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Estimating Acidity in Precipitation Using Sulphur Dioxide Satellite Imagery

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Abstract. **Acid rain is a major regional scale environmental problem around the globe. To control acid rain pollution and to protect the ecological environment, it is a major need to identify the occurrence of acid rains. This paper presents a methodology for identifying the occurrence of acid rain using pH values calculated from normality by applying k-means clustering and haar wavelet transform on the satellite imagery of precipitation and SO_2. If the computed pH value lies in the range of $1 \leq pH \leq 5$, it is identified as acid rain. The results indicate that wind direction, wind speed, amount of rainfall, atmospheric pressure and concentration of SO_2 show a considerable influence on the occurrence of acid rain.**

Keywords*:* Acid rain, Haar wavelet, Image processing, k-means clustering, Normality, Precipitation, pH value

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1. Introduction

Acid rain affects lakes, streams, rivers, bays, ponds and other bodies of water by increasing their acidity until fish and other aquatic creatures can no longer live. Acid rain harms more than aquatic life. It also harms vegetation. Acid deposition acidifies the surface water, damages the forest and deteriorates ancient monuments by dry and wet pathways [14]. Perhaps the most important effects of acid rain on forests result from nutrient leaching, accumulation of toxic metals and the release of toxic aluminum. Nutrient leaching occurs when acid rain adds hydrogen ions to the soil which interact chemically with existing minerals. This displaces calcium, magnesium and potassium from soil particles and deprives trees of nutrition.

There are numerous places around the globe affected by acid rain and here are the major ones. Well-known buildings like the Statue of Liberty in New York, the TajMahal in India and St. Paul's Cathedral in London have all been damaged by this sort of acid rain. The North-eastern section of the United States, the South-eastern section of Canada, India, Japan, China, Central Europe and Scandinavia were acid rains is caused by high numbers of factories, automobiles and power plants.

Acid rain is a rain or any other forms of precipitation like acid snow, acid dew, acid fog, acid frost, acid hail and acid dust that is usually acidic. Acidity is measured on the per-hydrogen (pH) scale. Acid rain is decrease of acidity of rain water due to the reaction between pollutants and water which forms new chemical composition in the air having acid properties and fall down with rain water, so the rain water has low pH [11]. pH is a measure of concentration of positively charged ions. It ranges from 14 (alkaline or negatively charged ions) to 0 (acidic or positive ions). Pure water has a pH of 7 (neutral). Generally rain with a pH value of less than or equal to 5 is considered acid rain.

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Acid rain or acid deposition, mainly caused by sulfur dioxide (SO_2) and nitrogen oxide (NO_x) through the burning of fossil fuels, has been a serious environmental problem worldwide in the past several decades until now [15]. It is generally believed that after long-term leaching of acid rain, soil, aquatic ecosystem and forests will be damaged and the recovery will be a long process even though the acid deposition has greatly declined.

Acid precipitation has both natural and human causes. Every time there is a flash of lightening, oxygen and nitrogen gases fuse with the moisture in the air and cause some nitric acid to be deposited in raindrops. In the soil the nitric acid is absorbed and acts as a nitrogen fertilizer for plants. Volcanoes and forest fires may emit sulphur dioxide (SO2) which mixes with water vapor in the air and sunlight to create small amounts of sulphuric acid.

Acid rain can affect health of a human being through the atmosphere or the soil from which food is grown and eaten from. Acid rain causes toxic metals to break loose from their natural chemical compounds. Toxic metals themselves are dangerous, and if they are united with other elements, they are more harmless. They discharge toxic metals that might be absorbed by the water, crops, or animals that human consume. These foods that are consumed could cause severe nerve damage, brain damage or it may leads to death especially in children. To control acid rain pollution and to protect from its adverse effects on environment, acid rain detection takes a immediate cause

Many studies have focused on developing effective methods for identification of acid rain patterns by applying techniques like decision trees, artificial neural networks, numerical weather prediction physics and statistical approaches. Unfortunately they do not seem able to provide accurate acid rain predictions at the temporal and spatial resolutions required for meteorology. Therefore interesting options is offered by the use of remote sensing observations through satellite images whose output may provide useful information about the acid rain patterns and also allow obtaining now casting with improved performances. The present work is carried out in four stages: In the first stage, satellite images containing precipitation and SO_2 are clustered using k means clustering technique [23-25] to identify the cloud features and SO_2 concentration. In the next stage, haar wavelet [20-25] is applied on the feature extracted images of cloud and SO_2 in order to compute the mean wavelength (µ). Thirdly, normality (N) measure is done to compute the amount of concentration of sulphuric acid. Finally in the last stage, based on normality pH value is computed and if it lies in the range between $1 \leq pH \leq 5$, it is treated as acid rain.

