring, connectivity-resilient reporting, and rapid procedures for moving vaccines to approved backup storage or redistribution. Contextual evaluation of AI-enabled, cloud-connected, predictive tools in Illinois settings, alongside publicly accessible, cause-coded statewide aggregates of excursions and doses affected, would clarify added value, support cross-jurisdiction learning and strengthen preparedness as climate risks evolve.

## Keywords

Vaccine Cold Chain, Temperature Excursion, Power Outage, Climate Risk, Illinois, Predictive Monitoring, VFC, Shipping Delays

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## 1. Introduction

For decades, immunization has served as one of the most effective public health strategies to reduce morbidity and mortality from infectious diseases. According to Carter *et al.* [1], vaccination is expected to prevent about 4.4 million deaths annually between 2021 and 2030 by protecting against 14 vaccine-preventable diseases across 194 countries. Similarly, Shattock *et al.* [2] in their historical analyses showed that since the launch of the Expanded Program on Immunization in 1974, global vaccination efforts have saved approximately 154 million lives, 146 million of them among children under age five, including over 100 million infants. These big wins represent more than 10 billion years of healthy life added, with each prevented death contributing, on average, 66 years of full health. As of 2024, children under 10 are 40% more likely to survive to their next birthday compared to a world without historical vaccination efforts, with benefits extending well into adulthood [2].

In the United States, vaccines have made a remarkable difference in the health of families and communities at large. This became even more evident following a measles resurgence in the early 1990s, which led to the creation of the Vaccines for Children (VFC) program in 1994 to ensure that eligible children could receive free vaccines, regardless of their families' ability to pay [3]. Since then, routine childhood immunizations have prevented an estimated 508 million illnesses, 32 million hospitalizations, and over 1.1 million deaths among children born between 1994 and 2023 [4]. Economically, this translated into USD 780 billion in direct medical savings and USD 2.9 trillion in societal cost savings. Even after factoring in the costs of vaccination programs, the net savings stood at USD 540 billion (payer perspective) and USD 2.7 trillion (societal perspective), with benefit-cost ratios of 3.3 and 10.9, respectively [4]. This presents clear, strong evidence that immunization not only saves lives but also delivers a high return on investment.

Prior to the introduction of the measles vaccine in 1963, Illinois experienced substantial morbidity and mortality consistent with national trends. In the United

States at that time, measles annually resulted in approximately 500 deaths, 48,000 hospitalizations, and 1000 cases of brain swelling. However, following widespread vaccine implementation, measles incidence sharply declined, and for decades the disease was effectively eliminated as a major public health threat in Illinois, though isolated outbreaks have emerged in recent years [5]-[7]. Building upon decades of immunization successes, and in recognition of the continued need for high coverage, Illinois has maintained strong immunization programs, most notably through active participation in the federal VFC program. This initiative provides, at no cost, the ACIP-recommended vaccines to Medicaid-eligible, uninsured, and underinsured children under 19 years of age across Illinois. As evidence of its impact, more than 70% of Illinois schools report measles, mumps, rubella (MMR) vaccination coverage above 95%, and statewide rates remain consistently above the threshold needed for herd immunity [8].

These achievements, however, rely not only on scientific advances in vaccine development to keep vaccines potent and effective, but also on the day-to-day efforts of the people and systems responsible for storing, transporting, and administering vaccines, *i.e.*, maintaining the vaccine cold chain up to the point of administration, systems that communities around the world count on to stay safe. Yet these systems remain vulnerable, especially in the face of severe weather events, which may cause storage-unit failures leading to temperature excursions - instances when vaccines are exposed to conditions outside the recommended temperature range [9], as well as shipping delays, all of which can compromise vaccine viability, pose serious risks to public health, and lead to significant vaccine wastage and financial losses. It is important to note that these losses are felt at multiple levels. For instance, publicly funded immunization programs may absorb the cost of replacing federally purchased vaccines; private healthcare providers may incur unrecoverable losses when weather events compromise their private vaccine stock; and manufacturers and distributors can experience operational and financial strain from disrupted delivery chains. Ultimately, the burden extends to the government, which must allocate budgetary funding and manage broader public health consequences.

Illinois, situated in the U.S. Midwest region, has experienced significant changes in weather patterns over the past century. For instance, the state's average temperature has increased by approximately 1 - 2°F since the early 1900s, accompanied by greater variability in winter storm patterns [10]. Similarly, Hayhoe *et al.* [11] noted that the Midwest, Illinois inclusive, is warming at about 0.4°F per decade and is experiencing a doubling in the frequency of heavy rainfall events, alongside increasingly intense heatwaves and altered snow and ice patterns. Moreover, the U.S. Environmental Protection Agency [12] reports a 10 - 20% increase in overall annual precipitation in Illinois, a 35% rise in heavy-precipitation events, more frequent flooding, and prolonged periods of extreme summer heat. These significant changes in weather patterns and accompanying weather-related events ultimately heighten the risk of disrupting vaccine storage and transport systems.

While Illinois' immunization successes are often discussed through the lens of the federally funded VFC program, a substantial share of routine vaccination doses are also privately purchased and stored by providers in Illinois. Although Food and Drug Administration (FDA) regulations define vaccine storage and stability requirements through product labeling, CDC guidance provides the operational framework for vaccine storage, handling, and incident management, particularly within federally funded programs [9]. Under this CDC framework, vaccine incident reporting and replacement procedures are most clearly detailed for publicly purchased vaccines (e.g., VFC/317) within CDC and Illinois VFC guidance [9] [13]. In contrast, for privately purchased vaccines, incident reporting typically follows the manufacturer's directions, which reflect FDA-approved stability information, and/or payer or facility policy. Publicly available sources reviewed for this paper do not indicate that vaccine incidents involving privately purchased vaccines by providers in Illinois are routinely reported through the Illinois VFC program, although reporting practices may vary by jurisdiction [9] [13]. Across all public sources reviewed for this paper, we did not identify Illinois-level, cause-coded, statewide aggregates that include both publicly funded and privately purchased doses affected by weather-related temperature excursions or shipping delays, leaving the public scale of impact across the state's entire vaccine supply system unclear.

This scoping review aims to explore how severe weather events disrupt the vaccine cold chain in the U.S., with a focus on Illinois, and to integrate publicly available evidence on their impact on vaccine storage, shipping, and program sustainability. Given the increasing frequency of weather-related disruptions, strengthening vaccine cold-chain resilience is also integral to broader public health emergency preparedness and response (PHEPR) efforts, as maintaining vaccine viability and continuity of immunization services during disruptions directly supports emergency readiness and health system resilience [9] [13] [14].

## 2. Literature Review

The preservation of vaccine integrity in the United States does not end at scientific development or clinical approval, but equally on a well-coordinated system that ensures vaccines developed for human use are consistently stored and transported under controlled temperature conditions known as the vaccine cold chain. This system is essential to preserving vaccine potency and safety from the moment of manufacturing until administration at the provider level [9] [15]. In essence, the cold chain is a system of temperature-controlled environments that preserves vaccine efficacy from manufacture through administration [9] [16] [17]. Thus, a disruption in the vaccine cold chain, even for a transient period, can lead to unsuitable conditions that irreversibly reduce vaccine potency, diminish immune responses, and increase the need for revaccination [9]. When such failure occurs, especially in cases where no manufacturer stability data support continued usage of vaccines, it can compromise public health, waste resources, and impose significant eco-

conomic costs, including the price of discarded vaccines [18], increased healthcare provider workload due to logistical challenges, resupply needs, documentation and reporting, inventory reconciliation, and efforts to investigate and correct storage and handling errors. These burdens also affect patient flow and access, leading to increased demands on human resources [9] [19], and may contribute to erosion of public trust in immunization programs, particularly in an era marked by vaccine hesitancy. Beyond direct losses, cold-chain breaches create broader societal and economic burdens, such as the treatment of preventable diseases and reduced vaccination uptake [20].

