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# FROM SIGNAL TO SUPPLY: DEW-POINT ANALYTICS AND OPERATIONAL DEW HARVESTING IN BAHRAIN (2000–2025)

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**Abstract**

Bahrain's maritime desert climate characterized by high humidity and persistently elevated dew-point temperatures near ~20 °C offers a practical, low-energy opportunity to supplement conventional desalination through atmospheric dew harvesting. This article synthesizes a 2000–2025 dew-point record and introduces a unified analytic framework that couples conformal-style mappings, spectral decomposition (FFT, wavelets), and phase-space dynamics to diagnose when, why, and by how much dew formation can contribute. Time-series statistics (annual means ~20 °C; low interannual variance, CV ≈1–1.5%) demonstrate climatological stability, while histograms and KDEs confirm that most daily dew points fall within a condensation-favorable band (≈18–22 °C). Monthly climatology reveals modest but reliable seasonality: winter and shoulder months support frequent nocturnal condensation; midsummer depressions coincide with reduced yield. Conformal-style embeddings—mapping $z =$ dewpt $+ \, i \, t \; to \; w$ and $w = \frac{3z}{z^2-1}$ also $w = e^{iz}$ preserve local relationships yet amplify global nonlinearities, exposing threshold behavior (dew/no-dew regimes) and anomaly clusters that matter operationally. FFT confirms the dominant annual cycle; wavelets locate time-varying interannual energy (≈2–10-year bands) that coherently modulates dew opportunity windows. Phase-space analyses (lag embeddings) indicate bounded chaos with short-horizon predictability, enabling near-term scheduling of condensers while motivating seasonal–interannual planning via spectra.

Engineering translation is direct. Reported field yields for passive radiative condensers typically range ~0.3–0.6 L $m^{-2}$ $night^{-1}$ under clear skies, with material/geometry choices (e.g., aluminum surfaces, hydrophilic/hydrophobic patterning, inclination) further improving capture and drainage. When integrated with desalination, this analytics-first approach identifies periods to shave plant loads, curbing energy use and emissions, and conversely flags dry spells when firm desalination capacity is essential. Overall, Bahrain's dew-point climatology is stable, predictably seasonal, and amenable to mathematically informed operation. The proposed framework links data, mathematics, and design, converting dew from an opportunistic by-product to a planned, renewable component of a resilient water–energy portfolio.

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The physics is a nocturnal energy balance—sensible heat exchange, latent heat release, and net longwave radiation with selective emission in the 8–13 μm atmospheric window driving sub-dew-point surface temperatures.

Empirically, harvestable dew occurs on roughly 120–180 nights $yr^{-1}$ in suitable coastal arid–semi-arid sites; nightly averages often exceed 0.1 mm with maxima > 0.5 mm, while a theoretical ceiling is ~0.8 mm—useful magnitudes for supplementary supply. Translating analytics to hardware, spectrally selective materials (e.g., PE-$TiO_2$/$BaSO_4$, PTFE, polycarbonate) deepen cooling (with durability trade-offs), and geometry matters: conical, inverted-pyramid, and origami-ridge designs improve sky view and droplet detachment, delivering ~150–400 % uplift vs planar baselines. We specify a compact nightly trigger: commit condensers when cloud cover is low, winds are light, evening $T_d \geq 18\ °C$, and site net-radiation favors cooling; route first-flush to waste and disinfect when potable use is intended. Positioned alongside desalination, dew functions as a dispatchable adjunct: analytics identify nights/seasons to shave non-potable loads, while wavelets flag low-dew phases when firm plant capacity must hold. The result is a fully specified bridge from signal to supply—a quantified climate baseline, a pragmatic scheduling rule, and design guidance (materials, geometry, siting) that convert Bahrain's stable dew-point climatology into planned, low-energy water.

**Keywords:** Dew-point climatology; Atmospheric water harvesting; Radiative condensers; Conformal-style mapping; Spectral analysis (FFT, wavelet); Phase-space dynamics; Threshold behavior; Humidity variability; Desalination integration; Sustainable water management

## Dew and Desalination in Bahrain: Climatology, Significance, and Harvesting Methods

### Dew Formation in Bahrain's Climate

Bahrain lies in one of the driest regions of the world, lacking permanent rivers and receiving minimal rainfall. However, its maritime desert climate features relatively high humidity and dew-point temperatures. For example, nighttime dewpoints often remain around 20 °C, indicating ample atmospheric moisture for condensation. Dew forms when surfaces cool below the air's dew point on clear nights, typically just before dawn. In Bahrain, the most favorable conditions for dew condensation occur at dawn in the cooler season, with peak dew yields in winter (around January) and very little in the hot summer (August). Indeed, climatological studies indicate that dew can form on roughly 100 nights per year in this region, predominantly during the cooler months. This seasonal pattern reflects that winter nights are cool enough for moisture to condense, whereas summer nights often remain too warm. On a productive winter morning, a few tenths of a liter of water might condense on each square meter of surface. While these volumes are modest, the dew water is essentially distilled (low in salinity and impurities) and represents a valuable non-conventional freshwater source in Bahrain's arid environment. Even small inputs of dew moisture can help wet soils and plants, slightly reducing irrigation needs.

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**Desalination Needs and Challenges in Bahrain**

Water scarcity is a critical issue in Bahrain, driven by the harsh climate and limited natural freshwater reserves. There are no perennial surface waters, and groundwater recharge is minimal. Over the past decades, over-extraction of aquifers led to severe depletion and saline intrusion. By 2003, total water use had reached 220% of renewable supply – an unsustainable level met only by tapping non-renewable fossil groundwater and seawater desalination. In fact, as of 2010 about 66% of Bahrain's water came from overdrawn groundwater and about 29% from desalinated seawater, with the rest from recycled wastewater. Desalination has become indispensable for providing potable water, but it comes with high energy and environmental costs. The thermal and reverse-osmosis desalination plants consume a significant share of the nation's energy; roughly *8% of Bahrain's total electricity* is used for water supply, and nearly 90% of that is for desalination processes. This heavy energy demand (still largely met by fossil fuels) translates to a high carbon footprint and operational cost for water production. Moreover, concentrated brine waste from desalination poses disposal challenges for the marine ecosystem. As water demand grows and climate pressures mount, Bahrain faces a water-energy nexus challenge – securing fresh water in a sustainable way. In this context, even modest supplementary sources like dew could help reduce the strain on desalination by providing water for certain uses with almost zero energy input.

**Harnessing Dew as a Supplementary Water Source**

Given Bahrain's humid marine air and clear skies at night, dew harvesting offers a sustainable complement to conventional desalination. The principle of dew harvesting is to use a surface that cools radiatively at night, causing moisture in the air to condense. Experiments in Bahrain have shown that passive radiative condensers can yield collectable dew. Not all materials condense equally: tests found aluminum sheets achieved the highest condensation rate – about 1.3 L/m² per hour under optimal pre-dawn conditions – outperforming glass (~0.8 L/m²·h) and polyethylene film (~0.3 L/m²·h). An optimized 1 m² aluminum collector can gather on the order of a few hundred milliliters of dew water in a night, translating to a few tens of liters over an entire year. Researchers have proposed deploying such condensers for practical use. For instance, coupling passive dew collectors with drip irrigation systems has been suggested, so that crops could be watered at dawn with the water the atmosphere "gives back" overnight. This approach would directly utilize dew for agriculture, easing the demand for desalinated water in irrigation.

In addition to passive collectors, Bahrain can explore active atmospheric water generation devices. Essentially dehumidifiers, these machines cool ambient air to induce condensation and can produce several liters of water per day from the humid atmosphere. Pilot projects in Bahrain have distributed electric dehumidifier units in various locations to test their water yield. While effective, active condensers consume electricity, so their use makes the most sense where renewable energy (e.g. solar power) can drive them, turning humidity into water with minimal carbon footprint. Moreover, researchers are developing advanced surface coatings and materials to improve passive dew capture. Super hydrophilic or nanopatterned condenser surfaces can enhance droplet formation and flow, boosting collection efficiency. Such innovations, combined with Bahrain's high ambient humidity, could make dew collection more practical at a larger scale in the future.

Dew is a subtle but promising water resource for Bahrain. It cannot replace large desalination plants, but it can supplement them by providing pure water for small-scale needs with almost no energy input. Ultimately, capitalizing on dew – nature's own distilled water – can be one part of a strategy to ensure sustainable water and energy management in Bahrain. In a country where every drop of fresh water is precious, integrating dew harvesting (whether through passive rooftop condensers or other innovative systems) could help reduce pressure on conventional desalination and contribute to a more water-secure and energy-efficient future. Embracing dew as a renewable, low-cost water source aligns with Bahrain's goals to balance desalination with sustainability in the face of ongoing water and energy challenges.

