

Atmospheric water vapour is a primary greenhouse gas and plays an important role in weather forecasting and climate monitoring. Global Navigation Satellite System (GNSS) signals experience a propagation delay, which is related to the amount of water vapour in the lower atmosphere. Hence GNSS observations can be processed to estimate this delay with millimetre-level accuracy and together with meteorological data can be used to compute the amount of atmospheric water vapour on various temporal and spatial scales.



GNSS METEOROLOGY IN LUXEMBOURG_

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The term Global Navigation Satellite Systems (GNSS) refers to a number of systems having a satellite constellation used to provide position, navigation and timing data. The Global Positioning System (GPS) of the US, the GLOBal'naya NAVigatsionnaya Sputnikovaya Sistema (GLONASS) of Russia, Galileo of Europe and the Compass/BeiDou Navigation Satellite System (CNSS) of China are examples of such GNSS. As of now, only GPS and GLONASS are fully operational. A GNSS consists of three segments namely the space segment, the ground segment and the user segment. The space segment comprises of satellites distributed in various orbits, the ground segment is composed of a number of globally distributed control stations and the user segment contains the GNSS receivers which can be ground-based, airborne or space-borne depending on the user application (Hofmann-Wellenhof et al., 2007). Today, GNSS dominate the fields of positioning, navigation and timing, and have a wide range of applications including those in engineering, geosciences and meteorology.

The term "GNSS meteorology" refers to the concept of assimilating GNSS derived information about the state of the atmosphere into Numerical Weather Models (NWM) for weather forecasting. As compared to conventional meteorological sensors, GNSS has some benefits such as higher temporal and spatial resolutions, all weather operation capability, lower cost, and often freely available data from national to worldwide networks of stations. All these characteristics make GNSS an efficient tool to detect and track extreme short-term weather events (Iwabuchi et al., 2009). Since the onset of GNSS many networks of continuously operating GNSS stations have been established for engineering and scientific purposes and often the organizations owning and maintaining these, so called, GNSS reference networks, provide their observation data free of charge for research. In Luxembourg and the Greater Region these organizations are the Administration du cadastre et de la topographie and the Service public de Wallonie (WALCORS), respectively, and both provide their service mainly for engineering and surveying purposes. For scientific applications the community has formed research organizations which collect GNSS data and provide related services on an international to global basis.

These include the International GNSS Service (IGS) (Dow et al., 2009) and the Reference Frame Sub Commission for Europe (EUREF) (Bruyninx et al., 2008).

Over the last decade, various research projects investigating the use of GNSS-derived water vapour estimates for meteorology have been conducted and some of them are still in progress. The European Cooperation in Science and Technology (COST) funded the "COST Action 716: Exploitation of ground-based GPS for climate and numerical weather prediction applications" from 1999 to 2004 (Elgered, 2001). Another project "Targeting Optimal Use of GPS Humidity measurements in meteorology (TOUGH)" was conducted in Europe from 2003 to 2006 (Huang et al., 2003). Currently, the EUMETNET EIG GNSS water vapour programme (E-GVAP) is a series of research projects since 2005 to study the use of near real-time (NRT) GNSS data for numerical weather prediction (<http://egvap.dmi.dk>). Analysis centres located all over Europe submit NRT GNSS-derived delay estimates to E-GVAP for validation, monitoring and research.

The developments from these projects lead to a rapid growth of GNSS meteorology and a number of European meteorological institutes continue to foster this technique. Météo France (Moll et al., 2008) and the UK MetOffice (Bennitt et al., 2008) are currently using products from NRT GNSS processing systems in their global, regional and local NWM. The Danish Meteorological Institute (<http://www.dmi.dk>), the Royal Dutch Meteorological Institute (<http://www.knmi.nl>) and Royal Observatory Belgium (<http://www.gnss.be>) are some other organizations with a current research emphasis on GNSS meteorology.