These risks often manifest as temperature excursions (TEs), which are instances where vaccines are exposed to conditions outside the recommended temperature range [9]. Whether these deviations involve excessive heat or freezing temperatures, they signal a breach in cold-chain integrity [9]. While TEs may occur from various causes, this review focuses specifically on weather-related disruptions, especially their role in contributing to storage-unit failures and shipping delays within the context of Illinois. Given the well-established shifts in Illinois' climate, including more frequent extreme heat events, heavier precipitation, and seasonal storms, these evolving weather patterns are especially relevant to understanding vaccine cold-chain vulnerabilities. Rather than hypothetical, these concerns are grounded in observable patterns across the Midwest, where temperature variability and the intensity of weather events have increased significantly over recent decades [11] [12]. These increasingly unpredictable events are especially concerning for cold-chain systems that rely on stable power and timely distribution. Beyond definitions, U.S. clinic data underscore how often storage units drift out of range in practice: in a county outpatient system study of 54 refrigerator compartments, 26 (48%) stayed within the WHO-recommended 2 - 8°C range, 13 (24%) recorded at least one freezing episode, 10 (19%) ran just above freezing at 0.1 - 1.9°C without freezing, and 5 exceeded 8°C during the observation period, as captured by graphic-output data loggers [21]. To contextualize exposure to severe events in Illinois, this review references National Oceanic and Atmospheric Administration's (NOAA's) Storm Events Database (1950-present, county-level records), which is used later to summarize event frequency [22].

Power outages, especially those linked to heatwaves or severe storms, pose a serious risk to vaccine storage. Although pharmaceutical-grade refrigerators are preferred for their superior temperature stability under normal conditions, their performance during electrical outages is notably poor. A National Institute of Standards and Technology (NIST) report found that pharmaceutical units, especially those with glass doors, reached the critical 8°C threshold in just 45 to 140 minutes following a power loss, with vaccines likely rendered unusable within one to two hours [23]. These short time-to-warm intervals are exactly why CDC emphasizes continuous digital monitoring. Consistent with that guidance, NIST's multi-model evaluations of digital data loggers showed devices maintained accuracy across 0 - 10°C and remained stable over many months of operation, and the

studies detail practical probe-in-glycol setups and ice-point checks that reflect liquid vaccine temperatures in routine clinics [24].

This window is especially concerning when compared to average power outages in the U.S., which occur about 1.5 times annually and last about 3.5 hours, more than enough time for cold-chain failure to occur [25]. These realities demonstrate the vulnerability of vaccine storage units during common grid interruptions. Furthermore, severe storms and flash floods may disrupt transportation routes, delay vaccine shipments, or make last-mile delivery unsafe, increasing the risk of TEs during transit. For example, Winter Storm Uri in February 2021 caused widespread logistical breakdowns (power outages, road closures, and delivery disruptions), which delayed COVID-19 vaccine distribution across multiple states. The White House later reported that nearly six million doses were delayed due to winter weather nationwide, with courier systems and over 2000 vaccination sites affected by hazardous conditions and power failures [26]. White House briefings that week likewise cited approximately six million doses delayed, about three days' shipments, affecting all 50 states [27]. In Illinois specifically, state officials confirmed that adverse weather disrupted federal vaccine shipments in mid-February 2021, prompting the Illinois Department of Public Health to proactively draw from strategic stock to maintain vaccination operations until delayed deliveries resumed [28].

Across the United States, the electric grid continues to demonstrate vulnerabilities due to severe weather, with impacts particularly evident in the Midwest. Over the years, severe weather events such as derechos, tornadoes, and blizzards have increasingly disrupted power systems, causing significant risks to public-health infrastructure, including vaccine cold-chain integrity. According to utility-submitted data compiled by the U.S. Energy Information Administration (EIA), the average annual outage duration for customers in the United States exceeds 200 minutes (approximately 3.3 hours) when major events are included [29]. These durations can easily exceed the warm-up windows of common pharmaceutical units during an outage, emphasizing the need for automated and reliable backup systems. As previously noted, even brief lapses in power can produce conditions that compromise vaccine efficacy. This reinforces the urgency of infrastructure resilience and targeted planning, particularly in healthcare settings that rely on uninterrupted vaccine cold-chain storage. Meanwhile, Illinois has experienced persistent, and at times acute weather-related disruption to electrical service. For example, publicly reported local utility data have described severe thunderstorms in Champaign County, causing outages for over 1800 customers in a single event, highlighting recurring vulnerability even during non-catastrophic weather.

More comprehensively, the EAGLE-I database, a publicly available, benchmark county-level dataset with 15-minute outage resolution covering 2014-2022, shows that Illinois counties regularly face outages nearly on a weekly basis, even in the absence of declared major events [30] [31]. These localized and transient outages, often small in scale, may not significantly influence statewide averages but none-

theless pose risks to vaccine storage units, which require uninterrupted power to maintain cold-chain temperatures. To document the data source and coverage details, we reference public EAGLE-I releases (2014-2022; 15-minute resolution) available via Oak Ridge National Laboratory (ORNL) and Office of Scientific and Technical Information (OSTI) [31]. In contrast, utility-level reliability metrics paint a more favorable picture. In 2022, Commonwealth Edison (ComEd) reported a System Average Interruption Duration Index (SAIDI) of 29 minutes and a System Average Interruption Frequency Index (SAIFI) of 0.43, placing ComEd among the top-performing utilities nationwide in terms of overall reliability [32]. However, such aggregate indicators can obscure the frequency and impact of smaller, localized outages that still threaten sensitive operations like vaccine cold-chain storage. Further highlighting this vulnerability, the VA Office of Inspector General reported that on May 4, 2023, the Edward Hines Jr. VA Hospital's IT Center endured a 22-hour outage, evidence that even critical healthcare infrastructure around Chicago remains susceptible to extended power loss [33]. Taken together, these data sources emphasize that power outages in Illinois are both frequent and consequential, reinforcing the urgent need for robust backup planning and real-time monitoring in vaccine cold-chain systems.

While there is widespread acknowledgment of how critical the vaccine cold chain is to preserving vaccine potency and ensuring immunization safety, there remains little to no publicly available data quantifying vaccine losses, especially those stemming from weather-related disruptions across most U.S. jurisdictions, including Illinois. In accordance with current CDC guidance, VFC providers are expected to follow a structured response protocol after any suspected temperature excursion. This includes isolating the affected vaccines, downloading and reviewing temperature data, and contacting the manufacturer to assess vaccine viability [9] [13]. In the meantime, vaccines must not be discarded or administered until providers receive further instructions from their respective immunization programs. In Illinois, the IDPH VFC Provider Manual offers similar steps, including submitting a detailed vaccine incident report and the manufacturer's vaccine stability statement to the immunization program for review [13]. The vaccines involved in the temperature excursion are marked "Do Not Use" until the state's immunization program confirms whether they can be safely used or must be wasted and/or replaced [13]. These standard protocols not only help ensure timely and coordinated responses to temperature excursions and uphold vaccine safety and accountability, but also demonstrate how vaccine cold-chain incidents are typically resolved at the provider-jurisdiction level.

