# Ground-based GPS networks for remote sensing of the atmospheric water vapour content: a review

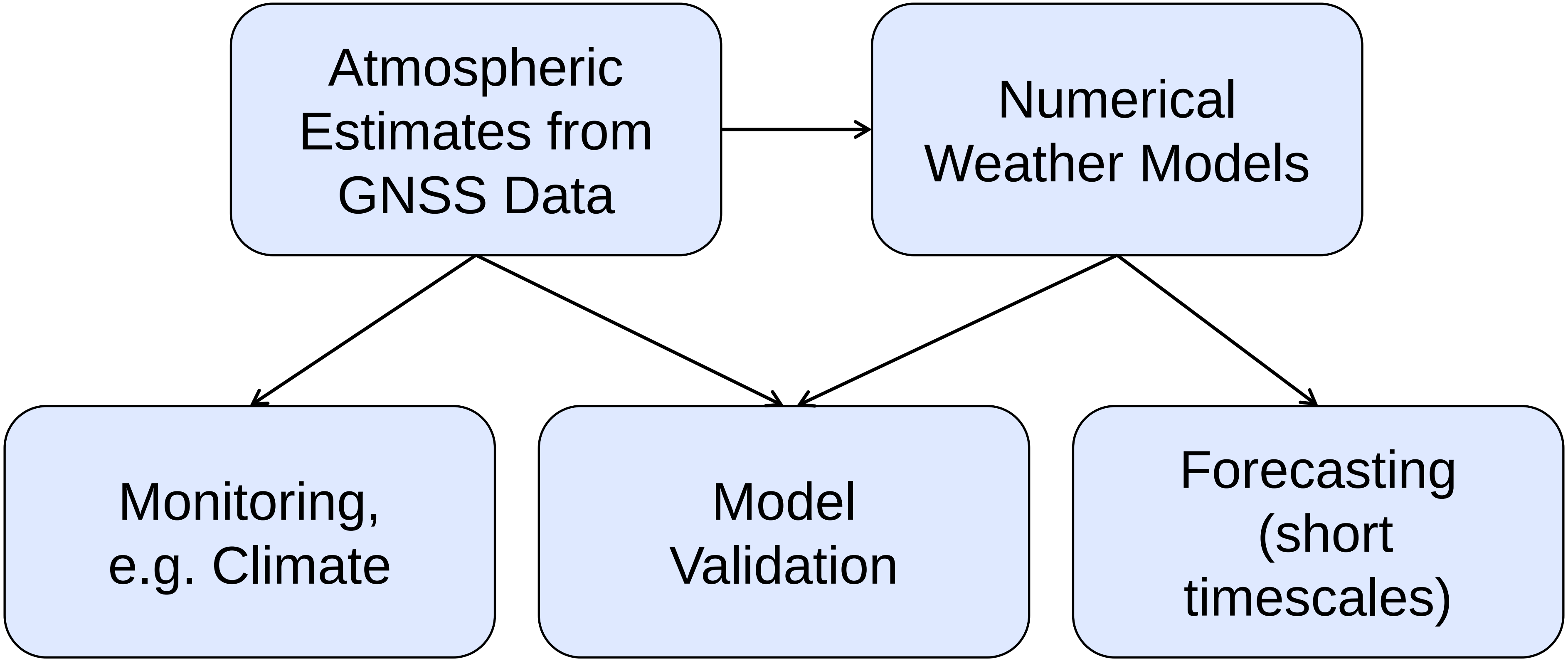
Gunnar Elgered

*Earth and Space Sciences,*
*Chalmers University of Technology,*
*Onsala Space Observatory, SE-43992 Onsala*

# Structure of presentation

- GPS/GNSS meteorology: background and European projects
- The method used to estimate the integrated water vapour (IWV) content in the atmosphere above each site — measured in $kg/m^2$
- Error sources: strengths and weaknesses — different time scales
- IWV results for weather forecasting
- IWV results for climate research
- Future?

# Applications for GPS/GNSS Meteorology



# European projects with ground-based GPS meteorology

- WAVEFRONT (GPS/ Water Vapour Experiment for Regional Operational Tools) 1996–1999
- NEWBALTIC I and II (focus on BALTEX) 1996–1998, 1998–2000
- MAGIC (Meteorological Applications of GPS Integrated Column Water Vapour Measurements in the Western Mediterranean) 1998–2001
- COST 716 (Exploitation of ground-based GPS for climate and numerical weather prediction applications) 1998–2004
- TOUGH (Targeting Optimal Use of GPS Humidity measurements in meteorology) 2003–2006
- EUMETNET: E-GVAP (near real time data analysis for forecasting applications) 2005–now

# COST Action 716 : Exploitation of Ground-Based GPS for Climate and Numerical Weather Prediction Applications (1999–2004)

