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Wave Forecasting at PTWC
--- Methods, Limitations/Uncertainties, and Case studies

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Content

1. Tsunami Forecasting Methods and Uncertainties
   (SIFT, ATFM, and RIFT)

2. PTWC RIFT model (uncertainties, limitations).

3. RIFT Case Studies

4. Summary Statements and Challenges

1. Tsunami Forecasting Methods

- **Database of precomputed scenarios of unit sources.**
  - **1) Unit sources of given types, such as thrust earthquakes (propagation database)**
    earthquake scenarios are obtained from the superposition of unit sources
  - **2) earthquake scenarios of given locations and magnitudes**
    (from propagation to inundation).
  - **3) Unit tsunamis: unit uplift of seafloor for a given region or the globe.**
    In theory, this 1) is a subset of this approach.
    Earthquake of any focal mechanism can be approximated via the superposition of the unit tsunamis.
- **Forward tsunami model completely run in real-time.**
  TWCs around the world began to add this approach in their toolbox (PTWC since 2009).

Tsunami Forecasting Models used at PTWC

1. Database of precomputed scenarios

SIFT: Short term Inundation Forecasting for Tsunamis, developed by NOAA's Pacific Marine Environmental Laboratory (PMEL). Underlying Model : MOST (nonlinear shallower water model, splitting method).

It consists of propagation database for ~2000 unit sources:

100 km x 50 km (Mag=7.5, 1 m slip), mostly thrust earthquake scenarios for subduction zones.

Computed at 4-arc-min. but archived at 16-arc-min. resolution in the database (still occupying a couple of TB of disk space).

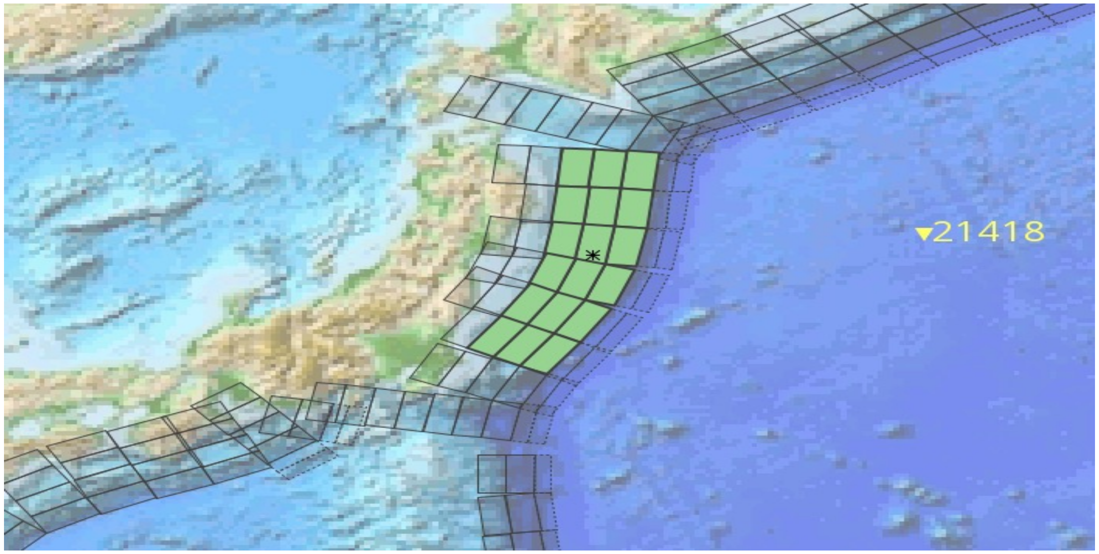
Method: superposition of unit sources (via inversion) to match observations at DARTs. The resulting propagation forecast is used as boundary/initial conditions to drive inundation models (standby inundation models or SIMs), which are mostly for the U.S. (62 in the Pacific and 22 in the Atlantic and Caribbean). They are run in real time during an event.

ATFM: Alaska Tsunami Forecast Model (Univ. Alaska and U.S. NTWC), non-linear shallow water equations.
Method: Precomputed coastal wave amplitudes (at about 450 U.S. locations in the Pacific and about 300 locations in the Atlantic/Caribbean) for about 1000 EQ scenarios (mostly of thrust type). Nested grids are used (including inundation results). EQ Magnitudes: 7,5, 7.9, 8.2, 8.6, 9.0, 9.2, 9.5 (operator selects the closest location and magnitude and scale with observed amplitudes).

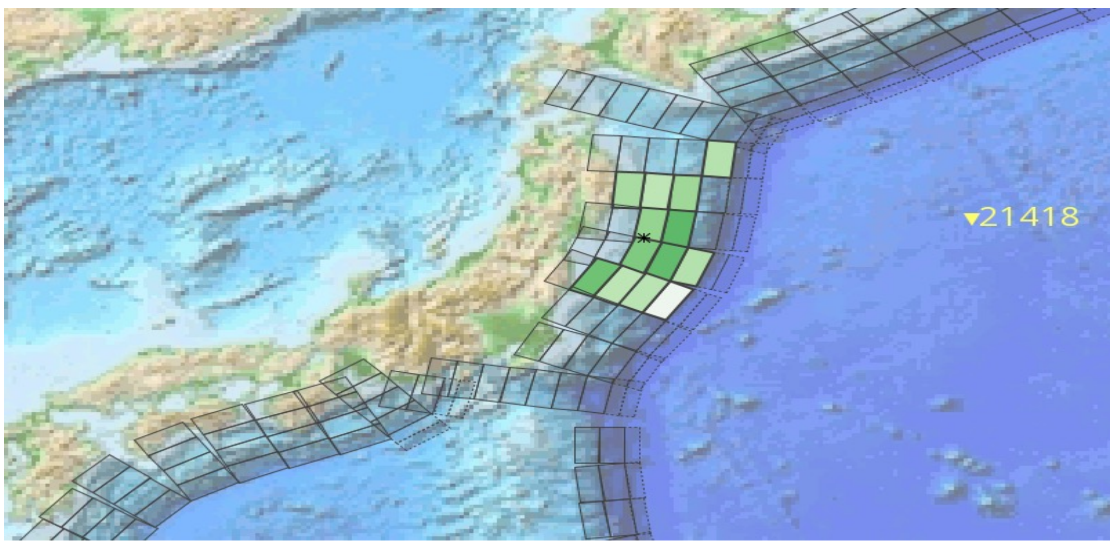
2. Rea-time model: RIFT (Real-time Inundation Forecasting for Tsunamis). Linear shallow water equations in spherical coordinates. Currently, there is no inundation component in RIFT, so the acronym is a misnomer.
An alternative name could be: Rapid Inclusive Forecasting for Tsunamis.

Strengths and weaknesses of different approaches of forecasting

	Scenario Database (ATFM)	Unit Sources Database (SIFT)	Real-Time Model (RIFT)
Strengths and features	1. Fastest. Basin-wide forecast can be obtained instantly. The database includes inundation results. 2. Scaling with OBS 3. Good for Hazard analysis	1. Fast (propagation) 2. Superposition of unit sources. 3. Inversion with DART observations 4. Have an real-time inundation component or SIMs for many (mostly U.S.) locations. 5. Good for Hazard analysis (TsuCat) Newer version has real-time propagation forecast capabilities. When will it be delivered to the TWCs?	1. Can accommodate any EQ (versatile) . 2. Fast enough for a regional domain (seconds) 3. Can handle global tsunamis, currently database models do have such capabilities.
Weaknesses and caveats	1. Finite number sources. Cannot cover all possible earthquakes. 2. Costly to generate and maintain a large database.	1. Finite number of sources. Cannot cover all possible earthquakes. 2. Costly to generate and maintain a large database. **If physics changes/model improves, entire database needs to be regenerated**	1. Linear model, Green's law for estimating coastal wave amplitudes is crude, order magnitude estimate. 2. RIFT currently does not have an inundation component.



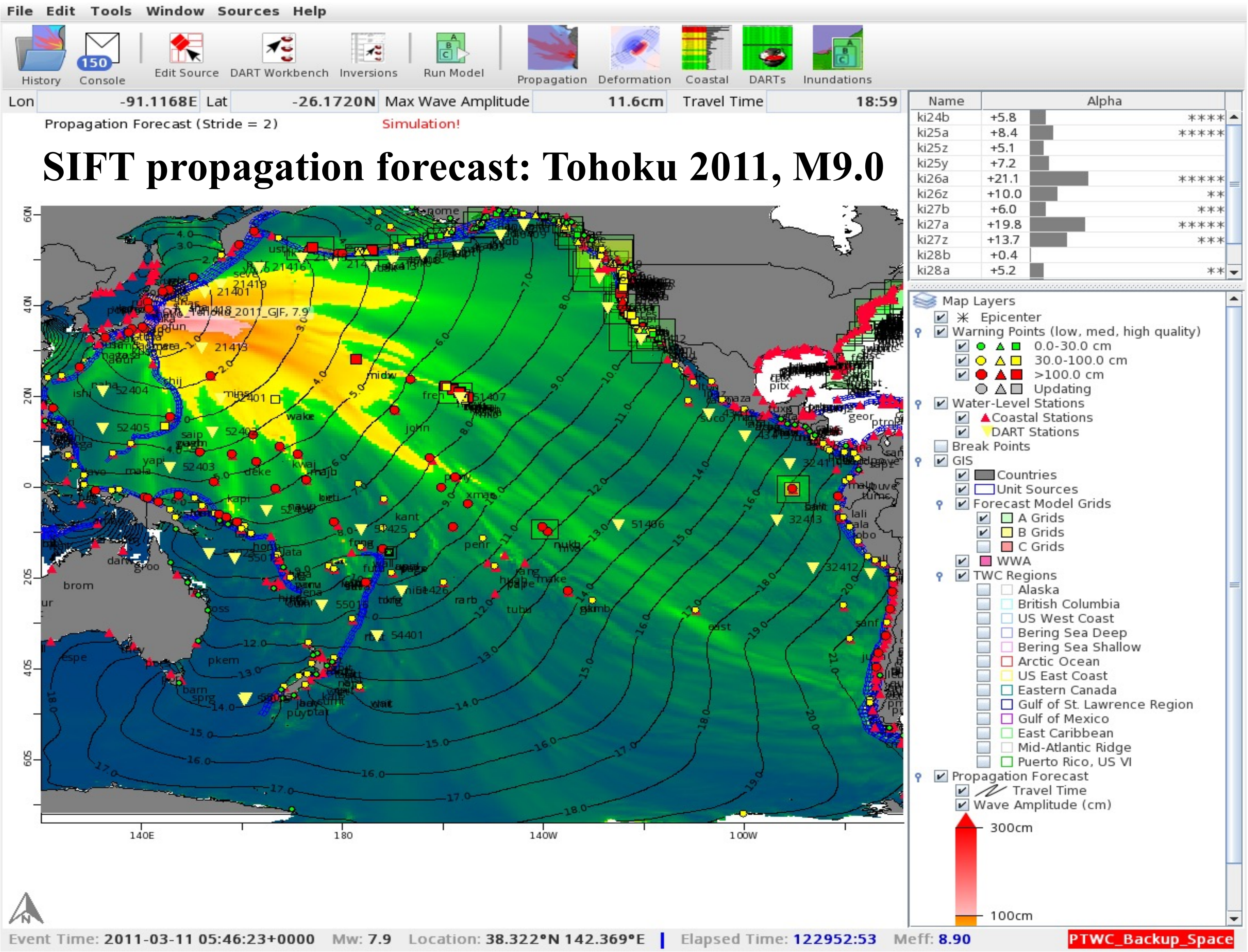
SIFT
Tohoku 2011, M9.0
Default source
Which you might use in ComMIT



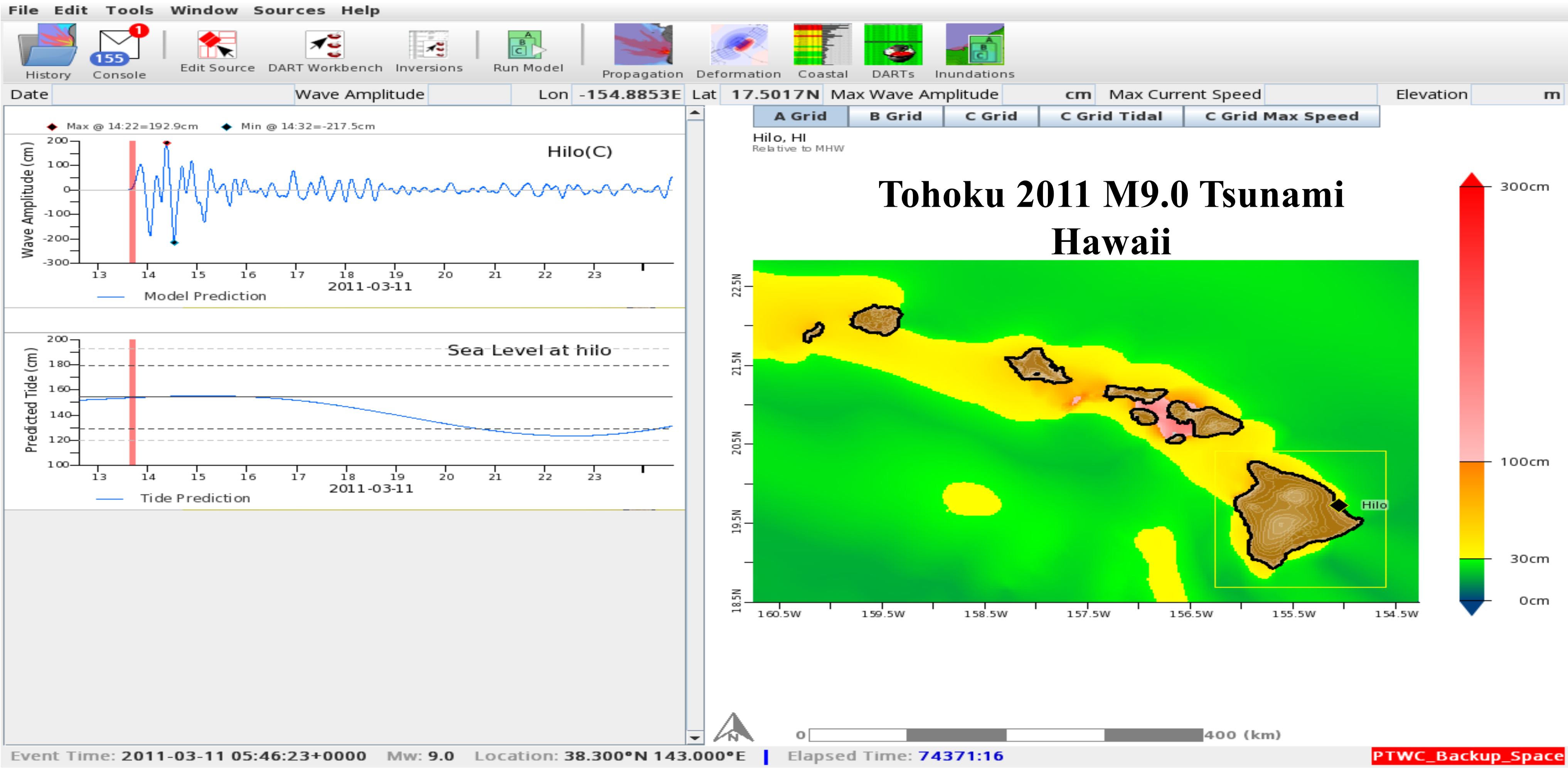
SIFT
Tohoku 2011, M9.0
Sources after
DART inversion

Resulted in very good forecast for the U.S. during the event.