The rest of the paper is organized as follows: Section II gives a glance to all the recent research carried on for the prediction of acid rain. Section III depicts the formation of acid rain. Section IV describes experimentation methodology. Section V illustrates the experimental results and finally Section VI gives a conclusion.

2. Recent Research

Investigation is a nonstop process. In the literature, there are many researches which are committed for identification of acid rain.

Miroslav Josipovic, Harold J.Annegarn, Melanie A.kneen, Pienaar JJ and Piketh SJ [1] tested the hypothesis that acidic atmospheric pollution deposition, originating from the South Africa central industries area, poses an environmental threat across a larger region within the dispersal footprints. Xiuying Zhang, Hong Jiang, Jiaxin and Qingxin Zhang [2] adopted decision tree method for the analysis of acid rain in north eastern china. Yoko Nagase and Emilson C.D.Silva [3] used game theoretic analysis for the identification of acid rain in China and Japan. Amrut G.Gaddamwar [4] used PH-Meter to predict weather studies zone is polluted or not. H.Morse [5] measured pH for rain, snow, and fog water. Mohsen Saeedi and Seyed Pejvak Pajooheshfar [6] examine acid rain and chemical composition of atmospheric precipitation in Tehran, Iran. S.H.Khoon, G.I.Issabayeva and L.W.Lee [7] tested air quality in Setapak district of kuala lumpar was studies by analysis the rain water chemical composition using ion chromatography method. Kan Huang, Guoshun Zhuang, Chang Xu, Ying Wang and Aohan Tang [8] showed that the chemistry of precipitation in Shanghai was under the influence of local pollution sources and the long and moderate range transport through back trajectory analysis.

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Shin-ichi Fujita, Akria Takahasi, Jian-Hua Weng and Lian-Fen Huang [9] analysis the chemical composition of precipitation in East Asia on the basis of the results of cooperative monitoring performed during the period from 1992 to 1993. Anita Singh and Madhookia Agarwal [10] showed the effect of acid rain and its ecological consequences. A.Santi, M.S.Saeni, T.June and N.A.Matjik [11] illustrated the impacts of air pollution and acid rain on the growth of orchid plants. R.Sequeina and M.R.Peart [12] analyzed the pH of daily rainfall at a rural site in Hong Kong. K.I.Hoi, K.M.Mok and K.V.Yuen [13] adopted Correlation analysis and cumulative distribution function to analyses the wet acid deposition in Macau. Fatma Ekmekyapar, Aysun Altikat, Zuleyha and Tuba Turan [14] analyzed acid rain and its effects in different sites in Turkey. SONG Xiaodong, Jiang Hong, YU Shuquan, Zhou Guomo [15] used hyper spectral data to detect the spectral change caused by acid stress to a native forest type in the Three Gorges region of China. Z.Lu, D.G.Streets, Q.Zhang, S.Wang and Q.Tan [16] studied the sulphur dioxide emission in china and sulphur dioxide trends in East Asia since 2000. S.J.Smith, A.N.Sharpley and R.G.Menzel [17] measured the pH of rainfall on agriculture watersheds during 1979 to 1983. R.A.Durst, W.Davison, K.Toth, J.E.Rothert,M.E.Peden and B.Griepink [18] used ion chromatography method for the determination of major anionic constitutes in wet deposition. David M. Eissenstat, James P.Syvertsen, Thomas J.Dean, Jon D.Johnson and George Yelenosky [19] illustrated the combined effects of ozone and acid rain on freeze resistance growth, and mineral nutrition using broad leaf-evergreen citrus and avocado trees. S.E.Schwartz and P.Warneck [26] uses the units in atmospheric chemistry.

