POLITECNICO DI MILANO

SCHOOL OF CIVIL, ENVIRONMENTAL AND LAND MANAGEMENT ENGINEERING

GEOINFORMATICS ENGINEERING DEPARTMENT

A THESIS REPORT ENTITLED

ADDITION OF METEOROLOGICAL INFORMATION TO goGPS SOFTWARE

BY

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DEDICATION

I dedicate this work to my Dad, Kobina Ebo Toffah and to my Mum, Aba Abokomah.

"Have I not commanded you? Be strong and courageous. Do not be afraid; do not be discouraged, for the Lord your God will be with you wherever you go."

(Joshua 1:9, NIV)

ACKNOWLEDGEMENT

ABSTRACT

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CHAPTER 1

INTRODUCTION

1.1 Background information and statement of problem

What do you want to say?

Weather forecasting, the application of science and technology for predicting the conditions of the atmosphere for a given location in future time, ~~is made by~~ requires collecting quantitative data about the state of the atmosphere at the desired place. that's not true! The forecasting technique requires capturing the trend of the state of the atmosphere from ~~the~~ regular observations and studying the study of historic phenomena. Notably, weather describes the condition of the atmosphere over a short period as compared to climate that describes changes in the atmosphere over a longer period.

also

What is the connection with the previous argument

Methods of weather forecasting include folklore, persistence forecasting, climatological forecasting, statistical forecasting, analogue forecasting, periodicity method, dynamical forecasting, numerical weather prediction, nowcasting, short and medium-range forecasts and longer-range forecasts (Linacre and Geerts, 1997). Dynamic forecasting technique, for instance, involves Meteorologists collecting data about temperature, humidity, wind direction and velocity, solar radiation, rain and atmospheric pressure (Linacre and Geerts, 1997). By measuring these variables, early warning systems can be put in place as proactive mechanism to save lives of people from weather and climate catastrophes. ?

The amount of water vapour in the atmosphere, which is usually the element of focus during Meteorological data collection, varies considerably over an area and across the globe. The water vapour and the interaction of the various elements of the atmosphere with electromagnetic radiation, such as solar radiation, plays a major role in the changing state of the atmosphere. Thus, having a measure of the water vapour content of the atmosphere is instrumental in forecasting techniques. Several instruments are available for measuring atmospheric parameters needed for weather prediction. These instruments operate on land (such as thermometer, wind vane and barometer at Meteorological stations), on sea (such as acoustic depth sounder and marine sounding probes) and in the air (such as artificial satellites, Meteorological aircrafts, aerosondes and radiosondes). Data collected by instruments that operate

??

in the air medium are very helpful as most parameters that influence the changing state of the atmosphere are found there. Among these, radiosondes (Figure 1) are commonly used to measure various atmospheric parameters including water vapour, pressure, and temperature. However, the cost of acquiring a radiosonde and establishing a radiosonde ground monitoring station makes it difficult to increase the spatial extent of a radiosonde network (Flores et al., 2013).

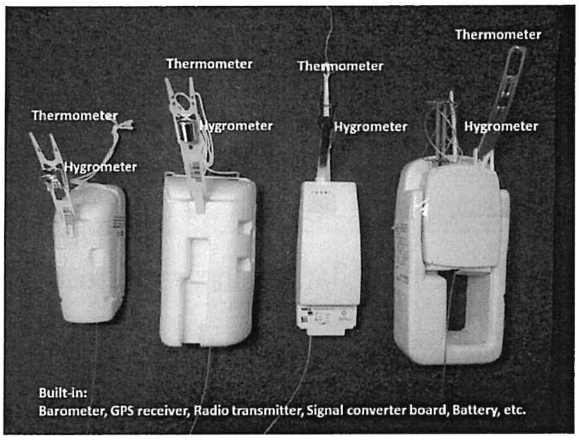

Figure 1 Radiosondes (source: Japan Meteorological Agency)

Although they do not physically operate in the air, Global Navigation Satellite SystemS (GNSS) measure space vehicle emitted signals that travel through and interact with the components of the atmosphere. The GNSS system is composed of space vehicles that operate in the skies, a control segment that monitors the space vehicles and user receivers that observe the signals emitted by the space vehicles for various purposes and applications. The varying state of the atmosphere and its consequent impact on the space vehicle signals make GNSS an innovative approach for measuring atmospheric water vapour contents ~~and for predicting the state of the atmosphere.~~ this is too much.

The use of GNSS for positioning and other scientific purposes has been widely explored and has gone through technological advancements. ~~This~~ Accurate positioning has been possible through appropriate modelling of the atmospheric interaction of ~~the ionospheric and tropospheric delays on~~ the satellite signals ~~and possibly accounting for relativistic effects.~~, which is subdivided in ionosphere and troposphere interaction —

The ionospheric delays are caused by the interaction of free electrons in the ionosphere (about 100 and 1000 km altitude) with the satellite travelling signal ~~of the~~

could be removed — a proper — observations on the

~~satellite~~. These delays ~~are accounted for~~ by ~~the~~ combination of the L1 (1575.42 MHz) and L2 (1227.60 MHz) frequencies ~~of the electromagnetic radiations of the satellite signals measured~~ made by double frequency receivers. For single frequency receivers, standard models (such as Klobuchar ionospheric model) exist for evaluating and removing thes ~~ionospheric~~ effect from the signal observations