Besides GNSS meteorology's use in operational weather forecasts other benefits arise from its application in climatology. As atmospheric water vapour is the primary greenhouse gas, changes in it as monitored by GNSS can provide important information for the study of climate variations (Nilsson et al., 2008, Stende, 2006). By analysing historical time series of GNSS-derived atmospheric water over longer time periods, variations in climate can be monitored on annual to decadal time scales. With sufficient length in these GNSS-derived meteorological products, important predic-

tions of the future climate will become possible which, in turn, can have consequences for the specifications of structures and other engineering projects.

In this article, we provide an overview and some preliminary results of the research project "The Potential of Precipitable Water Vapour Measurements using Global Navigation Satellite Systems in Luxembourg (PWVLUX)" which is funded by the Fonds National de la Recherche (FNR) Luxembourg and aims at studying the potential for the use of GNSS in operational meteorology and climatology in Luxembourg and the Greater Region.

Estimating Atmospheric Water Vapour using GNSS Observables

On its way from the satellite to the ground-based receiver antenna, a GNSS signal travels through various layers of the Earth's atmosphere e.g. the ionosphere and the troposphere. Each of these has an effect on the signal which introduces a certain amount of error in the measured position. When the received signal is processed, the corresponding amount of error induced by each of the layers is estimated and is corrected for.

Ionosphere is the uppermost layer of the Earth's atmosphere that starts at around 50 kilometres above the Earth's surface and contains charged particles due to solar radiation. The electromagnetic properties of the ionosphere affect satellite signals travelling through it, which can result in case of GNSS in signal delays of over 100 meters. As the effect of the ionosphere can be largely removed by using a linear combination of the GNSS observables, it is not considered further in this study.

The troposphere is the lowest layer of the Earth's atmosphere and has a thickness ranging approximately from 9 kilometres to 16 kilometres above the Earth's surface at the poles and on the equator respectively. The primary greenhouse gas, i.e. atmospheric water vapour constitutes about 10% of the total tropospheric effect on the GNSS signals and due to its nature, is often termed as the wet part. As compared to the hydrostatic part, which constitutes 90% of the tropospheric effects and is highly predictable using models, the water vapour content has a very high temporal

and spatial variability and hence plays a significant role in the formation and propagation of weather systems (Marshall et al., 2007).

Delay in the troposphere

The tropospheric propagation delay in the signal is dependent on the refractivity of the troposphere which can be expressed as (Thayer, 1974)

$$N = k_1 \frac{P_d}{T} Z_d^{-1} + k_2 \frac{P_v}{T} Z_v^{-1} + k_3 \frac{P_v}{T^2} Z_v^{-1} \quad (1)$$

where $P_{d,v}$ are the partial pressures of dry and wet air constituents in hPa, T is the temperature in K, $Z_{d,v}^{-1}$ are the inverse compressibility factors for dry air and water vapour and $k_{1,2,3}$ are experimentally determined coefficients in K/hPa. The path followed by the signal in the troposphere is assumed to be zenithal and therefore, the delay ΔL between a point at height h and infinity is

$$\Delta L = 10^{-6} \int_h^{\infty} N(h) dh \quad (2)$$

where ΔL is known as zenith total delay (ZTD) in mm and can be expressed as the sum of zenith hydrostatic delay (ΔL_h or ZHD) and zenith wet delay (ΔL_w or ZWD) i.e.

$$ZTD = \Delta L = \Delta L_h + \Delta L_w \quad (3)$$

ΔL_h can be approximated by using the surface pressure and location values in the widely used Saastamoinen hydrostatic model (Saastamoinen, 1972) i.e.

$$ZHD = \Delta L_h = \frac{2.2779 \pm 0.0024 \text{ mm} \cdot P_S}{1 - 0.00266 \cdot \cos(2\varphi) - 0.00028 \frac{1}{\text{km}} \cdot h} \quad (4)$$

where P_S is the surface pressure in hPa, φ is the station latitude in degree, h is the height of the station in km above the ellipsoid.

