

WeatherStream: Light Transport Automation of Single Image Deweathering

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(a) Snowy Input Image

(b) Model [57] trained on Previous Dataset

(c) Model [57] trained on Our Dataset

Figure 1. We propose a new dataset, publicly available, that makes all image-based deweathering models we tested perform better. In contrast to previous datasets, this dataset is not manually collected, but uses algorithms based on “light transport” [29] to automatically curate the dataset. Doing this algorithmically not only improves quality of the dataset, but also the scale. Download the dataset or test your model on the challenge website: <http://visual.ee.ucla.edu/wstream.htm/>.

Abstract

Today single image deweathering is arguably **more sensitive to the dataset type, rather than the model**. We introduce WeatherStream, an automatic pipeline capturing all real-world weather effects (rain, snow, and rain fog degradations), along with their clean image pairs. Previous state-of-the-art methods that have attempted the all-weather removal task train on synthetic pairs, and are thus limited by the Sim2Real domain gap. Recent work has attempted to manually collect time multiplexed pairs, but the use of human labor limits the scale of such a dataset. We introduce a **pipeline** that uses the power of light-transport physics and a **model trained** on a small, initial seed dataset to **reject approximately 99.6% of unwanted scenes**. The pipeline is able to generalize to new scenes and degradations that can, in turn, be used to train existing models just like fully human-labeled data. Training on a dataset collected through this procedure leads to **significant improvements** on multiple existing weather removal methods on a **carefully human-collected test set** of real-world weather effects. The dataset and code can be found in the following website: <http://visual.ee.ucla.edu/wstream.htm/>.

1. Introduction

Single-image deweathering aims to remove image degradations caused by rain, fog, or snow. Single-image

deweathering is a mainstay of modern computer vision, valued for the aesthetic appeal of removing weather degradations, as well as the ability to reuse pre-trained computer vision models, which work on clear weather conditions. Unfortunately, the **field is dataset bottlenecked**. State-of-the-art techniques use deep networks, but suffer from a common issue: the same scene cannot be observed at the same time, with and without weather artifacts. Therefore, it is not possible to train deep networks on **ideal pairs**, a pair of clean and degraded images of the same scene at the same time.

Previous work has attempted to solve the dataset bottleneck by using **simulated pairs**. A simulated pair is formed by starting with a clean image of a scene and artificially adding weather degradations. For example, one could carefully simulate the effect of raindrop streaks on a clean image. Unfortunately, simulating the diverse weather conditions that one can encounter is a very difficult path. Existing simulators for rain are difficult to generalize, and scaling simulators for rain, fog, and snow poses a further challenge. Nonetheless, simulated pairs have been the most common approach, and researchers have accepted the generalization errors that are encountered. Another emerging way to obtain pairs is to use **pseudo-real pairs**. A pseudo-real pair is a pair of clean and degraded images that is formed without the use of simulators. One way of doing so is to use a **video-based deraining method to remove rain (which is dynamic)** from a scene [60]. This form of ground-truthing

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assumes video-based deraining is itself a solved problem, which leads to limited performance, particularly in rain effects that are less dynamic (such as far-field veiling).

Perhaps the highest-quality pairs were obtained in the most recent work known as GT-RAIN [2]. This paper took a different tack, introducing time multiplexed pairs. A time multiplexed pair is obtained by taking an input video sequence and grabbing closely spaced frames in the video, with and without rain. This approach only works if nearby frames are grabbed in a magic moment when the scene conditions are just right, e.g., the rain is on the cusp of stopping, illumination constancy is observed, limited dynamic agents, and so on. In the less than one percent of videos that have suitable conditions, a time-multiplexed pair performs almost like real, ground truth.

Unfortunately, approaching time multiplexed pairing using human annotation (as has been done in previous work) is hard to scale to 100K+ pairs. As a generous lower bound, it would take 1 human labeler, 1 minute to carefully parse through 5 video sequences. Scaling this up to 2 million videos would take a whole year. Moreover, 99.6% of the video sequences do not meet the criteria for a magic moment. A further limit to scalability is that human observers must be highly trained to control for factors such as illumination shifts, weather API errors, and dynamic objects that are prevalent in over 99% of the videos.

In this paper, we formulate light transport techniques, which model the flow of light in a scene [29] to help us decide if frames should be included in training data. A key contribution is to formulate four principles of light transport to decide if a time-multiplexed pair is valid: (1) Background Conformity; (2) Particle Chromatic Variation; (3) Scatter-dependent Blur; and (4) Illumination Consistency.

Contributions: Our work is an initial attempt to use light transport to formulate how time multiplexed pairs should be selected, while the only previous approach is human annotated and limited to rain [2]. Automation scales the dataset, enabling us to obtain a dataset of 188K image pairs. This is the largest all-weather removal dataset to date, and includes diverse rain and snow of different shapes, sizes, and strengths, in various locations around the globe, with a plethora of backgrounds, camera settings, and illuminations. For this reason, we observe a 1.5 dB improvement in performance across various state of the art baselines. The dataset will be released conditional on acceptance.

2. Related work

Image deweathering aims to remove degradations caused by rain, fog, or snow for aesthetic appeal and the potential reuse of existing downstream task models, i.e. detection [27, 28], segmentation [6, 7], stereo [4, 12, 67], depth prediction [15, 19, 62], and completion [38, 42, 47, 64], trained on clear weather conditions.

