

SPATIAL AND TEMPORAL VARIABILTY OF PRECIPITABLE WATER VAPOR FROM ERA-INTERIM OVER ETHIOPIA DURING 2006-2012

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ELIASE AYALEW

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Signed by the Examining Committee:

Advisor: _____

Dr. Gizaw Mengistu

Examiner: _____

Prof A.V. Gholap

Examiner: _____

Dr. Kassahun T.

Abstract

Signals from the Global Positioning System (GPS) are used to retrieve the integrated amount of water vapor along the path between a transmitting satellite and a receiving station. This integrated quantity is called slant water vapor (SW). Measurements of SW allow for an improved assessment of the spatial distribution of water vapor within the atmosphere. A study of 7 years (2006-2012) Precipitable water vapour contents (PWVCs) from European Centre for Medium-Range Weather Forecasts (ECMWF) data have been used over the region ($3 - 15^0N$, $32 - 48^0$E) of Ethiopia for a particular time interval of 00:00, 06:00, 12:00 and 18:00 UTC has been carried out. The time series of PWV and its deviation from annual mean also brought out for all the years. Both dry and moist years in both monsoon and post monsoon season shows almost increasing trend of PWV for all the years. There exists a well defined seasonal variation in precipitable water vapor content with maximum during monsoon months (June-September) and minimum during the month of March. Variability in PWVC is higher during post-monsoon and winter months (October to February) and smaller during pre-monsoon and monsoon months (March to September). It indicates that local modification of weather systems either sea bridge or entrainment of dry or moist air also play an important role in rainfall.

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INTRODUCTION

The column humidity content of the atmosphere, expressed as the integrated column of water vapour in the zenith direction, usually called integrated precipitable water vapour (IPWV), or just precipitable water, is a fundamental quantity for all atmospheric sciences. The unit, mass per unit area, is in meteorological practice usually given as the thickness (height) of the layer of liquid water that would be formed if all the water vapour in the zenith direction were condensed at the surface of a unit area, hence a 1 mm layer corresponds to 1 kg/m^2 [1].

Water vapour is the most important greenhouse gas, contributing to about 60 percent of the natural greenhouse effect; carbon dioxide accounts for just 26 percent, and ozone for 8 percent [2]. In contrast to other greenhouse gases, water vapour has a much higher temporal and spatial variability which is not well observed, neither is it fully understood [3].

Water vapour strongly modulates the propagation of solar and terrestrial radiation and plays a crucial role in the Earth's radiation budget. Besides this, water vapour also has a significant influence on the accuracy of satellite monitoring information regarding surface properties (satellite images), GPS applications, describing hydrological cycle, analysis of transmittance of the direct solar radiation, etc. Changes in the atmospheric moisture budget as well as cloud coverage and properties belong to key factors controlling the strength of future Arctic climate change [4]. Accurate information on the air moisture is also essential for monitoring the climate: uncertainties in the water vapour content cause errors in satellite-based observations on the surface temperature, albedo [5] and sea ice concentration [6].

During recent decades, a strong improvement has been witnessed in the accuracy of atmospheric model analyses, re-analyses, and forecasts [7]. Due to changes in models and data assimilation systems, operational analyses do not provide a consistent long-term data set on the atmospheric moisture budget. Reanalyses, however, based on the utilization of the same model and data assimilation procedure, are better in this respect.

The objective of this thesis is to present:

- comprehensive picture of spatial and temporal variability of precipitable water in the Ethiopian region;
- overview of precipitable water vapor transport in the region;
- regional trends in IPWV in the region;

This thesis is organized as follows: Chapter 1 gives a short discription on the importance and availability of precipitable water vapor in the atmosphere. Chapter 2 gives a short overview of available methods for precipitable water vapor estimation. The modelling techniques of PWV on climate models are also discussed. In Chapter 3, some related parametric variables of PWV and accuracy estimation for ERA-Interim measured precipitable water is given. In Chapter 4, an overview of tcwv data used and interpretation of the results are given. This chapter also discusses the spatial and temporal variability. conclusion is presented in chapter 5.

Chapter 1

WATER VAPOR IN THE EARTH'S ATMOSPHERE

What is water vapor? Water vapor is water in its gaseous state-instead of liquid or solid (ice). Water vapor is totally invisible. If you see a cloud, fog, or mist, these are all liquid water, not water vapor. Water vapour is highly variable both in space and time across the Earth's atmosphere. Water vapor plays a fundamental role in a hydrological cycle. It has pecullar characteristics, first it is highly variable both in space and time. Water vapor is produced through the evaporation of liquid water (oceans, seas, lakes and rivers) or sublimation from a solid (ice or snow) to a gas. Once in the air, water vapour gets cold and as a result, the excess water vapour condenses (changes from a gas to a liquid) to form clouds and produce precipitation in terms of rain, snow, sleet, freezing rain and hail [1]. Second it is the dominant greenhouse gas in the atmosphere, which it plays an important role in the greenhouse effect, i.e., the effect which makes the Earth's surface become warmer. Water vapor is extremely important to the weather and climate. Without it, there would be no clouds or rain or snow, since all of these require water vapor in order to form. All of the water vapor that evaporates from the surface of the Earth eventually returns as precipitation - rain or snow. Water vapor is also the Earth's most important greenhouse gas, accounting for about 60^0 of the Earth's natural greenhouse effect, which helps keep the Earth warm enough to support life [8].

1.1 The hydrologic cycle

A hydrologic cycle is established with evaporation from ocean/land surface to the atmosphere, condensation of this humidity to rain/snow which in turn falls to the land surface/ocean as sketched in figure below. The cycle is referred to as the hydrologic cycle referring to water being recycled (examples of other cycles are the carbon and nitrogen cycles). The source that makes the cycle go is mainly the solar influx of energy (and the rotation of the Earth) which on global scale on average is I $\approx$ 340 Wm^2 . Of this a significant fraction (about 30 percent) is directly re-emitted as reflection from clouds, water and ice (this is referred to as the planetary albedo). Part of the remaining energy is tied up in evaporating water [5].

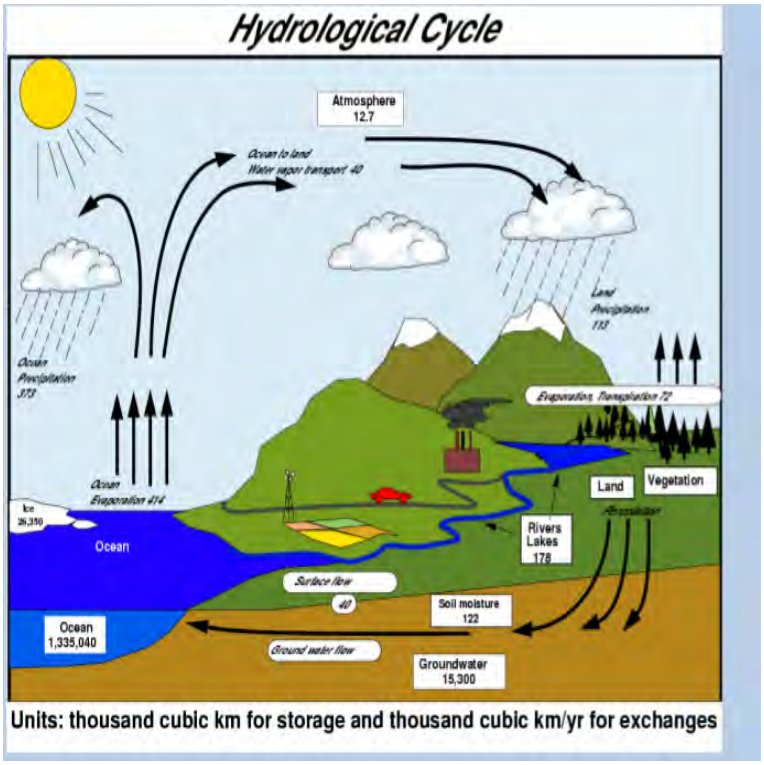


Figure 1.1: Hydrological cylce of PWV.

When liquid water is evaporated to form water vapor, heat is absorbed. This helps to cool the surface of the Earth. This "latent heat of condensation" is released again when the water vapor condenses to form cloud water. This source

of heat helps drive the updrafts in clouds and precipitation systems, which then causes even more water vapor to condense into cloud, and more cloud water and ice to form precipitation. Interesting facts: Water Vapor cools and Warms the Climate System? When water evaporates from the surface of the Earth, it cools the surface. This keeps the surface from getting too hot. But because that water vapor is also the atmosphere's primary greenhouse gas, water vapor acts to keep the Earth's surface warmer than it would otherwise be.

So which effect is stronger, water vapor's cooling effect or warming effect? Interestingly, it is seldom mentioned in the global warming debate that the surface cooling effect of evaporation (which creates water vapor) is stronger than its greenhouse warming effect [9].

Most of the water in the solid phase is referred to as the cryosphere. Ice is found mainly as polar ice-caps (8 percent on Greenland and 91.5 percent on Antarctica), but also to a smaller extend in other smaller glaciers (0.5 percent), snow and permafrosen in the ground. A very small amount is found as ice crystals at high altitudes in the atmosphere. These crystals seem to play an important role in the ozone balance as they transform inactive chlorine containing molecules into active ozone destroying molecules, hence acting as a catalyst for increased ozone destruction. Approximately 2 percent of the global water is stored as ice, with the polar ice caps containing $43 \cdot 10^{15}\ m^3$ ice, corresponding to $40 \cdot 10^{15}\ m^3$ liquid water. The interaction between the cryosphere and water vapour is rather weak as the ice is such a minor water reservoir.

Liquid water is covering more than 2/3 of the Earth's surface to an average depth of 2 km, resulting in a total of at least $7 \cdot 10^{17}\ m^3$ in the oceans (the hydrosphere). Only the upper few hundred meters of the oceans is exchanging energy with the atmosphere on time-scales of a few years. The oceans contains almost all the water on Earth, about 97 percent. A small amount (less than one percent) is found in lakes, rivers and soil moisture in the solid Earth, the lithosphere. An insignificant fraction (when considering mass) is found as drops in the atmosphere,

forming clouds and precipitation. The significance of this liquid water increase if the point of view is the energy balance in the atmosphere as clouds are responsible for both cooling and heating of the atmosphere as mentioned above.

Water in the phase of gas is one of the least acknowledged components of the atmosphere in the common public. It consists of single free water molecules and is invisible for the human eye. Only when it becomes small (liquid) drops it is visible. Unlike the generally spherical symmetrical distribution of the atmospheric constituents (nitrogen, oxygen etc), water vapour (and a few other constituents such as ozone) is distributed very irregularly. This is a result of the continuous production and destruction in different regions of the globe at different rates, and that the general motion of the atmosphere is not fast enough to homogenise the distribution. Other constituents of the atmosphere are better mixed because of the lack of production and destruction at high rates. Because the amount of water vapour is closely linked to the temperature of the atmosphere, the (hot) tropical region (latitude less than about 30^0) contains a large amount of water vapour. In total the atmosphere contains water vapour corresponding to a global cover of 2.5 cm liquid water (as compared to a kilometre scale layer if averaging the oceans globally).

1.1.1 The Greenhouse effect

Gases (and other substances) absorb radiation at some specific wavelengths and let the other wavevelengths pass through. The windows of transparency are found at various wavelengths for various gases depending on the atomic and molecular configuration. The surface of the Earth is heated by incoming solar radiation, in this way converting radiation with short wavelength into radiation with longer wavelength. If the atmosphere consists of gases which absorb long wave radiation and let short wave radiation pass, the atmosphere is heated because of the wavelength-transformation (from short to long wavelengths) taking place at the

surface. Gases acting in this way are named greenhouse gases [10].

A greenhouse gas (sometimes abbreviated GHG) is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect. In the Solar System, the atmospheres of Venus, Mars, and Titan also contain gases that cause greenhouse effects. Greenhouse gases greatly affect the temperature of the Earth; without them, Earth's surface would average about 33^0C colder than the present average of 14^0C (57^0F). Greenhouse gases are those that can absorb and emit infrared radiation, but not radiation in or near the visible spectrum. In order, the most abundant greenhouse gases in Earth's atmosphere are:

- water vapour (H_2O)
- carbon dioxide (CO_2)
- methane (CH_4)
- nitrous oxide (N_2O)
- ozone (O_3)

Atmospheric concentrations of greenhouse gases are determined by the balance between sources (emissions of the gas from human activities and natural systems) and sinks (the removal of the gas from the atmosphere by conversion to a different chemical compound) [10].

1.2 Use of precipitable water vapor in the atmosphere

The climate of Earth is able to support life in large part because of the atmospheric greenhouse effect and the workings of the hydrological cycle. Water in the gaseous phase, water vapor, is a key element in both of these. The hydrological cycle describes the movement of water, in all three phases, within and between the Earth's atmosphere, oceans, and continents. In the vapor phase,

water moves quickly through the atmosphere and redistributes energy associated with its evaporation and recondensation. The movement of water vapor through the hydrological cycle is strongly coupled to precipitation and soil moisture, which have important practical implications. The basic operation of the hydrologic cycle is well known, but some details are poorly understood, mainly because we do not have sufficiently good observations of water vapor [9].

