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Climate Changing in Microwave Telecommunication Links (Sleet)

MSc Wireless Systems Engineering

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ABSTRACT

Rec. ITU-R P.530-12 provides an internationally recognised prediction model for the fading due to wet snow (sleet) on horizontal, terrestrial microwave links. An important parameter in this model is the altitude difference between the link and the melting layer. This is the layer near the zero-degree isotherm (ZDI) where falling ice begins to melt into rain. Melting ice particles produce a specific attenuation up to four times that of the associated rain rate. This work will examine NOAA NCEP/NCAR Reanalysis 1 data to identify trends in the ZDI height o.

ZDI height is shown to have increased by approximately 10 m per year over the last 30 years in part of Europe as it shows some decrease in other parts of the world approximately 5 m a year. This has led to a slow decrease in the incidence of fading due to wet ice over southern Europe but isolated large increases in regions where the air temperature near the ground was close to zero during winter. The annual distribution of ZDI heights relative to the annual mean are calculated and compared to models in Rec. ITU-R P.530-12 as the theory for attenuation provided and plot of the mean ZDI Height will be compared with Rec. ITU-R 840-4.

DEDICATION

I would like to dedicate this thesis to my family especially my parents who are the source of support that fed me throughout the period of my settlement in the United Kingdom.

ACKNOWLEDGEMENTS

The first thankful that I would like to write is for my first supervisor, Dr. Kevin Paulson for his help and management. The main part of his patient was the comprehensive support for the software that we have done together. I am also thankful to Mr. Nick Riley for his useful lectures during the both semesters.

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CHAPTER ONE

INTRODUCTION

1.0 Introduction

Over the last three decades the changes in the climate have been clearly noted. The changing is reported by the environment research group and it is important for people who working in outdoor environment and who cares with these impacts. Whether the changing is increase or decrease of the air temperature the Zero Degree Isotherm (ZDI) will disturbed for microwave links and the consequences will influence proportional with the changes. These changing will also attenuate the signal as the height of the microwave link will not match the ZDI and the design of the link tower may be reconstructed after long period of time. Microwave links are widely spread nowadays especially with the invention of telecommunication protocol Worldwide Interoperability for Microwave Access WI-MAX for rural area. The links are installed in towers and these towers are located in wide area to cover vast area counted by kilometres. The considerations of the telecommunication signals are supposed to transmit and receive high data rate but the real rate that the customer received in such lodge at the top of the mountain may not be as high as the expected rate due to the location of microwave link.

1.1 Climate Changing

The term of climate changing is refer to the noticeable changing in the climate for specific region or planet which is measuring the difference between the last and first of such a long period of time linked with weather parameters such as temperature, wind, rain, disaster, sea level, polar bear, and season shift. Mankind sometimes however could not realise the change in the climate and people argue as it became a controversial topic but recently and according to the researches and weather forecasting, the change becomes for short period of time.

1.2 Microwave links

Microwave links are a system that used to join the radio wave system in the domain of microwave frequencies. After the world war two, the microwave links have had incredible developments which are used by the military in radar system. Microwave links are deliver the signals similar with radio system in all generations which is enable to send data, voice, and video. Microwave links have the line of sight transmission property and it send the signal via electromagnetic waves. Both of signal strength and data rate are affected by the medium that data goes through. These medium could attenuate the signal from time to time and with the weather change rapidly from year to year the signal is definitely in trouble. The use of microwave link is wide because it is suitable for all satellite communication, cellular systems, and it may use for short range indoor communication.

1.2.1 Advantages and disadvantages of microwave links

Microwave links are transmit a large capacity of data and broadcast these massive data through wide area since the higher frequencies have been used. The function of the amplifiers of the signals is using the repeaters which are installed to re-spread the signal to cover as much area as possible. Microwave links have more advantages than drawbacks and deliver a huge number of data may have to cost more than other telecommunication system including the construction of the towers which are built in different shapes. One of the properties of these links is the line of sight transmission which considered negative point. Line of sight means reflections and diffractions and they are not good for the medium that contain the signals. Wherever the signal goes through, it will contaminate by other unwanted signals due to the interference from the air or other internal factors. Different seasons along the year will change the medium to electromagnetic travelling wave. Microwave links are sensitive for the changing in the weather from the summer to the winter. It is more sensitive by the wet snow (sleet) than the heavy rain which is considered by the office of communication that sleet could attenuate the signal by four times over heavy rain.

There are main positive and negative points of microwave links properties and they are implemented in High quantity of flexibility since it enables Engineers to re-install the tower in other locations. Low cost and fast installations are also considered advantages for microwave links. On the other side, the limitation of coverage range could be a negative point hence the relay station is necessary for long transmission distance.

1.3 Zero Degree Isotherm (ZDI) height

It is obvious that the increase of approximately 150m height is likely corresponds to decrease the air temperature by one degree Celsius which is called Zero Degree Isotherm or 850 mille bar Zero Degree Isotherm. For cold areas such the Europe which has the majority of the year above freezing level it is important to determine the height of the ZDI and it is probably different in the year from the summer to the winter. ZDI Height is an important factors that taking into account to compute the total path attenuation through the rain or wet snow (sleet) and it sometimes known as a freezing height or level. There are many definitions for the ZDI and however one of them can be defined as the altitude at which the air temperature descends below the freezing level.

1.4 wet snow (sleet)

The term sleet is not internationally understood, however it has different meaning in the united state and the International Telecommunication Union (ITU) has replaced this name by wet snow. Sleet dose not happen as much as rain along the year but it attenuates the signal more than the one caused by heavy rain. It is known that sleet occurred during the winter time however, people still confuse about the difference between sleet and the hail or freezing rain. Sleet caused by raindrops penetrating cold layer of air and refreezing for long journey before reach the ground. Cummings, et al., (2008) organised a software programme shows a flow chart to detect the sleet and how to recognize sleet over the rain by the result of the attenuation which showed that sleet cause more attenuation in dB than rain. Sievert (2005) defined three types of the precipitation in his book and he described the term sleet as: “sleet begins as snowflakes. The snowflakes fall into warmer air and melt into rain drops. The rain drops fall from the warmer air into cold air. They freeze into small pieces of ice. Sleet bounces when it hits the ground. It dose not stick to things but you can hear it hit windows and rooftops”.

1.5 Aims and Objectives

The aim of this project is to understand the changing effects of rain and sleet on fixed terrestrial microwave links. Some modelling will be performed to predict the effects of temperature trends due to climate change on link outage. The weather and heavy rain in particular, limit the availability of microwave telecommunications links. The impact of this changing is occurred when the communications fail due to attenuation of the signal. However other climate change effects could increase or decrease the amount of link outage. In particular the amount of sleet will dominate in some areas such Europe. It is known that the difference between the south and north of the United Kingdom as a short term and it is recorded wider changing between the north and the south of the equator.

Climate change is considered the main problem of the last decades especially for people who are working for environment. For people who works for communication and microwave links the problem becomes more specify than the atmosphere as it concentrates on where the Zero Degree Isotherm Height (ZDI) located and how it is affected by decrease or increase the height of microwave link to be design in the tower.

The main objectives of this work are:

1. To understand the effect of sleet (wet snow) on microwave links and recognize the different of the attenuation between the sleet and rain.

2. To analyse data provided from National Oceanic and Atmospheric Administration (NOAA) and identify the changing of ZDI height for the worldwide.

3. To suggest or predict the changing in attenuation over coming decade regarding to the results which will achieved from the last three decades.

4. The purpose of predicting fading due to rain or wet snow (sleet) is to determine the 0.01% rain rate and height of the ZDI where the microwave link is suited.

All the headings showed above shall achieve by analysis the data provided by (NOAA) using the Mat lap programming and analysis the trends of these programming and compare the results with previous research in this field or the ITU Recommendation.

1.6 Chapter Summary

In this thesis, the work is divided to five sections. The first chapter has done and introduced the introduction of the whole work. Chapter two will introduce some attenuation background due to rain and wet snow (sleet) and literature review about this work will have written. Also data of the air temperatures and height is provided by (NOAA) which is available on their web site and free to download and it will be introduced in the third chapter which will analysis these data between the latitude and longitude. (ZDI) height will have plotted for thirty years starting from 1980 to the present in chapter four which include the simulation and discussion part. These trends will examinants the ZDI height trends over the world with some evidence of it is reliability. The annual distribution of deviation of ZDI height over the Europe and Beta parameters will be introduced in this chapter as well and the result of the distributions graphs and the ZDI height will be discussed and also some comparison with the

ITU Recommendation will be made in this chapter. The conclusion, suggestions, and future work shall take apart of the last chapter.

CHAPTER 2
LITERATURE REVIEW AND ATTENUATION THEORIES

2.0 Introduction

In this chapter the climate changing on the microwave link and the attenuation that caused by sleet will be looked at and literature review about this topic also included. First part of the section will review the results of the previous work while the second part will come up with the back ground and some theory about the attenuation.

2.1 Literature Review about the topic

The brief survey shows that some work has been done before and it may consider some of these achievements are related to the writer work.

2.1.1 Climate change in microwave environment

Climate changing is the main factor that people concern about the environment. Communication Engineers also aware about these changes last decades. Microwave links are installed in open door environment and receive/transmute signals through different changeable medium. Some modelling is performed to predict the effects of temperature trends due to climate change on link outage. The weather and heavy rain in particular, limit the availability of microwave telecommunications links. The impact of this changing is occurred when the communications fail due to attenuation of the signal. However other climate change effects could increase or decrease the amount of link outage. In particular the amount of sleet will dominate in some areas that have sleet in part of the year. The results of this literature review will be the first step in the writer thesis.

2.1.2 Attenuation due to melting layer:

Bauer, et al., (1999) estimated the effect of melting particles at the microwave frequencies between 10.7 and 85.5 GHz over the ocean. Their work based on the way to conclude the permittivity of the melting particles corresponding to the permittivity of water. Different approached were simulated to calculate the effective permittivity and comparison was made and the consequences were indicated that the maximum outcome for the particles is collected of mixed liquid in the melting layer. Most of the research of the microwave links was the concern to find out how much electromagnetic wave attenuated in this medium. Olson, et al., (2001) calculated the properties of electromagnetic wave in the melting layer which requires specifying the volume fraction of the medium individually which is a mixture of ice and air. It is potential explanations that sleet could decrease the transmission speed of the travelling wave as the higher melting layer is the lower attenuate and it is occurred in winter which bring about multipath activities in the summer and that cause 10 dB attenuation and cause the same value during the autumn (Braten, et al., 2002). Melting layer is the main layer that creates sleet and it is obvious for colder countries such United Kingdom and specifically in the north of Scotland. A Test was done for communication link at the frequency of 3GHz in the university of St Andrews in south east Scotland. Data was compared between radar measurements and rain gauges measurements which were taken from meteorological office as their gauges installed across the country. The comparison between radar measurements and the theoretical prediction in melting layer was made by University of Essex, UK (Paulson et al., 2003).

Paper has recently published by Paulson and it examined over 20 years of height resolution taking data from UK gauges spread in different places. The result of the paper recognized a considerable increase in rain rate which has resulted to doubling or tripling of outage rates on UK terrestrial links. It is obvious that the global warming causes significant risen in ZDI height. The majority of the north of Europe is spending most of the year above freezing level, this leads to the decrease in fading due to sleet. In places that spend most of the year below freezing level, the increase in temperature could greatly increase the average annual.

2.1.3 Sleet and how it is occurred

It is known that sleet occurred during the winter time however, people still confusing about the difference between sleet and the hail or freezing rain. Sleet caused by raindrops penetrating cold layer of air and refreezing for long journey before reach the ground. Cummings et al., (2008) organised a software programme shows a flow chart to detect the sleet and how to recognize it over the rain by the result of the attenuation which showed that sleet has more attenuate in dB over rain. According to the metrological office, sleet is occurred at the temperatures between 0 and 6 Celsius. A test was done for hours at temperature of 4 Celsius and good results were recorded, but it was recommended to installing thermometer at the higher end of the link which would give better result especially at dual frequency link. Experimenters did not provide data from metrological office as they read the measurements locally (Cummings et al., 2008). Sleet disturbs the signals that travelling from link to other and there is different Statistics consider how many disciples could sleet attenuate the signals. (Ali, et al., 1986) have published a paper and they counted the attenuation of different medium such rain, fog, snow, and sleet and they figured the loss caused by sleet of 4 dB under strong snowfall condition. Fade duration and slop were taken into account of calculation or measuring attenuation. Singliar et al., (2005) contributed these parameters in their work and they figured that for database was recorded along 2004 and showed the events with long duration more than 1000 seconds are caused by sleet and melting snow not by rain.