Removing artifacts from a single weather type: Many

Dataset	Multi-weather?	# Pairs	Time Multiplexed?	Scalable?
All-in-One [32]	✓	111.6K	✗	✓
Snow100k [40]	✗	100K	✗	✓
SRSS [8]	✗	15K	✗	✓
CSD [9]	✗	10K	✗	✓
Rain100L [69]	✗	300	✗	✓
Rain100H [69]	✗	1.9K	✗	✓
Outdoor-Rain [31]	✗	10.5K	✗	✓
RainCityscapes [24]	✗	10.62K	✗	✓
Rain12000 [73]	✗	13.2K	✗	✓
Rain14000 [17]	✗	14K	✗	✓
GT-RAIN [2]	✗	31.5K	✓	✗
WeatherStream (Ours)	✓	202K	✓	✓

Table 1. WeatherStream Dataset is the first automated time multiplexed dataset. Compare with GT-RAIN [2] which is manually collected and for rain only; or the All-in-One weather dataset [32] which combines various simulated pairs [31, 40, 48].

previous works have focused on the removal of artifacts from a specific weather condition like rain [16, 20, 25, 26, 31, 46, 51, 58, 60, 63, 69, 72, 73] or snow [8, 9, 32, 35, 40, 68]. Most of these methods are trained on synthetic data, where rain streaks or snowflakes are added to images taken in clear weather – leaving a sim2real gap when transferring these models to real weather. Some works rely on unpaired real data through GANs [13, 54, 63] (see Sec. H in the Supp Mat). Recent work, known as GT-RAIN [2] collects a dataset of real rainy and clean image pairs separated by a time interval, but the process involves manually determining when the rain stopped and filtering thousands of unsuitable internet videos that violate their ground truth criterion. Hence, even curating a set of 30k images becomes unscalable. Our method, on the other hand, allows us to collect these image pairs at scale yielding a dataset that is larger than GT-RAIN; better in its quality than GT-RAIN; and inclusive of diverse weather conditions.

Removing artifacts from multiple weather types:

While most papers focus on removal of a specific weather type, there are some works that can remove multiple weather conditions in a single model [10, 32, 57]. One example is the all-in-one network [32] that uses a multi-encoder single-decoder setup with neural architecture search and a discriminator to decide which encoder to backpropagate losses to. Meanwhile, TransWeather [57] uses a single encoder and decoder, with self-attention within patches to remove smaller weather degradations. A teacher-student scheme has also been explored to train a unified all-weather removal model by using multiple teachers for each weather condition [10]. While there has been tremendous progress in weather removal architectures, these prior methods for rain, snow, and fog again rely on the synthetic deraining and desnowing pairs. This paper introduces time multiplexed pairs for rain, fog, and snow. A comparison of representative datasets for weather removal can be found in Tab. 1.

3. Light Transport of Time Multiplexing

Time multiplexing pairs are a nascent form of training data, introduced only in one previous paper by Ba *et al.* [2]. This paper produced surprising visual improvements in image deraining results when compared to simulated pairs. Unfortunately, this previous work only works for rain; uses human annotation to grab time multiplexed pairs; and due to manual curation, consists of only a few scenes. Collecting the Ba *et al.* dataset is a laborious effort because less than one percent of time multiplexed pairs are suitable, due to changes in lighting or motion.

In this paper, we draw from a foundation of light transport principles to automatically determine what makes an informative time multiplexed pair that we can use for training data. We rely on four principles of light transport.

Principle 1 (Background Conformity): Objects in a suitable paired scene exhibit no motion and color constancy.

A paired scene with dynamic illumination/objects will not work. This creates brightness variations across the pair that are not a function of weather effects. But how do we know if a brightness variation is due to changes in weather or the environment? To address the problem, we appeal to forward models of image-based changes that weather can create i.e. for rain streaks [2, 11, 17, 30–32, 34, 57, 58, 60, 70, 73, 75]:

$$\mathbf{K}_r(x) = \mathbf{J}(x) + \sum_i^n \mathbf{S}_i(x), \quad (1)$$

where $\mathbf{K}_r \in \mathbb{R}^{3 \times H \times W}$ represents the rainy image, $\mathbf{J} \in \mathbb{R}^{3 \times H \times W}$ represents the clean image, \mathbf{S}_i represent the different rain streak layers, and x represents the spatial location on the image. A similar equation holds for synthetic snow particles [8, 9, 40] of the form:

$$\mathbf{K}_s(x) = \mathbf{J}(x)(1 - \mathbf{Z}(x)) + \mathbf{C}(x)\mathbf{Z}(x), \quad (2)$$

where $\mathbf{K}_s \in \mathbb{R}^{3 \times H \times W}$ represents the snowy image, \mathbf{Z} represents a snow mask, and \mathbf{C} represents a chromatic aberration map. According to [18, 45, 60, 74], these rain streak layers $\mathbf{S}_i(x)$ and snow particle masks $\mathbf{Z}(x)$ are randomly distributed spatially throughout the scene. As a property of these equations, the only discrepancy between \mathbf{K} and \mathbf{J} is the addition of weather effects. In accordance with this principle, we design blocks in our pipeline to detect motion and static object variations between the clean and degraded images that are not related to brightness changes caused by Eq. (1) and Eq. (2).

Principle 2 (Particle Chromatic Variation): Rain streaks and snowflakes exhibit isotropic derivatives in RGB pixel intensity [74].