The tropospheric delay ~~on the other hand~~ is partly caused by the presence of water vapour in the troposphere (0 to 40 km above the Earth Surface). This delay affects all the signals received by the GNSS station from all the satellites simultaneously in view at the time of the observation. In standard processing of GNSS observations, the delays on the signal path from all the satellites in view are ~~averaged as a~~ mapped in a common delay in the zenith direction above the receiver. This delay* – for instance can be modelled using the Saastamoinen model ~~and removed as a quantity~~ * known as Zenith Tropospheric (or Total) Delay (ZTD), ~~accumulated in a zenith direction above the receiver station~~. The ZTD, which ~~also varies with the height of the receiver~~, is ~~a~~ the sum of the delay caused by the ~~wet~~ water vapour (Zenith Wet Delay, ZWD) and the delay caused by the dry gases of the troposphere ~~hydrostatic~~ in hydrostatic equilibrium – (Zenith Hydrostatic Delay, ZHD) ~~components of the atmosphere~~. If temperature and pressure values are known at the time ~~of signal~~ observation, it is possible to exploit ~~this quantity~~ them to compute the ZHD component of the delay and to derive the wet component – This last can be used (especially the ZWD component) to monitor the presence of water vapour in the atmosphere. ~~These measurements~~ Both ZTDs and ZWDs can then be assimilated into numerical weather prediction models to ~~make the weather forecasts.~~ enhance the prediction of heavy rains –

TO RE-WRITE AGAIN

In the literature, GNSS has been applied in diverse ways on the variability of atmospheric water vapour, a parameter for weather forecasting. Barindelli et al (2018) studied the time variability of atmospheric water vapour associated with heavy rain using low-cost GNSS receivers. Also, Sangiorgio et al. (2019) used ZTD data provided at a GNSS station, combined it with neural networks, and obtained a 3-4% improvement in the accuracy of the prediction model. Lastly, Fermi et al., (2018) also used relative and absolute positioning techniques to estimate position coordinates and ZWD for Meteorological purposes and found the relative technique to outperform the absolute one.

the observation of moist by single GNSS stations

Before this sentence you have to say that

Due to the temporal and spatial variability of the water vapour content of the atmosphere, a more localised observation of GNSS derived ZTD will give more accurate results for weather forecasting. ~~Just like radiosondes~~, having a densified

dense networks of GNSS receivers are required for its monitoring

network of geodetic GNSS receivers ~~for monitoring purposes~~ has high costs of setup;
moreover ~~and~~ the risk of damages and losses can be discouraging. which favours the need for represent a possible solution -
A ~~a~~ monitoring system based on low-cost GNSS receivers. According to Biagi *et al.* (2016), low-cost GNSS receivers used for monitoring displacements and deformations achieve sub-cm accuracy levels. Also, Fermi *et. al* (2018) found that data from single frequency GNSS receivers (of which class belongs low-cost receivers) could provide more accurate results in estimating ZWD parameter for Meteorological purposes. In this light, many observation stations using GNSS satellite signals as an aid for meteorological purposes use a combination of both single and double frequency receivers. One software that can be used for post-processing GNSS observations is goGPS (see Chapter 4 for detailed description of the performance of goGPS). By making a plot of the post-processed information, goGPS produces among others plots of estimate of the amount of precipitable water vapour in the atmosphere (see Chapter 3 for further discussions) at an observation station (Figure 2).