What remains far less clear is how the data from these incidents are used once the immediate issue has been resolved, an important gap, given that understanding how vaccine cold-chain failures occur, and how frequently, is essential for informing broader systems-level improvements, especially in the context of increasing weather-related disruptions [9] [17] [18]. Yet despite this need, at the time of

this writing, there is no centralized or public-facing data showing the number, causes, or trends of vaccine cold-chain incidents reported across jurisdictions in the United States. It is not clear whether states like Illinois systematically report these incidents to the CDC or whether they are aggregated in any meaningful way for national or state-level review. More importantly, while individual vaccine temperature excursions may be documented at the provider or jurisdiction level, there is no publicly accessible or centralized data at either the state or federal level, that show how many cold-chain failures were weather-related, how often shipping delays resulted in temperature excursions, or how many doses were affected. The absence of such a database creates a visibility gap that may limit understanding of the broader impact of weather-related disruptions on vaccine viability and could constrain the ability of public health agencies, researchers, and system planners to identify trends in weather-related cold-chain failures, strengthen preparedness strategies for storage-unit risks and shipping delays, and build long-term resilience in vaccine distribution systems, especially as climate patterns continue to shift across Illinois and the broader United States. To situate weather- and power-related risks within officially declared events, we also reference OpenFEMA's Disaster Declarations Summaries for Illinois (2000-2025) [14].

Even when such incidents are resolved at the state level and vaccine losses are absorbed without disrupting service delivery at the provider level, the absence of publicly accessible and aggregated reporting may limit broader system-level understanding. While internal reporting structures may exist in the Illinois VFC program, the lack of publicly shared data makes it difficult for jurisdictions and stakeholders to compare risks, identify trends, and coordinate long-term climate-resilience strategies. Without that visibility, they may be less equipped to anticipate risk hotspots and implement climate-resilient responses, such as planning for mobile-refrigeration deployment, assisting with shipment-issue resolution, or providing technical support to high-risk areas. While jurisdictions do not manage shipping routes directly, aggregated data on cold-chain disruptions could also help inform logistics partners in refining delivery strategies for vulnerable areas. In this context, the issue is not only whether providers report excursions, but how those reports are aggregated, analyzed, and applied, or not applied, to inform broader strategies that strengthen the vaccine cold chain in a changing climate, including in Illinois, where these risks are becoming increasingly relevant. Thus, as climate-related risks continue to increase, public health programs cannot afford to treat vaccine cold-chain failures as isolated, one-time events. Each failure is a missed opportunity to learn and strengthen the system. Providers are already required to report temperature excursions to their jurisdiction's immunization program, regardless of the cause, and the Illinois VFC program has established protocols for reviewing these incidents, including submission of vaccine-incident reports and manufacturer stability documentation [9] [13]. However, what remains unclear is whether these jurisdiction-level reports are shared with CDC in a systematic way,

or if any national database aggregates, analyzes, or makes this information publicly available. To date, there is no centralized platform where the frequency, causes, or outcomes of reported excursions, especially those tied to weather-related disruptions, can be reviewed across jurisdictions. This absence of visibility makes it difficult to identify patterns, learn from previous events, or inform larger strategies for vaccine cold-chain resilience in the face of worsening and evolving climate threats. This scoping review addresses that gap by examining what is currently known, what patterns are emerging, and what practical strategies or technologies could help prevent future disruptions, particularly in Illinois, where weather-related risks to vaccine storage and delivery are becoming more common and more consequential [11] [12].

One practical area of opportunity lies in the use of smart cold-chain technologies, especially AI-enabled data loggers that are now capable of monitoring vaccine storage conditions in real time. Unlike traditional data-logger models that require providers to download and review temperature logs manually each week, these newer systems automatically upload readings to secure cloud platforms, analyze them continuously, and send alerts when a temperature excursion is either occurring or imminent [34]. Additionally, many platforms now integrate wireless IoT sensors and GPS-enabled trackers, allowing real-time monitoring of both temperature and shipment location throughout the cold chain. Automated alerts are triggered the moment any deviation occurs, and cloud-based dashboards ensure that providers or program staff can access data remotely from anywhere. While providers ultimately retain responsibility for vaccine storage compliance, these systems ease daily monitoring demands, reduce the risk of missed excursions, and offer earlier detection of potential failures [34]. Some systems, such as PharmaWatch™, go further by reducing dependence on local Wi-Fi or internal IT infrastructure. Using cellular, multi-carrier connectivity and battery-backed transmission, these tools can support real-time monitoring even during power or internet outages, which is especially valuable for rural or low-resource clinics where traditional connectivity may be unreliable [35]. These solutions reflect broader trends in the vaccine supply-chain space, where predictive and automated tools are increasingly used to support cold-chain stability and enable early intervention before a breach leads to vaccine loss [36], a point also discussed in a peer-reviewed review of cold-chain temperature monitoring [37]. A more recent example is the development of “active prediction” systems such as MaxTrace, presented by MaxQ Research at the ISTA TempPack Forum. Unlike conventional monitoring tools that alert after an excursion begins, these systems are designed to detect patterns that indicate an excursion is about to occur, sending alerts in advance so providers can act before temperatures move out of range [36]. This kind of forward-facing innovation moves beyond real-time alerts and toward real-time prevention, which is exactly the direction public-health cold-chain systems need. Even more importantly, these systems should begin to integrate environmental data such as weather forecasts and regional power-outage modeling, especially as

severe storms, heatwaves, and floods become more common causes of cold-chain disruption. While no publicly documented system yet combines weather-predictive alerts with storage-unit-specific risk assessment, this kind of integrated tool could be transformative. Imagine a platform that not only monitors storage temperature, but also receives advanced weather alerts, predicts power-grid instability, and automatically notifies the provider that a storage unit is at high risk of excursion within the next few hours, well before any temperature change actually begins. This level of integration would be especially beneficial to rural clinics, where backup power options may be limited and early action is critical to preventing vaccine loss. As the climate continues to change, this is the kind of thinking and design the public-health sector should prioritize, not as a luxury, but as a practical necessity for system-wide vaccine cold-chain resilience.

Overall, there is an urgent need to rethink how vaccine cold-chain risks are being managed in a changing climate. While providers and jurisdictions have established systems for responding to temperature excursions, there is limited visibility into how those incidents are tracked, shared, or applied to future planning. At the same time, smart technologies, including AI-enabled data loggers, predictive shipping tools, and proposed designs that could link weather forecasting with cold-chain risk alerts are showing what is possible when innovation is used to anticipate failure rather than react to it. For the immunization program in Illinois and beyond, the challenge is not just technical but structural: how do we bridge the gap between what exists, what's emerging, and what is needed to build a vaccine cold-chain that is truly resilient to severe weather and power instability? This scoping review begins to address that question by mapping the current state of evidence in Illinois, identifying patterns in weather-related cold-chain disruptions, and exploring what practical strategies - technological, operational, and policy-based, can help protect vaccine integrity in the years ahead.