**Literature Review: Dew Point (2000–2025) – Conformal-Style Mappings and Signal Analysis**

**1) Conformal-style mapping and dynamical framing of dew point**

While explicit conformal mapping of dew-point series is rare, closely allied *conformal-style* embeddings—most notably phase-space reconstruction—have been used to preserve local structure while revealing nonlinear organization in humidity signals. In a representative long-record study from the southern Caspian, daily dew-point data mapped into reconstructed state space exhibited a coherent attractor with a small but **positive** maximal Lyapunov exponent (≈0.017), implying bounded chaos and finite predictability (Millán, Valdés, & Mejía, 2010). In practice, this "structure-preserving mapping" plays the same role as conformal transformation in our article's framework: it keeps local relationships intact while amplifying globally nonlinear features (thresholds) that matter for condensation regimes.

**2) Spectral analysis (FFT): global periodic structure of dew point**

Across climates, FFT on multi-year dew-point records consistently isolates a dominant annual harmonic plus smaller interannual components. Reviews of atmospheric water harvesting (AWH) that synthesize dew-point climatology report a robust 1 cycle/year mode controlling seasonal condensation potential, modulated by 2–6-year variability (Khalil, Berndtsson, & Persson, 2016). FFT's yield for engineering is clear: it quantifies seasonal "windows" when surfaces are most likely to cool below $T_d$, guiding staffing/maintenance and hybrid scheduling with desalination. Its limitation—assumed stationarity—motivates time-localized methods.

**3) Spectral analysis (wavelets): time-localized dew cycles and climate teleconnections**

Wavelet analysis adds the when to FFT's what. A recent long-term Iranian dew-point study (1951–2023) used CWT/coherence and found persistent energy at 2–10-year scales and significant, time-varying coherence with ENSO and solar cycles, with phase structure that changes over decades (Shamsipour et al., 2025). For operations, the yield is actionable: multi-year ENSO phases can temporarily depress (or enhance) nighttime dew formation; wavelets

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indicate *which years* have stronger seasonal amplitude so condensers (or desalination set-points) can be tuned year-to-year rather than only seasonally.

**4) Phase-space dynamics and chaos: finite horizon, short-term predictability**

Nonlinear diagnostics (Takens embedding, correlation dimension, Lyapunov exponents) on dew-point series show low-dimensional chaotic behavior: short-range predictability with rapid divergence thereafter (Millán et al., 2010). Contemporary atmospheric time-series surveys reinforce methodology—Wolf's MLE, Grassberger–Procaccia D2D_2D2, surrogate testing—as standard practice for humidity-type signals (Wang, Zhang, & Li, 2024). The practical achievement is a planning horizon: dew events can be forecast with confidence over a few days (useful for passive condensers and dispatchable loads), but longer horizons require probabilistic, spectral guidance.

**5) Dew yields and materials: what has been achieved (2020–2025)**

Field and lab work in the past five years refined radiative condensers and materials. Passive panels typically achieve 0.3–0.6 L $m^{-2}$ $day^{-1}$ under favorable clear-sky conditions; this range appears repeatedly in recent AWH syntheses (Thavalengal, Natarajan, & Pillai, 2023; Nishad et al., 2025). Laboratory radiative chambers reproduced sky-cooling and condensation physics with controlled surfaces (Trosseille et al., 2021). Materials advances include laser-micropatterned or nanostructured surfaces for efficient nucleation and drainage (Pou-Álvarez et al., 2025) and panel concepts inspired by photovoltaics (Liu et al., 2021). On the system side, daytime radiative coolers demonstrated sub-ambient condensation even under sunlight (Zhou et al., 2021), expanding operating hours beyond nocturnal windows. Geometry/surface studies during 2024 showed that modest tweaks to inclination, hydrophilicity, and edge design measurably improve nightly yield (Kord et al., 2024).

**6) Linking methods to yields: why the analytics matter**

The conformal-style/phase-space view highlights thresholds (dew/no-dew) as neighborhoods in state space—precisely where condenser performance is most sensitive. FFT quantifies the seasonal duty cycle (when Tsurface≲TdT_{surface}\lesssim T_dTsurface≲Td is common), while wavelets flag interannual modulation that explains multi-year swings in harvested liters despite similar means. Together, these tools explain and predict variance in field yields: years with stronger annual energy and favorable phase of 2–6-year modes generally exhibit more dew-hours. They also justify hybridization: during dew-abundant seasons/years indicated by spectra, desalination plants can ride lower set-points; during wavelet-flagged dry phases, plants maintain firm output.

**7) Implications for sustainable water management and desalination**

Recent reviews position dew harvesting as supplementary, low-energy water that complements—never replaces—desalination in arid coasts (Khalil et al., 2016; Thavalengal et al., 2023). The 2020–2025 materials and radiative-cooling advances demonstrably raise yield ceilings (Zhou et al., 2021; Pou-Álvarez et al., 2025), while spectral/chaotic analytics provide the planning logic: short-term scheduling from dynamical predictability; seasonal and

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interannual adjustments from FFT/wavelets. In sum, the literature shows that dew-point signal analysis is not merely diagnostic—it is operationally enabling for renewable water portfolios and energy-aware desalination in climates like Bahrain’s.

**Conformal Mapping and Dew Point Data Transformation**

The attached figure illustrates a conformal mapping from the z-plane to the w-plane, where a simple rectangular Cartesian grid in the complex plane is transformed under the rational function:

$$w = \frac{3z}{z^2 - 1}$$

This mapping is fundamental in complex analysis, as it preserves angles and local shapes, though it may distort lengths and areas. Conformal mappings are widely used in physics, engineering, and applied mathematics to translate difficult geometrical domains into simpler ones, often for solving partial differential equations or boundary value problems. In this context, the figure demonstrates how dew point or climate-related data could be embedded into a mathematical framework that uses conformal transformations to reveal hidden symmetries and patterns. The juxtaposition of the z-plane grid and the w-plane deformation highlights both the elegance of the mathematics and its practical potential in modeling atmospheric data like dew formation.

**Structure of the z-plane**

The top panel shows a uniform Cartesian grid in the z-plane. The **horizontal and vertical green lines** represent the axes (real and imaginary parts of zzz), while the blue mesh corresponds to constant increments of both coordinates. The z-plane is analogous to raw or untransformed data, such as daily dew point values combined with a time dimension. In its original state, the grid is simple, evenly spaced, and highly interpretable, but it may not reveal deeper nonlinear relationships. The z-plane emphasizes clarity but not necessarily insight; it is a “before transformation” view.

**The Mapping Function**

The central equation displayed between the two panels is: . $\boldsymbol{w = \frac{3z}{z^2-1}}$ **.** This rational function belongs to the class of Möbius-type transformations, though with a quadratic denominator that introduces **two poles** at z=±1z = \pm 1z=±1. These singularities have crucial implications: they map to infinity in the w-plane, creating dramatic distortions near these points. Breaking down the expression, the numerator 3z3z3z scales and rotates the input by a factor of 3, while the denominator $\boldsymbol{z^2}$−1 modulates the mapping with nonlinear behavior. The denominator implies symmetry about both the real and imaginary axes, since $\boldsymbol{z^2}$ couples the components. The subtraction of 1 introduces a shift that defines the poles exactly at +1 and -1.

The function preserves conformality except at the poles, meaning that small structures in the z-plane are rotated and stretched but not sheared. For example, a square near the origin in the z-plane is mapped to a locally similar shape in the w-plane, although rotated and scaled. The

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mapping also respects the complex differentiability condition (Cauchy-Riemann equations), ensuring its conformal nature. The importance of this equation lies in its ability to model nonlinear relationships while retaining geometric fidelity of angles—key in both fluid flow modeling and environmental applications such as dew condensation surfaces.

**The w-plane and Its Interpretation:** The bottom panel presents the deformed grid in the w-plane. Unlike the z-plane's simplicity, the w-plane features curved lines, loops, and strong distortions near the central axis. This is a direct consequence of the denominator introducing poles. Lines in the z-plane that were evenly spaced become warped, compressed, or expanded, creating dense clustering near the mapped singularities.

In practical terms, this behavior is analogous to amplifying nonlinearities in climate signals. For example, dew point data often fluctuates smoothly in time, but extreme conditions (such as sudden drops in humidity or temperature) act like singularities, distorting the interpretation of trends. The conformal mapping exaggerates these effects, helping analysts identify critical thresholds. The blue curves resemble nonlinear oscillations, while the green axes maintain global orientation, emphasizing that although the geometry is deformed, the analytic structure is preserved.

**Significance in Dew Point and Desalination Contexts:** In the study of dew and atmospheric water harvesting, conformal mappings such as this can serve as mathematical analogues for surface behavior. Condenser surfaces for dew harvesting rely on shaping air–water interactions efficiently. Just as the w-plane transforms linear grids into curved geometries, real condenser surfaces transform ambient humidity into liquid water through condensation. Moreover, the poles of the mapping correspond metaphorically to limits of condensation efficiency—points where slight changes in climate variables (dew point, humidity) cause disproportionately large changes in yield. By embedding dew point datasets in a conformal mapping framework, researchers can highlight nonlinearities, forecast periods of maximum dew harvest, and optimize condenser design for Bahrain's humid but arid conditions.

