Applications of GPS in Meteorology

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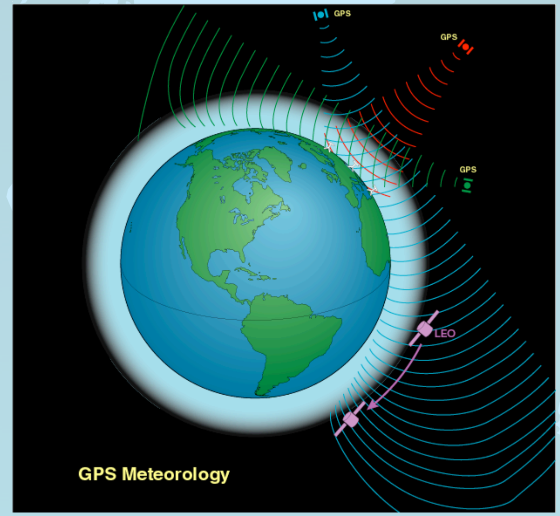
CGSIC Regional Meeting
Honolulu, Hawaii, June 23 – 24, 2009

OUTLINE

- Brief Review of GPS Meteorology
- Space-Based GPS Meteorology (COSMIC)
  - Atmospheric profiles
- Earth-Based GPS Meteorology
  - Integrated Precipitable Water Vapor (IPV)



One Person's Noise is Another's Signal

- GPS signals are slowed and refracted as they pass through the Earth's atmosphere.
- Measurement of the bending angle produced by atmospheric refraction provides the observable that is the basis of space-based GPS meteorology.
- Resolving the delay of GPS signals by the atmosphere using the most accurate geodetic receivers provides the observable that is the basis for ground-based GPS meteorology.
- Water vapor's permanent dipole moment provides a unique delay in the GPS signal that can be isolated.

Overview of GPS Meteorology

GPS Meteorology

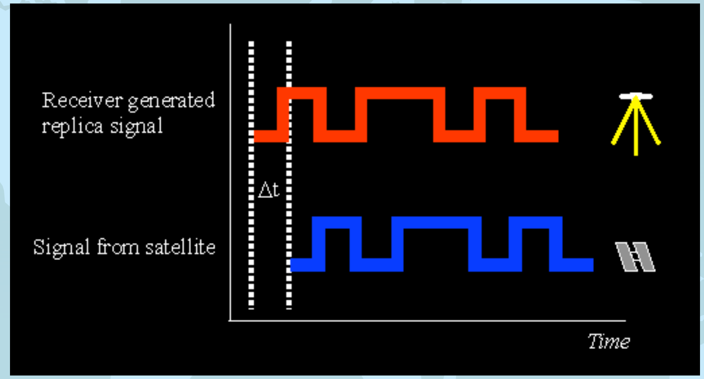
- **Ground Based** — Measures signal delay from fixed point on ground.
  - **Integrated Precipitable Water Vapor**
    - Gives total precipitable water vapor directly above site
  - **Slant-Path Signal Delay**
    - Gives line-of-sight signal delay to each satellite in view
- **Space-Based Occultation** — Measures bending angle from Low Earth Orbit (LEO) satellites with near-global coverage
  - Provides profiles of integrated refractive index (~ 1km x 300km)

One Person's Noise is Another's Signal

GPS Observables

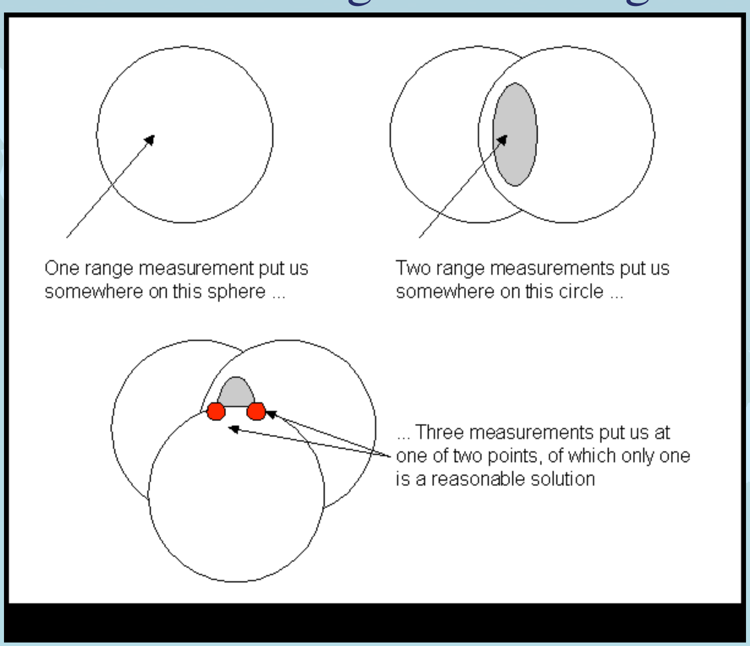
- PSEUDO-RANGE
  - Based on signal travel time from satellite to receiver
  - Accuracy: meters
- CARRIER PHASE
  - Compares phases from incoming signals
  - Accuracy: millimeters to centimeters