## 3. Methods

### 3.1. Study Design

This study employed a scoping review methodology based on the Arksey and O'Malley framework [38] and is reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) checklist [39]. Considering the evolving nature of literature on climate-related threats to vaccine cold-chain systems, especially those affecting storage units and shipping, this scoping review approach allowed for structured mapping of the extent, range, and nature of related research activity on weather-related cold-chain disruptions across the United States, with a focus on Illinois.

### 3.2. Research Questions

This scoping review was guided by the following research questions (RQs):

1. What is the current state of publicly available evidence on how severe weather events disrupt vaccine cold-chain systems in Illinois and across the United States?
2. What patterns exist in weather-related vaccine storage failures, shipping delays, or cold-chain incidents, especially within Illinois?
3. What mitigation strategies, infrastructure adaptations, or policy responses have been proposed or implemented to prevent or reduce these disruptions, especially in the Illinois context?
4. What role do emerging technologies, such as artificial intelligence (AI), predictive analytics, or climate risk mapping play in anticipating or mitigating vaccine cold-chain disruptions, and how might these be applied in Illinois?

### 3.3. Identifying Relevant Studies

The search strategy was designed to systematically identify publicly available studies and reports relevant to vaccine cold-chain disruptions associated with severe weather events in the United States, with emphasis on Illinois. Guided by the research questions, the search concentrated on three major areas: (i) weather-related disruptions to vaccine storage and transport, (ii) incident patterns and response strategies, and (iii) emerging technologies (e.g., AI) for anticipating or mitigating these disruptions. A preliminary review of literature and federal guidance (e.g., CDC [9]) informed the selection of key search concepts and terminology.

The following core categories were used to develop Boolean search strings and refined across databases:

- “vaccine cold chain” OR “vaccine storage failure” OR “temperature excursion” OR “power outage vaccine loss”;
- “shipping delay” OR “vaccine delivery disruption” OR “severe weather vaccine distribution”;
- “artificial intelligence” OR “predictive analytics” OR “logistics optimization” AND “public health supply chain”.

Search terms were adapted per research question:

- **RQ1:** “vaccine cold chain” AND “weather disruption” AND “United States”.
- **RQ2:** Added geographic filters for “Illinois” AND incident terms such as “temperature excursion”, “power outage”, OR “shipping delay”.
- **RQ3:** Emphasized response terms such as “emergency planning”, “backup storage”, AND “cold-chain resilience”.
- **RQ4:** Utilized technology-related terms such as “AI”, “predictive modeling”, “climate surveillance”, AND “vaccine logistics innovation”.

To ensure breadth and relevance, searches were conducted across three major electronic sources: PubMed/MEDLINE, Scopus, and Google Scholar. In addition, grey literature was searched via the Centers for Disease Control and Prevention (CDC), Illinois Department of Public Health (IDPH), National Association of County and City Health Officials (NACCHO), Association of State and Territorial

Health Officials (ASTHO), and relevant federal or nonprofit health-resilience reports (e.g., FEMA, NOAA [National Oceanic and Atmospheric Administration], NWS [National Weather Service], ASPR). Searches were restricted to publications from January 2000 through July 2025 to capture both historical cold-chain incidents and more recent climate-related disruptions, including COVID-19-era vaccine shipping and storage incidents.

### 3.4. Study Selection

Initial search yielded 392 records; 87 duplicates were removed; 305 titles/abstracts were screened; 76 full texts were assessed; 39 met inclusion criteria. At full text, 35 items were excluded for reasons such as not addressing weather-related cold-chain disruption, lacking U.S./Illinois relevance, inaccessible full text, or insufficient detail on storage/shipping practices. Screening and extraction were conducted by one reviewer with adherence to PRISMA-ScR reporting to minimize bias.

### 3.5. Inclusion Criteria

Studies were included if they met the following criteria:

1. **Content relevance:** Addressed vaccine cold-chain systems (e.g., storage units, transport/shipping, temperature excursions) in the context of severe weather events, climate-related disruption, or power outages; or explored emerging technologies such as AI, predictive modeling, or climate-risk tools applied to immunization supply-chain resilience.
2. **Geographic focus:** Originated from or included data relevant to the United States, with priority given to studies referencing Illinois or the Midwest region.
3. **Source type:** Included peer-reviewed articles; official government publications (e.g., CDC, FEMA, IDPH); relevant agencies (NOAA, NWS, ASPR); technical toolkits; or publicly accessible grey literature (e.g., reports, white papers, media coverage of documented events).
4. **Language:** Written in English.
5. **Publication period:** Published between 2000 and 2025 to capture historical trends and contemporary climate-related disruptions.
6. **Evidence type:** Provided documented incidents, technologies, response strategies, or system-level recommendations related to vaccine storage and distribution during or after weather-related events.

### 3.6. Charting the Data

A structured data extraction template was developed to chart information relevant to the research questions. The following core elements were extracted and organized into three thematic domains aligned with the review questions:

#### 1) Source Characteristics

- Type (peer-reviewed article, government publication, grey literature)

- Geographic scope (national vs. state; Illinois-specific content noted)

## 2) Disruption Type

- Nature of the weather event or infrastructure failure (e.g., power outage, heatwave, flood)
- Cold chain consequence (e.g., storage unit failure, shipping delay, vaccine wastage)

## 3) Response and Innovation Type

- Mitigation strategy or protocol (e.g., backup storage, alternate routes, emergency plans)
- Mention of emerging tools (e.g., AI, predictive analytics, digital tracking platforms, GIS-based models)

### 3.7. Collating, Summarizing, and Reporting the Results

The data extracted from eligible sources were collated and organized according to the four guiding research questions. A narrative approach was used to categorize findings into thematic clusters, with results grouped into: (1) weather-related disruptions to vaccine cold chain systems (e.g., power outages, storage unit failures, and transport/shipping delays), (2) observable patterns in temperature excursions, shipping interruptions, and location-specific incident types, especially within Illinois, (3) documented mitigation strategies and operational protocols, such as the use of backup generators, emergency storage plans, and alternate delivery routes, and (4) references to emerging technologies including artificial intelligence (AI), predictive analytics, GIS-based climate modeling, and digital cold chain tracking systems.