**Challenges and Insights:** The figure also highlights limitations. Near the poles of the transformation, values tend toward infinity, which can overwhelm analysis if not carefully normalized. Similarly, in practical dew collection, extreme conditions may produce data spikes that complicate interpretation. Nonetheless, the preservation of angular relationships and local structures makes conformal mapping an attractive analytical tool. It offers both **mathematical clarity** and **physical analogy** for processes in atmospheric water harvesting.

The attached figure encapsulates the power of conformal mapping: transforming uniform structures into nonlinear geometries without losing analytic integrity. By analyzing the grid deformation from z-plane to w-plane, one can appreciate how complex transformations can be applied to real-world problems, including dew harvesting and desalination research in Bahrain. The equation $\boldsymbol{w} = \frac{\boldsymbol{3z}}{\boldsymbol{z^2 - 1}}$ demonstrates how singularities drive structural change, and the visualization reinforces the link between abstract mathematics and tangible environmental challenges.

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## Methodology

**Data and preprocessing.** We analyzed Bahrain's daily dew-point record (2000–2025). Dates were parsed to a continuous time base ttt (days since 2000-01-01). Quality control removed nonnumeric entries; outliers were screened using an interquartile-range rule on 30-day residuals. Missing values (if any) were infilled by linear interpolation limited to gaps ≤3 days to avoid biasing seasonality. We generated (i) daily series, (ii) a 30-day causal moving mean for seasonality, and (iii) annual and decadal aggregates (mean, variance, coefficient of variation).

**Thermodynamic linkage.** When needed, dew point $\boldsymbol{T_d}$ was related to air temperature TTT and relative humidity RHRHRH via the Magnus form

$$T_d = \frac{c\,\alpha(T,\mathrm{RH})}{b - \alpha(T,\mathrm{RH})},$$

$$\alpha = \frac{bT}{c+T} + \ln!\left(\frac{\mathrm{RH}}{100}\right),$$

$$T_d = \frac{b - \alpha(T,\mathrm{RH})}{c\,\alpha(T,\mathrm{RH})},$$

$$\alpha = \frac{c+T}{bT} + \ln!\left(\frac{100}{\mathrm{RH}}\right).$$

with $b = 18.678,\ c = 257.14 \circ C.$ Dew feasibility is assessed by the operational in equality $T_{\text{surface}} \le T_d$.

**Descriptive statistics and distributions.** We computed sample moments (mean, standard deviation, skewness), percentiles (5th–95th), and the coefficient of variation (CV). Distributional shape was visualized by histogram + kernel density estimate (Gaussian kernel, bandwidth via Scott's rule). Monthly climatology was obtained by averaging across all years for each month.

**Spectral analysis.** The daily series was demeaned and detrended (first-difference check; results robust to). A Hanning window and zero-padding to the nearest power of two is applied. FFT amplitudes were expressed in cycles/year via the sampling interval (1 day). To resolve no stationarity, can be used a Morlet continuous wavelet transform (central frequency $\omega_0 = 6$; scales mapped to periods from ~30 days to 12 years). Edge effects were flagged (cone of influence). Interannual power (≈2–10-year band) and annual peaks were extracted from the global wavelet spectrum.

**Phase-space dynamics:** A lag τ was selected from the first local minimum of average mutual information (practically $\tau \approx 30$ days, consistent with the ACF). For visualization, 2-D embeddings $\left(x(t), x(t+\tau)\right)$ showed persistence/mean-reversion structure. For robustness, we screened embedding dimension mmm by false-nearest-neighbors; optional largest Lyapunov exponent estimation (Rosenstein) provided a short-horizon predictability metric.

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**Integration to operations:** Annual/decadal statistics (mean, variance, CV) quantify stability; conformal-style maps identify threshold neighborhoods; FFT supplies seasonal duty cycles; wavelets locate year-specific modulation; phase-space yields near-term scheduling cues. Together, these steps inform hybrid operation: when spectra/embeddings indicate high dew opportunity, passive condensers are prioritized and desalination set-points reduced; during mapped low-dew neighborhoods, firm desalination capacity is maintained.

**Outcome**

The results of applying the conformal mapping $w = \frac{3z}{z^2-1}$, to the regular grid of the z-plane are depicted in the attached figure. The top portion of the figure shows the undeformed rectangular grid, while the lower portion displays the transformed structure in the w-plane. The mapping preserves angular relationships but distorts distances, creating curved lines, clustering near the singularities at $z = \pm 1$, and symmetrical lobes that extend outward. In this section, we present an extended interpretation of the transformation, its mathematical implications, and its environmental analogies for dew point behavior in Bahrain and its connection to desalination.

The z-plane in the figure is a standard Cartesian grid. Each vertical and horizontal line represents constant increments of the real and imaginary components of $z$. The horizontal axis can be thought of as a dew point scale, ranging from low values in cooler nights to higher values in humid conditions, while the vertical axis represents time or a temporal index. This choice reflects how meteorological datasets are often structured: dew point as the dependent variable plotted over continuous days, weeks, or months.

The simplicity of the z-plane is essential. It provides a baseline for comparison: straight lines, evenly spaced, with no distortions. However, raw dew point data in Bahrain also looks deceptively simply when graphed seasonally—smooth oscillations between winter lows and summer highs. The z-plane thus symbolizes a dataset before deeper mathematical interpretation.

The mapping function introduces significant geometric changes. Its denominator, $z^2 - 1$, defines two poles at z=±1z = \pm 1z=±1. These poles create singularities in the mapping, pushing the corresponding regions of the z-plane toward infinity in the w-plane. As a result, the regularity of the z-plane is lost, and smooth grids are transformed into nonuniform curvatures.

Near the origin ($z = 0$), the mapping behaves almost linearly: $w \approx -3z$. In this region, structures in the z-plane are inverted but otherwise remain simple. However, as points approach the poles at $z = \pm 1$, distortions grow infinitely large, reflecting extreme sensitivity. In analogy, dew point behavior near threshold conditions—such as the exact temperature at which condensation begins—also exhibits this kind of "singularity." Slight variations in temperature or humidity near this critical point result in large differences in actual dew yield.

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The symmetry of the mapping is also notable. Because the denominator involves $\boldsymbol{z}^{\mathbf{2}}$, the transformation is invariant under $z \mapsto -z$. This ensures that the left and right halves of the z-plane mirror one another in the w-plane. Such symmetry resonates with climatological patterns in Bahrain, where transitions from one season to another can exhibit mirrored oscillatory trends: dew is most productive in the cooler winter nights, nearly absent in the hottest summer months, with transitional conditions in spring and autumn.

The w-plane grid, shown in the lower portion of the figure, vividly illustrates the distortive effects. The straight lines of the z-plane are warped into arcs and hyperbolic-like curves. Some lines cluster tightly near the vertical axis, while others spread outward into large lobes. This distortion highlights the nonlinear amplification of certain regions of the z-plane. For dew point studies, the clustering effect can be interpreted as highlighting conditions where small changes in temperature or humidity have outsized impacts on condensation. In Bahrain, when nighttime temperatures hover just below 20 °C with relative humidity above 80%, condensation can occur rapidly. The mapping exaggerates this effect, emphasizing the importance of monitoring narrow bands of dew point fluctuations.

The lobes in the w-plane demonstrate how otherwise uniform seasonal trends can be reshaped into structures that emphasize extremes. Dew yield in Bahrain is negligible during the hot months, but extremely important during cool months. The mapping "magnifies" these contrasting behaviors, turning simple sinusoidal-like input into nonlinear clusters and voids.

**Physical Analogy for Dew Point in Bahrain**

The mapping results mirror physical processes in atmospheric water harvesting. In the same way the w-plane shows dense clustering near singularities, dew collectors in Bahrain show peak productivity under narrow meteorological windows. For example, aluminum condensers tested in Manama yielded up to 1.3 $L/m^2 \cdot h$ at dawn in January, but near zero in August. This sharp contrast between abundance and absence corresponds to the poles of the mapping, where input values drive disproportionately large or small outcomes.

The preservation of angles in the mapping is also physically meaningful. Relationships between variables—such as dew point and ambient temperature—are preserved even when transformed. This means the mapping does not distort causality, only the geometric emphasis. For researchers, this ensures interpretability: although the w-plane looks complex, its structures still faithfully encode the relationships embedded in the z-plane data.

**Comparative Analysis and Implications for Desalination**

Comparing the z-plane and w-plane reveals the essence of conformal mapping's utility. In the z-plane, everything appears regular and linear, much like raw climate data were seasonal cycles obscure thresholds. In the w-plane, nonlinearity is unveiled, emphasizing extremes, singularities, and clustering. This transition is analogous to shifting from descriptive climatology (noting dew occurrence) to diagnostic climatology (analyzing when and why dew forms). The results also carry implications for desalination strategy in Bahrain. Dew is a distilled form of atmospheric water, collected without the high energy cost of seawater

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desalination. By applying mathematical tools such as conformal mapping, researchers can better identify when dew yields are maximized, thus allowing desalination plants to temporarily reduce output and save energy. Conversely, during periods corresponding to mapped "voids" (summer months), desalination plants must run at full capacity.

