Retrieval of Atmospheric Moisture from GNSS Signals and its Impact on the Weather Prediction

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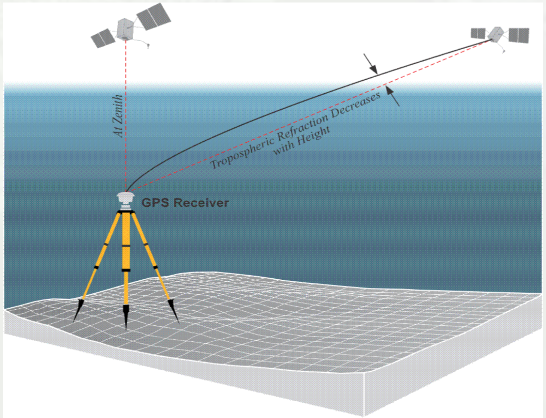
Why is atmospheric moisture or water vapour important ?

- Water vapor is the most important greenhouse gas in the atmosphere.
- Moisture is the source of clouds and precipitation, and an ingredient in most major weather events.
- Moisture fields are under-sampled and largest errors in Numerical Weather Prediction (NWP) come from limitation in our ability to describe moisture variability in time and space.
- Assimilation of moisture improves the weather prediction, particularly extreme weather events.
- Moisture is used as a proxy for convection initiation.

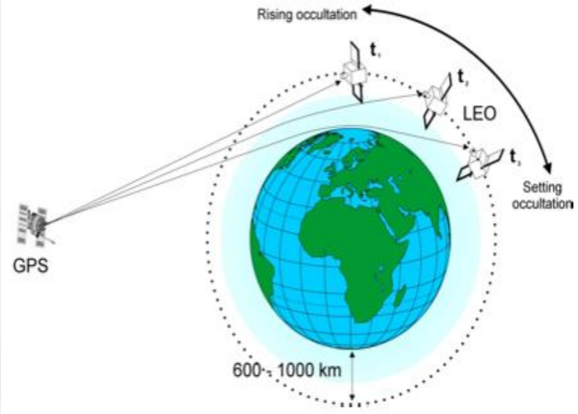
Why ground based GNSS network for atmospheric moisture ?

- Provides moisture under all weather conditions
- Validation of other remote sensing instruments
- Complements satellite IWV which is only available under clear sky.
- Complements space based GNSS meteorology

Ground based GNSS meteorology



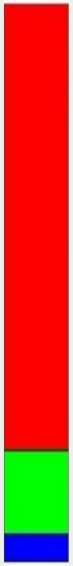
Spaced-based GNSS meteorology

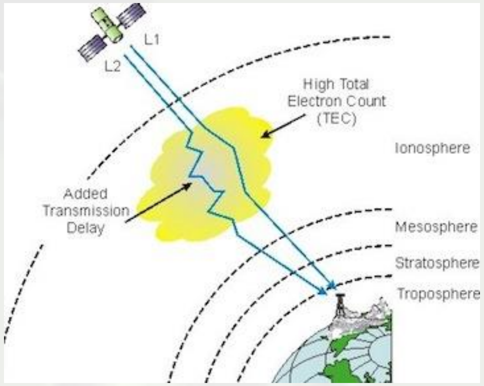


Atmospheric Signal Delay Estimation

Zenith Total Delay (ZTD)

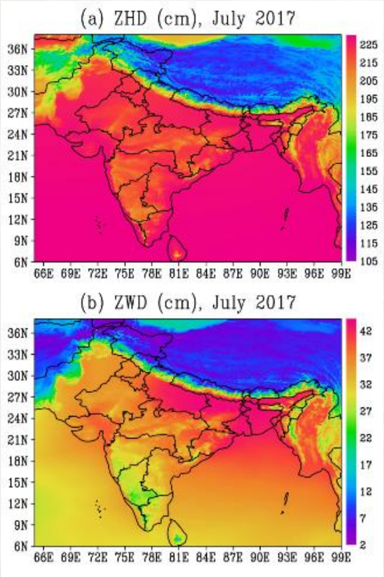
$$ZTD = 10^{-6}\left(\int_{z=za}^{toa}\frac{K_1 P}{T}dz + \int_{z=za}^{toa}\frac{e}{T}\left(K_2 - K_1 + \frac{K_3}{T}\right)dz + \int_{z=za}^{toa}\frac{n}{f^2}dz\right)$$

