I, Monisha Baskaran, hereby submit this original work as part of the requirements for the degree of Master of Science in Computer Science.

It is entitled:
Feasibility of Graphically Displaying Icing Information over a Large Geographical Area using Minimal Weather Data

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Feasibility of graphically displaying icing information over a large geographical area using minimal weather data

A thesis submitted to the Graduate School of the University of Cincinnati in partial fulfillment of the requirements for the degree of

Master of Science in the Department of Electrical Engineering and Computing Systems of the College of Engineering and Applied Science

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by

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ABSTRACT

Monitoring and evaluation systems form a major part in building a robust system in all fields of engineering. A real-time weather monitoring and warning system for many bridges in North America was developed by the UCII research team of University of Cincinnati. The existing system uses many weather parameters to detect and predict snowfall accumulation and subsequent shedding on the Veterans’ Glass City Skyway Bridge. It issues alarms and alerts to ODOT officials during an icing event based on the analysis done on the data collected from the weather stations and sensors on and around the bridge.

This thesis is developed to investigate the feasibility of applying the same accretion and shedding algorithm over a much larger geographical area using minimal and unreliable weather data. This thesis will compare and quantify the accuracy of the accretion and shedding algorithm in this scenario against the existing system scenario. The result of the new geographically distributed algorithm would be a two dimensional graphical representation that will allow the human mind to better understand the historical and current weather events and possibly help improve the system to predict future icing events.
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1 CHAPTER: INTRODUCTION

1.1 OVERVIEW

The University of Cincinnati Infrastructure Institute (UCII) handles health monitoring of infrastructure systems (civil) and development, testing and maintenance of weather monitoring systems for bridges. Weather Monitoring Systems developed by UCII aim at monitoring the weather conditions on and around bridges for ODOT and after analysis generate alarms that depict the severity of the weather on the bridges. These alarms help in the decision-making process for the concerned officials. One of the main reasons for developing a weather monitoring system was the ice accumulation and shedding issues on bridge stays and cables that causes traffic, accidents and property damage on the bridge.

1.2 MOTIVATION

There are numerous reasons that motivate this research topic and they are:

- As a part of the weather monitoring, the existing system depicts only the conditions on the bridge using the sensors installed on the location and the airport stations close to the bridge. It would be more helpful to investigate the feasibility of the same over a larger geographical area.

- The larger area coverage would help in issuing alarms earlier than the current system based on the inflow of inclement weather.

- A visual representation of the data is the easiest form of understanding information which can assist in depth analysis.
• The current dashboard enables the plotting of line graphs for all the different parameters collected from various sources.

1.3 ICING ISSUE

There are numerous places in the world which are affected by severe winter conditions. The inclement weather conditions over long periods of time causes ice and wet snow accumulation on structures like bridges and roads which in turn causes property damage and safety hazards to the motorists using these structures.

During the ice event, if the temperature is below freezing point and there is incessant snowfall, the wet snow sticks to the surface of the bridges and become ice. When ice persists on the bridges over a period of time, shedding can be triggered by different weather conditions like heavy winds, rise in temperature, rainfall, solar radiation and so on. During the shedding process, huge ice chunks and sheets shed from the bridge structure falling onto the moving traffic on the bridge causing accidents. As a precautionary measure, the lanes on the bridge must be closed for safety which is an inconvenience to the daily commuters on the bridge. Lane closures can also have an economic impact if the bridges affected by the ice events connect important places.

This thesis will focus on the issues faced on the Veteran’s Glass City Skyway (VGCS) bridge in Toledo, Ohio.
1.4 BRIDGE INFORMATION

The Veterans’ Glass City Skyway (VGCS) Bridge is a cable-stayed bridge across the Maumee River and carries 6 lanes of the Interstate 280 in Toledo, Ohio. The bridge has a length of 8800 feet and a height of 400 feet. It is considered as one of the largest and expensive projects undertaken in the history of Ohio Department of Transportation (ODOT).

![Veteran's Glass City Skyway Bridge, aerial view](image)

Figure 1.1: Veteran’s Glass City Skyway Bridge, aerial view [22]

The bridge has a history of icing problems like ice shards, sheets of ice melting and falling off the cables on to the traffic prompting the ODOT officials to close lanes for safety purposes. This ice accumulation and shedding processes could be because of the material used to make the cable stays like stainless steel and because of the large diameter of the stay which aids to the wet snow settling on them and accumulating to form ice.
1.5 WEATHER MONITORING SYSTEM

In order to mitigate and predict the onslaught of the ice events, University of Cincinnati Infrastructure Institute (UCII) along with the University of Toledo (UT) have developed a weather monitoring system that helps in understanding the microclimate on the bridge by
detecting the events like ice presence, accumulation, thickness etc. This is accomplished with the help of various sensors installed on the bridge and the local weather stations in the airports near the bridge. The weather monitoring system developed by UCII can be separated into three parts like:

- Data Collection
- Data Processing and Analysis
- Dashboard displaying data

1.5.1 DATA COLLECTION

The data is collected from different sources for the weather monitoring system like the following:

- Data Loggers on the bridge
- Sensors installed on the bridge
- Airport Weather Stations

The python scripts run at regular intervals acquiring data from these sources and storing it in a database for processing.

1.5.2 DATA PROCESSING AND ANALYSIS

The data from the database is accessed and run through different algorithms that help in determining the impact of the climate on the bridge. It helps in classifying the data into different levels of intensity and issuing alerts and warnings in the case of an ice event that can cause major damage.
1.5.3 DASHBOARD

The results of the analysis and the alarms are displayed to the ODOT officials in the form of a weather dashboard website. The website was developed in Zend Framework using PHP and HTML. The graphical user interface consists of the following tabs:

- **Dashboard** – shows the current stay icing conditions, last 48 hours of icing conditions, health of the different data sources.
- **Map** – shows the weather data by location.
- **History** – shows all the archived alerts issued and their triggers based on the timespan chosen.
- **Documentation** – shows all the reports and documents related to the VGCS icing project.

![Figure 1.4: Screenshot of the Dashboard Website](image)
• Plotting – shows the different sensors and their parameters and allows the plotting of the variables for selected timespans.
• Algorithm Parameters – shows the different algorithm parameters that can be modified by the user dynamically without delving into the actual code.

1.6 PROBLEM STATEMENT

The current weather monitoring system has algorithms that use many weather variables like temperature, precipitation, solar radiation etc. to predict the snowfall accumulation and the subsequent shedding process at specific geographic locations. This prediction is local to the VGCS Bridge and does not help much in predicting the inclement weather before it hits the bridge. It will be more useful if it is possible to investigate the feasibility of applying the same accumulation and shedding algorithms over a larger geographical area using minimal weather data. The thesis aims to quantify the accuracy of the shedding algorithm in this scenario. It also aims to represent the result of the geographically distributed shedding algorithm in the form of a two-dimensional animation which allows a human to visually see and understand better the current and historical events and pave way for a possibility of predicting future ice events.