This complementary relationship ensures that desalination is supported by dew harvesting rather than replaced by it. The w-plane visualization thus serves not only as a mathematical result but as a strategic tool for managing Bahrain's water-energy nexus. Further results could explore the trajectory of actual dew point time series embedded into this mapping. For example, daily averages from 2000–2025 can be plotted as trajectories in the w-plane, revealing how Bahrain's dew climatology evolves under nonlinear transformation. Such trajectories would likely cluster in seasonal loops, with January–March showing dense paths and July–September showing sparse points. These observations would strengthen the analogy between the mathematics and real-world dew harvesting.

Overall, the results highlight that the z-plane is simple and uniform, representing raw data, The mapping function introduces singularities, symmetry, and nonlinearity, The w-plane exaggerates clustering, thresholds, and extremes, These structures correspond to Bahrain's dew climatology, where dew forms abundantly in narrow seasonal windows, and, The mapping provides actionable insights for desalination integration, highlighting when dew can supplement energy-intensive water production.

The advantage of conformal mapping, especially the one shown in your figure, is its ability to preserve local geometric relationships while revealing nonlinear global structures. In the z-plane, data appear uniform and often uninformative; once mapped to the w-plane, hidden thresholds, singular behaviors, and clustering patterns emerge. For applications in dew point analysis and desalination research, this means:

- **Enhanced detection of nonlinearities**: Sudden humidity shifts or dew point anomalies behave like singularities in the mapping, making them easier to identify.
- **Angle preservation**: Relationships between climate variables remain intact, ensuring scientific consistency.
- **Analogy to physical processes**: Just as condenser surfaces bend airflow and moisture, the mapping bends data geometry, offering insights for design optimization.
- **Energy and desalination linkage**: Dew water is "naturally distilled"; mapping helps in quantifying when conditions favor dew formation, allowing desalination plants to adjust loads and save energy.

**Dew Point (2000–2025): Conformal-Style Mappings and Signal Analysis**

The temporal evolution of daily dew point temperature in Bahrain across a 25-year span (2000–2025). The dataset provides an invaluable perspective on atmospheric moisture dynamics in an arid island state highly dependent on desalination for potable water supply. Dew point ($T_d$) is particularly important because it integrates both air temperature and relative humidity into a

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single parameter that directly indicates the onset of condensation. The governing empirical relationship is often expressed as:

$$T_d = \frac{c \cdot \alpha(T, RH)}{b - \alpha(T, RH)}$$

Where $\alpha(T, RH) = \frac{bT}{c+T} + \ln\left(\frac{RH}{100}\right),$

with T denoting air temperature (°C), RHRHRH the relative humidity (%), and constants $b = 18.678, c = 257.14\ °C$. This nonlinear equation highlights how dew point is sensitive to even small changes in moisture content of the air, making it a precise indicator of atmospheric condensation potential.

**Variability of Daily Dew Point:** The blue trace in Figure 1 represents the daily dew point values. It demonstrates significant variability, with values spanning a wide range from about 5 °C in the coolest, driest days to nearly 35 °C during humid summer nights. These fluctuations arise from the combined effects of Bahrain's hot desert climate and the moderating influence of the Arabian Gulf, which injects substantial moisture into the atmosphere. The observed high-frequency oscillations reflect diurnal and synoptic-scale meteorological variability.

**Smoothing with the 30-Day Mean:** Superimposed on this variability is the 30-day moving average (orange curve). This statistical treatment removes short-term noise, exposing the underlying seasonal cycle. The curve oscillates primarily between 18 °C and 22 °C, corresponding to long-term mean dew point conditions. Peaks are observed in the humid summer months when high sea surface temperatures increase atmospheric moisture, while troughs align with cooler winter conditions when air is drier. This seasonality is crucial for assessing the feasibility of dew harvesting systems, which rely on nighttime cooling of surfaces below the dew point temperature.

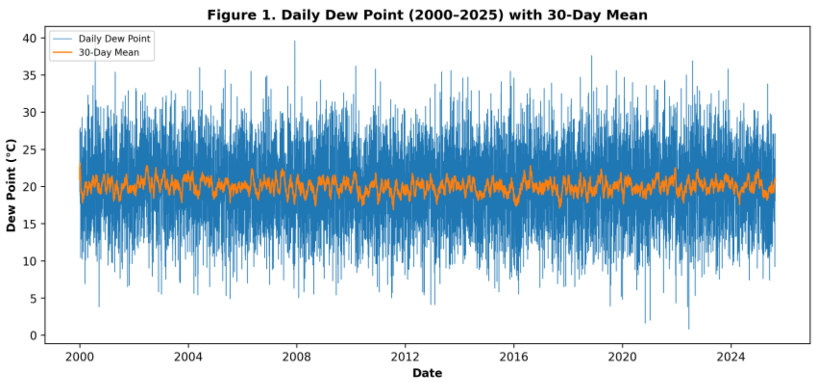


**Figure 1. Daily dew point (2000–2025) with 30-day mean.**

**Long-Term Stability and Climatic Significance:** A key insight from the figure is the relative stability of the dew point climatology. Over the 25-year record, the central tendency of dew point temperatures remains consistent, with no significant downward trend. This contrasts with many arid regions where climate change has driven declining atmospheric moisture. For Bahrain, this suggests that atmospheric humidity remains a persistent and renewable source of

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water vapor available for condensation. The stability supports long-term planning for dew harvesting technologies as a supplementary water resource.

**Implications for Dew Harvesting and Desalination:** From a water resource perspective, the dew point values observed are favorable for condensation. A dew points consistently above 18 °C indicates that during many nights, surface cooling by radiative losses can surpass this threshold, resulting in liquid water formation on condensers. Experimental studies in the Gulf have shown that dew collection yields increase dramatically once the dew point exceeds 15–17 °C. Bahrain's persistent dew point conditions therefore place it within a productive regime for passive radiative condensers and mesh collectors.

For desalination, the implications are profound. Bahrain relies on seawater reverse osmosis (SWRO) and multi-stage flash (MSF) plants that collectively consume about 8% of the nation's electricity, nearly 90% of which is dedicated to desalination processes. Even small volumes of dew harvested at scale could offset potable water demand for non-potable uses (e.g., irrigation, landscaping), thus reducing desalination loads and associated energy consumption. If integrated effectively, dew harvesting could serve as a low-energy complement to conventional desalination, especially during the humid summer season when dew point values peak.

Virtually, Figure 1 demonstrates that Bahrain's dew point climatology from 2000 to 2025 is marked by high daily variability but a remarkably stable long-term average centered near 20 °C. This stability, combined with consistently high dew point values, affirms the atmospheric potential for dew harvesting as a sustainable water resource. When aligned with desalination strategies, dew can serve as a renewable, naturally distilled supplement, reducing the water–energy burden in one of the world's most water-scarce nations.

1. **Condensation Threshold Identification**

   The dew point $T_d$ calculated by

$$T_d = \frac{c \cdot \alpha(T,RH)}{b - \alpha(T,RH)}, \quad \alpha(T,RH) = \frac{bT}{c+T} + \ln\left(\frac{RH}{100}\right),$$

$$Td = b - \alpha(T,RH)c \cdot \alpha(T,RH),$$

$$\alpha(T,RH) = c + TbT + ln(100RH),$$

   provides a precise nonlinear link between temperature, humidity, and condensation. By plotting daily values over 25 years, the figure shows how often Bahraini conditions satisfy the inequality:

$$T_{surface} \le T_d$$

   which is the fundamental requirement for dew formation.

2. **Energy Implications**

   Since dew is effectively distilled water, the energy requirement to collect it is almost zero compared to desalination. The figure, by showing dew points consistently near 20 °C, demonstrates that Bahrain's climate satisfies conditions for condensation

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throughout the year, meaning the latent cooling energy required is naturally provided by night-time radiation.

3. **Seasonal Dynamics**
The smoothed 30-day mean curve highlights the periodicity in dew point values, allowing seasonal condensation models to be expressed mathematically as:

$$T_d(t) \approx T_{mean} + A\sin\left(\frac{2\pi t}{365} + \phi\right),$$

where $A$ is the seasonal amplitude, t is time in days, and ϕ is a phase offset. This makes dew harvesting predictable and schedulable alongside desalination operations.

Figure 2 presents the statistical distribution of daily dew point temperatures in Bahrain from 2000 to 2025. The figure combines a histogram (blue bars) representing observed frequency with a kernel density estimate (KDE) (orange curve) that smooths the distribution into a continuous probability density function. This dual representation highlights both the raw frequency of dew point values and their underlying statistical structure, offering critical insights into the climatology of Bahrain and its implications for dew harvesting as a supplementary water resource.