The photometry of falling particles is consistent with Eq. (3) for particle intensity I_p : 這裡是計算 particle 對「整張」圖像的影響

$$I_p = \int_0^\tau E_p dt + \int_\tau^T E_{bg} dt, \quad (3)$$

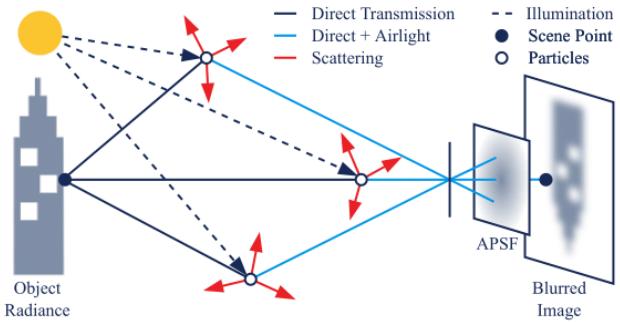


Figure 2. Objects in adverse weather tend to be blurred due to the existence of scattering effects (Principle 3). Figure adapted from multiscatter models in [22, 33, 44].

where T denotes the exposure time of the camera and τ the time in which the falling particle is in frame [18, 45]. Here, E_p and E_{bg} denote the irradiance of the particle and the background, respectively. Utilizing Principle 1, we know that E_{bg} should be constant throughout the exposure time. We can then obtain an expression for $I_p - I_{bg} = \Delta I$, where I_{bg} is the pixel intensity of the background:

$$I_p = \tau \bar{E}_p + (T - \tau)E_{bg}, \quad (4)$$

$$\bar{E}_p = \frac{1}{\tau} \int_0^\tau E_p dt, \quad (5)$$

$$\Delta I = \tau(\bar{E}_p - E_{bg}). \quad (6)$$

Empirical studies have shown that both rain and snow are bright regardless of background irradiance (as a result of compounding internal and specular reflections with a large refraction field) [18, 45, 60, 74]. Therefore, we can assume \bar{E}_p to be constant, yielding a linear relationship between ΔI and background intensity I_{bg} :

$$\Delta I = -\beta I_{bg} + \alpha, \beta = \frac{\tau}{T}, \alpha = \tau \bar{E}_p. \quad (7)$$

The implication of Principle 2 is that one can write the intensity between clean and degraded image data $I_p - I_{bg}$ as being linearly related to the background intensity I_{bg} . This is true across color channels, such that $\Delta R, \Delta G, \Delta B$ of pixel intensities in the three color channels should be similar for weather artifacts [56, 74]. One can use this principle to infer that $[\Delta R, \Delta G, \Delta B]^T$ should be isotropic, and anisotropic deviations in this vector provide a clue about brightness variations in scenes that are not due to weather (again, such as objects or lighting).

Principle 3 (Scatter-dependent Blur): A degraded image is blurrier than a clean image, due to scattering effects.

We need additional principles beyond Eq. (1) and Eq. (2), as these two equations do not represent the gamut of complex rain and snow related phenomenon [2, 8, 9, 25, 31]. For example, dense rain, snow accumulation, haze or fog may

辐照度，每單位面積上接收到的光能量的多少

粒子所造成的亮度變化
(但沒有很重要，下方
isotropic 才是重點)

如果 $\Delta R, \Delta G, \Delta B$ (在
RGB 上計算 intensity)
都是 isotropic(similar)
那這個 pair 就是我們要的

目標是找出適合的 pair

把雨雪相關
brightness 去除
後，看背景的
brightness 有沒
有改變（不改變就
是我們想要的）

藉此把動態物、不
同的靜態物、天空
移除

亮度是一個主
觀感知的量，
表示人眼或視
覺系統對光的
強弱感覺。

亮度強度，可以理
解為發出的總光
量，描述了光源發
出的能量總量，通
常以瓦特 (w) 或
瓦特每平方公尺
(w/m²) 來表示。

這裡的「Isotropic 各向同性」是指在圖像中的不同方向上，雨滴和雪花對 RGB (紅、綠、藍) 顏色通道的影響是均勻一致的。換句話說，當光穿過這些天氣粒子 (如雨滴或雪花) 時，它們對三個顏色通道 (紅、綠、藍) 的亮度變化是相似的，而不是只影響某一個顏色通道。

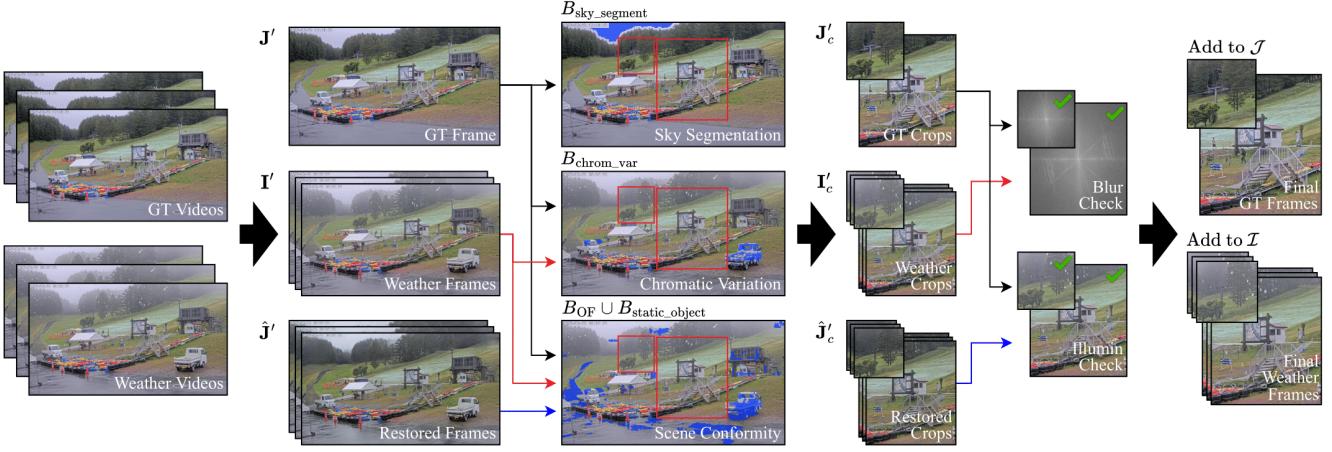


Figure 3. The proposed WeatherStream pipeline utilizes light transport principles to identify magic moments for various weather effects. It is capable of selecting high quality paired data from millions of candidate videos with diverse situations.