TO BE WRITTEN AGAIN

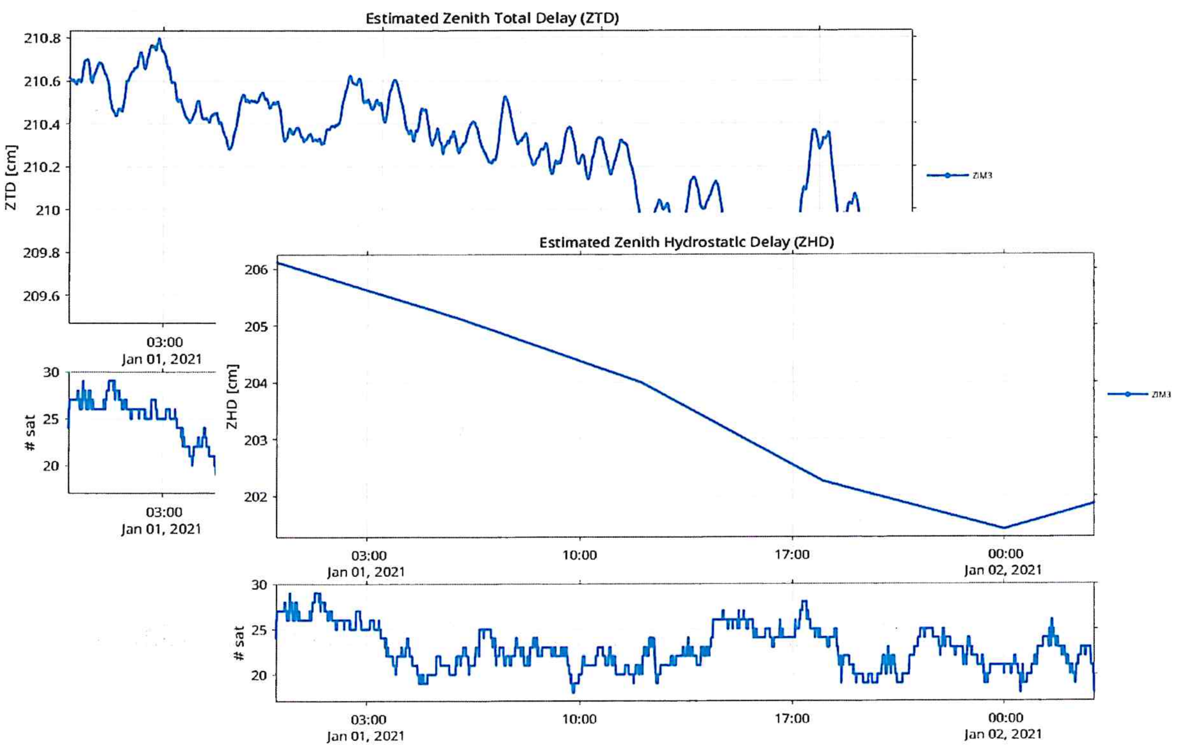

Figure 2 Current graphical outputs of goGPS

However, while making estimates of the amount of precipitable water vapour and monitoring the position coordinates and ZTD data of a GNSS station, it might be useful to know the state of the atmosphere such as the variability of temperature and pressure to better understand the impact of the atmosphere on the time variation of the ZTD and position coordinates. This is very essential as the observation station is exposed to the atmosphere and the observed signals traverse the atmosphere from the space vehicle to the receivers. The atmospheric condition can make a significant impact on the observations. Other meteorological events such as earthquake, tsunami and flood can significantly affect the estimated GNSS observations. Knowing these meteorological events and conditions will help better understand the trend of the plots and graphs produced by goGPS after post-processing the observation data.

The current interface of plots produced by goGPS is as in Figure 3. — it includes ... describe the plot.

Figure 3 Figure object with the menu items

goGPS plot of ~~ZWD~~ estimated ZWD

on

1.2 Objective

The objectives of this work is to develop a visualisation tool, as a component of the goGPS software, ~~and as an explanatory information for analysing the plots produced by goGPS.~~ The tool will allow the collection and visualization of humidity and temperatures from servers from meteorological stations (which ones? -- shown) -- insert a sentence explaining why those values are useful for goGPS --

1.3 Expected Output

To achieve the set objective, the explanatory tool has to be displayed on the figure containing the plots of goGPS (Figure 4). Also, it has to be accessed using a menu item on the figure containing submenu items as shown in Figure 5.

explain better

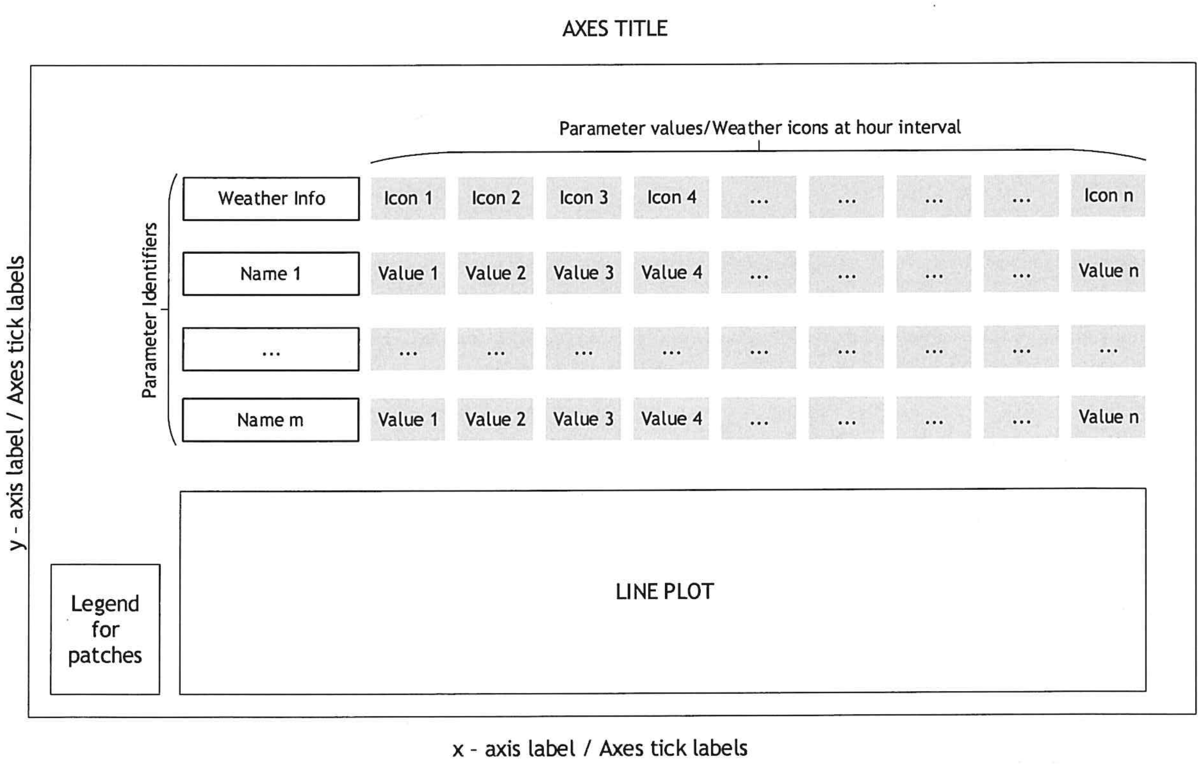

Figure 4 Format for the plot to contain the explanatory information

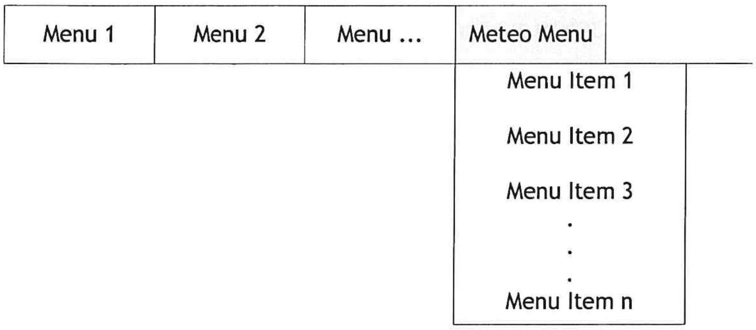

Figure 5 Expected menu item and its sub-items ?