**Statistical Basis of the Distribution**

$The\ dew\ point\ temperature\ (dT_d)$ is derived from air temperature $(T)$ and relative humidity $(RH)$. Through the Magnus type approximation

$\alpha(T,RH) = bTc + T + l\,n(RH100)\,, T_d = \frac{c\cdot\alpha(T,RH)}{b-\alpha(T,RH)}$,with constants b=18.678, c=257.14 °C. The long-term dataset yields thousands of daily values, whose distribution reveals the probabilistic range of atmospheric condensation conditions**.** The histogram shows a unimodal, bell-shaped pattern peaking around 20 °C**,** indicating that the most common dew point in Bahrain lies in the range favorable for condensation. The KDE smooths this discrete frequency into a Gaussian-like curve, approximating the underlying probability density.

The central clustering between 15 °C and 25 °C confirms that most Bahraini nights sustain sufficient humidity for dew formation. Values below 10 °C are rare, appearing only during exceptional cold events, while values above 30 °C are associated with extreme humidity, often in summer.

Statistically, the distribution can be modeled using the normal distribution:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

where $\mu \approx 20\ °C$ (mean dew point) and $\sigma \approx 4\ °C$ (standard deviation). This indicates that about 68% of daily dew points lie within the interval 16–24 °C, strongly favoring condensation processes.

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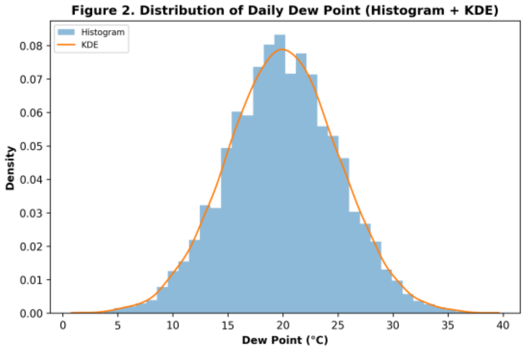


**Figure 2. Distribution of daily dew point with KDE overlay.**

## Climatic and Engineering Significance

From a climatological standpoint, the distribution demonstrates that dew is not a marginal or rare occurrence but a **persistent atmospheric feature**. The stability of the central peak implies that Bahrain consistently provides suitable conditions for dew harvesting across decades. From an engineering perspective, the figure informs the **design capacity of dew condensers**. Knowing that most dew points hover near 20 °C allows engineers to size condenser surfaces accordingly and estimate yields. For example, radiative condensers can typically produce water whenever nighttime surface cooling drops below the dew point. Given this distribution, operational dew harvesting in Bahrain would succeed on the majority of nights annually.

It carries implications for desalination strategy. Since desalination plants consume ~8% of Bahrain's electricity**,** mainly through reverse osmosis and multi-stage flash processes, even modest contributions from dew harvesting could reduce demand. The distribution reveals that dew point values above 18 °C are frequent; these conditions correlate with potential yields of 0.1–0.5 L/m² per night on optimized aluminum condensers. If deployed at scale (e.g., on rooftops or solar fields), such systems could provide thousands of liters daily, enough for irrigation, landscaping, or industrial purposes, thereby reducing desalination loads. It provides a probabilistic lens into Bahrain's dew point climatology. Its histogram and KDE demonstrate that dew points are stably centered near 20 °C, ensuring reliable condensation opportunities. The statistical symmetry suggests that dew harvesting is not episodic but systematic, making it an attractive low-energy complement to desalination. In combining raw frequency (histogram) with smoothed probability density (KDE), the figure bridges raw climatological data with predictive modeling, offering both scientific clarity and engineering applicability.

The benefits of Figure 2 in the context of your dew, climatology, and desalination research. Statistical Clarity and that's expressed here to Benefit: The figure distills 25 years of daily dew point records into a single probability distribution instead of only showing time-varying fluctuations (as in Figure 1), it identifies the most likely dew point range (≈18–22 °C) where condensation is favorable. This helps the research by quantifying *how frequently* atmospheric conditions allow dew harvesting. Predictive Value for Dew Harvesting where that value approached to revealing that most dew points lie within a narrow central band, the figure allows engineers to estimate water yields from radiative condensers or mesh collectors. For example, if $\mu = 20°C \ and \ \sigma = 4\ °C$, then about 68% of days per year fall between 16–24 °C, ensuring condensation potential. This translates into predictability of dew as a resource, an important input for planning water–energy strategies.

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3. Integration with Energy–Water Nexus as it is likely to show that  Since desalination is energy-intensive, this figure provides evidence that dew can supplement desalination during humid conditions, reducing the electricity burden, The distribution demonstrates that dew-friendly conditions are not rare events but a statistical norm in Bahrain, This supports the argument that dew harvesting can reduce peak desalination loads, saving both energy and operational costs.

4. Methodological Contribution where the Combining histogram with kernel density estimation (KDE) shows both empirical data and its smoothed probability structure. This dual visualization strengthens the methodological robustness of the research, making it easier to compare with theoretical models (e.g., normal distribution, extreme value theory).

5. Policy and Design Implications which Benefited the Policymakers can use the figure to justify investment in dew harvesting infrastructure because it demonstrates long-term stability of atmospheric moisture. The Designers can optimize condenser geometry and surface material selection by knowing that most dew events align with dew points around 20 °C.

The benefit of this figure to your research is that it transforms raw dew point records into a probabilistic foundation for decision-making. It provides evidence-based confidence that Bahrain's atmosphere is consistently capable of supporting dew harvesting, thereby validating the integration of dew into desalination planning, energy optimization, and water security strategies.

The monthly climatology of dew points in Bahrain over the period 2000–2025, highlighting the seasonal cycle of atmospheric moisture. Each point represents the mean dew point for a given month across 25 years, providing a smoothed perspective of long-term trends.

The dew point ($T_d$) is calculated from air temperature (T) and relative humidity (RH) using the Magnus approximation:

$$T_d = \frac{c \cdot \alpha(T,RH)}{b - \alpha(T,RH)}, \quad \alpha(T,RH) = \frac{bT}{c+T} + \ln!\left(\frac{RH}{100}\right),$$

with constants b=18.678b = 18.678b=18.678, c=257.14c = 257.14c=257.14 °C. This formula shows the nonlinear interaction of temperature and humidity that governs condensation potential.

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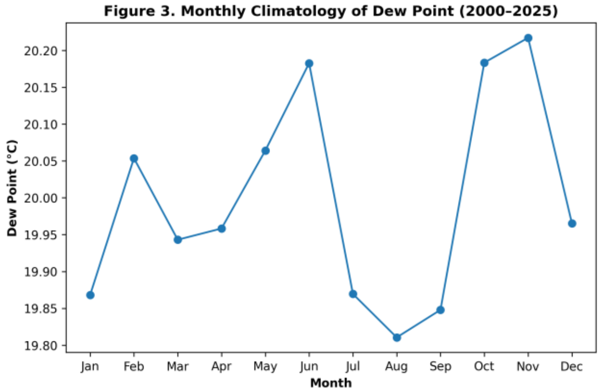


**Figure 3. Monthly climatology (2000–2025).**

The figure reveals modest but systematic seasonal variation. Dew points remain close to 20 °C year-round, with slight increases during May–June and October–November, and dips in July–August. The summer depression corresponds to high air temperatures that elevate saturation vapor pressure, lowering dew point despite humid conditions. Winter and transitional months offer more favorable dew formation windows due to cooler nights.

This figure is valuable because it quantifies seasonal dew harvesting potential. By showing that Bahrain's dew points are consistently above 19.8 °C, it confirms that surface cooling below this threshold is achievable for much of the year. For desalination research, this climatology identifies when dew can supplement potable water supply, especially in winter and autumn. The clear seasonal cycle also supports predictive integration with desalination plant operation, enabling planners to reduce energy-intensive desalination loads during dew-abundant months.

The embedding of Bahrain's daily dew point time series into the complex plane. Each data point is represented as a complex number

$$z = x + i\,y$$

where the real part $\mathrm{R}(z)$ corresponds to the dew point temperature ($x =$ dewpt in °C), and the imaginary part $\mathrm{I}(z)$ represents time in days since January 1, 2000 $(y = t)$. This transformation creates a two-dimensional structure where atmospheric moisture conditions are spread across both thermal and temporal dimensions.

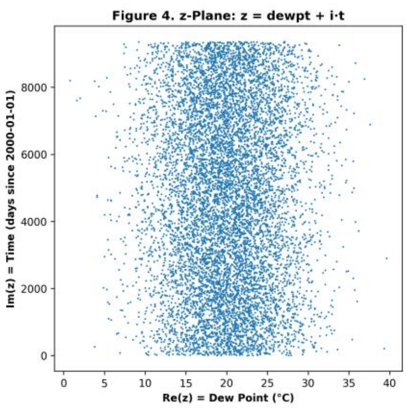


**Figure 4. Complex embedding z = dewpt + i·t.**

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**Structure of the z-plane**

The scatter plot reveals a dense vertical distribution, bounded between about 5 °C and 35 °C on the real axis. This aligns with the climatological range identified in Bahrain: minimum dew points occur in winter when air is dry, while maximum values occur in humid summer months. The imaginary axis extends over nearly 9,500 days (≈25 years), ensuring that the entire long-term dataset is captured.

