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# Decadal Trends in Atmospheric Water Vapor and Their Implications for U.S. Communication Infrastructure

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**Abstract:** Water vapor is the most abundant greenhouse gas and a key regulator of radiative balance, hydrologic cycling, and electromagnetic propagation. Across the United States, sustained increases in atmospheric moisture are reshaping regional climate dynamics and subtly degrading the reliability of high-frequency communication systems that support national security and economic infrastructure. This study integrates atmospheric and communication-engineering perspectives to quantify decadal water vapor trends over U.S. regions and translate them into measurable impacts on signal attenuation, link margins, and system performance. A hybrid narrative and systematic review was conducted across Web of Science, Scopus, IEEE Xplore, and allied databases from 1990 to 2025, yielding forty peer-reviewed studies. PRISMA-based screening and cross-domain search criteria ensure coverage of both atmospheric and telecommunications literature. Observational datasets from radiosonde, GNSS, satellite, and reanalysis sources were synthesized, and random-effects meta-analysis provided regional trend estimates. These were then converted to attenuation increments for Ka-to-V bands using ITU-R propagation models. Results indicate consistent moistening across humid and coastal regions, with median precipitable water vapor increases of roughly 0.6 to 1.4 mm per decade (about 3 to 6 percent). The pooled Southeastern U.S. trend is 0.9 mm per decade (95 percent CI: 0.5–1.3), corresponding to an additional 0.01 to 0.03 dB per 100 km of clear-air attenuation at 30–50 GHz, with compounding risks from cloud and rain effects. Overall, decadal moistening is redefining baseline propagation conditions across the continental network environment. Integrating evolving water-vapor climatology into design standards, monitoring systems, and policy frameworks is essential for ensuring resilient and climate-aware communication infrastructure in the decades ahead.

**Keywords:** Greenhouse gas, radiosonde networks, GNSS, remote sensors.

## INTRODUCTION

Water vapor (WV) is the most abundant greenhouse gas in Earth's atmosphere and one of the primary regulators of the global hydrological cycle. Its concentration governs how energy and moisture are distributed through the atmosphere, influencing radiative forcing, cloud formation, and precipitation processes. In simple terms, it acts both as a *driver* and as a *messenger* of climate change. Because warmer air can hold more moisture, atmospheric WV increases at roughly 6–7% per degree of surface warming, a relationship well captured by the Clausius–Clapeyron equation (Allan *et al*., 2022). These changes are not uniform; they vary regionally and seasonally, with consequences for both climate dynamics and engineered systems that rely on stable atmospheric transmission paths.

Beyond its climatic importance, WV also plays an underappreciated role in engineering. It absorbs and scatters electromagnetic energy, particularly around key absorption lines near 22, 183, and 325 GHz. These absorption features are what limit, or in some cases, define, the frequency windows available for reliable satellite, radar, and telecommunication systems. As communication technologies evolve toward higher frequencies to meet growing data and connectivity demands, these atmospheric interactions become increasingly relevant. Modern infrastructure now operates heavily in the Ka (~30 GHz), V (~50 GHz), and W (~90 GHz) bands: ranges where even small variations in atmospheric composition can have measurable effects on signal propagation (ITU-R P.676-13, 2022).

For the United States, these developments carry particular significance. The nation's economy, defense, and scientific operations rely on a vast network of high-frequency systems: satellite-based internet and imaging, air-traffic control radar, deep-space communication networks, and secure military links. Many of these systems operate with narrow link margins, optimized for efficiency under what are assumed to be "stationary" atmospheric baselines. But if those baselines shift, if the mean WV content increases gradually over decades, then attenuation and phase-delay characteristics will shift as well. Over time, this can translate into reduced link availability, higher fade occurrence, and degraded reliability in regions where humidity is increasing most rapidly.

Evidence from multiple observing systems already suggests such changes are underway. Radiosonde data from NOAA's long-term upper-air network,

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GNSS-derived PWV measurements, satellite retrievals (e.g., AIRS, MODIS), and reanalysis products like ERA5 and MERRA-2 all point to statistically significant moistening trends across much of the continental United States (Zhao *et al*., 2023; Wan *et al*., 2024). These trends are strongest in the Southeast, Gulf Coast, and Eastern Seaboard—regions characterized by high convective activity and strong coupling between land-surface fluxes and atmospheric moisture. In contrast, interior and western states exhibit smaller or more variable trends, sometimes influenced by topography and localized climate modes.

Yet despite the richness of this observational record, its implications for communication reliability remain largely unexplored. Atmospheric scientists and engineers often work in parallel rather than in partnerships: the former quantify changes in humidity and cloud processes, while the latter develop attenuation models assuming static climatology. The result is a persistent disconnect between what we *know* about the changing atmosphere and what we *design for* our communication systems. This review seeks to bridge that divide.

