Quick Determination of Earthquake Source Parameters from GPS Measurements: A Study of Suitability for Taiwan

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Introduction

Taiwan is currently running an earthquake early warning system (EEWS) based on the real-time strong motion network (e.g., *P*alert of Wu et al., 2013)--

- use the first few seconds of the P-wave displacement amplitude and peak ground acceleration to decide whether to trigger a warning
- quickly estimate the magnitude by the scaling relation of P-wave duration and earthquake magnitude

Accurate magnitude calculation for moderate-to-large magnitude events (e.g., Mw>6.5) in the near field is challenging--

- saturation prone seismic-based instrumentation
- low-gain (strong motion) accelerometers have limited low frequency recording ability due to baseline offsets (e.g., Boore and Bommer, 2005)

Introduction

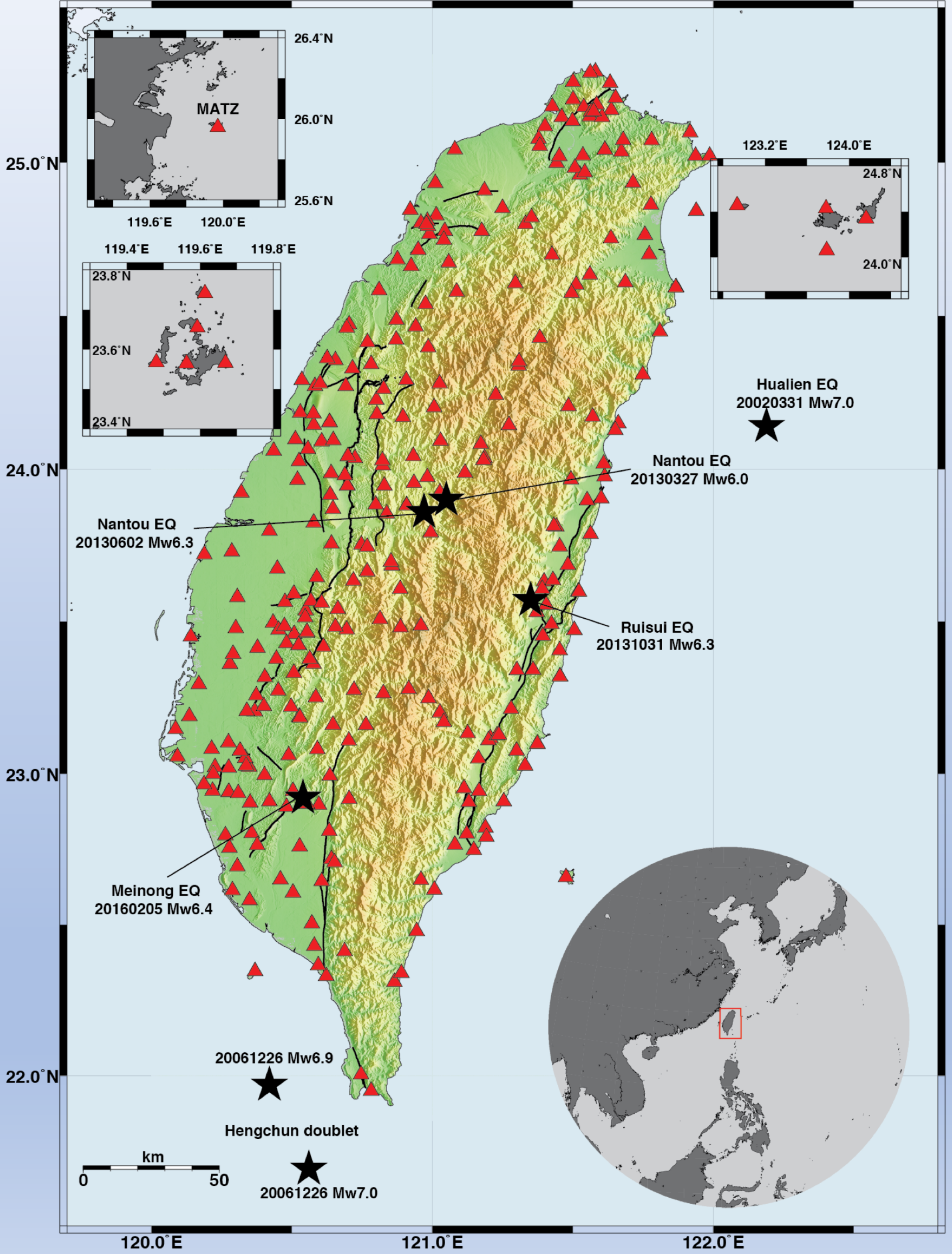
A different system based on non-inertial displacements from Global Positioning System (GPS) has been proposed to compensate the above near-field issue for moderate-large events (e.g. Melgar et al., 2015)--

- record and evaluate epoch-by-epoch coordinate solutions with sampling rates of 1 Hz and higher, thus measure both high and low frequency ground shaking during big earthquakes
- provide important information for estimating earthquake source parameters and rupture models (e.g., Miyazaki et al., 2004; Ji et al., 2004; Yue et al., 2011)
- provide better constraints on earthquake moment magnitude and focal mechanism for rapid response and can facilitate earthquake and tsunami early warning (e.g., Blewitt et al., 2009; Wright et al., 2012)

Study Outline

In this study we demonstrate that the dense GPS network now operating in Taiwan is well-suited to the CMT inversion method--

- Apply GPS CMT inversion to Taiwan without station selection and a priori knowledge of fault geometry
- Four moderate inland (Mw 6.0~6.4) and two large offshore (Mw~7.0) earthquakes
- High-rate GPS data (1-Hz) for the 02/05/2016 Meinong earthquake
- Perform a generalized sensitivity test for various scenario earthquakes
- Discuss how the method could be implemented in real-time