The carrier signals are the primary observables for high-precision GNSS positioning and the can be estimated from the carrier phase observable. This observable can be observed as

$$\Phi = \rho + c(\tau_{sat} - \tau_{rcv}) - \Delta L_{iono} + \Delta L_{tropo} + \lambda N + \epsilon_{\Phi}$$

(6)

where ρ is the geometric distance between the satellite and the receiver antenna in meters, c is the speed of light in vacuum in m/s, $\tau_{sat,rcv}$ are the clock biases between satellite and receiver in seconds, ΔL_{iono} is the ionospheric delay in meters, ΔL_{tropo} is the tropospheric delay or the ZTD in meters, λ is the wavelength in meters, N is the integer phase ambiguity term (not to be confused with the refractivity N in Equation 1) and ϵ_{Φ} are the unmodelled phase measurement errors in meters.

In this way, GNSS observations from a collection of ground-based receivers, in combination with auxiliary information (satellite and receiver positions, corrections computed from models of geophysical processes) are processed using various GNSS data processing software packages to obtain the ZTD estimates.

Once the ZTD has been estimated, ZHD is computed using Equation 4, and the ZWD can be obtained from

$$ZWD = ZTD - ZHD$$

(7)

ZWD can then be combined with meteorological data i.e. pressure and temperature to convert it to a quantity known as Integrated Water Vapour (IWW) which is given in kg/m² (Bevis et al., 1992, Bevis et al., 1994).

To convert the ZWD into IWW, the relation in Equation 8 can be used i.e.

$$IWW = \int_h^{\infty} \rho_v(h) dh \approx \kappa \Delta L_w$$

(8)

where

$$1/\kappa = 10^{-6}(k_3/T_m + k'_2)R_v$$

(9)

In Equation 9, R_v is the specific gas constant for water vapour and T_m is the mean temperature of the vertical

column of air above the GNSS receiver and is given by

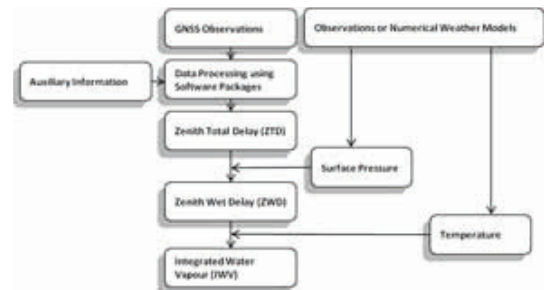
$$T_m = \frac{\int_h^{\infty} \rho_v dh}{\int_h^{\infty} (\rho_v/T) dh}$$

with the water vapour density

$$\rho_v = \frac{P_v}{R_v T}$$

such that the total density $\rho = \rho_d + \rho_v$.

The term IWW can be interchangeably used with the term Precipitable Water Vapour (PWV) which expresses IWW as the height of an equivalent column of liquid water in millimetres. The required meteorological data can be obtained either from observations, e.g. temperature and pressure sensors, or by interpolation from models of pressure and temperature, e.g. the Global Pressure and Temperature (GPT) model (Boehm et al., 2007). Figure 1 summarizes this process of estimating IWW from raw GNSS observations.