1.4 Technologies to be Used

- GitHub
- goGPS and MATLAB
- Figma
- Adobe Photoshop
- Microsoft Office (Word, Excel, PowerPoint)

maybe here you can specify for which purposes those software suites are used —

1.5 ~~Organisation~~ Thesis content

The organisation of the thesis is carried out as follows.

~~In Chapter 1, there are the Background Introduction to and objectives of the work~~

Chapter 2 gives our overview of the atmosphere dynamics and phenomena

why are you including this chapter, is it essential for the thesis ?

Chapter 3 ~~talks~~ is about the interaction of GNSS signals with the atmosphere and the derivation of precipitable water vapour from the observed signal.

ZTD ZWD PWV

Chapter 4 ~~talks~~ is about goGPS software and software component development

?

Chapter 5 gives the methodology and the implementation schedule used for the development of a unit component of goGPS software.

Chapter 6 gives the results, discussion and a guidance on the interpretation of the visualisation results of the developed component ?

? tool

Chapter 7 gives ~~the~~ conclusion and recommendations for further development of the work.

CHAPTER 2

ATMOSPHERE

In this chapter ...

2.1 Composition and Structure

The atmosphere is the layer of gases that surround(s) the Earth, retained by the Earth's gravity. Up to about 80 km, the atmosphere consists chiefly of nitrogen and oxygen in almost constant proportions forming a layer known as the homosphere. There are also varying amounts of water vapour and carbon dioxide in the layer, which have a significant impact on ~~the~~ weather~~,~~ and climate~~s of the Earth~~. In proportions, the atmosphere is composed of about 78 percent nitrogen, 21 percent oxygen, 0.9 percent argon, and 0.1 percent other gases which include water vapour, hydrogen, carbon dioxide, ozone, neon, etc.

Different classification of the atmosphere are given:

1 - The atmosphere is classified by composition of gases into the heterosphere and the homosphere, separated by the turbopause. 2 - In accordance with the change of temperature above the surface of the Earth, the atmosphere is divided into the exosphere, thermosphere, mesosphere, stratosphere and the troposphere.

1 - The heterosphere has a non-uniform composition of gases, with the heavier molecules lying beneath the lighter ones. ~~The heterosphere~~ It extends from about 80-100 km to the outermost part of the atmosphere. It ~~also~~ contains the thermosphere and the exosphere. Beneath the heterosphere is the turbopause, which caps the homosphere beneath. ~~In~~ The homosphere ~~are a~~ is characterised by a uniform mixture of gases.

The exosphere is the outermost layer of the atmosphere that fades into space. Beneath it is the thermosphere, separated by the thermopause.

The thermosphere lies between the thermopause on the upper part and the mesopause on the lower part. It extends from about 85 to between 500 and 1000 km above the surface of the Earth. The solar radiation from the Sun heats up the air molecules in this layer and causes the dissociation of the molecules. This results in the freeing of ions, creating many charged ions. Thus, the thermosphere contains

electrons ?

most of the ionosphere. The layer is also characterised by the low density of the air molecules and their thorough mixing due to the turbulence in the layer. rephrase

Beneath the thermosphere is the mesosphere, bounded on the upper layer by the mesopause and on the lower part by the stratopause. The layer extends from about 50 to 80 km above the Earth's surface. In the mesosphere, the temperature decreases with increasing height as there is less absorption of solar radiation in the region and increasing cooling by CO_2 radiative emissions. The coldest regions of the Earth's atmosphere are found on the upper section of the mesosphere.

From the surface of the Earth, the stratosphere is the second lower layer, lying above the troposphere and separated from it by the tropopause. The stratopause separates the stratosphere from the mesosphere above. The layer extends from about 12 km to 50 km above the surface of the Earth. The stratosphere is the layer of the Earth's atmosphere that has a high concentration of ozone gas. These gases absorb much of the solar ultraviolet radiation coming from the Sun, causing an increase in the temperature of the layer with height. This temperature trend creates an atmosphere of stability such that the layers of air are stable, free from the weather phenomena that characterise the troposphere.

Finally, the troposphere is the last layer and the one lying on top of the Earth's surface. It extends to about 12 km above the surface of the Earth, bounded on the upper part by the tropopause. Radiations from the Sun that reach the surface of the Earth heats up the air molecules in the lower parts of the troposphere, causing a decrease in the temperature of the layer with increasing height. ~~Also, because of its closeness to the surface of the Earth,~~ the water bodies on the Earth's surface (rivers, lakes, seas, etc.) humidify the troposphere through evaporation and thus, much of the water vapour in the atmosphere is located in the troposphere, causing significant changes in the weather conditions in the layer. In the application of GNSS for Meteorological purposes, the troposphere is very vital as the water vapour in this layer causes a significant delay on the travelling satellite signals. change this expression

Figure 6 gives a clear picture of the variation of temperature with height for the various layers of the atmosphere.