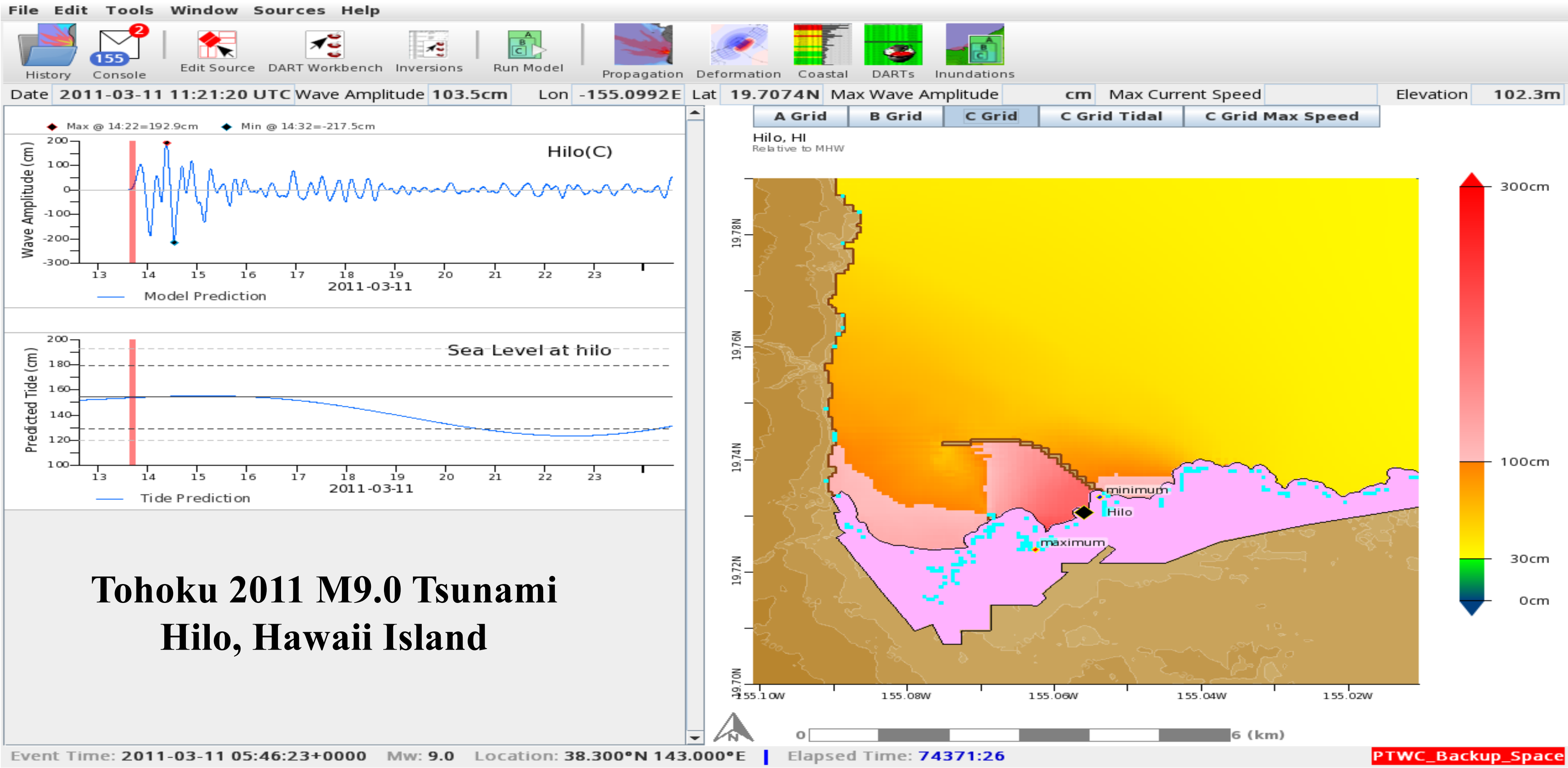
SIFT propagation forecast: Tohoku 2011, M9.0



Inundation forecast: A-grid

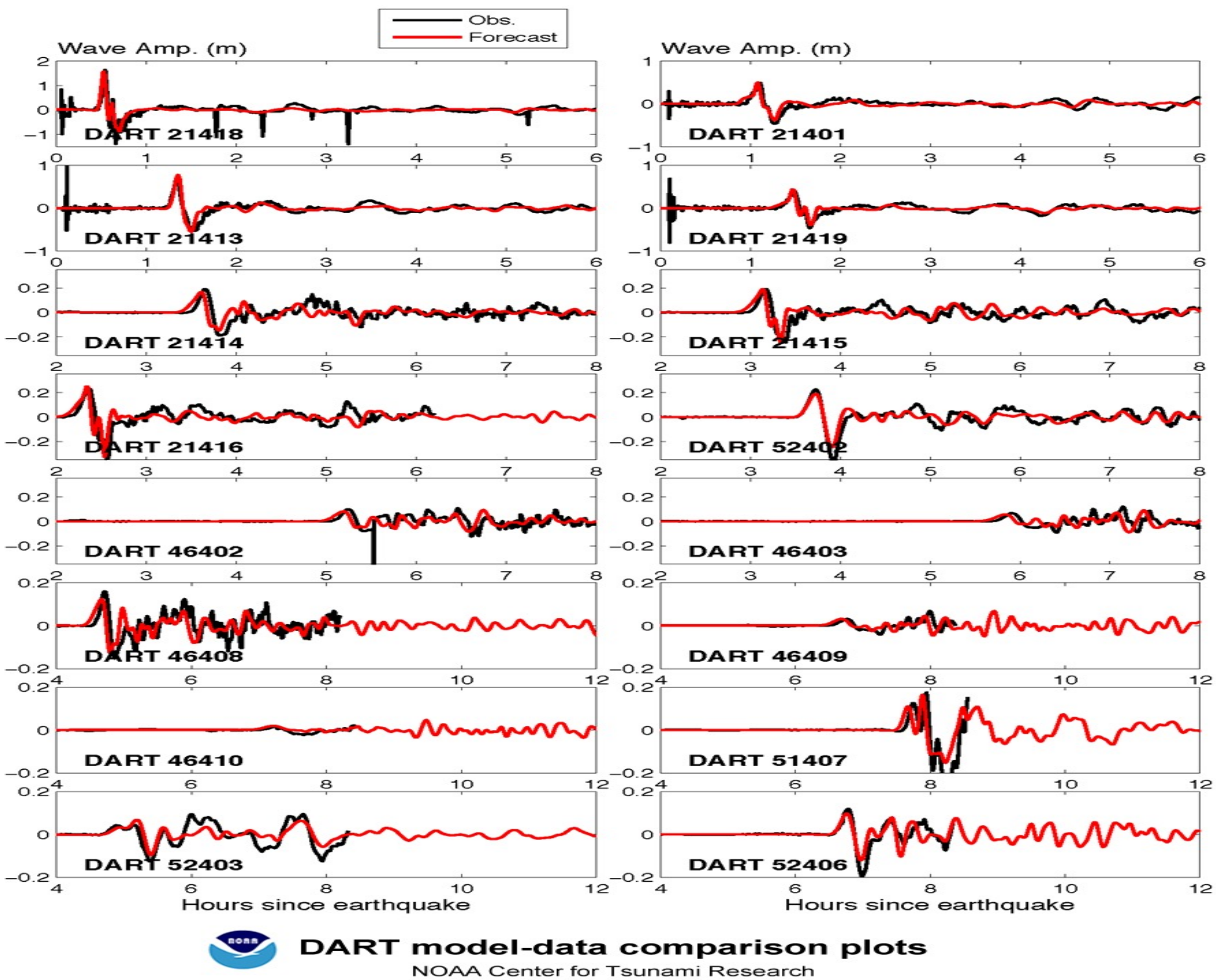


Inundation forecast: C-grid



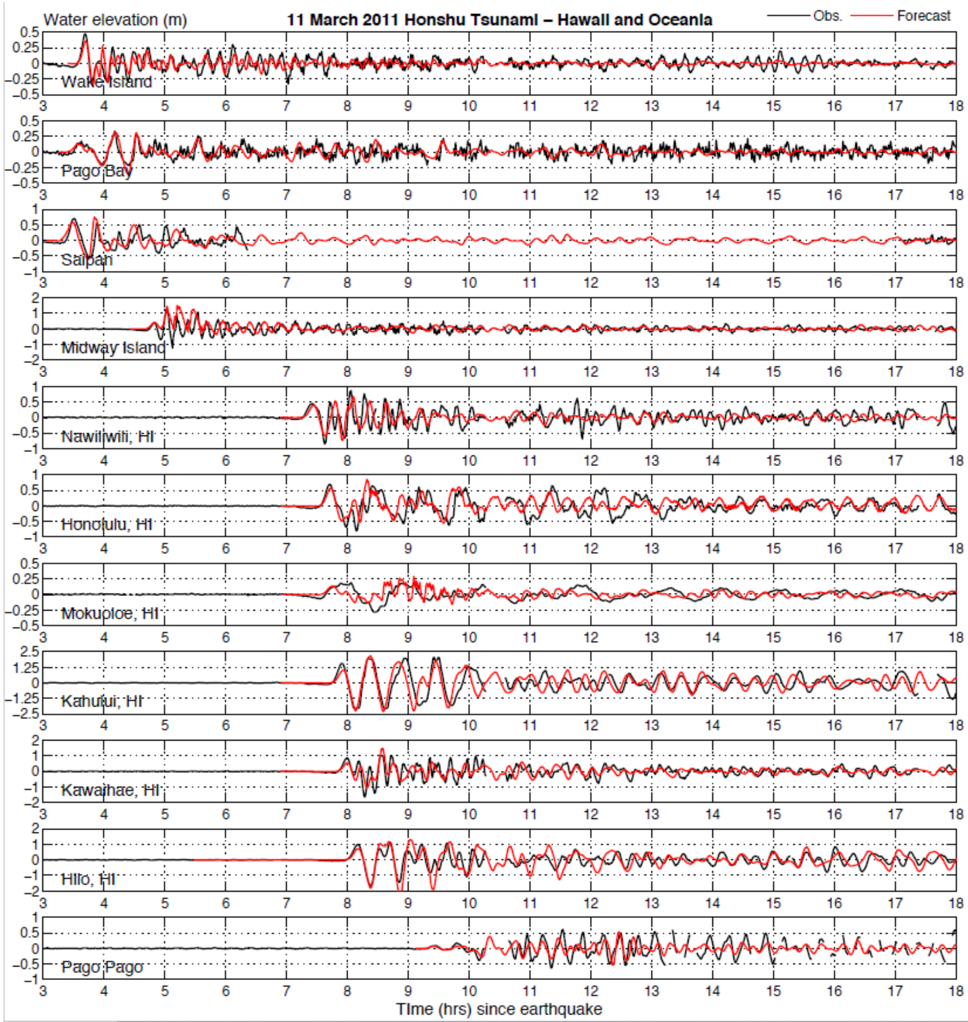
Tohoku 2011 M9.0 Tsunami
Hilo, Hawaii Island

2011 Tohoku Tsunami: SIFT vs. DART after DART inversion.



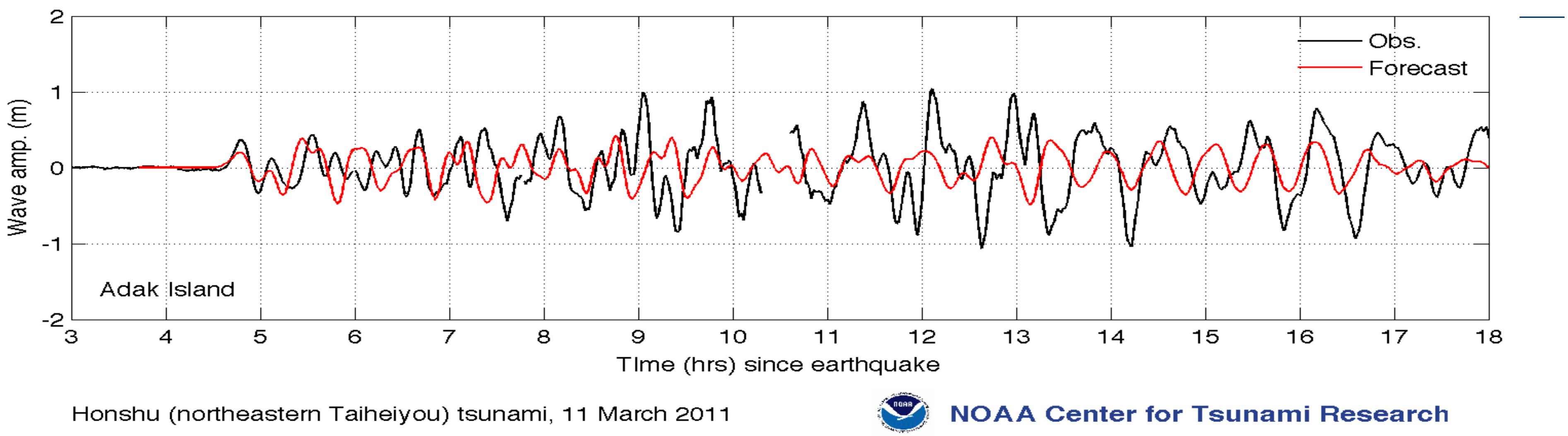
Before inversion, the results were not very good, but were spectacular after inversion using 3 DARTs.

2011 Tohoku Tsunami: SIFT/SIMs vs. DART after DART inversion.



SIM: standby inundation models (similar to the C-grid in ComMIT). Very good comparison for most of Hawaii gauges.

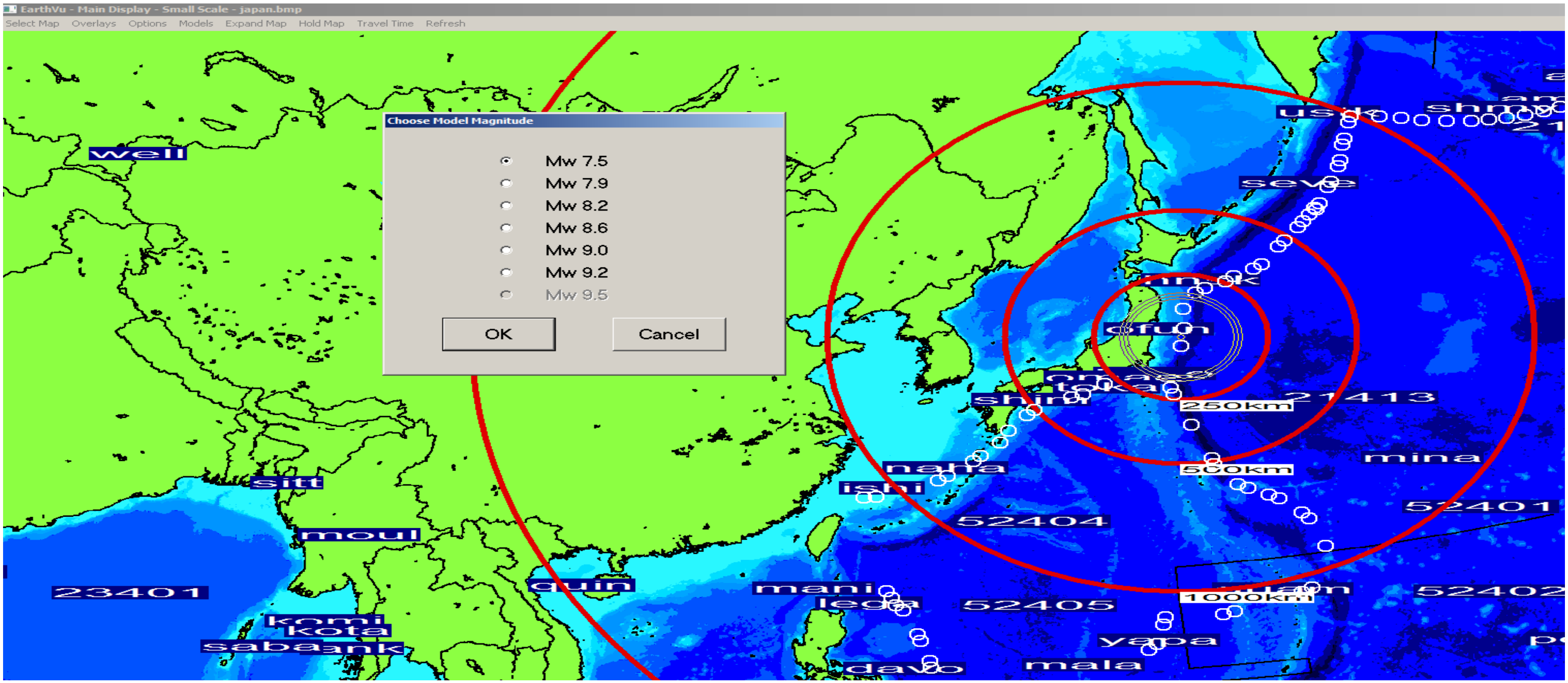
Maximum wave amplitude at Adak, Alaska occurred 9 hours after the initial arrival (Tohoku 2011 Tsunami)



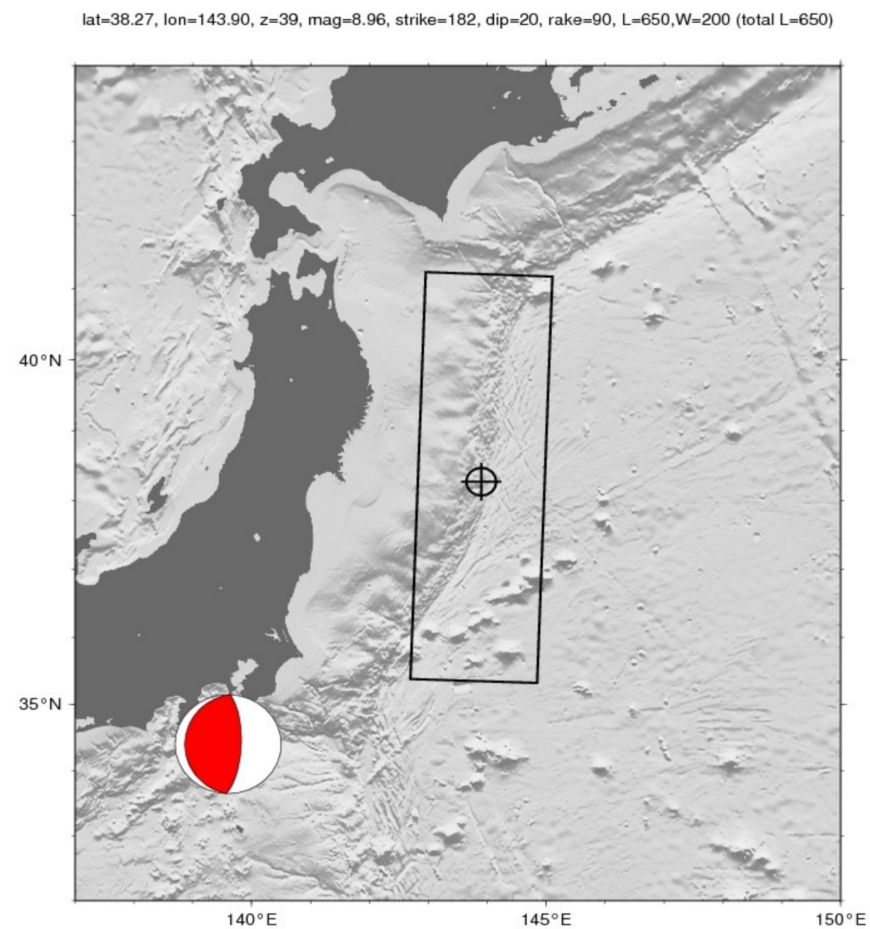
As good as SIMs are after DART inversion: inundation models at specific locations can still be in large error as seen above, the maximum amplitude from the inundation model (SIM) was only about 1/3 to 1/2 of the observed at tide gauge Adak, Alaska.

ATFM sources in the Japan Region

Source can be selected by entering EQ coord. or by mouse selection.