1_ Estimating IWW from GNSS Observations

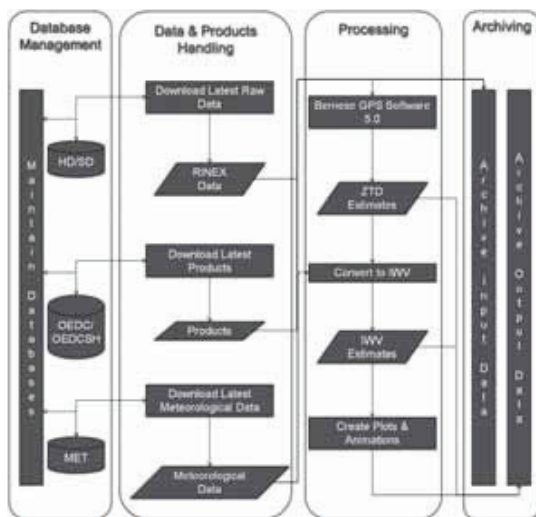
Surface pressure values at the locations of the GNSS receivers can be obtained from either observations or models. Using the pressure values, ZHD is computed and subtracted from the ZTD estimates to obtain ZWD. Finally, ZWD is converted to IWW using the temperature values, again either from observations or from models. Although IWW is of primary interest for weather forecasting and climate research, for consistency, it is only ZTD which is usually assimilated into NWM before it is converted to IWW using homogeneous temperature values within the model.

Near Real-Time GNSS

In order to assimilate the GNSS-derived ZTD estimates into the NWM which operate at high update rates e.g. hourly, it is necessary to obtain the estimates with a low latency i.e. in near real-time (NRT). Research has shown that assimilation of NRT ZTD in NWM has a positive impact on the quality of weather forecasts (de Haan 2011, Bennitt et al., 2011).

The University of Luxembourg in collaboration with the University of Nottingham has setup two NRT GNSS data processing systems for estimating ZTD and IWV. One of the systems (NRT1h) has an update cycle of 1 hour and the other (NRT15m) one of 15 minutes. The development of these systems is part of the PhD project PWVLUX.

Both the NRT systems collect GNSS data in Receiver Independent Exchange format (RINEX) from a distribution of GNSS stations spread all over Europe, process the RINEX data with auxiliary information to estimate the ZTD and convert the ZTD into IWV using meteorological data. Figure 2 illustrates the operation of the NRT systems.



2_ Operational diagram of the NRT Systems

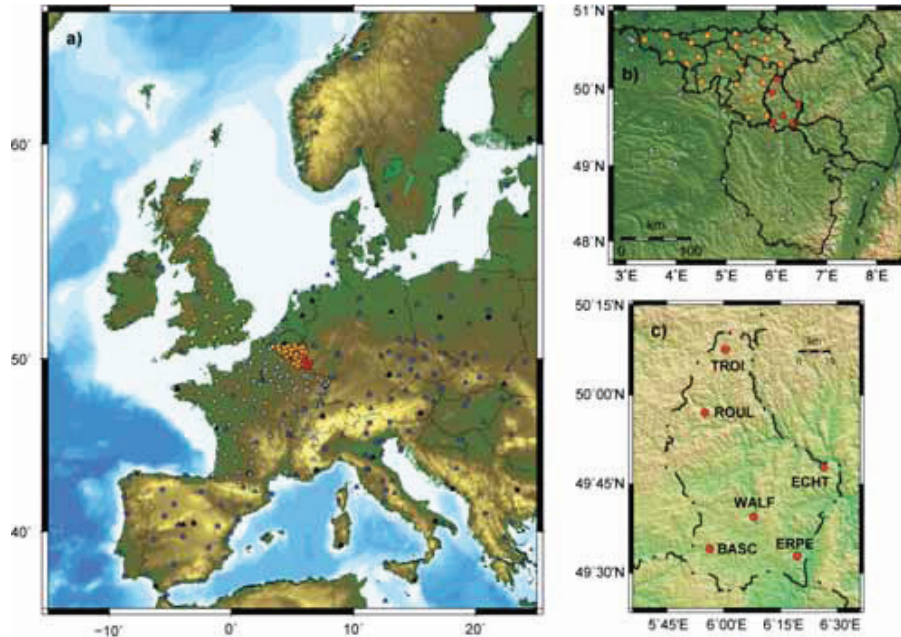
The overall operation of these systems is divided into four parts i.e. database management, data and products handling, processing and archiving. At the beginning of each session, the database management part is executed in which the databases containing information about available and required hourly (HD in Figure 2) and sub-hourly (SD in Figure 2) data, available and required products (OEDC, OEDCSH in Figure 2), and available and required meteorological data (MET in Figure 2) are maintained. The data and products handling part then downloads the required data and products onto the local server. After the data and products handling, the processing part is commenced which processes the downloaded raw data with the Bernese GPS Software 5.0 (Dach et al., 2007) and converts the obtained ZTD to IWV. Finally, the archive part archives the raw data, products and processing results on the local server.