cause a “veiling” effect throughout the scene, due to the introduction of scattering effects [3, 8, 21, 24, 31, 55], which are not modeled by Eq. (1) and Eq. (2). To extend this to a single scattering model (SSM), one can define the radiance L_s of the scene at a distance d as:

$$L_s(d) = L_o e^{-\int_0^d \beta dl} + \int_0^d L_\infty \beta e^{-\beta l} dl \\ = L_o e^{-\beta d} + L_\infty(1 - e^{-\beta d}). \quad (8)$$

Here, L_o represents the true underlying radiance and L_∞ the radiance of the airlight at the horizon. β is an atmospheric attenuation coefficient, which is constant throughout the scene. Though this approximation is in dehazing [21, 55], the model can be further refined to include multiple scattering effects (when scattered light is scattered again by different particles) [22, 33, 44, 59]:

$$L_m(d) = L_s(d) * \text{APSF}(d). \quad (9)$$

Here, the single scattering output radiance is convolved with the atmospheric point spread function (APSF), which accurately simulates the effects of multiple scattering, as illustrated in Fig. 2. Mapping this multiple scattering model to the RGB intensity space, and substituting rain and snow models for underlying radiance, allows us to obtain the following light transport model:

$$\mathbf{I}(x) = [\mathbf{K}(x) e^{-\beta d(x)} + \mathbf{L}_\infty(1 - e^{-\beta d(x)})] * h_{\text{APSF}}, \quad (10)$$

where distance d is a function of spatial location x , and \mathbf{K} represents the underlying scene with no fog effects (but with rain streaks and snowflakes). The h_{APSF} is a convolution kernel that represents the convolution operation with the APSF. From this equation, we arrive at Principle 3: Since the APSF can be approximated with a generalized gaussian distribution (GGD) [22, 43], we know that it has a low-pass

filter effect on our image, leading to a blur effect and lowered contrast. The exact parameters of this GGD approximation are dependent on particle size and particle atmospheric density, and are used in our pipeline to provide better scraping of time multiplexed pairs from webcam videos.

Principle 4 (Illumination Consistency): The ambient illumination should remain consistent despite weather effects. This is difficult to analyze in closed-form since illumination stimuli to uncontrolled scenes are not known a priori.

From Principle 1 and Eq. (10), we know that the ambient illumination L_∞ should be consistent between clean and degraded images. In reality, this property is difficult to quantify, since veiling effects from falling particles contribute to a global intensity change which can be confounded with illumination shifts in an uncontrolled scene. The fourth principle is that we cannot predict this illumination shift, and use a seed model to learn whether the illumination has shifted with a sufficiently high safety margin to avoid false positive selection. This is further described in Sec. 4.

如果 Scatter 的效果很明顯，那就是我們要的 pairs 內的 degraded image

後續比對 degraded image 的 blur 和 contrast 有沒有比 clean 模糊，有我們才要。

直接用 train 在 GT-Rain 上的 seed model 模型預測，illumination 外在光源有沒有改變

4. Pipeline to Obtain Time Multiplexed Pairs

We now describe our automated pipeline to build WeatherStream. We first begin with a seed dataset from previous work [2]. This seed dataset enables a model to be trained (“seed model”). The seed model is not used for the challenging task of deweathering, but to predict coarser light transport parameters. We detail the pipeline in Fig. 3 and explain how the light transport principles are used (Sec. 3).

Data Filtering: Without loss of generality, let us attempt to find a single pair of images (\mathbf{c}, \mathbf{d}) that represent a clean and degraded image, respectively.

The first goal is to download video streams within which, are candidates for the clean and degraded pair. This is done by analyzing attached weather metadata, discussed in Sec. 5. This yields a scraped data structure: $\mathcal{D}_c =$

- 公式 8:描述了光在單次散射時的衰減過程，表示了距離 d 處的輻射亮度
- 公式 9:將公式 8 的單次散射擴展到多次散射模型，加入了 APSF 來模擬光的多次散射，這會進一步模糊影像。
- 公式 10:基於公式 8, 9 和單次散射與多次散射的效應，構建了最終的light transport 模型，這個模型用來模擬影像中受天氣影響後的模糊和亮度變化。

$\{\tilde{\mathbf{c}}^n\}_{n=1}^N, \mathcal{D}_d = \{\tilde{\mathbf{d}}^m\}_{m=1}^M$, where the notation tilde in $\tilde{\mathbf{c}}^n, \tilde{\mathbf{d}}^m$ is used to emphasize that these are candidate clean and degraded images, respectively. Within these sets $\mathcal{D} := \mathcal{D}_c \cup \mathcal{D}_d$, we seek to find a suitable pair (\mathbf{c}, \mathbf{d}) that meets light transport constraints. Therefore, we seek an operator:

$$f_{\text{WeatherStream}} : \mathcal{D} \rightarrow (\mathbf{c}, \mathbf{d}). \quad (11)$$

Since the size of \mathcal{D} is larger than a possible 2-image pair (\mathbf{c}, \mathbf{d}) , the operator $f_{\text{WeatherStream}}$ acts as a filter. We filter \mathcal{D}_c and \mathcal{D}_d through four blocks, that each map to one of four light transport principles from the previous section.