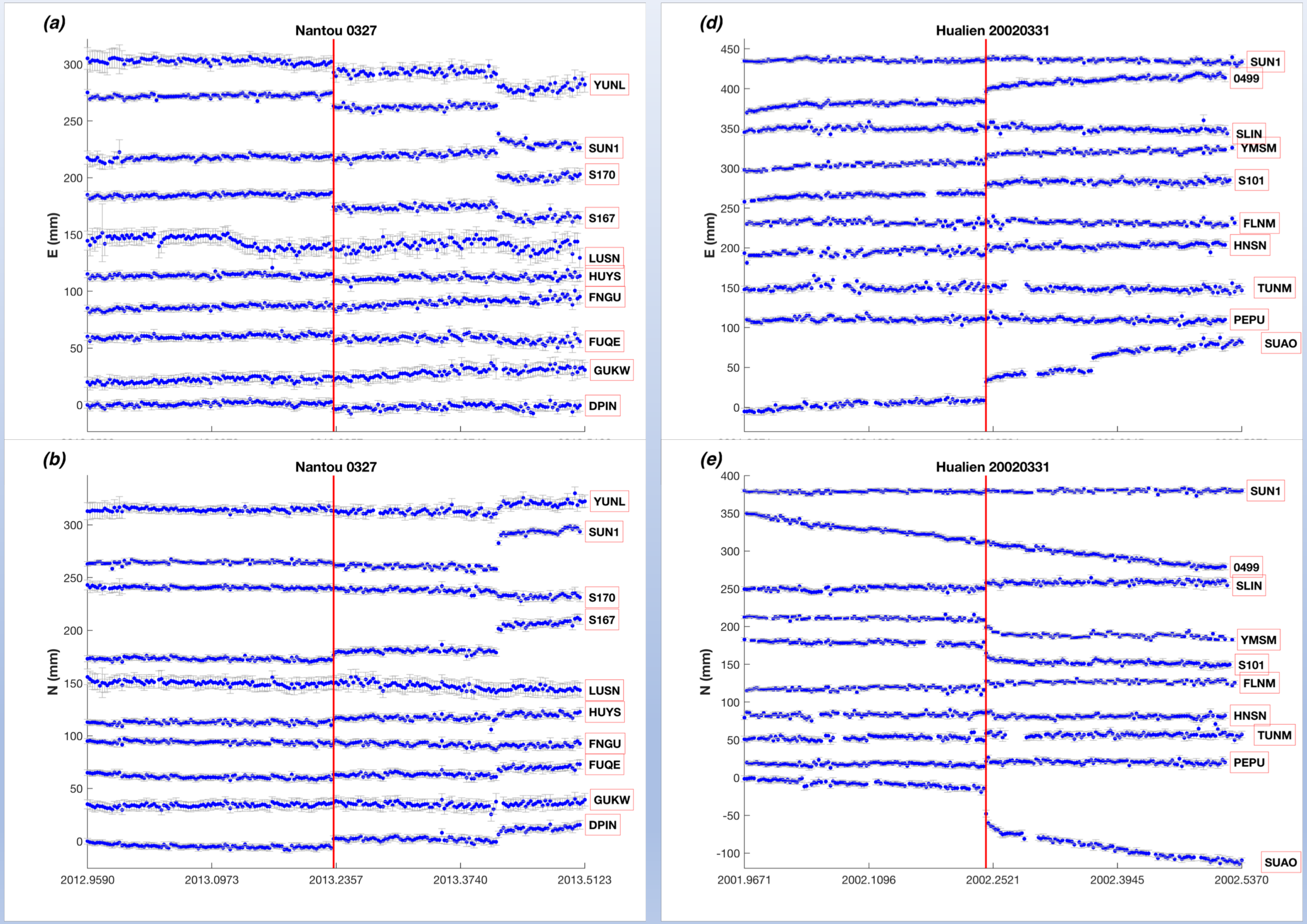


Taiwan Continuous GPS Network

- 300+ stations
- dual-frequency data with a sampling rate of 30 seconds
- Some newly installed instruments record 1-Hz or higher rates
- GAMIT/GLOBK software for data processing
- IGS final orbit data in the ITRF2008 reference frame
- ocean tide loading model FES2004 and troposphere mapping function VMF1

03/27/2013 Nantou EQ (Mw=6.0)

03/31/2002 Hualien EQ (Mw=7.0)



GPS Data

- coseismic displacement based on the change of average daily coordinates *three days* after and before the main shocks (not feasible for real-time)
- Vertical displacements are noisier but still included in the inversion with lower weights

CMT Inversion Method

Static-offset based Centroid Moment Tensor inversion (e.g., Melgar et al., 2012):

- We employed the frequency-wavenumber technique of Zhu et al. (2002) and the 1D Taiwan average velocity model of Chen et al. (1998) to build the source/station Green's functions, G, which calculates the static offsets d produced by a point source with the moment tensor M:

$$GM(m_k, x_i) = d$$

m_k = six linearly independent components of the moment tensor

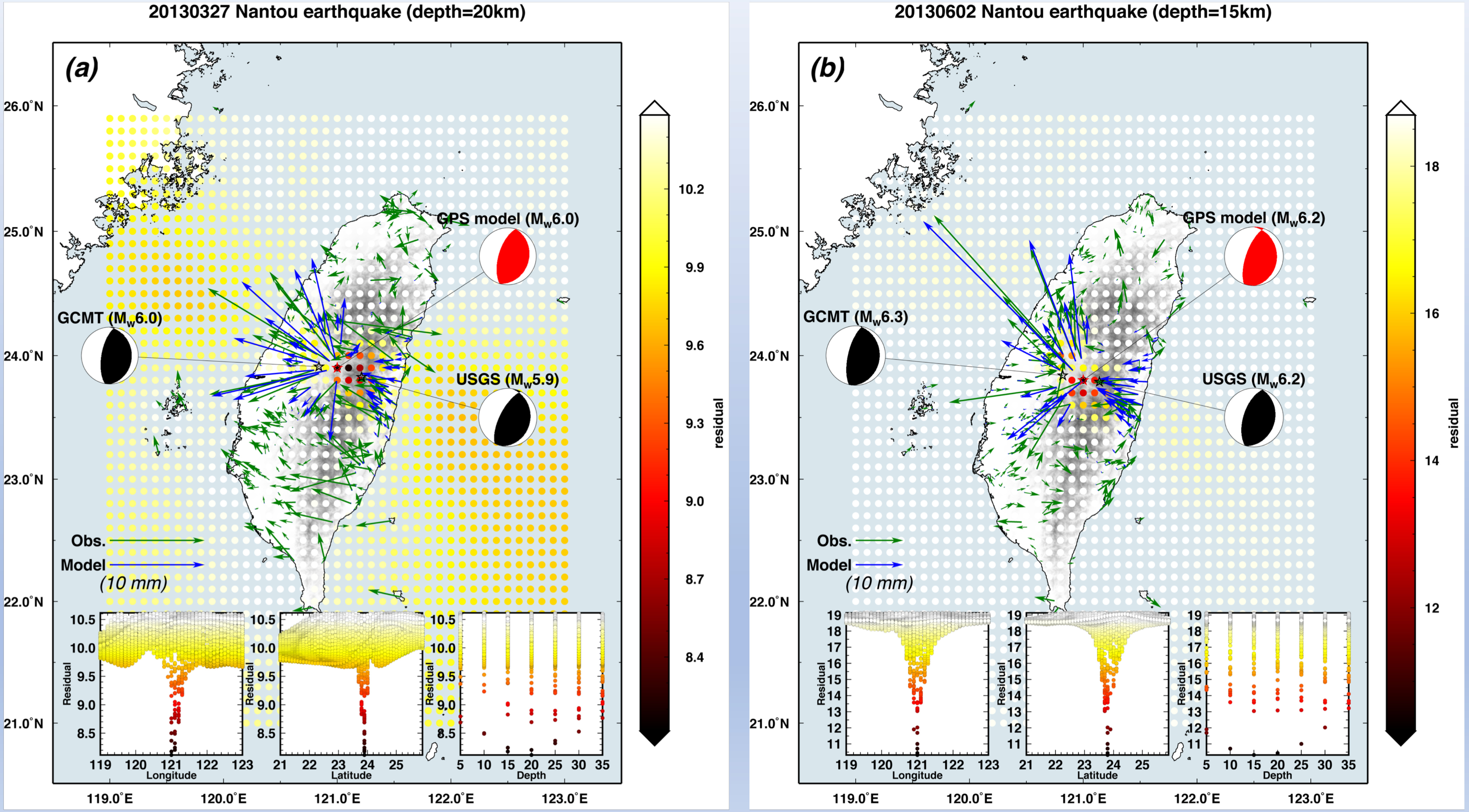
x_i =3-dimensional source location

- Use the standard deviation for each measurement as a data weight and then invert the moment tensor M: $\hat{M} = ({G_w}^T G_w)^{-1} {G_w}^T d_w$