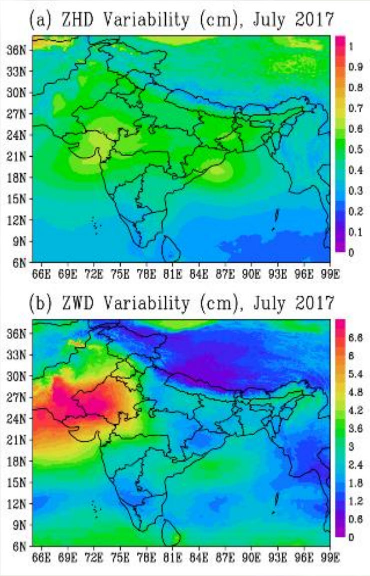


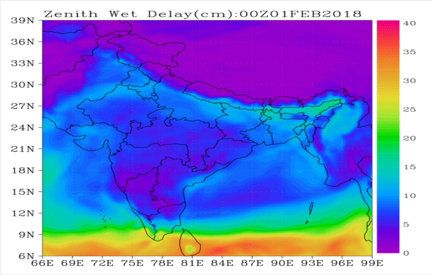


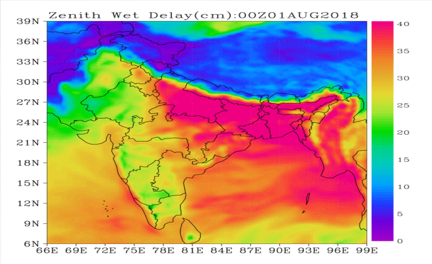
- Zenith Ionospheric Delay (ZID)
- Zenith Hdrostatic Delay (ZHD)
- Zenith Wet Delay (ZWD)

Pressure	-> Pascal
Temperature	- > Kelvin
Vapor pressure	-> Pascal
Humidity	-> kg/kg
Height	-> Meter
ZHD and ZWD	-> Meter









Integrated Water Vapor (IWV)

- Meteorological instrument (for surface pressure (Psfc) and temperature (Tsfc)) collocated with GNSS receiver is required for IWV estimation.

$$\mathrm{ZHD} = \frac{2.2768 \times \mathrm{Psfc}}{1 - 0.00266 \times \cos(2\varphi) - 0.00028 \times \mathrm{H}}$$

$$ZWD = ZTD - ZHD$$

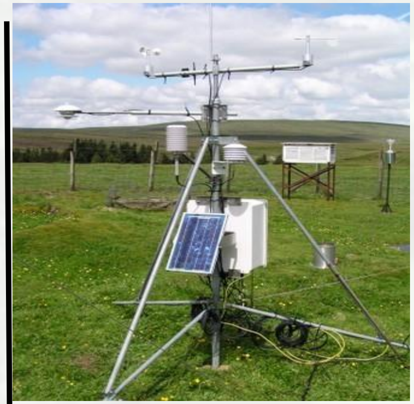
$$IWV = f(T_m) \times ZWD$$

$$f(T_m) = \frac{10^5}{461 \times \left[\left(\frac{3.776 \times 10^5}{T_m}\right) + 17\right]}$$

$$T_m = 70.2 + 0.72 \times T_{sfc}$$

$$T_m = \frac{\int \frac{e}{T} dz}{\int \frac{e}{T^2} dz}$$

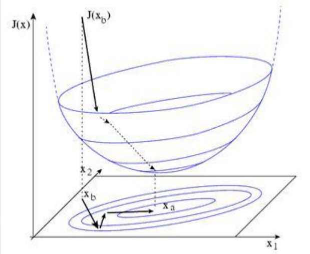
Meteorological Instrument



GNSS Receiver

Retrieval of Atmospheric Moisture Profiles from GNSS Signals

One-Dimensional Variational Retrieval (1D-Var)