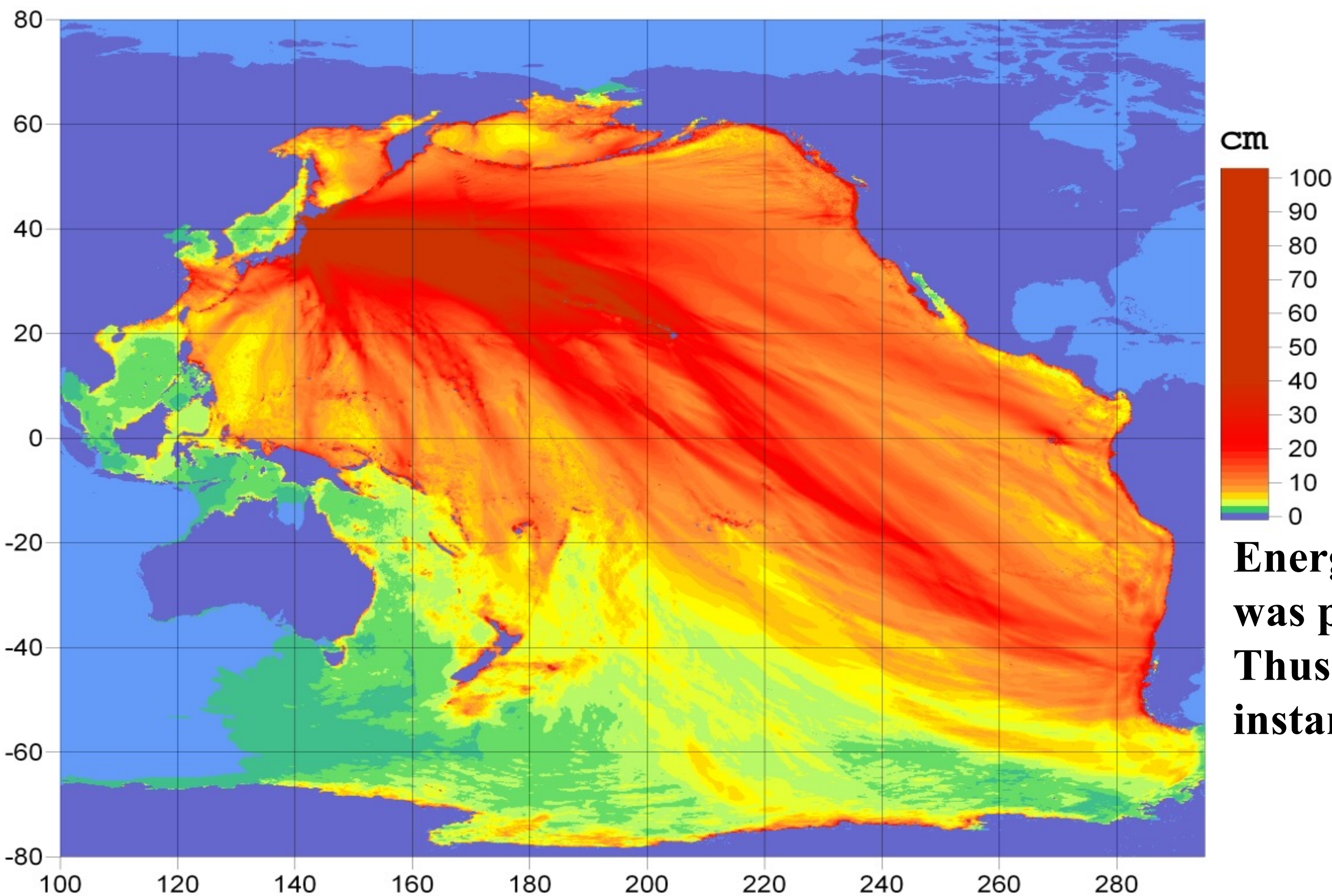


ATFM closest source for Tohoku 2011, M9.0



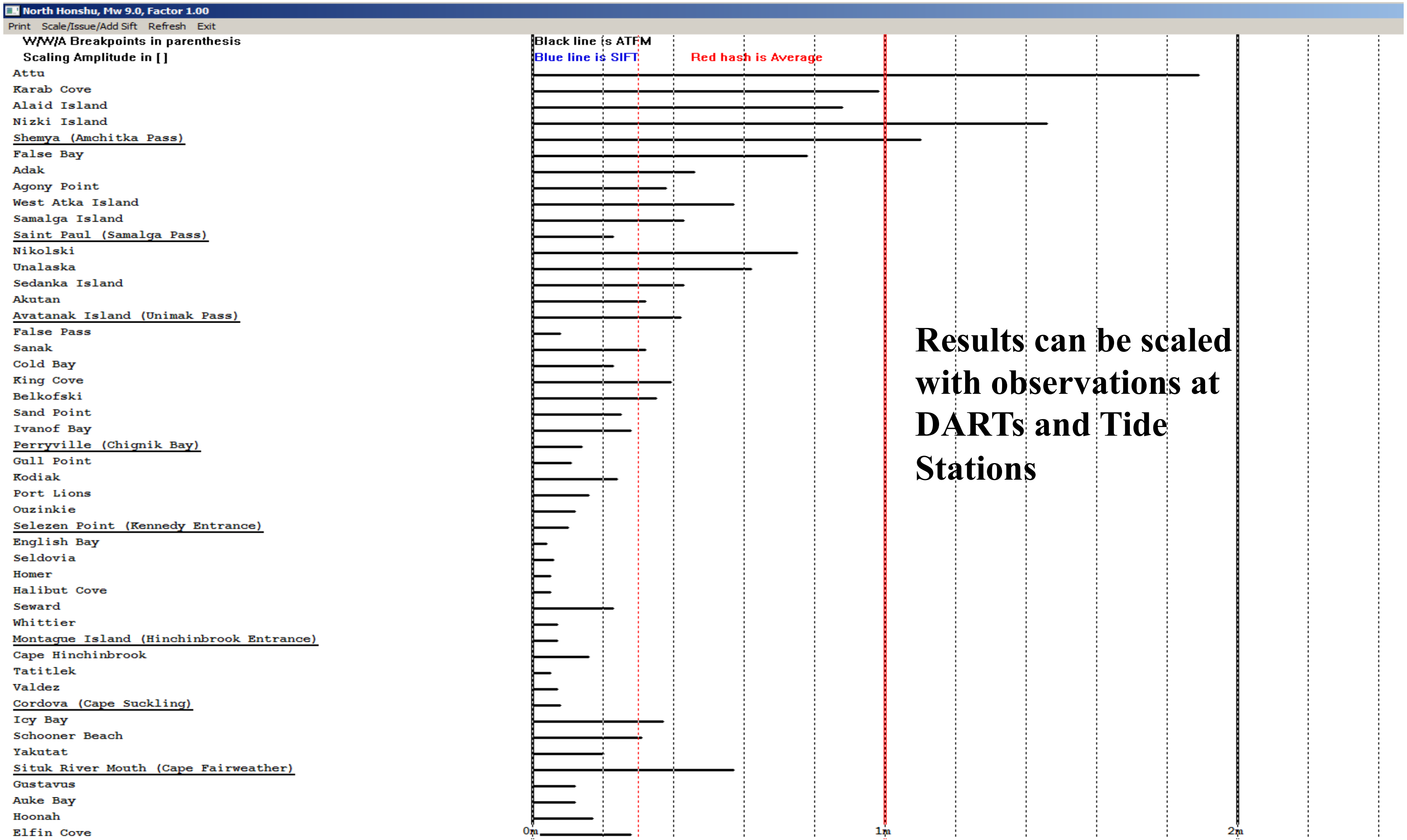
100 km from the epicenter but not significant because of the large size of the earthquake.

ATFM results for Tohoku 2011, M9.0



Energy map was pre-generated, Thus retrieving the results is instantaneous.

ATFM results for Tohoku 2011, M9.0



Results can be scaled with observations at DARTs and Tide Stations

2. RIFT
Real time forecasting using actual EQ parameters and focal mechanisms

Real-time computation is made possible by the advance in seismology: the so-called W-phase method (Kanamori and Rivera 2008), which solves the earthquake magnitudes and focal mechanisms in real-time, typically 10-30 min. after EQ origin.

PTWC started real-time tsunami propagation forecasting in 2009 (RIFT).
Now many tsunami warning centers around the world have the real-time forecast capability.
The newer version of SIFT will have real-time propagation forecast capabilities, to be implemented at U.S. TWCs.

Approach:
1. For speed, a regional domain is used for an initial forecast (within a few hours of tsunami arrival time), tsunami forecast can be obtained in a matter of seconds, using preliminary EQ parameters.

2. Basin-wide forecast is computed next. For the PTWC enhanced product Pacific domain (98E-50W, 75S-65N), It takes about 7 min. to obtain a 36-hr forecast at 4-arc-min. resolution on a 12-cpu Linux server.

Description of the PTWC RIFT Model

- **The RIFT model is run completely in real-time using real-time EQ parameters.**
- **Physics: Linear shallow water equations (shallow water model).**
  Numerics: Arakawa C-grid in space and leap-frog in time.

Bathymetry: GEBCO 30-arc-sec. grid

Currently, RIFT is the only model available at PTWC for forecasting tsunamis generated by local earthquakes in Hawaii (no SIFT/ATFM sources for Hawaii).

The RIFT Model domain

- Automated model domain based on tsunami travel time.
- For a large earthquake (M>=7.8), the model domain for an initial forecast includes regions within 5-6 hours of tsunami arrival time (typically takes order 10 seconds to finish at 4-arc-min. resolution).
- For smaller earthquakes (magnitude < 7.7), resolution and domain size are magnitude dependent. For a magnitude 6.6 earthquake, for example, 30-arc-sec. will be used (the computation domain will be smaller, as the tsunami will not impact far fields.
- There are about 40 Pre-defined ocean basins and marginal seas, including the global ocean. For the Pacific basin (98.5E-50W, 75S-65N) at 4-arc-min. resolution, 36-hour integration takes about 7 minutes.
- The operator can also enter domain parameters and integration length manually or select the domain graphically.

Default focal mechanisms:

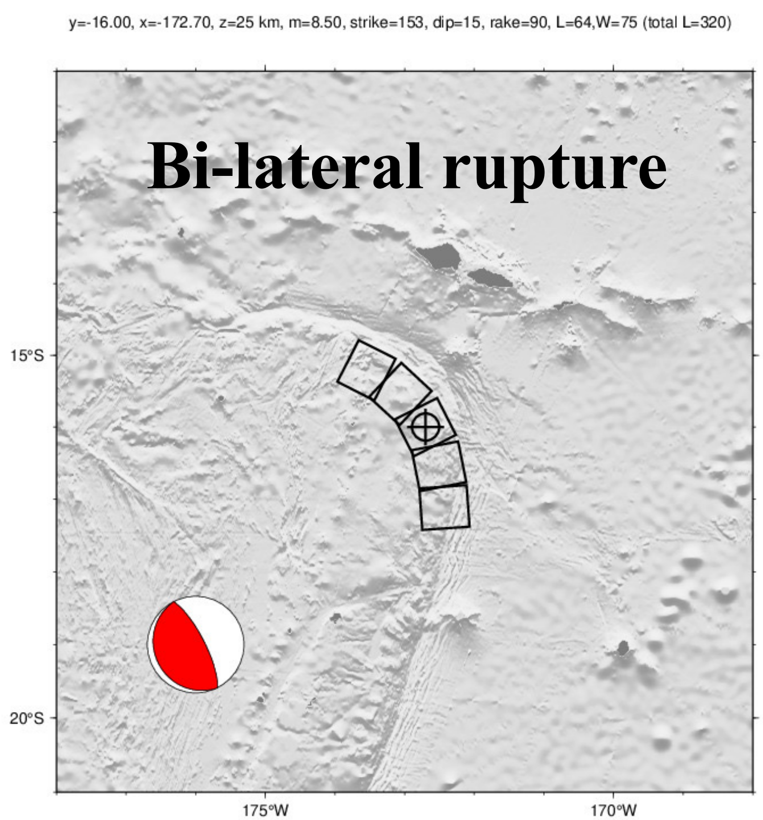
- Historical centroid moment tensors (>60,000 CMT solutions since 1976).
- Default focal mechanism based on EQ epicenter proximity to the type of fault type (USGS). For subduction zones, Slab Model 2.0 is used.

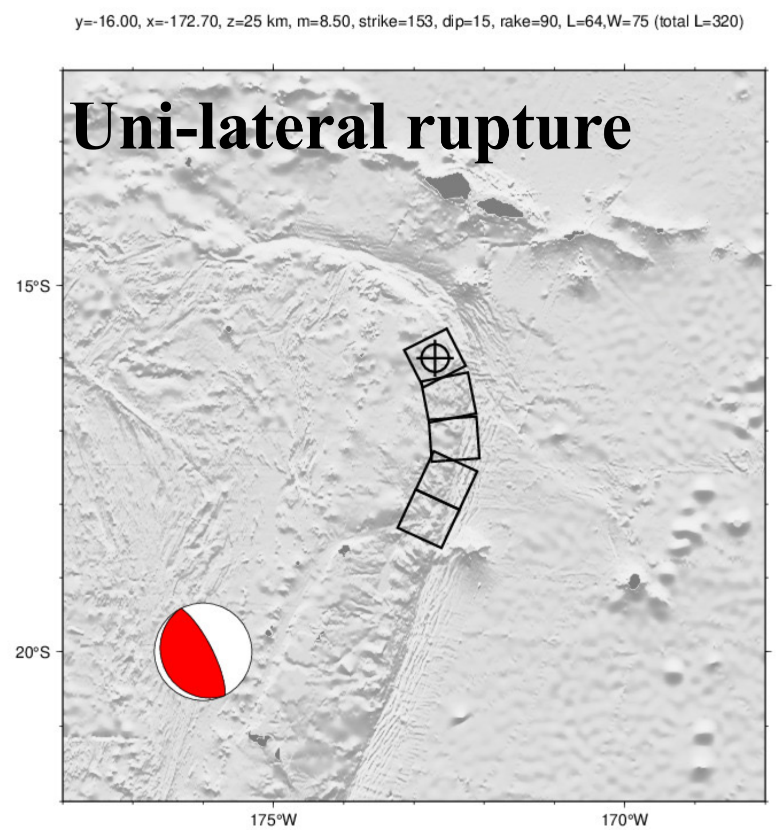
  For regions of curved fault lines, curved sources can be used.

- Real-time focal mechanisms:
  - W-phase Centroid Moment Tensors (PTWC, USGS, CPPT).
  - Global Centroid Moment Tensors (when available)
- Seafloor deformation: Okada (1985) static dislocation model, assuming uniform slip (RIFT can handle finite fault solutions, but the slip distribution on sub-faults are usually unknown early on during an event).

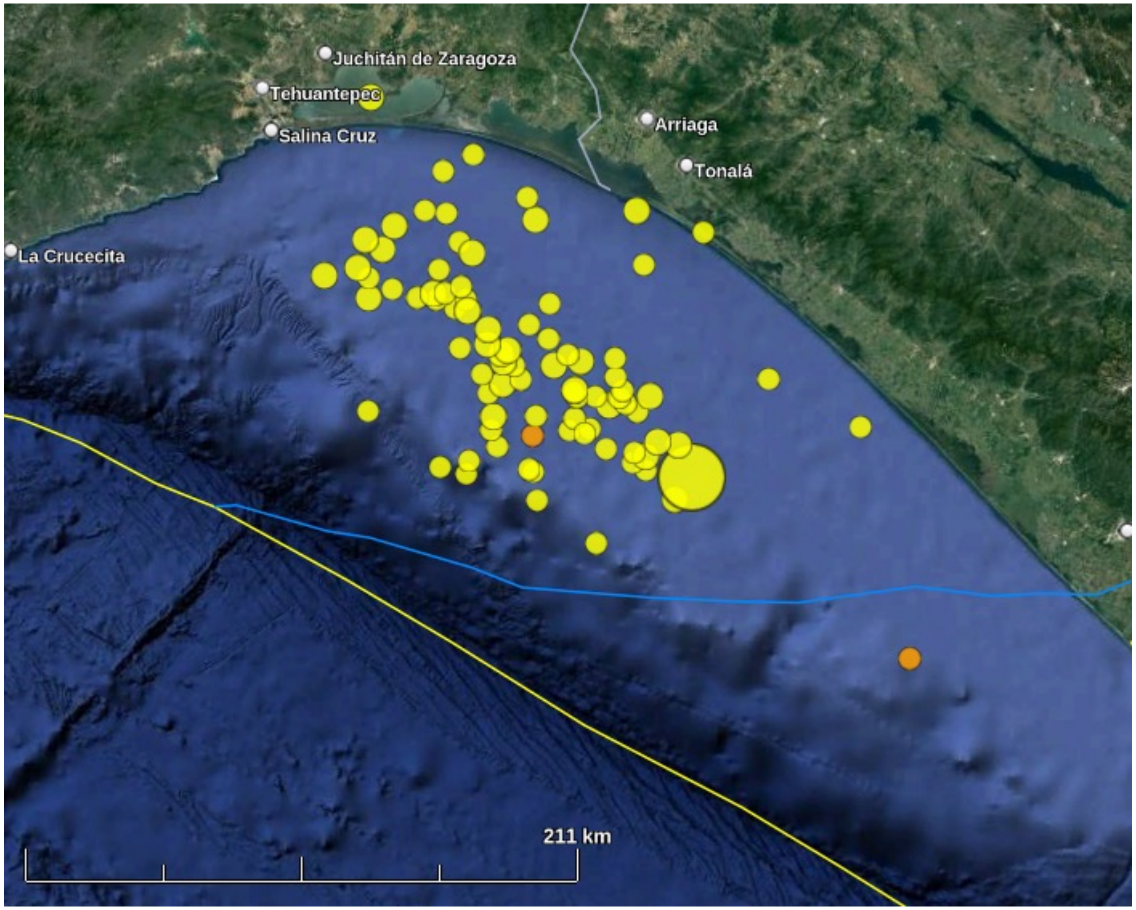
Leap-of-faith: CMT (point source) → rectangular fault → Seafloor deformation