## The primary objective:

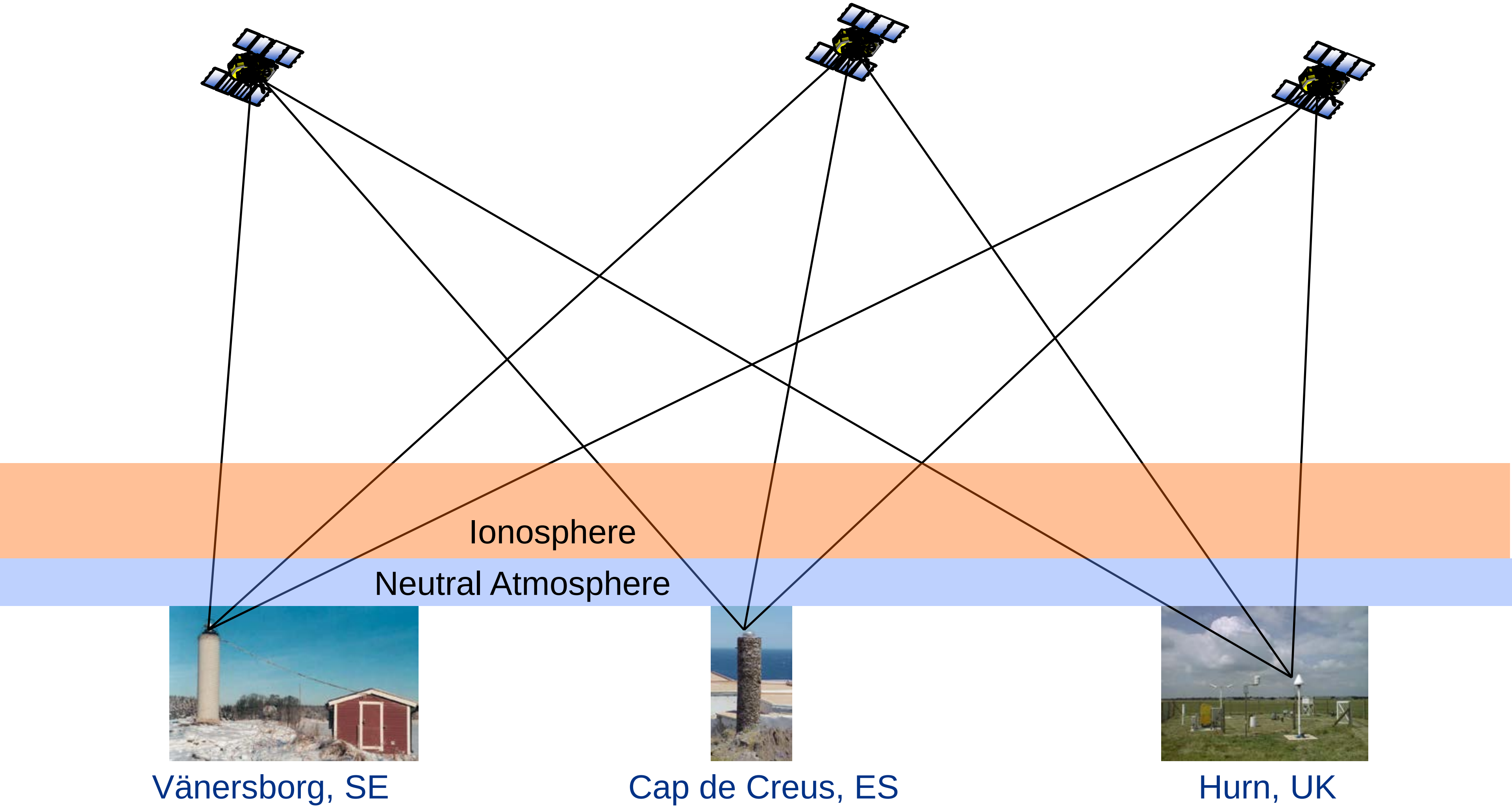
Assessment of the operational potential on an international scale of the exploitation of a ground based GPS system to provide near real time observations for numerical weather prediction and climate applications

## Secondary objectives:

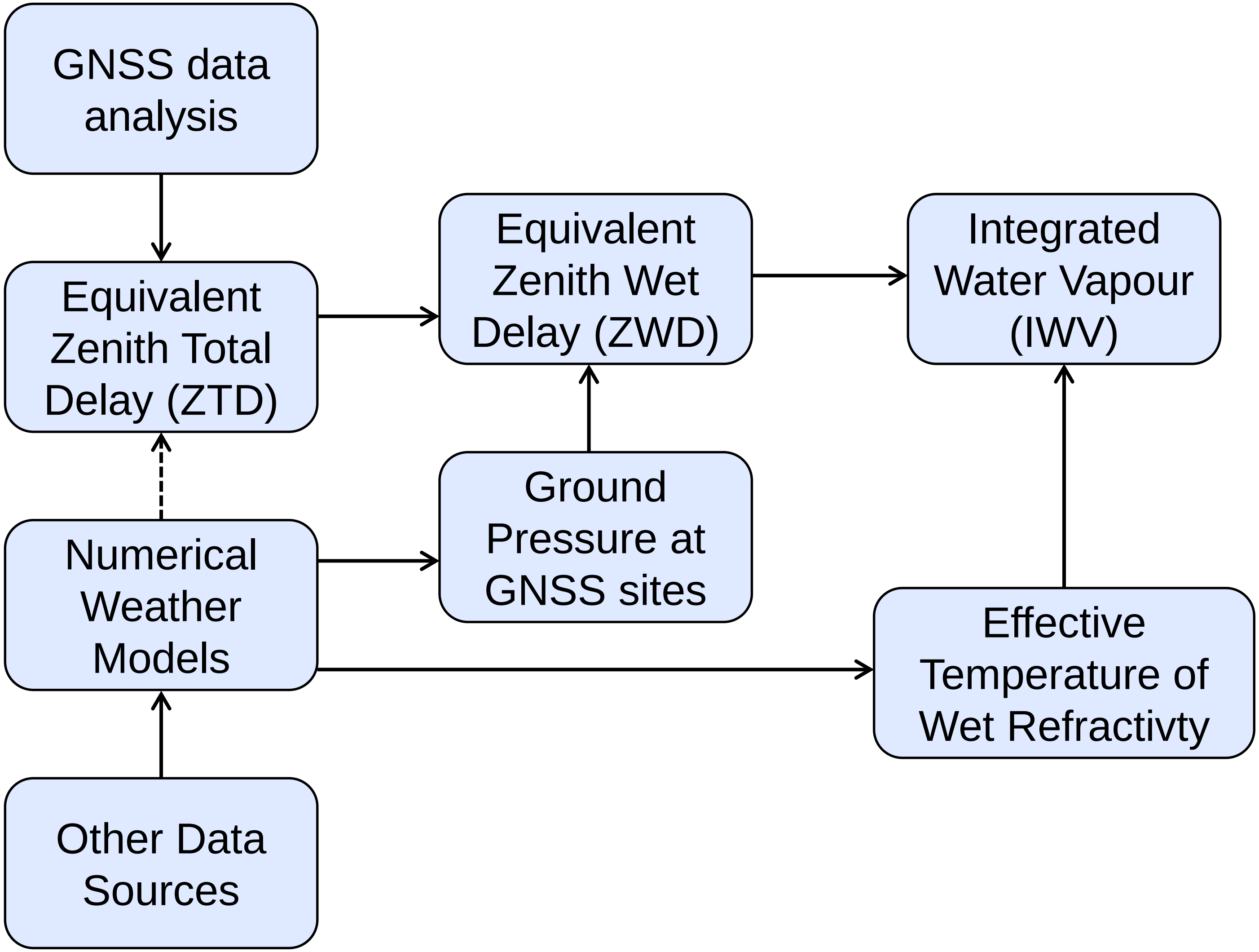
- Development and demonstration of a prototype ground based GPS system on an international scale
- Validation and performance verification of the prototype system
- Development and demonstration of a data exploitation scheme for NWP and analysis of data exploitation techniques needed for climatic applications
- Requirements for operational implementation of a ground based GPS system on an international scale