There are many atmospheric greenhouse gases, some naturally occurring and some resulting from industrial activities, but probably the most important greenhouse gas is water vapor. Water vapor is involved in an important climate feedback loop. As the temperature of the Earth's surface and atmosphere increases, the atmosphere is able to hold more water vapor [11]. The additional water vapor, acting as a greenhouse gas, absorbs energy that would otherwise escape to space and so causes further warming. This basic picture is complicated by important interactions between water vapor, clouds, atmospheric motion, and radiation from both the Sun and the Earth. There are some aspects of the role of water vapor as a greenhouse gas that are not well understood, again mainly because we lack the necessary observations to test theoretical models.

One of the most environmental parameters that play a key role in the Earth's atmosphere and a highly variable atmospheric constituent in determining and predicting the global climate system is the total available of atmospheric moisture measured by integrated precipitable water vapor (IPWV) [12]. PWV value represents the total amount of water vapor content in the lower atmosphere that would result from condensing all the water vapor in an atmospheric column at a particular time and over a given location from the surface of Earth to the top of the atmosphere , is an important input to hydrological, energetic and radiation models. Its unit is mass per unit area. In practice this unit is usually considered as the thickness of the layer of liquid water that would be formed if all the vapor in the zenith direction were condensed at the surface of a unit area: 1 mm of the layer corresponds to 1 kg m^{-2} , and 1 cm to 1 g cm^{-1} [9].

Greenhouse gases play a major role in determining the balance between the amount of radiation entering the Earth's surface, and the amount of radiation leaving the Earth's surface. The greenhouse effect keeps the Earth's surface about 33^0C warmer than it would otherwise be. There is far more water vapour in the atmosphere than other greenhouse gases, but the other gases are still very important. While human activity does not directly affect the amount of atmospheric water vapour, human activity has significantly increased the concentrations of the other greenhouse gases, such as carbon dioxide (CO_2), which cause the Earth's surface to warm and result in increased water vapour levels and further warming-a positive 'feedback'. To date, water vapor remains one of the most poorly characterized meteorological parameters. It is least understood constituents of the Earths atmosphere due to its rapid change and irregular spatial and temporal variability. Long-term changes in the amount of water vapor in the atmosphere need to be monitored to help detect and predict changes in the earths climate. PWV measurement can also be used to improve weather forecasting. Atmospheric water vapor is a critical component in the formation of clouds, precipitation, and severe weather.

Knowledge of accurate PWV quantification and interpretation of their physical characters are crucial in understanding how the global climate system such as global warming change over time [13].

Recent advancements in Global Positioning System (GPS) sensing technology and the availability of low-cost GPS receivers have allowed the measurement of atmospheric water vapor in all weather conditions and on a global scale. Presently, GPS observation is a major source of information about water vapor, which can be used to develop fine-scale climatic or meteorological models. These applications are enabled by observing the GPS signal after it has passed through the Earths atmosphere using a ground-based receiver and the surface meteorological (MET) measurements, which are known as ground-based GPS meteorology. The estimation of atmospheric water vapor from ground-based GPS systems started

in 1992 [14] and is being continuously improved and evaluated [14] because of its importance for operational weather forecasting, climate monitoring, atmospheric research, and numerous other applications. In addition to the GPS data, site-specific surface pressure and weighted mean temperature values are essential to derive the precipitable water vapor (PWV) from the atmospheric delay, which can be obtained from a collocated meteorological sensor, which records the surface pressure and temperature data at the GPS site to the prescribed accuracy. Weighted mean temperature values required for PWV estimation can be determined from the surface temperature using models tuned to the specific area and season.

Another important geographical frontier for GPS measurements is the tropics, a region that is a major source of global water vapor. The precise evaluation of water vapor in the tropics is important for climate studies. PWV reaches several tens of mm in the tropics, more than an order of magnitude larger than in polar regions. There have been relatively few GPS observations in the tropics, and thus the accuracy of GPS PWV in the tropics has not yet been fully investigated. Comparison with radiosondes is problematic because radiosonde measurements often have significant negative water vapor bias in very humid conditions.

In this method, GPS satellites send electromagnetic signals to the ground-based receivers, which are fixed in a location on the Earth. In other words, the microwave signals from the GPS satellites to the ground receiver are delayed by the variation of the refractive index due to temperature, pressure and water content characteristics. Total delay in the signals is measured and the PWV is obtained by the delay caused by the water vapor in the troposphere. Nowadays, several studies have demonstrated that the low-cost ground based GPS sensing technique can reliably be used to estimate PWV with 1-2 mm accuracy and relative uncertainty of 5-10 percent compared to the traditional ground-based techniques, which are made through balloon-borne radiosondes and water vapor radiometers (WVRs).

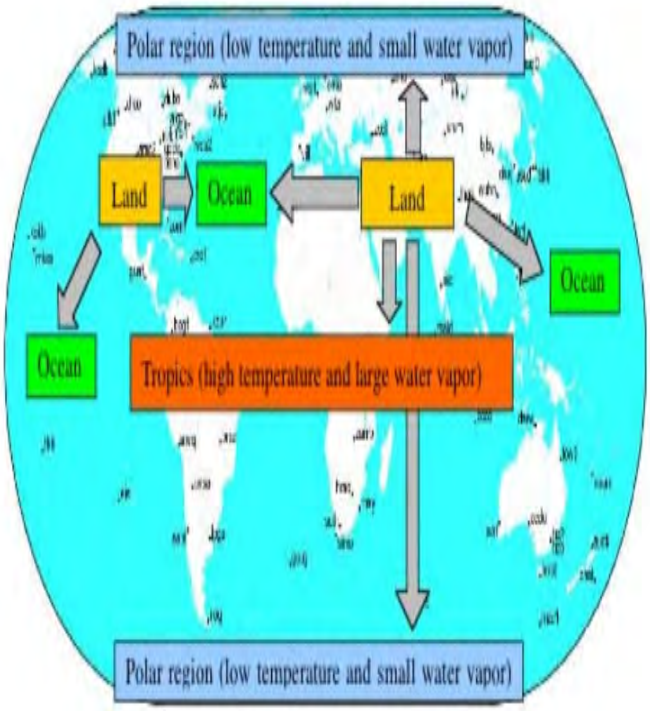


Figure 1.2: Geographical expansion of water vapor (PWV) measurements by ground-based GPS

This method also provides continuous measurements at a network of fixed stations than space-based GPS.

Measurement of water vapor in both space and time will be useful in the contexts for severe weather monitoring and to understand a wide variety of a process from a small-scale weather system to global climate change. Therefore, accurate prediction of global climate change requires good quality of water vapor information with high spatial and temporal resolution.

Chapter 2

MODELING PRECIPITABLE WATER VAPOR

Meteorologists use many tools to predict the weather. They use past data such as temperature observations, real-time data such as radar and satellite images, and models that look into the future. Many different parameters are plotted using the numerical forecast models, which are generated using computers. The models consist of numerical equations which use current conditions as the inputs. The resulting outputs are forecasts for what is likely to happen in the future, based on those initial conditions. There are many different models that all attempt to do the same thing [15].

2.1 Modeling climate

2.1.1 What is climate and how do we model it?

Climate refers to the average of weather conditions. It varies on timescales ranging from seasonal to centennial. Fluctuations result naturally from interactions between the ocean, the atmosphere, the land, cryosphere (frozen portion of the Earth's surface), and changes in the Earth's energy balance resulting from volcanic eruptions and variations in the sun's intensity. Since the Industrial Revolution significant changes in radiative forcing (Earth's heat energy balance) have

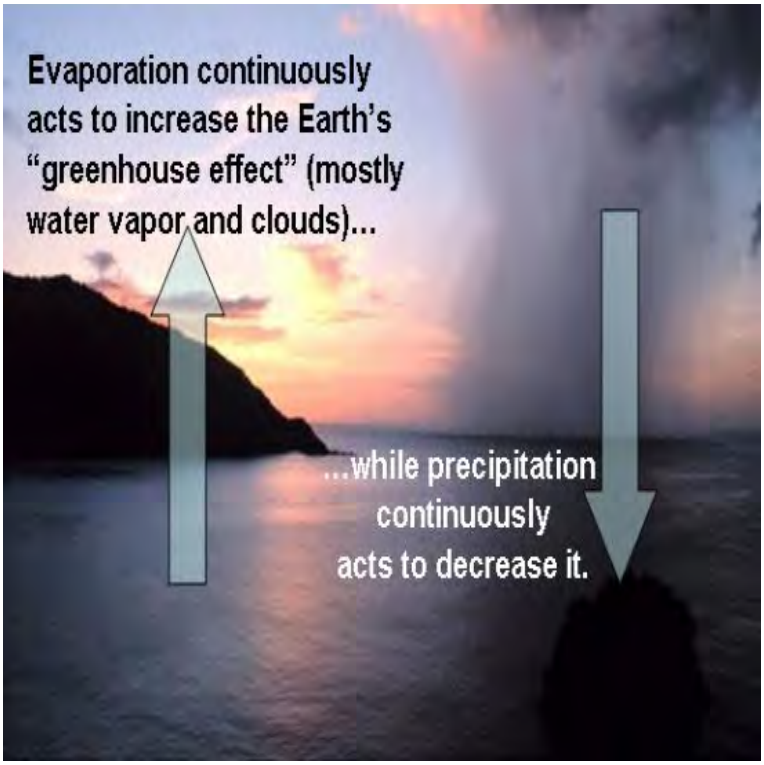


Figure 2.1: effects of hydrological cycle

resulted from the build up of greenhouse gases and trace constituents. The impacts on the planet of these anthropogenically-induced or man-made changes to the energy budget have been detected and are projected to become increasingly more important during the next century [16].

Computer models of the coupled atmosphere-land surface-ocean-sea ice system are essential scientific tools for understanding and predicting natural and human-caused changes in Earth's climate.

Climate models are systems of differential equations derived from the basic laws of physics, fluid motion, and chemistry formulated to be solved on supercomputers. For the solution the planet is covered by a 3-dimensional grid to which the basic equations are applied and evaluated. At each grid point, e.g. for the atmosphere, the motion of the air (winds), heat transfer (thermodynamics), radiation (solar and terrestrial), moisture content (relative humidity) and surface hydrology (precipitation, evaporation, snow melt and runoff) are calculated as well as the interactions of these processes among neighboring points [16]. The computations

are stepped forward in time from seasons to centuries depending on the study.

State-of-the-art climate models now include interactive representations of the ocean, the atmosphere, the land, hydrologic and cryospheric processes, terrestrial and oceanic carbon cycles, and atmospheric chemistry. The accuracy of climate models is limited by grid resolution and our ability to describe the complicated atmospheric, oceanic, and chemical processes mathematically. Despite some imperfections, models simulate remarkably well current climate and its variability. More capable supercomputers enable significant model improvements by allowing for more accurate representation of currently unresolved physics.

2.1.2 Methods for modeling precipitable water vapor in climate models

Changes in the distribution of water vapor in response to anthropogenic forcing will be a major factor determining the warming the Earth experiences over the next century, so it is important to validate climate models distribution of water vapor. Water vapor is a major greenhouse gas expected to play a key role in future human-induced global warming. Moistening of the relatively dry subtropical upper troposphere would be particularly important to the magnitude of warming obtained. It is important to determine how well climate models used for projections of future climate simulate water vapor in this region. A number of recent papers have investigated this question using General Circulation Models (GCMs) [17]. In general, they found reasonable agreement between climate model simulations and observations. However, these studies have two drawbacks. First, they were limited to atmospheric GCMs forced by observed sea surface temperatures (SSTs). Specifying the correct SST may constrain the model response, especially in the lower troposphere. Second, except for Gettelman et al. [2006], the comparison data came from HIRS type satellite systems, which have a broad vertical sensitivity extending from roughly 700 to 100 hPa [17]. The weighting down to 700 hPa, though small, can dominate the result since there is much more water

vapor lower in the atmosphere. Other work has examined simulated humidity in models other than global GCMs.

But, on the other hand, the water content of the atmosphere is a key climate response to increasing temperatures in global climate model (GCM) simulations. However, recent work has identified large differences among models on seasonal and regional scales. For example, in the CMIP3 AR4 A2 scenario, the NASA GISS model consistently shows nearly three times the water vapor content of the NCAR Community Climate model (CCSM3) during the summer season over North America. To better understand the water vapor feedback in models, observations are needed that provide good spatial and temporal resolution over both ocean and land areas. The AMSR-E sensor on the NASA Aqua platform has produced a long record of PWV over ice-free ocean areas while the Atmospheric Infrared Sounder (AIRS) on the NASA Aqua satellite was the first of a new generation of satellite sensors that provided the capability to retrieve water vapor profiles at high vertical resolution and good absolute accuracy over both ocean and land areas using the same algorithm.

A long record of observations from copies of these sensors is anticipated from this new network of advanced IR sounders. Among other atmospheric observables, the NASA AIRS science team has produced a global dataset of PWV beginning in September 2002 that is approaching ten years in length. In addition, the AIRS radiance data has been used to create a proxy-dataset for the NASA Decadal Survey mission named CLARREO. Atmospheric profiles have been obtained from this CLARREO-proxy data using a new retrieval algorithm that is designed to preserve the trace-ability of the sensor radiances to international standards (SI).

Global Positioning System (GPS) satellite radio signals are slowed as they pass through the Earth's atmosphere. This delays the arrival time of the transmitted signal from what is expected if there was no atmosphere [6]. The delay in the signal as it travels through the atmosphere originates from both the ionosphere and the neutral atmosphere. The ionospheric-caused delays can be corrected for

by using dual-frequency GPS receivers as they are frequency dependent. The delays from the neutral atmosphere, however, are not frequency dependent as they depend on its constituents, which are a mixture of dry gases and water vapor. Using the techniques first described by Bevis et al. (1992, 1994)[18] and Duan et al. (1996)[18], the signal delays caused by water vapor in the troposphere can be estimated and used to retrieve the total column water vapor or integrated precipitable water vapor (IPWV). This new technology opened the door for the development of a ground based GPS-IPWV network in the 1990s [6].