Data was taken from the source should be correct as it has been noted that unheated gauges might not give correct reading due to snow and melting ice. Gauges must be calibrated from time to time due to the regular maintenance to precise the reading. These comments were pointed near Bolton at the northwest of England however, it was difficult to install these gauges due to the environment shapes (hills and mountains) (Upton et al., 2005). Most of the research was carried out to calculate the attenuation caused by precipitation of rain. Rahimi et al., (2004) considered the way to measure attenuation caused by rain and they considered the method to measure the attenuation by using dual frequency to differentiate sleet from rain because it was quite difficult for sleet or melting ice.

2.1.4 Microwave Attenuation prediction

It has been pointed that sleet and melting snow cause attenuation to electromagnetic wave more than the attenuation that caused by rainfall which is the topic medium that affect on transmitting/receiving electromagnetic waves. There are many methods to calculate and predict the attenuation due to both the heavy rain and sleet. Some of theoretical and practical works have satisfied the expectations and others did not (Terje, et al., 2005). Most of researches showed that there was no method to predict the attenuation along the falling sleet and melting snow, but Braitn et al., (2003) Showed that the result of the project in Norway was supported by the International Telecommunication Union Bureau Recommendation (ITU-R) which was taken the measurement from the microwave link and data was examined and predicted sleet and rain using modern version of software. The consequence of the experiment was about 5 dB attenuation caused by sleet at 0.01 percent of time approximated. Holt, et al., (2007) figured that it can be recognized the transmission medium which affected by melting snow and the nonlinearity between the attenuation, amount of precipitations and the frequency dependence. The dual frequency was between 12.8 and 17.6 GHz and the microwave links were pointed near Bolton in North West of England and 10.5 to 17.5 GHz near Essen in Germany.

Higher frequencies microwave links (above 10 GHz) are applied point to multipoint terrestrial and satellite systems. These ranges of frequencies are more influences than lower 10 GHz which are affected with the rain precipitation and sleet that cause the attenuation in terms of Different fade mitigation techniques (FMT) (Heder and Bertok, 2009) . Also they set their test in five cities in Hungary as microwave links were spread around these cities. They found that attenuation caused by sleet is higher than that caused by rain, but sleet is not occurred as much as the rain in the year. All their measurements were based on the comparison between the attenuation caused by sleet and rain. Final result they found was that maximum value of fade slope which is calculated from sleet event is smaller than that one calculated from rain events.

Microwave links are suited in rural and urban areas and it send and receive signals via different free space environment. Since the weather is different and changing form hot to cold across four seasons these links are affected by ice, fog, rain, and sleet. As it showed above, sleet causes attenuation more than rain and it is quite similar with melting ice which was estimated about 5 to 10 dB more or less. As sleet dose not happen such rain then microwave links should be suited to be protected as much as it can be. Most of the work and experiments were done by comparing data whether it was taken from the local measurements or meteorological office with data from radar measurements or from analyzed data for mathematical equations.

Office of communication (Ofcom) has recently released at the end of 2009 recommendations to predict fading on microwave links caused by rain and wet snow and they scheduled method using ZDI height and they figured a problem that made the output is very sensitive to the accurate ZDI height. The method was done by calculating the probability density function (PDF) of ZDI height and divided it into bins. They summed their report up with the difference of the attenuation caused by the two medium rain and wet snow (sleet) which support that sleet is more attenuate than rain (Haslett, 2009).

2.2 Attenuation due to hydrometeors

One of the many causes of the attenuation is the absorption and scattering by hydrometers implemented by rain, snow, and fog. Rain attenuation can be negligible at the lower frequencies less than 10GHz and the consideration is focused on the higher frequencies where it is significantly increase. The ITU recommendation scheduled estimation for short and long terms statistics. The procedure for the long term was to predict the attenuation and it will discuss in the next section.

2.3 Combined method for rain and wet snow

The ITU recommendation provides prediction procedure and it is applicable over the world but it is quite difficult for specific frequency above 40GHz and for the line of sight path length up to 60km. The higher altitude suited link is the more attenuation and it may exceed the time proportion due to the consequences of melting ice particles or sleet in the melting layer.

The rain height is a main factor that taking into account to calculate the incidence of these particles in the melting layer. The recommendations are taking into account of the variation of the ZDI rain height which has taken 49 height values virtual to the medium of the rain height. The probability will have given later at the end of the equations procedure. The consideration of the mathematical equations is designed for the reason of the effectiveness of microwave link by the melting layer. If the link is suited in protected place then the consideration may not be included.

2.3.1 Long term statistics of rain attenuation

The procedure below is a number of steps that may be used to estimate the long term of rain attenuation.

1-Taking the rain rate exceeded for 0.01% by integration over minute. The information is available from the local source measurements of long term. If data was not available then the estimation can be achieved in Recommendation ITU-R P.837.

2-The specific attenuation γ_R (dB/km) can be calculated for many variable of the frequency, polarisation, and rain rate by using the methods which are provided in the Recommendation ITU-R P.838.

3-the effective path length of the link d_{eff} can be computed by multiplying the actual path length by the distance factor r which described by the equation below:

$$r = \frac{1}{1 + d/d_0} \qquad (2.1)$$

For $R_{0.01} \leq$ 100 mm/h then:

$$d_0 = 35\, e^{-0.015 R_{0.01}} \qquad (2\text{-}2)$$

Otherwise it can be used for value of 100 mm/h in place of $R_{0.01}$.

4- The total approximation of the path attenuation for 0.01% of the time is written as:

$$A_{0.01} = \gamma_R\, d_{eff} = \gamma_R\, d_r \quad \text{dB} \qquad (2\text{-}3)$$

5- For a specific latitude of the link sited in position of equal or greater than 30^0 south or north, the attenuation for other percentage of time for the range from 0.001% to 1% is extracted by the following given formula:

$$\frac{A_p}{A_{0.01}} = 0.12 p^{-(0.546 + 0.043 \log_{10} p)} \qquad (2\text{-}4)$$

The formula above is modified to give factors of 0.12, 0.39, 1 and 2.14 for 1%, 0.1%, 0.01% and 0.001% respectively and it will not work in different range.

6- For the rest of the links which are located on position less than 30^0 south or north, the attenuation is given by the formula:

$$\frac{A_p}{A_{0.01}} = 0.07\, p^{-(0.855 + 0.139 \log_{10} p)} \qquad (2\text{-}5)$$

Also the formula has been modified to give factors of 0.07, 0.36, 1 and 1.44 for 1%, 0.1%, 0.01% and 0.001% respectively and it will not work on different range as well. The procedure above is valid for just the rain and not designed for wet snow or any other medium. For the combined rain and wet snow (sleet) the attenuation can be found by the formulations above and following the procedure below:

1- Achieve the rain height h_{rain} above the mean sea level by using the previous recommendation, ITU-R P.839.

2- At the centre of the link path, the rain height h_{link} can be computed by including the Earth curvature by using the formula given by:

$$h_{link} = 0.5\,(h_1 + h_2) - (D^2/17) \text{ m} \quad \text{above mean sea level (AMSL)} \qquad (2\text{-}6)$$

Where:

$h_{1,2}$, are the heights of the link measuring by (AMSL) and D is the length of the path measuring by meter.

3- This step has a logical condition and it suppose to be work if the $h_{link} \leq h_{rain\,m}$-3600 then the link will not be influenced by melting layer and back to the previous procedure, otherwise the procedure will follow it steps.

4- Reset the multiplication factor F.

5- For consecutive values of the reference j = 0, 1, and 2, to 48 to:

a) Compute the rain height, h_{rain} by:

$$h_{rain} = h_{rain\,m} - 2400 + 100j \quad \text{m (AMSL)} \tag{2-7}$$

b) Compute the link height corresponding to the link height which is the difference of the height by:

$$\Delta h = h_{link} - h_{rain} \tag{2-8}$$

c) Now, it is the time to multiplying factor for this value of the index j:

$$\Delta F = \Gamma\,(\Delta h)\; P_j \tag{2-9}$$

Where:

Γ (Δh) is a multiplying factor that takes into consideration of differing specific attenuations corresponding to the rain height:

$$\Gamma(\Delta h) = \begin{cases} 0 & 0 < \Delta h \\ \dfrac{4\left(1-e^{\Delta h/70}\right)^2}{\left(1+\left(1-e^{-(\Delta h/600)^2}\right)^2\left(4\left(1-e^{\Delta h/70}\right)^2-1\right)\right)} & -1200 \leq \Delta h \leq 0 \\ 1 & \Delta h < -1200 \end{cases} \tag{2-10}$$

The variable P_j is the probability that the link will be at Δh, taken from Table showing below which is using Gaussian distribution:

Index j		Probability P_j
Either	Or	
0	48	0.000555
1	47	0.000802
2	46	0.001139
3	45	0.001594
4	44	0.002196
5	43	0.002978
6	42	0.003976
7	41	0.005227
8	40	0.006764
9	39	0.008617
10	38	0.010808
11	37	0.013346
12	36	0.016225
13	35	0.019419
14	34	0.022881
15	33	0.026542
16	32	0.030312
17	31	0.034081
18	30	0.037724
19	29	0.041110
20	28	0.044104
21	27	0.046583
22	26	0.048439
23	25	0.049588
24		0.049977

Table (2-1) Probability Data Function

d) the last step is to sum ΔF to the current value of F:

$$F = F + \Delta F \text{ dB} \tag{2-11}$$

6- Finally by multiplication between F and A_p to find the combined attenuation of the rain and wet snow which called by A_{rs}:

$$A_{rs} = A_p + F \tag{2-12}$$

Above h_{rain} the particles is probably ice which has an index nearly to the air which is linked with small attenuation. On the other side, below h_{rain} the factor Γ (Δh) increases since the melting leads to a large combined phase particles. The table above showed a numbers of propagation implemented in the melting layer in the range of 100 m period within 2.4 km of the mean level. Summing up the attenuations overreach at the same time percentage is not the mathematically correct method of combining distributions. Many users of ITU-R P.530, including the UK regulator Ofcom use the mathematically correct method of forming a weighted sum of overtaking percentages for the same attenuation. This process can be formulated in the equation below

$$P_{r+s}(A) = \int P_r\left(\frac{A}{\Gamma(\Delta h)}\right) W(\Delta h) d(\Delta h) \tag{2-13}$$

Where $P_{r+s}(A)$ is the average annual probability or time percentage that attenuation A is exceeded, due to rain and sleet, $P_r(A)$ is the attenuation overtaking due to rain and $W(\Delta h)$ is the (PDF) of(Δh).

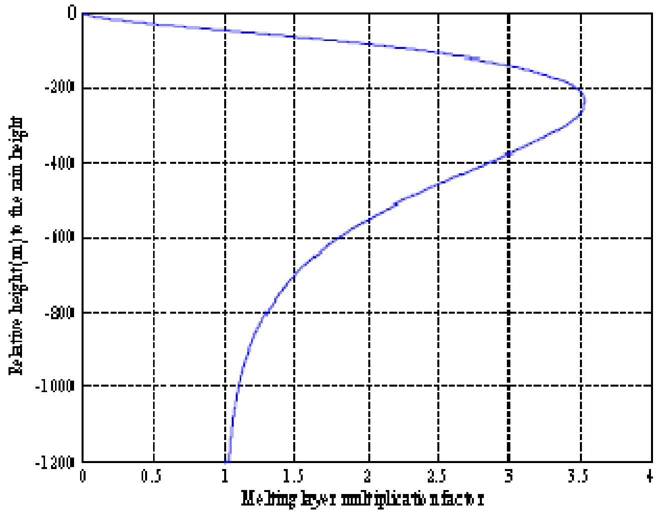

Figure (2-1) plot of the factor Γ (Δh)

(Terje, et al., 2005)

CHAPTER 3

PRINCIPLES AND STATISTICS BACK GROUND

3.0 Introduction

Because there was no comprehensive mathematical theories in this thesis the back ground and theory parts will not be as much as the other mathematic topics. The back ground is concentrates to microwave links from principle to design and some bros and cons may be incorporated. Beta distribution will have theoretically introduced in this chapter to be compared with distribution from the simulation results in chapter four.

3.1 Zero Degree Isotherm (ZDI) height or Freezing Level

The term ZDI is defined as the freezing level at the temperature of Zero degree in which height. It is also known as the Zero Degree Celsius and it is equal to 32 when it is measured by Fahrenheit unite. The variation in freezing level over time and space as meteorological conditions change is an important information for pilots and weather forecasters attempting to plan flights which will encounter a minimum of icing conditions. It can be the same for microwave people who devote his self to control and observe the links which are suited in the high altitude and suffering from the dramatic changing of air temperature from year to the previous. Whether the changing of the air temperature was up or down, by a period of time for example 30 years the link must have changed the position to match the ZDI height and work in good weather condition to avoid any unwanted attenuation and gives high performance. Life time will be taking into account as the links are sensitive for any significant changing in the ZDI height. Above the freezing level the temperature is below the ZDI and above the ZDI is under the freezing level.