Curved source, Uniform slips on each sub-fault
(can be non-uniform if desired: random or manually selected)



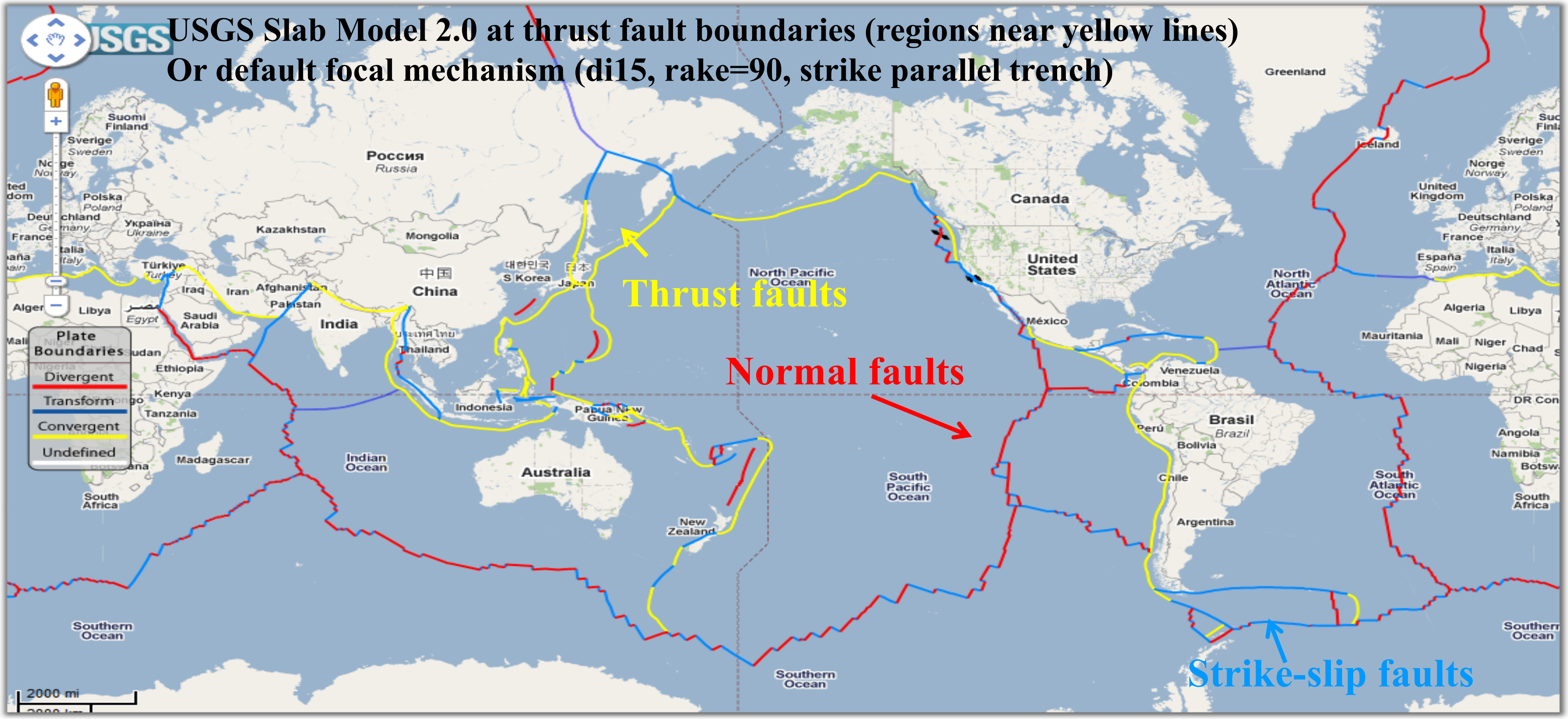


2023.09.08 Mexico M8.2 Earthquake



Uni-lateral rupture

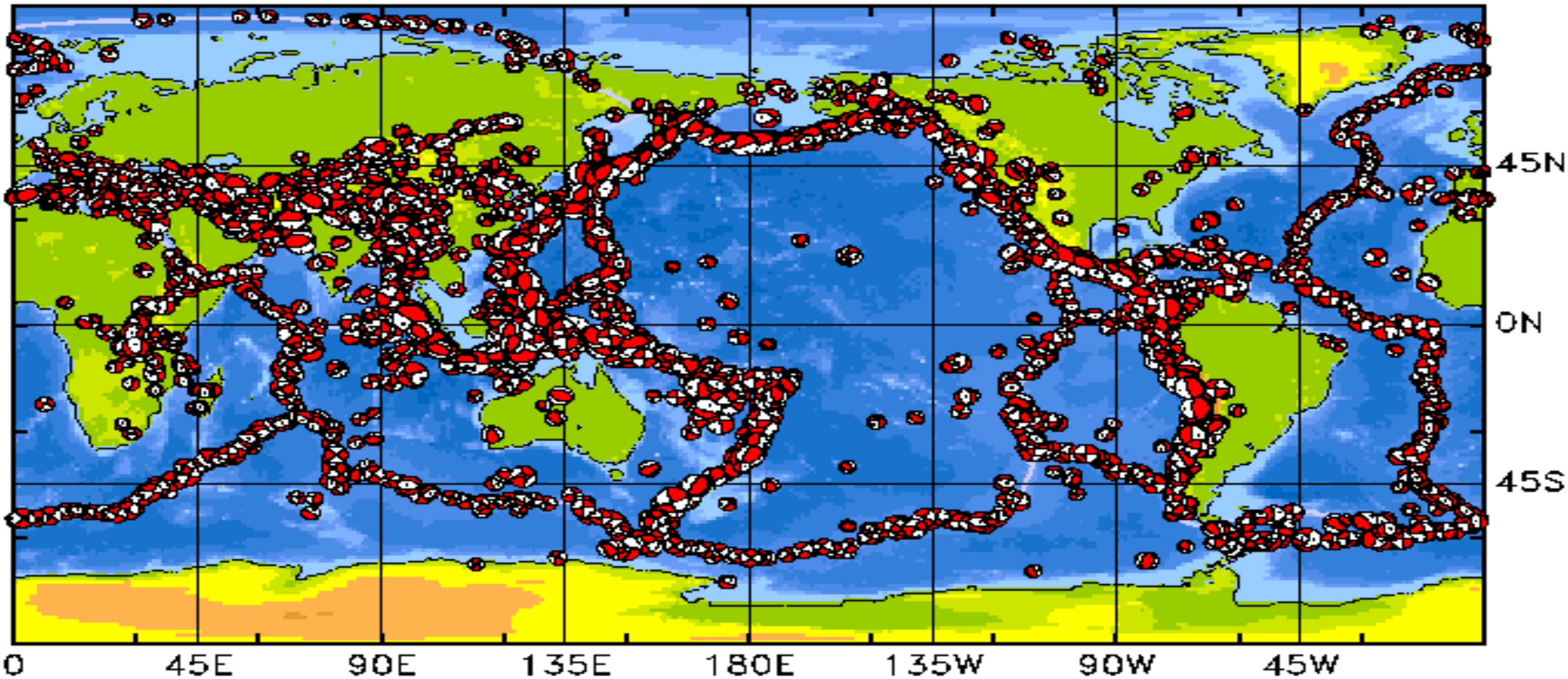
Automated default focal mechanisms based on earthquake's proximity to the type of plate boundaries (credit: USGS). For subduction zones, the Slab Model 2.0 will be used.



Manual search (for a given location) of historical focal mechanisms of the Global CMT catalog (>60,000 events as of 2023)

Map below shows shallow earthquakes, 1976-2005.

Credit: http://www.globalcmt.org/



Green’s Law Coastal Forecast (Green, 1837)

$$A_c = A_o \left(\frac{H_o}{H_c}\right)^{\frac{1}{4}}$$

Ho: water depth of an offshore point in deep water.
Hc: water depth of a coastal point (assumed to be at 1 m).
Ao: offshore wave amplitude in “deep water” = 0.5*(max-min)
Ac: Green’s law coastal wave amplitude

Offshore point in deep water: closest model grid point in deep water. The offshore water depth is chosen such that the waves with 10-min. period can be resolved by the model grid (eight grid points within one wavelength, Wang et al. 2012). Therefore, “deep water” is a function of resolution. For example,

At 4-arc-min. resolution, Ho >= 996 m (in regions of steep bathymetry, Ho can be
At 2-arc-min. resolution, Ho >= 249 m larger than these values, e.g., the closest
At 1-arc-min. resolution, Ho >= 62 m wet model point is already in deep water)
At 30-arc-sec resolution, Ho >= 16 m

This is probably too large. Used to be 50-100km

If an offshore point in deep water (z>=Ho) is not found within a 300 km radius from a coastal point, there will be no forecast at that point. This essentially excludes wide continental shelves at 4-arc-min. resolution. Higher resolution is needed to have a Green’s law forecast for those regions.

Line of sight exclusion: if the line connecting a coast point and offshore point encounters land, there will be no forecast for that coastal point.

Model grid points:

X X X X X X X X X X X X O O O O O O O O O O O O

X X X X X X X X X X X O O O O O O O O O O O O O

X X X X X X X X X X O O O O O O O O O O O O O O

X X X X X X X X X O O O O O O O O O O O O O O O

X X X X X X X X O O O O O O O O O O O O O O O O

X X X X X X X X X X O O O O O O O O O O O O O O

X: land/dry point (Z >= 0)
O: Model ocean/wet point (Z < 0).
Offshore point: the first ocean/wet point next to a dry point (blue Os).
It is also called coastal wet point.

Ocean point in deep water used in Green's law (red Os):
The closet wet point with Z>=Ho, where Ho is a function of resolution
(=992 or ~ 1000 m at 4-arc-min. resolution)

In the RIFT model: land, offshore, and deep water points used for Green's law are computed on the fly.

The true coastline (or 1-m isobath for Ac, Hc) is somewhere between the X and O points.

Underlying Assumptions/Caveats of the Green's Law

- **The coastline is linear and exposed to the open ocean. Therefore, it is assumed that tsunami waves near the coast behave like one-dimensional plane waves. It is not intended for forecasting at locations that are well-hidden from the open ocean (it tends over predict). It is also not intended for forecasting at bays or harbors that exhibit resonance behavior (at 4-arc-min. resolution, bays and harbors might be resolved).**

- **There is no significant wave reflection and there is no turbulence dissipation. In the real world, dissipation is important in shallow water. The seafloor composition has an influence on tsunami run-up (e.g., coral reefs tends to dampen the tsunami run-up).**

- **The bathymetry is assumed to be slow varying compared to the wavelength of the tsunamis. Thus, for locations with steep bathymetry (such as small islands and atolls), the Green's Law forecast tends to overestimate the wave amplitudes, everything else being equal.**

There are other kinds of implementations of the Green's laws:

NOAA/PMEL:

Offshore point is defined as the closest model wet point to a warning point or a tide gauge. To be changed?

Advantage: There is always a forecast for any coastal location.

Caveat: The water depth can be 20 m or 2000 m, i.e., not necessarily from the resolved waves (waves at 20 m water depth cannot be resolved by using 4-arc-min. resolution, for example.)

Slope dependent Green's law: Reymond et al (2012)

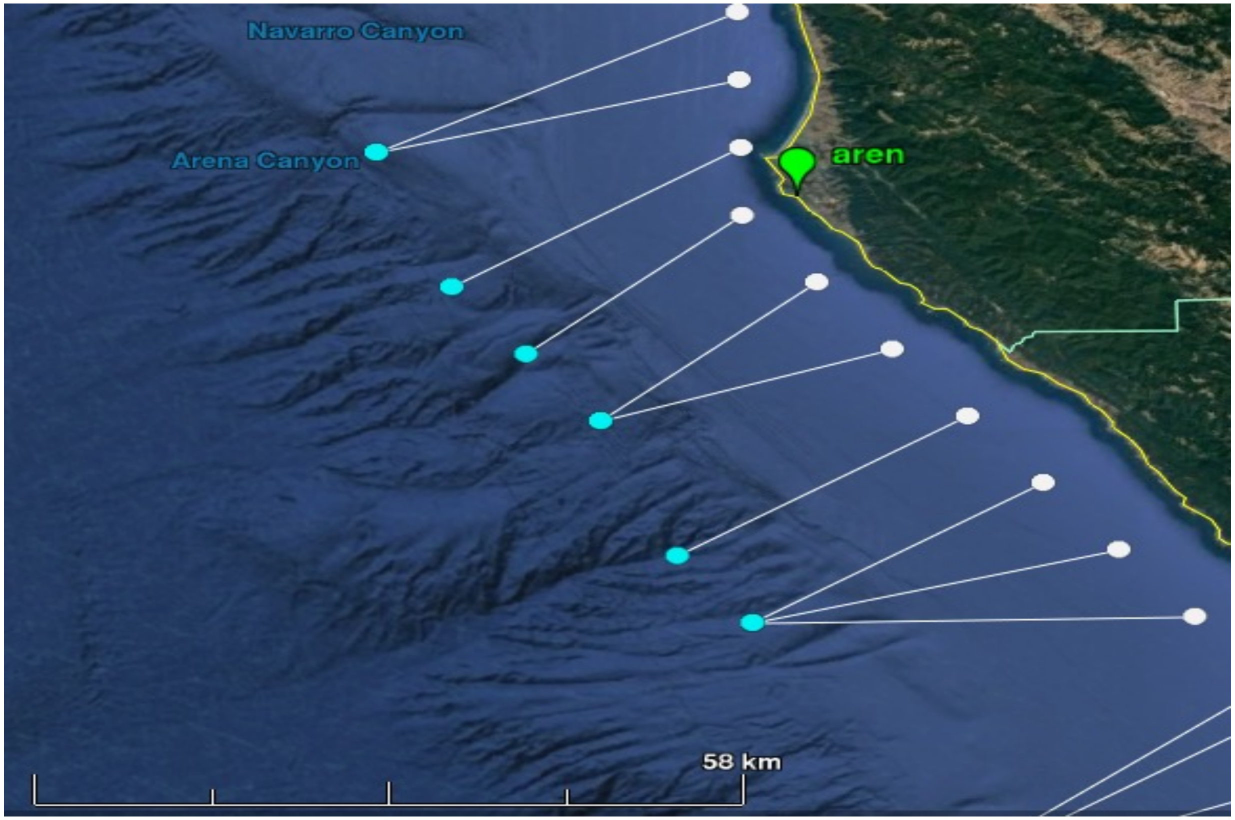
Advantage: worked very well for French Polynesia

Caveat: tuned to specific locations, difficult to apply to coastal locations where there are no historical data to compare/tune.

PTWC's approach of using offshore points in deep water within 300 km does not guarantee a forecast at every coast point at coarse resolution. With higher and higher resolution (1-arc-min. or 30-arc-sec resolution, for example), there will be more coastal points having a Green's law amplitude.

At 4-arc-min. resolution, the RIFT model does not really know where exactly the tide stations are located. However, comparisons with tide stations that are more exposed to the open ocean can be helpful in assessing the quality of forecast (e.g. for the tide station in Arena Cove, California, U.S.)

We call stations like are "open ocean" gauges



White dots are model wet points and cyan dots are offshore points in deep water (depths of which are used in the Green's Law computation)

Note that more than one coastal point might share the same closest offshore point, thus having the same forecast. In other words, the distribution of coastal wave amplitude might be more uniform than in reality.

Comparison of Green's law coastal forecast with tide stations that are hidden or too far from the open ocean is not meaningful, as is shown below (white dots are model coastal points, cyan dots are offshore points used in the Green's law).

sitk and paak are labeled as "hidden gauges"

Note the Sitka tide station is many kilometers away from the model coastal wet points (white dots).

Forecast at the model coastal wet points should be interpreted as forecast for the adjacent coastline exposed to the open ocean, not necessarily at the tide station location.

Another example of a hidden tide station. This tide station (in Kwajalein Atoll) is inside the lagoon, not exposed to the open ocean. Comparison of observation at this station with Green's law (meant for the open ocean side) would not be very meaningful.

Typical Workflow:

0-10 min: RIFT will be run automatically run for events with mag>=6.3 when an observatory message is issued, using a regional domain.

10-30 min: Refined Regional forecast using W-phase CMT for a regional domain, then the whole ocean basin, if warranted.

30 min.-end: Compare RIFT with observations, rerun RIFT with updated EQ parameters/focal mechanisms if necessary (such as scaling).

Forecast Sensitivity to Earthquake Parameters

Earthquake Parameters (depth, location, magnitude) refer to:

- **PTWC Preliminary EQ epicenter, depth, and magnitude**
- **W-Phase centroid moment tensor (WCMT) centroid location (depth and horizontal location), moment magnitude (Mww) and focal mechanisms (strike, dip, and rake angles of the fault planes).**

Forecast Sensitivity to Earthquake Magnitude

Estimates of earthquake magnitudes can be easily off by 0.2, which corresponds to roughly a factor of two in term of energy/moment release, and thus roughly a factor of two in tsunami wave amplitudes, if the source dimensions remain the same.

Source dimension (fault size) usually increases with magnitude/moment, a 0.2 increase in magnitude (or a factor of two in moment) roughly corresponds to 50% increase in fault size (a factor of 1.5), thus wave amplitude roughly increases by 2/1.5 = 33% (local effects can cause significant deviations from this).