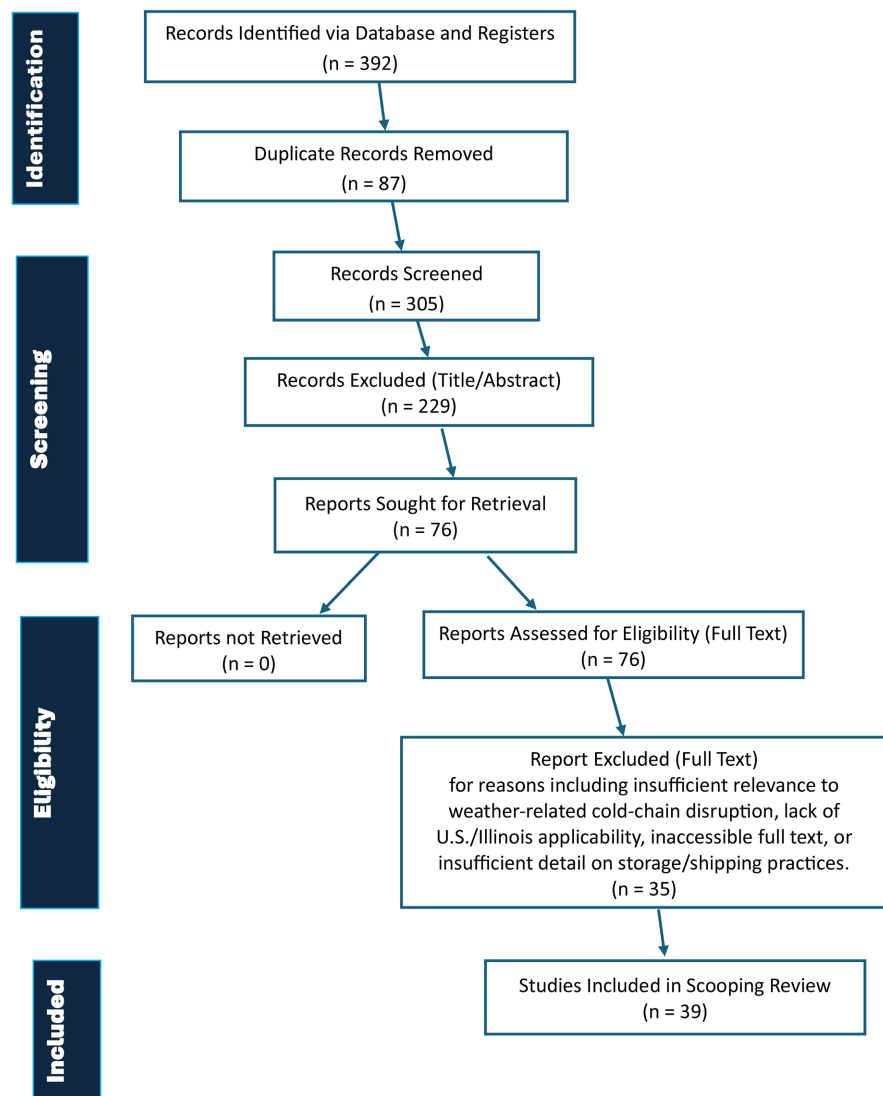
The review prioritized reporting on publicly documented cases, recurring types of system failure (e.g., storage unit failures, shipping delays leading to temperature excursions, and disruptions caused by severe weather such as floods, heatwaves or ice storms), and available guidance from public health agencies and logistics stakeholders. Illinois-specific references were highlighted and discussed relative to national trends.

In line with established scoping review methodology, no formal quality appraisal of included sources was conducted. The goal was to map the breadth and characteristics of existing evidence relevant to vaccine cold chain stability in the face of severe weather threats.

## 4. Results

### 4.1. Study Selection

The search yielded 392 records. After deduplication ( $n = 87$ ), 305 unique titles/abstracts were screened; 76 full texts were reviewed for eligibility (**Figure 1**). Forty-one met inclusion criteria and were charted for analysis; 35 were excluded at full text for reasons including insufficient relevance to weather-related cold-chain disruption, lack of U.S./Illinois applicability, inaccessible full text, or insufficient detail on storage/shipping practices.



**Figure 1.** PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) flow diagram.

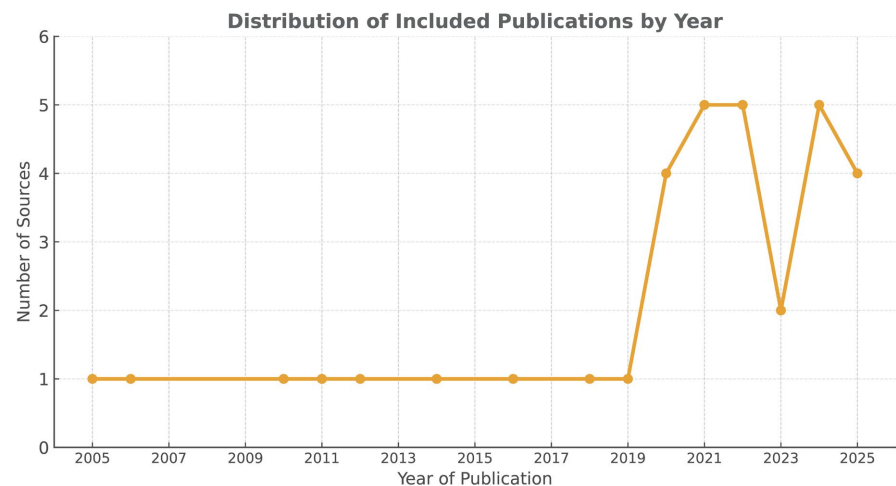
## 4.2. Study Characteristics

The 39 included items comprised peer-reviewed studies and reviews (e.g., [18] [20] [21] [25] [37]), federal and state guidance or technical reports [7]–[10] [12] [14], national datasets or program briefings [29]–[32], and mission-critical grey literature describing monitoring technologies and logistics performance (e.g., [34]–[36]). Publication years span 2006–2025, with an uptick after 2020 alongside pandemic-era distribution and more frequent extreme weather reports (Figure 2). Most sources address national patterns; a subset provides Illinois-specific references, including state program guidance [13], utility reliability summaries [32], outage datasets [30] [31], and a major medical center outage around Chicago [33] (Table 1).

**Table 1.** Characteristics of included sources (n = 39).

| Category                                    | Count (n) | % of Total |
|---------------------------------------------|-----------|------------|
| <b>Source type</b>                          |           |            |
| Peer-reviewed articles                      | 14        | 34.1%      |
| Government reports/datasets                 | 14        | 34.1%      |
| Technical toolkits/manuals                  | 2         | 4.9%       |
| Grey literature (NGO/corporate/media/trade) | 9         | 22.0%      |
| <b>Scope</b>                                |           |            |
| National/multi-state                        | 32        | 78.0%      |
| Illinois-specific                           | 9         | 22.0%      |
| <b>Publication period</b>                   |           |            |
| 2000-2010                                   | 3         | 7.3%       |
| 2011-2020                                   | 11        | 26.8%      |
| 2021-2025                                   | 24        | 58.5%      |
| Undated/not stated*                         | 3         | 7.3%       |

\*Undated items are official resources without a publication year on the citation (e.g., certain datasets/pages); included here for completeness.



Note: Undated items (n = 3) were official resources without a stated publication year and were excluded from the figure.

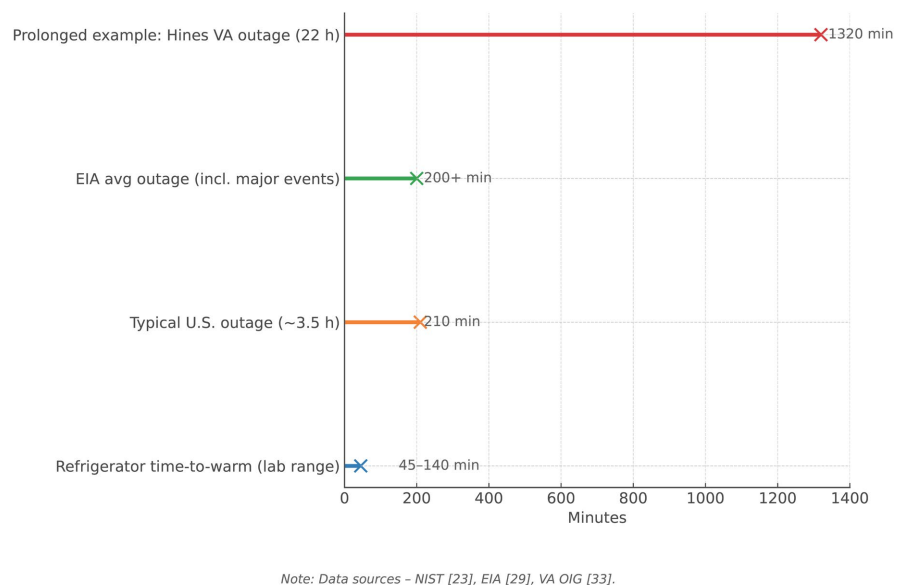
**Figure 2.** Distribution of included publications by year.