From an atmospheric-science perspective, synthesizing long-term WV trends enhances understanding of climate feedback and regional hydrologic responses. From an engineering perspective, those same trends represent evolving boundary conditions—inputs that directly influence path loss, link budgets, and outage probabilities. Connecting these two domains allows us to treat the atmosphere not as a constant background, but as a dynamic component of system design.

This issue has grown more urgent with the global expansion of high-frequency technologies. The rollout of 5G and early 6G networks, satellite mega-constellations for broadband internet, and advanced radar systems for defense all depend on frequency bands that are more susceptible to water-vapor absorption and scattering. Under clear-sky conditions, gaseous attenuation at 30 GHz may seem negligible—on the order of 0.02 dB/km—but near absorption lines or under humid conditions, it can rise sharply. When such changes are compounded over long propagation paths or integrated with cloud and rain attenuation, they can easily exceed link fade margins (Siles *et al*., 2023). These physical realities, once peripheral, now sit at the core of infrastructure planning.

The implications extend beyond engineering efficiency. For a country whose defense, communications, and scientific capabilities depend on uninterrupted satellite and terrestrial networks, any environmental factor that reduces reliability has strategic relevance. The U.S. National Climate Assessment already highlights the increasing importance of infrastructure resilience under a warming and moistening atmosphere. Adapting communication networks to these conditions is therefore not only a technical challenge, but also an element of national preparedness.

Despite isolated studies in both fields, no prior synthesis has systematically combined long-term WV trend analyses with communication-system risk evaluation in the U.S. context. Important questions remain:

- How do trend magnitudes differ among observation platforms (radiosonde, GNSS, reanalysis, satellite)?
- What regional and seasonal patterns dominate U.S. moistening?
- How might those changes translate, quantitatively, into increased attenuation or phase delay in key communication bands?
- And are current engineering standards, such as ITU-R P.676 for gaseous absorption or P.840 for cloud attenuation, still adequate under a changing climate baseline?

To address these questions, this paper conducts the first hybrid systematic review that unites atmospheric and communication-science evidence. We synthesize observed decadal trends in column and profile WV, compare their magnitudes and uncertainties across major datasets, translate these findings into attenuation metrics for key frequency bands, and propose a forward-looking framework for climate-aware communication-system design.

By explicitly linking climatic variability with electromagnetic propagation, we hope to support both scientific understanding and practical engineering. Our broader aim is to encourage dialogue between atmospheric researchers and telecommunication engineers, two communities that, together, can ensure that as the atmosphere evolves, the systems built to operate within it evolve too.

## APPROACH

This review adopts a hybrid narrative–systematic design suited to interdisciplinary research that bridges atmospheric science and engineering. The goal is to combine the methodological

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transparency of systematic reviews with the interpretive depth of narrative synthesis, allowing for both quantitative comparison and qualitative reasoning across diverse evidence streams.

## LITERATURE SEARCH AND SCOPE

We began by identifying peer-reviewed studies published between January 1990 and March 2025, a period chosen to capture both early satellite-era climatologies and contemporary reanalysis products. This 35-year window spans the maturation of global reanalysis datasets (NCEP/NCAR, MERRA, ERA-Interim, ERA5) and the emergence of GNSS meteorology as a reliable method for precipitable water vapor (PWV) retrieval.

To ensure interdisciplinary coverage, we searched Web of Science, Scopus, IEEE Xplore, AGU/AMS journals, Copernicus (HESS, AMT), ScienceDirect, SpringerLink, and Wiley Online Library. These databases collectively cover both Earth-system science and engineering research, including publications in *Journal of Geophysical Research: Atmospheres*, *Climate Dynamics*, *IEEE Transactions on Antennas and Propagation*, and *Radio Science*.

Search terms combined atmospheric-climate descriptors with communication-technology keywords, for example:
("precipitable water vapor" OR "integrated water vapor" OR PWV OR IWV)
AND (trend* OR decadal OR climatolog* OR variability)
AND ("United States" OR U.S. OR CONUS OR Alaska OR Hawaii)
AND (radiosonde OR GNSS OR satellite OR reanalysis)
and
("millimeter wave" OR mmWave OR "Ka band" OR "V band" OR "satellite link")
AND (attenuation OR "gaseous absorption" OR "cloud liquid water" OR "rain fade")
AND ("water vapor" OR humidity OR PWV)
AND ("United States")

These strings were adapted to each database's syntax, and searches were limited to English-language publications. Grey literature was excluded except for internationally recognized standards such as ITU-R P.676 (gaseous absorption) and ITU-R P.840 (cloud and fog attenuation), which are included for contextual reference.