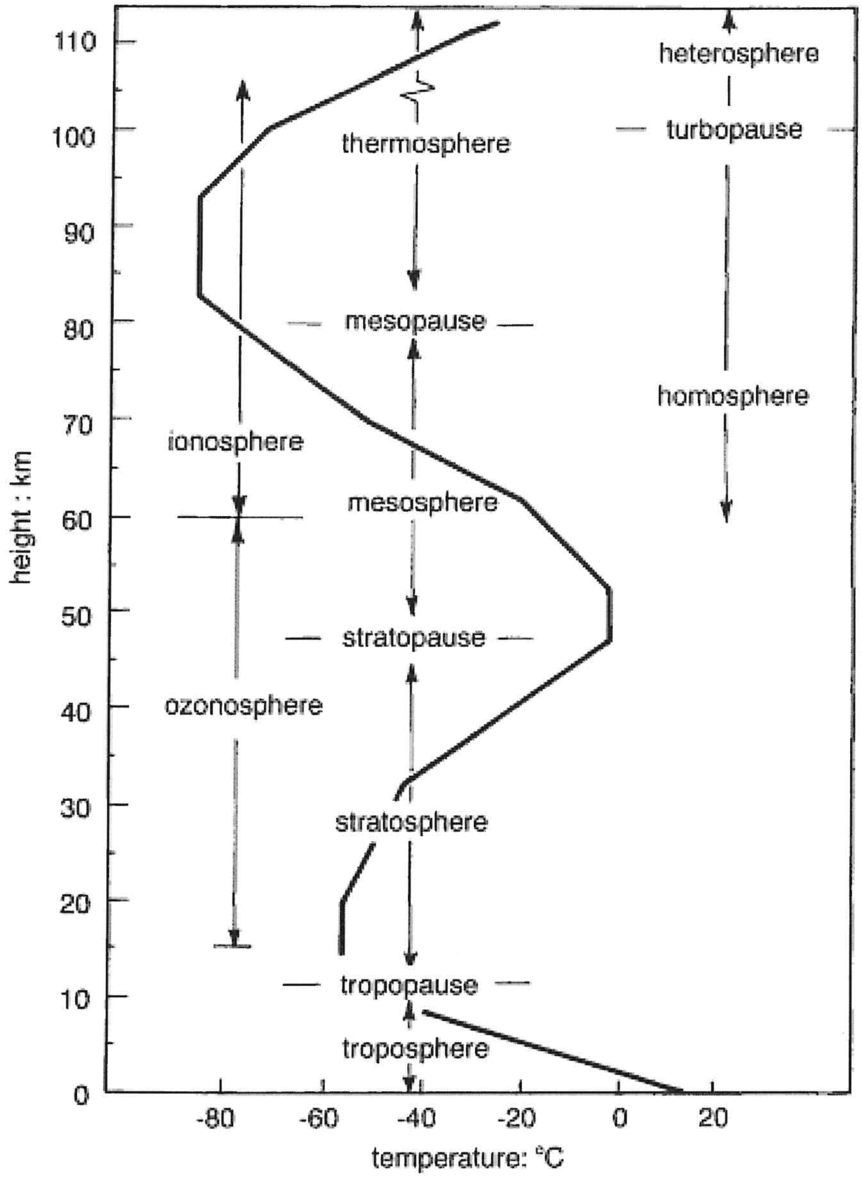

Figure 6 Variation of temperature with height of atmosphere

The atmosphere is essential for life on Earth as it makes available water, CO_2, oxygen and other essential gases for living organisms. It also protects life on the Earth surface by absorbing harmful ultraviolet solar radiations. Conversely, the atmosphere serves as the medium in which most Meteorological phenomena take place. These Meteorological phenomena are usually interrelated and categorised into (Linacre and Geert, 1997)

- those concerning the air's composition and structure such as air mass,
- those involving the Sun's energy such as thunderstorm and lightning,
- processes related to the transformations of water from liquid to vapour, cloud, rain and snow, and
- winds such as dust storms.

2.2 Atmospheric Humidity

2.2.1 Hydrologic cycle

~~An important gas that~~ Water vapour contributes greatly to the changing dynamics of the atmosphere ~~is water vapour~~, ~~and~~ It is ~~the~~ a fundamental variable of study in the hydrologic cycle and ~~also~~ in Meteorology. The hydrologic cycle describes the continuous circulation of water between the Earth and the atmosphere.

Solar radiations cause evaporation of water from the surface of the Earth to the atmosphere. This water vapour then condenses into clouds, fog etc. and falls as precipitates or rain to the Earth (land or ~~the~~ ocean). The water that falls on the surface of the Earth is ~~gets~~ transported to the oceans through surface runoff. Some of the rain percolates into the soil and is discharged into the ocean and other water bodies as groundwater. Figure 7 shows the phenomenon of the hydrologic cycle. In this cycle, the atmosphere holds less amount of water vapour, which also has a smaller molecular density compared to the oxygen (32 g/mol) and nitrogen (28 g/mol). Thus, the water vapour exerts less vapour pressure in the air. The atmosphere also holds very little of the world's water.

2.2.2 Humidity of the air

The amount of water vapour present in the atmosphere is defined as the humidity. Four indices are usually used for determining humidity, ~~are~~ absolute humidity, specific humidity, mixing ratio and relative humidity.