3. Formation of Acid Rain

Rain water is never totally pure. It always contains some impurities from dust particles or from absorbing gases from the air. It forms when clean rain comes into contact with pollutants in the air, like Sulphur Dioxide (SO_2), Carbon Dioxide (CO_2), and Nitrogen Oxides (NO_x). Although sulphur dioxide and carbon dioxide occur in the air naturally, burning fossil fuels adds more of these chemicals to the air. When these pollutants are released into the air, they mix and react with water, oxygen, and other chemicals to form acid rain. Acid rain then falls to the earth where it can damage plants, animals, soil, water, and building materials.

The other major acidic oxide that contributes to the formation of acid rain is nitrogen dioxide. Nitric oxide is formed in high localized temperatures created by lightning strikes and naturally reacts in the atmosphere to produce nitrogen dioxide. Nitrogen dioxide is also produced in the high temperatures of combustion chambers of power stations and motor vehicles [10]. Both sulphur dioxide and nitrogen dioxide are acidic oxides and react with water to form acids.

Sulphur dioxide reacts with water to form sulphurous acid.

$$SO_2 + H_2O \rightarrow H_2SO_3$$

Substances in the upper atmosphere then catalyses the reaction between sulphurous acid and oxygen to form sulphuric acid.

$$2H_2SO_3 + O_2 \rightarrow 2H_2SO_4$$

Similarly, nitrogen dioxide reacts with water to form a mixture of nitric acid and nitrous acid.

$$2NO_2 + H_2O \rightarrow HNO_3 + HNO_2$$

Substances in the atmosphere then catalyses the reaction between nitrous acid and oxygen causing the formation of more nitric acid.

$$2HNO_2 + O_2 \rightarrow 2HNO_3$$

Both sulphuric acid and nitric acid are soluble in water and are the major acids present in acid rain. As this forms and falls onto the Earth's surface, these strong acids are also brought to the surface causing harmful effects on the built and the natural environment. The formation of acid rain is shown in Figure. 1.

Sulphur dioxide is emitted through combustion of fossil fuels containing sulphur as an impurity. Coal combustion is by far the major source of sulphur dioxide emitted into the atmosphere. During combustion, sulphur is oxidized to form sulphur dioxide. Sulphur dioxide rises into the atmosphere and is oxidized once again in the presence of atmospheric hydroxyl radicals to form sulphur trioxide (SO_3).

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Sulphur trioxide reacts with atmospheric water droplets to form sulphuric acid (H_2SO_4). Sulphur dioxide emission is the most common contributor to acid deposition, responsible for about 70% of the total. The greatest source of sulphur dioxide is due to emissions by thermal power plants, which pump approximately 15 million tons of SO_2 into the atmosphere each year, out of the total 22 million tons generated annually by human activities. Other contributors of sulphur dioxide include industrial processes and automobiles and other motor vehicles [10].

Nitrogen oxides are also formed through fossil fuel use. In contrast to sulphur, nitrogen is not an impurity but rather an integral part of the organic material making up fossil fuels. Fossil fuel combustion releases nitrogen into the atmosphere, usually in the form of nitric oxide (NO).