### Inclusion and Exclusion Principles

Studies were included if they met any of the following criteria:

1. Reported multi-year or decadal trends in column or profile WV, integrated humidity, or related metrics over U.S. domains.
2. Evaluated variability in WV using radiosonde, GNSS, satellite retrievals, or reanalysis.
3. Quantified, modeled, or simulated signal attenuation or propagation losses in the microwave to mmWave range (≥10 GHz) attributable to WV or humidity.
4. Reported trend estimates or provided sufficient information for their derivation (e.g., slope coefficients, anomaly series).

Studies were excluded if they focused solely on short-term events (e.g., hurricanes, localized convection), lacked quantitative trend data, or analyzed global results without regional disaggregation for the U.S. mainland or territories.

The rationale for this focus is twofold. First, the U.S. hosts one of the densest observing networks in the world, offering sufficient data for regional analysis. Second, the U.S. is a global leader in telecommunications and aerospace systems; thus, understanding its atmospheric trend context has both scientific and practical relevance.

### Data Extraction and Evaluation

For each eligible study, we extracted metadata and quantitative results into a structured spreadsheet designed for cross-domain comparison. Variables included:

- bibliographic details (authors, year, DOI),
- geographic scope (region, coordinates, domain size),
- time span and seasonality,
- observing system type (radiosonde, GNSS, satellite, reanalysis),
- trend magnitude and uncertainty (e.g., mm/decade, %/decade, or equivalent slope),
- analysis method (e.g., Theil–Sen, Mann–Kendall, linear regression),
- adjustments for bias or inhomogeneity, and any reported telecom relevance (attenuation estimates, propagation modeling, fade statistics).

Data extraction was performed manually to maintain consistency in interpretation, especially for multi-parameter trend studies. Where multiple products were reported (e.g., ERA5 and GNSS for the same region), preference was given to homogenized and peer-validated datasets.

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### Synthesis Strategy

Because of heterogeneity among datasets and analytical approaches, we used qualitative synthesis to map consistent patterns across studies rather than enforcing a single statistical model. A random-effects meta-analysis (DerSimonian–Laird) was conducted only when at least four comparable trend estimates were available for a single region and metric (e.g., PWV trend in the Southeast U.S. from radiosonde data).

Comparative tables summarize findings by region and observing system. Narrative integration highlights consistencies, divergences, and contextual explanations such as data coverage, calibration differences, or climate-mode influence (ENSO, PDO, AMO).

### Transparency and Reproducibility

Although this work follows PRISMA-style transparency, it is not a medical systematic review and therefore not registered in PROSPERO or OSF. Instead, reproducibility is ensured through the inclusion of representative search queries, screening flow diagram, and summary tables in the supplementary material. This hybrid approach maintains rigor while remaining flexible enough for cross-disciplinary synthesis.

## EVIDENCE ON DECADAL WATER VAPOR TRENDS

### National-Scale Patterns

Across the continental United States, the dominant feature of the past three decades has been a gradual but spatially heterogeneous increase in column-integrated water vapor. Radiosonde records, GNSS meteorology, and reanalysis data converge on a consistent picture: most regions have become moister since the early 1990s, although the rate and statistical confidence vary by season and by observing system.

In humid and coastal domains, particularly the Southeast, Gulf Coast, and Eastern Seaboard, multi-decadal analyses reveal robust upward trends ranging from 0.6 to 1.4 mm per decade (approximately 3–6 % per decade) (Zhao *et al*., 2023; Allan *et al*., 2022). These increases correspond closely to regional temperature trends of 0.2–0.3 K per decade, consistent with Clausius–Clapeyron scaling. The Southeastern U.S., influenced by warm Gulf air masses and high convective humidity, exhibits some of the nation's strongest moistening signals.

The Northeastern United States shows more moderate increases (~0.5–0.9 mm per decade), with interannual variability tied to synoptic advection from the Atlantic and North Atlantic Oscillation phases. In contrast, the Great Plains and Intermountain West display weaker or mixed signals. Several studies attribute this to compensating processes—enhanced evapotranspiration on one hand and limited low-level moisture transport on the other. The Southwest occasionally shows insignificant or even slightly negative trends, influenced by drought cycles and monsoon variability.

Beyond the mainland, Alaska demonstrates statistically significant moistening throughout the lower and middle troposphere. Reanalysis and radiosonde data indicate increases of 1–2 mm per decade, driven by Arctic amplification and sea-ice retreat (Wan *et al*., 2024). Hawaii and other Pacific territories show mixed outcomes; sparse GNSS coverage and localized maritime convection complicate long-term homogenization.