1.7 THESIS ORGANIZATION OVERVIEW

Chapter 1 introduces the icing issues on superstructures and mentions the different bridges that have the same issue. It also introduces the Veterans’ Glass City Skyway Bridge and the ice/wet snow accumulation issue faced on the bridge. There is a small overview of the current weather monitoring system developed by the UCII and the problem statement.
Chapter 2 deals with the different research done in relation with the icing issues on structures, analysis of contour plotting and different methods of visual representation of data. It outlines the importance of the research done in the prediction and mitigation of icing events.

Chapter 3 introduces the different data processing done on the raw weather data to generate a uniform visual representation of the same. It also discusses the issues faced during the data filtering and how it was handled.

Chapter 4 is about the modifications to the existing algorithm that will enable the monitoring of inclement weather over a larger geographical area. It goes into the details of the flow of the algorithm to generate the two-dimensional representation of the weather data.

Chapter 5 goes in depth about the accumulation and shedding rules of the existing monitoring system and the new proposed system.

Chapter 6 discusses the results obtained for the different weather parameters using contour plotting and then focuses on analysis and comparison of ice events with the actual measurements from the existing records.

Chapter 7 deals with the future possibilities of this thesis work.
CHAPTER: LITERATURE SURVEY/BACKGROUND RESEARCH

2.1 INTRODUCTION TO ICING

Icing is the process of ice formation on different objects and structures when exposed to cold atmospheric conditions. There can be two types of icing based on the formation process. [1] They are:

- In-cloud icing

  When super cooled liquid droplets in the atmosphere like in clouds, come in contact with a structure or an object, it freezes and forms ice accretion. This can cause major issues depending upon the build-up of the ice on the structure.

- Precipitation icing

  When the temperatures are low and the ice formation on structures happen because of precipitation type like wet snow, freezing rain, it is called precipitation icing. This form of icing is much more rapid than in-cloud icing. [2]

![Figure 2.1: Types of Icing](image)

The ice accretion, shedding and researching ways to mitigate this issue is a common phenomenon that occurs in different fields of work. The following are some of the industries that are affected by harsh winter conditions:

- Aerospace Industry
In the aviation industry, aircraft icing is one of the main weather based threats that cause lots of hazards. [3] Aircraft icing is mainly caused due to presence of large super cooled water droplets in the clouds that condense on contact with the fast-moving aircraft. The temperature optimal for icing in flight is between 32degF and -4degF and the aircraft must be in contact with the cloud droplets for ice accretion to take place. [4]

Figure 2.2: Icing on the front end of an aircraft [24]

There are numerous factors that affect the rate and amount of icing on aircrafts like cloud type, duration of exposure, temperature, liquid water concentration(LWC), size and shape of the craft, airspeed of the vehicle and size of the water droplets. [5] The other aspect of ice accretion besides all the above is, the rate at which the water droplets freeze to form ice accumulation which is dependent on heat transfer from the aircraft surface. When the aircraft
passes through a cloud with supercooled water droplets, those droplets in contact with the body will release their latent heat and freeze on the aircraft parts to form ice accumulation. [5]

The icing on aircraft body has cumulative affects like increasing the weight of the aircraft, increasing the drag, decreasing the thrust of a craft etc. To understand how ice accretion affects the performance of the aircraft and the aerodynamic effectiveness of the wings, tails, propellers and other significant parts of the craft, numerous research centers like NASA Lewis Research Center in the USA, Defence Evaluation and Research Agency (DERA) in UK, agencies in Spain, Germany, Canada are leading the way in aircraft-icing analysis to identify ways to detect, mitigate and prevent in-flight icing. [5]

2.1.2 WIND ENERGY INDUSTRY

With the drastic change in the world’s climate due to global warming and other environmental hazards, researchers are earnest in their search for alternate cleaner sources of renewable energy. In that context, generation of electricity from wind energy is becoming a popular
method of producing electricity. Wind mills are set up in regions that are identified for their strong high winds and many of the largest wind farms are located in Germany, China and the United States especially Northeast United States. In many of the regions where the wind farms are located, they experience cold weather conditions. And along with low temperatures, the cold weather brings a lot of issues to the wind mills like ice accretion on the structures and surfaces especially the wind turbines.

![Figure 2.4: Ice on the turbine blades](image)

When conditions are suitable, ice forms on the turbine blades and cause variety of problems. Frequent shutdown of the wind mills leading to loss of production, reduced power generation from strong winds due to disrupted aerodynamics, performance degradation and reduction in the lifespan of the turbine and components due to imbalance of ice load are some of the issues. [6] There could also be damage caused by the shedding of large chunks of ice from the blades to property and even human life.
The ways to mitigate and monitor the icing on the blades include ice-detection sensors and controls. Rotor Monitoring Concept called RMS helps measure the bending moment of the turbine blades and if it detects any anomalies, the turbine is shutdown. [7] It also tracks the thickness of ice accretion on the blades so that de-icing techniques can be applied to the blades. The icing can be controlled by using materials and element that have a good low temperature resistance for the wind turbines and the tower. [8] Most of the strategies from the aviation industry to mitigate icing can be used in the wind energy sector too.

2.1.3 ICE ACCRETION ON TRANSMISSION LINES

Ice accretion on the overhead power transmission lines is a persistent issue during the winter weather conditions of low temperature, freezing rain, wet snow and so on. [9] The icing along with high winds increase the load of the transmission towers and are likely to be pulled down causing fatal accidents, major power outages for extended periods and costing millions of dollars in repair and restoration of the lines. [10]
The ice accumulation on the transmission lines is a common disaster in many countries of the world like Canada, Central and Southwest America, Russia, Japan, United Kingdom and Iceland. To mitigate and remove the ice accumulation from the power lines, numerous deicing technologies are in place like mechanical deicing, electric melting ice and natural passive deicing methods. Under mechanical deicing, mechanical force is used to force the ice to break and fall off using artificial pulling of the pulley on the power lines. Recently with technological development, deicing robot have made mechanical deicing easier. Electric melting ice method involves using the joule heating effect that heats the icing conductor with huge current so that the ice melts. [11] Natural passive deicing is using the natural elements like wind, temperature changes, precipitation which will melt the ice without external energy.

