Estimating Transient Water Storage from Hurricane Harvey using GPS observations of Vertical & Horizontal Land Motion

Chris Milliner, JPL – NPP Postdoc

Materna, K., UC Berkeley
Burgmann, R., UC Berkeley
Fu, Y., Bowling Green
Bekaert, D., JPL
Moore, A., JPL
Adhikari, S., JPL
Argus, D., JPL

Introduction

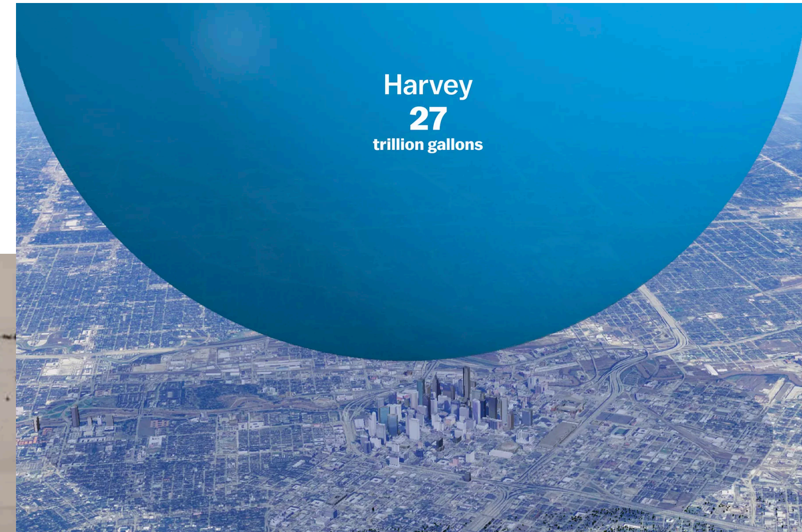
- **Question**: How does water accumulate and dissipate following a major hurricane? Can we measure this using GPS data?

- **Method**: Use cGPS data to measure Earth's deformation from water mass, this can be used to track the evolution of TWS
  - TWS = standing surface water, ground water + absorbed in soil.

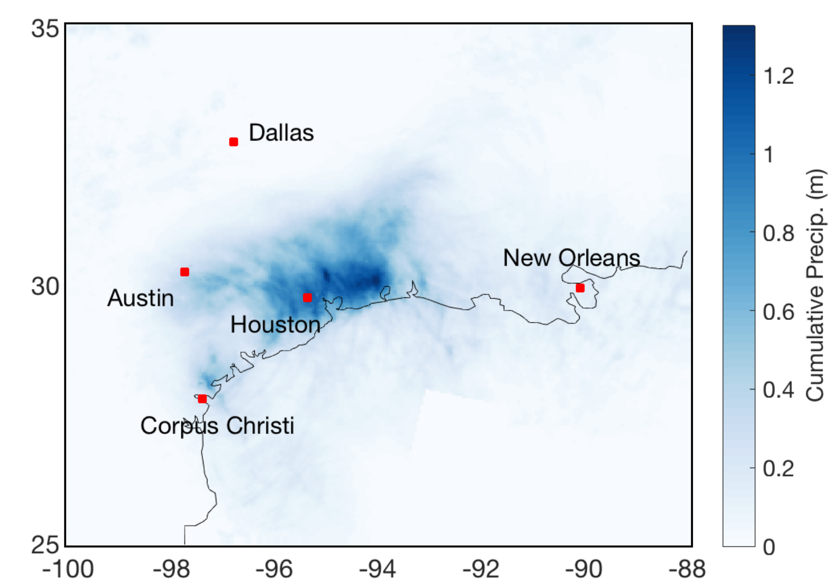
- **Motivation:** Quantifying TWS important for:
  - **Understanding**: ability of drainage systems to respond and retain extreme influxes of water.
  - **Applications**: Stored water poses a secondary and **continued flood hazard**, once released into nearby streams. Observations of water storage could potentially improve **operational flood forecasting** used by flood managers.

Background

- Cat 4 event – hit US mainland August 26th, lasted 7 days
- Stalled in southern Texas, → retreated → Louisiana → Ms, Tn
- Wettest recorded US hurricane
  - Total rainfall: ~102 km^3
  - ~1.54 m of cumulative rain recorded east of Houston.



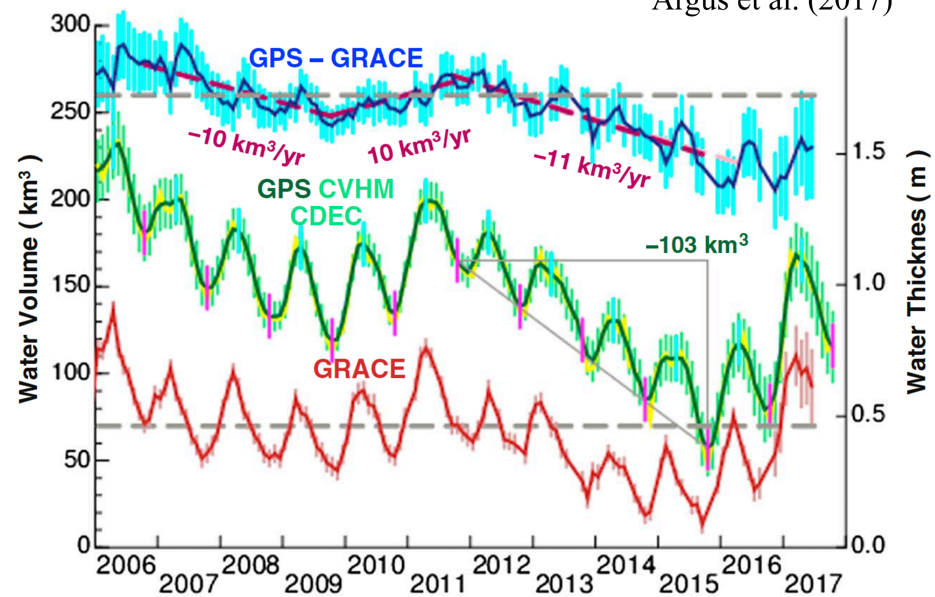
https://www.vox.com/science-and-health/2017/8/28/16217626/harvey-houston-flood-water-visualized



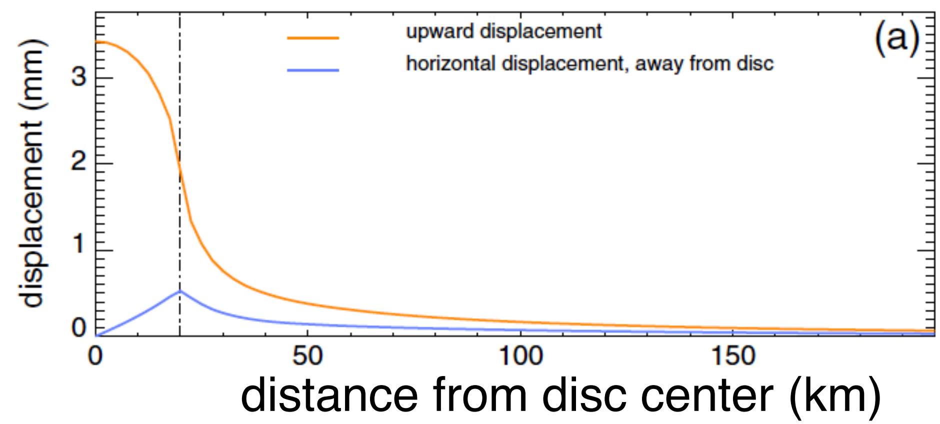
Outline

- Hydrologic loading primarily causes vertical surface motion
- **Challenge**: Noise level of vertical GPS is relatively high (~3 mm).
  - Usually we average over large areas (regional-continental)
  - Long timescales (months-seasons) to characterize loading.
- Is the stability of GPS positioning sufficient to resolve Harvey's transient loading signature?