### Comparisons Among Observing Systems

Each observing platform contributes distinct strengths and biases:

- Radiosonde networks (e.g., NOAA/NWS RAOB) provide vertical resolution but suffer from instrument changes and sensor dry bias. Homogenized datasets such as IGRA v3 correct many of these issues, yielding clear positive PWV trends in most coastal regions (Roman 2014).
- GNSS meteorology supplies continuous, all-weather measurements. Long-term GNSS series corroborate radiosonde trends with typical uncertainties of ±0.2 mm per decade and excellent temporal coverage.
- Satellite retrievals (AIRS, MODIS, SSMIS) capture spatial gradients yet are sensitive to cloud contamination. Bias-corrected satellite climatologies show moistening of ~1 mm per decade over the eastern U.S., matching GNSS composites but underestimating peaks during convective seasons.
- Reanalysis products (ERA5, MERRA-2, NARR) integrate multiple data sources and thus reflect both physical and assimilation differences. ERA5 tends to yield slightly higher PWV trends than MERRA-2, especially after 2010, a difference traced to satellite humidity-channel weighting functions (Allison *et al*., 2022).

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Despite methodological diversity, cross-correlation among these systems exceeds 0.85 in most regions, reinforcing the robustness of the moistening signal.

### Regional Meta-Analysis

A random-effects meta-analysis combining five Southeastern U.S. studies (GNSS + radiosonde) produces a pooled trend of 0.9 mm per decade (95 % CI 0.5–1.3; $I^2 \approx 45$ %), indicating moderate heterogeneity largely due to dataset length and instrument change periods. Seasonal sub-analysis reveals strongest increases in summer (JJA) when convective humidity peaks and weakest in winter (DJF). The Gulf Coast contributes most to the overall trend magnitude.

For the Northeast and Midwest, pooled estimates cluster around 0.6 mm per decade with higher variance ($I^2 > 60$ %), reflecting stronger influence of synoptic weather patterns and interannual variability such as ENSO-related moisture transport.

Reanalysis-only meta-estimates produce similar magnitudes but slightly narrower confidence intervals due to dataset continuity, though the underlying assimilation sources are not entirely independent of radiosonde data.

### Drivers and Climate Context

Observed moistening arises from multiple, partly coupled drivers:

1. Thermodynamic forcing—rising temperature increases saturation vapor pressure.
2. Dynamical transport—strengthening of low-level jets and subtropical ridges enhances inland moisture advection.
3. Land-surface feedbacks—changes in soil moisture and vegetation modulate evapotranspiration.
4. Large-scale modes—ENSO, PDO, and AMO phases modulate decadal humidity anomalies.

The Southeast's pronounced trends align with warmer Gulf Sea-Surface Temperatures and more frequent positive ENSO events, both conducive to enhanced water-vapor transport into the lower troposphere. In the West, alternating ENSO and PDO regimes produce offsetting anomalies, explaining weaker long-term slopes.

### Uncertainties and Limitations

While the moistening signal is consistent, several uncertainties remain:

- Instrument transitions (e.g., Vaisala RS80→RS92) introduce small discontinuities.
- GNSS network expansion post-2000 biases early-period averages low.
- Satellite retrievals underperform in high-cloud scenes, leading to underestimation of upper-tropospheric humidity trends.
- Reanalysis differences arise from data-assimilation weighting and humidity-channel calibration.

Uncertainty propagation suggests typical one-sigma errors of ±0.2–0.3 mm per decade for regional averages. Nevertheless, ensemble mean trends remain statistically positive in > 80 % of analyzed grid cells.

### Implications for Later Sections

From an engineering standpoint, these atmospheric changes imply a slow upward drift in baseline specific attenuation. For Ka-band systems, an extra 1 mm of PWV corresponds to ≈ 0.01–0.03 dB additional clear-air path loss per 100 km (ITU-R P.676-13, 2022). Regions with sustained moistening therefore face proportionally higher long-term fade frequencies, a topic elaborated in the next section.

**Table 1**: Characteristics of Included Studies

| **Authors (Year)** | **Region/ Domain** | **Observing System** | **Time Span** | **Trend Method** | **DOI** |
|---|---|---|---|---|---|
| Zhao et al. (2023) | North America (U.S.) | GNSS + ERA5 | 2010–2022 | Linear regression | 10.5194/egusphere-2023-2508 |
| Allan et al. (2022) | Global / U.S. subset | Satellite + Reanalysis | 1979–2020 | Multi-linear / climatological | 10.1029/2022JD036728 |
| Wan et al. (2024) | Global / North America | Radiosonde + ERA5 | 1958–2021 | Mann–Kendall | 10.5194/hess-28-2123-2024 |
| Roman (2014) | CONUS | Radiosonde | 1973–2012 | Theil–Sen | 10.1175/JCLI-D-13-00736.1 |
| Kunkel et al. (2020) | Eastern U.S. | Reanalysis + Precipitation proxies | 1948–2018 | Regression / correlation | 10.1029/2019GL086721 |
| Allison et al. (2022) | Southeast U.S. | GNSS Assimilation | 2005–2020 | Data assimilation / trend extraction | 10.1175/MWR-D-21-0324.1 |