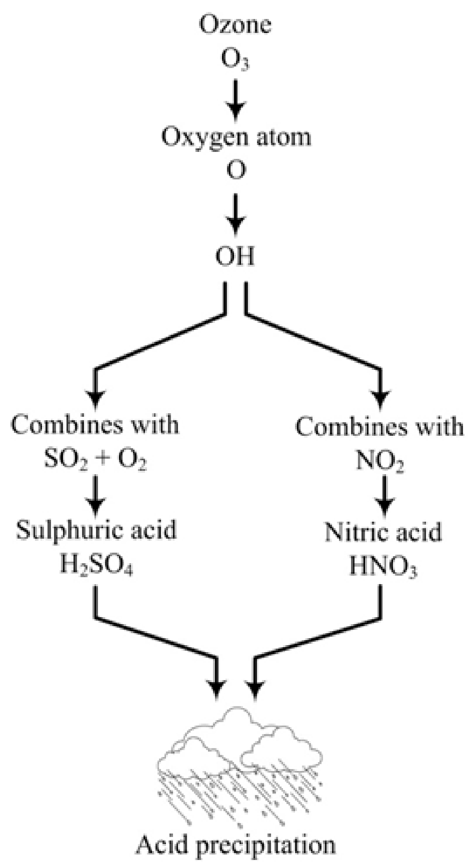

Figure 1. Formation of Acid Rain

Nitric oxide is oxidized by atmospheric molecules, such as ozone (O_3) or hydrogen dioxide (HO_2), to form nitrogen dioxide (NO_2). Nitrogen dioxide reacts with OH in the atmosphere to form nitric acid (HNO_3).

Nitric acid can also form when nitrogen dioxide reacts with the nitrate radical (NO_3) in the presence of atmospheric water or aldehydes. Nitrogen oxides account for approximately 30% of all acid deposition. Major sources of nitrogen oxide emissions are automobiles and fossil fuel burning power stations [10].These pollutants can be converted, through a series of complex chemical reactions, into sulphuric acid, nitric acid or hydrochloric acid, increasing the acidity of the rain or other type of precipitation, such as snow and hail.

The pH scale ranges in values from 1 to 14. The pH scale is used to indicate the nature of the substance as shown in Figure 2. When pH is below 7, it is acidic and an alkaline when pH is

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above 7. Any substance with a pH value 7 is considered a neutral substance. This means that the substance is neither an acidic nor alkaline. It also indicates the relative strength or concentration of each acid or base. Precipitation is considered as acid precipitation if it has a pH of less than or equal to 5.

4. Experimental Methodology

The purpose of this real time processing is to detect whether the satellite precipitation image is an acidic or alkaline. The overall process for determining the pH of rainfall from the images of precipitation and sulphur dioxide is shown diagrammatically in Figure 3. The inputs for this application are satellite imagery of precipitation and sulphur dioxide with noise or without noise. The satellite images obtained may contain the noise which is ought to be removed. There are different types of noise in satellite images such as striping noise, speckle noise, blurs and so on. These major noises are followed by minor obstructions such as illumination variations, occlusions, scale variations, deformation of objects and so on. When a satellite image contains noise, it is to be denoised before analysis as the value may deviate from original value [20].

The original image also contains various textures such as water bodies, forests, grass, asphalt, barren lands, concrete and clouds. These textures are to be separated to obtain the image of interest as the other textures does not affect acid rain prediction.

Clustering is the process of segmentation the data into several regions based on similarity measures using Euclidean distance. These segmentations are based on wavelength as similarity measure. The various pixel values of different textures are used for this segmentation which is shown in Table 1.