PseudoRange

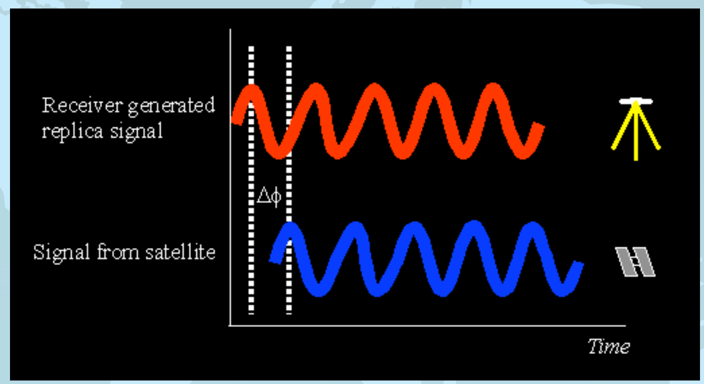


- $\Delta t * c = R$ (range from satellite)
- Low resolution measurement (1-10s of m)
- Unknown receiver (and satellite) clock offset

Pseudorange Positioning



Carrier Phase



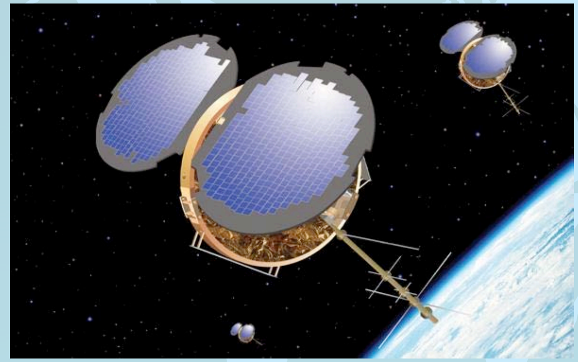
- $\Delta\Phi$ gives high-resolution differential range (sub-mm)
- Unknown number of total integer phase cycles - must be estimated

GPS Positioning Environmental Error Sources

- Ionospheric Delay
  - Mitigated by dual-frequencies
- Multipath
  - Mitigated by choke-ring antenna
- Solar activity
  - Mitigated by higher power signal/signal-tracking
- Troposphere
  - Basis for GPS meteorology

The COSMIC System

Constellation Observing System for Meteorology Ionosphere and Climate

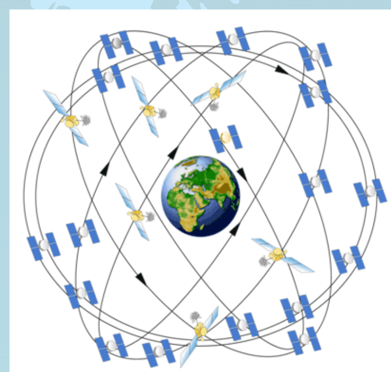


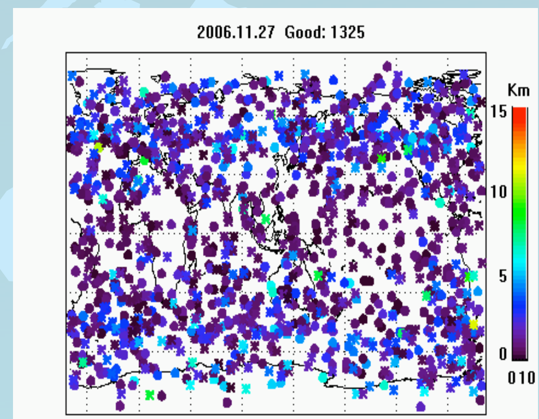
Six Low-Earth Orbit (LEO) micro satellites were launched on one rocket on 15 April 2006.

COSMIC System

- Three instruments: GPS receiver, TIP (tiny ionospheric photometer), Tri-band beacon
- Global observations of
  - Refractivity
  - Pressure, Temperature, Humidity
  - Ionospheric Electron Density
  - Ionospheric Scintillation
- Operational GPS limb sounding with global coverage in near-real time
- Climate Monitoring

FORMOSAT-3/COSMIC Daily Soundings

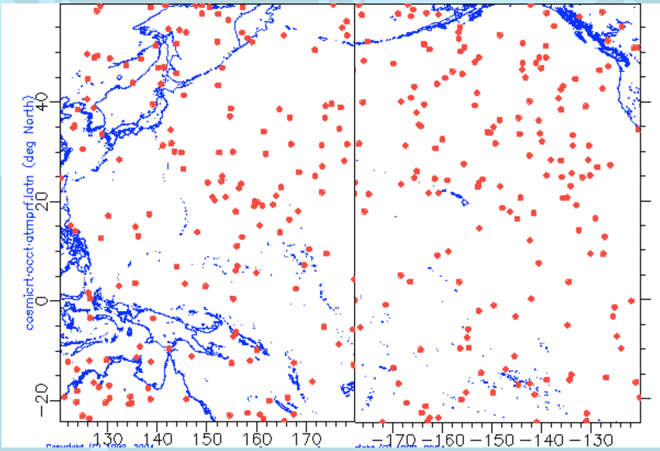




Distribution of occultation events observed by FORMOSAT-3

Color represents lowest height of vertical sounding profiles

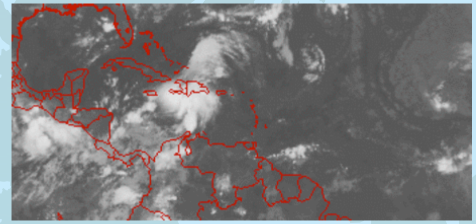
One-Day of COSMIC Soundings



January 29, 2007

Impact of COSMIC on Forecast of Hurricane Ernesto (2006)