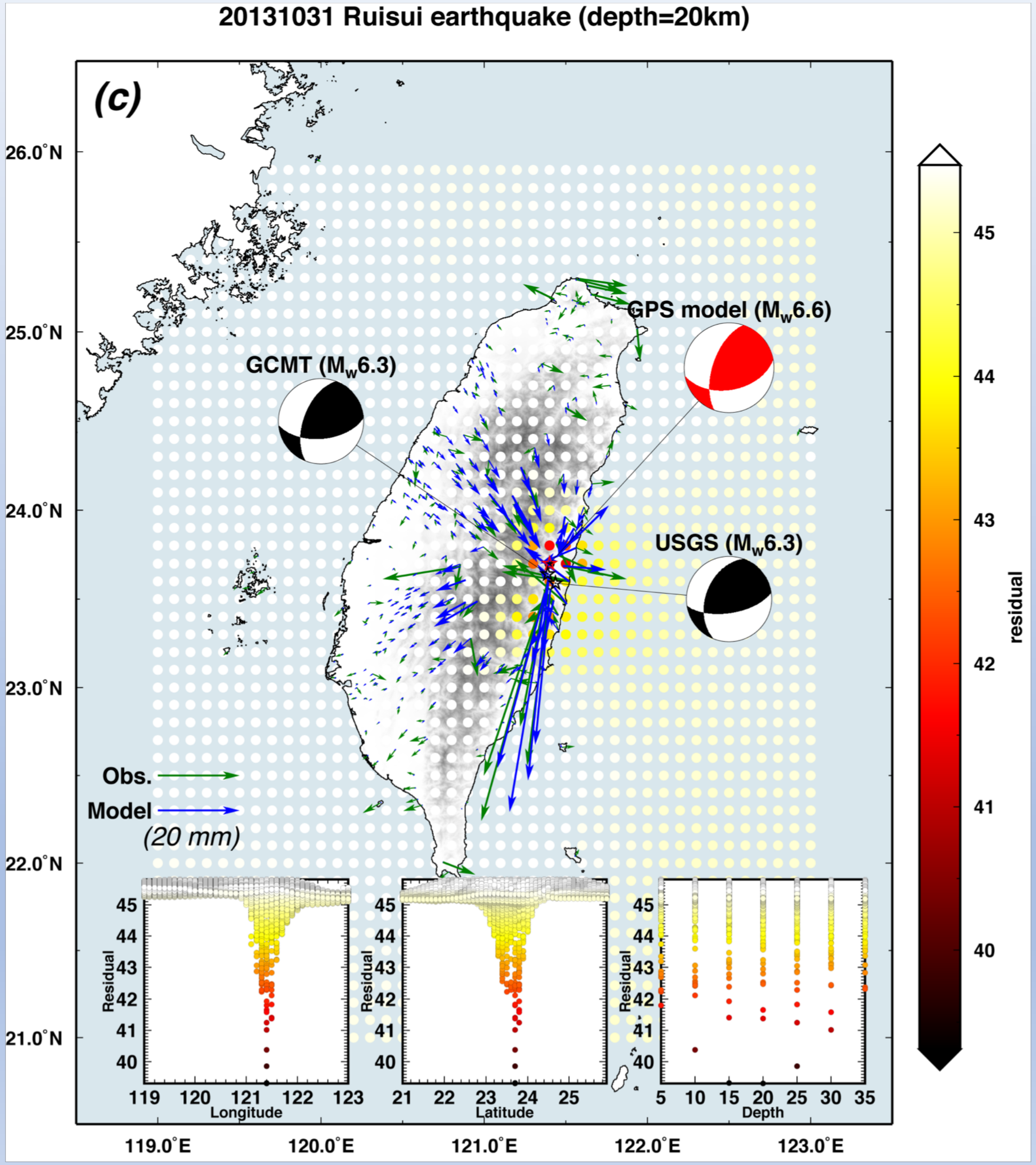
CMT Inversion Method

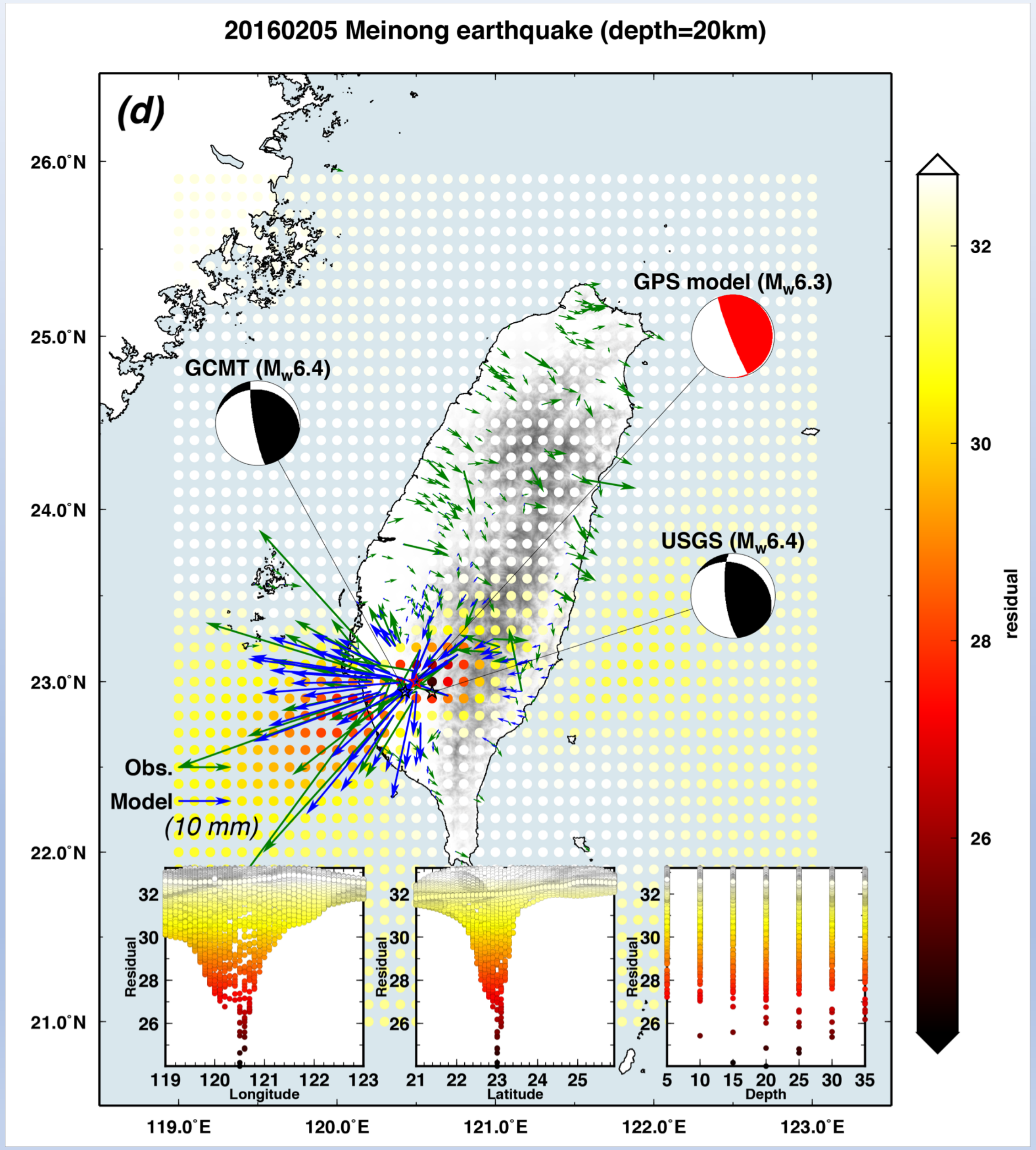
- We grid the study area into 14350 potential centroid locations (nodes) with intervals of 0.1° in latitude, 0.1° in longitude, and 5 km in depth, and pre-calculate the three-component Green Functions from each potential source location at every station.
- These GFs are saved in a database as they only need to be calculated once.
- The most plausible source position (node) and the associated focal mechanism is determined based on the minimum χ^2 misfit function.