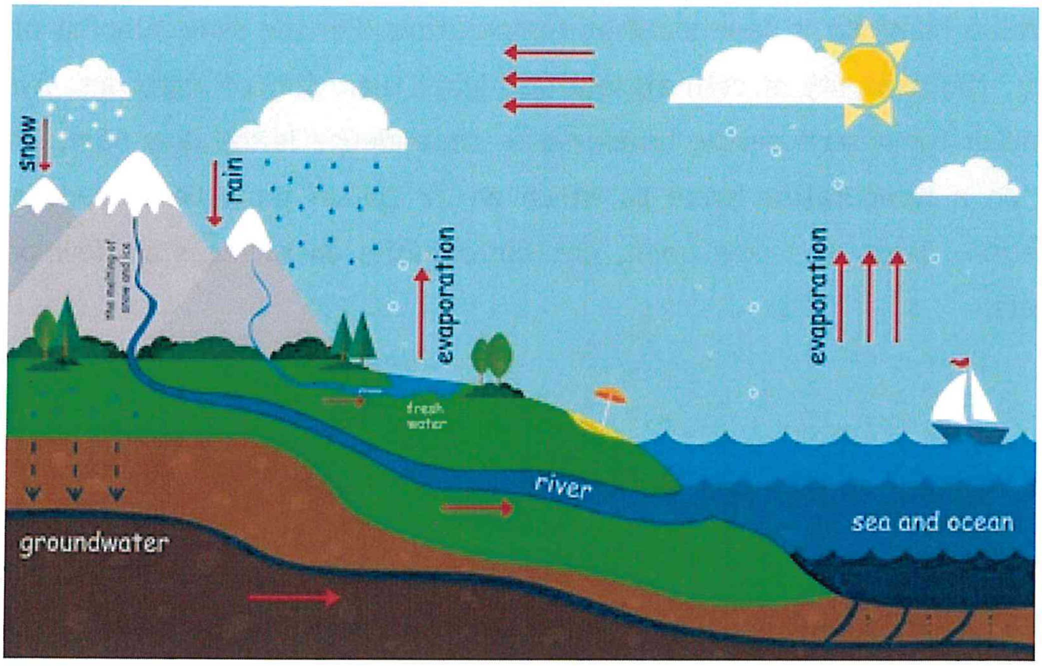

Figure 7 Hydrologic cycle

Absolute humidity refers to the mass of water vapour per unit ~~mass or~~ volume of moist air without taking into consideration temperature. The higher the amount of water vapour present, the higher the absolute humidity. It is expressed as grams of water vapour per cubic meter of air. Specific humidity refers to the mass of water vapour per unit mass of dry air and is measured as grams of water vapour per kilogram of dry air. It represents the actual amount of water vapour present in a unit mass of air. Mixing ratio is similar to the specific humidity, the only difference being that it considers mass of moist air instead of dry air. ~~On the other hand,~~ relative humidity is defined as the ratio of the partial vapour pressure of air to the saturated vapour pressure of the air at a specified temperature. In its simplest terms, it specifies how much of the water holding capacity of the air has been occupied by the water vapour at the specified temperature. At low temperatures, the water molecules tend to condense and the water holding capacity of the air decreases. Contrarily, warming the air will cause the water molecules to evaporate and the water holding capacity of the air to increase~~s~~. Relative humidity is expressed as a percentage and is the variable most commonly used in literature for expressing humidity of the air. It is also the variable ~~being~~ used to describe the humidity of the atmosphere in this work.

As already said

~~Generally,~~ humidity is dependent on temperature. For the same amount of water vapour, the humidity of cold air will be higher than that of warm air. A related parameter for describing the temperature dependence is the dew point. It is the point on a temperature scale to which an air parcel must be cooled to cause saturation. Below the dew point, the air deposits on surfaces as dew or cloud droplets.

2.2.3 Variation of humidity on the surface of the Earth

The amount of water vapour in the atmosphere at any point in time varies from place to place depending on factors such as elevation of an area with respect to the sea level, closeness to a water body, season of year, changes in weather phenomen~~on~~a during the day, latitude of the point of consideration etc.

Across the surface of the Earth, air masses originating from the continental landmasses are usually dry and have low humidity values as compared to those from the oceans, especially during the winter season in which the reduced temperature reduces the saturation vapour pressure of the air.

Also, regions of higher latitudes have lower vapour pressure and lower humidity.

Also, humidity decreases with increasing elevation and height of the atmosphere above the Earth surface. This is because moisture is added to the air mass nearer to the surface, which by convection is lifted upwards. At higher elevation, the temperature of the air reduces, the capacity of the air to hold moisture reduces, decreasing the humidity ~~at higher heights~~.

In addition, water vapour content of the atmosphere varies considerably during the day taking into perspective an air layer closer to the land surface. Lower temperatures at night cause condensation of water on cold surfaces and some also absorbed by colder soils. During clear or Sunny days, water vapour evaporates from warm surfaces and increases the moisture content of the air. Sea breeze during the day also adds moisture to the atmosphere. Thus, humidity is higher during the day and lower at night hours. Similarly, the moisture content of land areas closer to water bodies are higher than those inland.

Generally, wind moves air masses from one place to another. In windy hours, surrounding air is mixed with water vapour evaporating from surfaces, thus reducing the amount of water vapour in the atmosphere.

2.2.4 Measuring airs humidity

Humidity can be measured using several devices such as a psychrometer, electrical sensor and leaf wet sensor. Psychrometers are most commonly used in Meteorological stations. The device consists of wet and dry bulb thermometers. The wet bulb is covered with a moist wick. When air is passed over the wick, it evaporates the moisture, causing the bulb to register a lower temperature than the dry bulb.