2.1.4 ICE ACCUMULATION ON BRIDGES

Atmospheric icing on bridges is a winter weather phenomenon that is prevalent in all the countries that are affected by severe snow storms and low temperatures. High levels of
humidity, temperatures slightly below freezing point along with alternating cold and warm fronts result in the risk of ice accretion on the bridge stays and other surfaces. [12] Along with ice accretion, another process called ice shedding also happens. Shedding of ice can be induced by ice melting due to temperature increase, mechanical ice breaking, and electrical resistance heating technologies and so on. This icing can cause issues like damage to the bridge, traffic below on the bridge and to human life.

Figure 2.8: Ice chunks flying off the bridge on to the traffic (Red circles denote ice pieces) [2]

There are many bridges in the US that are affected by this icing issue. [13] Some of the known bridges with the icing issues are:

- Leonard P. Zakim Bunker Hill Bridge – Boston, Massachusetts
- Penobscot Narrows Bridge – Maine
- Port Mann Bridge – Vancouver, British Columbia
- Ravenel Bridge – South Carolina
- Severn Bridge – between England and Wales
- Uddevalla Bridge – Uddevalla, Sweden
- Great Belt Bridge – Denmark [12]
• Oresund Bridge – between Sweden and Denmark [12]

• Veterans’ Glass City Skyway Bridge – Toledo, Ohio

Figure 2.9: Known cable stayed bridges in the mainland United States and lower Canada overlaid onto the damaging winter storm footprint map (1946-2014) [13]

It is important to find ways to detect, mitigate and prevent ice accretion on the bridges. Many research teams are actively pursuing numerous methods of detection using sensors, cameras, drones, methods of predicting the ice accumulation using forecast data, sensor data et al.

During winter season, the icing issue prevails not only on the cable stays, bridge towers but also on bridge decks. When the moisture from the water below the bridge condenses and freeze on the deck this causes issues with motorist safety and cause traffic disruptions on the bridges. In order to prevent the snow and ice accumulation on bridge decks, in 1999, numerous heating technologies were implemented by the Federal Highway Administration under the Heated
Bridge Technology Program to convey heat to the surface of the bridge to melt the icing and prevent hazards. [14]

Figure 2.10: Icing on Bridge deck [27]

The instantaneous icing conditions on the deck have been reported that lasts for a short period of time causing roads with good traction change into a slippery slide where braking has no effect. This leads to accidents, damage to the bridge structure, vehicles and also causalities in some cases. Even with the presence of ice detectors and warning systems, the issues did not stop. Chemical freezing point depressants reduce the possibility of ice formation, but it is a temporary measure which has to be applied frequently to prevent hazards. Heating the bridge decks using different sources seemed to be a more permanent solution to mitigate this issue on those bridges identified by the Federal Highway Administration.
2.2 INTRODUCTION TO CONTOUR PLOTTING

Contour plot is a graphical representation method to display 3-dimensional surface on a 2-dimensional format. It is formed by variables represented on the vertical and horizontal axes connected by iso-lines. Usually, contour plot variables are restricted to a regular grid, but if the data does not form a regular grid, 2-dimensional interpolation of the data takes place to induce regularity into the dataset. [15]

Contour plotting is an excellent form of data visualization and complex data can be represented easily using these plots. Contour plots is useful to represent weather data like temperature, wind direction, precipitation, pressure et al. It is significantly used to represent correlation between different information to get a clear picture. In the research paper, ‘Modeling mortality fluctuations in Los Angeles as functions of pollution and weather effects’, contour plots were efficiently used to represent the correlation between the temperature and carbon monoxide to show the comparison between non-parametric and parametric regression methods in various scenarios. [16]

Temperature is a vital part for determining the thermal stress distribution in laser melting of metal powders in Additive Layer Manufacturing. The best way to represent the three-dimensional temperature field in multiple layers was using contour heat maps, temperature contour plots of the surface. [17]

Contours are useful in representing spatial data for research and analysis in various fields like climatology, environmental health etc. Since spatial data is highly multivariate and represented on maps, contour plots are an ideal choice. Seismic data is often represented in the form of
contour maps to visualize the slip distribution on a fault line, vertical and horizontal shifts can be observed using the structured contour maps of the region affected. [18]

![Contour Plot for amplitude of seismic activity](image)

**Figure 2.11: Contour Plot for amplitude of seismic activity [28]**

In this thesis, contour plots are utilized to visualize the movement of the cold front and also the ice accretion possibilities over a larger geographical region.

### 2.3 INTRODUCTION TO SCIENTIFIC COMPUTING USING PYTHON

Scientific computing is basically the application of algorithms and software to solve large scientific and engineering problems easily. Python programming language has numerous packages that facilitate large computations, graphical representation of large datasets etc. The following are some of the core packages that can be used to plot contours:

- SciPy Library
- Matplotlib Library
2.3.1 SCIPY LIBRARY

SciPy Library is an open source software for scientific computing in Python. There are many submodules to the SciPy library that help in mathematical calculation, in manipulating and visualizing data. This library has interpolation and smoothing splines package that help in organizing the datasets into a regular grid which helps immensely in plotting graphical representations. [19] Some of the functions in this subpackage are:

- Interp1d – to interpolate a 1-dimensional data/function
- Griddata – to interpolate unstructured multi-dimensional datasets
- Interp2d – to interpolate data/function over a 2-dimensional grid

2.3.2 MATPLOTLIB LIBRARY

Matplotlib is an open-source plotting library that helps generate different plot styles using built in code in Python language. It is function on the basis of the numPy package of Python. Matplotlib has a Matlab-like programming interface which could benefit MATLAB users while using Python for plotting. [20]

The different types of plots using matplotlib are:

- Line Plot
- Histogram
- Scatter Plot
- Contour Plot
- 3-D Plot
In order to increase the functionality of matplotlib, there are several toolkits that can be downloaded separately to assist the already existing functions. One such toolkit that is used for plotting is called Basemap. Basemap is a map based plotting tool with map projections, coastlines and political boundaries.

These python libraries are useful in a lot of research fields for graphically representing data and for mathematical computations. Audio signal processing applications use Python’s SciPy package to create audio programming libraries and identify ways to integrate python with two existing environments for music composition and signal processing. [21]
3 CHAPTER: DATA PROCESSING

This chapter deals with the different filtering and processing done on the data obtained from the various data sources. This is done to analyze the raw data in depth and obtain meaningful information which can be used in weather monitoring.

The data that is collected from the data sources have irregular collection intervals and a proper time series data is required to visually represent any time-dependent information. Irregular data distorts the purpose of the visual representation. For this reason, the raw data is processed before being used for plotting.