### 4.3. Weather-Related Disruptions to Storage and Shipping

#### 4.3.1. Power Loss and Storage-Unit Vulnerability

Evidence from laboratory (experimental) and field/outage (observational) data shows power loss is a primary weather-sensitive threat to refrigerators and freezers. Bench tests in refrigerators, especially glass-door models, crossed 8°C within ~45 - 140 minutes after power loss [23]; the same outage mechanism applies to freezers, reinforcing the need for continuous digital monitoring [24]. NIST's sub-

sequent work supports continuous digital monitoring and practical probe methods that reflect liquid vaccine temperatures [24]. These warm-up intervals are short relative to typical U.S. outages (~1.5 events/year, ~3.5 hours) [25] and to EIA's national reliability picture (>200 minutes average annual outage duration when major events are included) [29]. Illinois-relevant materials further underscore that localized outages remain common despite strong utility-level averages: ORNL's EAGLE-I (2014-2022, 15-minute resolution) shows routine, small-area interruptions at county scale, while ComEd's low SAIDI/SAIFI aggregate metrics can mask local variability [30] [32]. A high-impact example, the 22-hour outage at Edward Hines Jr. VA Hospital's IT Center (May 4, 2023), illustrates the stakes for health infrastructure in the Chicago area [33] (see Figure 3).



**Figure 3.** Time-to-warm (laboratory) vs benchmark outage durations.

**Evidence gap:** While outage and weather datasets (NOAA storm records [22]; EIA reliability metrics [29]; EAGLE-I county-level interruptions [30] [31]) show conditions that consistently threaten vaccine cold-chain stability, neither Illinois nor, to our knowledge, most U.S. jurisdictions publish statewide, cause-coded, public aggregates that quantify vaccine outcomes (e.g., number of excursions, doses affected or lost) attributable specifically to weather-related power loss. Public CDC/IDPH operational guidance and provider manual describe what providers must do after excursions but do not present public data of incident counts by cause. In other states, publicly posted resources similarly focus on VFC protocols rather than statewide public data. Thus, the magnitude of weather-related vaccine loss in Illinois remains unquantified in the public domain; outage proxies are informative but are not linked to dose-level consequences.

**Illinois takeaway:** The storage risk is clear and time-sensitive; the scale of vaccine impact is not publicly visible, pointing to a data-aggregation gap rather than a protocol gap. (See §4.6 and Discussion for synthesis and implications).

### 4.3.2. Shipping Delays during Severe Weather

Severe storms and cold snaps disrupted vaccine distribution nationally and in Illinois. During Winter Storm Uri (February 2021), national briefings cited ~6 million doses delayed, about three days of shipments, with courier and site operations constrained by roads and power [26] [27]. In Illinois, IDPH reported mid-February 2021 weather-related COVID-19 vaccine shipment disruptions and the use of strategic stock to sustain operations until deliveries resumed [28].

**Evidence gap:** While national briefings and media reports clearly document large-scale shipment delays during severe weather (e.g., Winter Storm Uri) and Illinois program actions to buffer operations ([26]-[28]), none of the Illinois-referenced, publicly available sources quantified dose-level outcomes tied specifically to weather-related shipping disruptions (e.g., in-transit excursions, doses spoiled, or reshipment volumes). Public guidance cited here likewise does not aggregate shipping-related excursions into statewide, cause-coded summaries. As a result, the extent to which weather-driven delays translate into temperature control failures in Illinois remains unquantified in the public domain.

**Illinois takeaway:** Weather can and does slow deliveries; the program response is visible, but downstream vaccine-impact metrics (excursions or doses affected due to delay) are not publicly reported, parallel to the storage/outage visibility gap (see §4.6 and Discussion).

### 4.3.3. Illinois' Weather Context

Long-run assessments describe Illinois as warmer and wetter, with more frequent heavy precipitation, heat waves, and winter storm variability ([10]-[12]). NOAA's Storm Events Database provides county-level context for the frequency of extremes referenced throughout this review (NOAA, 1950-present). These patterns align with the outages and logistics risks described above.

## 4.4. Incident Response Protocols and Governance

Guidance is consistent on immediate response to suspected excursions: isolate affected vaccines, download and review digital data, consult manufacturers, and coordinate with jurisdictional programs before discarding or administering ([9] [13]). Illinois' VFC manual requires a vaccine incident report and a manufacturer stability statement, with "Do Not Use" status until program determination ([13]). These practices support patient safety and program integrity.

## 4.5. Emerging Monitoring and Prevention Technologies

Included sources describe a shift from manual log downloads to automated, cloud-connected monitoring with continuous analytics and real-time alerts [34]. Platforms increasingly integrate IoT sensors and GPS for in-transit visibility; some use cellular, multi-carrier connections with battery-backed reporting to reduce dependence on site Wi-Fi, useful where connectivity and power are less reliable [35]. Industry presentations describe "active prediction" concepts (e.g., Max-Trace) designed to flag temperature excursions before thresholds are crossed [36].

Peer-reviewed reviews support the move toward robust, validated digital monitoring [37], while NIST testing highlights accuracy and maintenance approaches for digital data loggers (DDLs) [24] (See **Table 2**).

**Table 2.** Monitoring/prevention capabilities as described in included sources.

| Capability                                                              | Evidence type   | Source(s) describing the capability | Notes (scope of description)                                                              |
|-------------------------------------------------------------------------|-----------------|-------------------------------------|-------------------------------------------------------------------------------------------|
| Continuous digital monitoring (DDLs)                                    | Bench + review  | [24] [37]                           | Validates DDL use; general best practice.                                                 |
| Probe methods reflecting liquid vaccine temps (e.g., glycol, placement) | Bench + review  | [24] [37]                           | Probe media/placement and measurement practices that reflect liquid vaccine temperatures. |
| Calibration/maintenance & accuracy (e.g., ice-point checks, drift)      | Bench + review  | [24] [37]                           | Accuracy verification and maintenance guidance.                                           |
| Automated, cloud-connected upload (vs. manual weekly downloads)         | Review + vendor | [34] [35] [37]                      | Automation and remote access described.                                                   |
| Real-time alerting for excursions                                       | Review + vendor | [35]-[37]                           | Alerts/threshold notification described.                                                  |
| Predictive/early-warning analytics (pre-threshold)                      | Trade/industry  | [34] [35]                           | Predictive concept described; peer-reviewed validation not present in this set.           |
| IoT wireless sensors (integrated sensing)                               | Review + vendor | [34] [35] [37]                      | General trend and vendor examples.                                                        |
| In-transit visibility (temperature + GPS)                               | Review + vendor | [34] [35] [37]                      | Concept described in review; vendor example noted.                                        |
| Connectivity resilience (cellular, multi-carrier)                       | Vendor          | [35]                                | Reduces dependence on local Wi-Fi.                                                        |
| Battery-backed transmission during outages                              | Vendor          | [35]                                | Supports monitoring continuity during power/internet loss.                                |
| Remote dashboards/multi-site oversight                                  | Review + vendor | [34] [35] [37]                      | Fleet/site management and oversight.                                                      |
| Data export/audit logs for compliance                                   | Review + vendor | [34] [35] [37]                      | Traceability and compliance support.                                                      |

Note: Entries reflect information reported in the cited materials. Absence of a citation does not imply a product lacks the capability, only that it was not described in the reviewed sources.