Filtering Block One: Scene-level Verification: The first verification block conforms our data to *Principle 1* (Sec. 3). Images that exhibit object motion are filtered by computing optical flow between two temporally averaged and adjacent time frames. In particular, we compute the Gunnar-Farneback algorithm [14]. To avoid spurious motion in the flow field, we take the mean of consecutive frames that serve to average out rain streaks or snowflakes. As noted in Sec. 3, rain streaks and snowflakes are typically randomly distributed throughout the scene, and move at a much higher velocity compared to movements from scene objects. Prior works have shown that falling particles reach a terminal velocity of $200\sqrt{r}$, where the radius r of the falling particle is typically between 0.5-2.5 mm for rain drops and snowflakes [18, 45]. Due to the speed of these rain drops, and the framerate of our videos, the same streak will not appear in the same location in consecutive frames [74]. Thus, temporal averaging will remove weather particles. The magnitude of the resulting optical flow map is then thresholded through an indicator function to provide a binary map B_{OF} representing motion regions in the image. Then, we check for the presence of static objects that are different between $\tilde{\mathbf{c}} \in \mathcal{D}_c$ and $\tilde{\mathbf{d}} \in \mathcal{D}_d$ using the following:

$$\mathbf{1}_{\text{static}}^{\tilde{\mathbf{c}}, \tilde{\mathbf{d}}}(x) = \begin{cases} 1 & \text{if } |\tilde{\mathbf{c}}(x) - \tilde{\mathbf{d}}(x)| > \gamma_{\text{static}}, \\ 0 & \text{otherwise.} \end{cases} \quad (12)$$

$$\hat{\mathbf{d}} = f_{\text{weather_removal}}(\tilde{\mathbf{d}}), \quad (13)$$

$$B_{\text{static}}(x) = \mathbf{1}_{\text{static}}^{\tilde{\mathbf{c}}, \hat{\mathbf{d}}}(x) \text{ for } \tilde{\mathbf{c}} \in \mathcal{D}_c, \tilde{\mathbf{d}} \in \mathcal{D}_d. \quad (14)$$

The model, denoted by $f_{\text{weather_removal}}$, removes weather effects from $\hat{\mathbf{d}}$ leaving object discrepancies as the only remaining variability between clean and degraded images, which is reflected in the output binary map B_{static} . $\gamma_{\text{static}} = 0.1$, and is tuned such that the presence of rain streaks or snowflakes will not filter the scene. In addition to B_{static} , we also obtain a B_{sky} by running a sky segmentation algorithm [53] to avoid picking sky regions, as these are not typically regions that contain rain, snow, or fog weather effects. We then take their union i.e. $B = B_{\text{static}} \cup B_{\text{OF}} \cup B_{\text{sky}}$ and find all crops bigger than 256×256 that satisfies the complement of B in $\tilde{\mathbf{c}} \in \mathcal{D}_c$ and $\tilde{\mathbf{d}} \in \mathcal{D}_d$.

Filtering Block Two: Color Verification: We now pass what remains of \mathcal{D} into another filtering block to remove false positive pairs. This second block leverages *Principle 2* from Sec. 3 to avoid false detection of rain streaks and snowflakes by ensuring isotropic intensity variations across RGB channels. The filtering function we use takes the form of:

$$C_{\max}(x) = \max_{c \in \{r, g, b\}} \tilde{\mathbf{c}}_c(x) - \tilde{\mathbf{c}}_c(x), \quad (15)$$

$$C_{\min}(x) = \min_{c \in \{r, g, b\}} \tilde{\mathbf{c}}_c(x) - \tilde{\mathbf{c}}_c(x), \quad (16)$$

$$B_{\text{chrom_var}} = (C_{\max} - C_{\min}) > \gamma_{\text{chrom_var}}. \quad (17)$$

We threshold with $\gamma_{\text{chrom_var}}$ the gap between the maximum and minimum color channel intensities C_{\max} and C_{\min} . This $\gamma_{\text{chrom_var}}$ is set to .2 (for images ranging from 0 to 1). Removing pixels which have a high gap between ΔR , ΔG , or ΔB catches static object differences present in the image pairs while preserving rain streaks and snowflakes.

Filtering Block Three: Multi-scatter Verification:

The third filtering block is designed to verify that multi-scatter exists in a possible image that could be a candidate for the degraded part of the pair, d . According to *Principle 3* (Sec. 3), degraded images in all weather conditions contain a veiling effect which is represented through a multi-scattering model. An approximation of the accompanying APSF as a generalized Gaussian distribution leads us to consider two metrics: lower contrast and blur. In order to measure contrast and blur of a scene, we employ two commonly used metrics [37, 55]. The first metric f_{grad} is a normalized measurement of the difference between the magnitudes of the gradients of $\tilde{\mathbf{c}}$ and $\tilde{\mathbf{d}}$. We approximate the gradients using Sobel filters as:

$$\bar{\mathbf{d}} = \frac{1}{m} \sum_{i=0}^m \tilde{\mathbf{d}}, \quad (18)$$

$$f_{\text{grad}} = \frac{|\nabla \bar{\mathbf{d}}| - |\nabla \tilde{\mathbf{c}}|}{|\nabla \tilde{\mathbf{c}}|}. \quad (19)$$

算出來 > 0 就是 d 比較 high contrast, 不是我們想要的

The second metric f_{fft} is a normalized measurement of the difference between the magnitudes of the low-pass filtered reconstructions of $\tilde{\mathbf{c}}$ and $\tilde{\mathbf{d}}$.