3.1 DATA SOURCES

Since the basis of the thesis is to analyze the icing patterns over a large geographical area, it is important to collect as much information as possible. The main source of the raw data was weather website called weatherunderground.com. This website has access to meaningful weather data sets from around the globe.

For this thesis, data was collected from numerous personal weather stations that are situated around the Veterans’ Glass City Skyway bridge. More than 250 weather stations were identified, out of which 155 personal weather stations were chosen as they were live and active during the time of this thesis.
Besides the weather stations obtained from weather underground, data was collected from the airports around Veterans’ Glass City Skyway bridge. The airports are:

- Toledo Express Airport (KTOL)
- Metcalf Field Airport (KTDZ)

Furthermore, data was also collected from 20 RWIS (Road Weather Information System) stations. RWIS stations are weather stations consisting of meteorological and pavement sensors located along the highway road system.
There are number of sensors installed on the bridge that collect information on the microclimate on the bridge. The sensors that are installed on the bridge are the following:

- Ice Detector
- Leaf Wetness Sensor
- Sunshine Sensor
- Rain Bucket
- Stay Thermistors
3.2 DATA COLLECTION

The raw data collection from personal weather stations was done using scripts that are written in the Python language. The collection scripts run every hour collecting live data. The python algorithm will generate the URL (Uniform Resource Locator) that will be used to access the Weather Underground website and download the data for each weather station chosen for that hour. The data from the bridge sensors is collected using data loggers which is accessed using LoggerNet, an application that performs the scheduled data retrieval process.

All the collected data is then stored into the database in the form of tables.
3.3 VARIABLE SELECTION

The data sources provide information on many weather parameters and out of which the following were the variables that was collected using the collection scripts:

- Temperature
- Dew Point
- Pressure
- Wind Direction
- Wind Direction Degrees
- Wind Speed
- Humidity
- Hourly Precipitation
- Conditions
- Events
- Cloud Cover
- Daily Rain
- Solar Radiation

Out of all the variables that are collected, the most important variables are temperature, daily rain, hourly precipitation and conditions. This is because whether the winter conditions in a region produce snow or ice heavily depends on the atmospheric and ground temperature and
also the amount of moisture in the air. The ‘Conditions’ variable provides classification of weather data as snow, ice, freezing rain et al from the airport stations.

3.4 DATA HANDLING

3.4.1 INTERVALS OF DATA COLLECTION

The collected data should be organized in a clean and efficient manner that facilitates the proper analysis of the same. The data must be collected at regular intervals to have a uniform data set. But since they are obtained from different sources, they all have different intervals.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Data Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Personal Weather Stations</td>
<td>1min, 10 min, 15 min</td>
</tr>
<tr>
<td>Airports</td>
<td>30min, 60 min</td>
</tr>
<tr>
<td>Bridge Sensors</td>
<td>10min, 15min</td>
</tr>
<tr>
<td>RWIS</td>
<td>10 min</td>
</tr>
</tbody>
</table>

Table 3.1: Data Intervals for all weather stations

3.4.2 ISSUES WITH THE DATA AND HOW IT WAS HANDLED

The collected data should be meaningful and complete to generate informative contours. After analyzing the data in the database, numerous issues have been identified with the records that would result in the wrong visualization of the weather data. These issues had to be rectified to generate proper contour plots. The following are the issues identified:

- NULL and out-of-range values
• Faulty weather stations
• Intermittent data from weather stations

3.4.2.1 NULL VALUES AND OUT-OF-RANGE VALUES

This issue was mainly observed in the personal weather stations that was obtained from the weather underground website. When the data collected was analyzed, there were many fields that recorded null or reported out of range values like ‘-999’, ‘-700’, ‘+999’ et al. This could be because the weather station did not record a value at that timestamp, or the sensors were not calibrated as per standards. The out-of-range values could mean that the data is missing, or that specific station sensors do not report that weather parameter making the data non-existent. There could also have been software issues while uploading the data values leading to the generation of abnormal weather data value.

The issue was handled by removing all the data records that show null and out-of-range values from the database. A python data cleaning script would check the database for null values and values that were beyond the acceptable levels of the weather parameters and remove that data record for that specific station from the database.

3.4.2.2 FAULTY WEATHER STATIONS

On inspecting the data records from the 155 live personal weather stations that were identified around the Veterans’ Glass City Skyway bridge, it was evident that not all weather stations had valid data throughout the data collection timespan. Some weather stations had no data
recorded for a day, while some others were off the grid for months together. Some stations would be live every alternate week or month. These personal weather stations are operated by common people who install the system in their houses, backyard, terrace et al. The reasons for the faulty stations could be that the weather sensors at the location malfunctioned or they are broken and are not replaced leading to weather underground website not receiving any data to display. The personal weather station owners could have deleted the stations from the website or stopped uploading any information to the same causing large gaps in the database.

The faulty weather station issue was handled by removing all the unreliable weather stations that do not report for longer periods of time rendering itself futile to the contour plotting. For weather stations that did not have data for days together or weeks, those records were removed from the database by the cleaning script.

3.4.2.3 INTERMITTENT DATA FROM WEATHER STATIONS

Besides having faulty weather station issues, there were smaller gaps of bad data in the database like for a few hours the values would not make sense but after that the records are appropriate. This could occur when the personal weather stations malfunction for a few hours and report bad data or no data at all, when the signal gets disrupted during upload process to the database, or even when the outside conditions have drastically changed around the station which is beyond the capability of the sensors to record causing bad data to be reported intermittently.
The intermittent data issue was solved by checking if the data gap was less than or equal to three hours and interpolating the data points for those few hours. But if the duration of the gap is greater than three hours, that record for the station was removed since it was not logical to interpolate data for more than three hours.

3.5 DATA PREPARATION

After handling the different issues in the dataset, the cleaned data was used to plot contours. To successfully plot the data, the intervals between each record should be regular and the weather stations with no data should be identified. It was then decided that the dataset should have data with 60 minute intervals so that the movement of the climatic changes can be observed by the human eye. The inconsistency in the data intervals is handled by calculating the arithmetic mean of all the data records for each hour. For example, if a personal weather station has temperature data coming in at 15 min intervals, for each hour, there will be four records. The temperature value for that hour can be calculated by the arithmetic mean of those four records.

\[ T_X = \frac{T_1 + T_2 + T_3 + T_4}{4} \]

The python script for generating hourly data would read raw input from the database for each station and calculate the mean average for each hour of the day and insert a new record of hourly data for that specific weather station into a new hourly dataset table in the database. The entire dataset was run through a python script to identify all the personal weather stations with null values, out-of-range values and then write the no-data stations into a text file. This text file will be used by the algorithm to remove the weather stations with no data to plot smooth contours.
4 CHAPTER: IMPLEMENTATION OF ALGORITHM

This chapter deals with the algorithms used to generate the contour plots for the weather parameters. The algorithms are written in the object-oriented programming language called Python in the development environment called Eclipse. The data collection and processing is done using scripts written in Python. The data for the processing is called from the database using SQL queries.