Argus et al. (2017)



Earth's elastic response to unloading water disk 20 km diameter and 1 m thickness



Wahr et al. (2013)

GPS Data

- Total of 219 GPS stations
  - Daily sampling
  - East, north and vertical
- 72 day period: Aug-mid-October
- Data processed using GIPSY-OASIS II, in PPP
  - Ref frame IGS08
  - VMF1 troposphere mapping function (Boehm et al., 2006)
  - Remove ocean tide loading + solid Earth body tides
- Stations managed by assortment of agencies
  - Tx DOT
  - UT Austin
  - Univ. Houston
  - SmartNet
- Average spacing 20-30 km

Non-tidal atmosphere + ocean loading (IERS/GFZ)

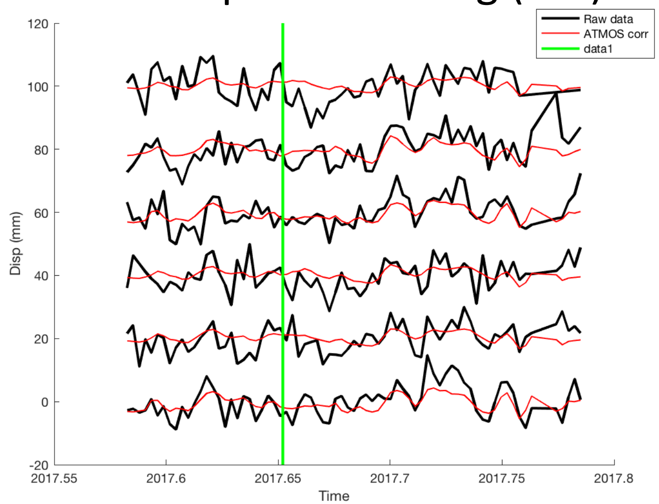
Black = data

Red = correction

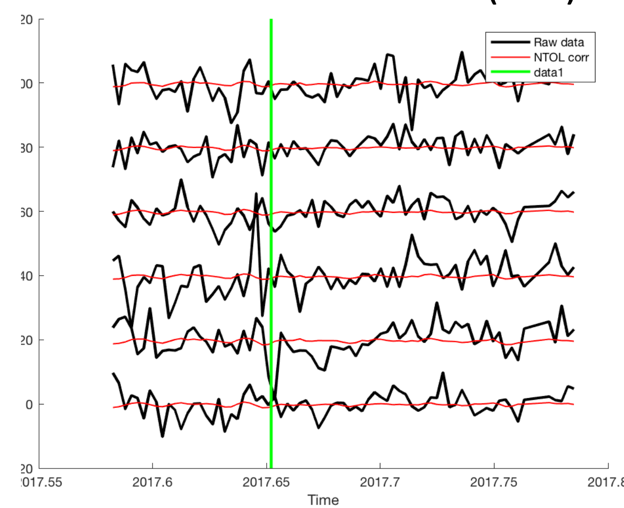
Green = landfall of Harvey

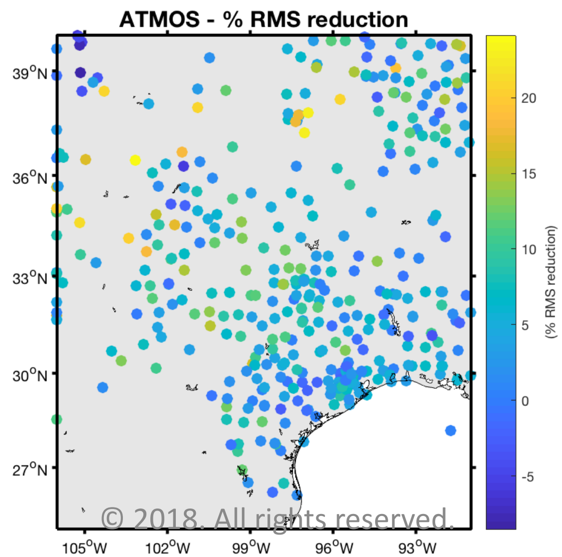
- Corrections for non-tidal atmospheric loading + ocean loading
- Effect of atmospheric pressure changes unloading-loading surface.
- ATMOS: RMS average reduction =up to ~20%
- NTOL RMS reduction up to 10% near-shore

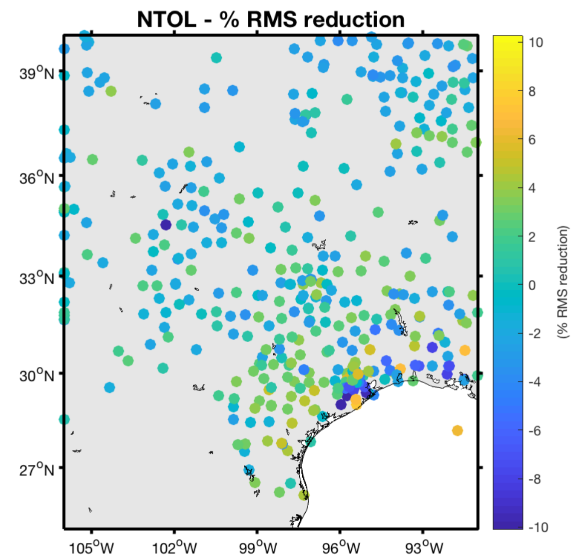
Atmospheric loading (red)



NTOL correction (red)



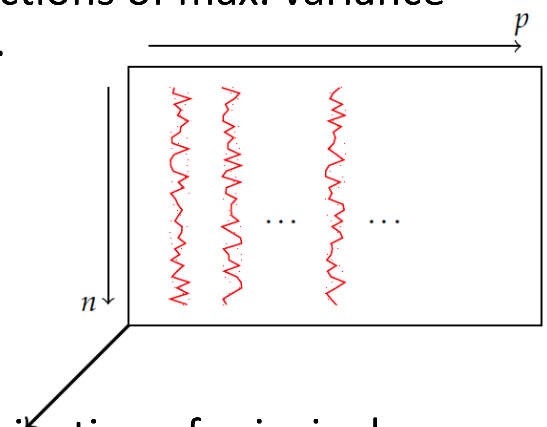




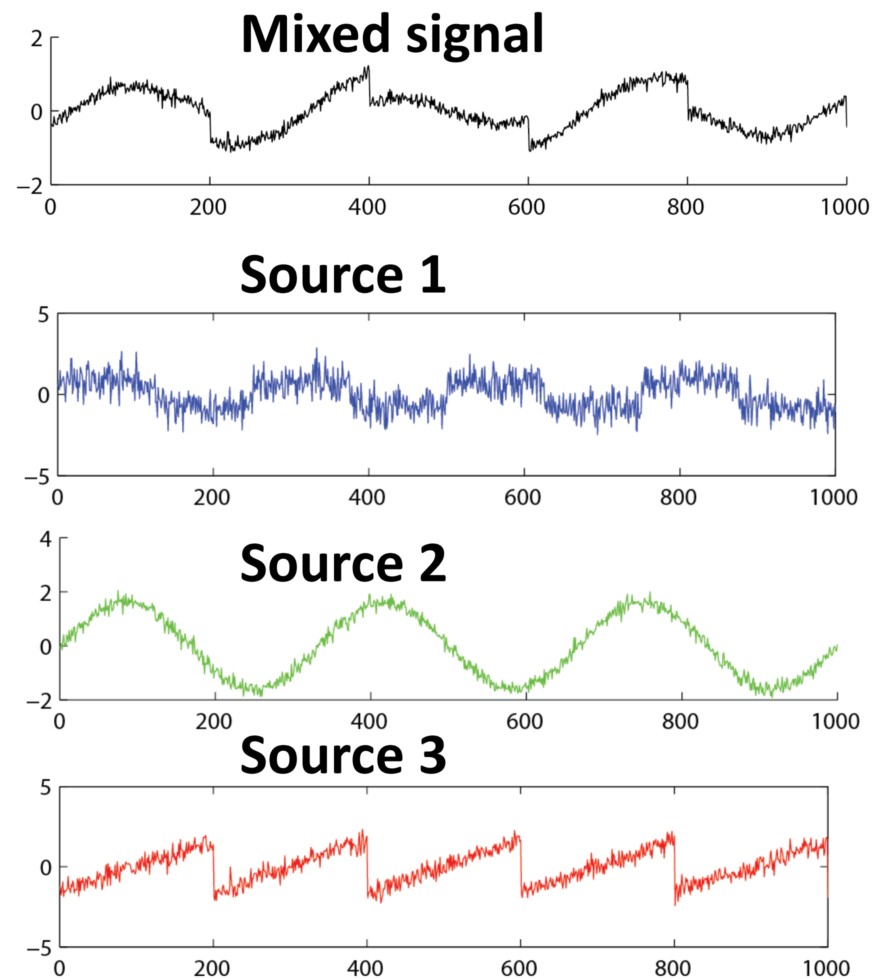
PCA – Principal Component Analysis

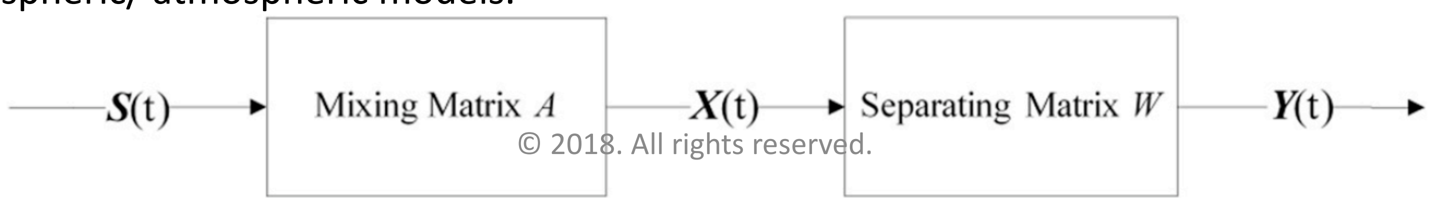
- GPS vertical most noisy → PCA to extract hydro signal
- PCA – statistical approach to compresses data by identifying directions of max. variance - Dong et al. (2006).