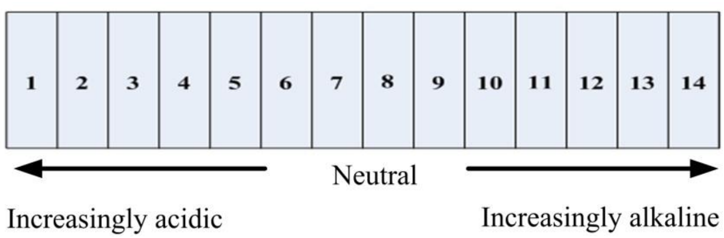

Figure 2. pH scale

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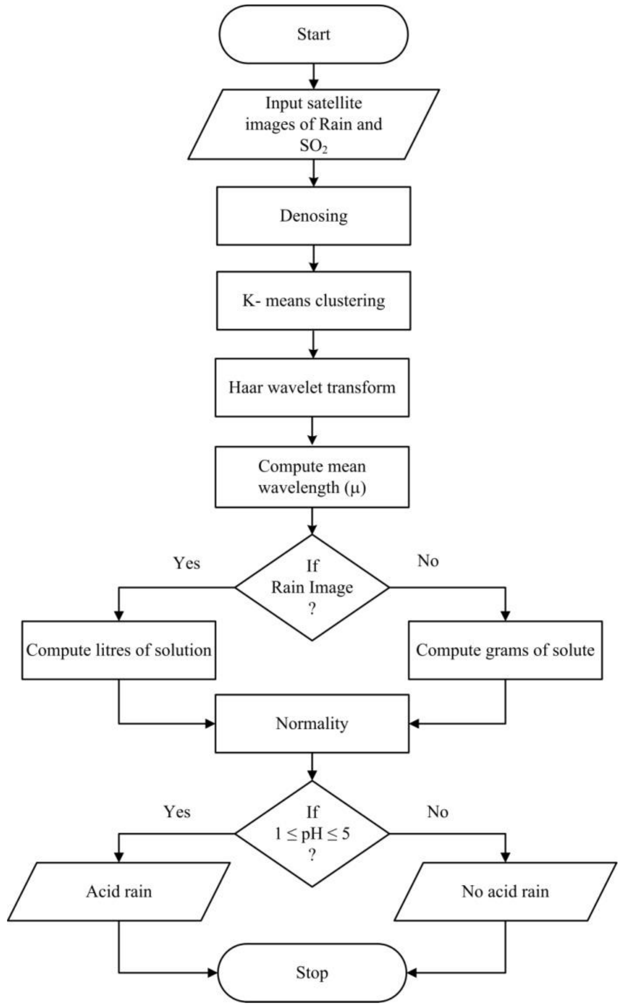

Figure 3. Real time detection of acid rain

Table 1. Pixel values of various textures

Textures	Pixel values
Water body	0-20
Forest	21-33
Grass	34-81
Asphalt	82-140
Barren lands	141-199
Concrete	200-224
Clouds	225-255

Based on the pixel values, the satellite image is segmented into various clusters to obtain the region of interest which is cloud and sulphur content texture. The cloud and sulphur content texture is found to be lying in between pixel values of 225 and 255.

Image segmentation using k-means clustering [23-25] is used to segment the data so that the objects in a cluster contain relatively similar data objects when compared with other clusters formed. K–means clustering algorithm is applied on water vapor precipitation image to form 4 segments and sulphur dioxide into 6 segments using Euclidean distance metric to provide local minima.

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The clusters obtained after segmentation process on the precipitation image shown in Figure 4 and sulphur dioxide image shown in Figure 5 are shown in Figure 6 and Figure 7 respectively. Here clustering is carried out using MATLAB 2011a tool box, which provide image segmentation algorithms and a comprehensive environment for data analysis, visualization and algorithm development.

The feature extracted cluster images shown in Figure 6(C) and Figure 7(E) are selected for further analysis to convert into frequency domain. The haar wavelet is chosen here as it is an efficient technique, where decomposition is applied to the image in rows and columns by transforming from data space to wavelet space in frequency domain [20-22]. As satellite images is an RGB image, Haar wavelet can automatically invert an RGB image into gray scale image which is later denoised and represented in one dimension.