3.2 Microwave links

The term microwave link is defined as a communication system that suited in beam of radio wave and working in the range of the microwave frequencies which transmit and receive information via many fixed locations. For example, by using these links, it is easy to broadcasting and sending data to far distance places. These links also provide customers with high speed data access with no need to cable connection for long distance. The use of microwave links is wider than any other wireless communication systems, for example, Vodafone network use microwave links to transmit calls between switching centres.

A simple microwave transmission system is consists of to four main parts which are implemented in transmitter, receiver, antenna, and the medium or transmission lines. The transmitter has the function to produce microwave energy corresponding to the necessary frequency and power level. Also the transmitter has the responsibility to modulate the singles that carrying the information. The receiver part is a mirror for the transmitter since it has the function of demodulation and receives the signals. Also the receiver detects and extracts the signal which is travelling and may amplifies it since electromagnetic wave travelling for a long journey. The antenna is the physical link that makes the transmitter and receiver demonstrate their energy by broadcasting it throughout the free space. Antenna is the third part of the system which is suited at the end of the transmitter and it emits the microwave energy into atmosphere to scatter it in many directions. In the receiver side, the antenna is pointed to catch as much signal as it can be and complete the role to reach the receiver functions. The fourth part of the system is the medium between the transmitter and the receiver. The medium is the main part to be discussed as it has mentioned above that medium is different from rain to others. Clear path is the high performance to microwave links since the line of sight is succeeded while the unlined of sight is the worst.

3.2.1 Design of microwave links

Microwave links are designed to include the following main points which are considered to taking into account of plenty of calculations such:

1- Loss and attenuation.
2- 1-fading and fade margins.
3- Frequency planning and interference.
4- Quality and availability.

The term attenuation is the source problem for microwave links and it caused by many reasons and depends on the geometrical area that the link suited in, also it depends on the place where the link located at which latitude and longitude in the earth. Clutter is the unwanted signal that destroys and disturbs the link and the important part in this research is the one caused by the precipitation.

3.2.2 Attenuation due to precipitation

The term precipitation is implemented on the one of the shapes of rain, snow, hail, fogs, wet snow (sleet), and haze. All of these shapes are created from the water and it just takes in different of shape and it may also depending on the size of the drops. The one caused by rain is considered the main and pointed by the commercial radio link and it is proportional with frequency. As the frequency increased as the high attenuation occurred. The rain intensity which is called rain intensity is the main parameter used to calculate the attenuation caused by rain and it may appear in the cumulative distribution function (CDF). It can be noted that the increase in attenuation can take the exponential raise with rain intensity.

3.3 Statistical Distributions

There are many statistical distributions used to calculate the PDF. These distributions are contributed here not to calculate the PDF but to compare some results of data with these distributions and just two distributions may be introduced such:

3.3.1 Beta Distribution

Beta distribution is a distribution using to calculate the probability at some points of curves. Beta density function is the common method to characterize the outcomes of the probability density function (PDF). This distribution is designed for two variables by integration the area under the curve which is equal to one.

3.3.1.1 Mathematical definition

It has been pointed above that the distribution of Beta is functioned to calculate the PDF for the variable x on the period (0, 1). The general mathematical formula of the PDF of beta distribution can be written as:

$$F(x) = \frac{(X - a)^{\alpha - 1}(b - X)^{\beta - 1}}{B(\alpha,\beta)(b - a)^{\alpha + \beta - 1}} \quad (1)$$

Where B is the beta function and it could be written as:

$$B(\alpha,\beta) = \int_0^1 t^{\alpha - 1}(1 - t)^{\beta - 1} dt \quad (2)$$

Where α and β are the shape parameters. The factors a, and b are the lower and the upper boundaries respectively. The function of Beta in the denominator is to make sure that the total area under the curve is equal to the unity. The PDF can be drawn for different values of α and β and for example at a specific value of α and β of 45 as follow:

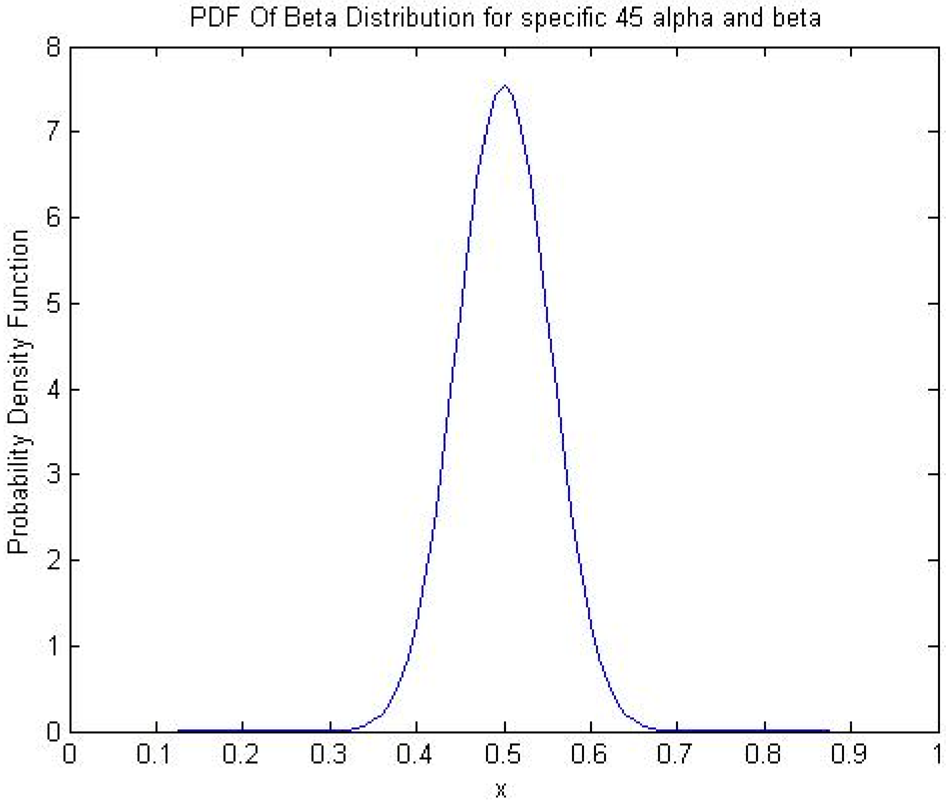

Figure (3-1) PDF of Beta Distribution for 45 alpha and beta

3.3.2 Chi Square Distribution

This distribution is used to calculate the probability PDF. It is also the distribution named by x^2-distribution regarding to the function of square. Also the distribution is defines as field of statistic analysis and shows how far some numbers of data to others.

3.3.2.1 Mathematical Description

This distribution is mathematically implemented by simplest way which is considered by the summation of the square standard distribution for example for different variable such as Z_1, Z_2 and so on and for the interval 0 to 1 then we have this expression:

$$Z_1{}^2 + Z_2{}^2 + \text{..............................} + Z_N{}^2 = \sum_{i=1}^{n} Z_i{}^2 \,.\, x_N{}^2 \qquad (3\text{-}1)$$

The PDF for Chi distribution for the function x= $\sum Z_i^2$ can be implemented as follow:

$$f\,(x_i) = \frac{x_i^{\left(\frac{N}{2}-1\right)\left(-\frac{x_i}{2}\right)}}{2^{N/2}\Gamma[\frac{N}{2}]} \qquad (3\text{-}2)$$

It is working throughout the interval $0 \leq xi \leq 1$. The figure show below illustrates five graphs for different values of N.

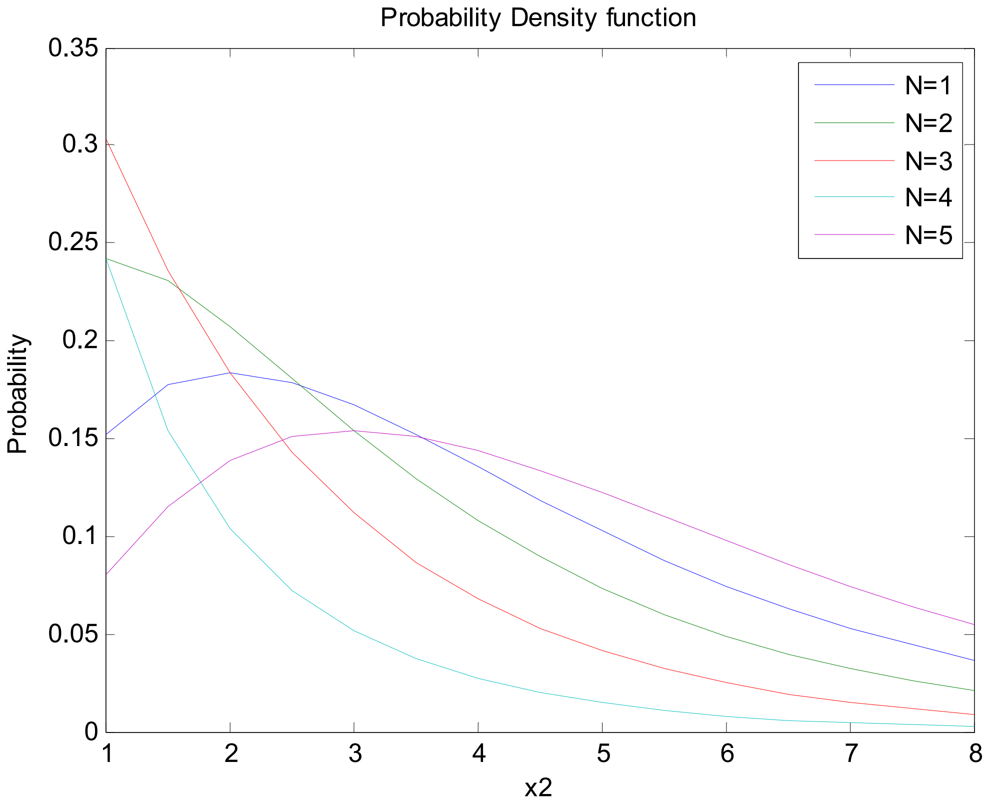

Figure (3-2) PDF of Chi Square Distribution

3.4 NOAA NCEP/NCAR Reanalysis1

The National Oceanic and Atmospheric Administration (NOAA) is an organisation working on many areas that related to weather and climate changing. The enthusiasm for the NOAA NCEP/NCAR Reanalysis project was given in 1996 by Kalnay and his colleagues. The National Centre for Environment Prediction (NCEP) and the National Centre of Atmospheric Research (NCAR) have analysed data for four times a day for17 Pressure levels of: 1000, 925, 850, 700, 600, 500, 400, 300 , 250, 200, 150, 100, 70, 50, 30, 20, and10 which have been measured by milli bar. These data is available online in their web site and free to download for the period from 1984 to the present. The reanalysis plan was started in 1991 while the consequences of the NCEP Climate Data Assimilation System (CDAS) have developed.

The inspiration for the CDAS project was the apparent "climate changes" that resulted from many changes introduced in the NCEP operational Global Data Assimilation System (GDAS) over the last decade to develop the prediction of the weather forecasting.

The solution, also given by Kalnay and his colleagues in their report and it showed that the purpose of the reanalysis project is to use a frozen state of the art analysis/forecast system and perform data assimilation using past data, from 1957 to the present (reanalysis). Moreover, the same frozen analysis/forecast system will be used to continue performing data assimilation into the future (CDAS), so climate researchers can assess whether current climate variance is significant if compared to a long reanalysis without changes in the data assimilation system.

The dataset provides a wide range of meteorological parameters over a global 2.5^{o} grid at 4 hours intervals calculated at 17 pressure levels. The two parameters will be used in this work and they are air temperature and altitude as a function of pressure level, averaged over each grid square. This data is combined to yield air temperature as a function of altitude and interpolated to estimate the ZDI altitude.

CHAPTER 4

SIMULATION RESULTS AND DESCUSSION

4.0 Introduction

This chapter will contribute the results of the simulation of given data of ZDI height and average annual for each year individually and combined for the thirty year to conclude the trend of the changing of ZDI height per year. The distribution part will be implemented in this chapter as well and trends of histogram and probability distribution also will be included. The mean of ZDI Height of Different years will be plotted and it may compare with Rec. ITU-R P.839-3, Yearly average ZDI Height.

4.1 ZDI height for a year

As the data is available in the web site and free to access then the first programme was to read in Network Common data File (Net CDF) files data for the two variables of annual temperature and height as a function of pressure Level and calculate Zero-Degree-Isotherm height and write to file over 2.5 degree pixels, globally, every 6 hours. These were written to files with names ZDI Height for each year which was done from 1980 to June 2010. The first figure is for the year of 2010 which consider a half year as the data updated daily. Data was not as big as the other years which are about 1G for both air temperature and height. The graph is divided from 0° to 360° in longitude and from +90° to –90° in latitude which is implements the 2.5 pixels. For a different location from the grid points, the 0° C isotherm height above mean sea level at the desired location can be derived by performing a bilinear interpolation on the values at the four closest grid points.