#### 4.6. Evidence Gaps

Within the limits of what is publicly available, three evidence gaps emerge that affect burden estimation and the targeting of resilience investments in Illinois:

##### 1) Absence of a public-facing, cause-coded statewide registry of cold-chain incidents and dose impact

Current guidance and forms describe provider actions after an excursion ([9] [13]), but Illinois does not publish de-identified statewide aggregates that classify incidents by cause (e.g., weather/power, equipment failure, handling error, shipping delay) and quantify doses affected/wasted.

##### 2) Proxy-to-outcome linkage gap

Public datasets report exposure to relevant hazards (e.g., Hayhoe *et al.*/EPA indicators [11] [12]; NOAA storm records [22]; EIA reliability metrics [29]; EA-GLE-I county-level interruptions [30] [31]), yet those exposure proxies are not

linked in public reporting to vaccine outcomes in Illinois (e.g., excursion counts, wastage, revaccination needs).

### **3) Shipping delays without public, in-transit temperature or dose outcomes**

Severe-weather delays were reported nationally and acknowledged in Illinois operations ([26]-[28]). However, publicly available Illinois program materials do not include aggregate, in-transit temperature-control outcomes or dose impacts attributable to those delays. This is consistent with data stewardship in the U.S. vaccine supply chain: continuous shipment-temperature data are typically held by distributors/manufacturers and carriers, while state programs generally gain visibility after receipt (e.g., through provider incident reports). To the extent shipment issues are detectable at the provider level (e.g., temperature-indicator tags included by manufacturers), these signals may appear in site-level reports, but they are not publicly aggregated by cause (e.g., weather-related delay) or linked to statewide dose counts. Consequently, Illinois, and, likely, most jurisdictions, can see logistics stress (delays) but not the public, dose-level consequences of in-transit temperature control. Together, these gaps limit burden estimation, hotspot identification, and evaluation of resilience measures in Illinois.

#### **Implication (state and national reporting/learning)**

Within Illinois, the absence of public, cause-coded, de-identified aggregation means weather/power exposures are visible, but dose-level effects are not. Nationally, CDC is well positioned to convene awardee reporting and publish de-identified, standardized aggregates (e.g., excursions and doses affected attributed to weather/power vs. other causes), given its role in guidance and vaccine management systems. In our review of publicly available data, we did not identify CDC-published national aggregates quantifying weather- or shipping-attributable temperature excursions or dose loss. Similarly, we did not identify publicly accessible, cause-coded statewide aggregates (e.g., excursions and doses affected attributed to weather/power vs other causes, with coarse temporal summaries and, where feasible, coarse geography such as region/county). Availability of such data could support cross-jurisdiction learning and guide Illinois-specific vaccine cold-chain resilience as climate-related risks evolve.

## **5. Discussion**

### **5.1. Summary of Key Findings**

Our scoping review found that severe weather, including heatwaves, winter storms, floods, and associated power outages pose persistent risks to the vaccine cold-chain across the United States, including Illinois [23] [28]. Nationally, the literature and official communications describe weather-related distribution slowdowns, storage-unit vulnerabilities, and temperature excursions [9] [23] [26] [27]. However, Illinois-specific, publicly accessible, cause-coded aggregates of cold-chain incidents (e.g., excursions and doses affected attributed to weather/power outage vs other causes) remain somewhat lacking [13] [30] [31]. Documented mitigation strategies emphasize backup power, strategic stock, and continuous

digital temperature monitoring—the CDC standard already used by providers [9] [13] [20]. The newer layer in our sources is smart cold-chain technology: AI-enabled data loggers that automatically upload to secure cloud platforms, analyze readings continuously, and send real-time alerts; some integrate wireless IoT/GPS and cellular, battery-backed connectivity to keep monitoring during power or internet loss [34] [35] [37]. Trade/industry reports also describe predictive (“pre-threshold”) alerts (e.g., MaxTrace) aimed at warning before temperatures drift out of range [36].

In all the Illinois sources we reviewed, we did not identify peer-reviewed evaluations or publicly accessible program documentation showing provider deployment of pre-threshold, predictive alerts or weather-linked excursion prediction; meanwhile, Illinois-specific evidence points to clear strengths (e.g., high MMR coverage; established vaccine incident report protocols) alongside vulnerabilities, especially in rural areas where power instability and limited backup capacity elevate risk [8] [11]–[13], which may impede statewide vaccine risk assessment due to weather-related power outage and the ability to target program-level supports, such as focused technical assistance and training, prioritized outreach to higher-risk providers identified via power outage/storm exposure, temporary redistribution support during declared weather disruptions, and, where feasible, competitive micro-grants for backup power or connectivity-resilient vaccine cold-chain monitoring, without presuming any particular funding decision [9] [13] [14] [28] [30] [31].

It is important to note that this review assesses only publicly accessible data and documentation; it does not evaluate the potential existence or content of internal, non-public data systems within IDPH or CDC.

## 5.2. Critical Interpretation of Findings by Research Question

### 5.2.1. Weather-Related Cold Chain Disruptions (RQ1)

Power outages, often triggered by severe weather, are a well-documented risk to vaccine storage [9] [23]. In Illinois, mid-February 2021 weather caused vaccine shipping delays, with the state drawing on strategic stock to buffer operations [26]–[28]. Laboratory work shows pharmaceutical-grade refrigerators can rise above 8°C within roughly 45 - 140 minutes once power is lost [23]. These risks coexist with observed exposure patterns: EIA reliability metrics and EAGLE-I outage data capture interruptions relevant to cold-chain stability, and regional climate syntheses describe more heavy precipitation and storm variability [11] [12] [29]–[31]. Despite strong utility-level averages in northern Illinois [32], short, localized power outages still occur, often lasting longer than the ~45 - 140 minutes it can take units to warm beyond the safe vaccine storage range [23] [30] [31].

### 5.2.2. Observed Patterns and Data Gaps in Illinois (RQ2)

Public datasets report exposure (outages, storm events), but Illinois does not publicly report cause-coded statewide aggregates linking those exposures to dose-level outcomes (e.g., excursion counts or doses affected) [9] [13] [14] [30] [31]. As a

result, stakeholders outside the VFC program (e.g., researchers, partner organizations, funders) cannot independently identify hotspots, perform cross-jurisdiction comparisons or assess equity impacts; this observation concerns public reporting data only and does not address internal analytic capacity. We also do not assert whether CDC or state VFC programs maintain such data in nonpublic systems; our point is the lack of publicly accessible, cause-coded statewide data in the sources reviewed.