GPS CMT Inversion Results

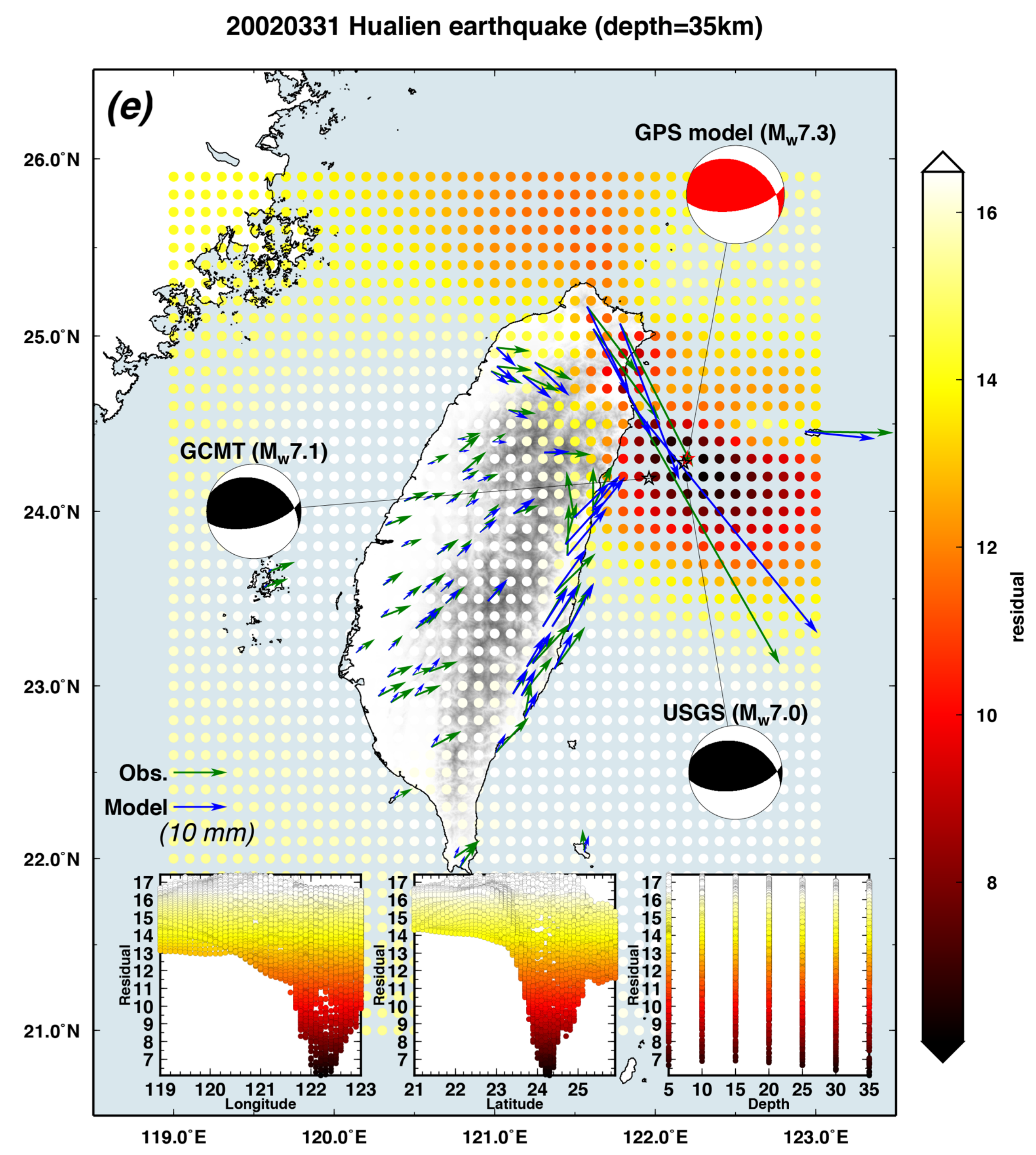


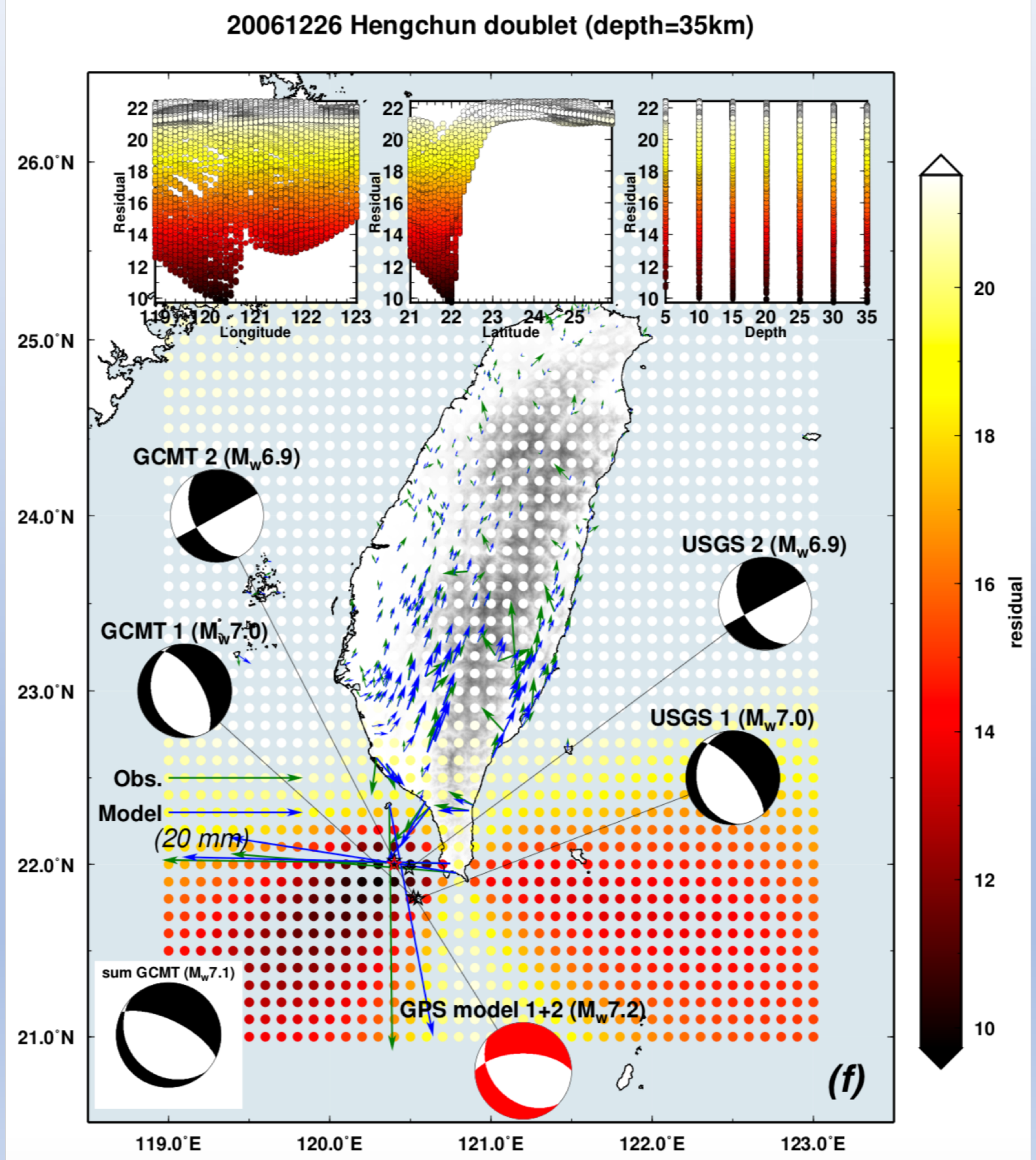
GPS CMT Inversion Results





GPS CMT Inversion Results





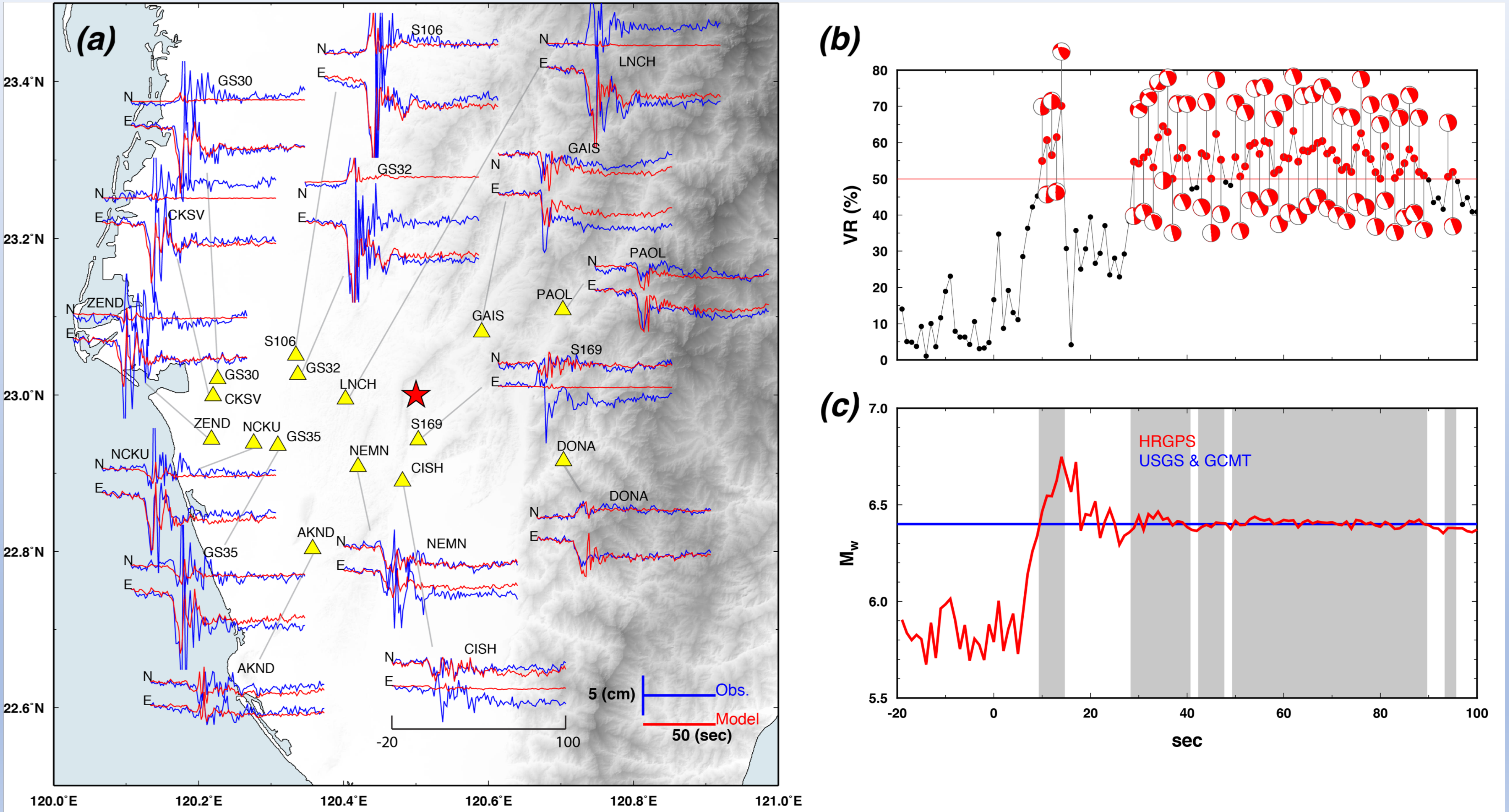
CMT Inversion of High-rate GPS

- A total of 15 stations with 1-Hz data within 30 km of the epicenter of the Meinong earthquake
- High-rate GPS (HRGPS) data were processed using the TRACK software package: relative positioning where the