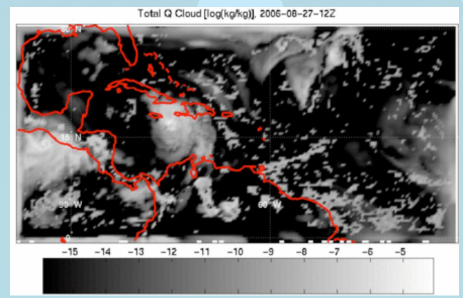
Sat. IR

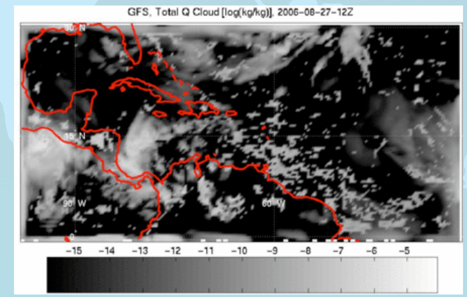


GPS all

2006-08-27-12Z (102h forecast)

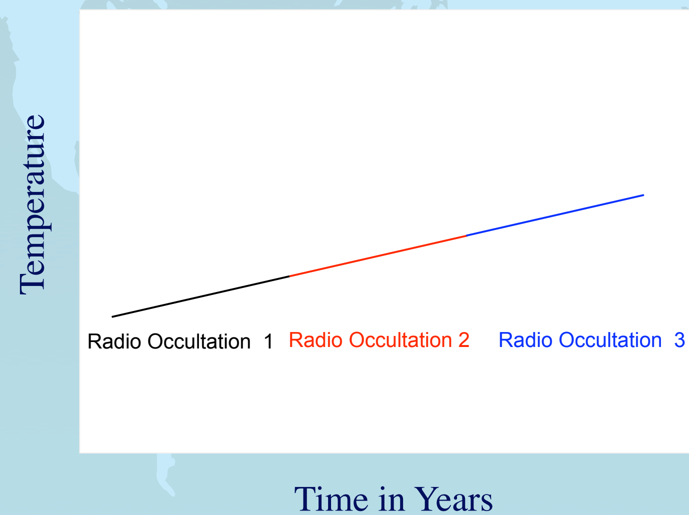
No GPS





Past Satellite Climate Missions Offsets between missions and Temperature Drift

GPS Satellite Climate Missions No offset between missions and Temperature Drift



COSMIC Summary and Conclusions

- First constellation of microsatellites to observe Earth atmosphere and ionosphere
- New cost effective paradigm for making observations of Earth atmosphere from space
- First demonstration of radio occultation soundings of pressure, temperature, and water vapor, with global coverage in near real time — for testing in weather models
- Unprecedented capability to measure atmospheric structure from 25 miles to surface in all weather (sees through clouds)

COSMIC Summary and Conclusions

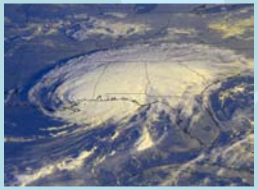
- World's most accurate, precise and stable thermometer for climate monitoring
- First satellite system to observe Earth's boundary layer (lowest mile of atmosphere above ground; important for weather forecasting and climate research)
- First global observations of ionospheric electron density in near real time – for monitoring space weather
- International cooperation; free and open sharing of data for benefit of all the world's people

Earth-Based GPS Met

Earth-based GPS Meteorolgy

- Special Role of Water Vapor
- National GPS IPW Network
- Some GPS-IPW applications

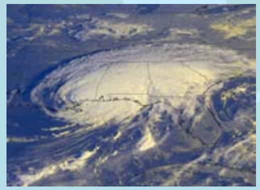




Role of Water Vapor in Weather

- The distribution of water vapor is highly variable and is not dynamically linked with temperature and pressure.
- Very large latent heat is released with condensation and deposition with immediate dynamic impact.
- Water vapor is under observed in time and space, especially during active weather when the information is needed most.