Data matrix



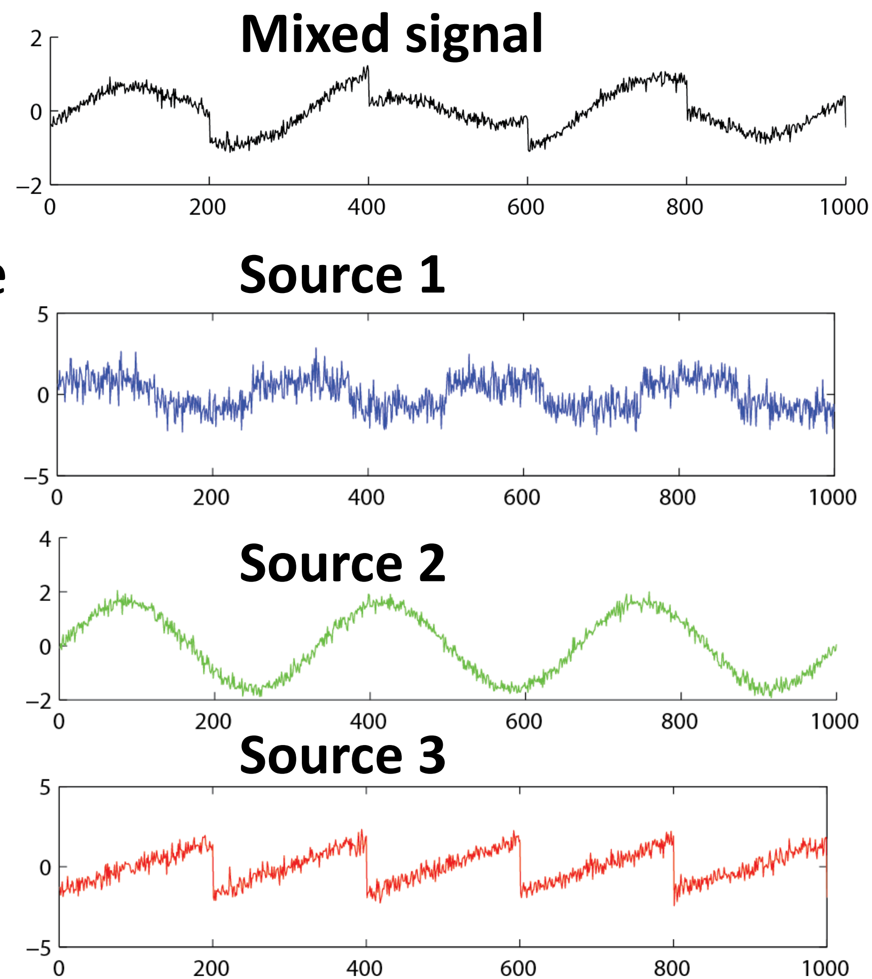
- Data = linear combination of principal components with spatial weight
- **CME** = artificial network wide motion due to inaccuracies in:
  - satellite orbits
  - ref. frame errors
  - Tropospheric/ atmospheric models.

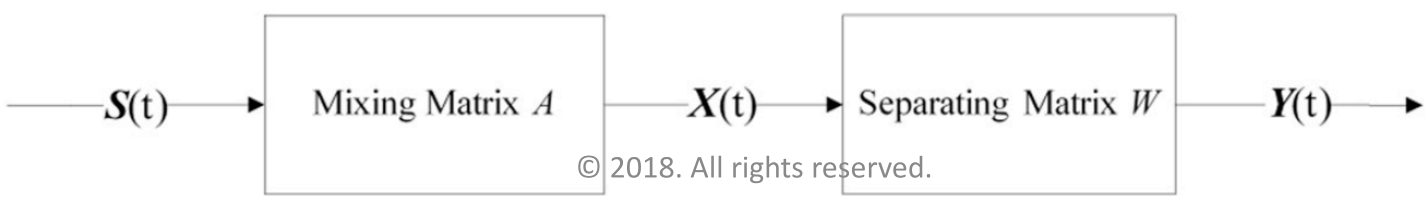




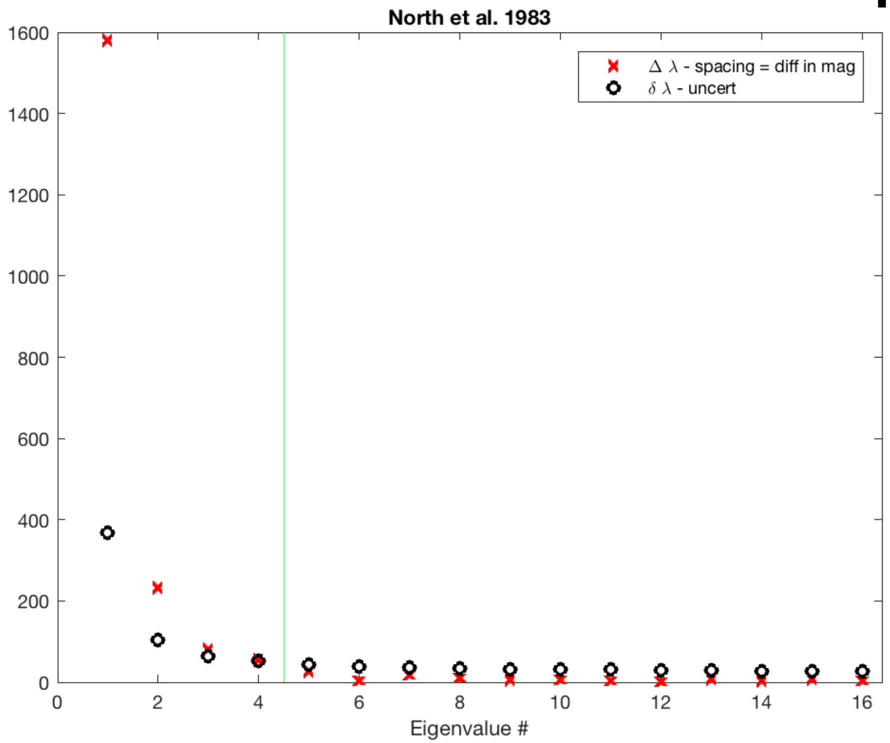
ICA - Independent Component Analysis

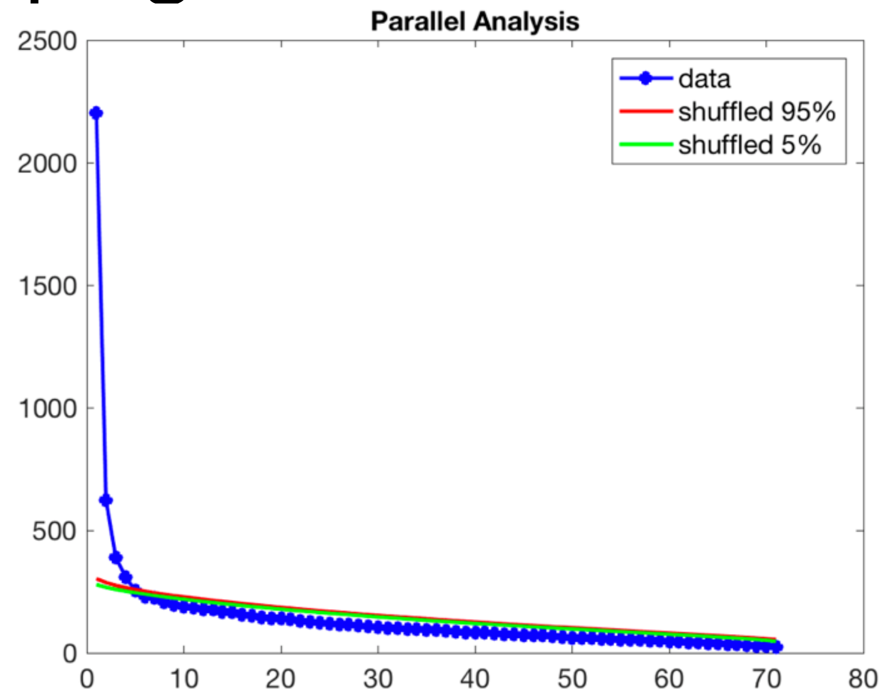
- ICA – identifies components that are statistically independent
- **Advantages**: ICA uses independence as a constraint to separate source, while PCA uses variance/ correlation.
    - ICA suited for non-Gaussian distributions
- Use reconstruction ICA algorithm, Hyvärinen & Oja (2000).