It is clear from the graph below that for lattitude around the equator recorded the highest air tempreture for the year 2010which recorded height more than 5000 masl. It is simlar for the rest of thirty year and was given just this year for just an example. The yellow colour for ZDI height slighlty decreases and goes down as it closes to the tropic concer in the north and it is the same for the south which is make it identical and recorded a height of 4000 amsl and continue to goes down until reach the ZDI height in the both poles.

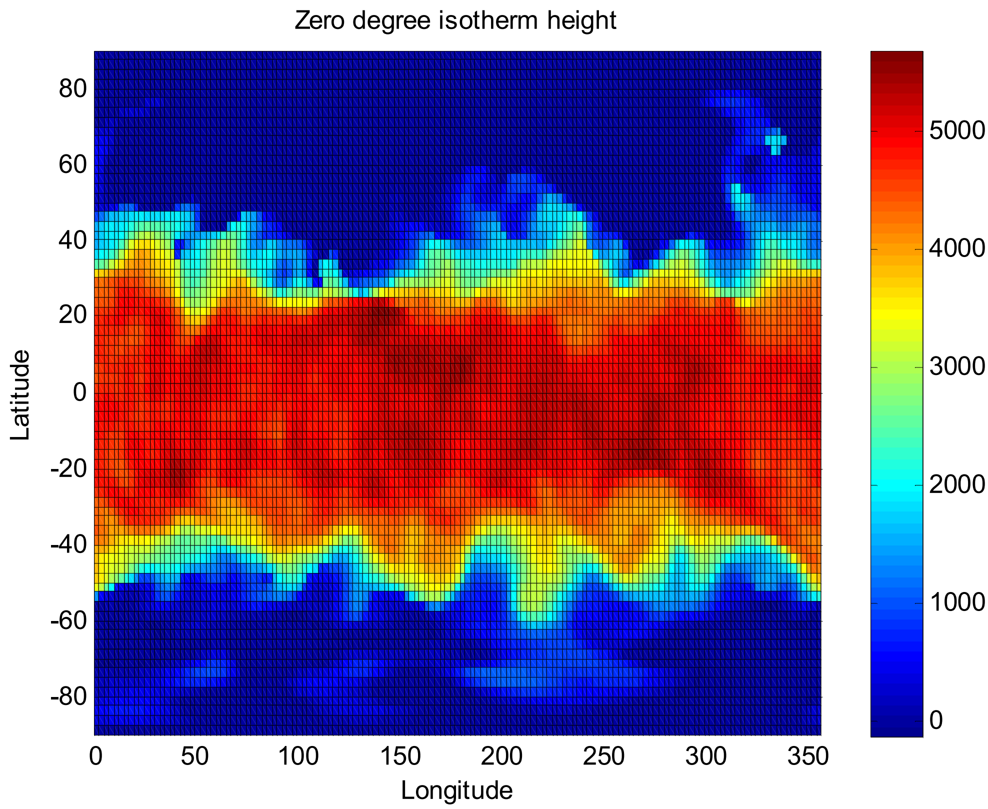

Figure (5-1) ZDI height for the year of 2010

4.2 Trend of ZDI height m/year

The second program is fabricated to read in the data produced by the first programme and built a 3D array of 6-hour ZDI Height. Using convolution, annual ZDI were formed and written to file. So far the first data was built by the first programme which is calculated the ZDI height and the second was built to read the annual mean ZDI height for each year. By using both data, the third programme has been built to read in these data files and calculate the linear regression line to the ZDI height time series at each pixel

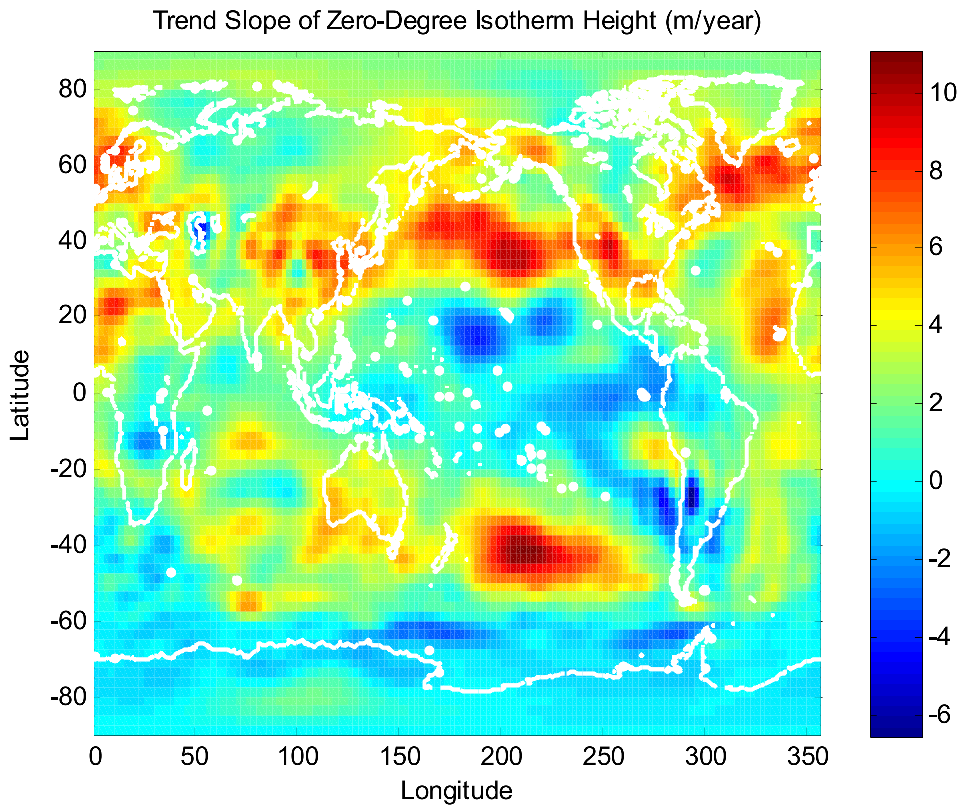

Figure (5-2) trend slop of ZDI height m/year

A plot is produced of the running average annual ZDI and the regression line. Another plot is produced of the regression slopes as a function of latitude and longitude. The figure above shows that the hot spots of the red colour which are mostly suited in the north half of the earth and implemented in the Europe and part of North America. These areas have recorded the highest of ZDI height proportional with a year and reach the maximum values of 10 m a year. Also some points are located in the Pacific Ocean and a large hot point between New Zealand and Chile. The graph over all is a mixed colours and that may confuse us and made no rules for the changing in the ZDI height for this period of time, this is clear at the closest red and blue points in the pacific ocean which have both the maximum and minimum heights per year. The blue colour may vary for little points and spread mostly in the oceans which are the only points recorded the decrease in ZDI height under mean sea level.

4.3 Time series of ZDI Height

The figure blow illustrates the time series for the considered period for a different three pixels. It can be seen that the slop from the black line and the increase of the ZDI height are proportional with the years. For example, the blue line which is imply the high latitude and probably the Europe, north America, and north Asia, the difference of the raise between 1980 and 2010 is corresponding to the slop shown between the first and last years since it was calculated in the previous figure by 10m a year and 300m for the thirty year to record 4500m in 2010. Over all, for the second pixels the increase of ZDI height is noticeable. The two other pixels red and blue which are imply the equator and the poles respectively are parallel with the first one and recorded the maximum to minimum changing in the period around 1998.

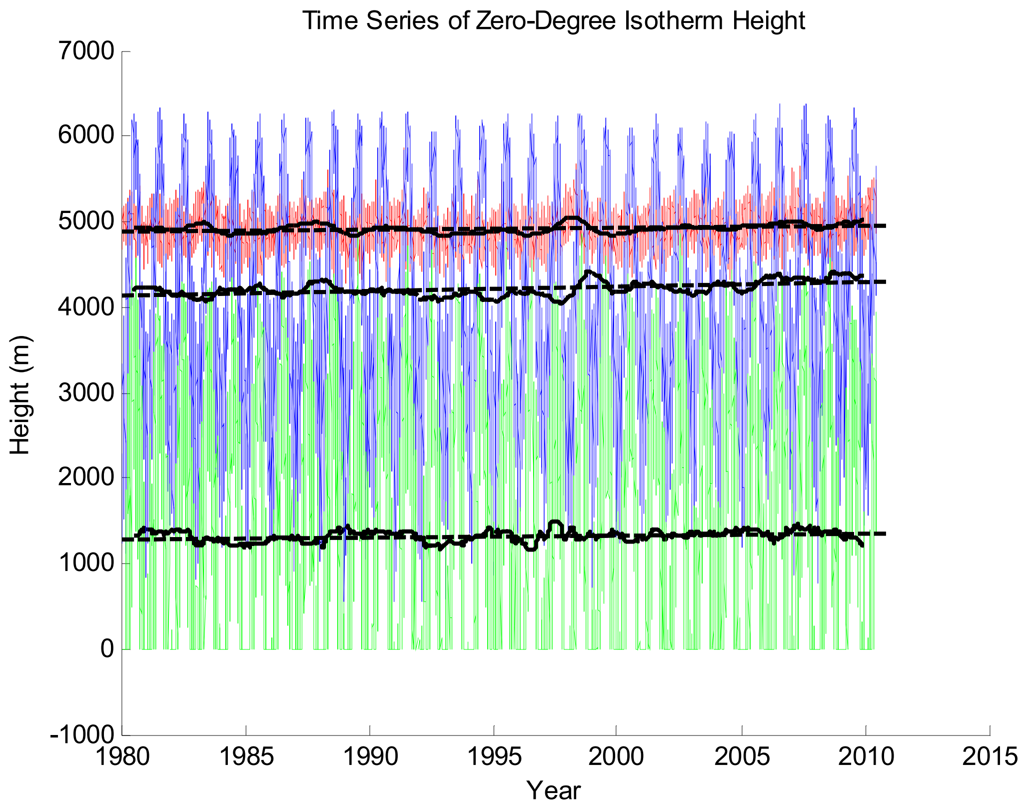

Figure (5-3) Time series of ZDI Height

4.4 ZDI Height Distribution

The distribution of ZDI height is implemented in many plots and as it shows below for the histogram which is fitted to match beta distribution. The histogram was created for a specific pixel at specific latitude and longitude of 35, and 35 and it shows for 60 bins histograms. The graph has fitted as much as it can for specific values of alpha and beta of 45 which is imply in the red line and it looks like the figure (3-1). It can be done for many different pixels from different places in the world and it can be fitted as much as it can be using beta distribution.

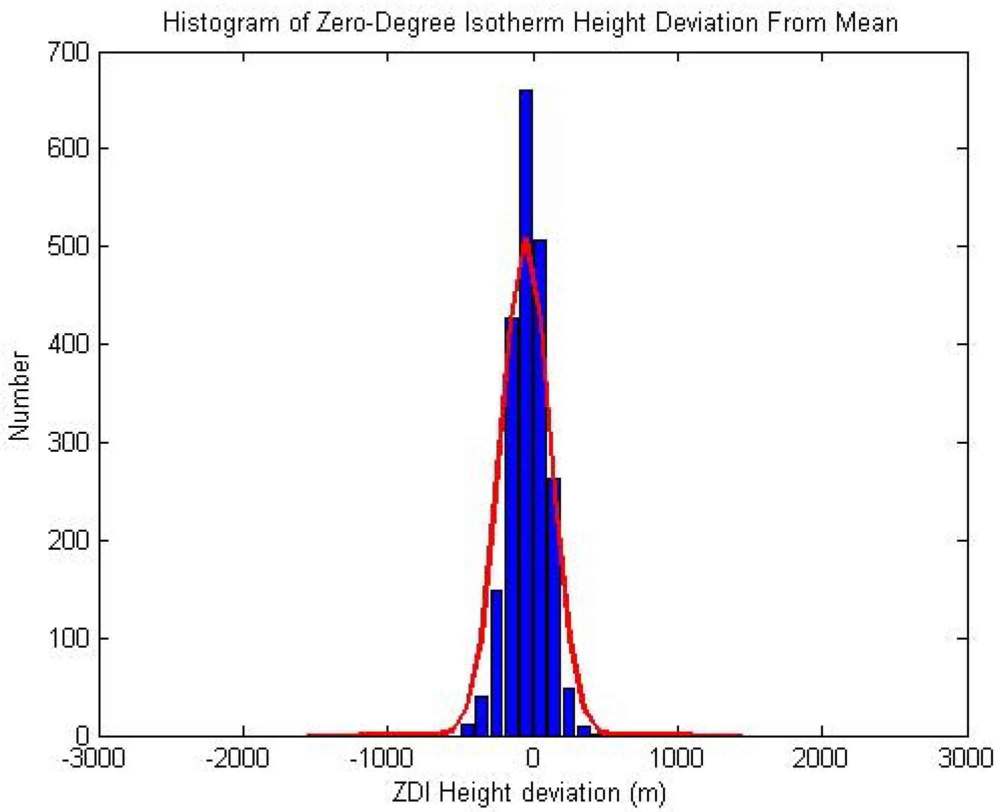

Figure (5-4) Time series of ZDI Height Histograms for specific pixel

4.5 Maximum and Minimum variation of ZDI Height

As it has been mentioned in page 14 chapter two that the Recommendation included table listing the proportion of a year that the melting layer is occupied a range of 100 m intervals within 2.4 km of the mean level. It is clear in the maximum variation figure below that the 2.4 km line above sea level from the mean and it considered in the north. As it goes close to the North Pole as it continues increasing in ZDI height and it may reach 3km or higher at the both poles. Comparing this result with ITU Recommendation shows that good results have achieved. It is also shown in the plot of minimum variation of ZDI height which is negative values and consider below ZDI height and it is similar with the maximum in 2.4km above sea level. In the poles which are recorded the lowest values of the minimum from the mean, the lower temperature implies the nearest values to ZDI height and vies versa. In the equator which has the sun vertical in specific time of the year, it shows the nearest height to ZDI and clearly opposite to the minimum variation figure.