The main weather parameters used in the algorithms are the temperature, hourly precipitation and daily rain. The algorithm can be divided into three sections and they are:

- Identifying the best Contour Plot Method
- Querying and grouping of data
- Filtering the data based on cutoff values
- Plotting the contours for weather parameters

4.1 IDENTIFYING THE BEST CONTOUR PLOT METHOD

Different python packages were used to plot contours for the weather dataset. Some of them are:

- Basemap
  
  This method is more applicable for world maps and maps without detail. It is not appropriate for plotting our region specific weather data.
Figure 4.1: Sample Basemap contour [29]

- `scipy.interpolate.interp2d`

Contour plots were generated using the linear and cubic interpolation methods of `interp2d`. Since the data set was extremely irregular, the contour plots were disfigured.

Figure 4.2: Sample contour plot using interp2d linear method
• matplotlib.griddata

This function also had different interpolation methods like linear and natgrid. In this method, the irregular data is interpolated over a grid to make it regular.
The natgrid is the natural neighbor interpolation which uses a weighted average method to interpolate data.

After much trial and error, the natgrid function yielded smoother lines and gave the best possible contour plots.

4.2 QUERYING AND GROUPING OF THE DATA

The weather data collected from the external sources using Python scripts is stored in the database after the initiate data handing process. As mentioned in chapter 3, the final data set is formed by generating hourly data for each weather station. As the first step of the algorithm, for a set of specific dates, data for all the stations in the selected list of personal weather stations around the bridge, is queried from the database. For every station, data from each record is split and the value of the weather parameter for each hour is appended to separate lists. This is done to facilitate mapping of the data from each station at a specific hour to
generate contour plots for the same hour. Once this grouping is complete, the data set was used to plot contours.

After plotting the preliminary set of contours, there were numerous issues that prevented the generation of smooth and regular contours. The issues were:

- Data outliers
- Lack of edge points
- Large gaps in the plot
- Colormaps

### 4.2.1 DATA OUTLIERS

In the first set of contours plotted, there were many concentrated peaks in the contours which distorted the shape and color scheme of the entire contour map. The reason for this issue was that many personal weather stations had data that was distinctly out of the normal range. For example, if the average temperature at midday on the bridge was around 60°F, there would be stations that report very low temperatures or extremely high temperatures causing the concentrated peaks on the plots. These personal weather stations could be calibrated incorrectly or could be recording incorrect data due to issues with the sensors, damage to the weather station set up et al.
The method to rectify these outliers was to identify an appropriate cut-off value for the weather parameter that would not compromise the quantity and quality of the data set for each station. The standard deviation of each value from the mean of the dataset for that hour for every station was calculated for analysis. After the analysis of the standard deviation from the mean values for all the data in the database, it was found that a $3\sigma$ cutoff mark was appropriate to eliminate the outliers and keep up the quantity of the data set.

4.2.2 EDGE POINTS AND LARGE GAPS IN THE CONTOUR PLOT

The personal weather stations were chosen based on the proximity to the Veterans’ Glass City Skyway Bridge and validity of the data from these stations. The initial contour plotting for temperature did not have a defined boundary to the map which made these plots look incomplete and disconnected. This was because there were no proper personal weather
stations that determine the outer boundary to the contour plot. The plots also had large gaps due to the lack of personal weather stations over the region like the Lake Erie region.

Figure 4.7: Lack of edge boundaries and gaps with no data generate bad contours

The best way to handle the issue of lack of distinct boundary to the plot image is to add extra data points along the perimeter of the contour plot to smooth out the contour lines and add the least number of extra points to the areas without weather stations filling in the large gaps to generate a more fluid contour plot. The contour plotting region is divided into a grid of equidistant lines based on the latitude and longitude co-ordinates of the stations. The value of the edge points will be the average of its nearest neighbors. The nearest neighbors of the extra point are the stations closest to the co-ordinates of the Extra Point(EP) restricted to a maximum of three stations with valid data.
\[ T(EP) = \frac{\sum T(\text{Nearest Neighbors})}{N} \]

where \( N \) = Number of weather stations.

### 4.2.3 COLORMAPS

Every contour plot will require a color bar to map the values to the colors shown on the contour lines. For this thesis, the color bar will show the temperature value range, precipitation range et al. The average value of temperature throughout the year ranges from -15º F up to 60º F, this data range is too large to represent in one single color bar as it will not show the subtle changes in temperature clearly. After analysis of the maximum and minimum temperatures over the years for all the months, the year can be divided into three sections based on the seasons thereby solving the issue of having one color bar for the entire dataset. The three sections are:

- **December to March:** It is the coldest months of the year and the temperature are significantly in the low ranges.
- **April to August:** It is the spring - summer seasons and the temperature are in the range of moderate to high.
- **September to November:** It is the rainy autumn months and the temperatures lie between moderate and cold.

This separation of the year into three different color bars enables the human eye to see the smallest changes in climate patterns easily since the temperature ranges are restricted.
4.3 FILTERING THE DATA BASED ON CUTOFF VALUES

After rectifying the issues that occurred in the initial contour plotting, the algorithm was modified to add the filtering of weather stations, addition of extra points and multiple color bars.

As mentioned in Chapter 3, the no-data weather stations were identified and compiled into a text file. Once the data was grouped into different lists based on the hour, the first set of filtering happens by removing all the weather stations from the stations list that do not have any data. Then identify the weather stations that are nearby the extra points that are added to generate continuous contours. For each station in the final weather stations list, if it is one of the neighbors of the extra added points, append the values to a new list so that the average of all the nearest neighbors can be used to populate the extra points. Once the edge point and the extra points added to cover the large gaps are populated, the dataset is complete and ready for the next filtering step.

![Standard Deviation Chart for 9/22/2015](image)

Figure 4.8: Sample graph of a station for one day to show the validation of the cutoff to be $3\sigma$
In this step, for each temperature list per hour, calculate the standard deviation and the $3\sigma$ cut off mark. A list of all the weather stations with data beyond the $3\sigma$ cutoff was made. Based on the list, all the stations and their data is removed and the final dataset for plotting contours is generated.