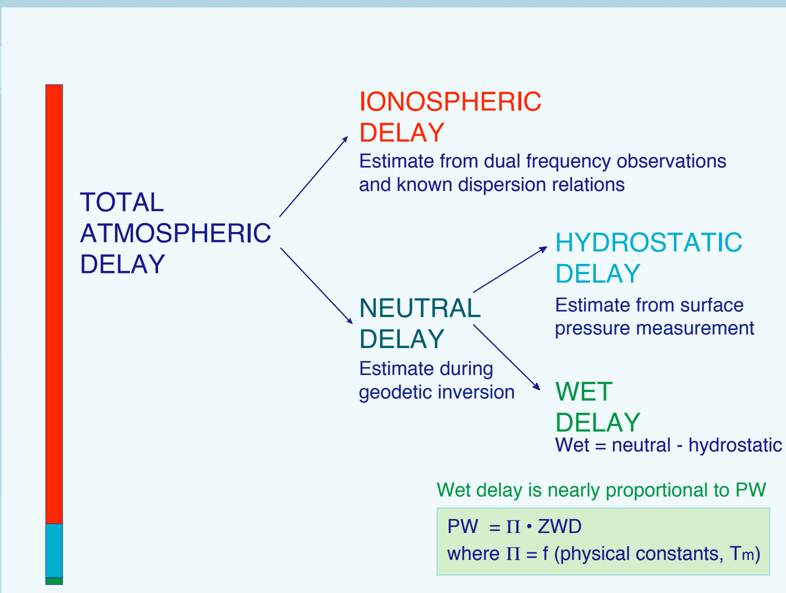


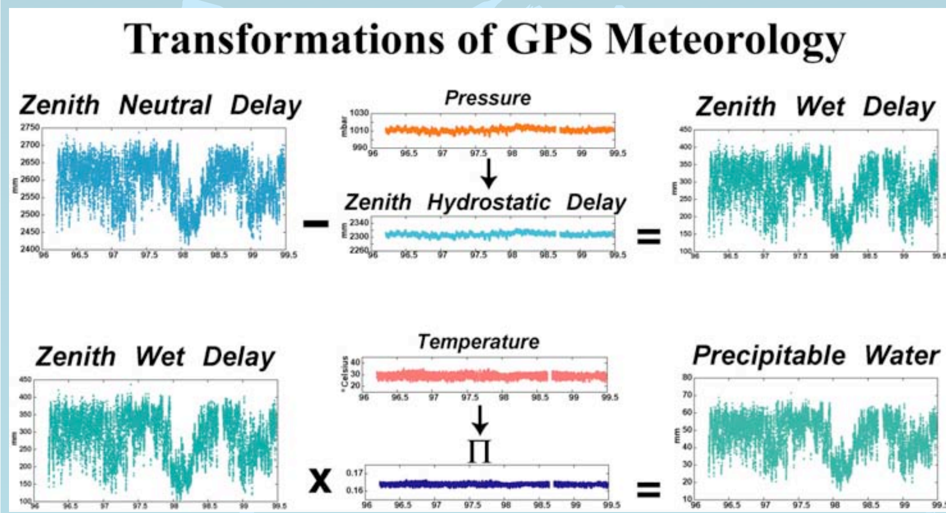
Role of Water Vapor in Climate

- It is the most plentiful greenhouse gas.
- Effects the formation of clouds, aerosols, atmospheric electricity, and the chemistry of the lower atmosphere.
- In turn, clouds absorb and reflect energy from the sun.
- Multi-year climate changes are linked to large changes in SST and water vapor in the tropical Pacific associated with the El Niño-Southern Oscillation.