How many components to decompose data? - Stopping rules





"North's rule of thumb": Measure of seperability

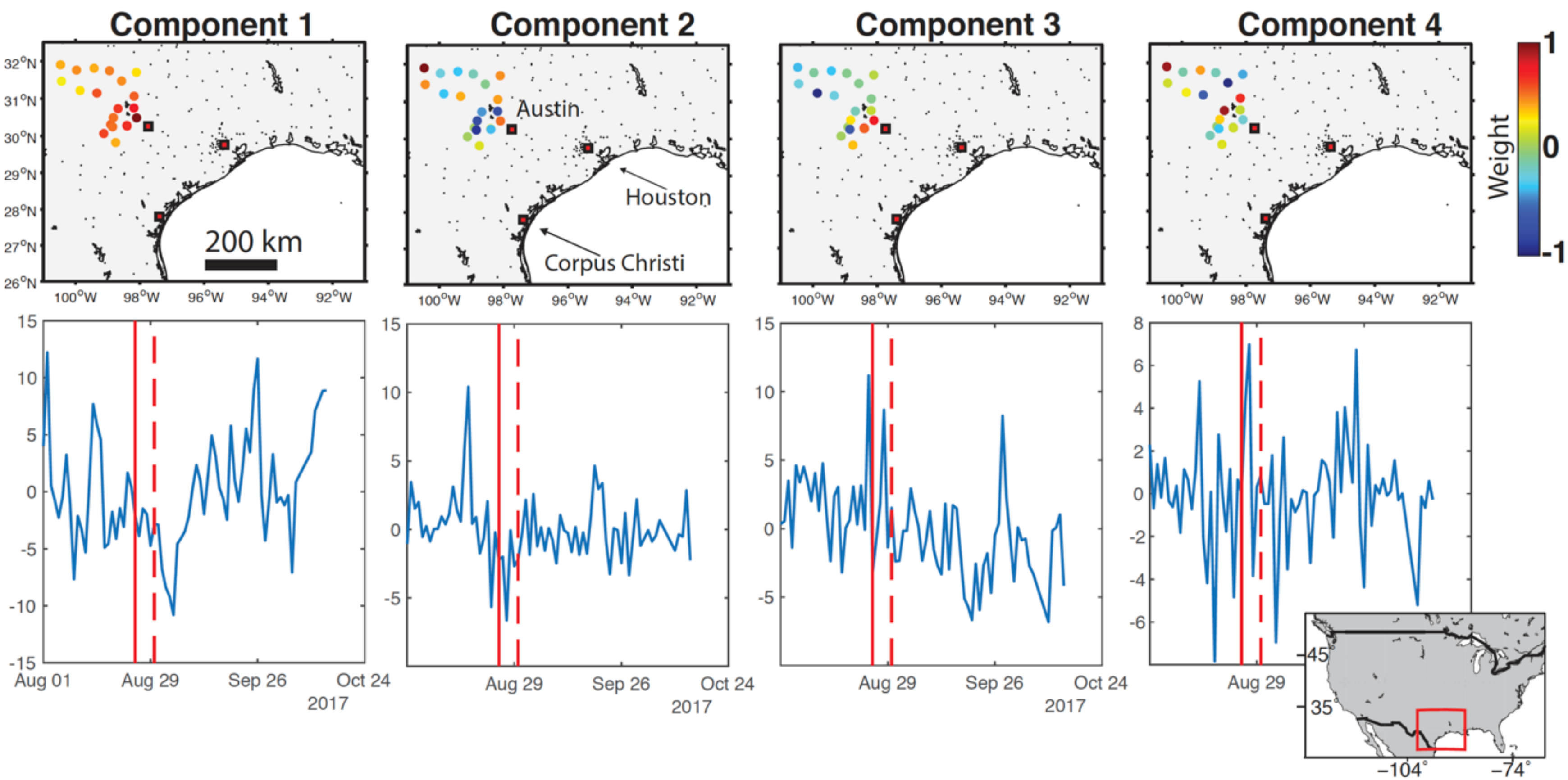
Idea: Assess which eigenvalues exceed that expected from a random process:

1. If uncert. exceeds separation, then component is deemed difficult to separate from its neighbor and from noise.

Horn's Parallel Analysis

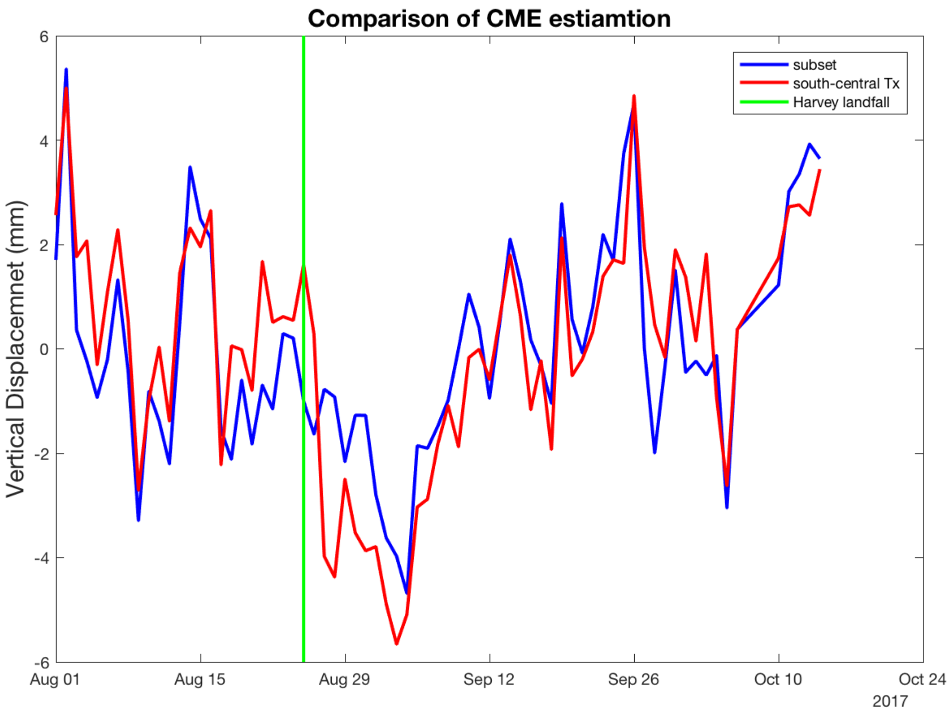
- Randomly scramble the data → suite of random samples and eigenspectra with 95% CI.
- If eigenvalue > 95% of eigenvalues from random data then component is retained.

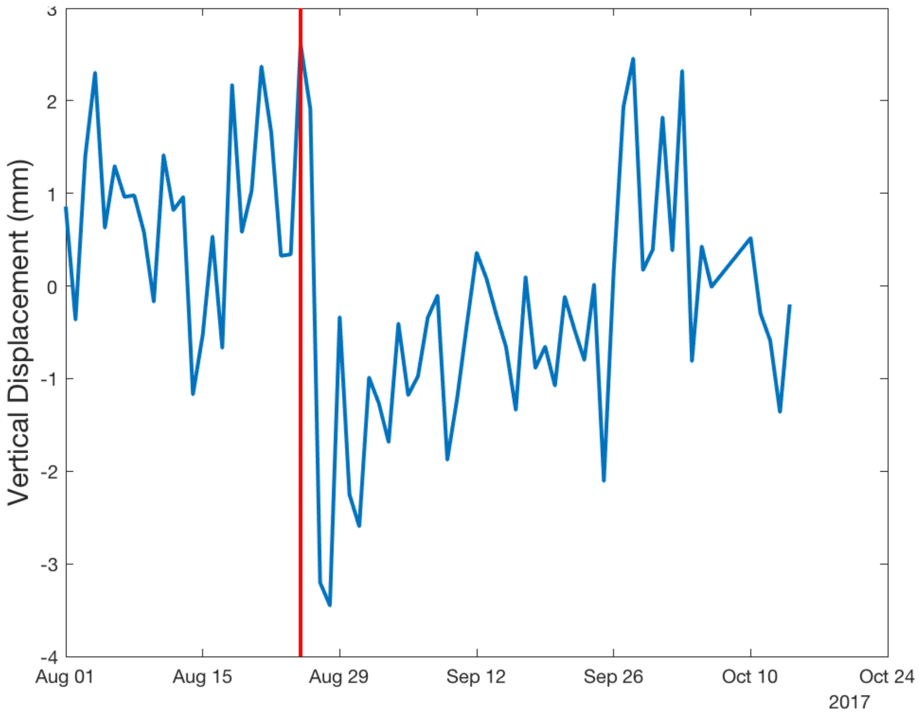
ICA filtering



- Components ordered in amount of motion explained.
- CME shows ~10 mm of subsidence, second landfall not detected.
- Hydrologic signal mixed onto first component
- Instead we estimate 'CME' from a subset of stations, distal from known precipitation
- Assume this CME is uniform across network