2.3 Atmospheric pressure

The gravitational force of the Earth pulls the gaseous molecules in the air towards the centre of the Earth. In result, the gaseous molecules exert an amount of pressure. By measuring the pressure of the atmosphere, it is possible to know how much air there is above the measuring station. A reduction in atmospheric pressure value indicates a loss of air above the column. Atmospheric pressure is usually measured using a barometer made up of a column of mercury in a glass tube.

2.4 Atmospheric temperature

The temperature of the atmosphere is one variable whose variation is significantly felt. It also has predominant impact on the changing scenes of the atmosphere and weather phenomena though pressure, water vapour and wind also have impacts. Solar radiation from the Sun is divided ~~in the form~~ into visible, infra-red, ultraviolet and shorter wavelength radiations. Passing through the atmospheric layers, some of the radiations are absorbed by the molecules contained in the atmosphere. For instance, ozone molecules in the stratosphere absorb the ultraviolet radiations. A minimal amount reaches and warms the Earth surface. Insolation defines the amount of solar radiation that reaches the surface of the Earth. Air masses in the lower troposphere closer to the Earth surface get warmed-up by the radiations reflected from the surfaces, rise to higher heights in the atmosphere, and undergo several transformations resulting in the changing conditions of weather. Approximately all weather phenomena occur in the troposphere due to the heating of the air mass near the surface of the Earth.

Temperature varies at different heights relative to the Earth's surface as discussed in Section 2.1 ~~And~~ or as shown in the corresponding profile shown in Figure 6. In the troposphere, where most atmospheric phenomena occur, temperature decreases with increasing height above the Earth surface. This is due to the warming of the air mass near the Earth. Same also applies to higher elevations and mountains. Average temperatures tend to decrease by about 4.2 K per kilometre extra elevation (Linacre and Geerts, 1997).

Water has an especially high heat capacity at 4.18 $Jg^{-1}{}^{\circ}C^{-1}$ ~~and~~ while for land, it is usually less than 1 $Jg^{-1}{}^{\circ}C^{-1}$ (Anon., 2022). ~~which~~ This heat means it takes more heat to warm a gram of water than a gram of land. As a result, the ocean responds very slowly to temperature changes than the land. Hence, the land has a higher temperature than the ocean. Thus, air masses over the land surface will be much warmer than air masses over the oceans.

Latitude of a station on the Earth's surface is also another factor that causes variation in temperature. Around the equator (low latitudes), the solar insolation is higher than the thermal radiation, resulting in considerable net heat gain. The polar regions (higher latitude), ~~however~~, are characterised by a higher rate of thermal radiation than insolation, hence, more heat losses. These impacts may be nullified by the wind and ocean currents that carry air masses from the areas of higher temperatures to the areas of lower temperature.

The variation of temperature during the 24-hour period of a day is known as diurnal temperature variation. The maximum temperatures usually occur after noon as the air still keeps hold of some of the solar radiations absorbed at noon. The lowest temperatures occur at night, usually after dawn. This occurs as the Earth surface undergoes radiative cooling processes, especially when the night is clear and heat can escape through the atmosphere. The air above however gets warmer than the surface resulting in an inversion of temperature.

In the same way, there are seasonal contrasts in temperature. During summer, the air above land has a higher temperature than the oceans. In winter ~~Nevertheless~~, the air above oceans gets higher temperature than landmasses ~~in winter~~.

2.4.1 Measurement of atmospheric temperature

Temperature is usually measured using a thermometer. At a ~~M~~meteorological station, the standard height for the thermometer above the ground has to be between 1.25 and 2 m according to the World Meteorological Organisation and protected with the Stevenson screen. There is no single thermometer measuring the global temperature, however, individual measurements taken every day at several thousand stations over the land areas of the world are combined with thousands more measurements of sea surface temperature taken from ships moving over the oceans to produce an estimate of global average temperature every month (Trenberth et al., 2007). Such is the data source of Dark Sky upon which this work is being carried out.

2.5 Clouds, categories, formation and processes

The data source being used for this work, DarSky, classifies the state of the atmosphere in five major groupings: clear, cloudy, rain, sleet and snow. These are formed from clouds as a result of the changing conditions of the atmosphere due to the heating of the Earth surface by the Sun. The ultraviolet radiation of the Sun reaches the Earth's surface unevenly creating variations in air pressure. Low air pressure causes rising air that is lighter than the surrounding air masses. Rising air makes the water vapour in the air condense and form clouds, leading to rain, thunderstorms and hurricanes. On the other hand, high air pressure causes heavy and sinking air that makes the environment unstable. High air pressure is usually related to clear skies and Sunshine. The condition of the sky at any point in time is determined by the predominance of a state (such as mostly cloudy, overcast, and cloudy) over other conditions of the sky.

Clouds are made up of tiny droplets of water and ice crystals suspended in the atmosphere. Clouds play an essential role in the hydrologic cycle of the planet Earth. They reflect some of the incident solar radiation into space and also absorb infrared radiations reflected from the Earth surface. On the other hand, clouds have a significant impact on the changing weather conditions.

Cloud droplets have a diameter of about 10 - 15 microns (1 micron = 1/1000 mm), each cubic metre of air will contain about 100 million droplets (Anon., 2022) and can remain in liquid form in temperatures of -30°C.

Clouds are generally formed when molecules of water vapour in the air condense into water droplets or ice crystals. It is essential that the air be saturated to a point that it is unable to hold any more water vapor molecules. Also, there has to be availability of cloud condensation nuclei such as dust, clay and soot, to provide a surface on which the water molecules will condense. There are two basic ways in which saturation can be reached (Anon., 2021)

- By increasing the water vapour content of the air to a point such that the air is unable to hold any more water. This can be realised when the Sun heats up the ground, which in turn heats the air in contact with it, causing the air to rise to higher atmospheres.