Unknown (to be Retrieved)

Error in First Guess

Observation error

$$J(x) = \frac{1}{2}(x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}\left\{[y - H(x)]^T R^{-1}[y - H(x)]\right\}$$

First Guess profiles
(6h/12 h NWP model forecast)

Observed Tropospheric Delay

Observation Operator/Forward Model

$$H(x) = \left(\int_{z=za}^{toa} \frac{K_1 P}{T} dz + \int_{z=za}^{toa} \frac{e}{T}\left(K_2 - K_1 + \frac{K_3}{T}\right) dz \right)$$

The Error Covariance Matrix (B)

$$n = number\ of\ vertical\ levels\ \times number\ of\ variables$$

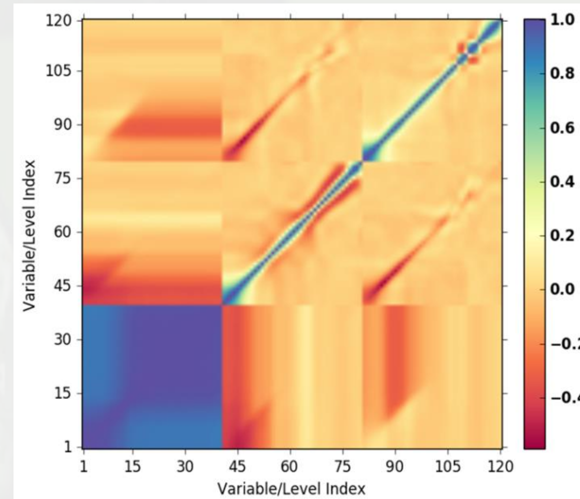
$$n = 40 \times 3$$

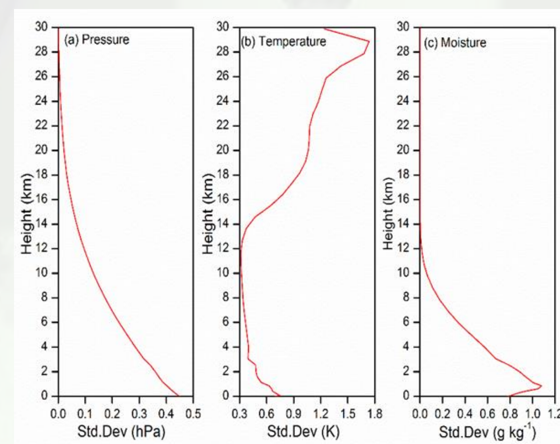
$$\varepsilon^T = (e_1\ e_2\ e_3\ .\ \ .\ \ .\ \ .\ \ .\ e_n)$$

$$< e_i e_i > = \sigma_i^2$$

$$\varepsilon = \begin{pmatrix} e_1 \\ e_2 \\ e_3 \\ . \\ . \\ . \\ . \\ . \\ e_n \end{pmatrix}$$

$$B = <\varepsilon\varepsilon^T> = \begin{pmatrix} <e_1e_1> & <e_1e_2> & . \ . \ . & <e_1e_n> \\ <e_2e_1> & <e_2e_2> & . \ . \ . & <e_2e_n> \\ . & . & . \ . \ . & . \\ . & . & . \ . \ . & . \\ . & . & . \ . \ . & . \\ <e_ne_1> & <e_ne_2> & . \ . \ . & <e_ne_n> \end{pmatrix}$$