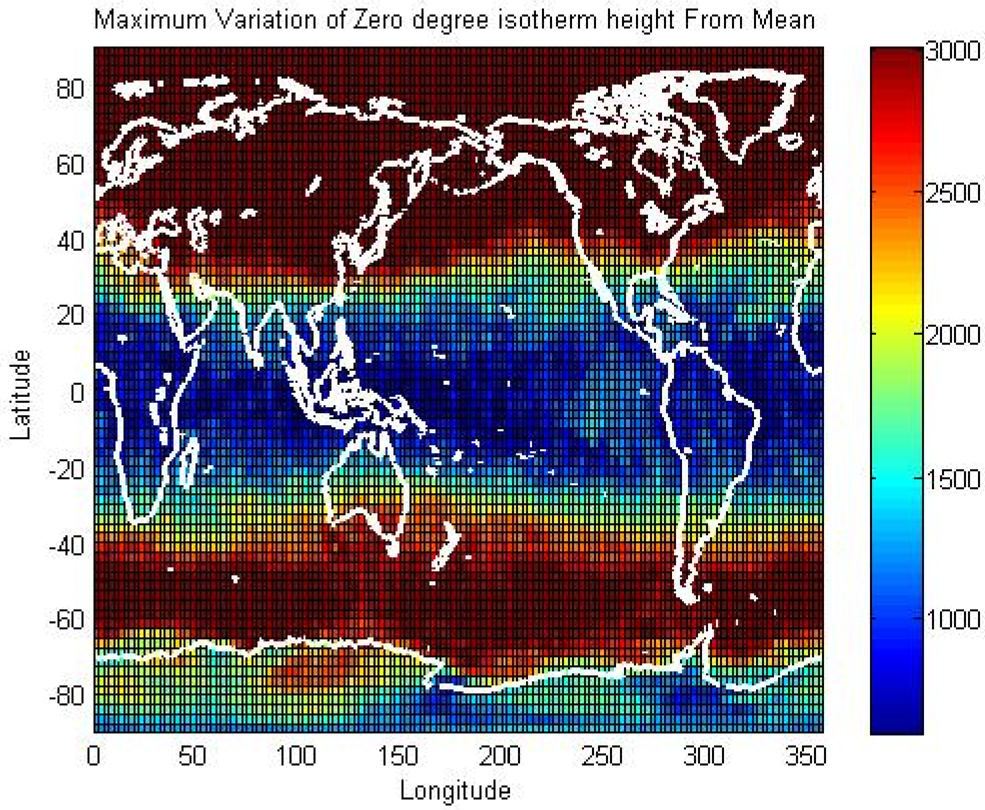

Figure (5-5) Maximum variation of ZDI Height from mean

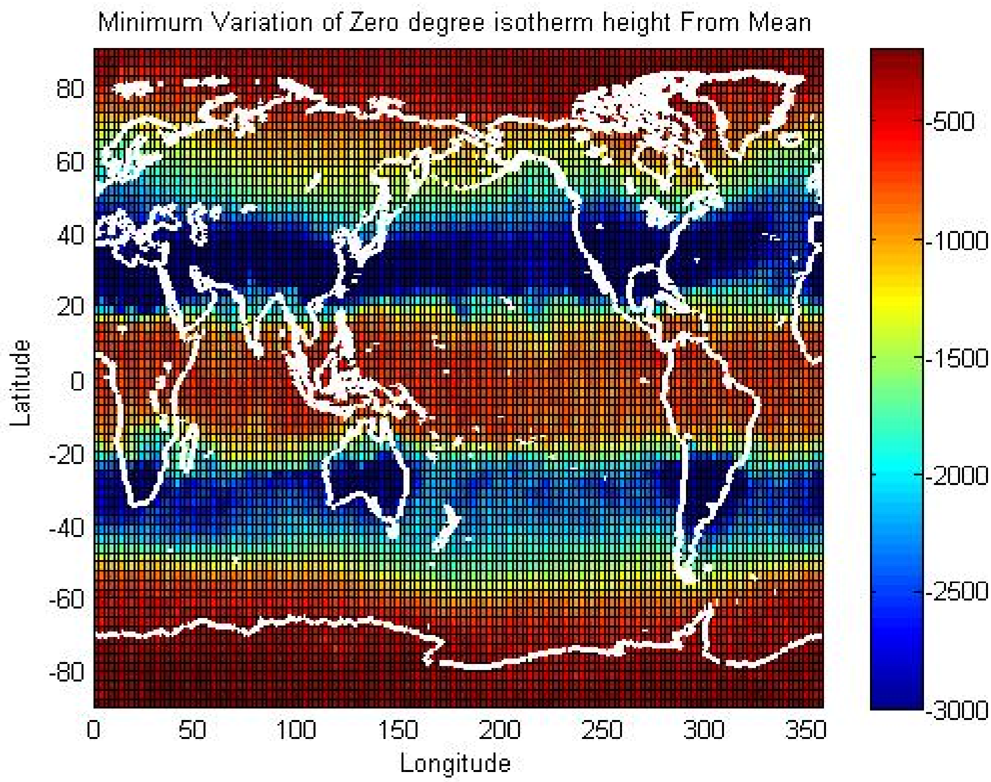

Figure (5-6) Minimum variation of ZDI Height from mean

The beat distribution of alpha and beta variation of ZDI height shown in the graphs below and it illustrates that the variation looks quite similar between them except the area close to the south pole and it is more vary for beta than alpha as it has been affected as goes near to the equator. The similarity between alpha and beta graphs means that as the value of alpha and beta are equal as it shows the peak in the middle of the curve which is clear at the value showed above at 45 figure (3-1).

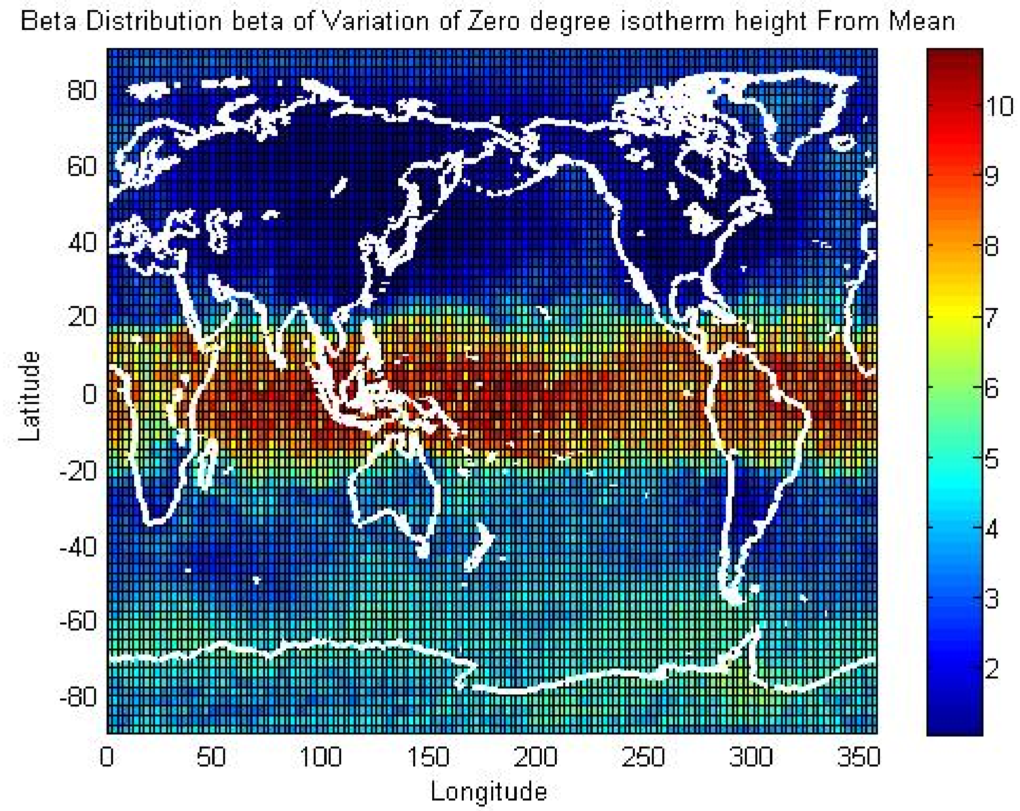

Figure (5-7) Beta Distribution beta of variation of ZDI Height from mean

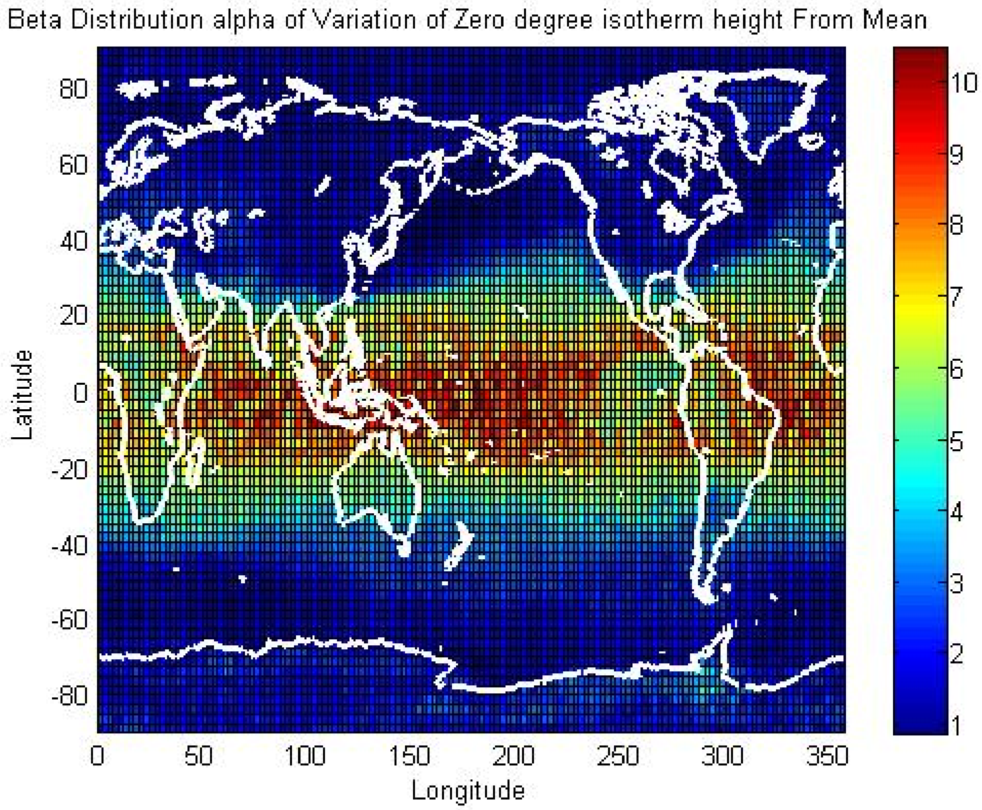

Figure (5-8) Beta Distribution Alpha of variation of ZDI Height from mean

4.6 Mean ZDI Height for Different years

The two figures below describe the mean height of ZDI at the first and last years of the analysis period. The first one shows January first 2010 with resolution of 2.5 pixles. The three above lines which are identical for the south and north imply the height of 1000, 3000, and 4500 m above mean sea level corresponding to the colours of blue, red, and yellow respectively. While the second graph is for January first 1980 and the only year that shows only different in most part of Africa with no reason can explain for this missing plot. Now, it is likely to compare these results with figure (5-9) which is provided by ITU-Recommendation with resolution of 1.5 pixels for altitude and lonitude. The graph is designed quite similar to the one produced in this thesis and it is also from 0 to 360 in longitude and from -90 to +90 latitude. The three different height are located at the same position in the ITU graph except the red one with height of 3000 which consider the most effective area (Europe and north). More over, it is showed the 2.5 km height and it can be support the thesis results.