Figure 2.2: GPS III Satelite.

The number of measurement techniques for observations of IPWV increased considerably in the 1990s and GPS-IPWV complements other systems capable of measuring atmospheric moisture such as radiosondes, surface-based radiometers, satellite-based infrared and microwave sensors, research aircraft, and commercial aircraft [e.g., Aircraft Communication Addressing and Reporting System (ACARS)]. However, it is not a substitute as it does not provide information about moisture profiles.

GPS water vapour provides an effective technique to measure precipitable water vapour (PWV) with a higher time resolution. This technique is based on the estimation of the tropospheric delay using global positioning system (GPS)

in combination of surface pressure and temperature. Ground-based GPS water vapour estimation is not affected by rainfall and clouds, so it is called all-weather system. It takes minor effort to obtain GPS water vapour estimates from the existing GPS system and its temporal and spatial resolution is higher than the other techniques used.

Radiosondes provide tropospheric moisture profiles, but have limited spatial coverage and are only launched twice-daily in some countries only once per day. Surface-based radiometers are capable of high temporal resolution but are costly, require frequent calibration, and their performance is adversely affected by the presence of rain [6]. Satellite-based infrared (IR) and microwave sensors offer planetary scale coverage, but IR sensors are reliable only in cloud-free regions, and microwave sensor-based retrievals, although valid in cloudy regions, are most reliable over oceans (less reliable over land) and have limited temporal resolution. Aircraft measurements are beginning to provide moisture observations using the Water Vapor Sounding Systems (WVSS) or Tropospheric Airborne Meteorological Data Reports (TAMDAR). However, these observations are limited to commercial operational locations and flight times, and are generally less continuous than GPS-IPWV observations [18].

The GPS-IPWV network provides unattended, continuous, independent, frequent, and accurate observations of IPWV that are unaffected by weather conditions or time of day. The main limitations of the GPS-IPW network are that the IPW retrievals do not provide information about the vertical distribution of water vapor, and the spatial resolution is limited (although this is becoming somewhat alleviated by the fast expansion of the network) [18]. The amount of precipitable water has significant correlation with several meteorological parameters measured near the underlying surface: partial pressure of water vapour, dew-point temperature, air temperature, relative humidity, etc.

Chapter 3

WATER VAPOR, HUMIDITY, AND DEWPOINT, AND RELATIONSHIP TO PRECIPITATION WATER VAPOR

Atmospheric Water Vapor, Precipitable Water Vapor, or Humidity is a measure of the water vapor content of the air. Air will normally contain a certain amount of water vapour. The maximum amount of water vapour, that air can contain, depends on the temperature and, for certain temperature ranges, also on whether the air is near to a water or ice surface. If you have a closed container with water and air (like a beaker) then there an equilibrium will develop, where the air will contain as much vapour as it can. The air will then be saturated with respect to water vapour. The real world outside is not closed, so that the air normally will contain less vapour as it could. Sources of vapour are evaporation processes from water and ice surfaces and transpiration from plants and respiration from animals. The expression "evapotranspiration" takes into consideration plants' large share of evaporation over land areas. Sinks of water vapour are clouds or condensation on surfaces. Dew is created when a surface temperature has such a low temperature that the air chills to the dew point and the water vapour condenses. Physically at the dew point temperature the vapour loses the energy that it gained at evaporation, the latent energy, again.

The precipitable water vapor (total column water vapor) is strongly correlated ($r > 0.9$) with the surface dew point on most days. There are number of atmospheric variables that are used to express the amount of water vapor present in the atmosphere. Some of them are briefly described below:

- Water Vapor : Water is a unique substance. It can exist as a liquid, solid(ice), and gas (water vapor). A primary way water vapor increases in the atmosphere is through evaporation. Liquid water evaporates from oceans, lakes, rivers, plants, the ground, and fallen rain. A lot or a little water vapor can be present in the air. Winds in the atmosphere then transport the water vapor from one place to another. Most of the water vapor in the atmosphere is contained within the first 10,000 feet or so above the Earth's surface. Water vapor also is called moisture.
- Absolute Humidity : Absolute humidity (expressed as grams of water vapor per cubic meter volume of air) is a measure of the actual amount of water vapor (moisture) in the air, regardless of the air's temperature. The higher the amount of water vapor, the higher the absolute humidity. For example, a maximum of about 30 grams of water vapor can exist in a cubic meter volume of air with a temperature in the middle 80s. SPECIFIC HUMIDITY refers to the weight (amount) of water vapor contained in a unit weight (amount) of air (expressed as grams of water vapor per kilogram of air). Absolute and specific humidity are quite similar in concept.
- Vapor Pressure : is the fraction of the ambient pressure that is due to the fraction of water vapor in the air. Saturation vapor pressure is the maximum vapor pressure that the air can support (non supersaturated) at a given temperature. Vapor pressure can vary from 0 (verrry dry) to the maximum, saturation vapor pressure. Saturation vapor pressure is a function of temperature .

- Relative Humidity : Relative humidity (RH) (expressed as a percent) also measures water vapor, but RELATIVE to the temperature of the air. In other

words, it is a measure of the actual amount of water vapor in the air compared to the total amount of vapor that can exist in the air at its current temperature. Warm air can possess more water vapor (moisture) than cold air, so with the same amount of absolute/specific humidity, air will have a HIGHER relative humidity if the air is cooler, and a LOWER relative humidity if the air is warmer. What we "feel" outside is the actual amount of moisture (absolute humidity) in the air. For example, a relative humidity value of 45 percent means the air has 45 percent of water vapor it would have when saturated. In other words, relative humidity expresses how close you are to saturation, similar to a gas gauge in a car. The gauge does not tell you how many gallons of gas are in the tank; just how close or far it is from being full. Mathematically , it is expressed as ;

$$RH = \frac{amount\ of\ water\ vapor\ in\ air}{amount\ in\ saturated\ air} \times 100 \tag{3.0.1}$$

- Dewpoint Temperature : Meteorologists routinely consider the "dewpoint" temperature (instead of, but analogous to absolute humidity) to evaluate water vapor, especially in the spring and summer. The dewpoint temperature, which provides a measure of the actual amount of water vapor in the air, is the temperature to which the air must be cooled in order for that air to be saturated. Although weather conditions affect people differently, in general in the spring and summer, surface dewpoint temperatures in the 50s usually are comfortable to most people, in the 60s are somewhat uncomfortable (humid), and in the 70s are quite uncomfortable (very humid).

Dewpoints as high as 80 or the lower 80s have been recorded, which is very oppressive but fortunately relatively rare. While dewpoint gives one a quick idea of moisture content in the air, relative humidity does not since the humidity is relative to the air temperature. In other words, relative humidity cannot be determined from knowing the dewpoint alone, the actual air temperature must also be known. If the air is totally saturated at a particular level (e.g., the surface), then the dewpoint temperature is the same as the actual air temperature, and the relative humidity is 100 percent.

3.1 Determination of PWV in ECMWF Interim Reanalysis (ERA-Interim)

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an independent intergovernmental organisation supported by 20 European Member States and 14 Co-operating States. ECMWF has in the past produced three major reanalyses: FGGE, ERA-15 and ERA-40. The reanalysis product, ERA-15, generated re-analyses for approximately 15 years, from December 1978 to February 1994. The product, ERA-40 (originally intended as a 40-year reanalysis) begins in 1957 (the International Geophysical Year) and covers 45 years to 2002. As a precursor to a revised extended reanalysis product to replace ERA-40, ECMWF has recently released ERA-Interim, which covers the period from 1979 to present.

ERA-Interim is the latest global atmospheric reanalysis of the period 1979 to present produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA-Interim project was conducted in part to prepare for a new atmospheric reanalysis to replace ERA-40, which will extend back to the early part of the twentieth century and which a combination of model and observation through assimilation. ERA-Interim was originally planned as an 'interim' reanalysis in preparation for the next-generation extended reanalysis to replace ERA-40 and is being continued in real time. In addition to re-analysing all the old data using a consistent system, the reanalyses also make use of much archived data that was not available to the original analyses. This allows for the correction of many historical hand-drawn maps where the estimation of features was common in areas of data sparsity. The ability is also present to create new maps of atmosphere levels that were not commonly used until more recent times.

The analysis or reanalysis data from the European Center for Medium-Range Weather Forecasts (ECMWF) is high quality over the regions with sufficient dense data, but the accuracy is uncertain over areas with sparse observations. Some

studies have been done using ECMWF data to correct tropospheric delay for satellite navigation and positioning, and some improved tropospheric delay correction models were established [21].

3.1.1 Data assimilation

The ERA-Interim reanalysis is produced with a sequential data assimilation scheme, advancing forward in time using 12-hourly analysis cycles. In each cycle, available observations are combined with prior information from a forecast model to estimate the evolving state of the global atmosphere and its underlying surface. This involves computing a variational analysis of the basic upper-air atmospheric fields (temperature, wind, humidity, ozone, surface pressure), followed by separate analyses of near- surface parameters (2 m temperature and 2 m humidity), soil moisture and soil temperature, snow, and ocean waves. The analyses are then used to initialise a short-range model forecast, which provides the prior state estimates needed for the next analysis cycle[19].

The forecast model has a crucial role in the data assimilation process. Use of the model equations makes it possible to extrapolate information from locally observed parameters to unobserved parameters in a physically meaningful way, and also to carry this information forward in time. The skill and accuracy of the forecast model determines how well the assimilated information can be retained; better forecasts mean that smaller adjustments are needed to maintain consistency with observations as time evolves[19].

Additionally, while producing a forecast, the model estimates a wide variety of physical parameters such as precipitation, turbulent fluxes, radiation fields, cloud properties, soil moisture, etc. Even if not directly observed, these are constrained by the observations used to initialise the forecast. The accuracy of these model-generated estimates naturally depends on the quality of the model physics as well as that of the analysis. The data assimilation thus produces a coherent record of the global atmospheric evolution constrained by the observations available during

the period of reanalysis.

3.1.2 Atmospheric analysis

The core component of the ERA-Interim data assimilation system is the 12-hourly 4D-Var of the upper-air atmospheric state. The defining feature of 4D-Var is that it uses the forecast model to constrain the state evolution within each analysis window. The version of 4D-Var used for ERA- Interim also updates a set of parameter estimates that define bias corrections needed for the majority of satellite-based radiance observations.

Mathematically, the analysis can be described as the minimisation of

$$\tau(X,\beta) = (X^b - X)^T {B_X}^{-1}(X^b - X) + (\beta^b - \beta)^T {B_\beta}^{-1}(\beta^b - \beta) + [y - h(X,\beta)]^T R^{-1}[y - h(X,\beta)] \tag{3.1.1}$$

jointly with respect to the control variables (X, β). In 4D-Var the control X is typically the model initial state (at the beginning of the analysis window), which, in view of the model constraint, defines the state at any other time within the window. The additional control β contains parameters for the variational bias corrections (VarBC) applied to the radiance observations[19].

Input data for the analysis consist of prior (background) estimates (X^b, β^b) for the controls, and a set of observations y that are valid within the current analysis window. Additional information needed to solve the minimisation includes specifications for the covariances (B_X, B_β) of errors in the background estimates, and covariances R of errors in the observations. The latter account for measurement errors as well as the inability of the model to represent small-scale information contained in some of the observations. The background state estimate X^b is obtained from a short-range forecast, which is initialised using the analysis produced in the previous cycle. Background estimates β^b for the bias parameters are simply the estimates produced by the previous analysis.

The observation operator $h(X, \beta)$ can be regarded as an extension of the forecast model; it is used to simulate observations given a model state, possibly making use of bias parameters to adjust for systematic errors. Its implementation involves integration of the model equations to advance the state estimate to the time of observation, followed by interpolation to the actual observation location, followed by simulation of the observable (e.g. surface pressure, temperature, humidity, wind speed and direction, emitted radiance, atmospheric refraction, etc.). The ability of the observation operator to accurately model observations affects the quality of the analysis; errors or inaccuracies in the observation operator result in incorrect or suboptimal interpretation of the available data. However, this source of error is in principle factored in the definition of R, and may also be compensated by bias corrections[19].

The 4D-Var analysis in ERA-Interim is obtained by successive linearisations of the model and observation operator. The algorithm consists of a pair of nested loops. The outer loop integrates the nonlinear forecast model, producing a 4D state estimate and simulated observations. The inner loop then solves a linearised version of Eq. (3.1.1) for the control variable increments, using the tangent linear and adjoint of a simplified version of the forecast model at lower horizontal resolution. For ERA-Interim, the spectral resolution of the outer loop is T255 (79 km), and two successive inner loops at resolutions T95 (210 km) and T159 (125 km) are used for the minimisation.

3.2 Deriving ZTD from ECMWF meteorological data at GPS stations

Calculating the ZTD from ECMWF meteorological data at a GPS station includes two steps - deriving the ZTD for each grid point from ECMWF meteorological data and then calculating the ZTD at the GPS stations from the ZTD of the grid points. Two methods are used to calculate the ZTD from ECMWF

meteorological data: the integration method and the Saastamoinen model method [20].