### 4.4 Plotting the Contours for Weather Parameters

In order to plot the contours, the latitude, longitude and the temperature data is stored in the $x$, $y$ and $z$ variables. The weather parameter data is irregularly placed data on the map so it is required to interpolate it to a regular grid and then plot the contour lines. The matplotlib library of the python language is used in the algorithm to plot contours. The `griddata` method performs the natural neighbor interpolation of irregularly spaced temperature data into a regular grid, and then using the contour, `imshow` functions the contour lines are generated for each hour. The contour lines are plotted on a map image of the region around Veterans’ Glass City Skyway Bridge. Based on the month of the dates being plotted, the color map of the contour lines is determined and the color bar is populated. Using all the information, the final temperature plots are made and saved as an image file.
4.4.1 CONTOUR PLOTS FOR HOURLY PRECIPITATION

The other weather parameter that affects the icing conditions besides temperature is hourly precipitation. The presence of precipitation during low temperatures are the favorable conditions for ice accretion. To plot contours for hourly precipitation, the algorithm is the same as that of plotting temperature contours. The issues encountered during the plotting of hourly precipitation was data outliers and single value contour plots. The data outliers issue was handled the same way as that mentioned earlier in the chapter for temperature plots. The data for the entire year was analyzed to identify the outliers and the best value for the cut-off mark and based on the statistics for each weather station an upper limit for hourly precipitation of 4 in/hr was picked.
The next issue is when there is no precipitation in some regions around the VGCS Bridge, the contour function of the matplotlib library cannot plot contour lines leading to small concentrations of contours or extremely distorted lines which do not make sense. This was solved by using the filled-contour function that produces contours filled with colors based on the color map and not just lines.
5 CHAPTER: ACCUMULATION AND SHEDDING RULES

This chapter is about the accumulation and shedding rules that determine the presence of ice and its falling and how the existing system rules can be incorporated to the new weather stations data. Ice accumulation is the process of ice formation on structures when the conditions are favorable like low temperature, presence of precipitation like rain, snowfall, fog. When these conditions change, that is when the temperature increases, or when there is ample sunshine, the ice formed starts to melt and chip off resulting in the process called ice shedding.

After extensive analysis of all the icing events that occurred on the Veterans’ Glass City Skyway Bridge before 2011 and the reasons for the ice accretion and shedding process, the UCII research team developed an algorithm to evaluate the weather data based on these conditions that triggered the events between 2007 – 2011.

The existing weather monitoring system has various data sources like the METAR(airports), RWIS stations and different sensors located on the bridge. The main components for developing the accumulation and shedding rules are temperature and precipitation. The RWIS and METAR stations record different types of precipitation conditions as shown in the table below. To make analysis easy and efficient, the precipitation conditions were grouped into three categories named Rain, Snow and Others/None.
Table 5.1: Different form of precipitation for METAR and RWIS stations [30]

With the above categories of precipitation and the criteria that the air temperature and stay temperature should be below 32º F, the following Accumulation Rules were established in the algorithm:

<table>
<thead>
<tr>
<th>Accretion Rule</th>
<th>Temperature</th>
<th>Conditions/Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cold and Rain</td>
<td>Temperature &lt; 32º F</td>
<td>Rain</td>
</tr>
<tr>
<td>2 Cold and Fog</td>
<td>Temperature &lt; 32º F</td>
<td>Fog</td>
</tr>
<tr>
<td>3 Warm and Snow</td>
<td>Temperature &gt; 32º F</td>
<td>Snow</td>
</tr>
</tbody>
</table>

Table 5.2: Accumulation Rules for the existing weather monitoring system
If the atmospheric conditions around the bridge satisfy any of these rules, it is defined as ice accumulation or a possibility of the same on the bridge.

As for ice shedding, after analysis of the reasons for shedding it was identified that if the air and stay temperature is greater than 32º F and there are sunshine, clear skies or any form of precipitation, it is defined as ice falling or a possibility of the same. The following are the Ice Shedding Rules establish for the algorithm:

<table>
<thead>
<tr>
<th>Shedding Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
</tbody>
</table>

**Table 5.3: Shedding Rules for the existing weather monitoring system**

There have been numerous events on the bridge after the weather monitoring system was set up. These accumulation and shedding rules have been able to detect presence of ice and issue reasonably accurate alarms for accretion and shedding when the event is taking place on the bridge.

The same rules for accumulation and shedding could not be incorporated into new system which collects data from numerous weather stations all around the VGCS bridge. The main drawback is the lack of data from Precipitation Conditions/Events field in all those local weather stations. They did not have distinct conditions like Rain, Snow, Freezing Rain et al. instead they
had a value for hourly precipitation. Using the values of air temperature and hourly precipitation, the new modified rules for possibility of accumulation was formed as below:

<table>
<thead>
<tr>
<th>Rule</th>
<th>Temperature</th>
<th>Hourly Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Possible Accumulation - LOCW</td>
<td>23º F &lt;= Temperature &lt;= 33º F</td>
</tr>
<tr>
<td>2</td>
<td>Possible Accumulation – RWIS &amp; METAR</td>
<td>23º F &lt;= Temperature &lt;= 33º F</td>
</tr>
</tbody>
</table>

Table 5.4: New Accumulation Rules for the proposed monitoring system

There was no data for global or diffused radiation available in these local weather stations that was collected for contour plotting. Hence, the rules for possibility of ice shedding was formed with temperature parameter alone as below:

<table>
<thead>
<tr>
<th>Rule</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Temperature &gt;= 32º F</td>
</tr>
</tbody>
</table>

Table 5.5: New Shedding Rule for the proposed monitoring system

5.1 CONTOUR PLOTS FOR ACCUMULATION AND SHEDDING

The data collected from all the data sources is subjected to the new accumulation and shedding rules to generate alarms if the weather conditions are met for the same. The list of stations is split into three types and then the alarms are generated. The data is queried from the database and then for every station at each hour, the following happens:
• Personal Weather Stations: It is checked to see if the temperature is between 23º F - 33º F and hourly precipitation is greater than 0 inches to satisfy the accretion condition. If 50% of the records for that hour satisfy the condition, the value appended to the list is 1, else the value 0 is appended. If there is no sufficient data to determine the outcome of the condition, the value 2 is appended to indicate no data.

• RWIS Stations: It is checked to see if the temperature is between 23º F - 33º F and precipitation type indicates Rain, Snow or Others to satisfy the accretion condition. If 25% of the records for that hour satisfy the condition, the value appended to the list is 1, else the value 0 is appended. If there is no sufficient data to determine the outcome of the condition, the value 2 is appended to indicate no data.

• METAR Stations: It is checked to see if the temperature is between 23º F - 33º F and precipitation type indicates any type of Rain, any type of Snow or other forms of precipitation to satisfy the accretion condition. If 50% of the records for that hour satisfy the condition, the value appended to the list is 1, else the value 0 is appended. If there is no sufficient data to determine the outcome of the condition, the value 2 is appended to indicate no data.