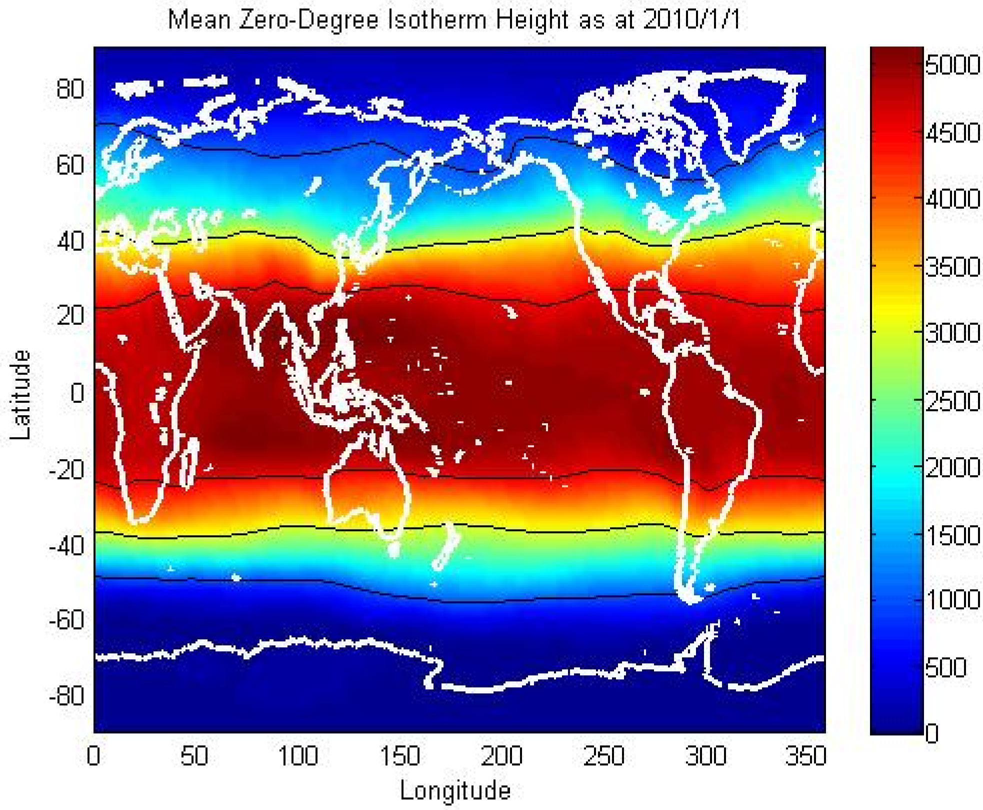

Figure (5-9) Mean ZDI Height of January first 2010

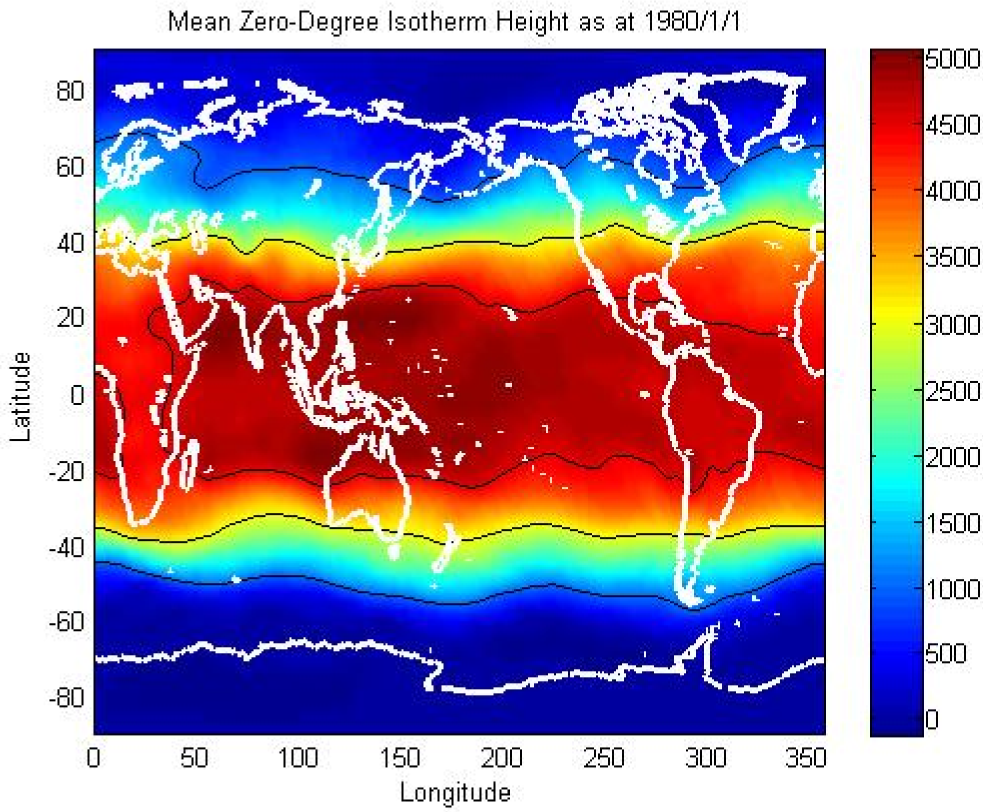

Figure (5-10)Mean ZDI Height of January first 1980

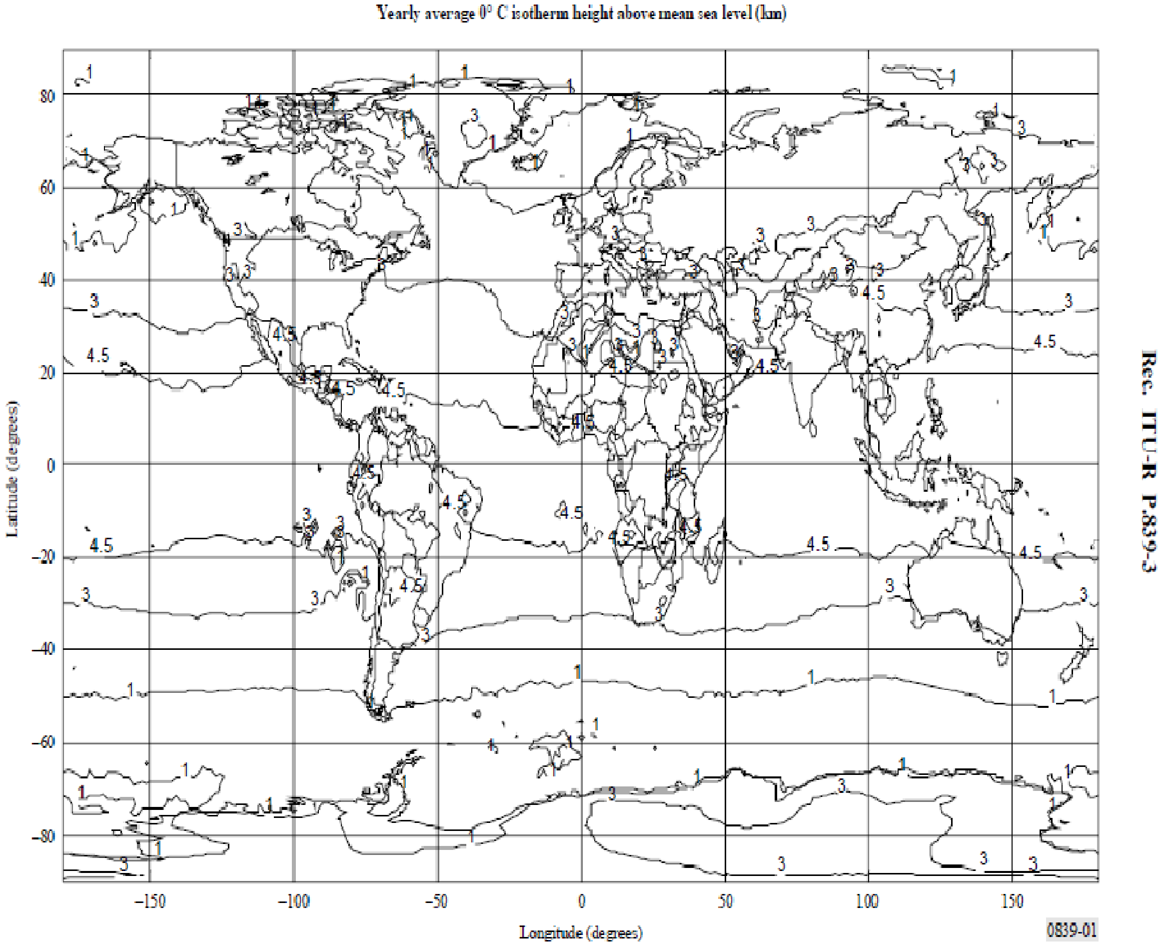

Figure (5-11) Rec. ITU-R P.839-3,Yearly average ZDI Height above mean sea level (Km)

Rec. ITU-R P.839-3, (2001)

.

CHAPTER 5
CONCLUSIONS AND FURTHER STUDY

5.0 Conclusion

To sum up, two goals were achieved in this thesis which are done to verify and compare results with ITU recommendation and other work and it would be more likely to conclude these work in two main points:
The first one is implemented in the noticable increase in the ZDI height as reach the maximum height at the most effected area which is in the north half of the earth. Increasing by about 10 m a year or more is considerably high increase in ZDI height and will have more affected if it keeps continue increasing each year. Comparing the results with a previous work and it shows that a slight different in results with maximum incearse of ZDI height of 8m a year . The most affected area in the earth that show the significant increase in ZDI height is the north half of the earth including the equator with high slop for the studied period. 300 m increase in thirty years make it fastly close to melting layer which is mean more attenuation will be occured since the attenuation cused by sleet is four time that of ossociated with rain rate.
The second point in this thesis which is implemented in the distribution part with many different study and analysis for a specific pixel as an example and it can be fitted to match beta destribution to make it easy to implimented and mathmatically described. Comparing the achieved results with ITU-Recommendation of P.839-3,Yearly average ZDI Height above mean sea level at specific point of latitud and longitude of 1000, 3000, and 4500 metr above sea level for specific time of the year shows an identical results especially for the altitude of 4500m above mean sea level and other data was scattered in the ITU graph and shows some mixed area and not much organized as the one achieved. The data is taken from different sources and that may be consider a good comparision achivemnt with different analytic .
Sometimes result dose not make the sence that it would be expected and for the year of 1980 at the altitude of 4500 above mean sea level it shows for big part of Africa such a plot of missing data and it is for the only year. Also comparing the result that achieved in this thesis with the attenuation theory in chaper two is leading to that a good result for the 2.4 km line above sea level is achieved and it quitly verify the theory part to be accepted as a good results.

5.1 Further Study

The writer suggestion in this topic for the future work is to run this work for more than 30 years and he expectes to have a slight different results for ZDI height and may be vary more or less of 10 m ayear.

The choosen randomly pixels for the equator, poles, and Europe are clearly shown an increase of ZDI height for the slop trends and it would be useful to discover many other pixels in different areas with specific altitude and latitude such south America and Australia. The ITU- recommendations are wider and provide many suggestions for the attenuation caused by sleet and fog or cloud or any other meduim. It would be more helpful to do many works with different plots and graphs and compare the results with the corresponding one from ITU recommendation. The study of climate changing is very important nowadays for microwave people and it should carry on as it is expected that for a century with increase about 1Km of ZDI height across the Europe if it keeps continuing increasing.