http://www.oso.chalmers.se/~kge/cost716.html/

# Estimation of propagation time delay due to the atmosphere above ground-based GPS stations



# Data Flow in GPS/GNSS Meteorology



# GNSS error sources when estimating IWV

**Table 1.** Uncertainties of the GPS-Derived IWV Calculated From the Uncertainties Associated With Input Variables for Two GPS Sites: MEDI and BODS

| Input Variable | MEDI | BODS | Uncertainty | Corresponding IWV Uncertainty | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | MEDI | | | BODS | | |
| | | | | [kg/m$^2$] | [%][h] | [%][i] | [kg/m$^2$] | [%][h] | [%][i] |
| ZTD [mm] | 2438 | 2366 | 4[a] | 0.63 | 3.1 | 70.2 | 0.61 | 5.8 | 71.8 |
| | | | 6 | 0.95 | 4.6 | | 0.91 | 8.7 | |
| Ground pressure $P_0$ [hPa] | 1014.2 | 1009.1 | 0.9[b] | 0.32 | 1.5 | 18.0 | 0.30 | 2.9 | 17.5 |
| Constant[c] [mm/hPa] | 2.2767 | 2.2767 | 0.0015 | 0.24 | 0.6 | 10.1 | 0.23 | 1.0 | 10.2 |
| Mean temperature $T_m$ [K] | 278.3 | 267.9 | 1.1[d] | 0.08 | 0.4 | 1.0 | 0.04 | 0.4 | 0.3 |
| $k'_2$ [K/hPa] | 22.1 | 22.1 | 2.2[e] | 0.03 | 0.2 | 0.1 | 0.02 | 0.2 | 0.1 |
| $k_3$ [$10^5 \times K^2$/hPa] | 3.739 | 3.739 | 0.012[e] | 0.06 | 0.3 | 0.6 | 0.03 | 0.3 | 0.1 |
| IWV [kg/m$^2$] | 21 | 11 | | | | | | | |
| Conversion factor $Q$ | 6.3 | 6.5 | | | | | | | |
| Total IWV uncertainty (1)[f] | | | | 0.75 | 3.6 | | 0.72 | 6.5 | |
| Total IWV uncertainty (2)[g] | | | | 1.03 | 5.9 | | 0.99 | 9.0 | |
| Uncertainty of monthly mean (1)[f] | | | | 0.31 | 1.5 | | 0.29 | 2.6 | |
| Uncertainty of monthly mean (2)[g] | | | | 0.54 | 2.6 | | 0.52 | 4.7 | |

From Ning et al. 2013 JGR Atmospheres

# Effects due to antenna phase centre variations

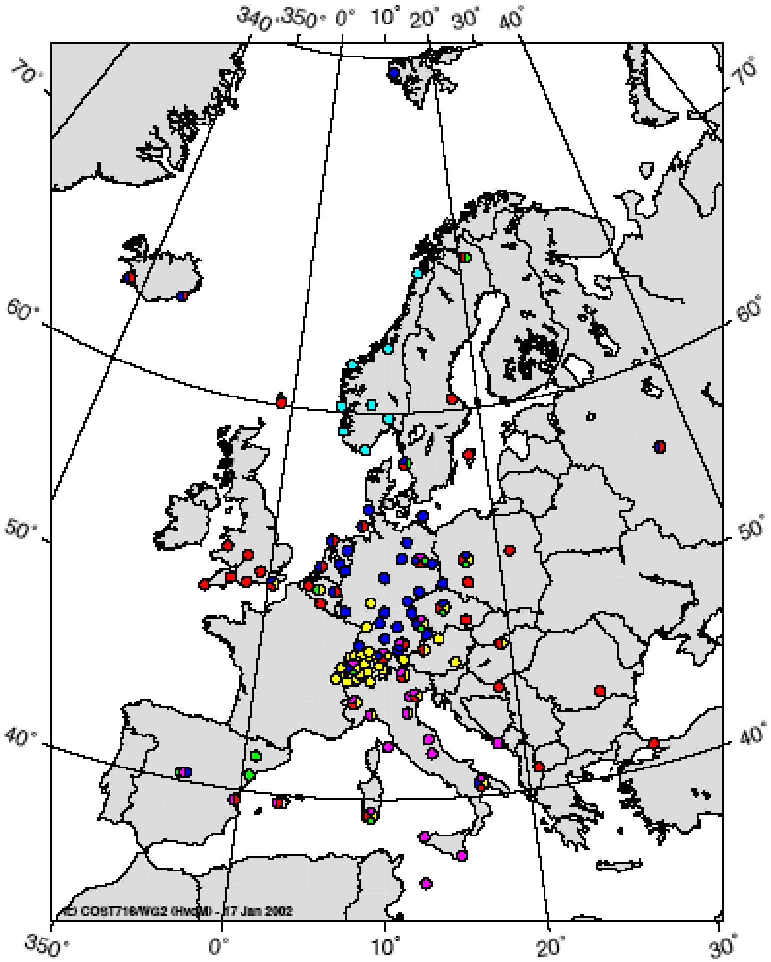

The impact of the ECCOSORB: offset in the IWV decreases from 1.6 kg/m$^2$ to 0.3 kg/m$^2$ compared to results from the ONSA IGS site