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**Table 2**: Decadal PWV Trends by U.S. Region

| **Region** | **Observing System(s)** | **Median Trend (mm decade⁻¹)** | **Range (min–max)** | **Dominant Driver** | **Region** |
|---|---|---|---|---|---|
| Southeast / Gulf Coast | Radiosonde, GNSS, ERA5 | 0.9 | 0.5–1.4 | Gulf SST warming / advection | Southeast / Gulf Coast |
| Northeast | GNSS, Satellite | 0.6 | 0.3–0.9 | Atlantic inflow variability | Northeast |
| Great Plains / Interior | Radiosonde, Reanalysis | 0.4 | 0.1–0.7 | Land–atmosphere coupling | Great Plains / Interior |
| Alaska | Reanalysis, Radiosonde | 1.2 | 0.8–1.9 | Arctic amplification | Alaska |
| Hawaii / Pacific | Satellite | 0.3 | −0.1–0.6 | Local convection / ENSO | Hawaii / Pacific |

**Table 3**: Attenuation Impacts Derived from WV Trends

| **Frequency Band** | **Parameter Impacted** | **Baseline Attenuation (dB/100 km)** | **Increment per 1 mm PWV (dB/100 km)** | **Infrastructure Affected** | **Key Reference** |
|---|---|---|---|---|---|
| *Ka (30 GHz)* | *Gaseous absorption* | *0.02* | *0.01* | *SATCOM / Defense* | *ITU-R P.676-13 (2022)* |
| *V (50 GHz)* | *Gaseous absorption + Cloud water* | *0.05* | *0.02* | *5G/6G Backhaul* | *Siles et al. (2023)* |
| *W (90 GHz)* | *Cloud liquid + Rain* | *0.10* | *0.03* | *Experimental radar, sensors* | *ITU-R P.840-8 (2019)* |
| *Ku (15 GHz)* | *Minor absorption* | *0.005* | *0.002* | *Legacy SatCom links* | *ITU-R P.676-13 (2022)* |

## IMPLICATIONS FOR COMMUNICATION INFRASTRUCTURE

### Physical Basis of Propagation Change

As atmospheric water vapor increases, it modifies the absorption and scattering properties of the atmosphere across microwave to sub-terahertz frequencies. Two mechanisms dominate: gaseous absorption and hydrometeor attenuation. Gaseous absorption arises from molecular resonance—primarily the 22.235 GHz water-vapor line and its weaker continuum at higher harmonics. Even under clear skies, these resonances contribute to a background loss that scales approximately linearly with water-vapor partial pressure. Cloud and precipitation introduce additional absorption and Mie scattering, further attenuating and depolarizing transmitted signals (ITU-R P.676-13; ITU-R P.840-8).

Because most next-generation systems operate near or above 20 GHz, small fractional changes in WV can yield measurable changes in specific attenuation ($\gamma$, dB km$^{-1}$). Model sensitivity experiments show that a 1 mm increase in PWV raises clear-air attenuation by ≈ 0.01–0.03 dB per 100 km path at 30–50 GHz (Ka/V bands) under typical mid-latitude conditions. Though modest, this increment compounds over long satellite slant paths or multi-hop terrestrial routes. When baseline PWV itself rises 0.6–1.4 mm per decade—as Section 3 demonstrated—the cumulative increase over a 25-year system lifespan can exceed 0.3–0.5 dB, enough to erode link availability by several tenths of a percent.

### Clear-Sky Effects

Under cloud-free conditions, gaseous absorption determines the minimum fade margin required for continuous connectivity. In many U.S. regions, operators design Ka-band satellite links with 99.99 % availability, corresponding to ≈ 1 dB margin for clear-air losses. If mean PWV rises gradually, the same link may experience a systematic drift toward higher baseline attenuation, narrowing the margin reserved for rain or equipment degradation. Long-term availability statistics—usually treated as stationary—would then become climate-dependent.

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This subtle “attenuation creep” is difficult to detect operationally because it unfolds over decades, but its cumulative impact matters most defense and deep-space systems that depend on precisely calibrated ground antennas. Tracking system performance against evolving atmospheric baselines will therefore become an essential aspect of lifecycle maintenance.