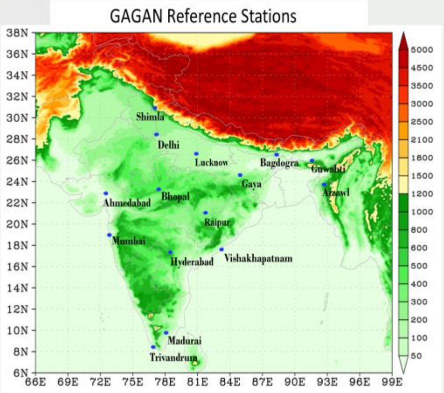




GNSS Datasets

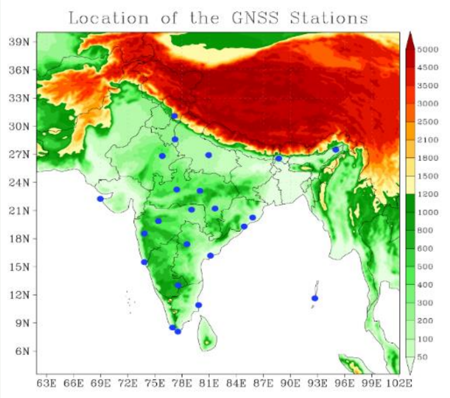
GAGAN Data

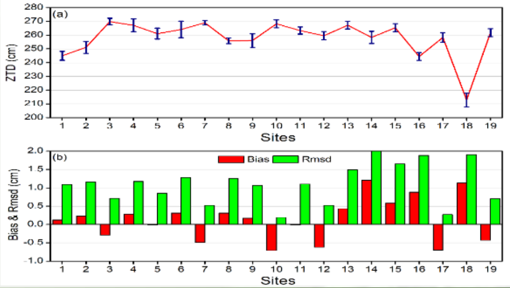
- RINEX files (Phase and code measurements, Courtesy Rajat Acharya)
- Ephemeris and clock products (https://cddis.nasa.gov)
- Period: July 2017 , Locations: 12
- GAMIT version 10.7 software (Herring et. al., 2010; http://geoweb.mit.edu/gg/)

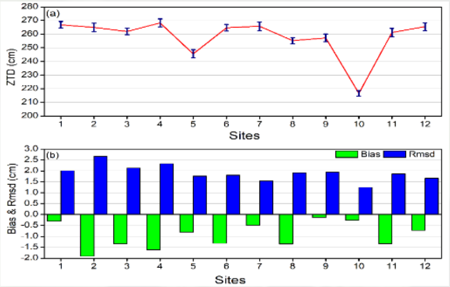


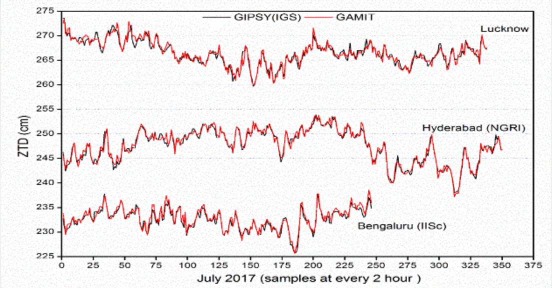
IMD Data

- RINEX files (Phase and code measurements, IMD
- Ephemeris and clock products (https://cddis.nasa.gov)
- Period: July 2017 , Locations: 19
- GAMIT version 10.7 software (Herring et. al., 2010; http://geoweb.mit.edu/gg/)