APPENDICES

APPENDIX A Temp Height TO ZDI height programme code

```
% shift and scale factors from NetCDF files
HGT_add_offset = 32066.0;   % float
HGT_scale_factor = 1.0;     %float
TMP_add_offset = 477.66;    % float
TMP_scale_factor = 0.01;     %float

YearStringArray = [ '2004'; '2003'; '2002'; '2001'; '2000'; '1999'; '1998'
];
[ nYear str4 ] = size( YearStringArray );

for iYear = 1:nYear

YearString4 = YearStringArray(iYear,:);

TemperatureFile = [ Path '\air.' YearString4 '.nc' ];
HeightFile      = [ Path '\hgt.' YearString4 '.nc' ];

ZeroCinKelvin = 273.15;         % zero degrees Celcius in Kelvin.

% Input lattitude and longitude from temperature file

ncid = netcdf.open(TemperatureFile,'NC_NOWRITE');              % Open
temperature file.
varid = netcdf.inqVarID(ncid,'lon');                           % Get
variable ID of the variable, given its name.
Longitude = netcdf.getVar(ncid,varid);                         % Get the
value of the variable, given its ID.
varid = netcdf.inqVarID(ncid,'lat');                           % Get
variable ID of the variable, given its name.
Latitude = netcdf.getVar(ncid,varid);                          % Get the
value of the variable, given its ID.
varid = netcdf.inqVarID(ncid,'time');                          % Get
variable ID of the variable, given its name.
Time = netcdf.getVar(ncid,varid);                              % Get the
value of the variable, given its ID.
netcdf.close(ncid)

Nsamples = length(Time);
Nlevels = 17;
Nlatiutude =length(Latitude);
Nlongitude = length(Longitude);

ZDI = zeros(Nsamples,Nlatiutude,Nlongitude);

for iSample = 1:Nsamples

    if iSample == 100*floor(iSample/100)
        disp( [ YearString4 '  ' num2str(iSample) ] );
    end

    % get temperature data
    ncid = netcdf.open(TemperatureFile,'NC_NOWRITE');              % Open
temperature file.
    varid = netcdf.inqVarID(ncid,'air');                           % Get
variable ID of the air temperature variable
```

```
    start = [0 0 0 iSample-1];
    count = [144 73 7 1 ];
    TMP = netcdf.getVar(ncid,varid,start,count);
    netcdf.close(ncid)
    TMP = TMP_add_offset + TMP_scale_factor*squeeze(single(TMP));

    % get height data
    ncid = netcdf.open(HeightFile,'NC_NOWRITE');                    % Open
temperature file.
    varid = netcdf.inqVarID(ncid,'hgt');                            % Get
variable ID of the air temperature variable
    start = [0 0 0 iSample-1];
    count = [144 73 7 1 ];
    HGT = netcdf.getVar(ncid,varid,start,count);
    netcdf.close(ncid)
    HGT = HGT_add_offset + HGT_scale_factor*squeeze(single(HGT));


    for iLat = 1: Nlatiutude

        for iLong = 1: Nlongitude

            TMPi = TMP(iLong,iLat,:);
            HGTi = HGT(iLong,iLat,:);

            TempLT0 = TMPi < ZeroCinKelvin;
            nLT0 = sum(TempLT0);
            if nLT0 == 7                                            % all
temp<0
                ZDI( iSample, iLat , iLong ) = -9999;
            else
                if nLT0 == 0                                        % all
temp>0
                    if TMPi(7) < TMPi(6)                % temerature
decreasing with altitude
                        % extrapolate the highest two temperature values.
                        ZDI( iSample, iLat , iLong ) = HGTi(7) +
(ZeroCinKelvin - TMPi(7))/(TMPi(6) - TMPi(7))*(HGTi(6) - HGTi(7));
                    else                                            %
temerature increasing with altitude so give up
                        ZDI( iSample, iLat , iLong ) = -19999;
                    end
                else
                    % There is atleast one zero-crossing with temperature
                    % decreasing with altitide so find the lowest
                    Index = find( diff(TempLT0) == 1 );         % find
indices where the temp goes from -ve to +ve
                    i = Index(1);
                    ZDI_1 = HGTi(i+1) + (ZeroCinKelvin -
TMPi(i+1))/(TMPi(i) - TMPi(i+1))*(HGTi(i) - HGTi(i+1));
                    ZDI( iSample, iLat , iLong ) = ZDI_1;
                end

            end

        end % loop over longitude

    end % loop over latitude

end % loop over time sample
```

```
% Output to Mat file
OutPutFileName = [ Path '\ZDI_Height_' YearString4 ];
save(OutPutFileName, 'ZDI');

% plot ZDI as function of lat and long for the first sample period
ZDI_plot = squeeze( ZDI(1,:,:) );
Index = find( abs(ZDI_plot) > 9990 );
ZDI_plot(Index) = 0;
pcolor(Longitude,Latitude,ZDI_plot)
ylabel('Latitude');
xlabel('Longitude');
title('Zero degree isotherm height');

end
```

APPENDIX B Trends in Average Annual ZDI Height

```
Path = 'E:\Abdueorouf Europe ZDI Trend Terrestrial';
%Path = 'E:\Abdueorouf Europe ZDI Trend Terrestrial';
Path_Out = 'E:';
nFilter = 365*4;                    % days in year times samples per day

% Years to analyse

FirstYear = 1997;
LastYear  = 1999;
nYear = LastYear - FirstYear + 1;
if nYear<2
    disp('cant work on less than two years');
    stop
end

% load first two years
% year 1
Year1str4 = num2str( round( FirstYear ) );
FileName = [ Path '\ZDI_Height_' Year1str4 '.mat' ];
load(FileName);
[ LengthY1 nLat nLong ] = size(ZDI);
MultiYearZDI = ZDI;

% year 2
Year2str4 = num2str( round( FirstYear+1 ) );
FileName = [ Path '\ZDI_Height_' Year2str4 '.mat' ];
load(FileName);
[ LengthY2 nLat nLong ] = size(ZDI);
MultiYearZDI = vertcat( MultiYearZDI , ZDI );

nSamples = LengthY1 + LengthY2;

% remove cases where ZDI is too high or too low
MultiYearZDI( abs(MultiYearZDI)>9998 ) = 0;

% caclulate the one year running average
RunningAnnualZDI = zeros( nSamples-nFilter+1 , nLat, nLong);
for iLat = 1:73
    for iLong = 1:144
        X = squeeze(
conv2(squeeze(MultiYearZDI(:,iLat,iLong)),ones(nFilter,1)/nFilter,'valid')
);
        RunningAnnualZDI(:,iLat,iLong) = X;
    end
end
```

```
% Form a vector of days in daynum format
DayNumber = (0:nSamples-1)./4 + datenum( [ FirstYear 1 1 0 0 0 ] ) ;
% Form a vector of the year centres
YearCentre = conv2(DayNumber,ones(1,nFilter)/nFilter,'valid');

% work out the running average data from this year
YearStart = datenum( [ FirstYear 1 1 0 0 0 ] );
YearEnd = datenum( [ FirstYear+1 1 1 0 0 0 ] );
Index = find( YearCentre>=YearStart & YearCentre<YearEnd );

% save the running average data from this year
ThisYearRunningZDI = RunningAnnualZDI(Index,:,:);
ThisYearCentre = YearCentre(Index);
FileName = [ Path_Out '\AnnualMeanZDI_' Year1str4 '.mat' ];
save(FileName,'ThisYearRunningZDI','ThisYearCentre');

% remove data already used
MultiYearZDI(1:LengthY1,:,:) = [];
RunningAnnualZDI(Index,:,:) = [];
YearCentre(Index) = [];

for iYear = FirstYear+2:LastYear

    LengthY1 = LengthY2;       % remember length of new first year
    Year1str4 = Year2str4;
    Year2str4 = num2str( round( iYear ) );
    disp( Year2str4 );

    % load next year of data
    FileName = [ Path '\ZDI_Height_' Year2str4 '.mat' ];
    load(FileName);
    [ LengthY2 nLat nLong ] = size(ZDI);
    % remove cases where ZDI is too high or too low
    ZDI( abs(ZDI)>9998 ) = 0;
    MultiYearZDI = vertcat( MultiYearZDI , ZDI );

    nSamples = LengthY1 + LengthY2;

    % calculate the one year running average
    NewRunningAnnualZDI = zeros( nSamples-nFilter+1 , nLat, nLong);
    for iLat = 1:73
        for iLong = 1:144
            X = squeeze(
conv2(squeeze(MultiYearZDI(:,iLat,iLong)),ones(nFilter,1)/nFilter,'valid')
);
            NewRunningAnnualZDI(:,iLat,iLong) = X;
        end
    end
    % RunningAnnualZDI = vertcat( RunningAnnualZDI , NewRunningAnnualZDI );

    % Form a vector of days in daynum format
    DayNumber = (0:nSamples-1)./4 + datenum( [ iYear-1 1 1 0 0 0 ] );
    % Form a vector of the year centres
    NewYearCentre = conv2(DayNumber,ones(1,nFilter)/nFilter,'valid');

    % work out the running average data from this year
    YearStart = datenum( [ iYear-1 1 1 0 0 0 ] );
    YearEnd   = datenum( [ iYear   1 1 0 0 0 ] );
    Index = find( NewYearCentre>=YearStart & NewYearCentre<YearEnd );
```

```
    % save the running average data from this year
    ThisYearRunningZDI = vertcat( RunningAnnualZDI ,
NewRunningAnnualZDI(Index,:,:) );
    ThisYearCentre = [ YearCentre NewYearCentre(Index) ];
    FileName = [ Path_Out '\AnnualMeanZDI_' Year1str4 '.mat' ];
    save(FileName,'ThisYearRunningZDI','ThisYearCentre');

    % remove data already used
    MultiYearZDI(1:LengthY1,:,:) = [];
    RunningAnnualZDI = NewRunningAnnualZDI(max(Index)+1:end,:,:);
    YearCentre = NewYearCentre(max(Index)+1:end);

end

% work out the running average data from this year
YearStart = datenum( [ LastYear   1 1 0 0 0 ] );
YearEnd   = datenum( [ LastYear+1 1 1 0 0 0 ] );
Index = find( YearCentre>=YearStart & YearCentre<YearEnd );

    % save the running average data from the last year
ThisYearRunningZDI = RunningAnnualZDI;
ThisYearCentre = YearCentre(Index);
FileName = [ Path_Out '\AnnualMeanZDI_' Year2str4 '.mat' ];
save(FileName,'ThisYearRunningZDI','ThisYearCentre');
```

APPENDIX C Regression Plot Multi Year ZDI Height

```
Path = 'E:\Abdueorouf Europe ZDI Trend Terrestrial';
%Path = 'E:\Abdueorouf Europe ZDI Trend Terrestrial';

% Years to analyse

%YearsToAnalyse = [ '2008' ; '2009' ; '2010' ];
YearsToAnalyse = [ '1980' ; '1981' ; '1982' ; '1983' ; '1984' ; '1985' ;
'1986' ; '1987' ; '1988' ; '1989' ; '1990' ; '1991' ; '1992' ; '1993' ;
'1994' ; '1995' ; '1996' ; '1997' ; '1998' ; '1999' ; '2000' ; '2001' ;
'2002' ; '2003' ; '2004' ; '2005' ; '2006' ; '2007' ; '2008' ; '2009' ;
'2010' ];
[ nYear str4 ] = size( YearsToAnalyse );

% Initialise linear regression variables

S = netcdf([ Path '\air.2010.nc' ],'var',2);
Latitude = S.VarArray(2).Data;
S = netcdf([ Path '\air.2010.nc' ],'var',3);
Longitude = S.VarArray(3).Data;

nLat = length( Latitude );
nLong = length( Longitude );
N = 0;
Sum_Day  = 0;
Sum_Day2 = 0;
Sum_ZDI  = zeros(73,144);
Sum_ZDI2 = zeros(73,144);
Sum_DayZDI = zeros(73,144);

figure(1)
hold on

for iYear = 1:nYear
```

```
    FileName = [ Path '\ZDI_Height_' YearsToAnalyse(iYear,:) ];
    load(FileName);
    ZDI( abs(ZDI)>9998 ) = 0;
    [ nSamples nLat nLong ] = size(ZDI);

    % Form a vector of days in daynum format
    DayNumber = (0:nSamples-1)./4 + datenum( [
str2num(YearsToAnalyse(iYear,:)) 1 1 0 0 0 ] ) ;

    plot(DayNumber,ZDI(:,35,35),'r')
    plot(DayNumber,ZDI(:,25,35),'b')
    plot(DayNumber,ZDI(:,15,35),'g')

    FileName = [ Path '\AnnualMeanZDI_' YearsToAnalyse(iYear,:) '.mat' ];
    load(FileName);
    plot(ThisYearCentre, ThisYearRunningZDI(:,35,35),'k','LineWidth',2)
    plot(ThisYearCentre, ThisYearRunningZDI(:,25,35),'k','LineWidth',2)
    plot(ThisYearCentre, ThisYearRunningZDI(:,15,35),'k','LineWidth',2)

    N = N + length( ThisYearCentre );
    Sum_Day  = Sum_Day  + sum( ThisYearCentre );
    Sum_Day2 = Sum_Day2 + sum( ThisYearCentre.^2 );
    Sum_ZDI  = Sum_ZDI  + squeeze( sum( ThisYearRunningZDI ) );
    Sum_ZDI2 = Sum_ZDI2 + squeeze( sum( ThisYearRunningZDI.^2 ) );
    for iSample = 1:length( ThisYearCentre )
        ThisYearRunningZDI(iSample,:,:) =
ThisYearCentre(iSample)*ThisYearRunningZDI(iSample,:,:);
    end
    Sum_DayZDI = Sum_DayZDI + squeeze( sum(ThisYearRunningZDI,1) );

end
xlabel('Year')
ylabel('Height (m)')
title('Time Series of Zero-Degree Isotherm Height')
datetick('x',10)

% calculate regression coefficients ZDI = A + B*DayNumber

B = ( Sum_DayZDI - Sum_Day*Sum_ZDI/N )./( Sum_Day2 - Sum_Day^2/N );
A = ( Sum_ZDI - B*Sum_Day )/N;

FirstDay = datenum( [ str2num(YearsToAnalyse(1,:)) 1 1 0 0 0 ] );
LastDay = datenum( [ str2num(YearsToAnalyse(end,:)) 12 31 0 0 0 ] );

plot([ FirstDay LastDay ], A(35,35)+B(35,35)*[ FirstDay LastDay ],'k--
','LineWidth',2);
plot([ FirstDay LastDay ], A(25,35)+B(25,35)*[ FirstDay LastDay ],'k--
','LineWidth',2);
plot([ FirstDay LastDay ], A(15,35)+B(15,35)*[ FirstDay LastDay ],'k--
','LineWidth',2);

B_m_per_Year = B*365;
figure(2)
%pcolor(Longitude,Latitude,B)
pcolor(Longitude,Latitude,B_m_per_Year)
ylabel('Latitude');
xlabel('Longitude');
title('Trend Slope of Zero-Degree Isotherm Height (m/year)');
colorbar;
shading interp
```

```
%h=pcolor(peaks(42))
%set(h,'edgecolor','none')

% overplot with map of world
fid = fopen([ Path '\WorldCoastline.dat' ] );
C = textscan(fid,'%n%n');
fclose(fid);


CoastLat = C{1};
CoastLong = C{2};
Index = find(~isfinite(CoastLat));
hold on
for i=1:length(Index)-1
    plot(CoastLat(Index(i)+1:Index(i+1)-1) ,
CoastLong(Index(i)+1:Index(i+1)-1), 'w','LineWidth',2 );
end

% plot mean ZDI height
figure(3)
ZDI_2000 = A + B*datenum([2000,1,1,0,0,0,]);        % 1 Jan 2000
pcolor(Longitude,Latitude,ZDI_2000)
ylabel('Latitude');
xlabel('Longitude');
title('Mean Zero-Degree Isotherm Height as at 2000/1/1');
colorbar;
shading interp

% plot coast
CoastLat = C{1};
CoastLong = C{2};
Index = find(~isfinite(CoastLat));
hold on
for i=1:length(Index)-1
    plot(CoastLat(Index(i)+1:Index(i+1)-1) ,
CoastLong(Index(i)+1:Index(i+1)-1), 'w','LineWidth',2 );
end

% plot contour levels

contour(Longitude,Latitude,ZDI_2000,[1000 3000 4500],'--k')
```