Comparing CME estimates





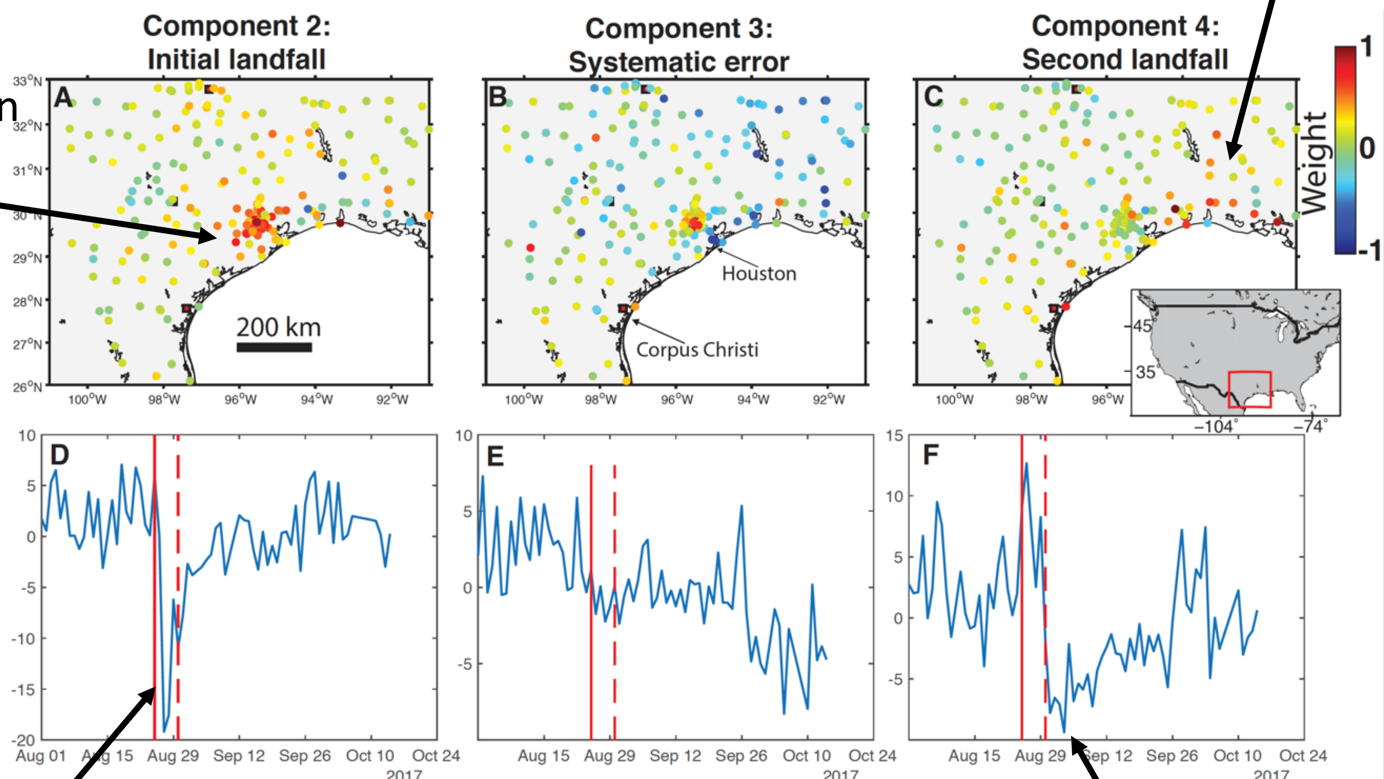
Red = CME from entire network
Blue = CME from subset of stations
Green = Landfall

- Above: Difference between two CME estimates
- Marked subsidence coincident with Harvey landfall (red line)
- Followed by gradual uplift
- Suggests hydrologic signal is mixed with CME

CME removed

Hydrologic signal:
Area of second landfall

Hydrologic signal:
Area of known precipitation



Hydrologic signal:
Coincident with initial landfall
Marked subsidence, gradual uplift

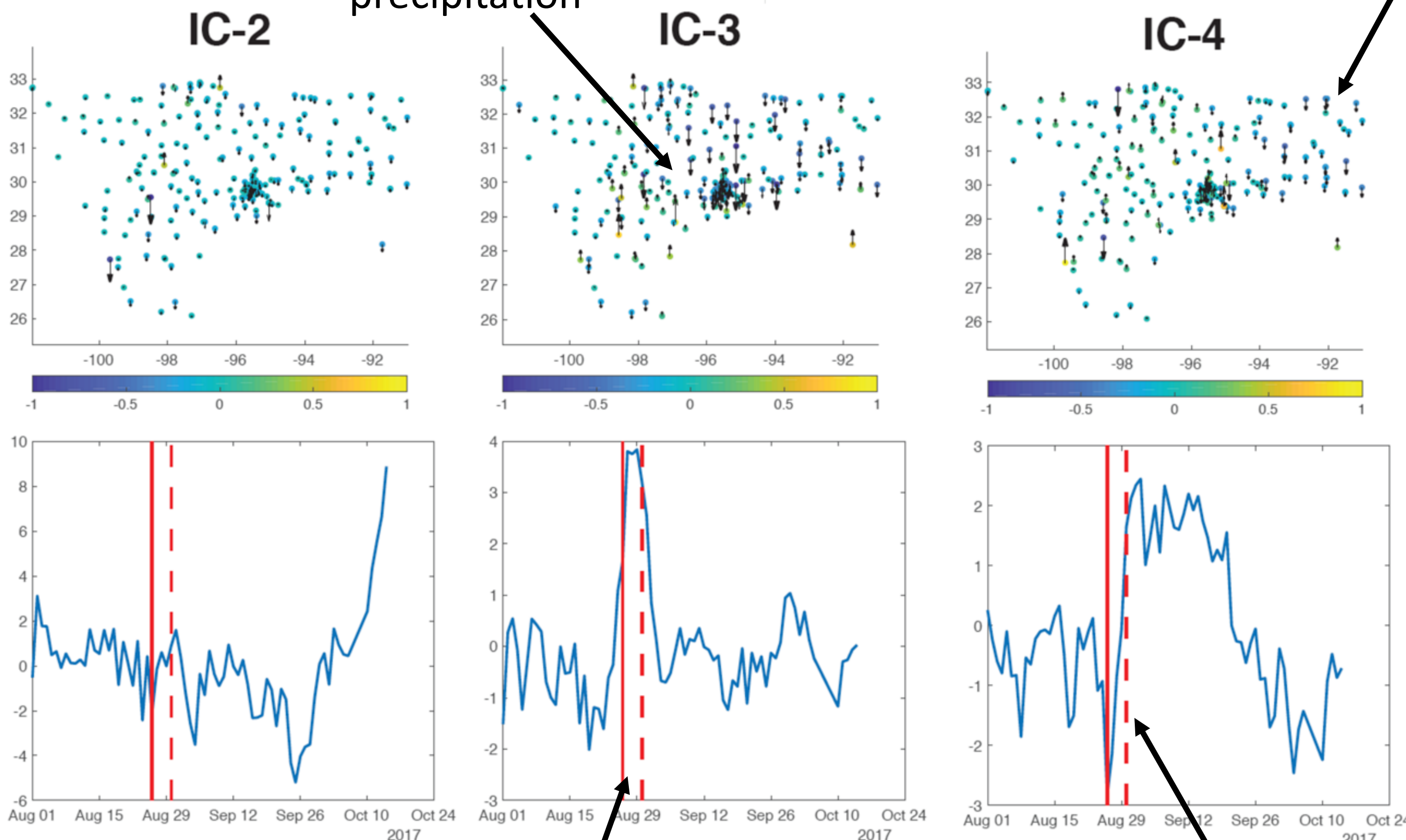
3rd component, a linear trend
Groundwater extraction