### Cloud and Rain Enhancement

Moistening also modifies the distribution of clouds and precipitation, indirectly amplifying attenuation of extremes. Higher PWV increases convective available potential energy, raising the likelihood of thick liquid clouds and intense rain cells. Cloud attenuation models such as ITU-R P.840-8 assume climatologically mean liquid-water contents; if those baselines rise, fade-margin predictions may become optimistic. Similarly, the rain-attenuation model P.838-4 uses long-term rainfall-rate statistics that implicitly assume stationary moisture supply. A 5–10 % increase in extreme rainfall intensity, already observed across the eastern U.S., can translate into a similar percentage increase in rain-fade events.

Field campaigns in Florida and the Gulf Coast have documented Ka-band rain fades exceeding 15 dB during convective storms (Siles *et al*., 2023). If such events become even marginally more frequent, system availability targets could be breached without corresponding design adaptation. For 5G and 6G backhaul operating near 70–90 GHz (W band), additional cloud-liquid-water absorption could reach 0.5–1 dB/km under dense stratiform cloud, further stressing adaptive-modulation algorithms.

### Regional Vulnerability Across the U.S.

- Southeast & Gulf Coast: Highest baseline PWV (~45–55 mm in summer) and strongest moistening trends. Satellite and terrestrial systems here face the greatest compound risk from both increased mean attenuation and intensified convective rain.
- Northeast: Moderate moistening combined with frequent frontal cloud decks yields frequent mid-level attenuation events affecting commercial SATCOM.
- Great Plains & Interior West: Smaller PWV increases but large temperature gradients; dry-air subsidence limits water-vapor-induced loss. Still, local convective outbreaks can cause episodic high fades.
- Alaska & Arctic: Lower absolute humidity but rapid relative increase (1–2 mm per decade) under warming; relevant for polar-orbiting satellite downlinks and defense radar.

This spatial heterogeneity implies that adaptation strategies should be region-specific rather than uniform nationwide.

### Implications for System Design and Standards

1. Fade Margin Planning: Design margins derived from static climatologies should incorporate a progressive correction term reflecting observed WV trends. If PWV increases ~1 mm/decade, a Ka-band link should add ≈ 0.3 dB to its 25-year fade margin.
2. Dynamic Link Budgeting: Inclusion of time-dependent atmospheric parameters in link-budget simulations enables forecasting of availability drift.
3. Propagation Model Revision: Current ITU-R P.676 and P.840 coefficients were empirically tuned to historical datasets. Periodic recalibration using modern reanalyses (ERA5, MERRA-2) would align models with present-day humidity distributions.
4. Infrastructure Siting: New ground terminals for SATCOM or 6G gateways should preferentially locate in drier inland climates or higher altitudes where WV variability is smaller. A 5–10 % reduction in mean PWV can yield several-fold improvement in fade statistics.
5. Monitoring and Feedback: Deploying co-located GNSS PWV sensors at communication hubs would provide real-time atmospheric input for adaptive control and calibration.

### National Security and Economic Dimensions

The U.S. relies on reliable high-bandwidth links for defense command, aerospace operations, and critical civilian services. As systems migrate upward in frequency to exploit spectral availability, their vulnerability to atmospheric moisture increases. Failure to incorporate climatic drift could lead to gradual performance degradation that remains invisible until operational thresholds are crossed.

Economically, the U.S. telecommunications sector invests billions annually in spectrum auctions and network rollouts; even small reliability losses translate into substantial financial exposure. For

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instance, a 0.5% reduction in availability for a large satellite internet constellation could represent millions of lost service hours. Proactive adaptation, therefore, offers both resilience and competitive advantages.

**Broader Scientific Relevance**
These findings also hold implications beyond telecommunications. Remote-sensing instruments, radiometers, interferometers, and synthetic-aperture radars, depend on accurate knowledge of atmospheric transmittance. Changing WV baseline affects retrieval algorithms and calibration constants, linking infrastructure resilience directly to climate-data integrity. The intersection of atmospheric science and engineering thus becomes mutually reinforcing: better climatology informs better system design, while better system monitoring improves climate diagnostics.

## DISCUSSION

### Synthesis of Evidence

The collective evidence from radiosonde, GNSS, satellite, and reanalysis observations provides a consistent narrative: the United States has experienced a statistically significant moistening of the lower and middle troposphere over the past three decades. Although regional magnitudes vary, the direction of change is overwhelmingly positive. These findings align with global assessments that identify water-vapor amplification as dominant feedback in the climate system (Allan *et al*., 2022; Charlesworth *et al*., 2023). The Southeast, Gulf Coast, and Eastern Seaboard emerge as hotspots of long-term increase, while interior and mountainous regions show weaker or more variable trends (Zhao *et al*., 2023).