Each of the updated list is then stored in the database so that it can be used to indicate possible accumulation in stations on the contour map.
The contour plots with accumulation alarms are generated the same way as that of temperature and hourly precipitation with the addition of a scatter plot. The scatter plot has points indicated by three different markers at the location of each of the personal weather stations, RWIS and METAR stations. The colors of the scatter plot markers will reflect the alarms at that location.
6 CHAPTER: ANALYSIS OF RESULTS

This chapter is all about the results of the algorithm generating contour plots for various weather parameters.

6.1 TEMPERATURE PLOT

The X axis represents latitude co-ordinates and the Y axis represents longitude co-ordinates on the map. The color bar on the right of the image indicates the temperature range for the plot. The lowest temperature is at the bottom of the bar and the temperature increases as you go up the color bar.

Figure 6.1: Temperature Contour Plot
6.2 HOURLY PRECIPITATION PLOT

The X axis represents latitude co-ordinates and the Y axis represents longitude co-ordinates on the map. The color bar on the right of the image indicates the hourly precipitation range for the plot. The bottom of the color bar indicates 0 in/hr and the values increase as you go up the color bar. The different markers indicate the three types of stations - personal weather stations, RWIS and METAR.

![Hourly Precipitation Contour Plot](image)

- ● Yes (Presence of precipitation)
- ● No (Absence of precipitation/ Clear)

Figure 6.2: Hourly Precipitation Contour Plot

6.3 ACCUMULATION PLOT

The X axis represents latitude co-ordinates and the Y axis represents longitude co-ordinates on the map. The color bar on the right of the image indicates the temperature range for the plot.
The bottom of the color bar indicates the least temperature on the plot and the values increase as you go up the color bar. The color bar on the left of the image indicates the hourly precipitation range for the plot. The bottom of the color bar indicates 0 in/hr and the values increase as you go up the color bar. The different markers indicate the three types of stations - personal weather stations, RWIS and METAR.

- **Yes (Accumulation conditions met)**
- **No (Accumulation condition not met/Clear)**

Figure 6.3: Accumulation Contour Plot

### 6.4 ICING EVENTS ON VGCS BRIDGE

There are numerous bridges all over Northern America that is affected by the icing issue. Since the time of opening the VGCS bridge to the public, there have been significant winter icing events with falling ice shards that has made the ODOT officials close the traffic lanes to prevent
damage to the public traveling on the bridge and the vehicles. These events have occurred over time and the following are the most significant event dates:

<table>
<thead>
<tr>
<th>Significant Event Dates</th>
<th>Dashboard Present</th>
<th>Bridge Sensors Installed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 December 9 – 12, 2007</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2 March 27 – 28, 2008</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3 December 17 – 24, 2008</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>4 January 3 – 21, 2009</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>5 February 20 – 25, 2011</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>6 February 26, 2013</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>7 March 16, 2013</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>8 March 25, 2013</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>9 December 9, 2013</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>10 April 3, 2014</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>11 January 3, 2015</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>12 January 21 – 25, 2015</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>13 March 3, 2015</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 6.1: All the icing events on the VGCS bridge

For the thesis, the winter icing event of January 21 – 25, 2015 was studied in detail.
6.5 EVENT ANALYSIS

6.5.1 January 21 – 25, 2015

This event was one of the major events of 2015 that took place on the VGCS Bridge. According to the existing monitoring system, there was significant ice accumulation on the cable stays and shedding was observed too.

The same event was analyzed visually using the data from the new proposed monitoring system. The data from all the personal weather stations, the RWIS stations along with the data from the METAR and bridge sensors was run through the new accumulation and shedding rules to see if they issue out alarms at the similar times as that of the existing monitoring system. Contour plots for temperature, hourly precipitation and accumulation was generated for the event.

As per the existing monitoring system, the dashboard went to accumulation level 1 alarm state on January 21\textsuperscript{st}, 2015 at 8 AM. The dashboard was triggered to the alarm state because of the KTOL airport reporting freezing rain, the thermistor temperature was less than 32\textdegree F and the Leaf Wetness Sensor was reporting a dielectric constant greater than the set threshold of 275mV.
Once the presence of ice on the cable stays was confirmed by the ODOT officials, the dashboard went into the Alert state and remained in that state throughout the day and well into the morning of January 22\textsuperscript{nd}, 2015. During the Alert state, the stay thermistor temperatures were below the freezing line and there was some form of precipitation throughout.

Based on the contour plots generated from the proposed monitoring system, it was seen that there was precipitation happening around locations southwest to the VGCS Bridge in the early hours of the morning and the cold temperatures were closing in on the bridge area from the north east. Based on the ice accretion criteria for this minimalistic dataset, many stations
around the bridge were reporting that the accumulation conditions were met much before the 8AM mark when the existing monitoring dashboard reported accumulation.

Figure 6.5: Accumulation Plot for January 21st, 2015 5AM

Figure 6.6: Accumulation Plot for January 21st, 2015 6AM
Figure 6.7: Accumulation Plot for January 21st, 2015 7AM

Figure 6.8: Accumulation Plot for January 21st, 2015 8AM
The contour plots leading up to the shedding event around mid-morning of January 22\textsuperscript{nd}, 2015 show low temperatures and precipitation over the region, satisfying the conditions for accumulation in many stations. The following contour images show the status of the stations around the bridge over different intervals of time.
Figure 6.11: Accumulation Plot for January 21\textsuperscript{st}, 2015 4PM

The cold temperature is slowing moving in around the VGCS Bridge area and the hourly precipitation contours are present indicating some form of precipitation in those regions. Based on the accretion rule, the stations that satisfy the conditions are reporting accumulation alarms.
This condition was the same throughout the night and well into the morning of January 22\textsuperscript{nd}, 2015. The contour below shows some precipitation in regions around the bridge.
According to the weather monitoring dashboard, sometime around 10AM on January 22\textsuperscript{nd}, 2015, the stay thermistor temperatures started increasing and there was some sunshine, because of which the dashboard went into shedding level 1 alarm state and then level 2. Since there was still significant amount of ice left on the cable stays, the ODOT officials reported presence of ice and the dashboard moved back into the Alert state.