RIFT Forecast Sensitivity and Uncertainties

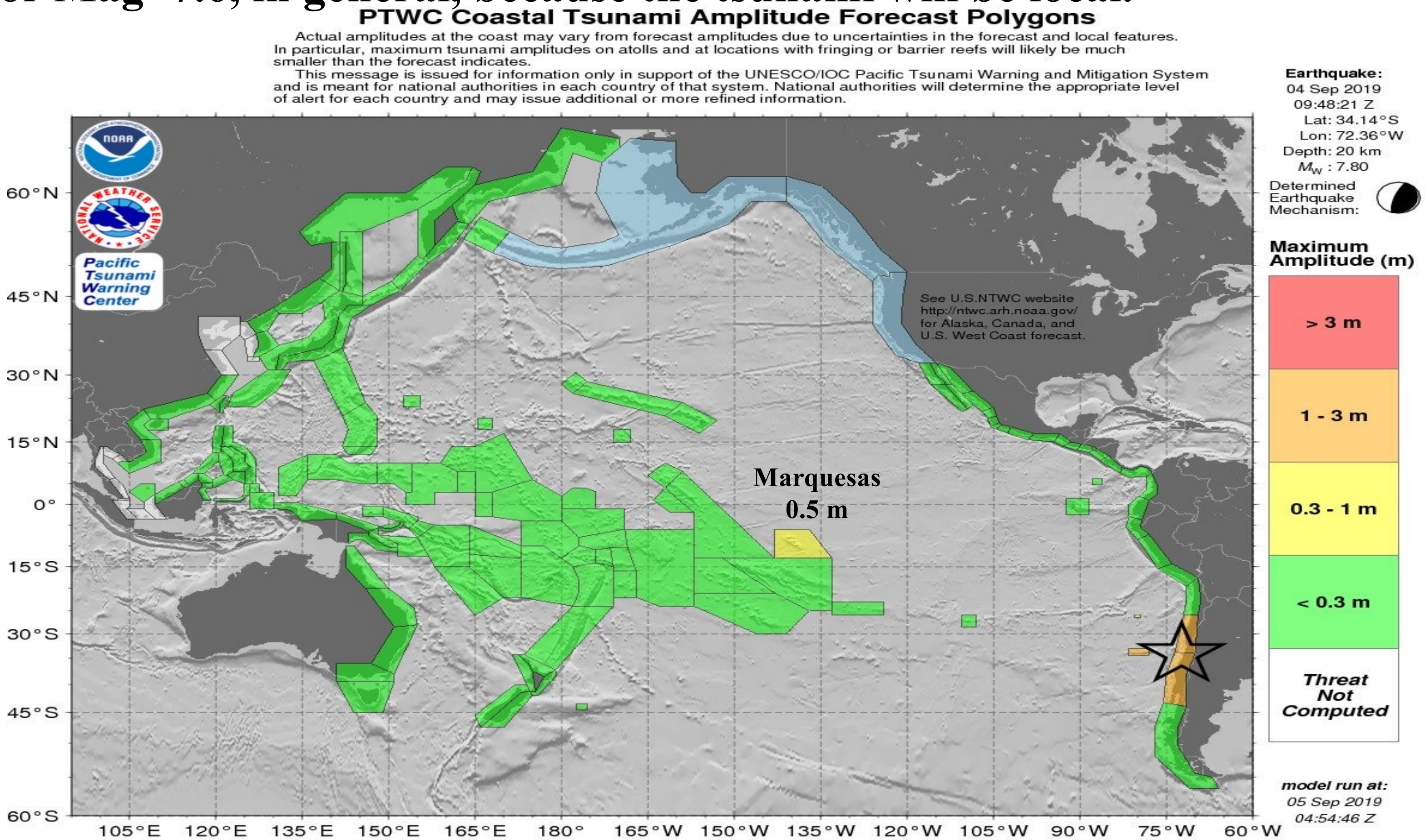
- There are many uncertainties in the RIFT forecast due to uncertainties in earthquake magnitude (can be easily off by 0.2), location, depth, and focal mechanism (strike, dip, rake). Any of these uncertainties can easily result in a factor of two or more difference in forecast.

- For very large earthquakes, the uniform slip assumption on a rectangular fault might be unrealistic, resulting in erroneous propagation forecast and thus erroneous coastal forecast. Details of rupture, which might be unknown during the event can be important, especially for the near field. (Sumatra 2004 tsunami resulted from a unilateral rupture). (uniform slip can underestimate tsunami significantly).

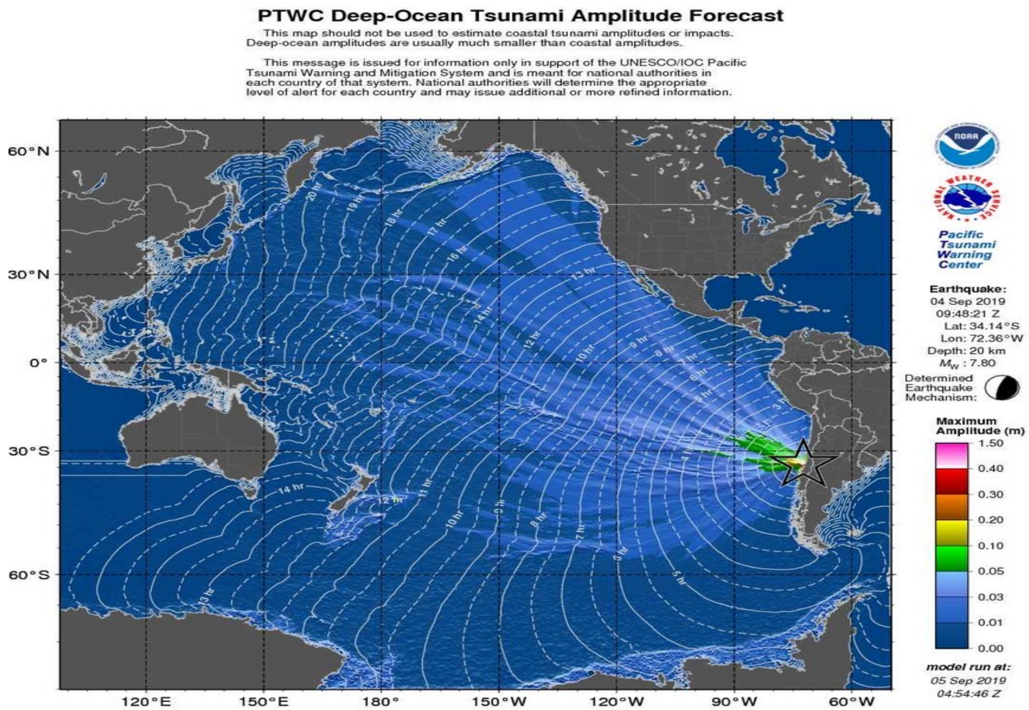
- The Green's law coastal forecast is crude. Even if the propagation forecast is correct, the coastal forecast might still be in error, especially for regions of complex bathymetry (e.g., the tendency to under-predict for resonant harbors and over-predict for coastlines well-hidden from the open ocean).

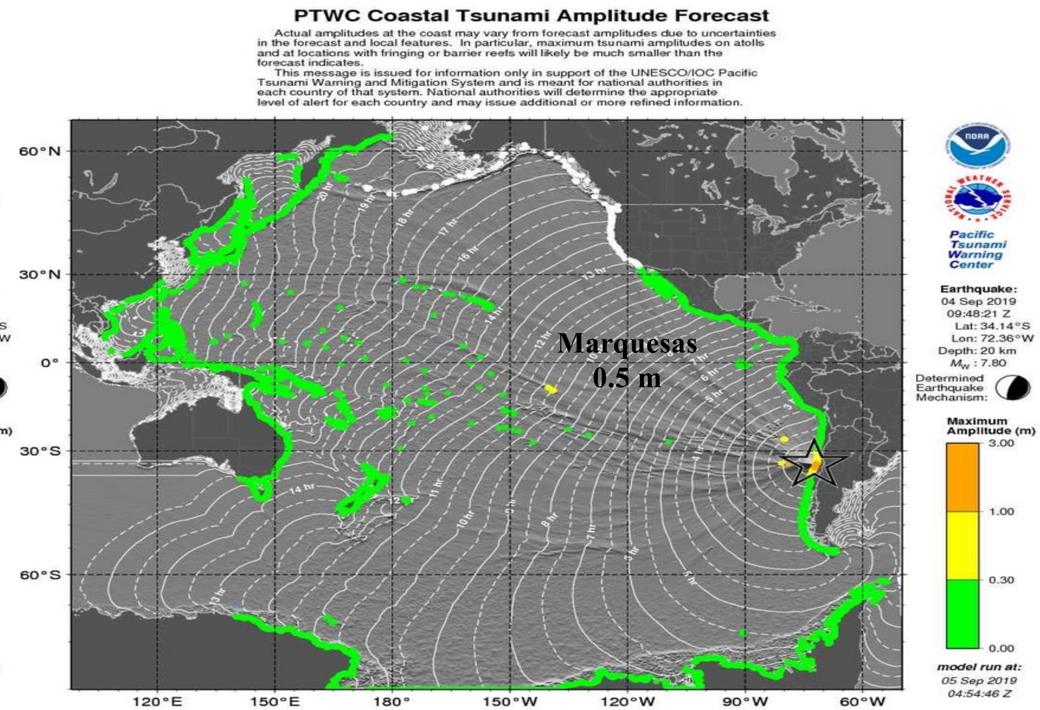
- Model resolution used might also have some effect.

Mw (Mag)=7.8
There is no need to integrate the model for the whole Pacific basin for Mag<7.6, in general, because the tsunami will be local.

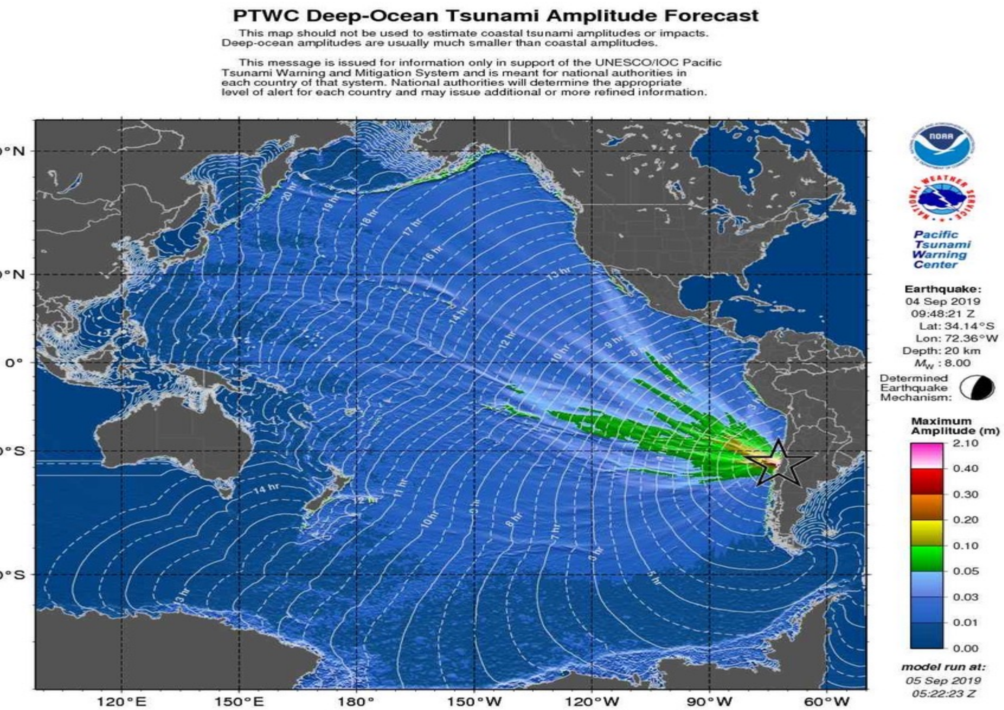


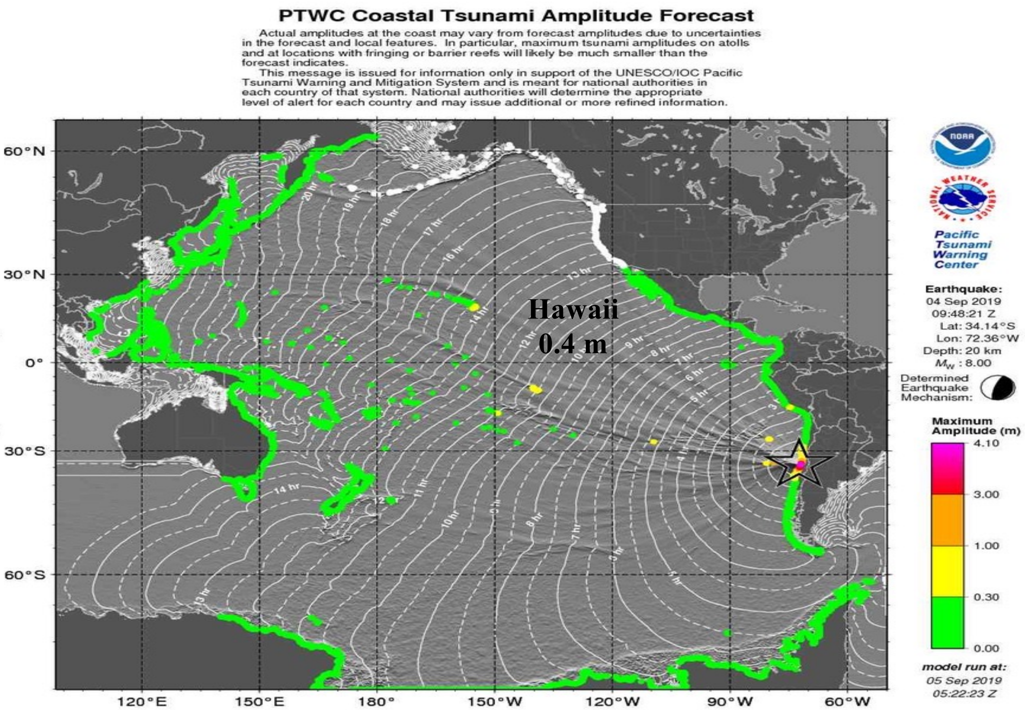
Mw (Mag)=7.8


PTWC Deep-Ocean Tsunami Amplitude Forecast
This map should not be used to estimate coastal tsunami amplitudes or impacts. Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
Mw : 7.80
Determined Earthquake Mechanism:
Maximum Amplitude (m)
1.50
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
04:54:46 Z

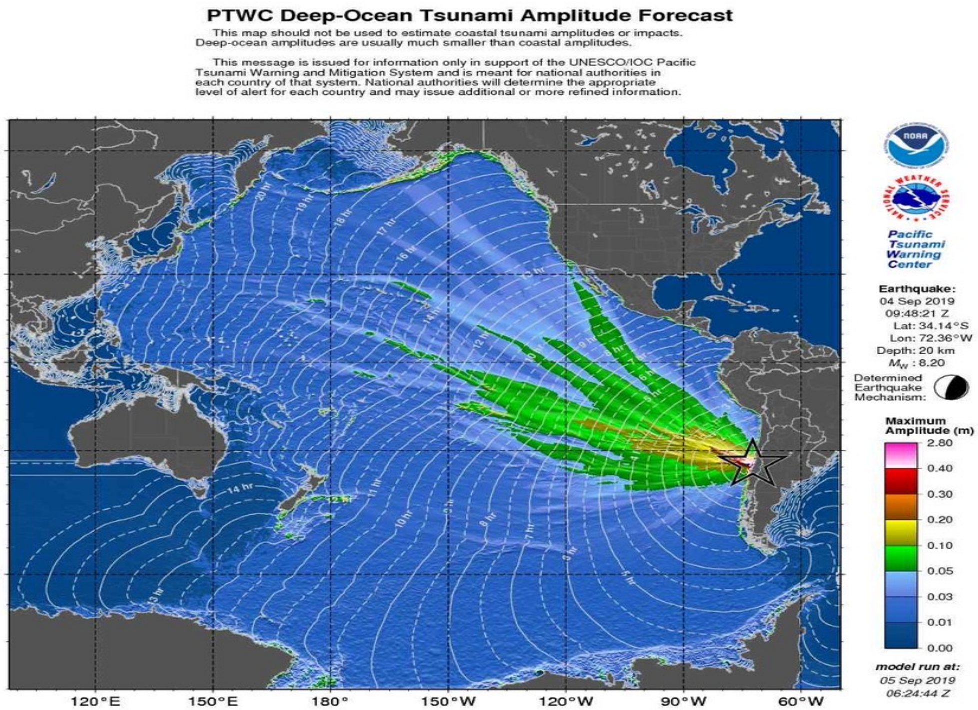

PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
Marquesas
0.5 m
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
Mw : 7.80
Determined Earthquake Mechanism:
Maximum Amplitude (m)
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
04:54:46 Z