The network of GNSS stations (Figure 3) has been selected with the aim of achieving good spatial coverage of Europe with a focus on Luxembourg and the Greater Region. The triangles represent the GNSS stations providing hourly data and circles represent those providing real-time streams. Table 1 shows the list of the GNSS networks used. The hourly NRT system processes data from the stations that either provide real-time streams or hourly data. On the other hand, the sub-hourly NRT system only processes data from real-time stations.

Network	Region
SPSLux (red)	Luxembourg
WALCORS (orange)	Wallonie (Belgium)
RGP (gray)	France
CSGB+Geonet (yellow)	UK
EPN (blue)	Europe
IGS (black)	Global

Table 1 GNSS data providers

In both the hourly and sub-hourly NRT systems, the computation of ZTD involves the formation of baselines between the neighbouring stations and therefore, the density and distribution of the network has an influence on the ZTD estimates. Another important factor that influences the quality of the estimated ZTD is the type of GNSS satellite orbit product used as these are available with different accuracy



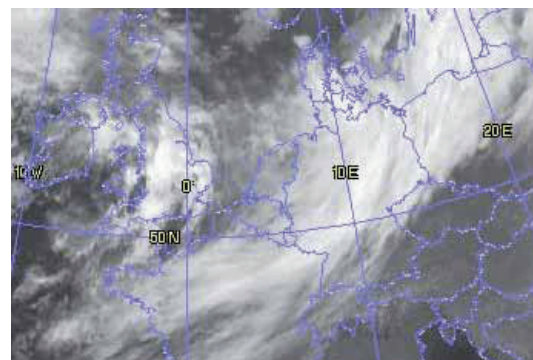
3_ NRT Network used for PWVLUX on scales of a) Europe, b) the Greater Region and c) Luxembourg

levels depending on their latency (Douša 2010, Ge et al., 2002). Along with its benefits, NRT processing imposes a requirement of large computing power and efficient data communication in order to timely provide the results for assimilation into the NWM.

For the climate variability analysis, it is possible to combine the NRT ZTD estimates for long time spans by calculating the mean values at low sampling intervals e.g. twice a day. A global set of GNSS data is available since 1994 and post-processing of this data is possible using the most accurate satellite orbit products and models. For the dense GNSS station distribution in Luxembourg and the Greater Region this is possible for the period since 2006, and provides, at the time of writing, an initial six year record of the regional variations in atmospheric water vapour.

Preliminary Results

During 22-23 February 2012, a warm front (i.e. a warm air-mass moving towards a cold air-mass) moved over northern France, Belgium and Germany. A satellite picture of the cloud distribution, as taken by Meteosat second generation (<http://www.esa.int/SPECIALS/MSG/>), associated with this front at 2012-02-23 00:00UTC is shown below.