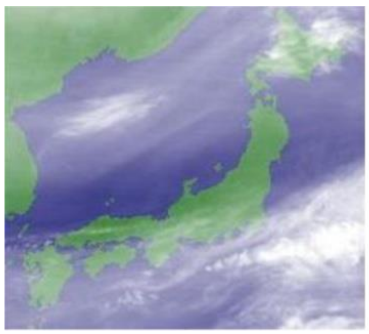

Figure 4. Original image of precipitation

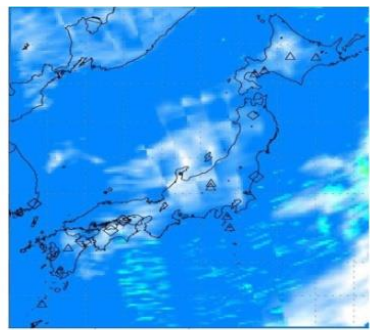

Figure 5. Original image of sulphur dioxide

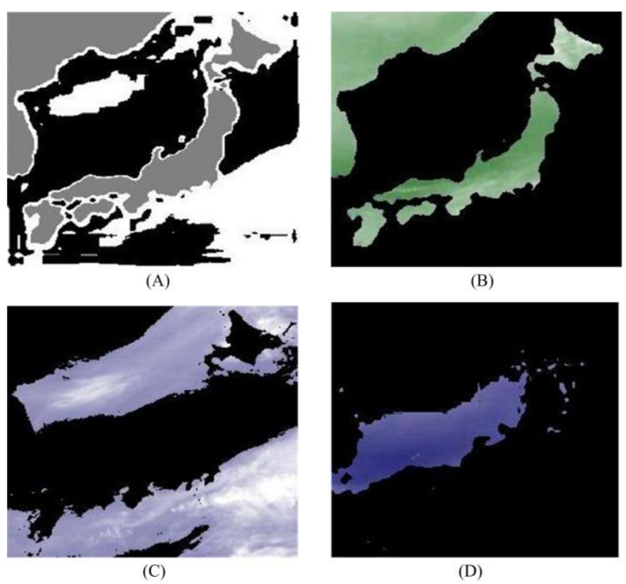

Figure 6. Precipitation images segmented into four clusters

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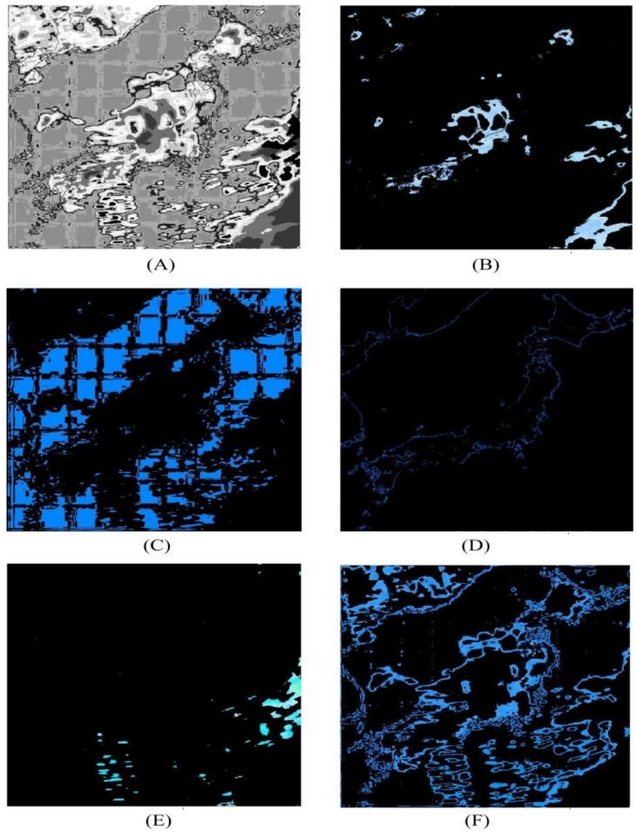

Figure 7. Sulphur dioxide images segmented into six clusters

Further we need to compute the pH value of rain, mean wavelength (μ) has to be estimated from the feature extracted images. Further, it is also required to compute ozone molecules, grams of sulphur dioxide, liquid molecules and liters of solution is to be calculated using equations 1, 2, 3, 4 and 5.

As a satellite image taken is in the form of visible (VIS) infrared, the wavelength of the spectrum would range in between 400 nm - 700 nm. This range of 300 nm wavelength of visible spectrum constitutes 2 dabson units. Therefore 1 nm consists of 0.0067 dabson unit. One DU is 2.69×10^{20} per square meter [26]. Avogadro's number 6.023 x 10^{23} mol^{-1} is a quantity of mole which is used to calculate the number of atoms present in the substance. The area of sulphur dioxide present in ozone molecules is to be taken for the input image being processed. Using these we compute ozone molecules, grams of sulphur dioxide, liquid molecules, liters of solution and normality using equations 1,2,3,4 and 5 respectively.

$$Ozone\,Molecules = \frac{Area\ of\ SO_2\ x\,0.0067\,x\,2.69\,x\,10^{20}}{Quantity\ of\ a\,mole} \quad (1)$$

$$Grams\,of\ SO_2 = \mu\,of\ SO_2\ x\,Ozone\,molecules\,x\,Molecular\,weight\ of\ SO_2 \quad (2)$$

Where, Molecular weight of SO_2 is 64.04 g/mol.

$$Liquid\ Molecules = \mu\,of\ H_2O\,x\,Ozone\,molecules\,x\,\frac{Molecular\,weight\ of\ H_2O}{Valence\,of\ O_2} \quad (3)$$

Where, molecular weight of H_2O is 18 and Valence of Oxygen is 2.