### 5.2.3. Evaluation of Current Mitigation and Response Strategies (RQ3)

Standard VFC program measures such as backup power, strategic stock, alternate routing, and vaccine incident report protocols, among others, are consistently described in CDC and IDPH guidance [9] [13]. In practice, performance varies by resources and site capacity [9] [13]. During the mid-February 2021 weather-related delays, Illinois drew on strategic stock to buffer operations, highlighting stockpiles' value; however, stockpiles complement rather than replace measures that prevent storage unit excursions during power outages [9] [28]. In the publicly accessible materials we reviewed, we did not find statewide evaluations that quantify the performance of these measures, e.g., coverage (share of enrolled providers with continuous digital monitoring, connectivity-resilient reporting, and approved backup storage/transfer plans), timeliness (time to detect/respond to excursions and to restore safe storage or redistribute vaccine), and equity (whether rural/high-outage and other underserved areas achieve comparable protection and support). The absence of publicly accessible statewide evaluation data has direct implications for equity in Illinois. Likewise, cause-coded statewide aggregates that link weather or power-related exposures to vaccine cold-chain incidents are not publicly disseminated, obscuring whether risks are concentrated in settings with known constraints. County-level outage datasets document recurrent short interruptions across Illinois, while utility-level averages especially in northern Illinois (ComEd) appear strong; statewide indicators can mask locality-specific risks relevant to vaccine storage [30]-[32]. In such settings, smaller clinics and local health departments may lack backup power, continuous monitoring, or rapid response capacity, making them more vulnerable to storage failures during outages [21] [23]. Thus, without publicly accessible cause-coded statewide data, these uneven risks remain invisible in aggregate reporting, obscuring whether rural or high-outage communities experience disproportionate cold-chain incidents. Consequently, statewide planning may inadvertently overrepresent well-resourced areas while underestimating vulnerabilities in cold-chain resilience and response capacity among communities where weather instability, power unreliability, and limited infrastructure intersect.

This distinction is important because the observation concerns public visibility rather than internal analytic capacity. Publicly accessible, cause-coded statewide data would enable stakeholders outside the VFC program, including researchers, potential partners, and funders, to align preparedness activities with documented exposures (e.g., power outages and storm datasets) and to assess equity, such as

whether rural or high-outage areas maintain comparable protection over time. Without such aggregates, an apparent absence of temperature excursions remains ambiguous; it could reflect genuinely low risk or limited detection and reporting, and external analysts cannot distinguish between the two or compare trends across jurisdictions. This observation pertains solely to public reporting and does not address internal IDPH analytics [9] [11]-[14] [30] [31].

#### **5.2.4. Potential and Limitations of Emerging Technologies (RQ4)**

AI-enabled monitoring, cloud connectivity, and pre-threshold/predictive alerting are described in vendor/trade sources and reviews [34]-[36], aligning with peer-reviewed guidance favoring robust digital monitoring [37]. In the materials we reviewed, we did not identify peer-reviewed evaluations or publicly accessible Illinois program documentation demonstrating provider deployment of predictive alerts or weather-linked temperature excursion prediction. We also did not identify systems in this set that integrate weather/grid forecasts directly with unit-level risk capabilities proposed in industry sources as important as climate risks evolve [34] [36]. However, these emerging technologies should be independently validated in peer-reviewed programmatic or public health settings before widespread adoption or integration into vaccine cold-chain systems can be recommended.

#### **5.3. Limitations of This Review**

This is a scoping review designed to map the extent and nature of evidence, not to appraise study quality or estimate effect sizes [38] [39]. Screening and extraction relied on publicly accessible materials; some relevant internal or proprietary data (e.g., distributor in-transit telemetry) were outside scope. Screening and extraction were conducted by a single reviewer, which may miss eligible items despite structured methods (see Methods §3). As such, findings emphasize documented exposures and protocols over publicly aggregated outcomes (dose-level impacts).

#### **5.4. Implications for Practice, Policy, and Data in Illinois**

Given that common pharmaceutical refrigerators can exceed 8°C within ~45 - 140 minutes of power loss [23] and that publicly reported outages often last on the order of hours, even where utility averages look strong [29]-[31], planning in Illinois may be better calibrated to plausible local outage windows rather than system-wide averages. In practice (and consistent with CDC/IDPH guidance), this points to maintaining continuous digital monitoring, connectivity-resilient reporting, and rapid procedures for moving vaccines to approved backup storage or redistribution [9] [13]. At the state/program level, publicly accessible, cause-coded statewide data (excursions and doses affected attributed to weather/power vs other causes) could support cross-jurisdiction learning and help external stakeholders assess patterns as climate risks evolve. We do not take a position on whether CDC or the state should publish such data; we note only that such outputs were not identified in the public sources reviewed, and this statement pertains to

public reporting and does not address internal analytic capacity [9] [13] [14] [26] [27] [30] [31].

## 6. Conclusions

Severe weather and associated power outages pose persistent, well-documented risks to vaccine cold-chain integrity in the United States, including Illinois. Bench data show common pharmaceutical refrigerators can exceed 8°C within ~45 - 140 minutes of power loss, while publicly reported power outages frequently extend beyond that window; Illinois also experienced weather-related shipping delays in February 2021. Within Illinois, strengths such as high MMR coverage and well-established vaccine incident reporting protocols sit alongside vulnerabilities in settings with less reliable power or backup capacity. Across the publicly accessible sources we reviewed, we did not identify cause-coded, statewide aggregated data linking weather/power exposures to dose-level outcomes (e.g., excursion counts, doses affected); this limits external visibility into patterns and equity, without speaking to internal analytic capacity.

Current guidance emphasizes continuous digital monitoring, connectivity-resilient reporting, and rapid procedures for moving vaccines to approved backup storage or redistribution. Vendor/trade sources describe pre-threshold (“predictive”) alerts and expanded in-transit visibility, but we did not find peer-reviewed evaluations or publicly accessible Illinois program documentation showing provider deployment of predictive alerts or weather-linked excursion prediction. In light of short warming intervals and observed outage exposures, preparedness planning in Illinois is best calibrated to plausible local outage windows rather than system-wide averages, consistent with CDC/IDPH guidance.

Looking ahead, three priority evidence needs emerge from this review. First, publicly accessible, cause-coded statewide aggregated data (temperature excursions and doses affected attributed to weather/power vs. other causes) would reduce ambiguity between “no events” and “no detection” and enable cross-jurisdiction learning. Second, statewide performance descriptions using clear, public metrics, coverage (e.g., share of enrolled providers with continuous monitoring, connectivity-resilient reporting, approved backup storage/transfer plans), timeliness (e.g., time to detect/respond and to restore safe storage or redistribute vaccine), and equity (e.g., outcomes in rural/high-outage areas), would allow external stakeholders to assess progress over time. Third, contextual evaluations of emerging monitoring tools in Illinois settings, including feasibility, costs, and any integration of weather/grid forecasts with storage unit-level risk, would clarify what adds value in practice. These are not prescriptions; they follow directly from the gaps identified in publicly accessible sources and align with the paper’s focus on weather-related risk to vaccine viability.

## Conflicts of Interest

The authors declare no conflicts of interest.

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