motions of each station are relative to a reference or base station (we chose MATZ in this study)
- Coseismic displacement of each epoch t_i (every second) is defined as $D_{ti} = d_{ti} - d_{t0}$, where t_0=20 sec before the earthquake initiation.
- Use the variance reduction (*VR*) for automatically detecting the quality of inversion:

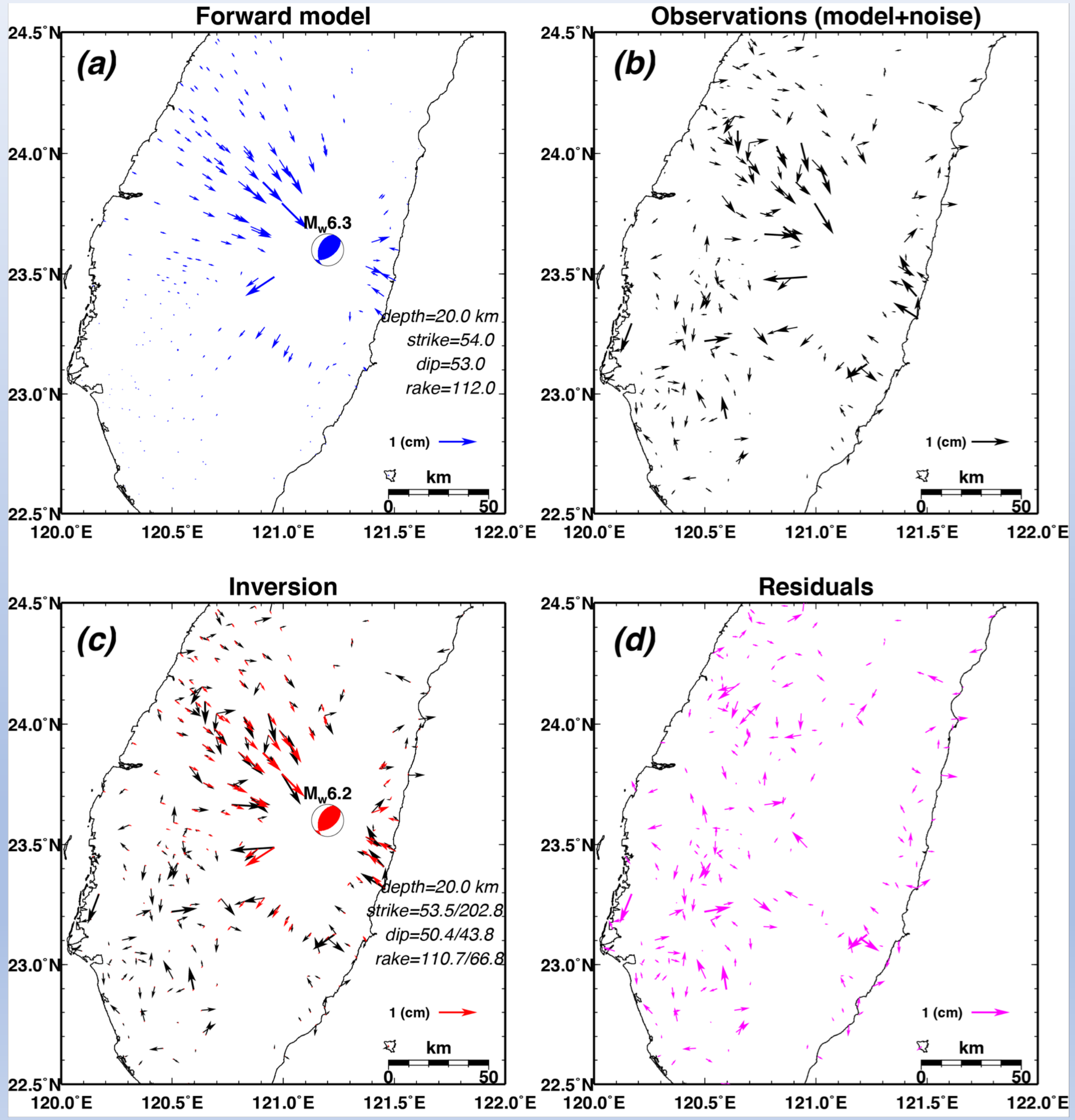
$$VR = \left(1 - \frac{\sum (d - \hat{d})^2}{\sum d^2}\right) \times 100\%$$