From equation 3, the amount of liquid present in the cloud can be analyzed by using the specific gravity of water i.e., 1.003 liters.

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$$Liters\ of\ solution = \frac{Liquid\ Molecules}{Specific\ gravity\ of\ water} \tag{4}$$

Normality is a way of expressing the concentration of a solution. The normality of a solution is the concentration expressed as the number of equivalent weight of solute per liter solution. It is based on an alternate chemical unit of mass called the equivalent weight.

$$Normality = \frac{Grams\ of\ solute}{Equivalent\ weight\ of\ solute\ x\ Liters\ of\ solution} \tag{5}$$

Where, equivalent weight of sulphuric acid is 49 grams.

Since, it is a diprotic acid the normality is used as a measure of reactive species in solution. In acid-base chemistry, normality is used to express the concentration of protons (H^+). Hence,

$$Normality = \left[H^+\right] ions.$$

To measure the acidity of a solution pH value is considered which is defined as negative logarithmic value of a hydrogen ion $H+$ concentration. This pH value also included with a correction factor as shown in equation 6.

$$pH = \left\{\left(-\log\left[H^+\right]x10\right) - 14\right\} \tag{6}$$

This Problem is extensively studied on 596 precipitation images and examined on 300 images to estimate the acidity. The pH values on a sample of 10 acid rain images are tabulated in Table 2. Our test data considered publicly available precipitation images on http://www.jma.go.jp and sulphur dioxide images on http://so2.gsfc.nasa.gov/. The pH value lies in the range of 1 to 5, justifying that the feature extraction images produce acidity, hence it is treated as acid rain.

Table 2. Estimation of pH in precipitation

Image No	μ SO_2	μ H_2O	Area of SO_2	Grams of SO_2	Liquid Molecules	Liters of Solution	Norm-ality	pH value
Image 51	2.457	17.78	16611 $x10^6$ m^2	7816.19 $x10^3$	7953.98 $x10^3$	7930.19 $x10^3$	0.02	2.96
Image 52	1.296	11.38	1069 $x10^6$ m^2	265.32 $x10^3$	327.62 $x10^3$	326.64 $x10^3$	0.02	3.8
Image 53	3.296	22.35	6571 $x10^6$ m^2	4147.75 $x10^3$	3955.18 $x10^3$	3943.35 $x10^3$	0.02	2.68
Image 54	3.408	22.08	44434 $x10^6$ m^2	29000.75$x10^3$	26422.34 $x10^3$	26343.31 $x10^3$	0.02	2.48
Image 55	3.791	24.09	13926 $x10^6$ m^2	10110.54$x10^3$	9034.83 $x10^3$	9007.81 $x10^3$	0.02	2.4
Image 56	2.67	24.68	12781 $x10^6$ m^2	6535.37 $x10^3$	8495.07 $x10^3$	8469.66 $x10^3$	0.02	4.03
Image 57	4.995	25.93	2293 $x10^6$ m^2	2193.48 $x10^3$	1601.27 $x10^3$	1596.48 $x10^3$	0.03	1.52
Image 58	2.53	23.57	13462 $x10^6$ m^2	6522.65 $x10^3$	8545.27 $x10^3$	8519.71 $x10^3$	0.02	4.06
Image 59	5.826	29.66	3773 $x10^6$ m^2	4209.70 $x10^3$	3013.80 $x10^3$	3004.79 $x10^3$	0.03	1.44
Image 60	2.526	22.04	19389 $x10^6$ m^2	9379.57 $x10^3$	11508.63 $x10^3$	11474.21 $x10^3$	0.02	3.78

5. Experimental Results

An attempt is made to examine the precipitation and estimating the acidity by calculating pH value to know the rainfall acidity in the precipitation using SO_2 satellite images.

The analysis has been carried out from 596 images obtain from Japan metrological department. The preliminary results in Table 3 is shown for 50 images where seventeen images cause acid rain and thirty three images are depicted as no acid rain.