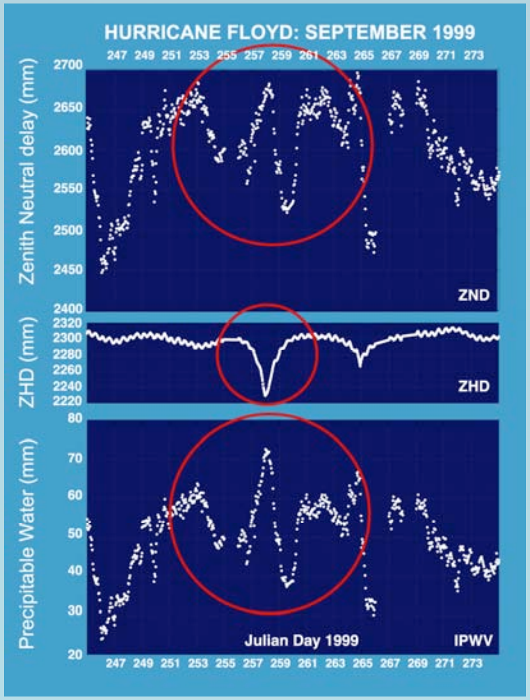


Structure of the GPS signal delay





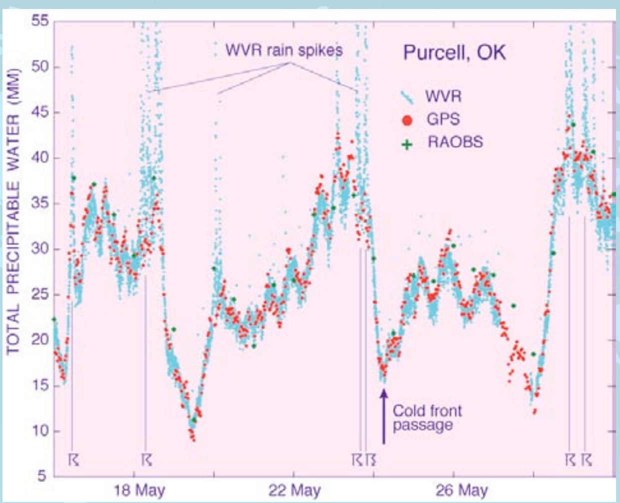
IMPACT OF HYDROSTATIC DELAY



GPS IPW APPLICATIONS USING TIME-SERIES DATA

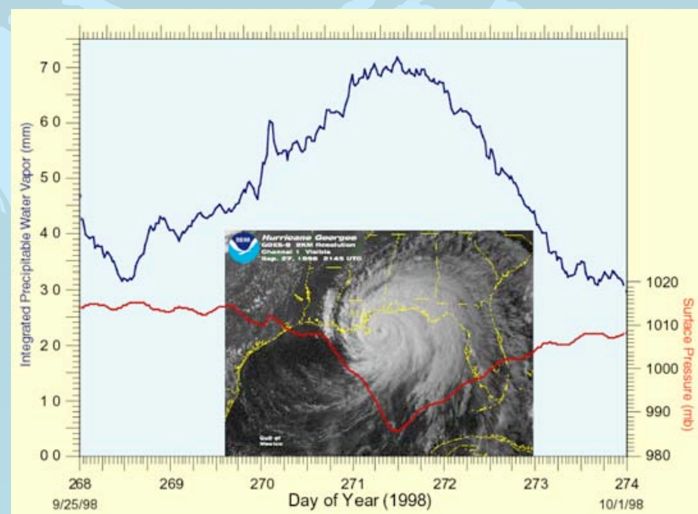
- Numerical Weather Prediction
- Predict Lightning
- Predict Flash Flooding
- Predict Fog Formation
- Calibrate Satellite IPW Algorithms

GPS IPWV TIME SERIES

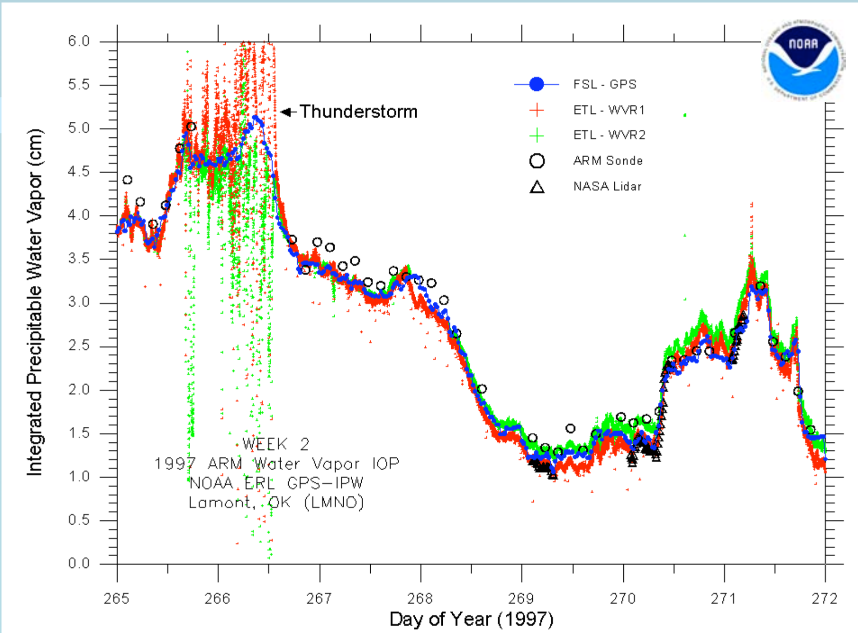


Integrated precipitable water vapor at Purcell, Oklahoma from 16 to 30 May 1993.