The integration method is mainly used for the pressure-level data and based on the formula,

$$N = \frac{k_1(P-e)}{T} + \frac{k_2 \times e}{T} + \frac{k_3 \times e}{T^2} \tag{3.2.1}$$

$$e = \frac{h \times P}{0.622} \tag{3.2.2}$$

where $K_1 = 77.604$K/Pa, $K_2 = 64.79$K/Pa, and $K_3 = 377600.0\ K^2$/Pa, N is the total refraction, P is the atmospheric pressure, e is the vapor pressure, and h is the specific humidity [20]. After calculating the total refraction, the ZTD is derived by using the formula:

$$ZTD = 10^{-6} \int Nds = 10^{-6} \Sigma_i N_i \Delta s_i \tag{3.2.3}$$

The Saastamoinen model method is mainly used for the surface meteorological data (Saastamioinen 1972),

$$ZTD = 0.002277 \times \frac{[P_o + (0.05 + \frac{1255}{T_o+273.15})e]}{f(\varphi, H)} \tag{3.2.4}$$

$$e = rh \times 6.11 \times 10^{\frac{75T_o}{T_o+273.15}} \tag{3.2.5}$$

$$f(\varphi, H) = 1 - 0.00266cos2\varphi - 0.00028H \tag{3.2.6}$$

where P_o is the surface pressure, T_o is the surface temperature, e is the vapor pressure, rh is the relative humidity, u is the latitude, and H is the altitude above ellipsoid surface.

After deriving the ZTD by integration method from the pressure-level meteorological data, the zenith delay above the top level needs to be added, which is the total integration along the signal path. Because there is no meteorological data above the top level, the Saastamoinen model is used to calculate the zenith delay above the top level, and the meteorological data of the top level is used as

input values of the model [20].

3.3 Diurnal and seasonal variability of precipitable water vapor

Water vapour plays an important role in the transfer of energy and moisture to the atmosphere. By continually cycling through evaporation and condensation, water vapor transports latent heat energy between the surface and the atmosphere. This process plays a crucial role in the global energy and hydrological cycles. The Precipitable Water (PW) is the vertically integrated total mass of water vapor per unit area for a column of atmosphere [21]. Determination of total precipitable water content of the atmosphere column provides an idea of the possible amount of rain that may be expected from the overlying air if conditions become favorable for precipitation. Water vapor is essential for cloud convective activity. Knowledge of the distribution and temporal variation of atmospheric water vapor is, therefore, important in forecasting regional weather and for understanding of the global climate system. However, monitoring the variation of water vapor with high temporal and spatial resolution by conventional techniques, such as radiosondes and water vapor radiometers, is difficult.

Generally, Information of precipitable water vapour is very important and critical variable for climate studies and significantly contributed to the green house effect. Its temporal and seasonal variation is very important to understand the energy budget of the atmosphere over the area. The uneven distribution of water vapour is even more pronounced in the vertical direction. Earlier studies have shown the importance of vertical distribution of water vapour for the quantitative definition of the infrared radiation emitted by the atmosphere, as well as for the assessment of the seasonal variations of the precipitable water [21]. The knowledge of its distribution is therefore important to better initialize the constraints

of the mesoscale numerical model. The vertical distribution of precipitable water in tropics and extratropical regions are different. In the extratropical regions, the maximum precipitable water vapor is usually found near 700 mb. The study by [22] suggests that this is true for the monsoon region also.

Chapter 4

DATA ANALYSIS AND INTERPRETATIONS

4.1 Data sources

The pressure-level and surface meteorological data of ECMWF from the IFS (Integrated Forecast System) are used. The time resolution of the data is 6 h, namely at 0, 6, 12, 18 UTC. The data used in this study has a horizontal resolution of $1.5^0 \times 1.5^0$ and a vertical resolution of 60 pressure levels reaching 0.1 mbar at the top level. The pressure-level meteorological data are altitude, air temperature, specific humidity, and pressure. The surface meteorological data include surface pressure, dewpoint temperature at 2 m, and temperature at 2 m. The ERA-Interim data in this study is extracted for domain from 3^0N to 15^0N and from 33^0E to 48^0E.

4.2 Spatial and temporal variability of precipitable water vapor

There is relatively little information available on the variability of water vapor over short time (shorter than a few hours) and spatial scales (smaller than a few

hundreds of kilometers). Knowledge of realistic spatial and temporal variations of moisture allows climate and weather modelers to compare statistics of their simulated moisture fields to realistic observations. These comparisons are essential in quantifying how well the models perform. Satellites provide measurements of upper troposphere humidity [23] and can continuously monitor the atmosphere, but do not have the spatial resolution to observe features smaller than a few tens of kilometers. Generally, the studies of small-scale atmospheric water vapor utilize either microwave water vapor radiometers (MWRs) or GPS estimates of total column water vapor. These studies mostly focus on the measurement of precipitable water (PW) measured in units of kg/m^2, relating the integrated amount of water vapor in a column of air to an equivalent column of liquid water.

4.2.1 Study area and climate condition

The studies were conducted in the region, Ethiopia and the region have distinct climate characteristic. Ethiopia is a mountainous country located in east Africa situated between 3^0 and 15^0 N and 33^0 and 48^0 E. The country has an area of 1,112,000 square kilometers with a total population of more than 80 million [16]. The major physiographic features of the country are a massive highland complex of mountains and plateaus divided by the Great Rift Valley and surrounded by lowlands along the periphery. Ethiopia is in the tropical zone laying between the Equator and the Tropic of Cancer, the area which is experiencing high variation and large amount of water vapour. The country has a high central plateau that varies from 1,290 to 3,000 m (4,232 to 9,843 ft) above sea level, with the highest mountain reaching 4,533 m (14,872 ft). Elevation is generally highest just before the point of descent to the Great Rift Valley, which splits the plateau diagonally. A number of rivers cross the plateau - notably the Blue Nile rising from Lake Tana.



Figure 4.1: Map of Ethiopia

The area is exposed to intense sunlight all year round, with average temperature of 15.9^0C (61^0F). The mean annual rainfall in Ethiopia is ranges from 2000-mm over some pocket areas in the southwest highlands, and less than 250-mm in the lowlands. In general, annual precipitation ranges from 800 to 2200-mm in the highlands (>1500 meters) and varies from less than 200 to 800-mm in the lowlands (<1500 meters) and the mean relative humidity for an average year is recorded as 60.7 percent and on a monthly basis it ranges from 49 percent in February to 82 percent in July.

Rainfall also decreases northwards and eastwards from the high rainfall pocket area in the southwest.

4.2.2 Spatial variability of precipitable water vapor

The average planetary mass of atmospheric water vapour is estimated to be 13.11015 kg (Peixoto, 1992). Dividing it by the Earth surface area, the planetary average value of precipitable water is IPWV = 25 mm. In Ethiopia the IPWV

values range from about 3 mm (cold dry winter weather) to about 60 mm (warm damp weather). Spatial variability in the precipitable water generally depends on the latitude. This is due to the northward decrease in air temperature, which controls the atmospheric capacity to contain water vapour. In addition, spatial variability depends on orography, continentality, underlying surface type (land, water or ice), atmospheric circulation, the properties of the underlying surface, etc. Intergovernmental Panel on Climate Change [24] states that water vapour concentration in the atmosphere mainly depends on air temperature.

Fig. 4.2 show the distribution of total column water vapor content for each

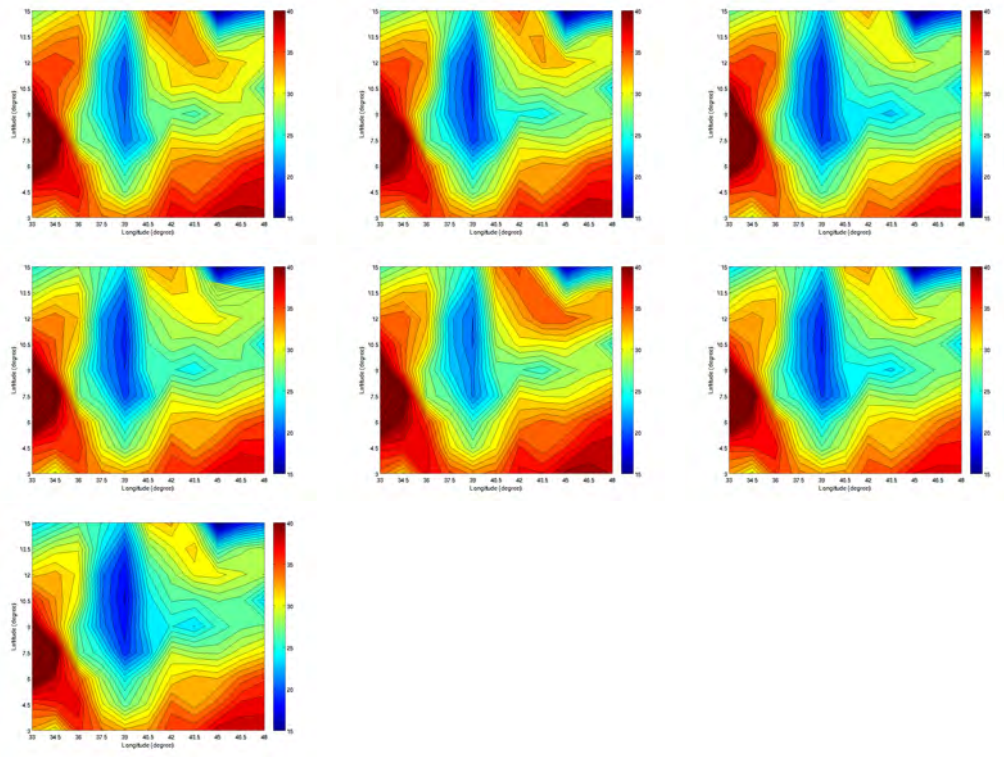


Figure 4.2: PWV at 00 UTC for 2006 to 2012.

year recorded at 00 utc over Ethiopia and Fig. 4.3 show the distribution of total column water vapor content from the year 2006-2012 at 00 utc. The mean annual range of atmospheric tcwv content is about 15-45 kg/m^2.

The largest atmospheric tcwv content area exists in the west and southwest part of Ethiopia. The second largest value area of the atmospheric tcwv content is in the southeast, northeast, southwest and northwest part of the country. The

low amount of atmospheric tcwv content appears in the central part of Ethiopia. With the high elevation of this area and the natural barrier formed by the mountains, it is hard for the tcwv of the ocean, to be transported to central part of the country. Therefore, the tcwv content in this area is low and only 15-20 kg/m^2 of mean annual tcwv range is observed over this region.

From the spatial distribution of the annual mean precipitation over Ethiopia (Figure 4.3 below), the precipitation decreases gradually from southeast and west part to the central part of the country.

Because, the tcwv content is obviously affected by the elevation and decreases

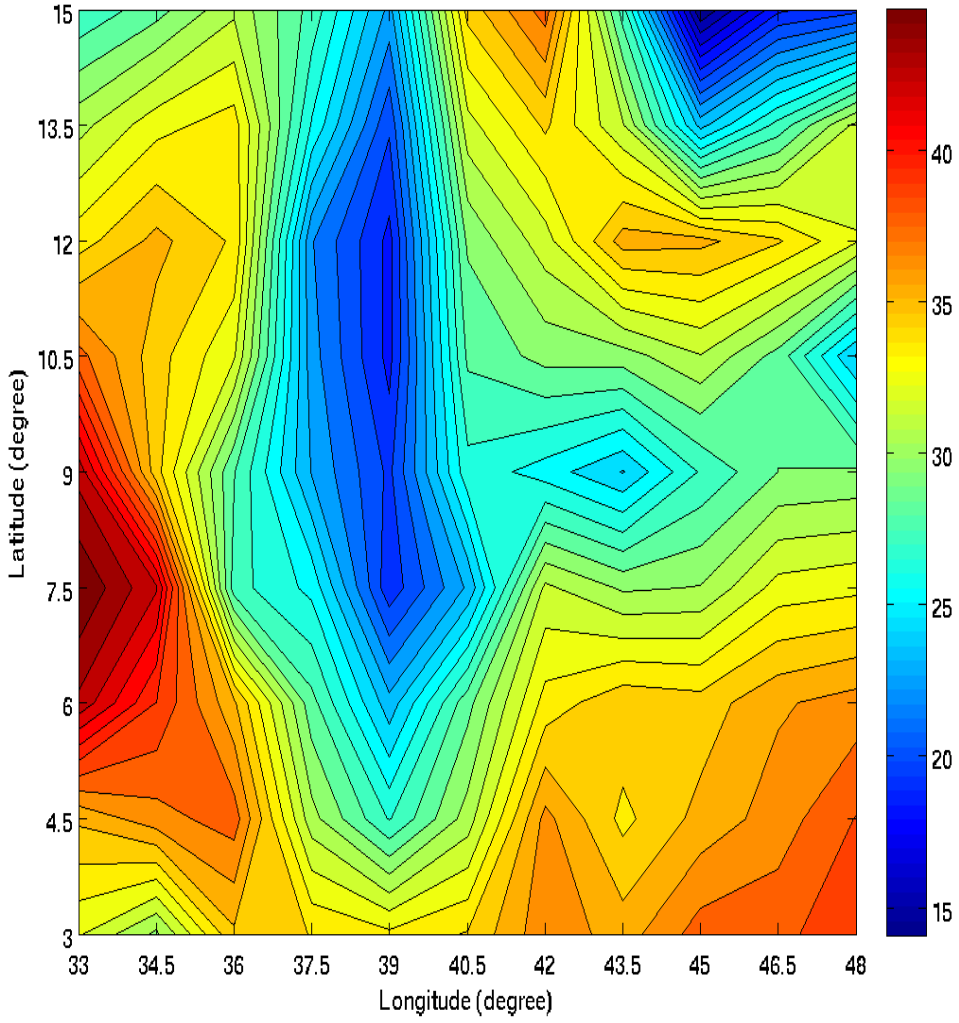


Figure 4.3: Distribution of mean WV content (kg/m2) at 00 utc from year 2006-2012 in Ethiopia and its surroundings

with elevation. The fact that the southeast, northeast, southwest and northwest parts are humid and almost the central part is dry is in accordance with the rainy nature of the southeastern, northeastern, southwestern and northwestern parts and cold, dry and rainless feature of the central part. Therefore, the spatial distributions of tcwv content over the country are different.
Generally, temperature and water vapor content in the troposphere decrease rapidly with altitude.