- By cooling the air to its dew point so that the air is unable to hold any more water vapour, making it favourable for condensation to occur. This cooling is realised
  - When a mass of warm air moves over a mass of cold air creating a frontal boundary.
  - When the air mixes with colder air

- Through Interaction of the air with mountains or undulated topography of an area
- by nocturnal radiation loss

2.5.1 Categories of Clouds

There are various clouds identified by their shape and other attributes, however only ten are recognised according to the World Meteorological Organisation standards. These 10 basic classifications of clouds, also referred to as genera, describe the height where they are formed and their appearances. These classes are listed in Table 1.

Table 1 Classification of Clouds

Cloud Level	Altitude (Km)	Class According to Shape
High	6-10	Cirrus, Cirrocumulus, Cirrostratus
Medium	3-6	Altocumulus, Altostratus, Nimbostratus
Low	Less than 3	Stratocumulus, Stratus, Cumulus
towering vertical	0.6-6	Cumulonimbus

These genera are further divided into secondary classes of 14 species, which are further divided into 9 varieties of tertiary classes. The species describe the internal structure of the cloud while the varieties describe the transparency and arrangement of the clouds. These categories are as shown in table 2.

Table 2 Categories of Clouds

Classification	Categories
Species	calvus, capillatus, castellanus, congestus, fibratus, floccus, fractus, humilis, lenticularis, mediocris, nebulosus, spissatus, stratiformis, uncinus
variety	cumulogenitus, duplicatus, intortus, lacunosus, opacus, perlucidus, radiatus, translucidus, undulates, vertebratus,

To understand the various weather phenomena that this work seeks to show while monitoring a station, the primary classification of the clouds based on the height of cloud formation and its appearance will be studied.

Cirrus

This is the main type of high cloud occurring in the upper troposphere. They appear as tufts and whitish and sometimes greyish in colour (Figure 8). It is made up chiefly of ice crystals that form because of the low temperatures at the top of the troposphere. On falling, these ice crystals evaporate on warmer layers and usually do not fall to the ground. They also give precipitation when they join together and form thicker components. They can be an indication of rain.

Figure 8 Cirrus

Cirrocumulus

Cirrocumulus (Figure 9) is a layer of cloud made up of small elements in the form of ripples that form as a result of the transformation of cirrus and cirrostratus. They are whitish but sometimes appear greyish. They are smaller than the width of the littlest finger when one holds up the hand at arm's length. It consists, chiefly, of water vapour. Cirrocumulus clouds indicate an unstable atmosphere and lead to heavy showers.

Figure 9 Cirrocumulus

Cirrostratus

Cirrostratus clouds (Figure 10) are high layer clouds with no variation in tone from part to the other. They are formed at the forefront of the frontal weather system and also through the trails left by an air plane as it flies through the atmosphere. Cirrostratus clouds sometimes signal the approach of a warm front if they form after cirrus and spread from one area across the sky, and thus may be signs that precipitation might follow in the next 12 to 24 hours.

Figure 10 Cirrostratus

Altocumulus

This is a mid-level layer cloud that looks like it is made of regular cotton-wool balls. Altocumulus clouds (Figure 11) are comparatively larger in size than the cirrocumulus clouds and they give an indication of storm or development of thunderstorms later in the day.

Figure 11 Altocumulus

Altostratus

Altostratus (Figure12) appears as a greyish or bluish layer of fibrous or striated cloud that often blurs the Sun or makes it appear as if one is looking through a frosted glass. They can be formed when a layer of cirrostratus descends from the higher atmospheres. Altostratus clouds do not usually produce rain but may thicken with progressive lowering of the base to form nimbostratus which give an indication of rain.

Figure 12 Altocumulus

Nimbostratus

Nimbostratus (Figure 13) is a layer of low-level greyish cloud that precipitates rain reaching the ground. They form from the thickening of altostratus and are also thick enough to obscure the Sun from view.

Figure 13 Nimbostratus

Stratocumulus

Stratocumulus (Figure 14) are low-level patches of clouds that vary in colour between white and grey. They might have gaps between them or joined together. They are formed from the spreading out of cumulus clouds. Stratocumulus clouds do not often produce precipitation and when they do, they give out light rain or snow.

Figure 14 Stratocumulus

Stratus

These are low-level clouds with greyish or whitish colour (Figure 15). The clouds form under stable atmospheric conditions when gentle breezes raise moist air over a cold surface. They can sometimes be very close to the ground in the form of fog or mist. Stratus cloud produces little to no rain and if it is thick enough, it can drizzle.

Figure 15 Stratus

Cumulus

Cumulus clouds (Figure 16) are detached, cauliflower -shaped clouds that usually appear in fair weather conditions during the day. They usually form a few hours after daybreak and scatter before the Sun goes down. Cumulus clouds produce no rain or snow and lazily drift across the sky on a Sunny day.

Figure 16 Cumulus

Cumulonimbus

Cumulonimbus clouds (Figure 17) are dense and heavy clouds that extend into the atmosphere in plumes. The upper part of it is fibrous and spreads out in the shape of anvil. The base however is very dark with small clouds hanging with it or attached to it. They are formed through convection from small cumulus clouds. Cumulonimbus clouds are often associated with heavy downpours, hailstorms, lighting, thunder and even tornadoes.

Figure 17 Cumulonimbus