No significant (< 0.4 kg/m$^2$ in IWV) impact detected due to the use of radome

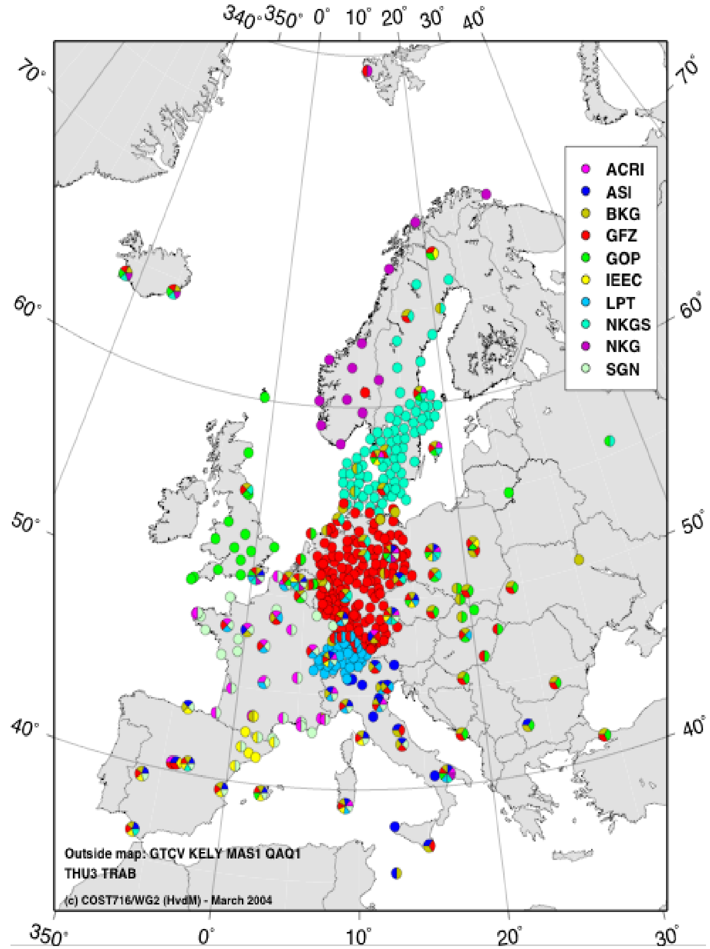
(From Ning et al., The impact of microwave absorber and radome geometries on GNSS measurements of station coordinates and atmospheric water vapour, Advances in Space Research, 2011)