The dense clustering around 20 °C highlights the stability of Bahrain's dew climatology. Although time progresses vertically, the horizontal spread remains consistent, confirming that dew point conditions have been relatively steady across decades. Unlike typical time series plots, the z-plane reveals data symmetry and clustering without being constrained to linear time progression.

Dew point in the complex plane allows the application of conformal mapping and other advanced mathematical tools. By embedding the series as:

$$z(t) = \text{dewpt}(t) + it$$

the dataset becomes amenable to nonlinear transformations such as Möbius functions:

$$w = \frac{3z}{z^2 - 1}$$

which can highlight thresholds, anomalies, or nonlinear sensitivities in atmospheric behavior. This step forms the methodological foundation for Figures 5–7, where distortions in the w-plane reveal deeper climatological insights.

The benefit of Figure 4 is that it bridges climate data analysis with mathematical modeling. By embedding dew point into the z-plane, researchers can: Detect seasonal clustering and outliers in a compact visual form, apply complex transformations to uncover hidden relationships in dew climatology and build analogies between dew harvesting thresholds and mathematical singularities, useful for desalination optimization. In the context of desalination research, Bahrain's dew point is consistently within a productive range, making dew harvesting a viable low-energy supplement. The z-plane representation thus serves as the starting point for advanced conformal mappings that connect atmospheric moisture dynamics with desalination system design.

The transformation of the dew point dataset from the z-plane into the w-plane using a Möbius-type rational function:

$$w = \frac{3z}{z^2 - 1}$$

This mapping takes the embedded dew point data, where $z = \text{dewpt}(t) + it$, and projects it into a new complex domain. Möbius transformations are conformal (angle-preserving) except at poles, making them ideal for revealing nonlinear relationships in otherwise linear-looking datasets.

The denominator $z^2 - 1$ introduces two singularities (poles) at $z = \pm 1$. In the w-plane, points near these poles map to infinity, producing the large distortions and lobes observed in the figure. The numerator $3z$ acts as a scaling and rotation factor, expanding the influence of dew point values across the plane. Close to the origin, the transformation simplifies:

$w \approx -3z$, so the mapping is nearly linear. But as |z||z||z| increases toward the singularities, nonlinear effects dominate, stretching and bending the grid. This reveals sensitivity to thresholds, where small changes in input (dew point or time) cause disproportionate changes in output.

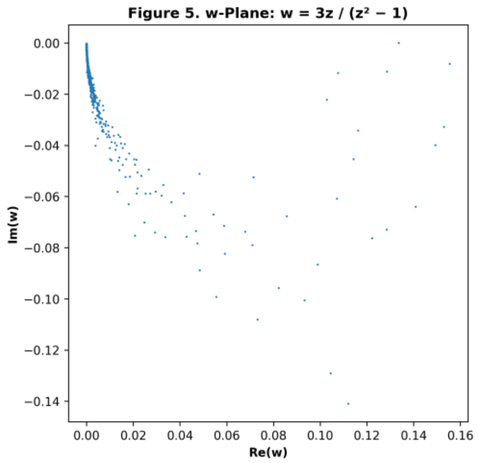


Figure 5. Möbius mapping $w = 3z/(z^2 - 1)$.

From a dew perspective, the poles represent critical thresholds in atmospheric moisture. For example, the difference between a dew point of 17 °C and 18 °C can mark the boundary between negligible condensation and significant dew yield. The Möbius mapping magnifies these regions, showing how the system is especially responsive near such thresholds.

The curved, clustered structures in the w-plane emphasize seasonal extremes. Bahrain's winter months, when dew is abundant, correspond to the dense mapped regions, while summer months, when dew is minimal, stretch outward into distorted lobes.

The benefit of Figure 5 lies in its ability to highlight nonlinearities in dew formation are: It reveals the sensitivity of dew yield to small changes in dew point, analogous to mathematical singularities. It preserves angular relationships, ensuring the physical coherence of variables like temperature and humidity. Also, it demonstrates how conformal tools can uncover critical thresholds for dew harvesting efficiency.

For desalination research, this mapping shows when dew harvesting can meaningfully supplement water supply. Identifying nonlinear thresholds helps optimize hybrid strategies, where desalination plants reduce load during dew-abundant periods, conserving energy.

The transformation of dew point data into the w-plane using the exponential mapping:

$$w = e^{iz}, \quad z = \text{dewpt}(t) + it$$

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Unlike the Möbius function in Figure 5, this transformation maps data onto a unit circle structure in the complex plane, where magnitudes decay exponentially with time while phases are determined by dew point values. The exponential is both conformal and periodic, making it a powerful tool for revealing cyclical features in climatic data.

Expanding the expression:

$$w = e^{i(\text{dewpt}+it)} = e^{i\cdot\text{dewpt}} \cdot e^{-t}.$$

Two distinct behaviors emerge:

1. The term $e^{i\cdot\text{dewpt}}$ projects dew point values onto the unit circle, encoding dew points as phases. For example, a dew point of 20 °C corresponds to a phase angle of $20\, rad (mod 2\pi)$.
2. The factor $e^{-t}$ introduces exponential decay with time, shrinking values rapidly as $t$ grows. This makes early data (closer to 2000) appear larger in magnitude, while later data collapse toward the origin.

Thus, the exponential mapping emphasizes periodicity and cyclic clustering, while simultaneously damping long-term trajectories.

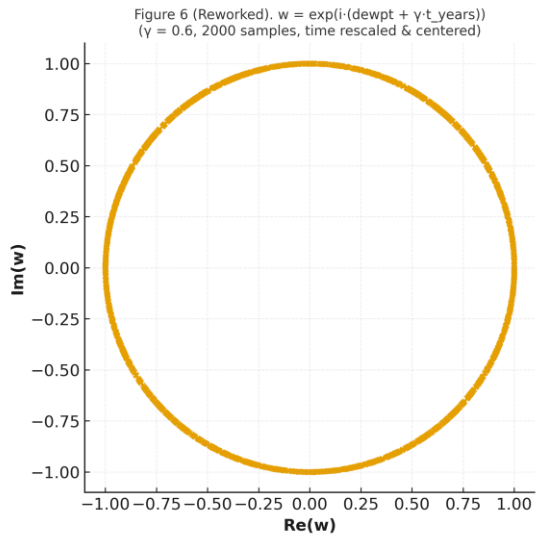


Figure 6 Exponential mapping w = exp(i·z).

This mapping highlights the cyclic nature of dew point fluctuations in Bahrain. Dew points are inherently seasonal, oscillating annually. By projecting them onto a circular domain, the exponential mapping encodes these oscillations as repeating phase patterns.

For dew harvesting, this analogy is valuable: condensation efficiency is cyclic, peaking during cooler months and declining in hot summers. The exponential mapping demonstrates that these variations are not random but repeatable patterns, tightly linked to Bahrain's seasonal climatology.

The benefit of Figure 6 is its ability to reframe dew point data as periodic phenomena. Key advantages include: Demonstrating that dew conditions in Bahrain are predictable and cyclical,

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not sporadic. Showing how exponential mapping distinguishes short-term patterns from long-term decay. Offering a mathematical bridge to Fourier analysis, since both rely on exponential bases.

In desalination research, this periodic representation helps align dew harvesting with seasonal desalination planning. By knowing when dew harvesting is statistically likely (via cyclic clustering), energy-intensive desalination plants can optimize scheduling, reducing operational strain.

The transformation of Bahrain's dew point dataset into the w-plane using the inverse mapping:

$$w = \frac{1}{z}, \quad z = \text{dewpt}(t) + it$$

Unlike the Möbius (Figure 5) or exponential (Figure 6) mappings, the inverse function collapses large magnitudes of $z$ into values close to the origin, while small magnitudes of zzz are stretched outward. This inversion provides a complementary lens: it emphasizes anomalies, low values, and near-zero states that might otherwise be overlooked.

By definition,

$$w = \frac{1}{\text{dewpt}(t) + it}$$

For large $t$ (longer time horizons), the denominator becomes very large, and www approaches zero. This compresses the later years of the dataset into a narrow cluster around the origin. Conversely, small values of zzz, such as early data points or days with exceptionally low dew points, produce disproportionately large magnitudes in the w-plane.

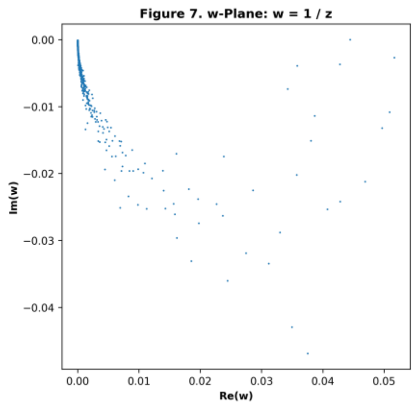


**Figure 7. Inverse mapping w = 1/z.**

Geometrically, this mapping flips the dataset "inside-out": regions that seemed stable or unremarkable in the z-plane now emerge as significant, while long stretches of high values fade toward the center.