higher *VR* represents model predictions $\hat{d}$ closer to observations d

CMT Inversion of High-rate GPS



Recovery Map for GPS CMT Inversion

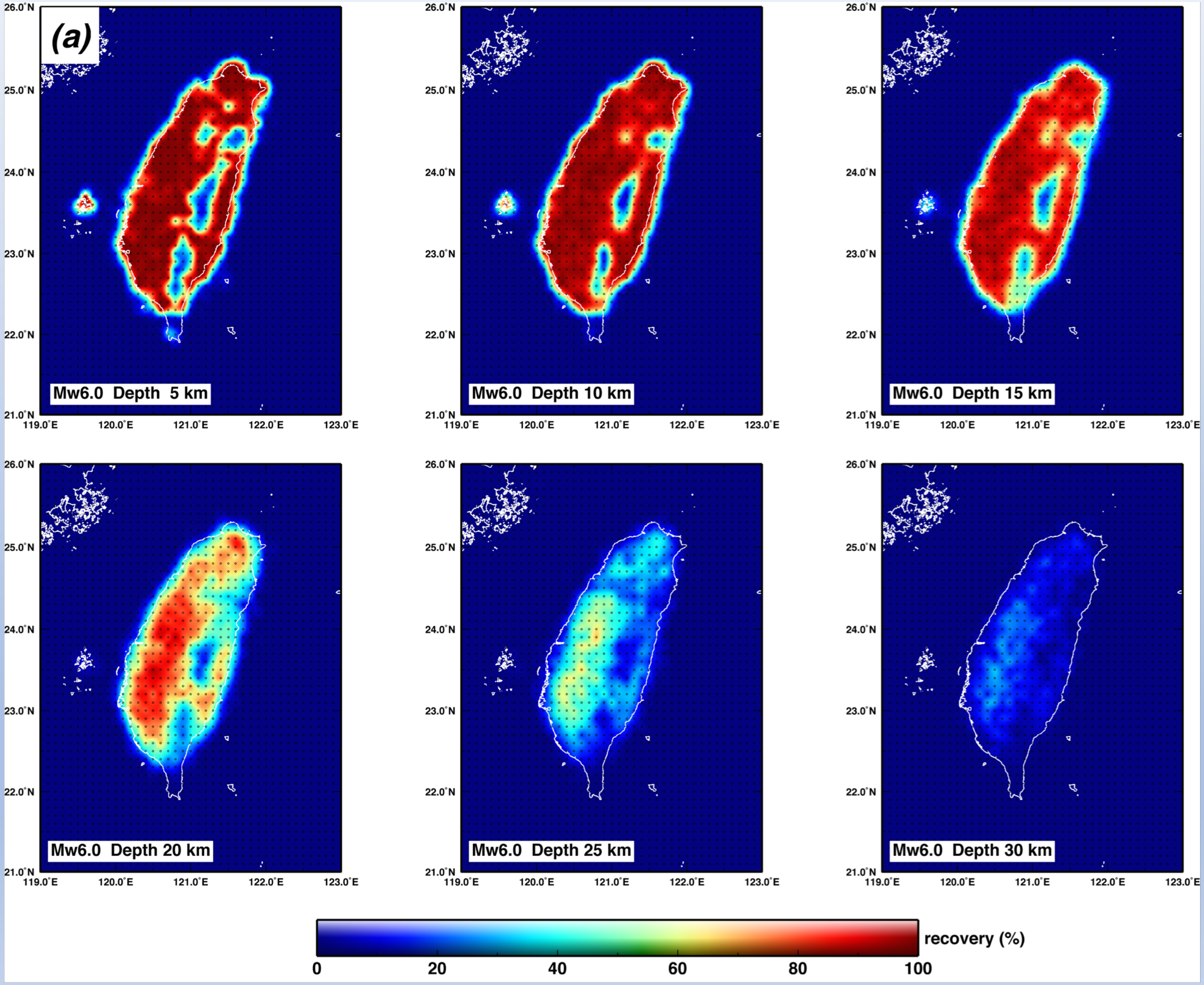


- GPS noise level of 2 mm was applied
- Successful inversion:

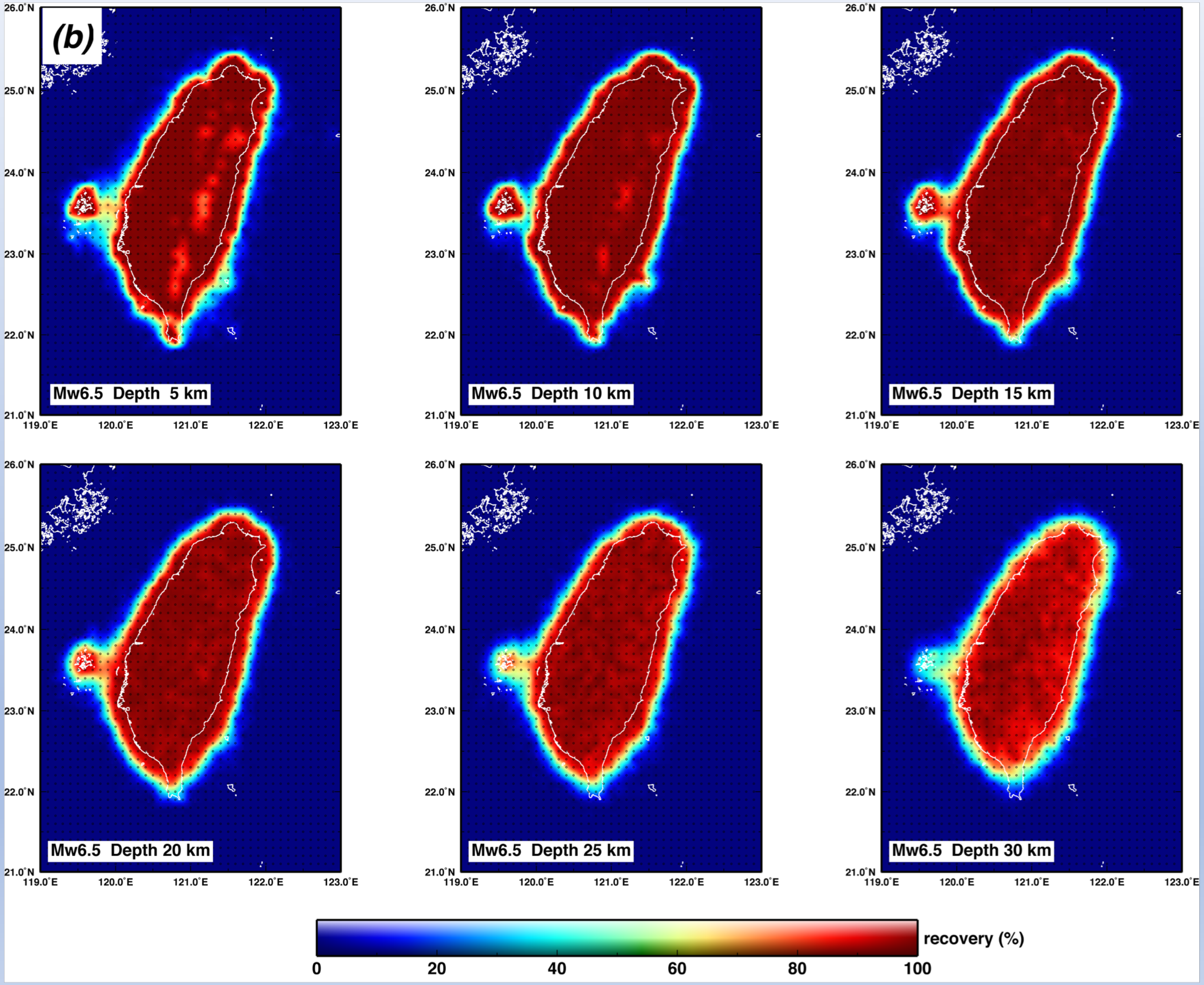
  (1) the difference between the input and inverted strike, dip, and rake of the point source is less than 10% of its value