Hydrologic signal:
Coincident with second landfall
Marked subsidence, gradual uplift

East component (after CME removed)

Hydrologic signal:
Area of known precipitation

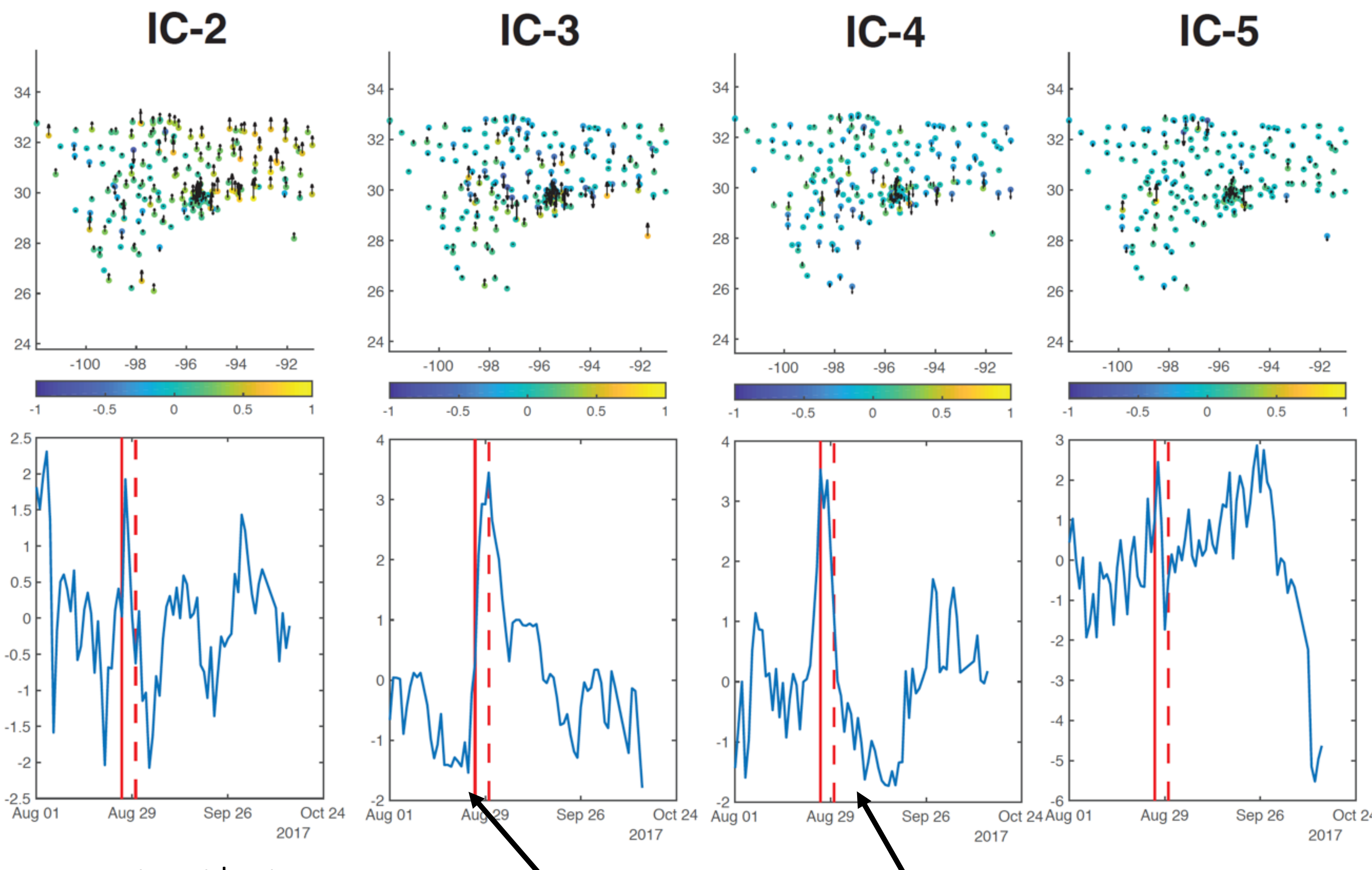
Hydrologic signal:
Area of second landfall



Hydrologic signal:
Coincident with initial landfall

Hydrologic signal:
Coincident with second landfall

North component (after CME removed)



Other components not kept, show temporally inchorenet motion or spatial patterns not consistent with Harveys landfall pattern

Hydrologic signal: Coincident with initial landfall

Hydrologic signal: Coincident with second landfall

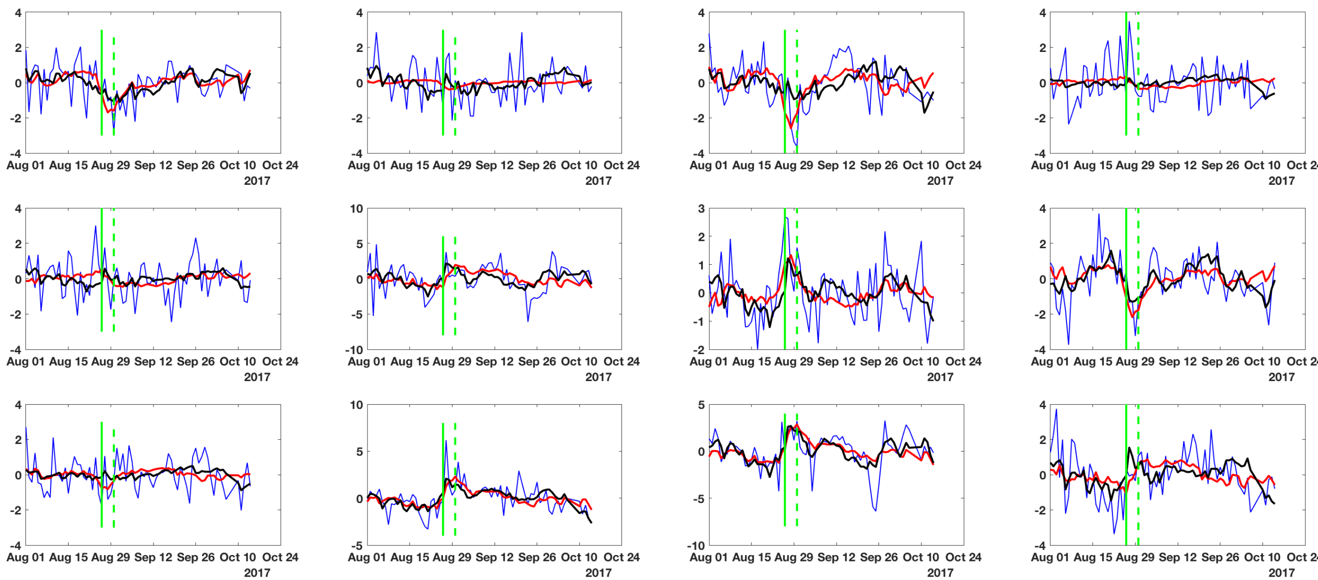
Filtered data

- PCA and ICA give similar results.
- Marked subsidence coincident with Harvey
- Return to pre-Harvey positions after ~5 weeks