Table 3. Analysis of Acid Rain

Image number	Normality (N)	pH value	Detection
Image 1	0.03	1.12	Acid Rain
Image 2	0.04	0.18	No Acid Rain
Image 3	0.02	2.67	Acid Rain
Image 4	0.01	5.77	No Acid Rain
Image 5	0.03	1.66	Acid Rain

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Image 6	0.01	4.26	Acid Rain
Image 7	0.04	0.30	No Acid Rain
Image 8	0.02	2.80	Acid Rain
Image 9	0.04	-0.47	No Acid Rain
Image 10	0.02	2.62	Acid Rain
Image 11	0.02	4.19	Acid Rain
Image 12	0.03	0.79	No Acid Rain
Image 13	0.02	3.34	Acid Rain
Image 14	0.02	2.20	Acid Rain
Image 15	0.03	0.78	No Acid Rain
Image 16	0.03	0.64	No Acid Rain
Image 17	0.02	4.18	Acid Rain
Image 18	0.05	-1.01	No Acid Rain
Image 19	0.04	-0.49	No Acid Rain
Image 20	0.10	-3.78	No Acid Rain
Image 21	0.03	1.16	Acid Rain
Image 22	0.07	-2.35	No Acid Rain
Image 23	0.08	-2.87	No Acid Rain
Image 24	0.11	-4.47	No Acid Rain
Image 25	0.06	-1.86	No Acid Rain
Image 26	0.05	-1.08	No Acid Rain
Image 27	0.05	-0.62	No Acid Rain
Image 28	0.05	-1.27	No Acid Rain
Image 29	0.10	-4.21	No Acid Rain
Image 30	0.04	-0.30	No Acid Rain
Image 31	0.06	-1.57	No Acid Rain
Image 32	0.04	0.13	No Acid Rain
Image 33	0.05	-0.75	No Acid Rain
Image 34	0.03	0.72	No Acid Rain
Image 35	0.05	-0.71	No Acid Rain
Image 36	0.05	-0.89	No Acid Rain
Image 37	0.08	-2.88	No Acid Rain
Image 38	0.03	1.84	Acid Rain
Image 39	0.05	-0.61	No Acid Rain
Image 40	0.04	-0.17	No Acid Rain
Image 41	0.06	-1.77	No Acid Rain
Image 42	0.04	0.15	No Acid Rain
Image 43	0.04	-0.19	No Acid Rain
Image 44	0.09	-3.71	No Acid Rain
Image 45	0.04	-0.25	No Acid Rain
Image 46	0.03	1.98	Acid Rain
Image 47	0.03	1.43	Acid Rain
Image 48	0.02	2.86	Acid Rain
Image 49	0.03	1.01	Acid Rain
Image 50	0.03	1.53	Acid Rain

Consider image 3, its calculated pH value is 2.67 which lies in the range established for acidity, hence it is an acid rain image. Also consider another image 4, its calculated pH value is 5.77 which does not lie in the range established for acidity, hence it is no acid rain image.

Estimating acidity in precipitation image is one of the challenging tasks that researchers of present day are experiencing. After a lot of research, still there is lack of an accurate model as the acid rain detection is not unidisciplinary but it is a multi disciplinary task which depends on various parameters. The detection of acid rain from satellite images is even more challenging as the images are always covered with different textures. A lot of research has been performed on the development of accurate techniques for the prediction of acid rain. But, these techniques are unable to perform up to their true extent.

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As the recognition of acid rain obtained from the present research is more than previous model, the proposed model proves to have more potential.

6. Conclusions

We presented a methodology to find acidity in precipitation using sulphur dioxide imagery. This problem is addressed for the first time which is computationally efficient and adapt to as well with respect to measured pH value.

This paper is only a step-towards utilizing the image processing and clustering methodologies for analyzing the satellite images. It would be of future interest to consider extensions of this method by using additional parameters like Nitric acid, Carbonic acid can be considered which would be emphasized in the future work. A more detail study on the data is planned to incorporate estimation of acidity in both wet and bulk precipitation, however the present method became a base for future research.

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