$$f_{\text{fft}} = \frac{|f_{\text{lp}}(\bar{\mathbf{d}}, \gamma_{\text{lp}})| - |f_{\text{lp}}(\tilde{\mathbf{c}}, \gamma_{\text{lp}})|}{|f_{\text{lp}}(\tilde{\mathbf{c}}, \gamma_{\text{lp}})|}. \quad (20)$$

算出來 > 0 就是 d 的 low pass 比 clean 的 low pass 大，表示輪廓比較明顯， d 比較 sharp，不是我們想要的

The function f_{lp} is the log scale magnitude spectrum of a low-pass filtered reconstruction of an image with cutoff frequency γ_{lp} . Low-frequency components are filtered as per [37]. The chosen cutoff frequency depends on characterization of the APSF, which is dependent on two factors: optical thickness T , which is a function of particle density in the atmosphere, and forward scattering parameter q , which is a function of the particle size [59]. The

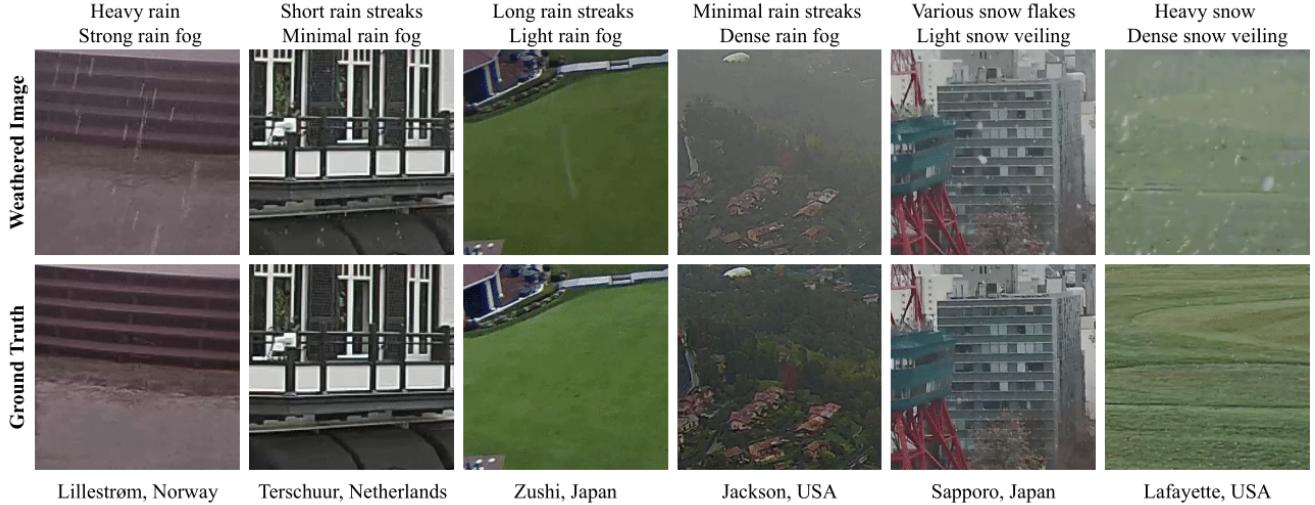


Figure 4. **WeatherStream Dataset contains diverse weather effects under rain, fog, and snow conditions.** Visualization highlights some representative image pairs with various weather effects across the world.

exact location of the cutoff we use is found through empirical analysis of the range of these factors in our dataset. For both of these metrics, we subtract degraded sharpness from clean sharpness, normalize, and **reject scenes in which the degraded image is sharper than the clean image**. To leave a gap for noise, we do not filter a scene if the degraded image is below 5% sharper than the clean image.

Filtering Block Four: Illumination Verification: As noted in *Principle 4* (Sec. 3), a particularly difficult part of the pipeline is **determining whether a global change of intensity arose due to the veiling effect, or a stimulus change of illumination** that may occur when time multiplexing. Here, we bring in the seed model comes into play [2]. The **seed model** can be **adapted to distinguish between illumination shifts and veiling effects**, indicating that **training on a small seed dataset conveys enough** scene understanding for the model to generate a coarse binary decision boundary to assess if the illumination is consistent between frames. The details of the network used are deferred to the supplement.

Final Output: Frames that **remain in \mathcal{D}_c and \mathcal{D}_d** are assigned as pairs based on **temporal closeness** within a hysteresis threshold.

5. WeatherStream Dataset

Scraping Weather Videos with Metadata: To download videos, we **built a webscraper** to automatically collect and maintain a database of **over 5000 YouTube live streams** and corresponding geographic coordinates. These streams cover a **diverse range of scenes**, camera parameters, and unique locations spanning 94 countries. Streams must adhere to a minimum resolution of 1280×720 pixels and a minimum frame rate of 30fps to be considered for inclusion. A quantitative evaluation of the streams used in our pipeline shows an NIQE score of 2.938 (lower is better), comparable to other weather removal datasets such as

Snow100K [40] (2.904) or notable detection datasets like COCO (3.648). We continuously determine the level of daylight and weather condition of the scene using the OpenWeatherMap API [41]. If a scene is **between sunrise and sunset**, and **contains an adverse weather condition**, a **ten second video is downloaded** with detailed weather metadata. **Candidate videos are scraped for an additional hour when the weather condition ends**. We expect one to process over **2 million candidate videos** within a **ten month time frame**, of which a few hundred can be aggregated as pairs (because $> 99\%$ of videos will not meet light transport constraints).

Dataset Statistics: As of the time of writing, **136.9K pairs have been automatically collected by the WeatherStream pipeline**. The manual seed dataset consists of 38.2K pairs from [2]. See Fig. 4 for representative samples.