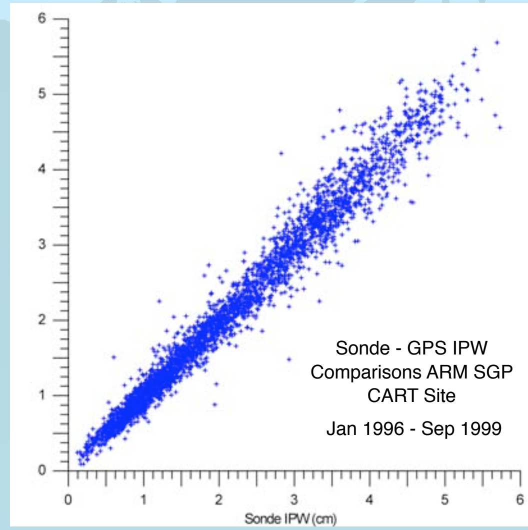
GPS IPWV TIME SERIES



Hurricane Georges, September 1998



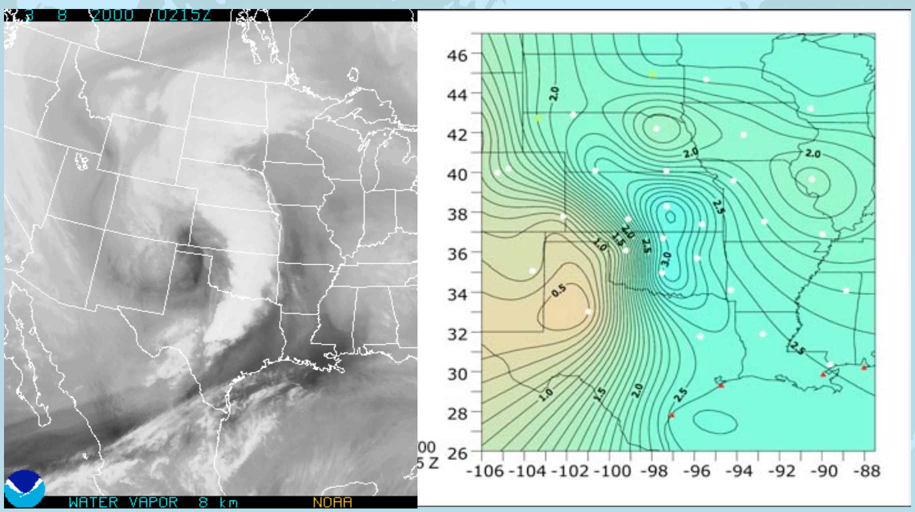
Long-Term Comparison of GPS and Rawinsondes



	1996	1997	1998	1999	1996 - 1999
N	= 1382	= 813	= 771	= 551	= 3600
Mean Dif.	= 0.0346 cm	= 0.0501 cm	= -0.0431 cm	= -0.0460 cm	= 0.0080 cm
Std. Dev.	= 0.1977 cm	= 0.1965 cm	= 0.2308 cm	= 0.2070 cm	= 0.2102 cm
Corr.	= 0.9886	= 0.9874	= 0.9817	= 0.9851	= 0.9854

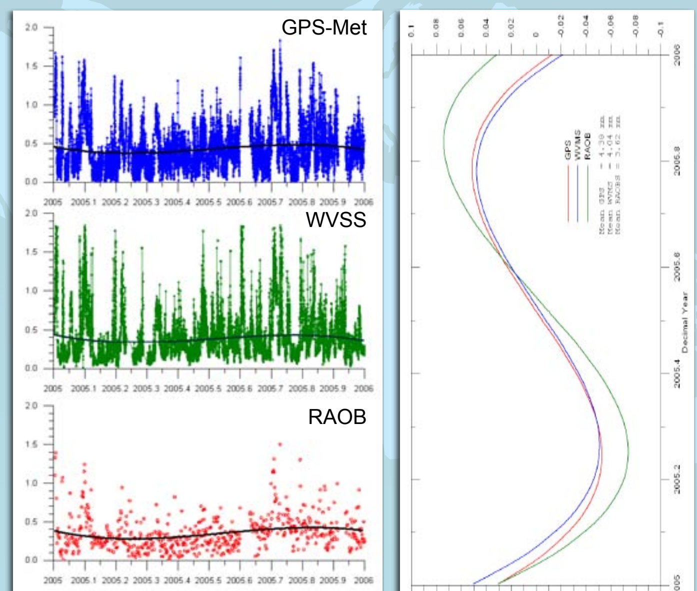
Equation of best fit line
Y = 0.9876125443 * X + 0.01837114798

Strong spatial moisture gradients across a dryline resolved by GPS in an



8 March 2000

Middle-upper tropospheric water vapor at Mauna Loa observatory in 2005 suggests GPS role in climate monitoring