# Ground-based GPS for meteorology during COST 716

January 2002

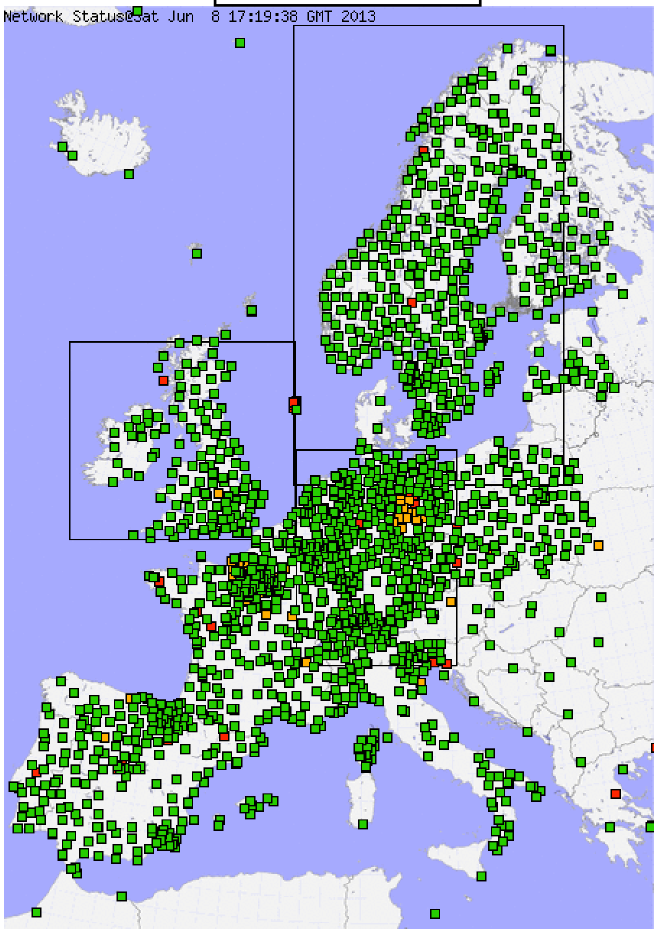



March 2004

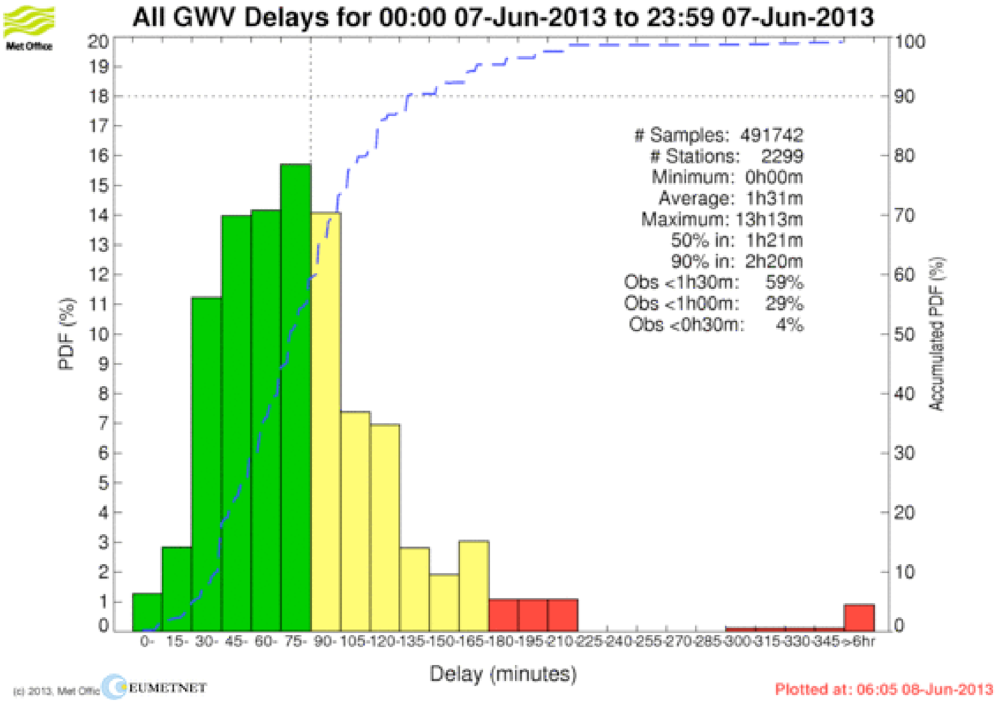


# Present GNSS/GPS network within E-GVAP (EUMETNET)

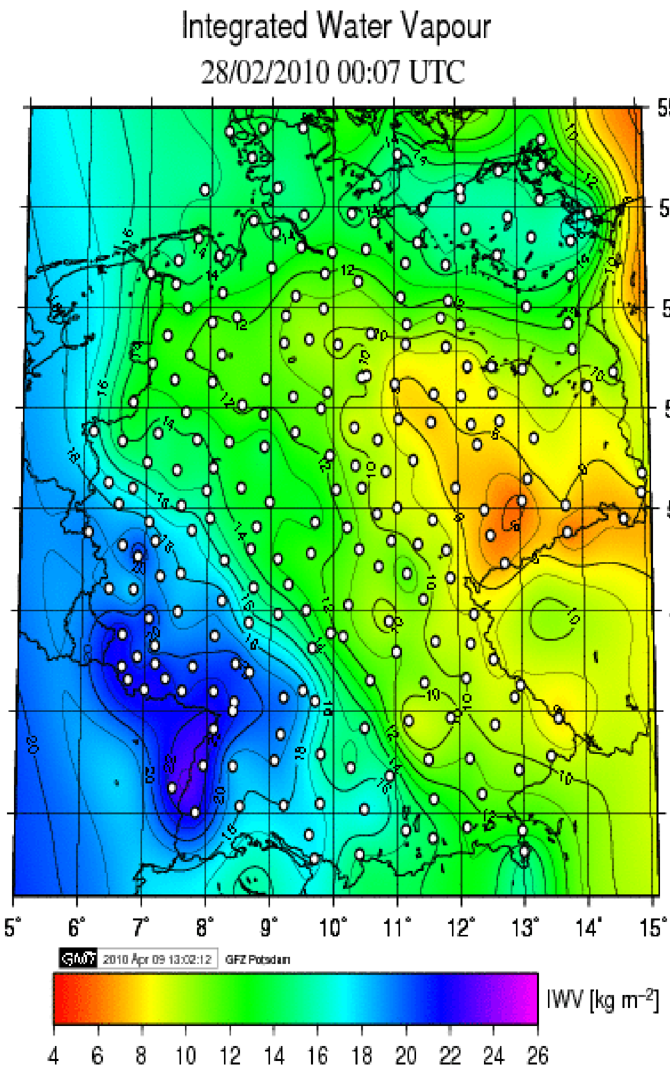
June 2013




(from http://egvap.dmi.dk/).



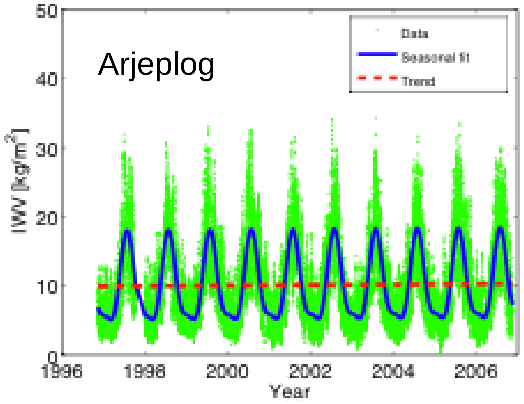
# Example of estimated IWV over Germany

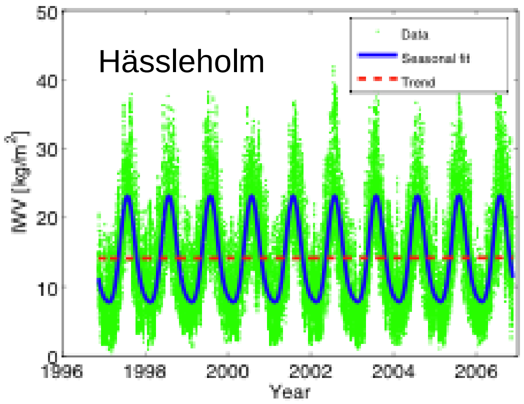



- GFZ (Potsdam) derives the IWV from a network consisting of more than 300 GNSS stations.
- Results available within one hour to European weather services
- Main usage in regional weather forecasts, especially the precipitation forecast.

(from Jens Wickert, GFZ)

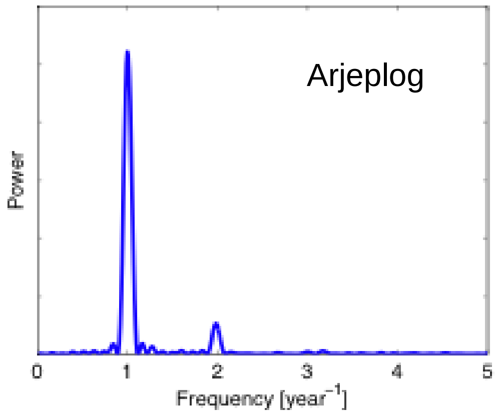
# Estimating IWV trends from ten years of GPS data

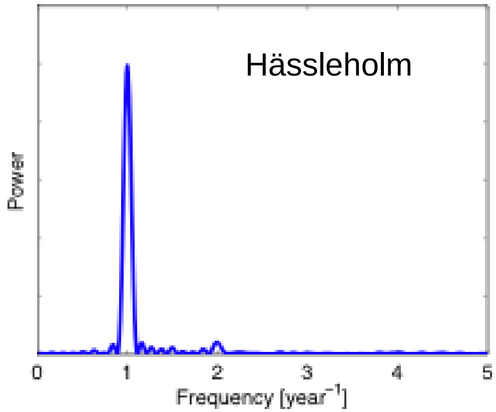



Both annual and semi-annual terms are used to describe the seasonal variations.