- **Blue = raw**
- **Red = ICA**
- **Black = PCA**
- **Green = Harvey landfall**

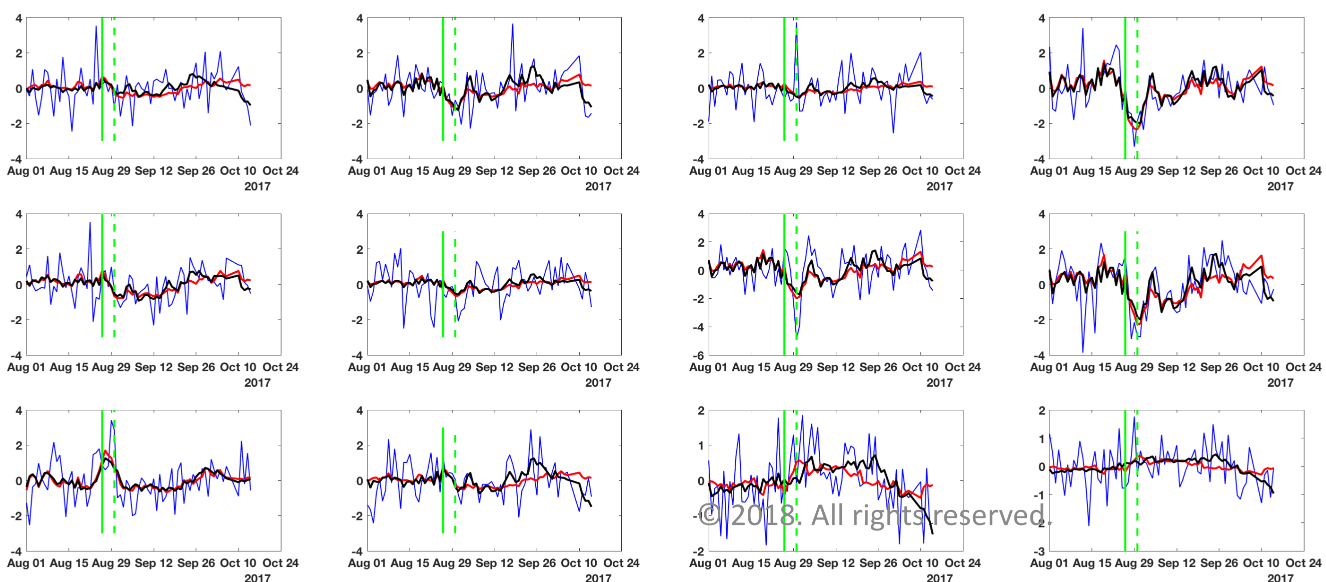
Data horizontals

North



- Blue = raw
- Red = ICA
- Black = PCA
- Green = Harvey landfall

East



- Up to 4 mm change in position
- Coincident with Harvey
- Return to pre-Harvey positions after ~5 weeks

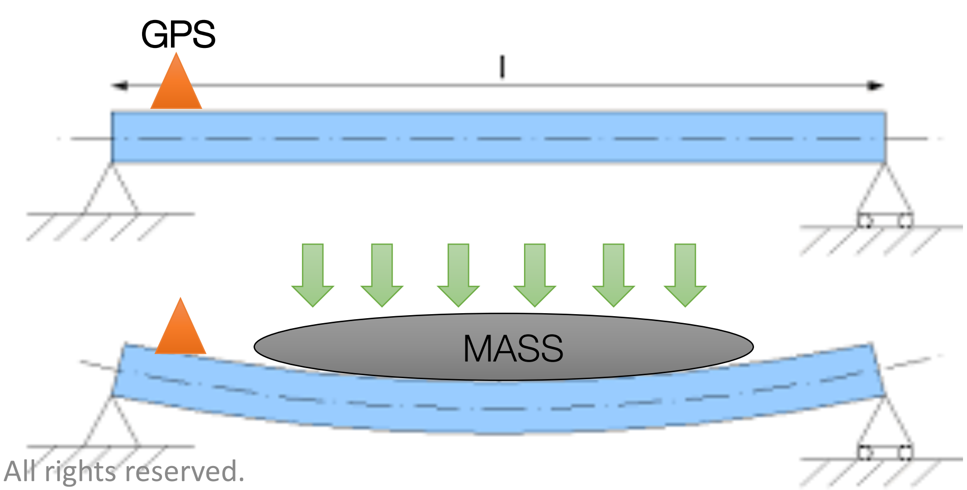
Motions in different areas

- 1. Largest subsidence around Houston (up to 21 mm).
- 2. Fastest uplift around Houston.
- 3. Smaller subsidence to east (up to 8 mm), along Texas-Louisiana border
- 4. Return of positions to pre-Harvey values after ~5 weeks. Possible small subsidence remains - remaining groundwater...?

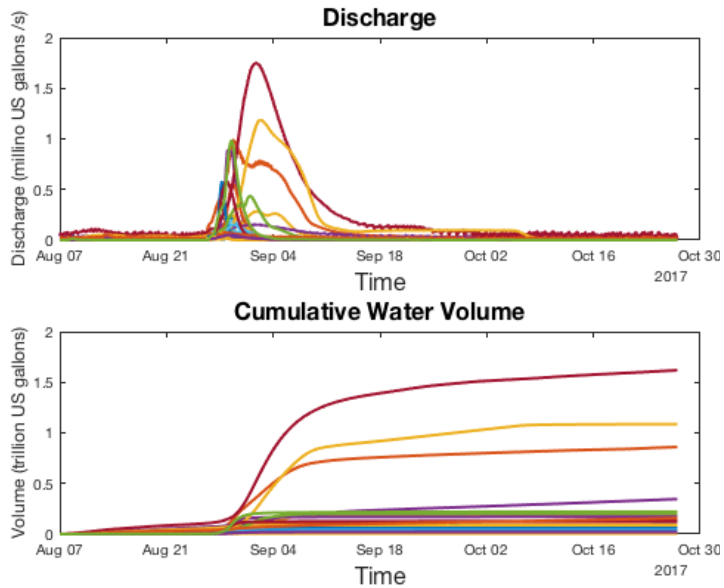
Invert GPS (E,N,V) → water thickness

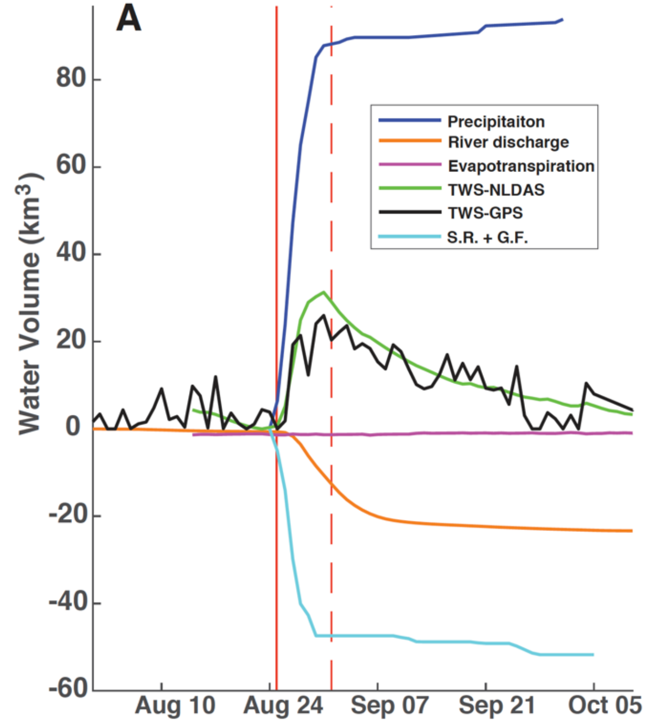
- Invert subsidence for water mass (Farrell, 1972).
- Assume a 1D layered, spherical elastic structure - PREM velocity model (Dziewonski and Anderson, 1981).

$$\begin{bmatrix} WG_v \\ WG_u \\ WG_u \\ \lambda S \\ \beta U \end{bmatrix} [m_t] = \begin{bmatrix} Wd_t^v \\ Wd_t^e \\ Wd_t^n \\ 0 \\ \beta U m_{t-1} \end{bmatrix}$$



Discussion – Components of the hydrologic system



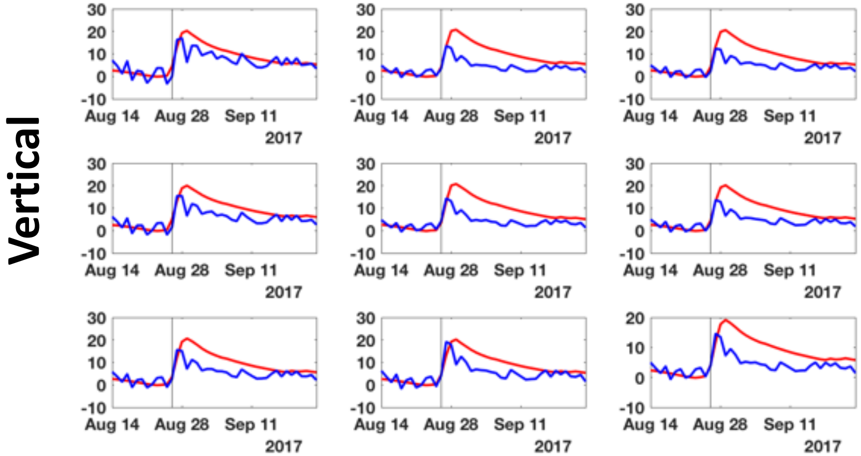


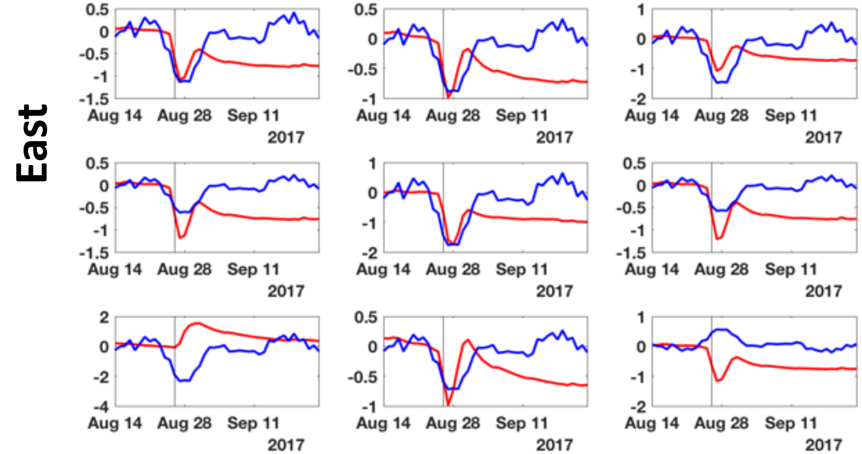
Surface runoff + groundwater flow → $S = P - \Delta TWS - ET - R$ ← **River discharge**