When integrated with radiative-transfer theory and propagation modeling, this moistening translates into a slow but measurable drift in atmospheric transmittance. Using ITU-R P.676-13, an additional 1 mm of column PWV adds roughly 0.01–0.03 dB/100 km clear-air loss in the Ka/V bands. This may appear negligible in isolation, yet across a 40-year operational baseline it can erode link margins by several tenths of a decibel—comparable to component aging or antenna-gain degradation. The implication is that environmental change is now an engineering parameter, not a boundary condition.

### Consistency and Discrepancies among Datasets

Agreement across independent observing systems strengthens confidence in the moistening signal, but differences among products remain instructive. Radiosonde networks provide vertical detail yet suffer from instrument changes (e.g., RS80→RS92 transitions) that introduce dry biases of ~2–4 %. GNSS retrievals are highly consistent but spatially clustered around population centers, leaving western and polar regions under-sampled. Satellite sensors such as AIRS and MODIS observe broader gradients but lose accuracy in heavy cloud. Reanalyses like ERA5 and MERRA-2 integrate all these data streams; their residual spread (0.2–0.4 mm decade$^{-1}$) mainly reflects differing humidity-channel weighting and assimilation schemes (Allison *et al*., 2022; Wan *et al*., 2024).

These systematic differences underline a key message: data heterogeneity is not noise, it is part of the signal of methodological evolution. Recognizing how instrument physics shapes apparent climate trends is vital when translating them into design thresholds for propagation models (Suthari &Mohan, 2025)

### Mechanistic Interpretation

The observed moistening arises from both thermodynamic and dynamical drivers. Rising temperatures increase the saturation vapor pressure (Clausius–Clapeyron), while altered circulation patterns, particularly strengthening of the Gulf and Atlantic moisture plumes, enhance horizontal advection into the continental boundary layer. Land-surface feedback such as irrigation expansion and vegetation changes further modifies local humidity (Kunkel *et al*., 2020). Together, these processes amplify near-surface PWV and extend high-humidity layers upward, thickening the effective absorbing column for microwave propagation.

From a propagation standpoint, this implies not only greater mean attenuation but also increased variability. More humid air masses raise the refractivity gradient, altering beam bending and scintillation statistics, phenomena seldom considered in current network-planning software.

### Engineering and Standards Implications

Engineering practice assumes climatological stationarity: attenuation coefficients, fade-margin tables, and reliability curves are treated as fixed constants derived from historical data. The results of this review suggest that such constants may drift on decadal scales. Updating propagation models every 5–10 years using contemporary reanalysis of humidity fields would therefore improve prediction accuracy.

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The ITU-R P.676 (gaseous absorption) and P.840 (cloud attenuation) recommendations remain valid in form but require recalibration of key coefficients. IEEE and defense-sector standards could integrate a "climate adjustment factor," analogous to component derating in hardware reliability engineering. In practice, a 0.3 dB increase in design fade margin over 25 years would offset the mean moistening projected for humid U.S. regions (Siles *et al*., 2023).

Furthermore, system architectures that employ adaptive coding and modulation (ACM) can exploit real-time atmospheric sensing to mitigate these effects. Co-locating GNSS PWV sensors at ground terminals would allow automatic link-budget compensation based on current humidity, bridging meteorology and network control.

### Policy and Economic Dimensions

At the policy level, integrating atmospheric trends into infrastructure design supports the U.S. Climate-Resilient Infrastructure Initiative and aligns with the *National Climate Assessment's* call for adaptive engineering standards. The economic rationale is straightforward: telecommunications outages or degraded throughput translate directly into financial losses. For a nationwide Ka-band network with 99.99% availability, a 0.5% downtime increase equals millions of dollars in lost service hours annually. Pre-emptive adaptation is thus cheaper than reactive mitigation.

Defense systems face an additional imperative. Secure satellite communications and radar networks rely on precise link budgets; even marginal performance drifts can compromise mission readiness. Treating atmospheric monitoring as part of national-security maintenance—on par with spectrum management or cybersecurity—would ensure continuity under changing climate baselines .

## RESEARCH GAPS AND FUTURE DIRECTIONS

Several knowledge gaps emerged during this synthesis:

1. Co-located atmospheric and signal datasets are rare. Establishing long-term observatories where GNSS PWV, cloud radar, and mmWave link data are jointly recorded would permit direct validation of climate impacts on propagation.
2. Bias-corrected trend analysis requires uniform homogenization across instruments; joint reprocessing of radiosonde and GNSS archives would improve confidence intervals.
3. Regional process attribution, linking WV trends to sea-surface-temperature patterns, land-surface fluxes, and circulation anomalies, remains incomplete. High-resolution coupled modeling can disentangle these mechanisms.
4. Integration with machine learning. Emerging AI/ML techniques can mine large archives of link-quality telemetry to infer hidden climatic signals (Patel 2023; Nyamukondiwa *et al*., 2023). Such approaches complement traditional regression by capturing nonlinear dependencies between humidity, cloud phase, and attenuation.
5. International coordination. Since atmospheric moisture transport crosses national borders, harmonizing measurement protocols within the WMO and ITU frameworks would enhance global applicability of revised standards.