This is motivated from the Lomb-Scargle periodograms:



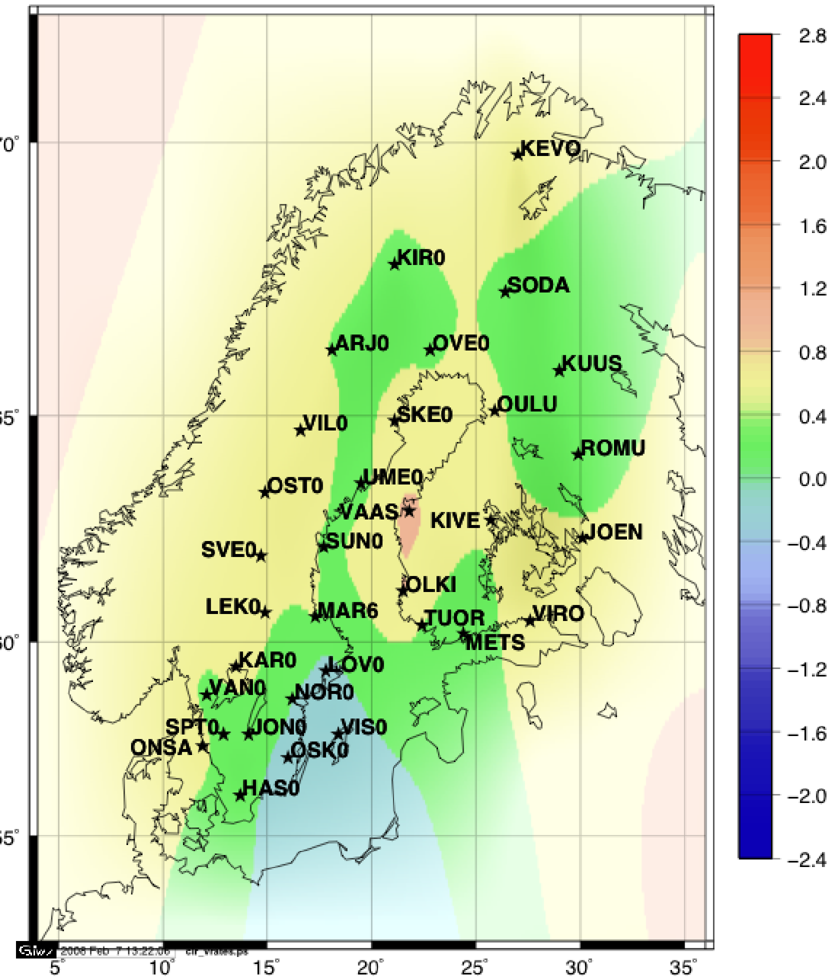




The IWV data are fitted to the model:

$$IWV = I_0 + At + B\sin(2\pi t) + C\cos(2\pi t) + D\sin(4\pi t) + E\cos(4\pi t)$$

where $t$ is the time in years and the coefficients $I_0$, $A$, $B$, $C$, $D$, $E$ are estimated.

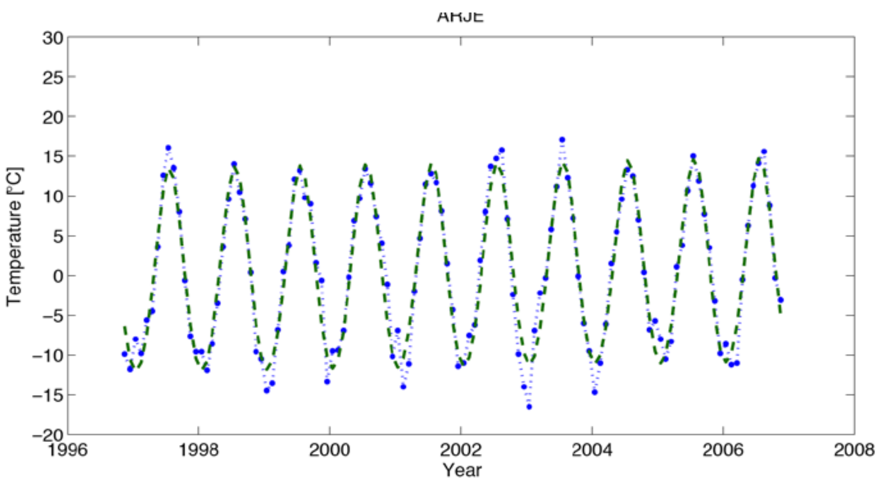
# IWV trends over Sweden and Finland

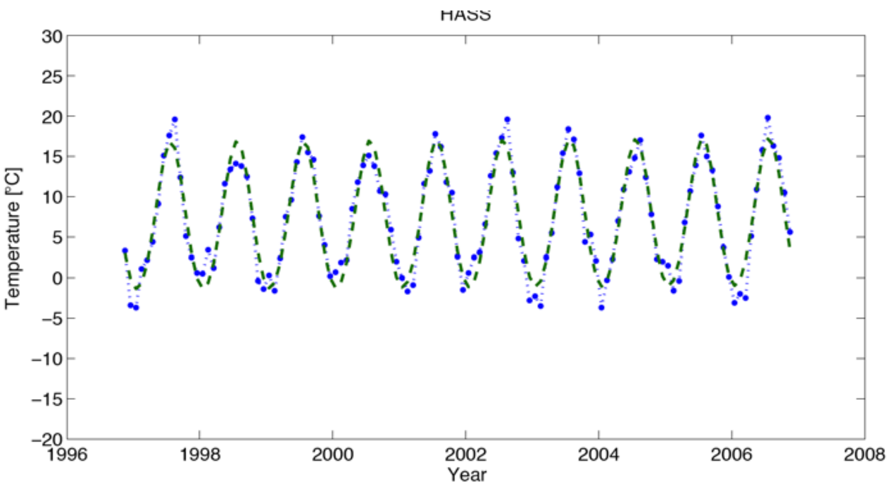



(Nilsson and Elgered, JGR, 2008)