APPENDIX D Plot histogram and best fit beta distribution for a particular pixel

```
%YearsToAnalyse = [ '2008' ; '2009'  ];
YearsToAnalyse = [  '1981' ; '1982' ; '1983' ; '1984' ; '1985' ; '1986' ;
'1987' ; '1988' ; '1989' ; '1990' ; '1991' ; '1992' ; '1993' ; '1994' ;
'1995' ; '1996' ; '1997' ; '1998' ; '1999' ; '2000' ; '2001' ; '2002' ;
'2003' ; '2004' ; '2005' ; '2006' ; '2007' ; '2008' ; '2009'  ];
[ nYear str4 ] = size( YearsToAnalyse );

% Initialise latitude and longitude variab;es

S = netcdf([ Path '\air.2010.nc' ],'var',2);
Latitude = S.VarArray(2).Data;
S = netcdf([ Path '\air.2010.nc' ],'var',3);
Longitude = S.VarArray(3).Data;
nLat = length( Latitude );
nLong = length( Longitude );
```

```
% Initialise ZDI_Deviation histogram variables

MinDZDI = -3000;
MaxDZDI =  3000;
nBin = 60;
BinSize = (MaxDZDI - MinDZDI)/nBin;
edges = MinDZDI+(0:nBin)*BinSize;
DZDI_Hist = zeros(nBin+1,nLat,nLong);

for iYear = 1:nYear

    FileName = [ Path '\ZDI_Height_' YearsToAnalyse(iYear,:) ];
    load(FileName);

    FileName = [ Path '\AnnualMeanZDI_' YearsToAnalyse(iYear,:) '.mat' ];
    load(FileName);

    Index = find( abs(ZDI)>9998 );
    [ nSamples_ZDI  ] = size(ZDI);
    [ nSamples_annualZDI junk junk ] = size(ThisYearRunningZDI);
    nSamples = min([nSamples_ZDI nSamples_annualZDI]);

    DZDI = ZDI(1:nSamples,:,:) - ThisYearRunningZDI(1:nSamples,:,:);

    DZDI_Hist = DZDI_Hist + histc(DZDI,edges,1);

end


% specify pixel to plot
Plot_Lat = 35;
Plot_Long = 35;

% plot bar chart of observed values
figure(1)
BinCentres = ( edges(2:end) + edges(1:end-1) )/2;
Observed = squeeze(DZDI_Hist(1:end-1,Plot_Lat,Plot_Long) );
bar( BinCentres , Observed , 'b')
xlabel('ZDI Height deviation (m)')
ylabel('Number')
title('Histogram of Zero-Degree Isotherm Height Deviation From Mean')

% over-plot with expected values for given beta distribution

% specify beta distribution parameters
alpha = 45;                            % SET THIS VALUE YOURSELF
beta = 45;                             % SET THIS VALUE YOURSELF

% specify transformation from altitude to [0,1]
First = 15;                             % SET THIS VALUE YOURSELF
Last = 45;                              % SET THIS VALUE YOURSELF
Low = edges(First);
High = edges(Last+1);

% calculate Expected values
Transformed_Edges = (edges(First:Last+1)-Low)/(High-Low);
BinProbability = diff( betacdf(Transformed_Edges,alpha,beta) )';
nTrials = sum(Observed);
Expected = nTrials*BinProbability;
```

```
% add to plot
ExBinCentres = ( edges(First+1:Last+1) + edges(First:Last) )/2;
hold on
plot( ExBinCentres , Expected , 'r', 'linewidth',2)

figure(2)
Ex = zeros(size(Observed));
Ex(First:Last) = Expected;
bar(BinCentres, [ Observed Ex ] );
xlabel('ZDI Height deviation (m)')
ylabel('Number')
title('Histogram of Zero-Degree Isotherm Height Deviation From Mean')
colormap summer
```

APPENDIX E Build ZDI Deviation Histograms

```
Path = 'E:\Abdueorouf Europe ZDI Trend Terrestrial';
%Path = 'E:\Abdueorouf Europe ZDI Trend Terrestrial';

% Years to analyse

%YearsToAnalyse = [ '1981' ; '1982' ; '1983' ; '1984' ; '1985' ; '1986'  ];
YearsToAnalyse = [  '1981' ; '1982' ; '1983' ; '1984' ; '1985' ; '1986' ;
'1987' ; '1988' ; '1989' ; '1990' ; '1991' ; '1992' ; '1993' ; '1994' ;
'1995' ; '1996' ; '1997' ; '1998' ; '1999' ; '2000' ; '2001' ; '2002' ;
'2003' ; '2004' ; '2005' ; '2006' ; '2007' ; '2008' ; '2009'  ];
[ nYear str4 ] = size( YearsToAnalyse );

% Initialise latitude and longitude variab;es

S = netcdf([ Path '\air.2010.nc' ],'var',2);
Latitude = S.VarArray(2).Data;
S = netcdf([ Path '\air.2010.nc' ],'var',3);
Longitude = S.VarArray(3).Data;
nLat = length( Latitude );
nLong = length( Longitude );
clear S

% Initialise ZDI_Deviation histogram variables

MinDZDI = -3000;
MaxDZDI =  3000;
nBin = 60;
BinSize = (MaxDZDI - MinDZDI)/nBin;
edges = MinDZDI+(0:nBin)*BinSize;
DZDI_Hist = zeros(nBin+1,nLat,nLong);

for iYear = 1:nYear

    FileName = [ Path '\ZDI_Height_' YearsToAnalyse(iYear,:) ];
    load(FileName);

    FileName = [ Path '\AnnualMeanZDI_' YearsToAnalyse(iYear,:) '.mat' ];
    load(FileName);

    Index = find( abs(ZDI)>9998 );
    [ nSamples_ZDI junk junk ] = size(ZDI);
    [ nSamples_annualZDI junk junk ] = size(ThisYearRunningZDI);
    nSamples = min([nSamples_ZDI nSamples_annualZDI]);
```

```
    DZDI = ZDI(1:nSamples,:,:) - ThisYearRunningZDI(1:nSamples,:,:);

    DZDI_Hist = DZDI_Hist + histc(DZDI,edges,1);

end
clear ZDI ThisYearRunningZDI

DZDI_Hist(nBin+1,:,:) = [];                          % get rid of last row
of histogram

BinCentres = ( edges(2:end) + edges(1:end-1) )/2;
bar( BinCentres , squeeze(DZDI_Hist(:,1,1) ) )
xlabel('ZDI Height deviation (m)')
ylabel('Number')
title('Time Series of Zero-Degree Isotherm Height')

% Fit a beta distribution to each histogram

MinZDIDev = zeros(nLat,nLong);
MaxZDIDev = zeros(nLat,nLong);
BetaDist_alpha = zeros(nLat,nLong);
BetaDist_beta = zeros(nLat,nLong);

global Edges Observed
for iLat = 1:nLat
    disp( num2str(iLat) );
    for iLong = 1:nLong

        % Build the Observed data to be passed to Chi-Squared routine via
        % global statement
        Index = find( DZDI_Hist(:,iLat,iLong) > 0 );
        First = Index(1);
        Last = Index(end);
        Low = edges(First);
        High = edges(Last+1);
        Edges = (edges(First:Last+1) - Low)/(High-Low);
        Observed =  DZDI_Hist(First:Last,iLat,iLong);

        BetaParam = fminsearch('Chi_Squared_Beta_Fit' ,[1,1]);

        MinZDIDev(iLat,iLong) = Low;
        MaxZDIDev(iLat,iLong) = High;
        BetaDist_alpha(iLat,iLong) = BetaParam(1);
        BetaDist_beta(iLat,iLong) = BetaParam(2);

    end

end

% Output to Mat file
OutPutFileName ='BetaDistrParameters';
save(OutPutFileName, 'MinZDIDev', 'MinZDIDev', 'BetaDist_alpha',
'BetaDist_beta');

% do lots of plots


% overplot with map of world
fid = fopen([ Path '\WorldCoastline.dat' ] );
C = textscan(fid,'%n%n');
```

```
fclose(fid);

CoastLat = C{1};
CoastLong = C{2};
Index = find(~isfinite(CoastLat));

figure(2)
pcolor(Longitude,Latitude,MinZDIDev)
hold on
for i=1:length(Index)-1
    plot(CoastLat(Index(i)+1:Index(i+1)-1) ,
CoastLong(Index(i)+1:Index(i+1)-1), 'w','LineWidth',2 );
end
ylabel('Latitude');
xlabel('Longitude');
title('Minimum Variation of Zero degree isotherm height From Mean');
colorbar

figure(3)
pcolor(Longitude,Latitude,MaxZDIDev)
hold on
for i=1:length(Index)-1
    plot(CoastLat(Index(i)+1:Index(i+1)-1) ,
CoastLong(Index(i)+1:Index(i+1)-1), 'w','LineWidth',2 );
end
ylabel('Latitude');
xlabel('Longitude');
title('Maximum Variation of Zero degree isotherm height From Mean');
colorbar

figure(4)
pcolor(Longitude,Latitude,BetaDist_alpha)
hold on
for i=1:length(Index)-1
    plot(CoastLat(Index(i)+1:Index(i+1)-1) ,
CoastLong(Index(i)+1:Index(i+1)-1), 'w','LineWidth',2 );
end
ylabel('Latitude');
xlabel('Longitude');
title('Beta Distribution alpha of Variation of Zero degree isotherm height
From Mean');
colorbar

figure(5)
pcolor(Longitude,Latitude,BetaDist_beta)
hold on
for i=1:length(Index)-1
    plot(CoastLat(Index(i)+1:Index(i+1)-1) ,
CoastLong(Index(i)+1:Index(i+1)-1), 'w','LineWidth',2 );
end
ylabel('Latitude');
xlabel('Longitude');
title('Beta Distribution beta of Variation of Zero degree isotherm height
From Mean');
colorbar
```

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