![Figure 6.14: Dashboard shedding alarms for January 22, 2015 [23]](image)

As per the contour plots generated from the new rules, it is seen that the temperatures are increasing from 9AM in the morning of January 22\textsuperscript{nd}, 2015 and by the time it is 11AM, the temperatures in many regions around the bridge are more than 32\textdegree F which satisfy the conditions for shedding rule of the proposed monitoring system.
Figure 6.15: Accumulation Plot for January 22\textsuperscript{nd}, 2015 9AM

Figure 6.16: Accumulation Plot for January 22\textsuperscript{nd}, 2015 10AM
Figure 6.17: Accumulation Plot for January 22\textsuperscript{nd}, 2015 11AM

Figure 6.18: Accumulation Plot for January 22\textsuperscript{nd}, 2015 12PM
The shedding happens only after the accumulation process, so those stations that are pink indicate accumulation and as per the images, the temperature around those stations are clearly higher than 32deg F showing the possibility of a shedding event in all those stations in that region.

Figure 6.19: Accumulation Plot for January 22\textsuperscript{nd}, 2015 3PM
Figure 6.20: Accumulation Plot for January 22$^{nd}$, 2015 5PM

The temperatures suitable for shedding was observed till 5PM on January 22$^{nd}$, 2015 after which the temperatures dropped and the contours showed possible accumulation in some stations around the bridge region. The low temperatures persisted till late morning on January 23$^{rd}$, 2015 and then slowly there was an increase in the air temperatures, kicking in the shedding process in many stations that reported accumulation.

The reports from the dashboard showed that the air temperature and the stay thermistor temperatures dropped below the freezing line and stayed that way till noon of January 23$^{rd}$, 2015. Three lanes were closed on the North Bound side of the VGCS bridge on January 23$^{rd}$, 2015 morning as ice was still present on the stays. As the stay thermistor temperature increased above the freezing line in the afternoon, there was shedding observed and dashboard was in shedding alarm state.
Towards the end of the day on the 23\textsuperscript{rd}, the stay thermistor temperatures dropped and the ice presence was confirmed by the ODOT officials after a check, pushing the dashboard to the Alert state again.

The contour plots also favored the dashboard record and showed shedding conditions from 10AM with temperature slowly on the rise in many regions.
Figure 6.22: Accumulation Plot for January 23rd, 2015 10AM

Figure 6.23: Accumulation Plot for January 23rd, 2015 11AM
Figure 6.24: Accumulation Plot for January 23rd, 2015 12PM

Figure 6.25: Accumulation Plot for January 23rd, 2015 1PM
Figure 6.26: Accumulation Plot for January 23rd, 2015 2PM

Figure 6.27: Accumulation Plot for January 23rd, 2015 3PM
Figure 6.28: Accumulation Plot for January 23\textsuperscript{rd}, 2015 4PM

Figure 6.29: Accumulation Plot for January 23\textsuperscript{rd}, 2015 5PM
As the day ends, the temperatures slowly drop and it remains that way until January 24th, 2015 afternoon.

On January 24th, 2015, the dashboard showed that the air temperature and the stay thermistor temperatures started increasing steadily and there was snowfall on the bridge, causing ice shedding and pushing the dashboard to shedding alarm state. The dashboard returned to normal when one of the ODOT officials reported no ice presence on the stays around 1 AM on January 25th, 2015.

The above can be validated by the contour plots for January 24th, 2015 because the temperatures over the region in the image started increasing steadily from 11AM in the morning and there was no drop in the temperatures after that. In the late afternoon, many stations popped up on the map showing some form of precipitation. With increase in temperature, shedding possibilities in the region increases and precipitation only added to the process.
Figure 6.30: Accumulation Plot for January 24\textsuperscript{th}, 2015 11AM

Figure 6.31: Accumulation Plot for January 24\textsuperscript{th}, 2015 12PM
Figure 6.32: Accumulation Plot for January 24\textsuperscript{th}, 2015 1PM

Figure 6.33: Accumulation Plot for January 24\textsuperscript{th}, 2015 2PM
Figure 6.34: Accumulation Plot for January 24\textsuperscript{th}, 2015 4PM

Figure 6.35: Accumulation Plot for January 24\textsuperscript{th}, 2015 6PM
Figure 6.36: Accumulation Plot for January 24th, 2015 9PM

Figure 6.37: Accumulation Plot for January 24th, 2015 11PM
The above contours indicate that the weather stations went back to normal state towards the end of the day bringing the event to an end.

6.1.2 ALERT COMPARISON

The comparison between the proposed system alarms and dashboard alarms for accumulation and shedding can be depicted in a time-line format. The following graphs show the comparison for each of the days of the event analyzed.

![Alerts Comparison Graphs](image)

Figure 6.38: Alerts Comparison Graphs

The X-axis indicates the hours of the day and the Y-axis indicates different levels like 0.25 is the accumulation alerts from the existing system, 0.5 is the accumulation alerts from the proposed system, 0.75 is the shedding alerts from the existing system and 1 is the shedding alerts from the proposed system.
This comparison is made by analyzing the personal weather stations that are within the 15 mile radius from the VGCS bridge and analyzing the current dashboard alarms. The graph is represented in different levels to represent all the alarms in one single time-line. The comparison between the dashboard alarms and the contour image alarms showed that even with minimal data, the spatial analysis of accumulation and shedding patterns over the region surrounding the bridge depicted a condition similar to the micro climate observed on the VGCS Bridge.

![Alert Comparison Graph](image)

**Figure 6.39: Quantitative Alerts Comparison**

The figure above shows the number of alerts per day by the current and proposed system respectively. The difference between the numbers are extremely less indicating that the alerts from the proposed system is similar to the current dashboard alarms and the current icing algorithm can be optimized to monitor a larger geographical region.
7 CHAPTER: FUTURE WORK AND CONCLUSION

The best way to analyze data and identify patterns is through visual representation of the same. The contour plots are an ideal way to see how the climatic changes move over a region. The temperature plots and hourly precipitation plot, each provided a lot of information about the pattern of the cold front coming in from the arctic flow and the movement of precipitation over the region and showed us which regions receive more precipitation than others. The main reason for a contour plot is the ease of representing a lot of information, the accumulation plots showed us the temperature, precipitation and also the accumulating and shedding stations.

Accumulation and shedding patterns can be identified with minimal datasets. But to make the system more accurate and act as a warning system rather than a monitoring system, more weather parameters should be considered while generating the accumulation and shedding rules. For example, wind speed and wind direction parameters could add more value to the rules as shedding can happen due to high winds and the wind direction could possibly tell more about the direction of the snow storm. Finding the correlation between all the parameters that are recorded will help make the system more robust and reliable.

The future work on this thesis should include implementing this contour plotting as an embedded animation on the weather monitoring website, making it easier for everyone to view the images. It would be interesting to incorporate forecast data and see how the contour plots look like and make a comparison on how the forecast and the actual weather data different visually.
REFERENCEs


[19] “Interpolation (scipy.interpolate).”