4.2.3 Temporal variation of the tcwv

Water vapor content is increasing from the central part to southeast and east part. But now we will see the distribution of WV content for a particular time, i.e 00 , 06, 12 and 18 utc over the country. Therefore, Fig. 4.4 below shows how much the mean tcwv content varies with time of the day from 2006 to 2012 in Ethiopia.

The mean PWV content at 00, 06, 12 and 18 utc gradually increases from the central part to the southern parts of the country. In Fig 4.4 (top-left), the tcwv is high in the southern and northeastern part and low in the central and central eastern part of the country. And the remaining region i.e the southern, southeastern and northwestern part have a medium range of water vapor content. But In fig 4.4 (top-right), the WV content is high in the southwestern, northeastern part and to some extent in the southeastern part. And the country has samll WV content in the central part and has medium value in the eastern, southern and northwestern part.

While in fig 4.4 (bottom-left), the tcwv content is highly accumulted only in the southwestern part and it has a medium value in the southeastern, northeastern, southern and to some extent in the northwestern part and becomes small in the central and east part of the country. in fig 4.4 (bottom-right), the tcwv content becomes high in the west part and has a medium value in the south, southeast,

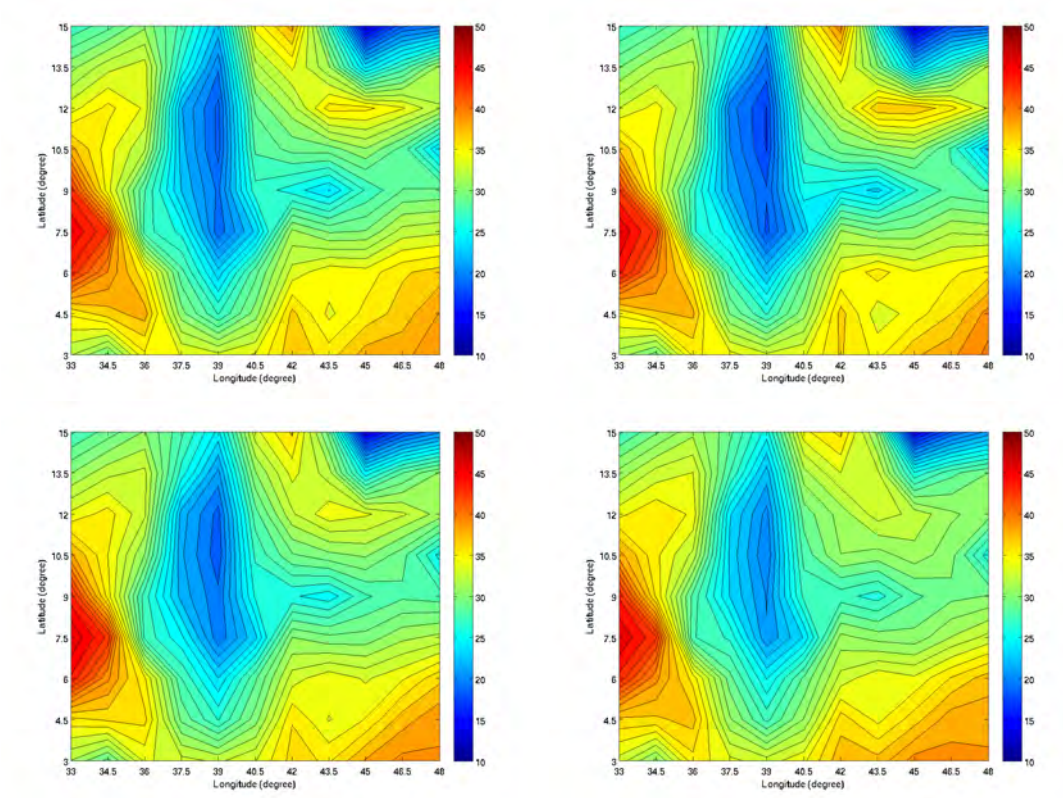


Figure 4.4: The PWV distribution over Ethiopia at 00 UTC (top-left); 06 UTC (top-right); 12 UTC (bottom-left); and 18 UTC (bottom).

northeast and to some extent in the northwest part and samll in the central and east part of the country.

Therefore, the amount tcwv is high at 00 utc and gradually decreases to at 18 utc with in a particular day of a year and generally the country has maximum WV content in the southern area because the area is found near in the equator, since temperature and water vapor content in the troposphere decrease rapidly with altitude. And all these variations of tcwv content of the country for a particular time of a specific year, is due to a change or variation in temperature of a day. That means at 00 utc (9:00 am, local time of the country) the temperature is high and gradually decreases up to 18 utc (3:00 am of local time).

4.2.4 Seasonal precipitable water vapor content over Ethiopia

Season is defined as, meteorologically, a period when an air mass characterized by homogeneous weather elements such as temperature, relative humidity, wind, rainfall etc., dominate a region or part of a country [16]. In Ethiopia, the seasons and rainfall regimes are classified based on mean annual and mean monthly rainfall distribution. There are three main rainfall regimes in Ethiopia. These three rainfall regimes are delineated as:

a. Mono-modal (Single maxima)

b. Bi-modal type-1 (Quasi-double maxima)

c. Bi-modal type-2 (Double maxima)

As shown in Fig 4.5 below, Mono-modal, Bi-modal type-1 and Bi-modal type-2 are designated by letter B, A and C, respectively. The area designated



Figure 4.5: Rainfall Regimes of Ethiopia

as region B in Fig 4.5 is dominated by single maxima rainfall pattern. However, the wet period decreases northwards from about ten month in the south west to only about four month in the north. Thus region-B is sub-divided into three parts designated as b1, b2 and b3, where the wet period runs from February/March

to October/November, April/May to October/November and from June/July to August/September, respectively.

The area designated as region A is characterized by quasi-double maxima rainfall pattern, with a small peak in April and maximum peak in August. The central and most of the eastern half of the country is included in this rainfall regime. The two rainy periods are locally known as Kiremt (June to September) and Belg (February to May), which are the long and short rainy periods, respectively. Short dry period, which covers the rest of the year (i.e. October to January), is known as Bega. The area identified as region C in the Fig 4.5 is dominated by double maxima rainfall pattern with peak during April and October. The southern and the southeastern parts of the Ethiopia are included in this rainfall regime. Two rainy periods are from March to May and from September to November. Two dry periods are from June to August and from December to February.

Now let us see the seasonal PWV distribution over the different parts of Ethiopia for different years. Fig.4.6 shows the variations of PWV content over the different parts of the region at a particular season. In order to study the southward

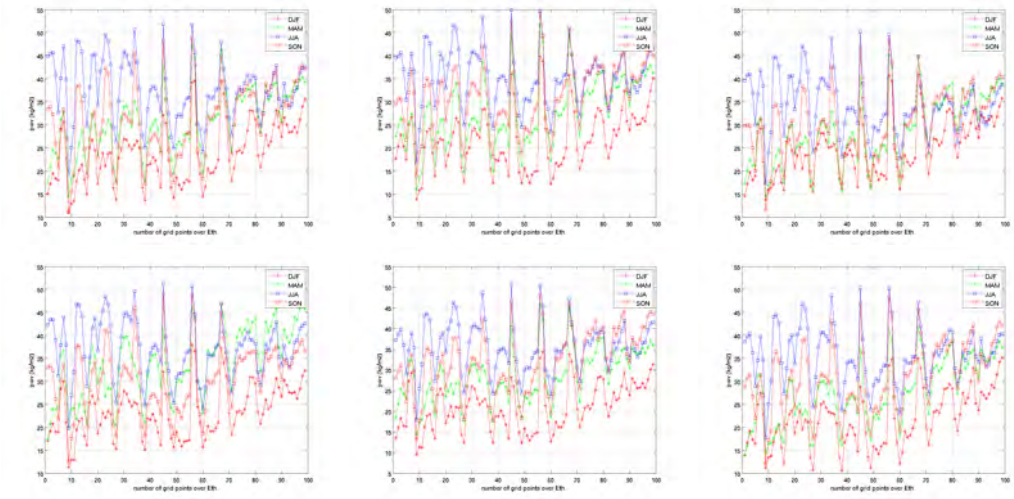


Figure 4.6: Seasonal mean PWV at 12 UTC in 2007 (top-left); 2008 (top-middle); 2009 (top-right); 2010 (bottom-left); 2011 (bottom-middle); and 2012 (bottom-right).

increase of precipitable water, ERA-Interim IPWV values were averaged over the

four seasons: spring (MAM), summer (JJA), autumn (SON) and winter (DJF). The figures indicate the averaged PWV over the four seasons and blue designated JJA, red designated SON, green designated MAM, and red star designated DJF season. Almost all seasons of the years (i.e from 2006-2012) have a similar PWV distribution over the country.

That means, at the first season of all the years, i.e the SON season (the red one), the northern part have a medium PWV content ranged from 25-28 kg/m^2 and gradually the amount increases in the central part reached to a maximum of around 40 kg/m^2. And the southern part have large amount of PWV content, ranges from 30-44 kg/m^2 relative to the other parts of the country. And in the DJF season, since the season is dry and winter there is a relatively small amount of PWV content is recorded over all the region. In this season, the northern part has a content from 15-27 kg/m^2 and gradually decreases in the central part reached the amount from 12-20 kg/m^2 but it increases as we move in the southern part of the country with a minimum and a maximum of 20 and 30 kg/m^2 respectively. In the MAM season, since it is a short rainy period and is locally known as Belg, so the amount of PWV content is increases in over all the country. The last season is the JJA months and is a long rainy period and is locally known as Kiremt. In this season the maximum amount of the PWV content over the country is reached up to 50 kg/m^2 and th minimum one is around 25 kg/m^2.

Generally, we observed that almost in all seasons of the years, intially the amount of PWV content is greater in the northern part then it becomes decreases in the central part again the amount increases in the southern part of the country. As the seasonal periods progressed, a rapid reduction in the polar vapor amounts was observed, together with a more gradual increase of vapor at the equatorial and southern latitudes.

Now let us see the averaged seasonal PWV distribution over the region. Fig 4.7 below shows the mean PWV content of each season of the country from 2006 to 2012. Spatial domain representing northern Ethiopia covers grids from 1 to 44;

likewise grids from 45 to 77 covers the central part and grids from 78 to 99 covers the southern part of Ethiopia. In Fig. 4.7, the PWV content is highly dominated in the summer months or JJA season and it increases in the northeastern part with a maximum value of 50 kg/m^2. But it decreases rapidly in the central part with an average minimum and maximum value of 24-35 kg/m^2 respectively. And again it rises in the southwest part of the country.

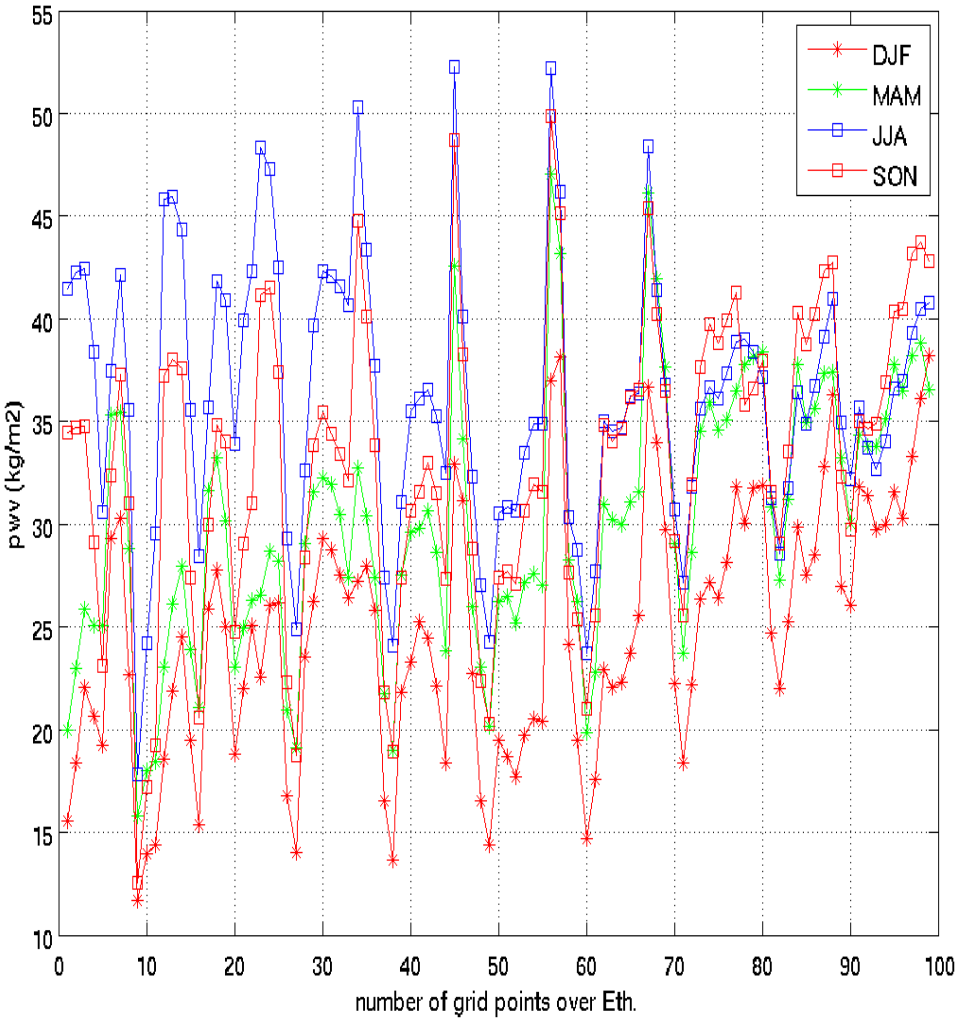


Figure 4.7: Seasonal precipitable water vapor at 12 utc averaged over 2006-2012 period over Ethiopia.