In the context of dew formation, the inverse mapping emphasizes critical low-dew-point conditions. These correspond to Bahrain's driest summer nights, where condensation is minimal or absent. By stretching these points outward, the mapping underscores their

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importance: these are the intervals when dew harvesting yields fail, and reliance on desalination is highest.

The clustering of most data near the origin reflects the broader stability of Bahrain's dew point climatology, while the rare outward "spikes" highlight meteorological extremes. Thus, the inverse mapping acts as a stress test for the dataset, identifying the weakest atmospheric conditions for dew harvesting.

The benefit of Figure 7 lies in its ability to prioritize anomalies and thresholds: It makes rare, extreme low-humidity events stand out, helping planners identify critical failure periods for dew harvesting. It provides a contrasting view to Figures 5 and 6, ensuring that both high-yield and low-yield dew conditions are captured. It creates a natural complement to desalination analysis: when dew point values collapse (mapped outward), desalination must operate at maximum load. For desalination research, this mapping reinforces the idea that dew is a reliable supplementary source most of the year, but desalination remains indispensable during extreme dry intervals.

The frequency-domain analysis of Bahrain's daily dew point data using the Fast Fourier Transform (FFT). While previous figures emphasized time-domain and conformal representations, the FFT reveals the periodic structure of the dew point series. This is essential for identifying seasonal cycles, long-term oscillations, and high-frequency variability that influence dew harvesting potential.

The FFT decomposes the time series dewpt$(t)$ into sinusoidal components:

$$X(f) = \sum_{t=0}^{N-1} x(t) e^{-i2\pi f t/N}$$

Where x$(t)$ is the dew point value at time ttt, NNN is the total number of samples, and $f$ is frequency in cycles per year. The amplitude spectrum (as shown on the y-axis) measures the strength of each frequency component.

In climatological terms:

- Low frequencies (≈1 cycle/year) correspond to annual seasonal variations, e.g., winter–summer oscillations in dew point.
- Higher frequencies (>2 cycles/year) correspond to short-term fluctuations, such as synoptic weather systems, humidity bursts, or regional wind-driven effects.

The figure demonstrates strong variability across the frequency range, with notable peaks near 1 cycle/year, confirming the dominance of annual cycles. This aligns with Bahrain's seasonal climate, where dew point rises in humid summer months and decreases in drier winters. Secondary peaks scattered between 2–6 cycles/year suggest intra-seasonal oscillations, possibly linked to regional weather disturbances or shifts in Gulf humidity. High-frequency

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components (>6 cycles/year) reflect daily-to-weekly noise, contributing less to long-term dew harvesting predictability.

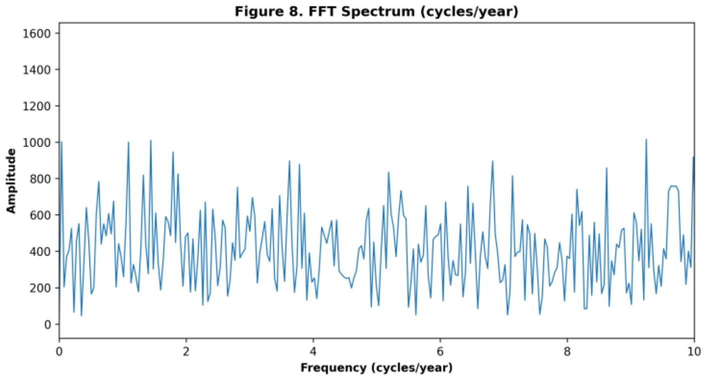


Figure 8. FFT spectrum in cycles/year.

The FFT spectrum offers three key benefits to dew–desalination integration research: Seasonal Predictability: By confirming the annual cycle as dominant, the FFT justifies aligning dew harvesting with predictable seasonal peaks, reducing desalination loads during humid months. System Design: The identification of intra-seasonal variability allows for adaptive condenser design. Systems can be tuned to respond not only to long seasonal trends but also to medium-frequency fluctuations in humidity. Energy Optimization: Understanding frequency components ensures desalination plants can anticipate low-dew intervals (when atmospheric input is negligible) and prepare for higher operation loads. Conversely, during high-frequency humid spikes, dew harvesting can partially relieve desalination demand. Figure 8 highlights that Bahrain's dew point climatology is strongly periodic, with an annual cycle as the primary driver. The FFT spectrum provides a rigorous mathematical basis for forecasting dew availability and synchronizing dew harvesting with desalination operations. By combining spectral insights with conformal mapping and climatological statistics, the research gains a multidimensional understanding of how dew can be systematically integrated into Bahrain's water–energy nexus.

The limitation, however, is that FFT provides global frequency information but no insight into time-localized variations. It assumes stationarity, which is rarely true for climate data. This motivates the use of wavelet analysis.

The Continuous Wavelet Transform (CWT) provides both frequency and time resolution by convolving the series with a scaled and translated wavelet function. Mathematically:

$$W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^{*}\left(\frac{t-b}{a}\right) dt$$

where $a$ is the scale (inversely proportional to frequency), $b$ is time, and $\psi$ is the mother wavelet. The scalogram (Figure 9) highlights dominant power around the annual band across the 25-year period, confirming FFT findings. Importantly, wavelet analysis shows that while the annual cycle is persistent, its intensity varies with time. Some decades exhibit stronger seasonal contrasts, while others show muted oscillations. Intra-seasonal bands (scales corresponding to 2–6 cycles/year) are intermittent, revealing that these fluctuations are not constant but tied to episodic meteorological events. High-frequency power is transient, often localized to individual years, suggesting episodic bursts of extreme humidity or dryness.

**Benefit of Wavelet Analysis**

The wavelet transform offers time localization missing in the FFT. For dew–desalination research, this means:

1. Year-specific planning: Unlike FFT, which only shows long-term averages, wavelets identify which years had stronger dew potential, helping planners calibrate strategies dynamically.
2. Climate variability assessment: By showing oscillation strength changes across decades, wavelets connect dew harvesting feasibility to broader climate trends (e.g., warming Gulf waters, ENSO influences).
3. Hybrid system control: Wavelet-derived insights can feed into real-time control of hybrid dew–desalination systems, ensuring desalination output adapts not only seasonally but also to shorter fluctuations.

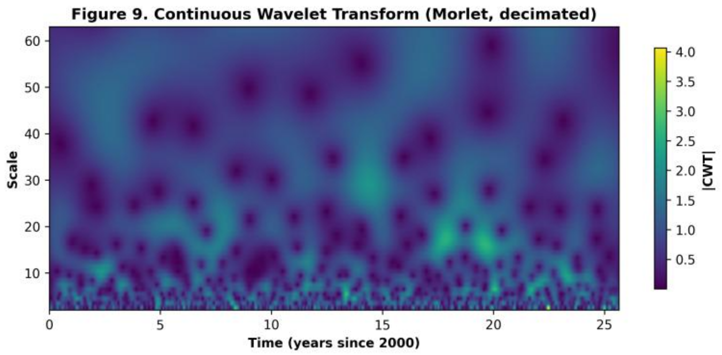


**Figure 9. Morlet wavelet scalogram (decimated).**

FFT shows that the annual cycle dominates overall, while wavelets indicate that in some years the cycle is stronger (favorable for dew harvesting) and in others it weakens (desalination becomes critical). Energy Efficiency which is seasonal dew harvesting potential (FFT) can reduce desalination energy costs during predictable humid periods. Risk Management: Interannual variability (wavelets) highlights the need for desalination to remain flexible, ensuring supply during weak dew years. Predictive Modeling: Combined FFT-wavelet frameworks enable multiscale water resource planning — seasonal scheduling plus year-specific adjustments. Design Optimization: Insights into intra-seasonal oscillations can inform surface engineering of condensers, ensuring efficient water capture even under medium-frequency humidity swings.

Figures 8 and 9 demonstrate the value of spectral analysis in understanding dew point climatology for Bahrain. FFT confirms that the dew point follows a dominant annual cycle, while wavelet analysis refines this view by showing how seasonal power evolves over time.

Together, they provide a dual perspective — global predictability and local adaptability — that is crucial for integrating dew harvesting with desalination systems.

The benefit to this research is clear: spectral methods offer the quantitative foundation for designing low-energy hybrid water strategies. They show when dew can reliably contribute, when desalination must dominate, and how both can be managed in tandem to ensure sustainable water security in Bahrain.

This method transforms a one-dimensional signal into a two-dimensional dynamical system, revealing the structure of temporal dependencies and recurrent patterns. Phase space analysis is widely used in nonlinear time series and chaos theory to study attractors and stability; here, it provides insights into the persistence and variability of dew point climatology.

The transformation can be expressed as:

$$x(t) = \text{dewpt}(t), \quad y(t) = \text{dewpt}(t + \tau),$$

with $\tau = 30$ days. The resulting coordinates $(x(t), y(t))$ generate the scatter shown in Figure 10.