Collectively, these priorities outline a research roadmap toward climate-aware propagation science: a field that merges physical climatology, signal processing, and infrastructure planning.

### Broader Scientific Significance

The implications of rising water vapor extend well beyond communication systems. Remote-sensing calibration, radiative-transfer retrievals, and climate-model parameterizations all depend on accurate transmittance estimates. Improvements driven by telecom needs can therefore feed back into climate science. Conversely, continuous monitoring of communication networks offers a new observational asset for atmospheric research: every microwave link is, in effect, a humidity sensor. Harnessing this dual function transforms infrastructure into an instrument of environmental stewardship.

Finally, this interdisciplinary lens reinforces a philosophical point: the boundary between *the environment* and *infrastructure* is dissolving. Climate change is no longer external to technology; it is embedded within it. Understanding and designing for that reality will define the resilience of 21st-century systems.

## CONCLUSION

This review demonstrates that the United States has entered a period of sustained atmospheric moistening whose effects are not confined to climate statistics; they extend directly into the physical performance of national communication

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infrastructure. The synthesis of multi-platform observations shows coherent increases in precipitable water vapor across most U.S. regions, particularly the Southeast, Gulf Coast, and Eastern Seaboard. These trends are consistent with global analyses that attribute enhanced tropospheric humidity to thermodynamic warming and evolving circulation patterns.

When interpreted through the lens of radio-wave propagation, even seemingly small increments in water vapor acquire strategic meaning. A rise of one millimeter in column PWV adds roughly 0.01–0.03 dB of clear-air attenuation per 100 km in Ka/V-band systems; enough, over the lifespan of satellites and ground terminals, to narrow design margins and alter long-term availability statistics. In humid and coastal regions, the combined effect of increased background absorption, thicker clouds, and more intense rainfall will likely redefine reliability baselines for both civilian and defense communication networks.

These findings reinforce three central insights. First, the boundary between atmospheric science and communication engineering is porous. The atmosphere is not a static backdrop but a dynamic participant in system performance. Designing for the twenty-first century therefore requires climate literacy as much as electronic precision. Second, resilience must become a design philosophy, not an afterthought. Fade margins, propagation models, and network-reliability metrics should evolve in tandem with environmental baselines. Third, collaboration across disciplines and agencies is no longer optional; it is the prerequisite for safeguarding national competitiveness in a warming world.

**Practical Implications**

For engineers, the message is clear: climatic trends must be integrated into every stage of network planning; from spectrum allocation to ground-station siting. Updating ITU-R propagation coefficients with contemporary humidity fields will improve predictive accuracy and reduce unanticipated losses. The deployment of co-located GNSS PWV sensors at major communication hubs would enable real-time monitoring and adaptive modulation schemes that automatically compensate for atmospheric variability.

For policymakers, these results highlight the economic rationale for proactive adaptation. A modest 0.5 % reduction in availability for nationwide Ka-band services could translate into millions of dollars in lost productivity each year. Conversely, incorporating climate-aware design into federal procurement and standards development would yield high returns on investment. The findings support current federal initiatives that call for climate-resilient critical infrastructure and align with the National Climate Assessment’s emphasis on cross-sectoral integration.

For the research community, the review underscores the need for continuous, interdisciplinary dialogue. Atmospheric datasets should be analyzed not only for their meteorological content but also for their engineering implications. Communication networks, in turn, generate data streams, link-quality logs, fade statistics, signal delays, that can serve as valuable atmospheric sensors. By closing this feedback loop, researchers can create a self-reinforcing system where climate science informs engineering design and engineering infrastructure expands climate observation capacity.

**Future Directions**

The path forward involves both scientific refinement and institutional collaboration. Establishing long-term observatories that combine GNSS meteorology, cloud radar, and mm-wave link measurements would provide the empirical foundation for next-generation propagation models. Integrating machine-learning techniques with physical models can uncover nonlinear relationships between humidity, temperature, and signal degradation (Patel 2023; Nyamukondiwa *et al*., 2023). Internationally, coordinated calibration efforts through the WMO and ITU would ensure that evolving standards reflect the global nature of atmospheric change.

Education and workforce development are equally critical. Training a new cohort of engineers fluent in both radiative transfer and network optimization will sustain U.S. leadership in aerospace and telecommunications. Interdisciplinary graduate programs, jointly hosted by atmospheric science and electrical engineering departments, could become incubators for the climate-resilient technologies of the coming decades.

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