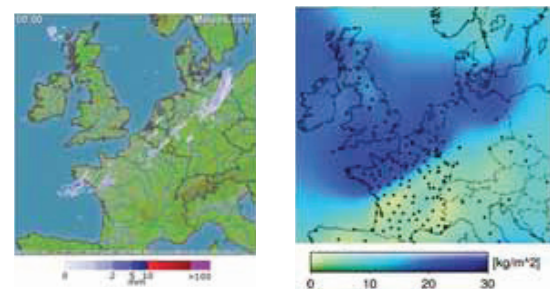


4_ Satellite picture of cloud distribution at 2012-02-23 00:00UTC

This front was associated with a low-pressure system situated over southern Scandinavia. Cloud formation and

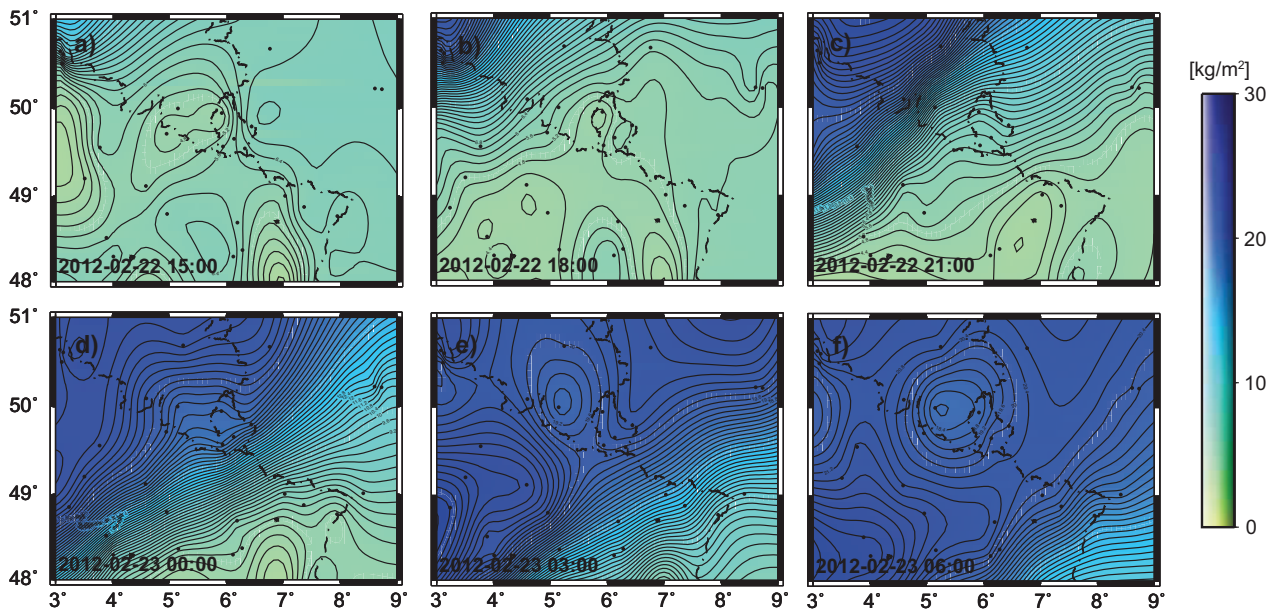
stratiform precipitation was caused by riding of warm air-mass over the cold air-mass and a light rainfall at 04:00UTC was observed in Luxembourg. For this event it is possible to compare the 2D IWV maps generated by the NRT1h system with precipitation information obtained from the weather radar (www.meteoex.de) and this comparison is shown in Figure 5.

Figure 5(a) shows the precipitation in millimetres at 2012-02-23 00:00UTC over Europe as captured by weather radar whereas Figure 5(b) is a 2D map of the IWV distribution over the same region at the same time. The black dots in Figure 5(b) represent the ground-based GNSS stations which are included for processing in NRT1h. To generate the IWV maps like that in Figure 5(b) in the NRT1h system, IWV is first estimated over all the individual stations and then a grid with a resolution of 15 minutes is computed by block averaging followed by an adjustable tension continuous curvature surface gridding algorithm (Smith et al., 1990). Therefore the density of the network of GNSS stations has an influence on the quality of these maps. It must be noted that at this point the systems do not automatically detect and remove outlying ZTD or IWV estimates. It can be seen that the zones with the largest gradients in IWV overlap with the fore-front of the precipitation events caused by the warm front as identified by the weather radar.