  (2) the centroid position difference is less than 10 km

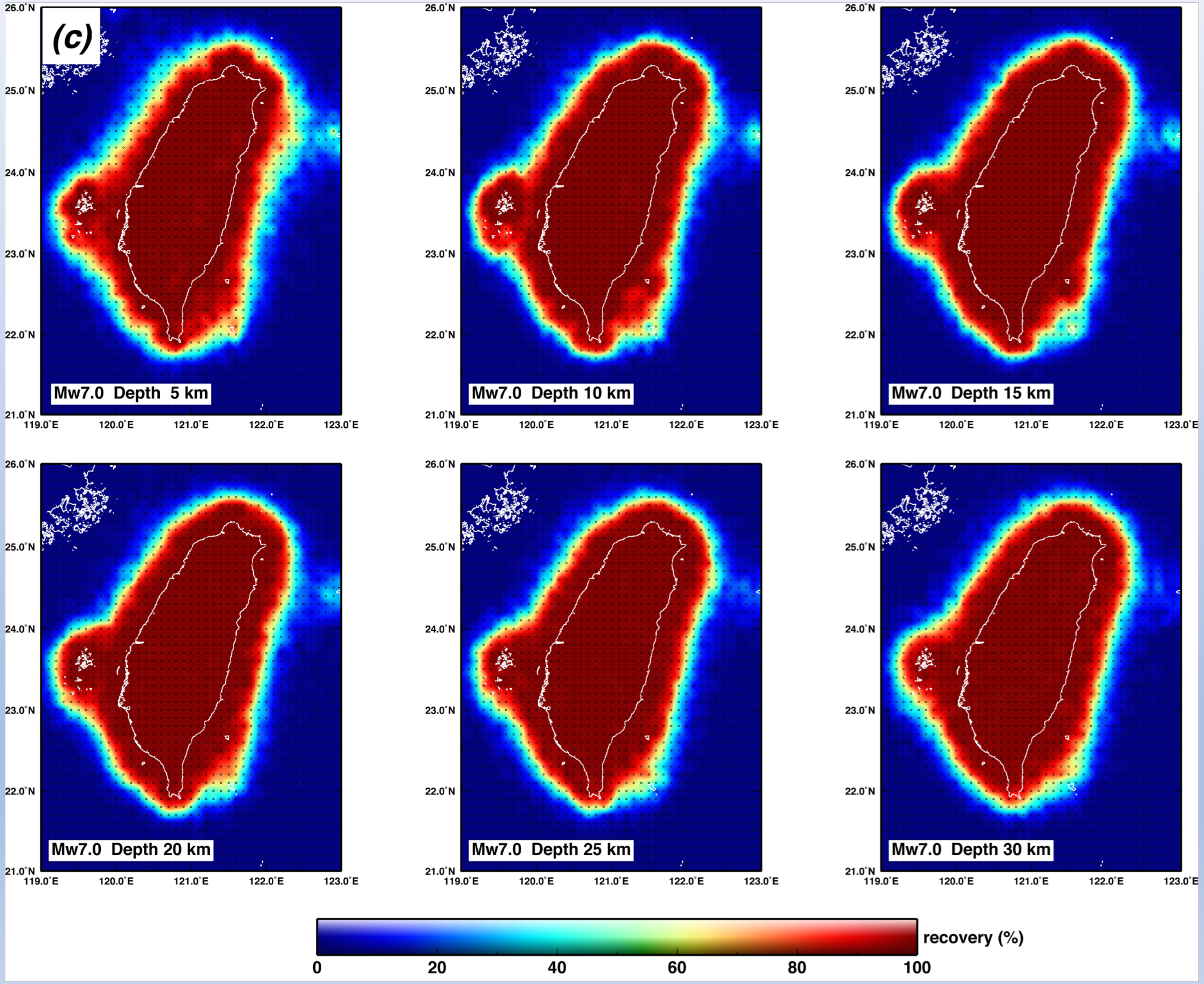
Recovery Map for GPS Inversion, Mw=6.0 events



Recovery Map for GPS Inversion, Mw=6.5 events



Recovery Map for GPS Inversion, Mw=7.0 events



Summary

- All CMT inversions in this study show comparable focal mechanisms and magnitudes with the solutions from GCMT and USGS, indicating that the GPS network in Taiwan can be a powerful tool, running parallelly with seismometer-based EEW system, to rapidly and stably determine earthquake CMT.
- Our results support the notion that a fully automated GPS-based CMT model could function in real-time and provide fast preliminary estimates of location, moment, and focal planes after an earthquake has occurred.
- These source parameters can be used to constrain the subsequent finite fault modeling, which is crucial for evaluating earthquake ground-shaking and tsunami hazards.