- Analysis period: 10 years, November 16, 1996 – November 15, 2006
- IWV trends varies from –0.5 to +1.5 kg/m$^2$/decade
- Uncertainties in the trends are ~0.4 kg/m$^2$/decade (taking temporal correlations into account)

# Estimating trends in ground temperature from observed monthly means



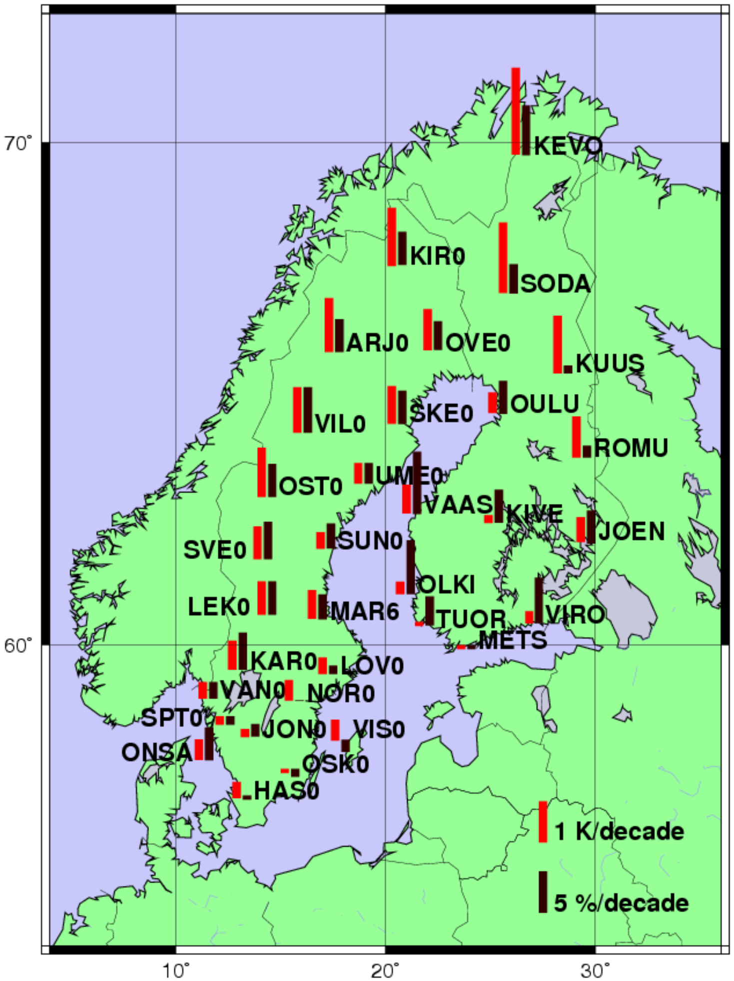



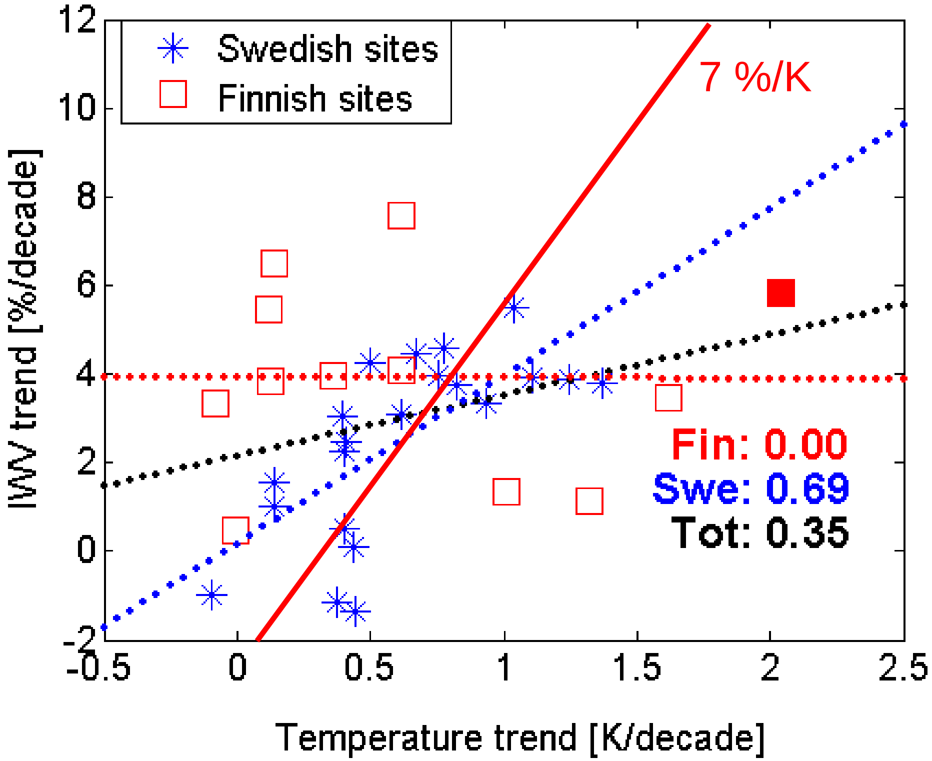

The temperature data are fitted to the same type of model as earlier used for the GPS IWV results:

$$T = T_0 + At + B\sin(2\pi t) + C\cos(2\pi t) + D\sin(4\pi t) + E\cos(4\pi t)$$

where $t$ is the time in years and the coefficients $T_0$, $A$, $B$, $C$, $D$, $E$ are estimated.