Mw (Mag)=8.0
Hawaii can be vulnerable to basin-crossing tsunamis





Mw (Mag)=8.2



PTWC Deep-Ocean Tsunami Amplitude Forecast
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Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
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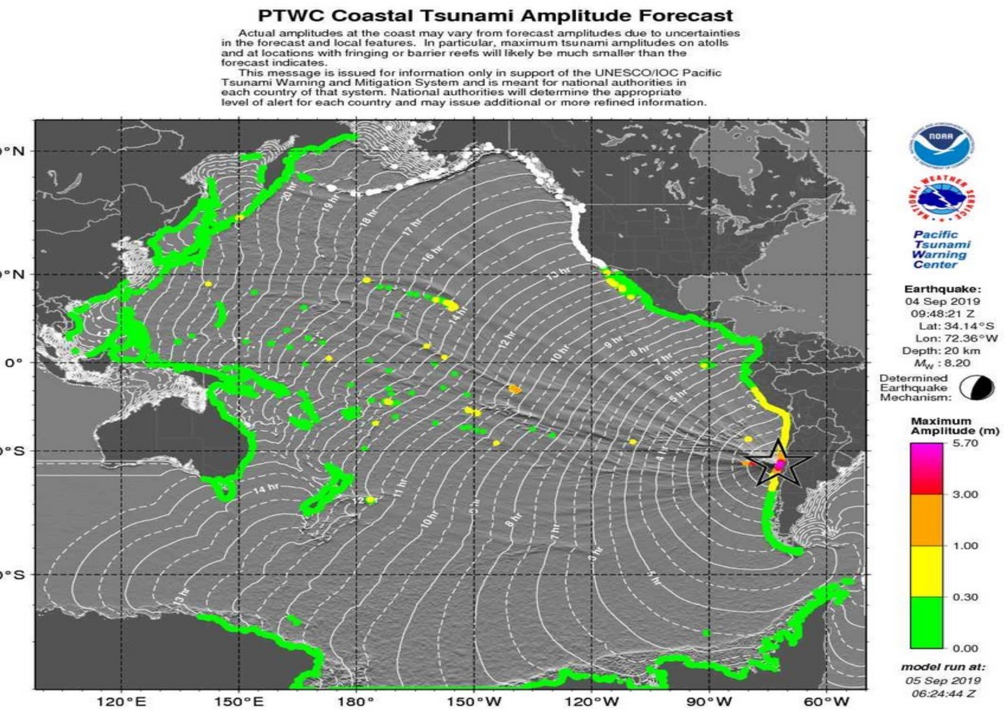
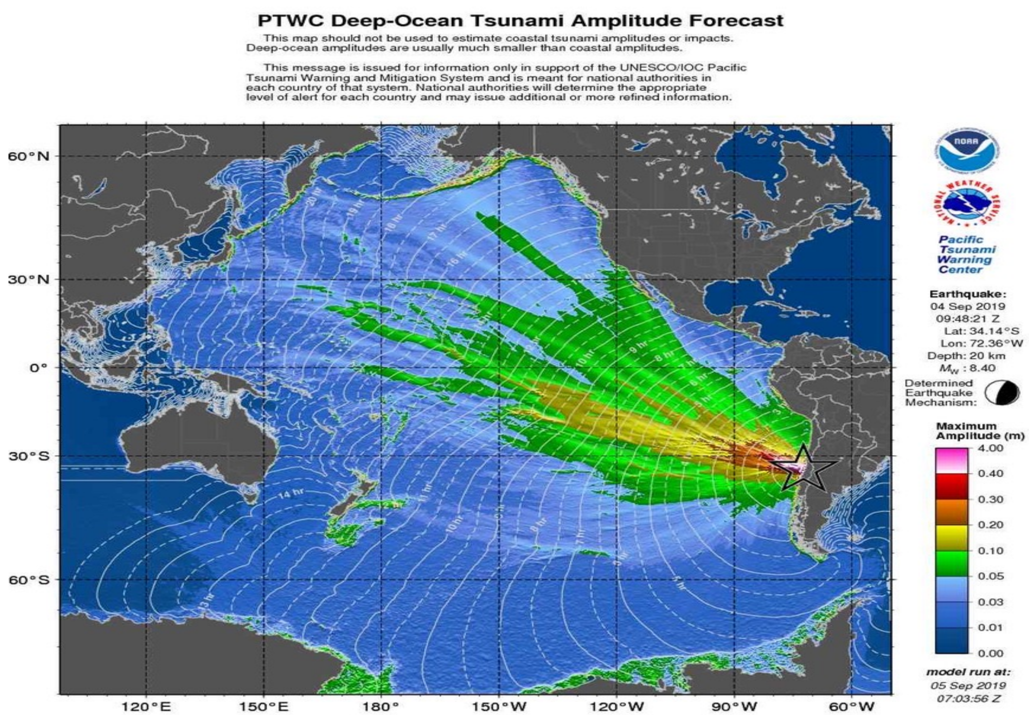
level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 8.20
Determined Earthquake Mechanism:
Maximum Amplitude (m)
2.80
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
06:24:44 Z

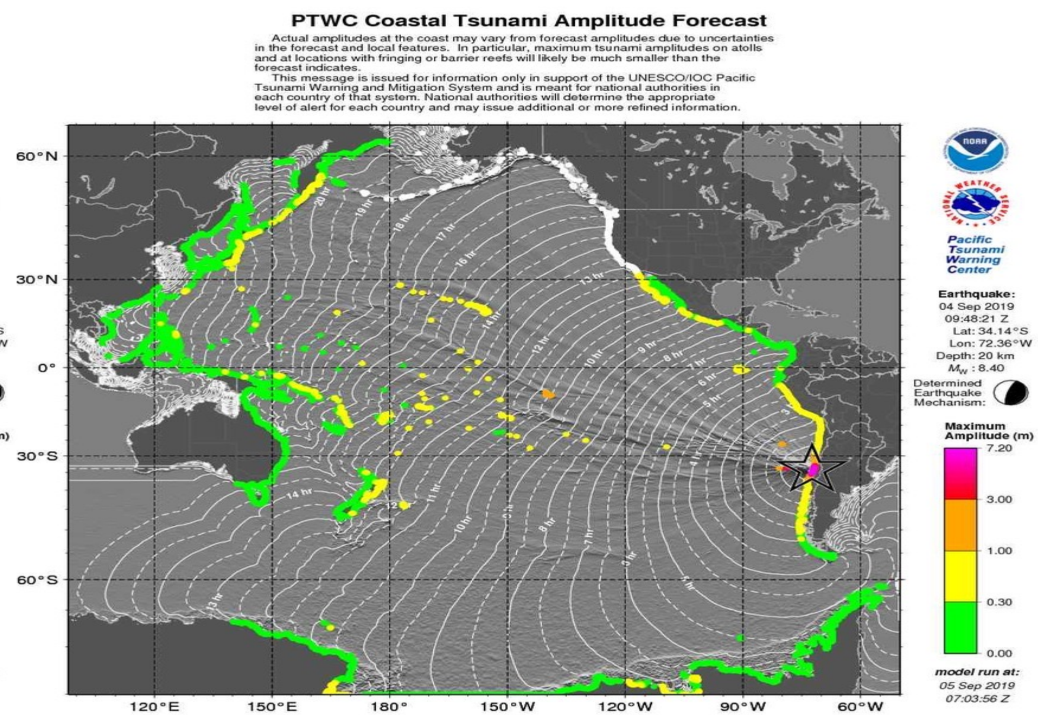


PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties
in the forecast and local features. In particular, maximum tsunami amplitudes on atolls
and at locations with fringing or barrier reefs will likely be much smaller than the
forecast indicates.
This message is issued for information only in support of the UNESCO/IOC Pacific
Tsunami Warning and Mitigation System and is meant for national authorities in
each country of that system. National authorities will determine the appropriate
level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 8.20
Determined Earthquake Mechanism:
Maximum Amplitude (m)
5.70
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
06:24:44 Z

Mw (Mag)=8.4



PTWC Deep-Ocean Tsunami Amplitude Forecast
This map should not be used to estimate coastal tsunami amplitudes or impacts.
Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 8.40
Determined Earthquake Mechanism:
Maximum Amplitude (m)
4.00
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
07:03:56 Z



PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.
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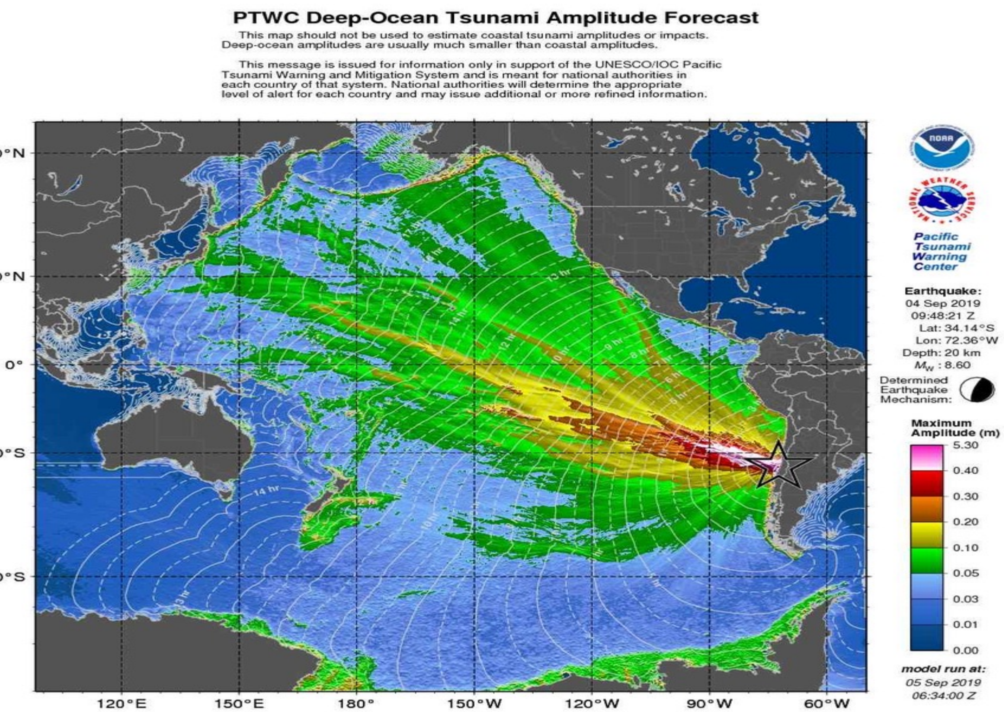
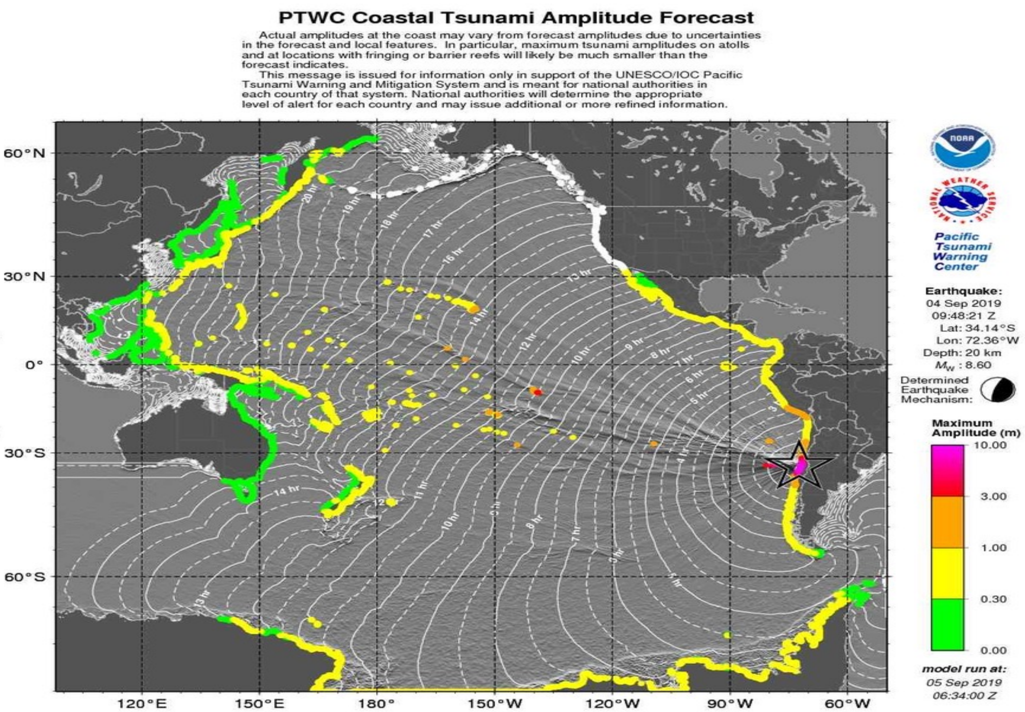
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 8.40
Determined Earthquake Mechanism:
Maximum Amplitude (m)
7.20
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
07:03:56 Z

Mw (Mag)=8.6



PTWC Deep-Ocean Tsunami Amplitude Forecast
This map should not be used to estimate coastal tsunami amplitudes or impacts. Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
Mw : 8.60
Determined Earthquake Mechanism:
Maximum Amplitude (m)
5.30
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
06:34:00 Z



PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.
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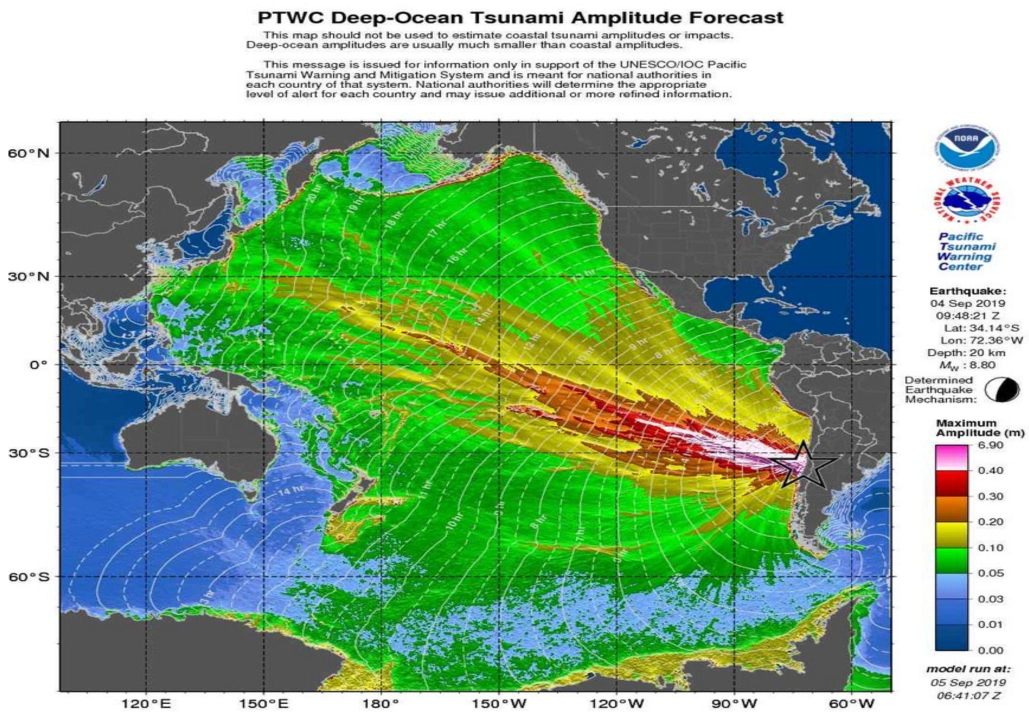
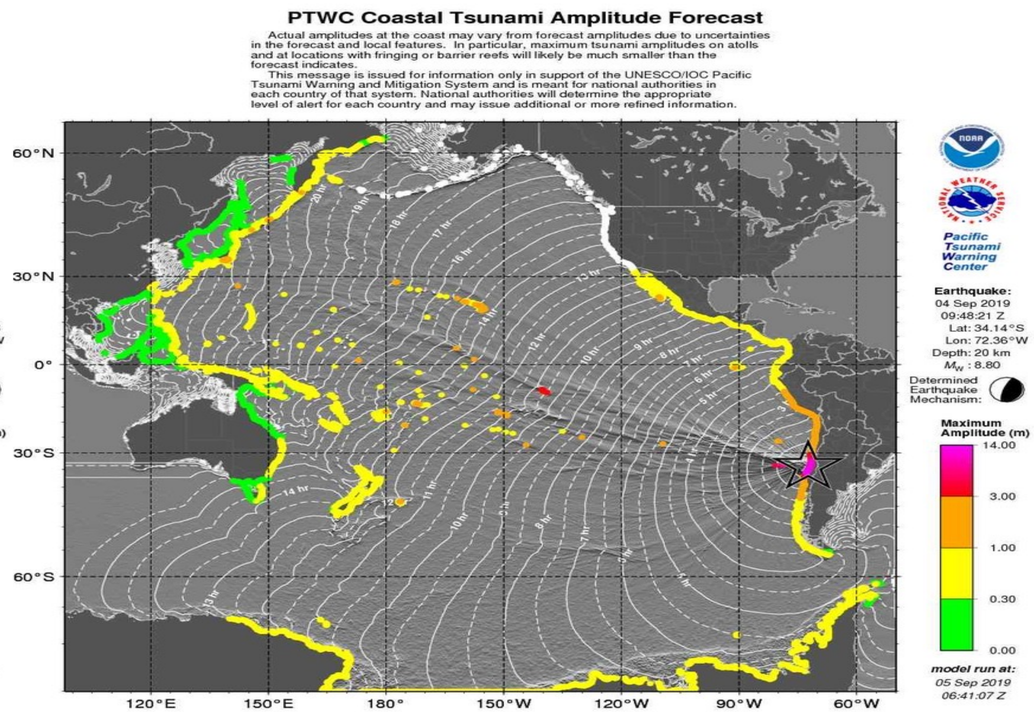
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
Mw : 8.60
Determined Earthquake Mechanism:
Maximum Amplitude (m)
10.00
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
06:34:00 Z

Mw (Mag)=8.8


PTWC Deep-Ocean Tsunami Amplitude Forecast
This map should not be used to estimate coastal tsunami amplitudes or impacts. Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 8.80
Determined Earthquake Mechanism:
Maximum Amplitude (m)
6.90
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
06:41:07 Z


PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.
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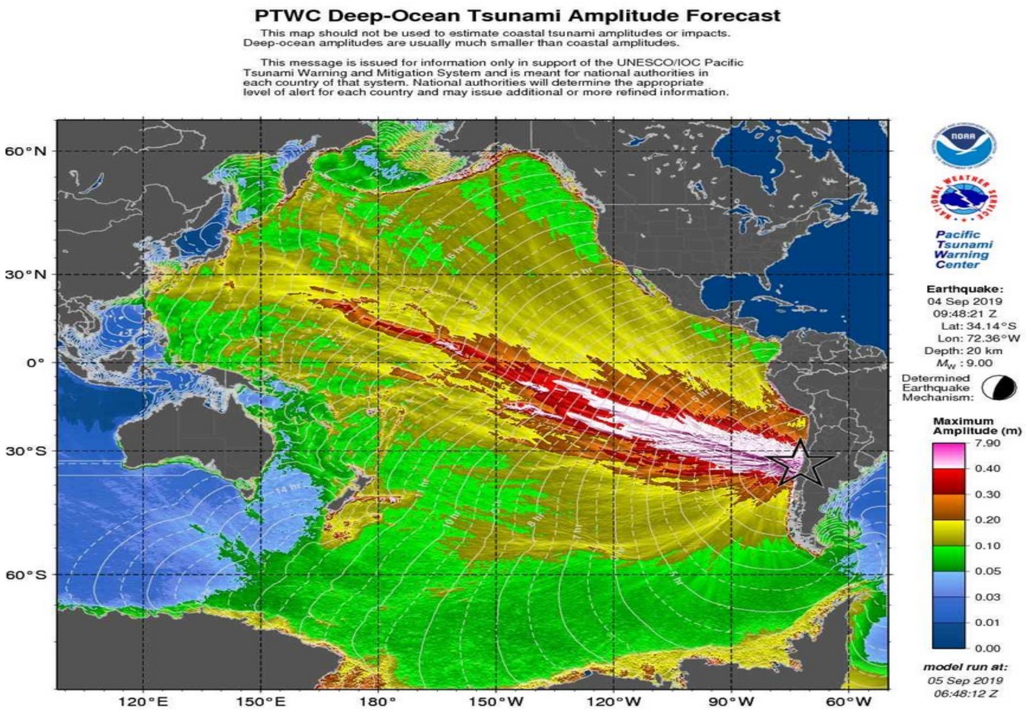
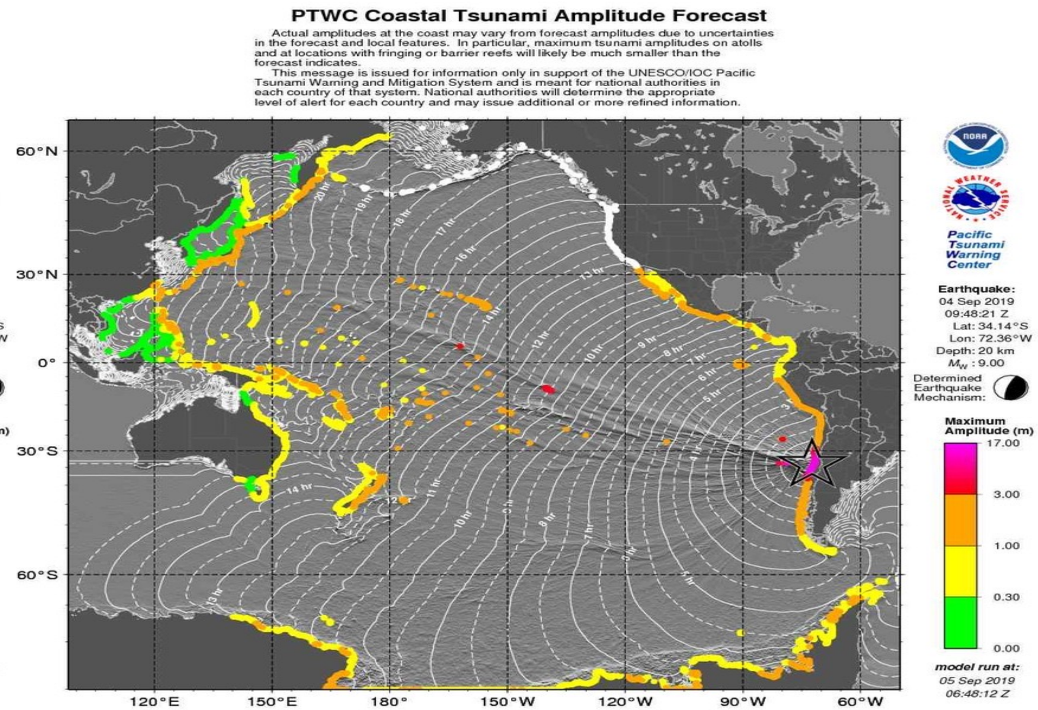
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 8.80
Determined Earthquake Mechanism:
Maximum Amplitude (m)
14.00
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
06:41:07 Z

Mw (Mag)=9.0


PTWC Deep-Ocean Tsunami Amplitude Forecast
This map should not be used to estimate coastal tsunami amplitudes or impacts. Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 9.00
Determined Earthquake Mechanism:
Maximum Amplitude (m)
7.90
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
06:48:12 Z


PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.
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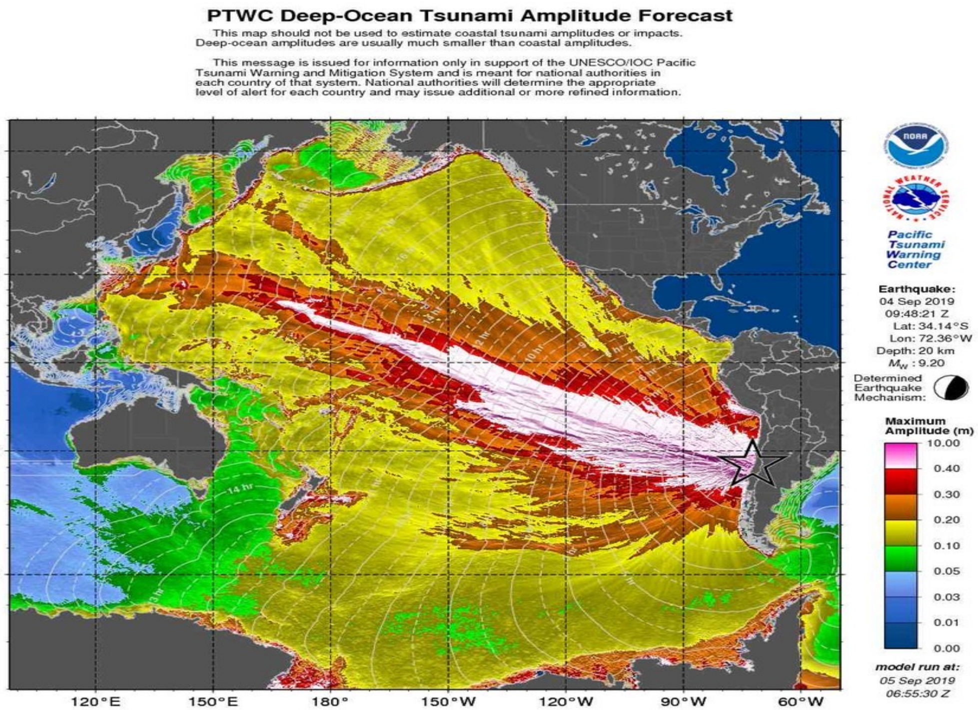
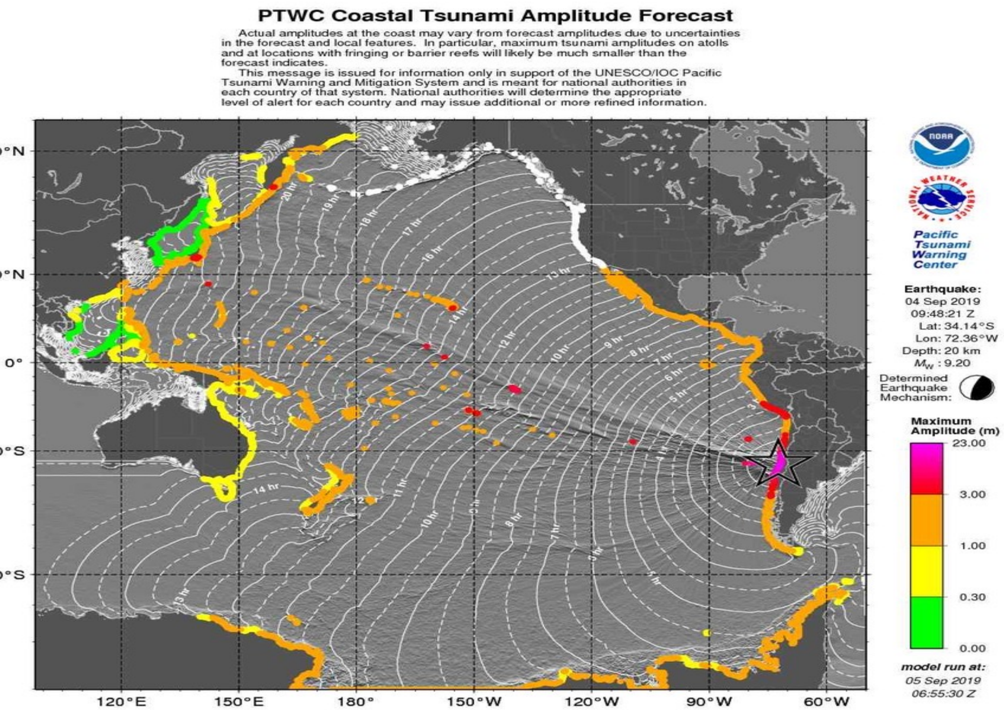
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_W : 9.00
Determined Earthquake Mechanism:
Maximum Amplitude (m)
17.00
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
06:48:12 Z

Mw (Mag)=9.2


PTWC Deep-Ocean Tsunami Amplitude Forecast
This map should not be used to estimate coastal tsunami amplitudes or impacts.
Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_w : 9.20
Determined Earthquake Mechanism:
Maximum Amplitude (m)
10.00
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
06:55:30 Z


PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.
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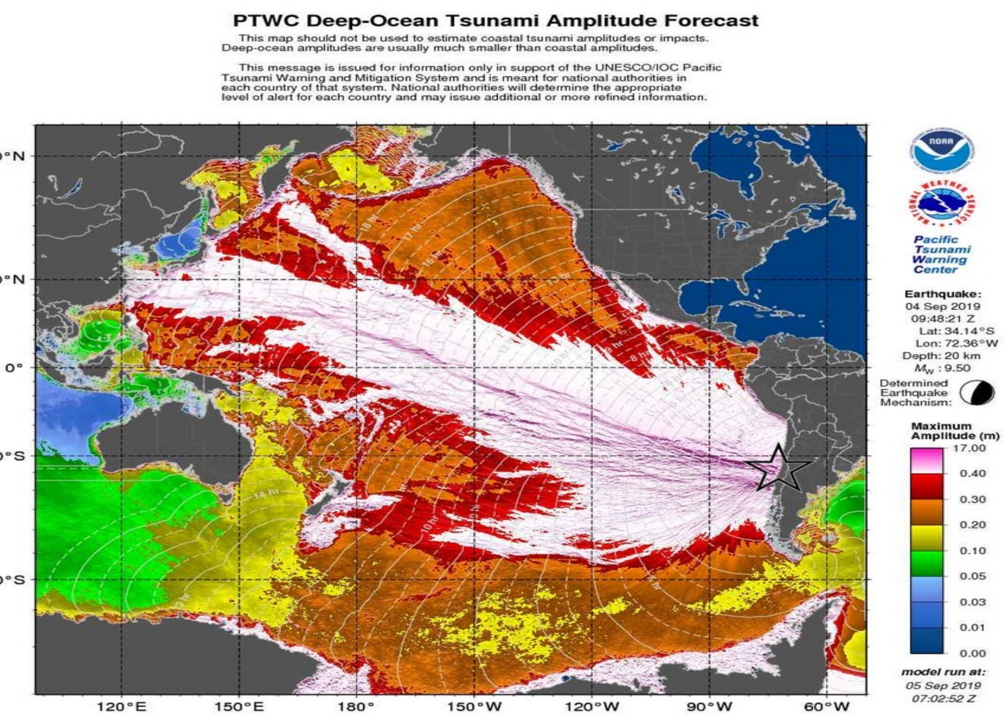
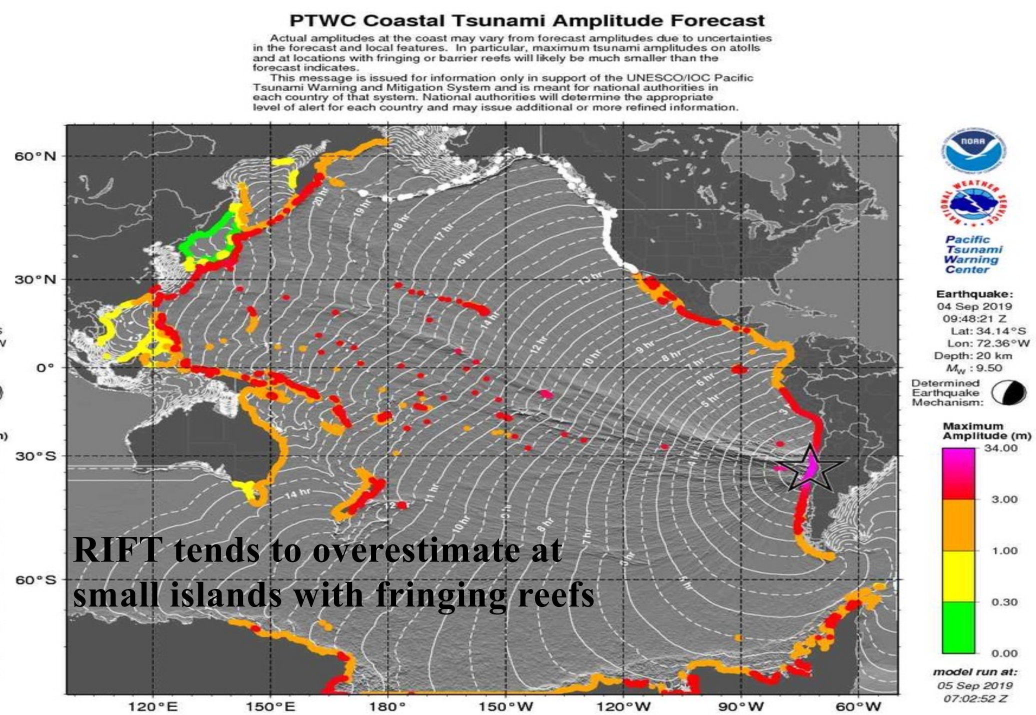
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_w : 9.20
Determined Earthquake Mechanism:
Maximum Amplitude (m)
23.00
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
06:55:30 Z

Mw (Mag)=9.5



PTWC Deep-Ocean Tsunami Amplitude Forecast
This map should not be used to estimate coastal tsunami amplitudes or impacts. Deep-ocean amplitudes are usually much smaller than coastal amplitudes.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_w : 9.50
Determined Earthquake Mechanism:
Maximum Amplitude (m)
17.00
0.40
0.30
0.20
0.10
0.05
0.03
0.01
0.00
model run at:
05 Sep 2019
07:02:52 Z



PTWC Coastal Tsunami Amplitude Forecast
Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.
This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.
60°N
30°N
0°
30°S
60°S
120°E
150°E
180°
150°W
120°W
90°W
60°W
RIFT tends to overestimate at small islands with fringing reefs
Pacific Tsunami Warning Center
Earthquake:
04 Sep 2019
09:48:21 Z
Lat: 34.14°S
Lon: 72.36°W
Depth: 20 km
M_w : 9.50
Determined Earthquake Mechanism:
Maximum Amplitude (m)
34.00
3.00
1.00
0.30
0.00
model run at:
05 Sep 2019
07:02:52 Z

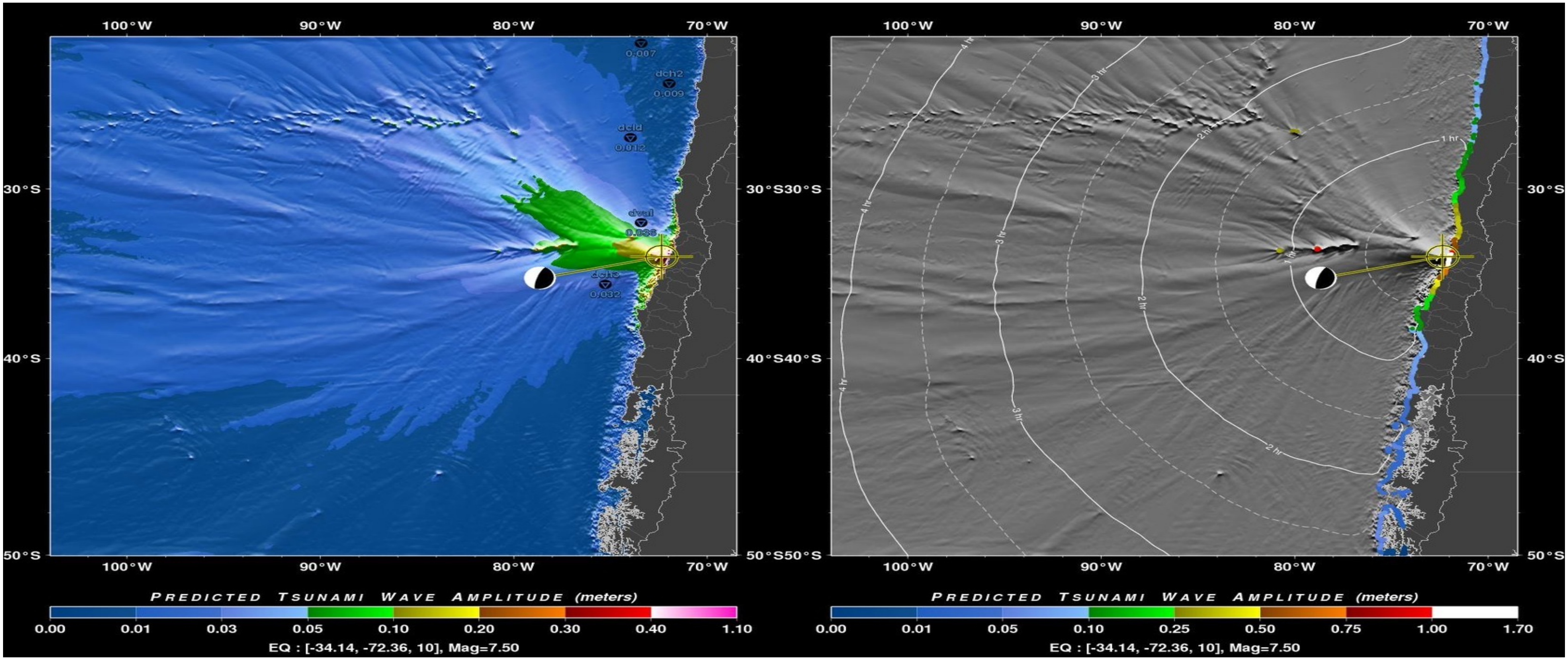
Forecast Sensitivity to Earthquake Depth

Determination of earthquake depth can be unprecise, given the time constraint warning centers face (only using limited number of seismic stations near the epicenter). Even the W-phase centroid depth can have substantial errors.