In the autumn months (SON season), the tcwv content decreases in amount

from the summer season but is relatively high from the remaining seasons, beacause since it is the second season that high amount of tcwv content is achieved in the region and it is a short rainy period. Similarly, the amount is high in the north east direction and it decreases in the central part, but it has a peak in the south west direction. And in the spring months (MAM season), the amount of tcwv content is medium and almost similar value except a small variation over the different parts of the country. In the last season, the DJF season (winter months), the amount is relatively very small from the other season due the amount of WV content in the troposphere is very low. Since the amount of PWV is highly dependent on the amount of WV content in the atmosphere. And in this season the PWV is relatively highly dominated in the south and south east parts of the country with a maximum value of 35 kg/m^2.

Generally all these variations of the amount of tcwv on the different parts of the country with the same and different seasons is due the unique characteristics of the seasons. That means the Sun is the source of all the energy that drives Earths weather and climate. Solar energy is not distributed evenly over Earths surface. The amount of energy received varies with:

- Latitude
- Time of day
- Season of the year

And the main 2 major factors Change With the Seasons are:

• Gradual changes in the length of daylight between Summer and Winter

• The angle of the Sun above the horizon

The closer the sun angle is to 90^0, the more intense the solar rays and the longer the path through the atmosphere the greater chance that sunlight will be absorbed, reflected, or scattered by the atmosphere, all of which reduce solar intensity at the surface. Therefore all these allows to bring the variations of the tcwv content on the different parts of the country with the same and different

season of a particular year.

Now let us see the variations of Seasonal precipitable water vapor content for a particilar time all over the country. Fig. 4.8 below shows the averaged distribution of seasonal tcwv content over the different parts of Ethiopia for a particular time 00, 06, 12 and 18 utc respectively from 2006 to 2012. Therefore, the Figures clearly shows how much the seasonal PWV varies over the particular time with in the specified year and almost in all time of the day that the different parts of the country have similar (with a very small change) amount of tcwv content.

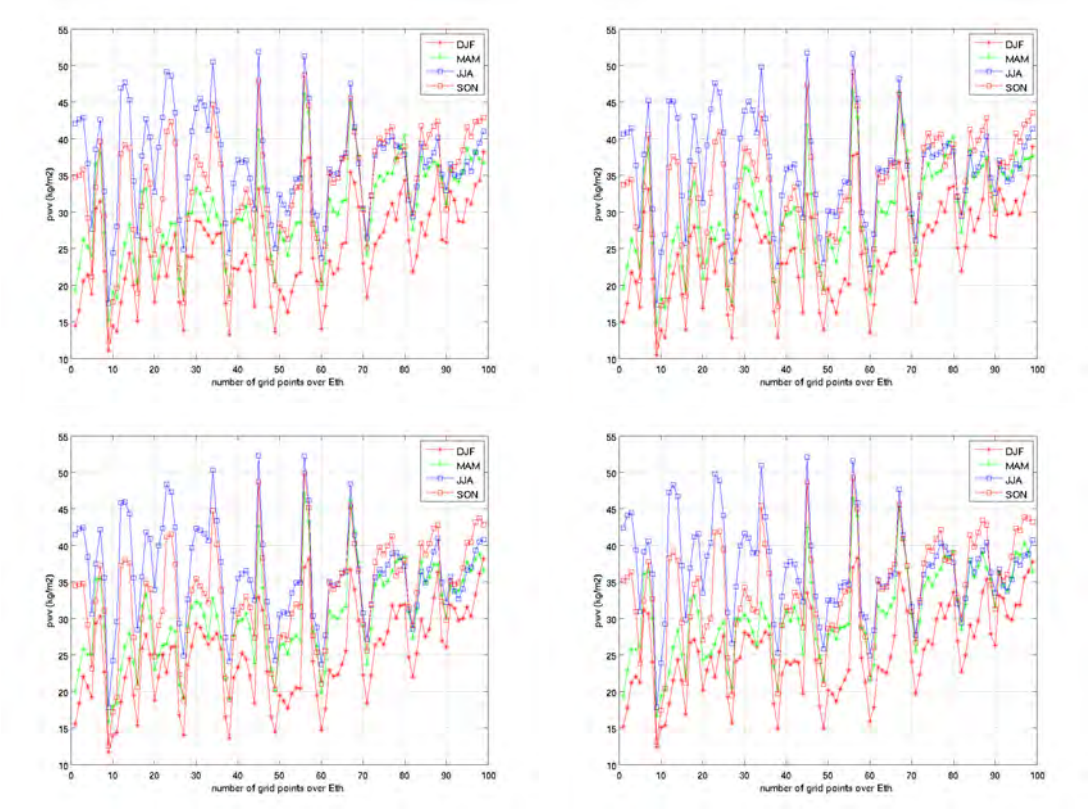


Figure 4.8: Seasonal mean PWV distribution over Ethiopia at 00 UTC (top-left); 06 UTC (top-right); 12 UTC (bottom-left); and 18 UTC (bottom-right).

4.3 Temporal variability of precipitable water vapor

4.3.1 Seasonal variability of precipitable water vapor

Daily 15 to 45 values of PWV are available during the period 00:00-18:00 h local time depending on the season and sky conditions. Data collected from ERA-Interim continuously for the seven-year period, January 2006 to January 2012, has been analyzed here to compute daily and monthly means to investigate temporal, seasonal variations. From this data, daily averages were computed for those days when at least a few observations are available in both forenoon and afternoon hours. To investigate the overall seasons variations in precipitable water, monthly mean PWV for the entire seven years period from January 2006 to January 2012 has been obtained.

Fig. 4.9 below shows the overall monthly mean PWV obtained from ERA-

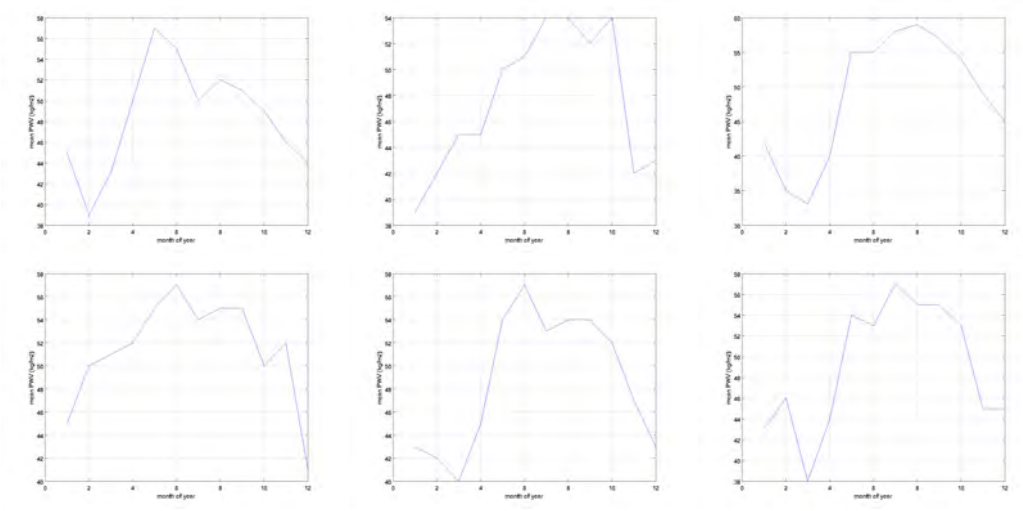


Figure 4.9: Monthly average PWV for 2007 (top-left); 2008 (top-middle); 2009 (top-right); 2010 (bottom-left); 2011 (bottom-middle); and 2012 (bottom-right).

Interim along with the number of days of observations in each month, for the period January 2006-January 2012. Almost in all of the specified years the variability in PWV is smaller during the months (August to December) and it is higher starting from the winter months (January-July).

Average values of tcwv from ERA-Interim data for tropical area $(3-15^0N)$ are 28.05 kg/m^2 in spring, 36.63 kg/m^2 in summer, 32.89 kg/m^2 in autumn and 23.72 kg/m^2 in winter, so there is more than 1.5 times difference in summer and winter

average values. Seasonal variability in IPWV strongly depends on the location (Fig. 4.10 below). Higher variability (summer average more than 1.5 times the winter average) takes place in a region covering the northern, northeastern and to some extent the southeastern part. The variability is highest in the region almost

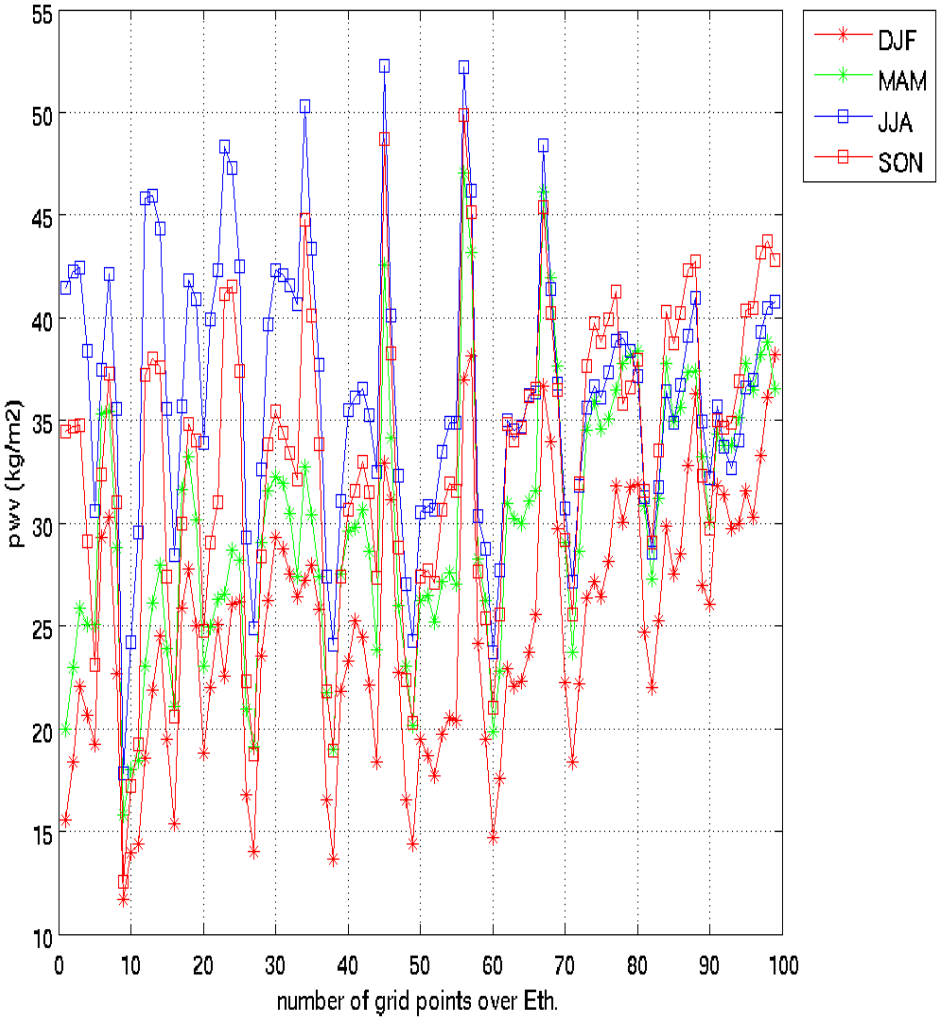


Figure 4.10: Average seasonal precipitable water vapor at 12 utc from 2006-2012 over Ethiopia.

in the southeastern part of Ethiopia and all seasonal averages are in the range of 15-45 kg/m^2. In the whole study area, the autumn values are 1.17 and 1.39 times higher than the spring and the winter ones respectively. This shows that local factors, such as latitude, altitude, and surface type do not play a significant role for the autumn and spring ratio in IPWV (in contrast to the summer and winter

ratio). Generally, these spatial and temporal variations are caused by transport and mixing of water vapor in the neutral atmosphere in the lower atmosphere. These motions occur over a range of spatial scales. Turbulent wind vortices are small-scale flow irregularities that efficiently transport and mix water vapor and heat. Since water vapor is an approximate tracer of atmospheric motions, its flow-induced spatial and temporal variations occupy a range of scales as well.