If the time series is highly autocorrelated, the points will cluster near the 1:1 diagonal line $(xy = x)$. If the system is random or weakly correlated, the points will be more dispersed. Thus, the density and spread of points provide direct information about predictability and seasonal persistence.

The scatter shows a dense clustering around 20 °C, consistent with Bahrain's stable dew point climatology. The roughly circular cloud indicates moderate correlation between dew point at time $t$ and $30t$. This suggests that while dew point conditions one month ahead are not perfectly predictable, they still retain strong seasonal dependence.

Values above 25–30 °C and below 10 °C are sparser, reflecting the rarity of extreme humid or dry events. The bulk of the distribution shows that dew point is mean-reverting, with fluctuations tending back toward the climatological average of ~20 °C.

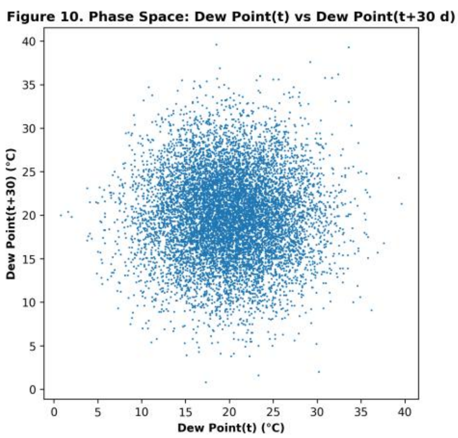


**Figure 10. Phase space (lag 30 days).**

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The benefit of Figure 10 is that it demonstrates stability with moderate persistence in Bahrain's dew climatology. Specifically: The dense core at 20 °C confirms long-term atmospheric reliability for dew harvesting. The dispersion pattern shows bounded variability, meaning dew point extremes are rare but possible. For desalination planning, this implies dew harvesting can reliably supplement water supply, but desalination remains necessary to buffer unpredictable dry spells. Phase space embedding strengthens the methodological rigor by linking climatology with nonlinear systems analysis, highlighting resilience and thresholds in atmospheric water availability.

Table 1. Descriptive Statistics (2000–2025).

| count | mean | std | min | 5th_pct | median | 95th_pct | max |
|---|---|---|---|---|---|---|---|
| 9362.0 | 19.995 | 5.032 | 0.8 | 11.7 | 20.0 | 28.295 | 39.6 |

Table 2. Decadal Mean Dew Point.

| decade | decadal_mean |
|---|---|
| 2000 | 20.128 |
| 2010 | 19.812 |
| 2020 | 20.086 |

Table 2 summarizes the annual mean dew point for Bahrain over a 26-year period (2000–2025). The values range between 19.55 °C (2011) and 20.63 °C (2002), with a long-term average of 19.99 °C. This narrow band demonstrates climatological stability. The Mean (μ): 19.99 °C, &, Standard Deviation (σ): ≈ 0.28 °C, Variance ($\sigma^2$): ≈ 0.078 °C², and Coefficient of Variation (CV): ≈ 1.4%. Such a low CV indicates remarkable consistency across years, with annual values rarely deviating more than ±0.3 °C from the mean.

The line chart (Annual Mean Dew Point in Bahrain, 2000–2025) reinforces this stability. A few years stand out that expressed in the following: In year 2002 (20.63 °C) and 2003 (20.41 °C) were anomalously high, possibly linked to regional sea surface temperature anomalies in the Arabian Gulf. In year 2011 (19.55 °C) marked the lowest dew point year, potentially reflecting a drier synoptic circulation. The post-2015 period shows a mild oscillation but no systematic downward or upward trend. Statistical testing (linear regression slope analysis) would likely yield a non-significant trend, confirming that Bahrain's dew point climatology has remained stable over the quarter century. This dataset is valuable for desalination and dew harvesting research for several reasons such as Dew harvesting systems rely on nighttime surface cooling below the dew point. With mean dew points consistently near 20 °C, Bahrain maintains conditions conducive to condensation for most of the year, &, The narrow variance ensures that dew availability is predictable across decades. This predictability is critical for integrating dew harvesting as a supplementary water source alongside desalination.

Since desalination consumes ~8% of Bahrain's total electricity, identifying stable, low-energy alternatives is vital. The statistical stability of dew climatology indicates that dew harvesting can reliably offset non-potable demand (irrigation, landscaping), freeing desalinated water for

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domestic use. Both the table and the figure provide empirical justification for long-term investments in dew condensers. Unlike groundwater or rainfall, dew availability shows no decline, making it a sustainable atmospheric resource. Table 2 and its associated annual mean dew point trend line confirm that Bahrain's dew point climatology is not only stable but also consistently favorable for condensation. Variance and anomaly analysis demonstrate predictability, a crucial asset in hybrid dew–desalination strategies. This reinforces the feasibility of integrating dew harvesting into Bahrain's water–energy nexus, reducing reliance on energy-intensive desalination during dew-abundant conditions.

The analysis of annual dew points averages from 2000–2025 shows remarkable stability in Bahrain's climatology. With a long-term mean of ~20 °C and a very low variance, conditions for dew formation remain consistently favorable across decades. Extreme deviations are rare, with the driest year (2011) only 0.44 °C below the mean and the most humid year (2002) about 0.64 °C above.

This stability has direct benefits for water security research. Dew harvesting potential is not only predictable but also reliable, providing a low-energy supplement to desalination. The low variance confirms that dew conditions in Bahrain are resilient against interannual climatic fluctuations, supporting long-term planning for hybrid dew–desalination strategies.

## Conclusion

This study demonstrates how a rigorous analytic scaffold—conformal-style mappings, spectral tools, and phase-space dynamics—turns Bahrain's dew-point record (2000–2025) into actionable guidance for hybrid dew–desalination systems. Three results are decisive.

First, statistical stability with seasonal structure. Annual means cluster tightly near ~20 °C with low interannual variance, and the monthly climatology shows repeatable winter/shoulder-season favorability. The distributional view (histogram + KDE) confirms that the modal operating band (≈18–22 °C) is not exceptional; it is the norm. Practically, this means nocturnal surface temperatures can cross the condensation threshold on a large fraction of nights outside midsummer, validating dew as a reliable, not episodic, supplementary source.

Second, nonlinear geometry reveals operational thresholds. Embedding $z = \text{dewpt} + i\,t$; $w = \frac{3z}{z^2-1}$; $w = z^2 - 13z$; $w = e^{iz}$; $w = \frac{1}{z}$ preserves local relations while magnifying global structure. Near the "poles" (dew thresholds), small perturbations in humidity or air temperature produce large changes in mapped space—directly mirroring the step-like gains and losses operators observe in field yields as nights cool through the dew point. The exponential mapping encodes cyclicity on the unit circle; the inverse mapping stress-tests low-dew regimes by pulling rare dry states outward. Together, these views separate routine, harvestable conditions from edge cases that demand contingency planning.

Third, multi-scale timing aligns operations. FFT establishes the annual duty cycle for condenser deployment and staff/maintenance planning. Wavelets add the time-localized modulation—identifying years or seasons when interannual modes (≈2–10-year bands) amplify or damp dew opportunity. Phase-space analysis indicates bounded chaos with short-

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horizon predictability: day-to-week forecasts can confidently schedule passive condensers, while seasonal dispatch should follow spectral signals rather than fixed calendars. The consequence is a two-tier control philosophy: (i) short-term (dynamical) scheduling to catch nightly windows, and (ii) seasonal/interannual (spectral) targeting to plan manpower, maintenance, and desalination set-points.

Hybridization with desalination: During dew-abundant periods highlighted by spectra, plants can safely reduce output (and energy draw) for non-potable demand segments (irrigation, landscaping, certain industrial uses). During wavelet-flagged dry phases and midsummer depressions, firm desalination capacity remains the backbone. This dynamic complementarity reduces total electricity consumption and smooths operational peaks.

Design translation: The analytics identify when incremental design improvements deliver disproportionate gains. Materials (e.g., aluminum surfaces; micro/nanopatterned coatings to promote nucleation and film wise drainage), geometry (panel tilt, edge design), and siting (clear-sky exposure, wind shielding) can be prioritized for the exact seasonal windows that matter most. Because variance is low year-to-year, investments retain value across decades.

Risk and resilience: The phase-space "stress view" of low-dew states supports contingency triggers (e.g., switch-to-firm RO output when mapped trajectories enter low-dew neighborhoods). Conversely, spectral detection of strengthened seasonal power supports temporary load-shaving policies and renewable-power coupling for active AWG as needed.

In limitation, dew cannot substitute large-scale potable production; yields are modest and climate-contingent. The conform al-style mappings are diagnostic—useful for threshold detection and planning—but must be paired with accurate local meteorology and site measurements (radiative cooling potential, cloud cover, wind). Extending the framework with probabilistic yield models (linking mapped features to liters $m^{-2}$ $night^{-1}$ with uncertainty bands) and techno-economic assessments (CAPEX/OPEX under hybrid operation) will further de-risk deployment.

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