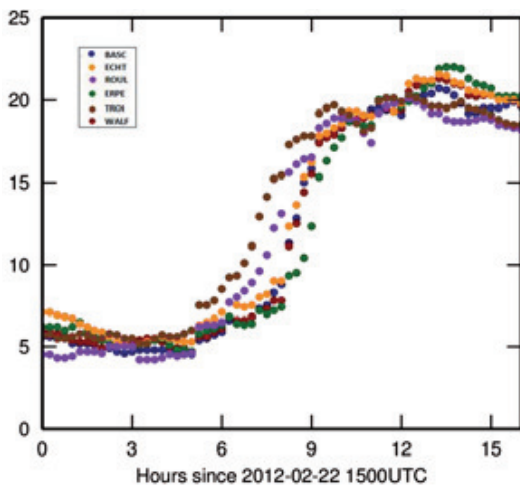
5_ Comparison of weather radar (a) and IWV (b) at 2012-02-23 00:00UTC

The output of the NRT systems has a sampling interval of 15 minutes and hence the IWV maps are generated for every 15th minute. This makes it possible to graphically observe the changes in the amount of IWV and compare these



6_ 3-hourly plots for IWV over Luxembourg and the Greater Region for 2012 - 02 - 22 15:00UTC to 2012 - 02 - 23 06:00UTC

changes with the weather processes. Such an example is presented in Figure 6 which shows the IWV maps obtained by NRT1h for a) 2012-02-22 15:00UTC, b) 2012-02-22 18:00UTC, c) 2012-02-22 21:00UTC, d) 2012-02-23 00:00UTC, e) 2012-02-23 03:00UTC and f) 2012-02-23 06:00UTC. The sequence of IWV maps in Figure 6 shows the evolution of the distribution of IWV corresponding to the passage of the warm front shown in Figure 5 over Luxembourg and the Greater Region.



7_ IWV Time series for the 6 GNSS stations in Luxembourg for the period 2012 - 02 - 22 15:00UTC to 2012 - 02 - 23 06:00UTC

Figure 7 presents the time series of IWV over the six GNSS stations in Luxembourg for the same time-period as that in Figure 6. It can be seen that the amount of IWV increases by approximately 15kg/m^2 as the warm front passes over Luxembourg. The station Troisvierges (TROI) is the first to observe this change and as the front proceeds in a southeasterly direction, the other stations observe this change too. Over TROI, IWV reaches a value of 15.2kg/m^2 at 2012-02-22 22:45UTC whereas over Erpeldange (ERPE), the same value is reached at 2012-02-23 00:15UTC which indicates that the warm front has taken about 90 minutes to travel from Troisvierges to Erpeldange (approximately 28km/h). This demonstrates the possibility of calculating

the speed and direction (not explicitly shown) of a moving weather front using GNSS and hence storms can be tracked.

Conclusions

GNSS meteorology has been introduced as a tool for monitoring atmospheric water vapour for weather forecasting and to monitor annual to decadal climate variations. Two near real-time (NRT) processing systems have been developed at the University of Luxembourg to estimate zenith total delay and integrated atmospheric water vapour with hourly and 15-minute update cycles, respectively. First preliminary results for the hourly NRT system for a warm front and its corresponding precipitation events crossing over Luxembourg and the Greater Region on 22-23 February 2012 are presented. The 2D maps of IWV are compared with cloud distribution and precipitation maps from satellite and weather radar data, respectively, and a good agreement in the location of the front system has been found. Furthermore, it has been demonstrated how GNSS-derived atmospheric water vapour estimates could play an important and complementary role in short-term weather forecasting for Luxembourg and the Greater Region. In order to extend these benefits to regional climate studies it is of uttermost importance for the existing GNSS infrastructure to be maintained at current levels. In this way the GNSS measurements will be able to support long-term consistent atmospheric water vapour estimates over decades.

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