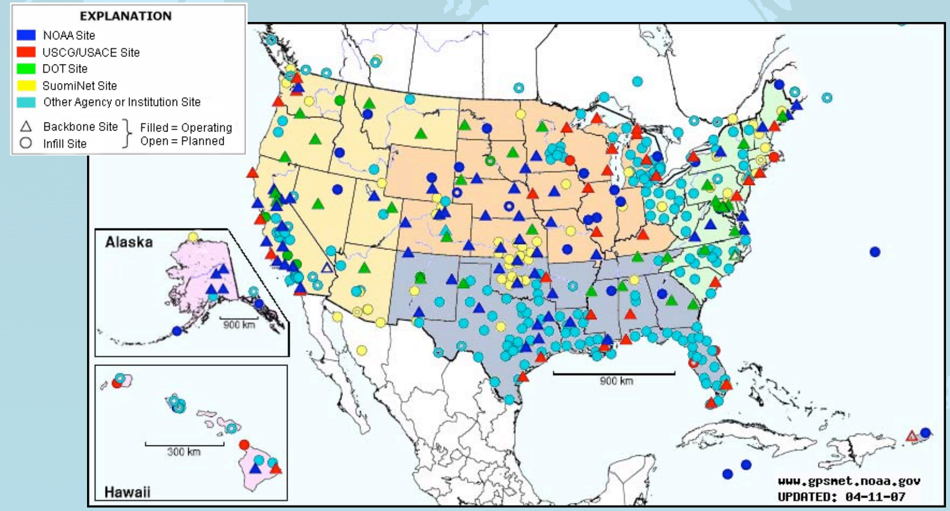


National GPS IPWV Network

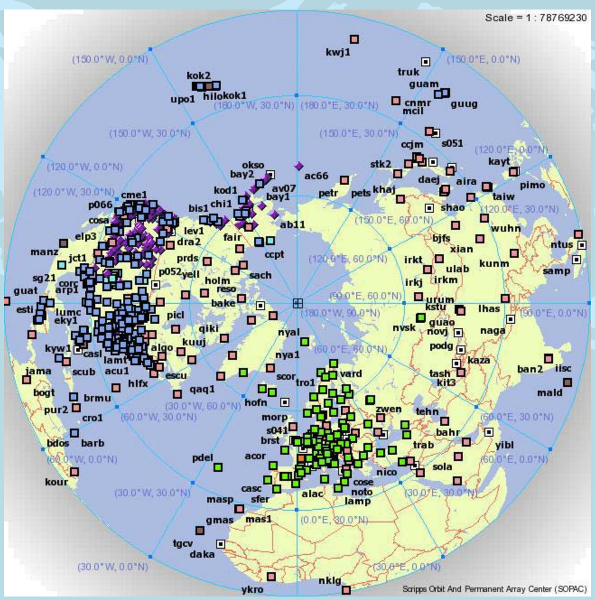
Motivation

- Improve precipitation and severe weather forecasts
  - Improved transportation safety depends on accurate weather forecasts
  - Our ability to produce accurate forecasts is compromised by the lack of timely and accurate observations of the atmospheric water vapor distribution.

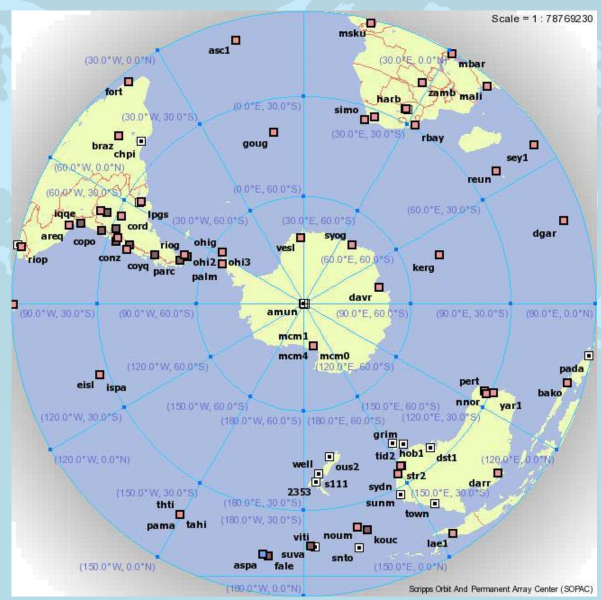
Current Configuration of the NOAA GPS Water Vapor Network



Global GPS Water Vapor Networks



Global GPS Water Vapor Networks



GSOS Surface Met Sensors

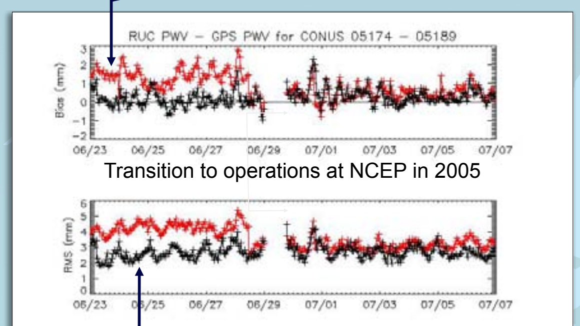
Typical GPS Water Vapor Network Sites

NOAA Wind Profiler Sites, Platteville, CO (PLTC)

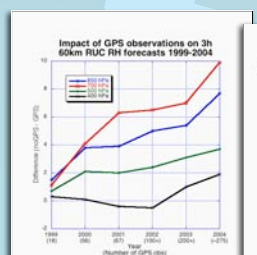
Other NOAA Sites Blacksburg, VA WFO (BLKV)

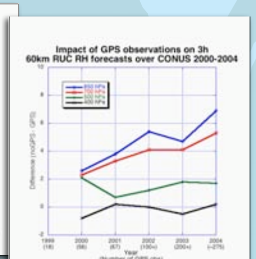
USCG and FHWA NDGPS Sites Clark, SD (CLK1)