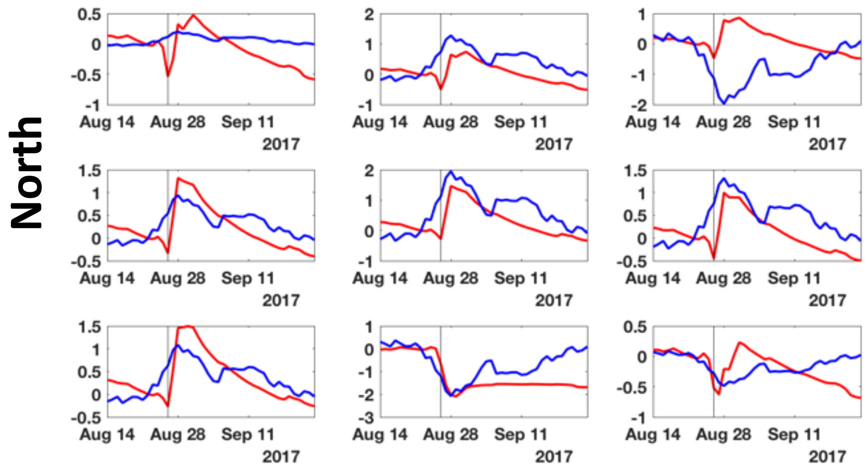
Precipitation (P), **Water storage** (ΔTWS), **Evapotranspiration** (ET)

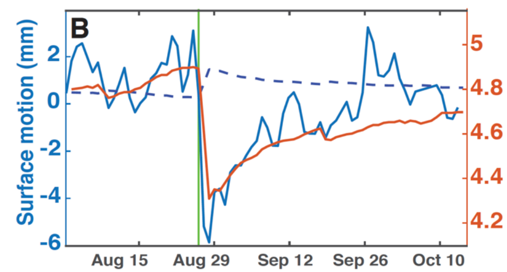
- River discharge from 31 USGS gauges – accounts for 25 km^3 water loss, (minimum) ~27% of total,
- Evapotranspiration – accounts for ~18% of water loss, estimated from Fisher et al. (2008) using:
  - FLUXNET eddy covariance towers --> water + energy fluxes
  - MODIS instrument for radiation and vegetation indices
- Surface runoff and groundwater flow not well constrained.
- Closing water budget we estimate (maximum) ~50 km^3 of water lost via *S*, ~54% of total water.

Validation

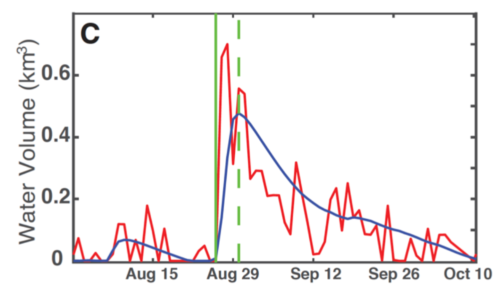








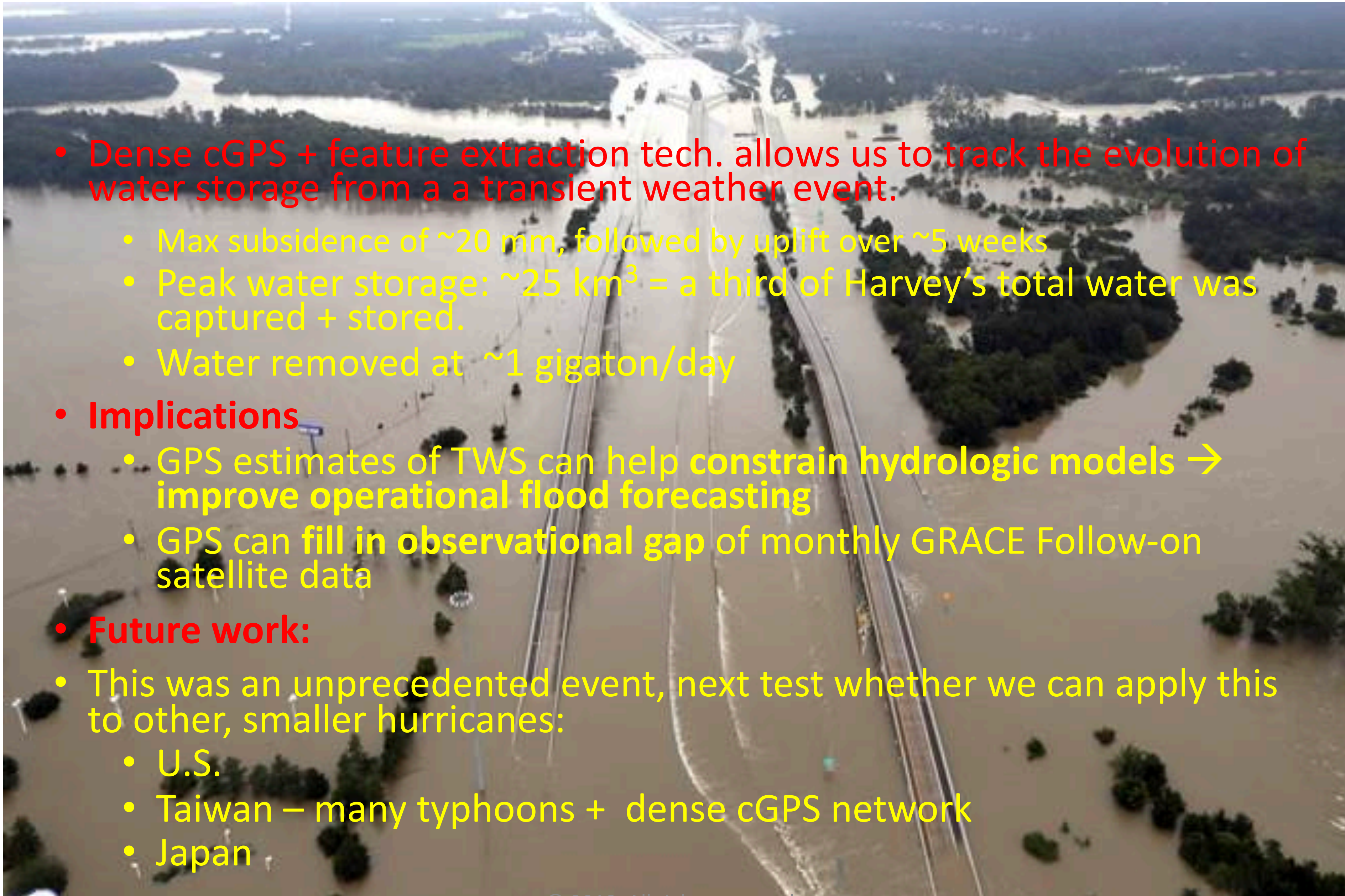
Well head water levels are inconsistent with poroelastic motions



USGS water volume measured at Barker and Addicks Reservoirs vs our TWS estimate

- NLDAS – National Land Data Assimilation model – hydrologic model driven by:
  - observed precipitation.
  - Shortwave radiation.
- Simulates TWS hourly and at 1/8^o degree

Conclusions



- Dense cGPS + feature extraction tech. allows us to track the evolution of water storage from a a transient weather event.
  - Max subsidence of ~20 mm, followed by uplift over ~5 weeks
  - Peak water storage: ~25 km^3 = a third of Harvey's total water was captured + stored.
  - Water removed at ~1 gigaton/day
- **Implications**
  - GPS estimates of TWS can help **constrain hydrologic models → improve operational flood forecasting**
  - GPS can **fill in observational gap** of monthly GRACE Follow-on satellite data
- **Future work:**
- This was an unprecedented event, next test whether we can apply this to other, smaller hurricanes:
  - U.S.
  - Taiwan – many typhoons + dense cGPS network
  - Japan

JPL