Where is Human Intervention Used?: With 100K+ pairs automated, we recommend that one human spends a few hours a month managing the dataset, e.g., to make sure the scraper is working, or removing erroneous pairs, especially since weather metadata has errors and webcam streams terminate from time-to-time.

6. Experimental Configuration

Baseline Dataset: The baseline dataset is simulated pairs of all-weather data [32, 57]. We use configurations provided by the authors.

Models Evaluated: We **retrain several state of the art models** [2, 57, 61, 71] on both the **synthetic baseline dataset** and **our time multiplexed dataset**.

Quantitative Evaluation: We follow the protocol of Ba *et al.* [2]. However, Ba *et al.* is only for rain; we replicate the procedure for multiple weather conditions by manually collecting more test scenes with a strict set of criterion similar to the GT-RAIN collection process. The result is a test set merged with GT-RAIN of size 13.5K covering 5.1K rain,

Method	Rain		Fog		Snow		Overall	
	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑	PSNR↑	SSIM↑
Syn.	TransWeather [57] (CVPR'22)	21.36	0.7434	17.49	0.7118	21.04	0.7736	19.98
	Restormer [71] (CVPR'22)	21.29	0.7664	18.22	0.7532	20.84	0.7890	20.14
	Uformer [61] (CVPR'22)	22.15	0.7723	18.20	0.7519	20.66	0.7920	20.40
	Rain-robust [2] (ECCV'22)	17.96	0.7075	17.13	0.6931	17.52	0.7318	17.56
Manual	TransWeather [57] (CVPR'22)	21.73	0.7622	21.59	0.7612	21.42	0.7932	21.59
	Restormer [71] (CVPR'22)	22.63	0.7940	20.14	0.7700	21.62	0.8123	21.51
	Uformer [61] (CVPR'22)	22.13	0.7759	18.65	0.7445	20.91	0.7821	20.62
	Rain-robust [2] (ECCV'22)	22.83	0.7887	20.95	0.7691	22.17	0.8058	22.01
Ours	TransWeather [57] (CVPR'22)	22.21	0.7716	22.55	0.7735	21.79	0.7919	22.20
	Restormer [71] (CVPR'22)	23.67	0.8027	22.90	0.8029	22.51	0.8279	23.08
	Uformer [61] (CVPR'22)	22.25	0.7911	18.81	0.7628	20.94	0.8009	20.72
	Rain-robust [2] (ECCV'22)	23.43	0.7961	22.84	0.7901	22.29	0.8128	22.90

Table 2. **Improvements in PSNR and SSIM across many models demonstrate the significance of the data in WeatherStream.** “Syn.” denotes the models trained on the synthetic pairs used by [57], “Manual” denotes the models trained on the initial manually collected dataset (similar to [2]), and “Ours” denotes the models trained on the final WeatherStream Dataset.

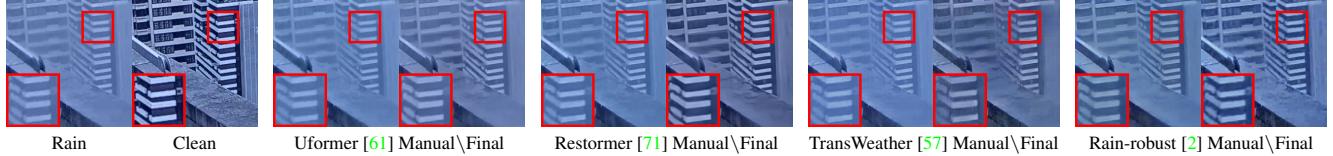


Figure 5. **Automation is not only more scalable, but also provides better color quality than manual collection.** Results on WeatherStream test set contrasted with manual curation from Ba *et al.* [2].

Metric	Input	No BG	No Illum./Blur	No Illum.	No Blur	Final
PSNR ↑	20.18	20.37	21.57	22.27	22.45	23.08
SSIM ↑	0.7699	0.7575	0.7863	0.7976	0.7863	0.8100

Table 3. **Improvements in PSNR and SSIM with the removal of each filtering block demonstrate the importance of each successive block.** “BG” refers to the first and second filtering blocks; “Blur” refers to the third; “Illum.” refers to the fourth.

3.9K snow and 4.5K fog weather conditions. PSNR and SSIM metrics are used as quantitative metrics of quality.

Qualitative Evaluation: Qualitative evaluation is performed at inference time on internet images.

Ablation Studies: We store intermediate outputs from the pipeline before certain filter blocks. The Restormer model [71] is retrained for results in Tab. 3.

7. Results

The results show that performance is impacted more from the introduction of large-scale time multiplexed pairs, rather than the specific model architecture.

Quantitative Results: Tab. 2 shows that our dataset improves almost all PSNR and SSIM metrics for all weather modalities, with the Restormer model notably improving by 1.49dB. This dataset provides improvements for both transformer and CNN architectures. As we can see from Fig. 5, the PSNR/SSIM increase is most likely due to over-smoothing in the manual model from lack of consideration

for the blurring effect from the multiple scattering model, as described in Sec. 3, which WeatherStream strongly favors. Additionally, we notice some color shifting in some of the outputs from the manual model, likely a result of an inability to generalize to certain scenes and backgrounds.

Qualitative Results: In addition to quantitative improvements, we see an increased ability to remove snowflakes and rain streaks (Fig. 6). This is also likely due to increased generalizability from more data, as well as considerations for the particle chromatic variation. Notice the removal of raindrops and snowflakes, as well as removal of the veiling effect when using WeatherStream. The inter-model variation appears less than inter-dataset variation going from synthetic to our proposed WeatherStream. This reinforces the importance of having the right data.