Now let us see the map of the distribution of PWV for the different seasons

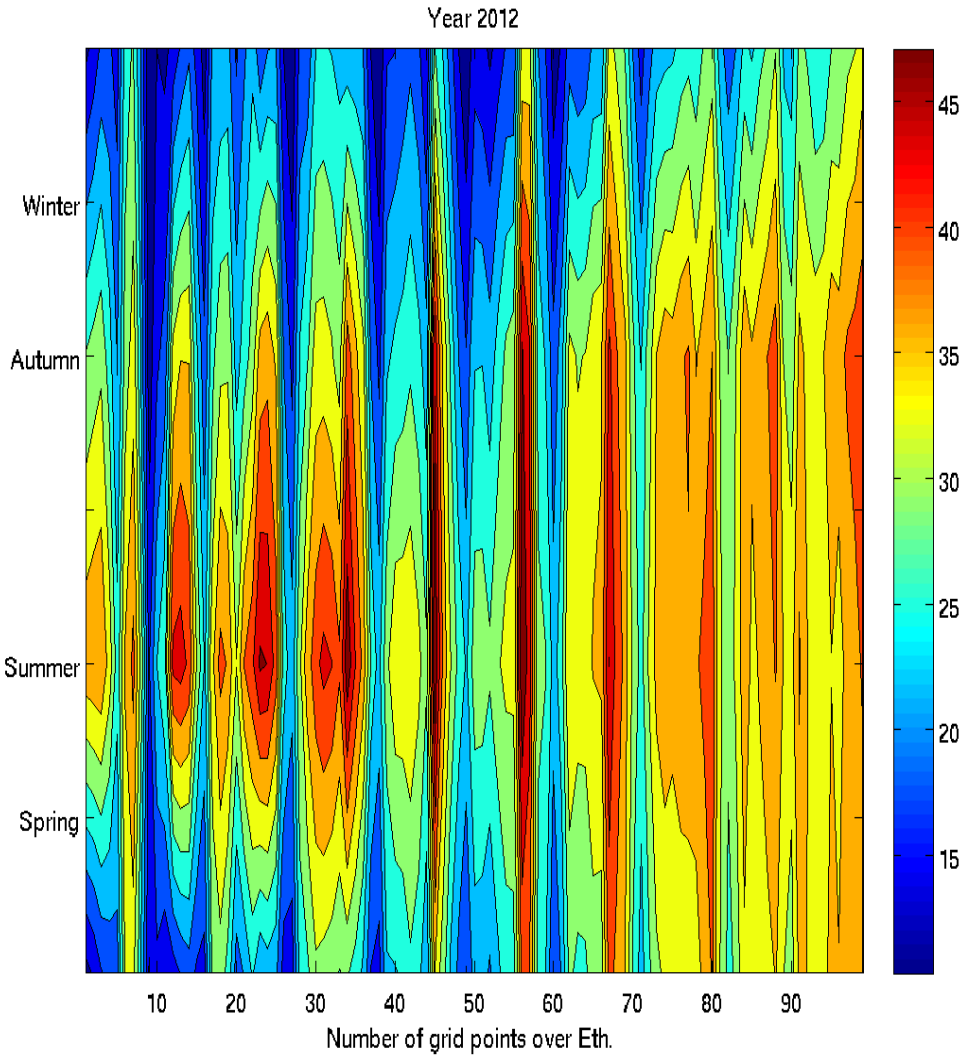


Figure 4.11: Seasonal values of precipitable water vapor (kg/m2) at 00 utc of 2012

of the year 2012 over Ethiopia. Fig. 4.11 below shows the distribution pattern of PWV observed at 00 utc for the four typical seasons of the year 2012 over the

region and is plotted the number of grid points over Ethiopia versus seasons of a year, i.e starts the bottom to the top from MAM, JJA, SON, to DJF.

In the spring seasons (MAM months), the northwestern and northeastern parts of the country have relatively small concentrations of PWV content reached around 17 kg/m^2. And the concentration is gradually increases in the northern part by a amount reached up to 10 kg/m^2. But towards the southern regions the PWV content is become relatively high or reached maximum, because the PWV content is highly depend on air temperature and altitude. So the southern part of the country is very nearer to the equator, due the PWV content will become large, since in the equator there is high temperature and large amount of water vapor is found than the polar regions. In the summer seasons (JJA months), since the season is the country's main rain month's, almost all parts of the regions have relatively large amount of PWV recorded up to 45 kg/m^2 is obtained. However the amount is more dense in the southern part. The concentration is gradually decreases in the Autumn and Winter seasons, especially the PWV content decreases up to 12 kg/m^2.

Now let us see the seasonal variation of PWV content over the region at different particular time. Fig.4.12 below shows the seasonal variability of PWV over Ethiopia at a particular time 00, 06, 12, and 18 utc respectively of the year 2012. The PWV concentration gradually increases from 00 utc to midnight and decreases after midnight to 18 utc with in a particular day of a year. And all these variations of tcwv content of the country for a particular time of a specific year, is due to a change or variation in temperature of a day. That means at 00 utc (9:00 am, local time of the country) the temperature is high and gradually decreases up to 18 utc (3:00 am of local time).

4.3.2 Mean precipitable water vapor over 1979-2012

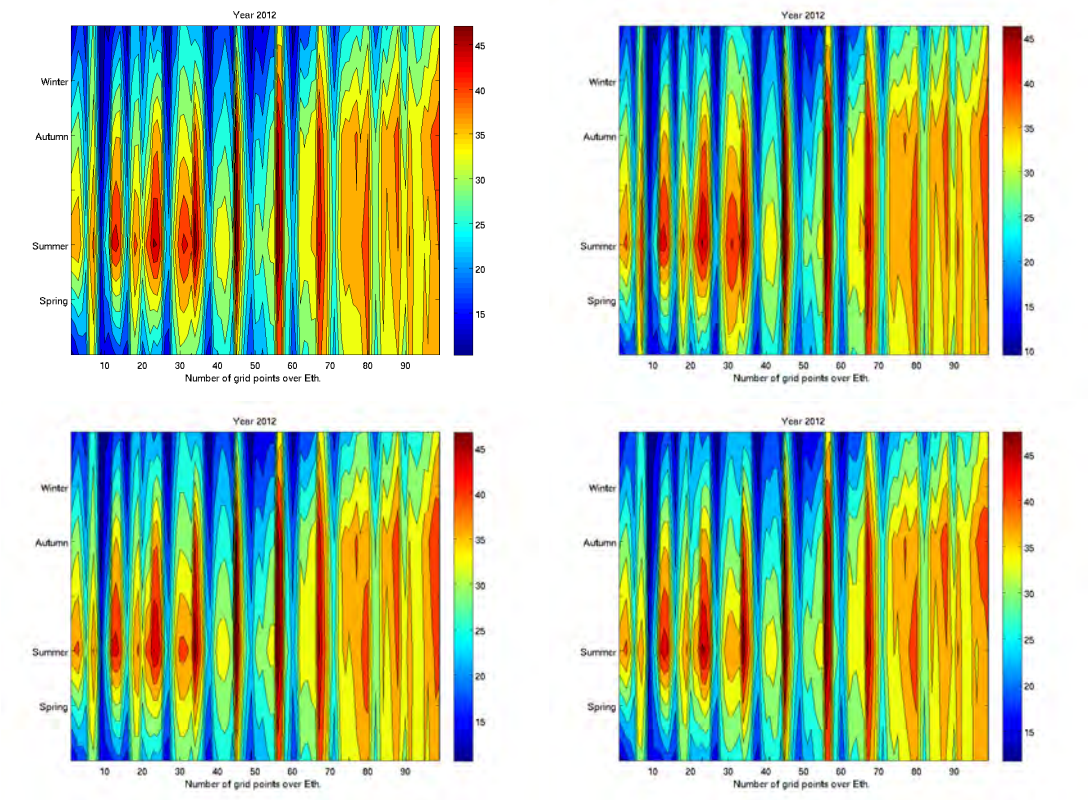


Figure 4.12: Seasonal mean PWV distribution over Ethiopia at 00 UTC (top-left); 06 UTC (top-right); 12 UTC (bottom-left); and 18 UTC (bottom-right).

The mean annual distribution of tcwv content over Ethiopia over a particular time of a specific year is presented as follows. Fig. 4.13 below shows the distribution pattern of tcwv content at 00 utc over the country for 34 years (i.e from 1979-2012). And Fig 4.14 below shows how much the distribution of tcwv is varies over a particular time 00, 06, 12, and 18 utc respectively of a day for a different years of Ethiopia.

4.3.3 Diurnal variability of precipitable water vapor

- Day-to-day variations

Daily mean daytime (with 6 h time interval) values of precipitable water content drived from ERA-Interim for the 7 years (2006-2012) for all the 365 days in individual years is shown below in fig. 4.15. The annual/seasonal oscillation is almost similar in all the years with higher values of PWV in summer months

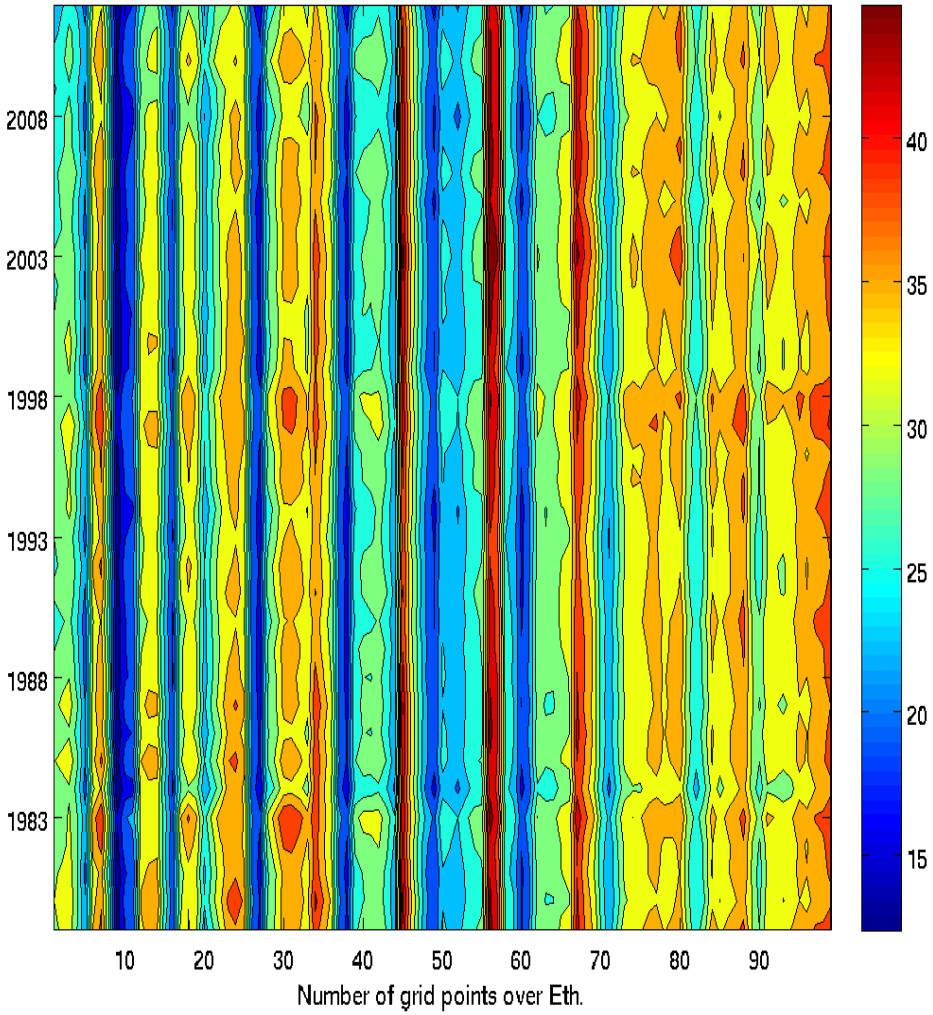


Figure 4.13: Annual variability of tcwv (kg/m2) at 00 UTC

and smaller values during winter. But on a closer observation it can be seen that there are year to year differences in magnitude of the seasonal oscillation. Larger fine structure in temporal variation (variability) on day-to-day scale can be seen mainly during winter and pre-monsoon months. This could be due to the fact that surface meteorological conditions vary considerably from day to day during these seasons and PWV drived from ERA-Interim is solely dependant on surface temperature and relative humidity. Daily mean time series of precipitable water vapor obtained from ERA-Interim for all the days during period January 2006-December 2012 at 00:00 utc are plotted below.