Operational RUC



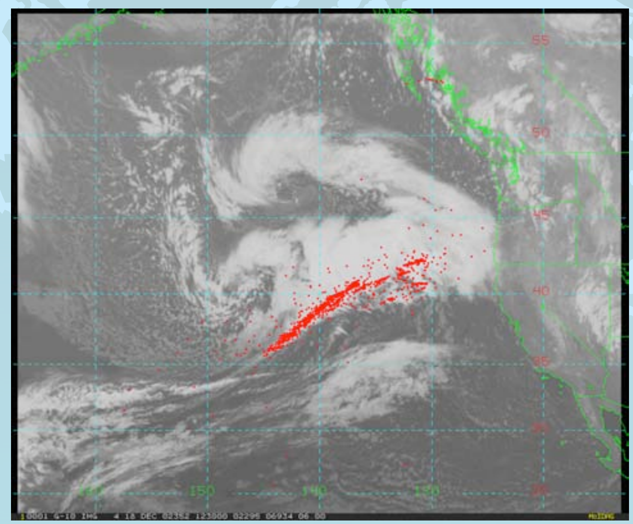
Research RUC





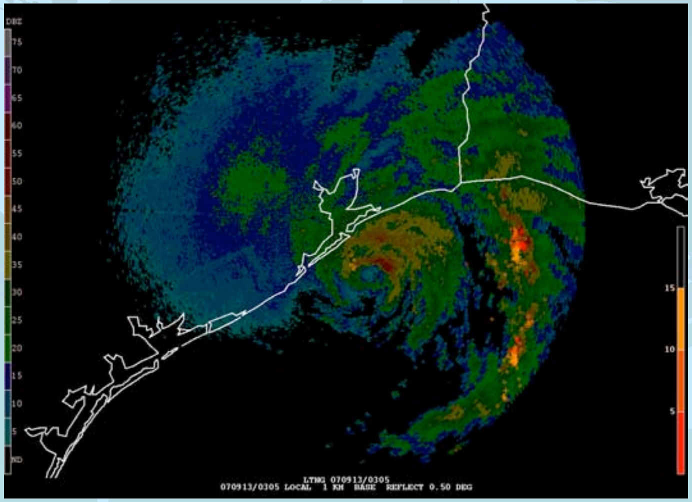
- Hourly assimilation of GPS into RUC, especially at asynoptic times, reduces model moisture bias; error by ~ 50%.
- 10% improvement in 3h RH forecasts below 500 hPa in Midwest (lower left); 6% over entire CONUS (lower right).
- Significant improvements in 3h CAPE forecast and skill scores (ETS) for heavy precipitation events are also observed.

Long-Range Lightning Detection Made possible by GPS



Northeast Pacific Winter Storm 18-20 December 2002

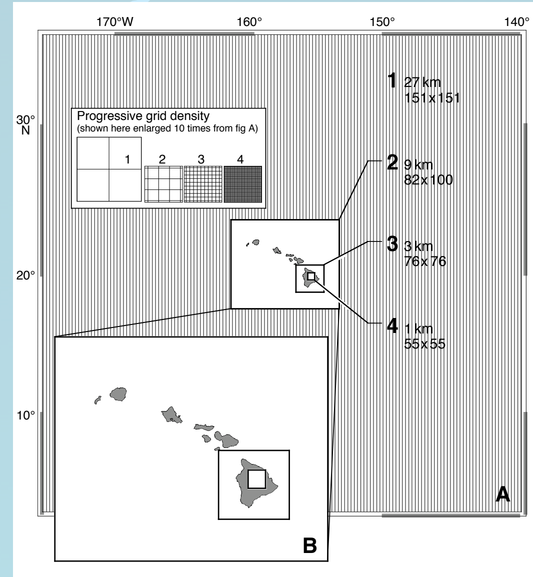
Applications – Hurricanes



Hurricane Humberto – September 2007

Improving Weather Models

1. Collect Observations
2. Divide data onto a map.
3. Apply laws of air motion.
4. Visualize model predictions on forecast maps.



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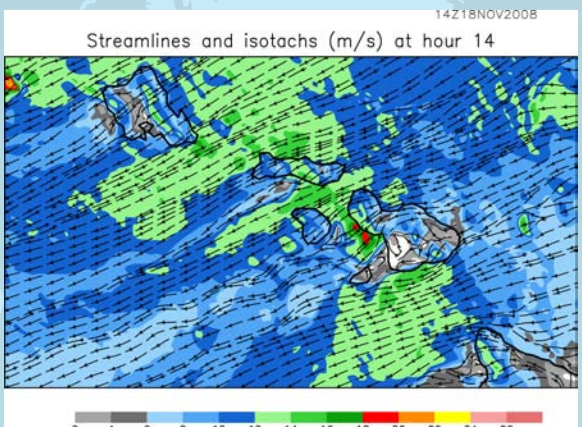
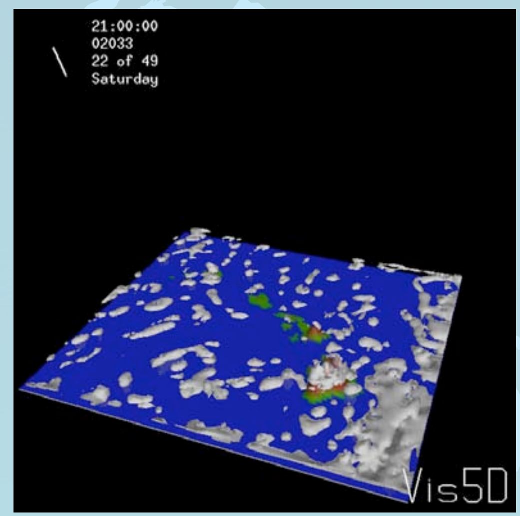


Computer Model of Hawai'i's Atmosphere

A high resolution model of the atmosphere can simulate the impact of the Big Island on the wind field.

GPS Met data improves these forecasts.

Custom forecasts available for Hawaii at: http://weather.hawaii.edu



SUMMARY/CONCLUSIONS

- Ground-based GPS improves forecast accuracy, especially under conditions of active weather when it is most needed.
- The use of GPS for weather forecasting enhances the value of federal (DoT, DoD, and NOAA) programs at little or no additional cost. By leveraging the federal investment in GPS, an IPW observing system can expand quickly, at low cost and risk.
- As observation density increases, assimilation of slant path data may provide 3-D distribution of water vapor.
- Many research opportunities exist for use of time series IPW data to develop tools for forecast guidance.