# Correlation between trends in ground temperature and IWV 1996–2006

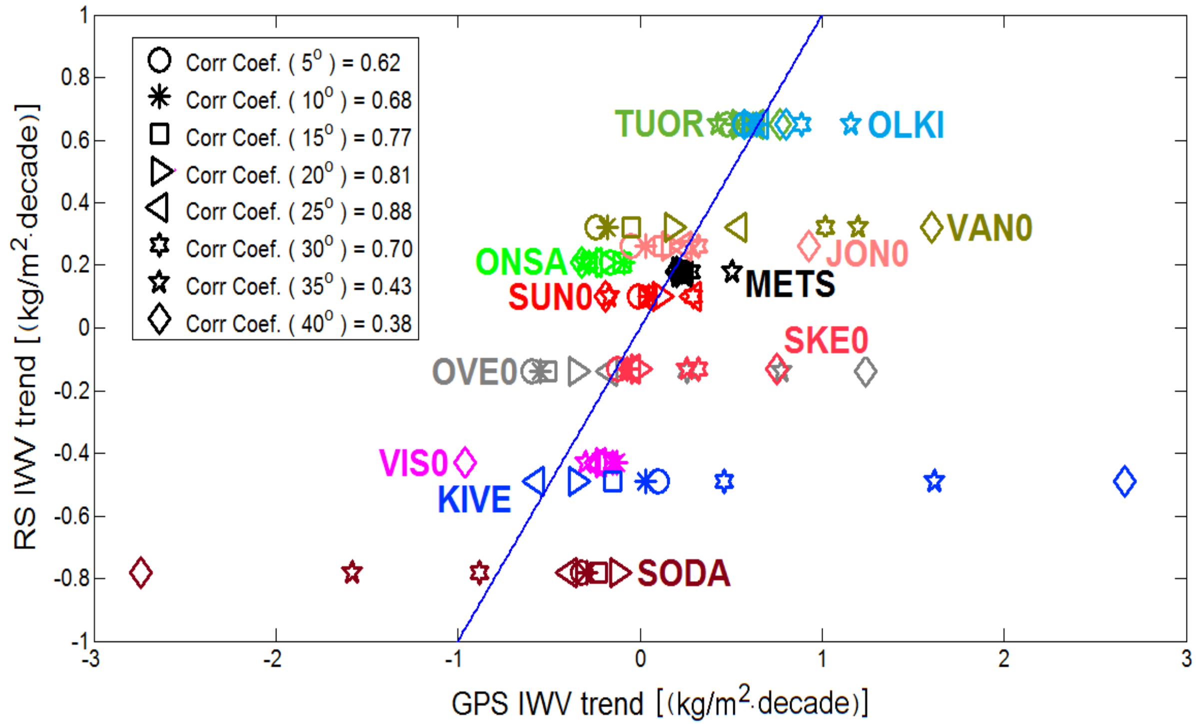



Assuming conservation of relative humidity [Trenberth et al., Bull. Am. Meteorol. Soc., 2003] we obtain for the IWV ~ 7 [%/K].

# IWV trends from radiosondes and GPS

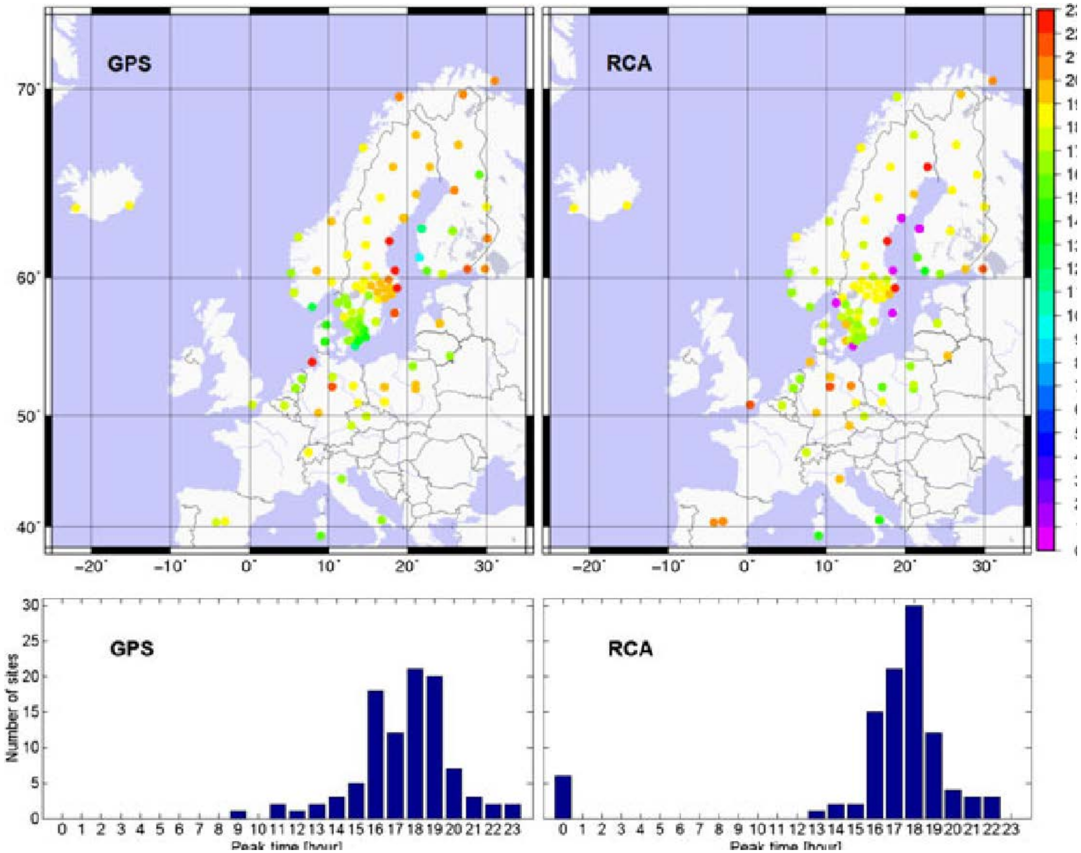
Using 14 years (1997–2011) linear trend of the IWV were estimated for several GPS data sets, each one with a different elevation cutoff angle




The best fit in is seen for the 25° cutoff angle solution (corr. coef. = 0.88)

The best RMS agreement for individual estimates are however obtained for cutoff angles of 10° –15° , depending on the site.

# The phase of the diurnal cycle in the IWV




Averaged over all sites, and 14 summers, a peak at 17 local solar time is obtained from the GPS data while it appears later, at 18, in the Rossby Centre Atmospheric climate model (RCA) simulation.

# Future

COST ES1206:
Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC)

- In total 25 countries signed up so far
- Kickoff in Brussels 17 May 2013
- 1$^{st}$ workshop in October 2013 in Italy?
- End date: 16 May 2017