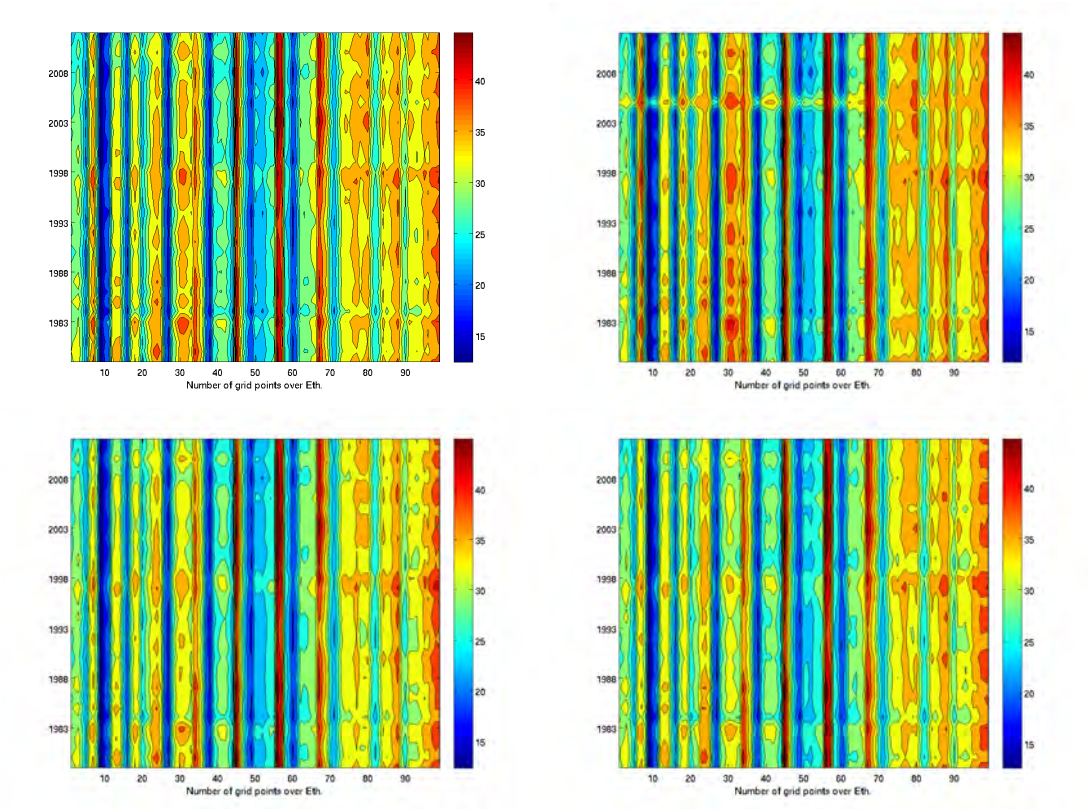


Figure 4.14: mean PWV over 1979-2012 at 00 UTC (top-left); 06 UTC (top-right); 12 UTC (bottom-left); and 18 UTC (bottom-right).

Factors influencing the diurnal changes of IPWV are divided into two groups. The fast and extensive but irregular IPWV variations are due to changes in synoptic situation and the substitution of air masses above the GPS site leading to rapid and large variations in the vertical profiles of water vapour. However, these kind of abrupt changes are very rare and small, regular diurnal variations of IPWV are driven by the diurnal cycle of solar radiation linked with the evapotranspiration processes in the atmosphere and on the underlying surface, and by local air circulation.

- long-term temporal variations

precipitable water vapor content drived from ERA-Interim are generally made at a particular time 6 h interval during all daytime for all grid points of the country. In all days from January 2006-December 2012, data has been collected at 6 h intervals throughout the daytime to study long-term variations, if any, in PWV. Some typical days of observations made during the month of May for each years

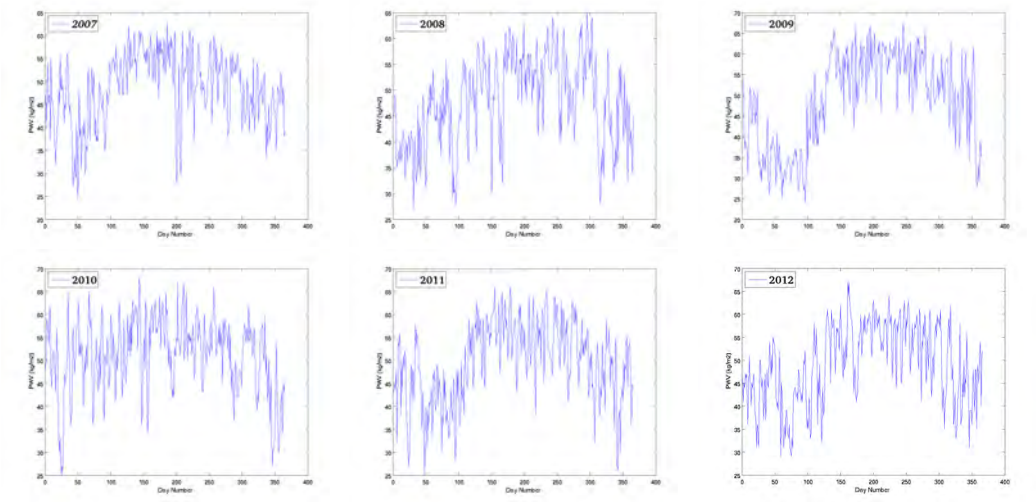


Figure 4.15: Daily PWV time series for 2007 (top-left); 2008 (top-middle); 2009 (top-right); 2010 (bottom-left); 2011 (bottom-middle); and 2012 (bottom-right).

have been presented in this paper to investigate in detail the temporal variations in PWV content obtained from ERA-Interim during the transition phase of pre-monsoon summer and monsoon conditions at this tropical area.

The results obtained are presented case by case and discussed. On the days of the begining of the wet monsoon of the year 2012, the sky was mostly clear in the forenoon hours and small patches of clouds started appearing in the afternoon around 00:00 UTC to 06:00 UTC (9:00 Am to 3:00 Pm LT). The tcwv content are available from ERA-Interim from 00:00 UTC to 18:00 UTC for each day of the year.

Fig. 4.16 below shows the daily temporal variation in PWV content at a particular time interval of 6 h obtained from ERA-Interim. The tcwv content is start increase from late May to September (the Spring and Summer season) and it gradually decreases to a small amount upto late January. But the amount is relatively small from February to late April. After 18:00 utc when scattered cloud patches started appearing in the sky, thus we observe a significant increase in PWV content.

The Precipitable water vapor content derived from ERA-Interim varied from 33 to about 60 kg/m^2 in the particular time of the day. The magnitude of PWV values is rather high and is typical of pre-monsoon/monsoon conditions. It is to

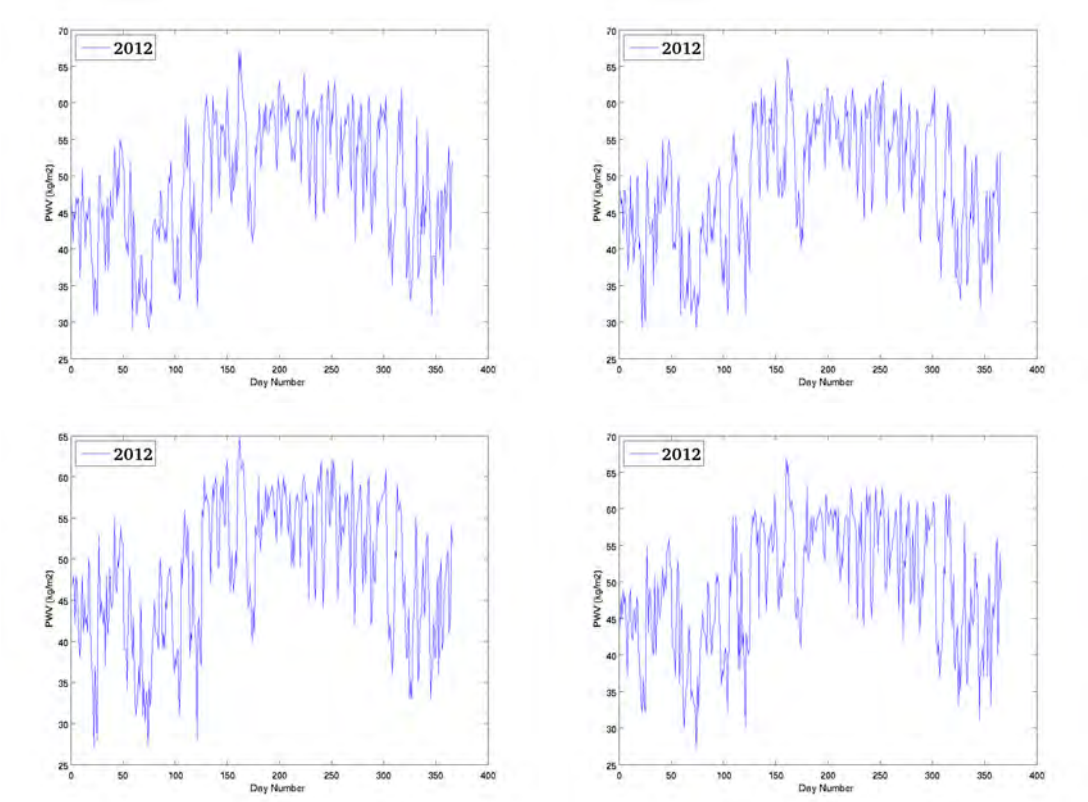


Figure 4.16: PWV during 2012 at 00 UTC (top-left); 06 UTC (top-right); 12 UTC (bottom-left); and 18 UTC (bottom-right).

be noted here that on each recorded time of day, PWV values from ERA-Interim have almost a similar distribution pattern except some small amount of flactuation for the specified years, like in the day-to-day PWV averages described earlier. It is seen that the difference in the amount of tcwv content for each particular time increased steadily from 12:00 utc to 18:00 utc. One reason for this could be that additional layers of water vapor may be forming at cloud height levels in the post noontime hours, either due to convective activity or advection. Long-term fluctuations are more significant in the time series of PWV obtained from ERA-Interim. Here it is seen that ERA-Interim derived values of PWV are gradually increased with a very small amount almost at all times of observation. Therefore, temporal variations showed a slight decrease in PWV until 18:00 utc and then PWV remained more or less constant with time. Some local meteorological changes or transport of water vapor due to winds could have caused this long duration increase in PWV, which was sensed only by the optical extinction method.

Chapter 5

CONCLUSIONS

This study, the precipitable water vapor was drived from ERA-Interim over Ethiopia, the ERA-Interim data obtained from January 2006 to December 2012 with high time resolution were processed. Water vapour is the most important greenhouse gas, contributing to about 60 percent of the natural greenhouse effect. In contrast to other greenhouse gases, water vapour has a much higher temporal and spatial variability, which is not well observed, neither is it fully understood. In this thesis, I have tried to clarify precipitable water, IPWV, variability in detail for the Ethiopia region and more generally for the region northward 15^0N. Spatial variability in the precipitable water depends generally on the latitude. This is due to the northward decrease in air temperature, which controls the atmospheric capacity to contain water vapour. In addition, spatial variability depends on orography, continentality, underlying surface type (land, water or ice), atmospheric circulation, the properties of the underlying surface, etc. (discussed in Thesis Section 4). In the Ethiopia region, seasonal average precipitable water depends mainly on the latitude, especially in transition seasons spring and autumn (discussed in Thesis Section 4). Intergovernmental Panel on Climate Change states that water vapour concentration in the atmosphere mainly depends on air temperature. Temporal variability in precipitable water has been analyzed in different time scales seasonal, interannual and diurnal variability. Seasonal variability is the largest the

highest values of IPWV are in summer and the smallest values are in winter. For the Ethiopia region, seasonal averages differ 1.5 times (discussed in Thesis Section 4.2.4). Diurnal variations of IPWV have large distribution pattern in spring and summer with the maximum in the afternoon and the minimum after midnight. Generally, based on the ERA-Interim data over Ethiopia from 2006 to 2012, the spatial and temporal distribution of tcwv content over the region are analyzed. Therefore, the following points are concluded.

The study showed the following results:

- The spatial distribution characteristic of tcwv decreases with increasing altitude, having the largest value area observed in the northwestern and southwestern part of the country and the second largest value area in the southern part of the country, while the central and northeastern part is the lowest value area. So the southwestern and northwestern parts of the region are humid and the central and northeatern parts are dry.
- In the dry season, PWV changed widely in the range of 14 kg/m^2 to 36 kg/m^2 with 1-4 weeks duration. PWV increased before rainfall and decreased after rainfall. In the wet season, however, change of PWV was much smaller than that in the dry season, although PWV keeped at high value and almost constant between 28 kg/m^2 to 50 kg/m^2. The diurnal variation by mean of PWV in dry and wet season was investigated. The difference of diurnal change of the two seasons was small and they showed that the PWV had the minimum value in the morning, it increased in the afternoon and keeped with the high value from the evening to the midnight.
- Intergovernmental Panel on Climate Change states that water vapour concentration in the atmosphere mainly depends on air temperature. According to the results and analysis, however, this relation does not apply to all seasons and all regions. As there is cold bias in the analysis over Ethiopia from 2006 to 2012, better databases are needed for the relationship between IPWV and temperature.

- There exists a well defined seasonal variation in PWV content with maximum during summer monsoon months and minimum during winter months.
- Temporal variability is divided into three components seasonal, interannual and diurnal components. The highest component is seasonal variability the difference between IPWV summer and winter averages is 1.5 times, depending on locations. The highest seasonal variability in IPWV is in the northwestern and southwestern regions and the smallest is in the central region.

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A LIST OF SOME OF THE ACRONYMS USED

DJF	December, January, February
ECMWF	European Centre for Medium-range Weather Forecast
GPS	Global Positioning System
IPWV	Integrated Precipitable Water Vapor
JJA	June, July, August
MAM	March, April, May
PWVC	Precipitable Water Vapor Content
PWV	Precipitable Water Vapor
SW	Slant Water Vapor
SON	September, October, November
tcwv	total column water vapor

Declaration

Here I declare that, this thesis is my original work and has not been presented for a degree in any other university. All sources of material used for the thesis have been duly acknowledged.

Name: Eliase Ayalew

Signature: .....

This thesis has been submitted for the examination with my approval as university advisor.

Name: Dr. Gizaw Mengistu

Signature: .....

Addis Ababa University

Department of Physics

June, 2013