Ablation Studies: Tab. 3 shows the improvement in PSNR and SSIM with the introduction of each successive filter block, demonstrating the contribution of each light transport property towards the final result.

8. Discussion

In summary, this dataset is important because we observe larger inter-dataset change in performance, as compared to inter-model performance. Although simulated pairs are scalable and valuable, one can see visible weather effects in many of the models trained on simulated pairs in this paper.

The introduction of large-scale time-multiplexed pairs

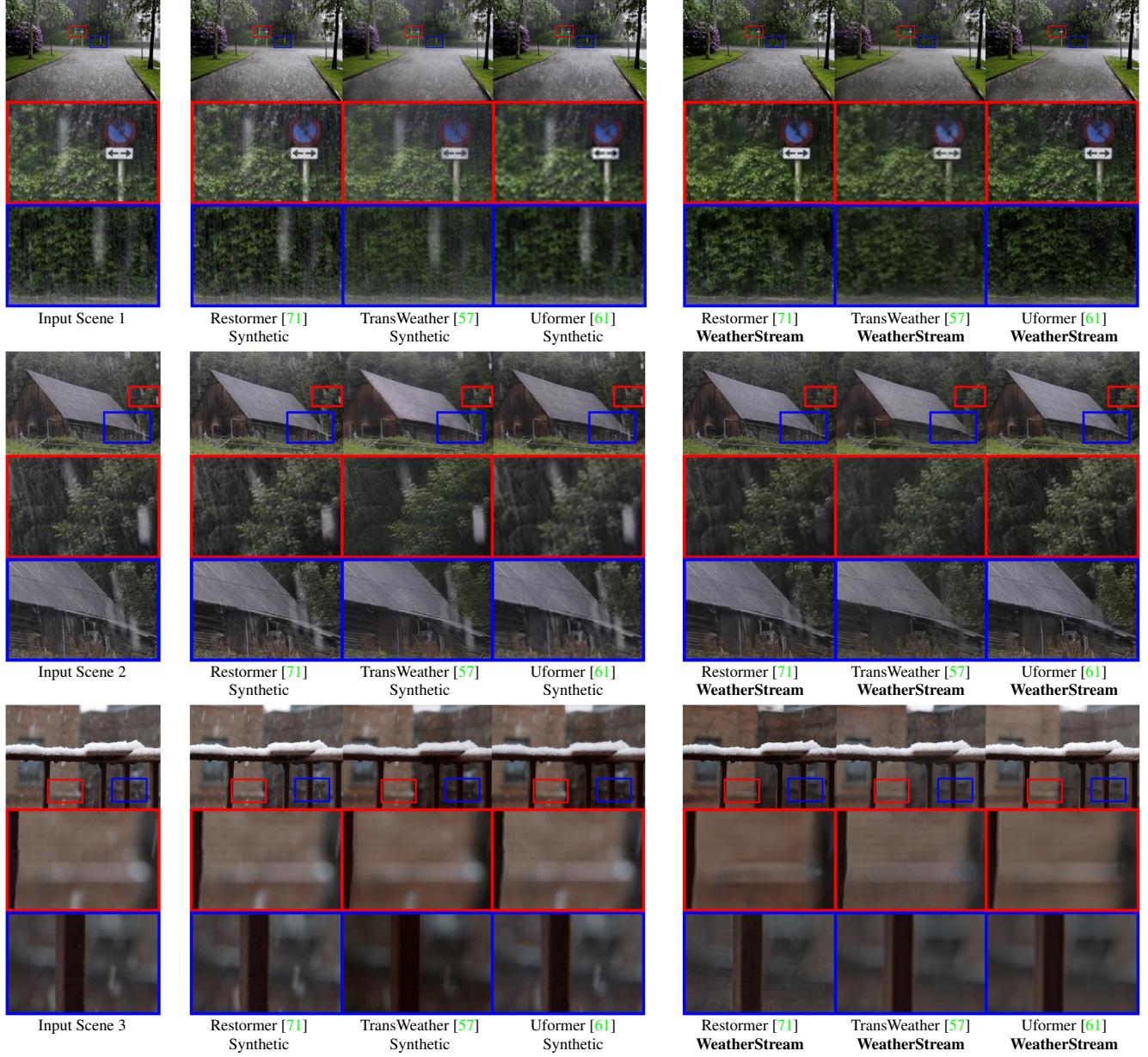


Figure 6. **Qualitative results showing generalization capability of synthetic data and WeatherStream**. Trained on internet images. Models trained on WeatherStream are better at removing particles and veiling effects.

leads to larger changes in performance and visual quality for deweathering, as compared to changing the model architecture. WeatherStream employs light transport properties with an initial model trained on a small seed dataset. The end-result: all models trained on WeatherStream perform better. The improvements are not just about scalability; automating light transport leads to more consistent ground-truth pairs, laying a foundation for future challenges.

An area of future work is to combine our dataset with simulated datasets. We did not do so in this paper, as time multiplexed datasets are not widely used and need to be established on their own first. WeatherStream is also an on-

going effort, and we aim to later include paired segmentation labels to support recognition tasks in adverse conditions. Deweathering models trained on WeatherStream may also support the re-use of pretrained models for downstream tasks such as detection [39, 50], segmentation [5, 36, 52], depth prediction [1, 49, 65], and completion [23, 66].

Acknowledgements: We thank members of the Visual Machines Group (VMG) at UCLA for feedback and support. This research was partially supported by ARL W911NF20-2-0158 under the cooperative A2I2 program. A.K. was supported by an NSF CAREER Award IIS-2046737 and Army Young Investigator Program (YIP) Award.

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