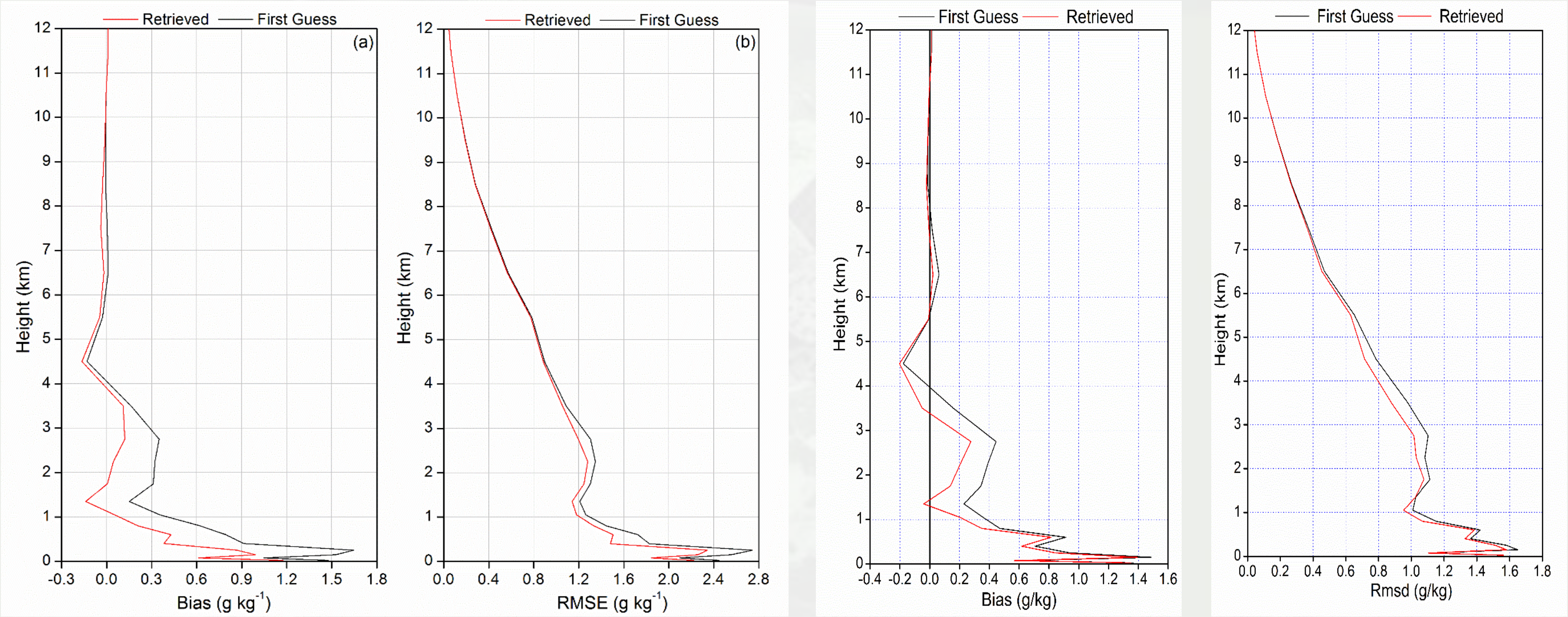




Performance of moisture retrieval algorithm

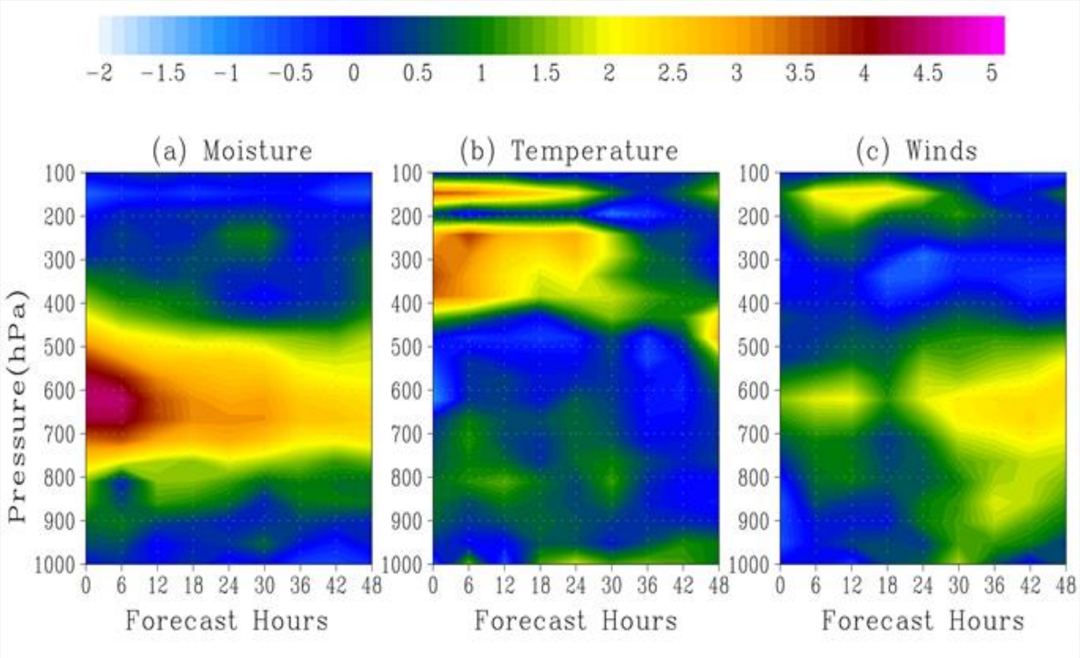
GNSS/IMD Network

GAGAN's Network



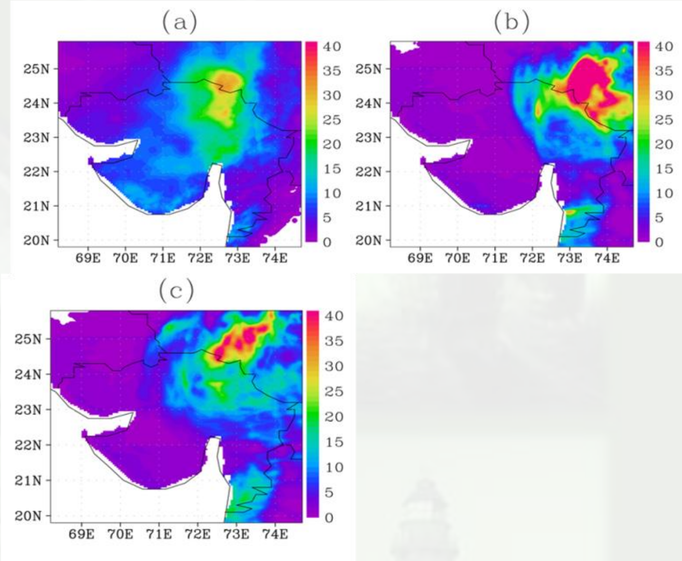
Vertical profiles of bias and root mean square error (RMSE) of radiosonde observed minus first guess and GNSS based moisture retrieval. Statistics is based on ~ 8000 to 1000 profiles over the Indian region.

Impact of GNSS derived moisture information on weather prediction



Relative improvement parameter (RIP) of (a) specific humidity, (b) temperature, and (c) vector wind as a function of forecast range and pressure. A set of 31 forecasts from CNTL and GNSS is compared with ECMWF analysis.

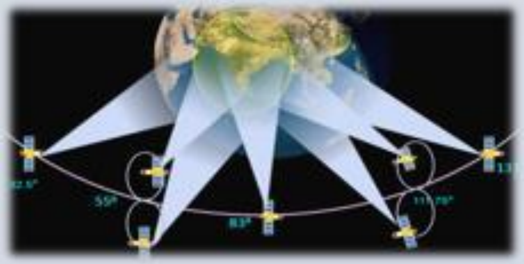
Gujarat Heavy Rainfall



Rainfall accumulated for whole event (23 to 25 July 2017), (a) CHIRPS observed, (b) CNTL 24h predicted rainfall, (c) GNSS 24h predicted rainfall

Conclusions

- 1D-Var Retrieval algorithm has been developed to retrieve the vertical profiles of humidity from GNSS signal delay.
- When compared to the first guess profiles, the retrieved profiles have improved by as large as 20%, particularly lower tropospheric moisture fields.
- Developed algorithm is not restricted to GPS ZTD but also applicable to NavIC derived ZTD.
- GNSS ZTD data has a good potential for improving the weather prediction and advocates the strengthening of the ground-based GNSS network over the Indian region, which is currently very sparse.



Thank You