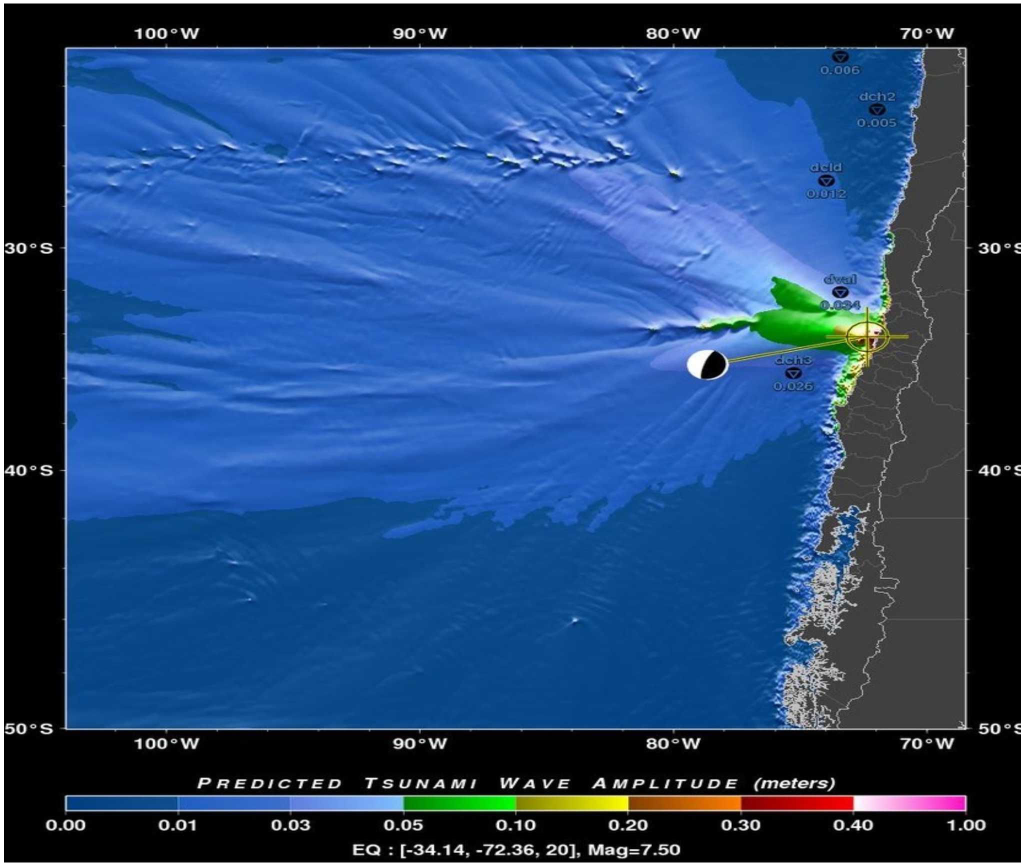
The earthquake depth/centroid can be easily off by a few tens of km.

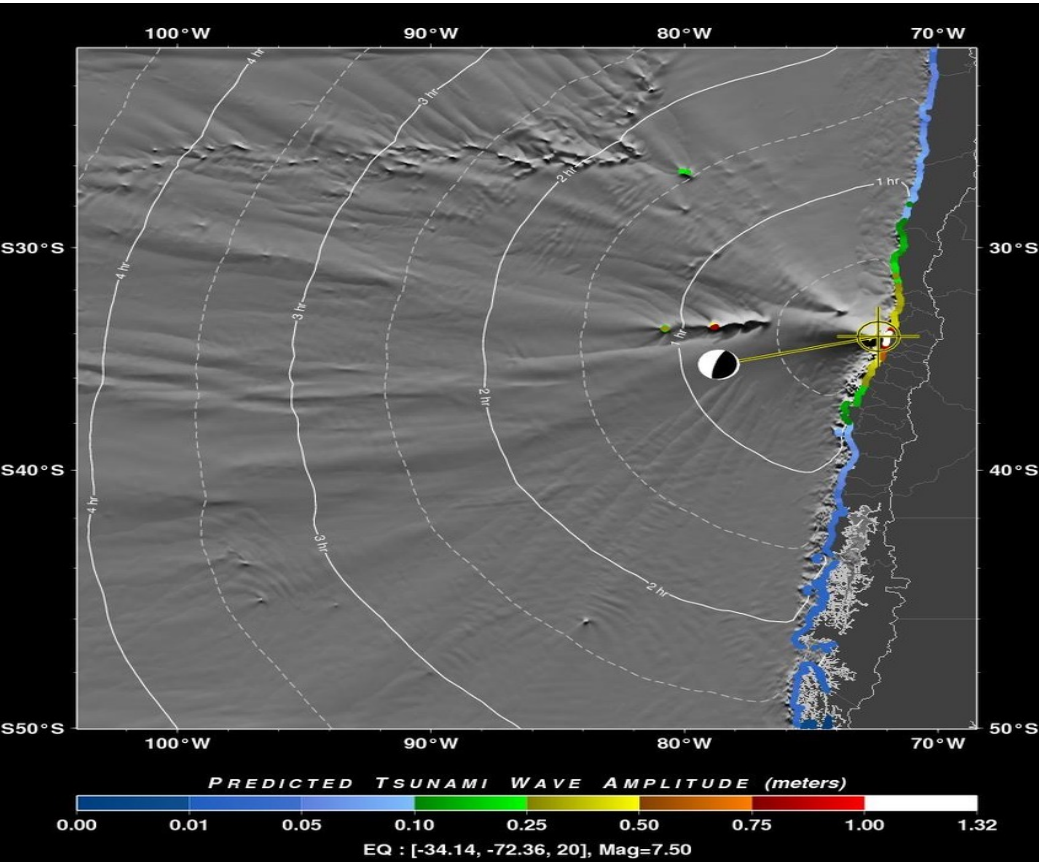
EQ depth has significant control on tsunami forecast, especially for smaller EQs (Mag<7.5, for example).

Mw (Mag)=7.5, depth = 10 km, Max coastal wave amp: 1.7 m

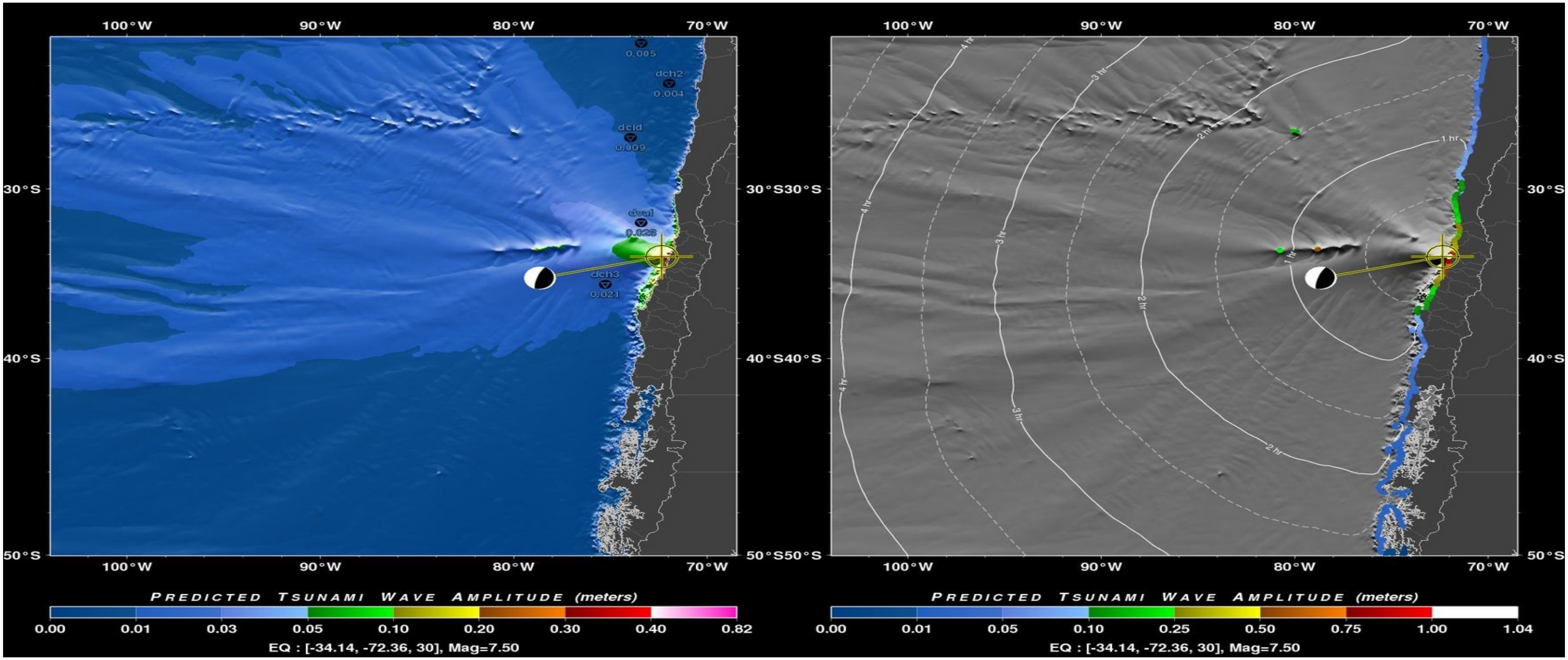


Mw (Mag)=7.5, depth = 20 km, Max coastal wave amp: 1.3 m

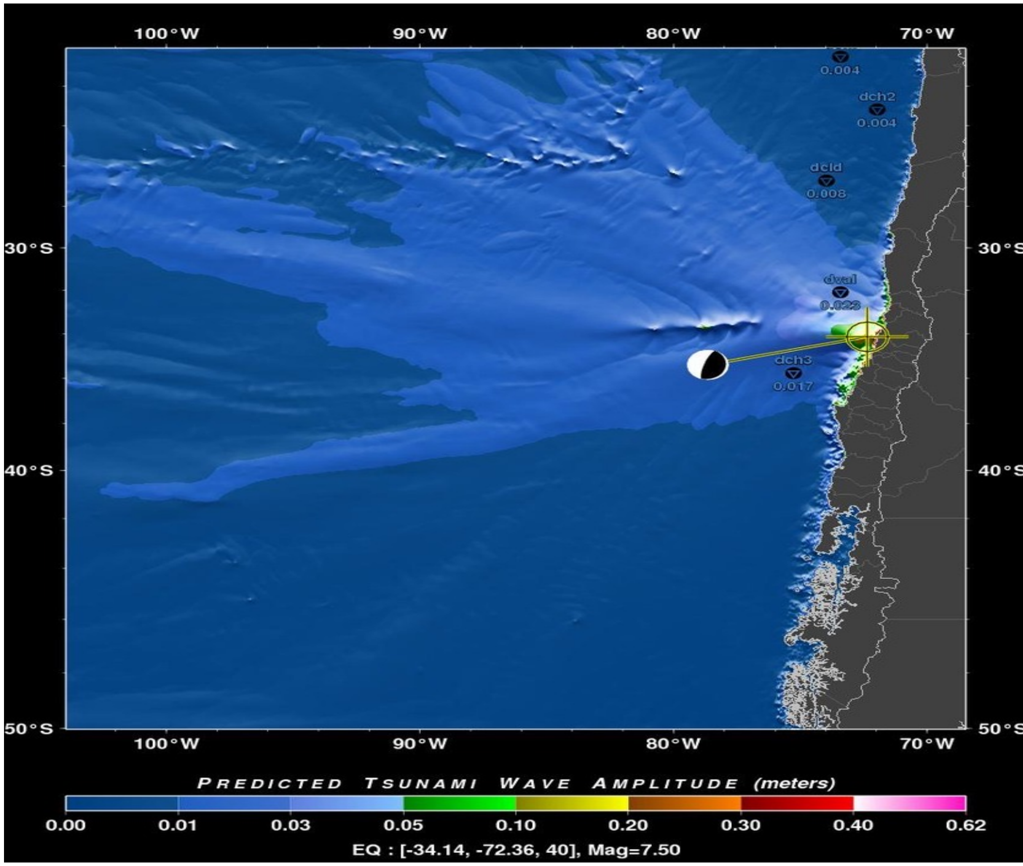


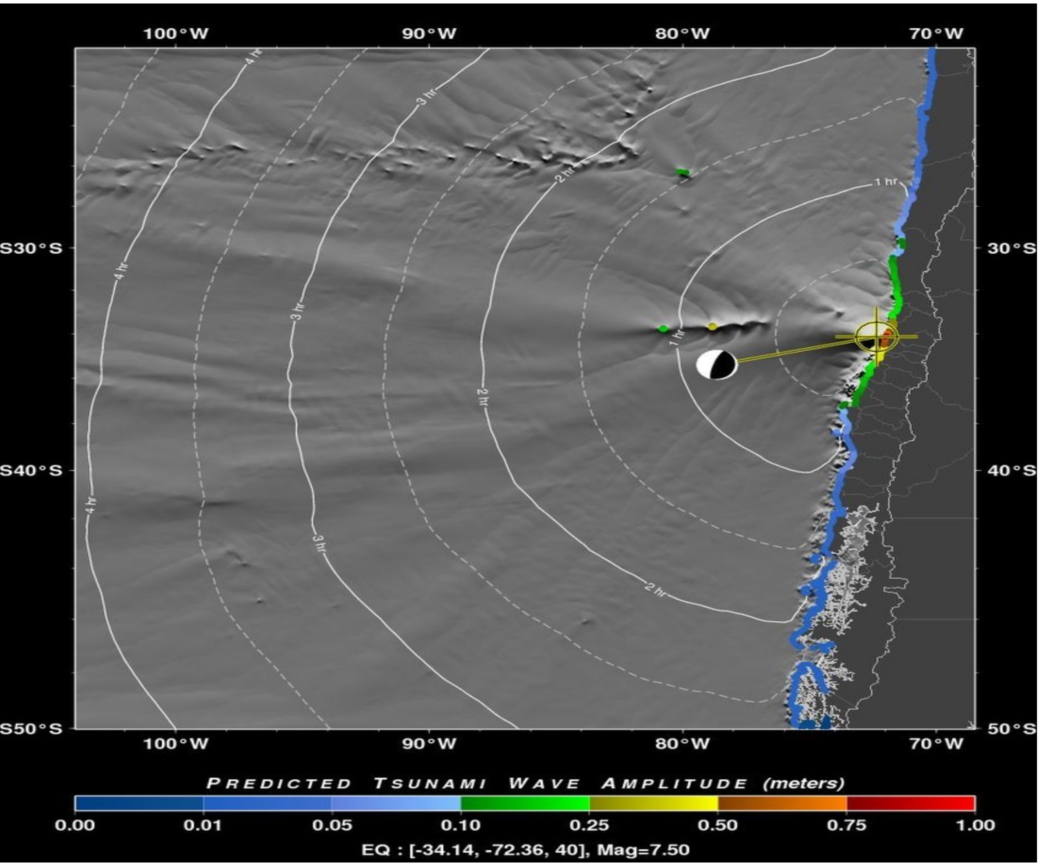


Mw (Mag)=7.5, depth = 30 km, Max coastal wave amp: 1.0 m



Mw (Mag)=7.5, depth = 40 km, Max coastal wave amp: 0.80 m





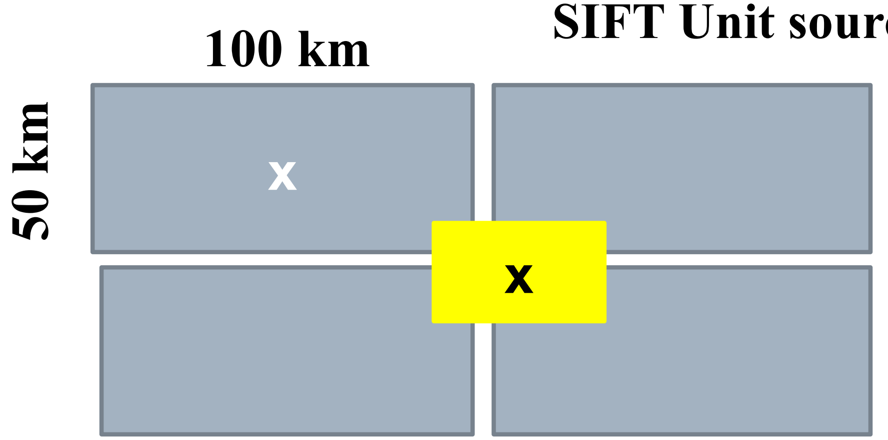
Forecast Sensitivity to Earthquake Location

Earthquake horizontal location can have errors, from one tenth of a degree to one or even two degrees.

Location can have a significant influence on tsunami forecast, especially for smaller EQs near land or inland.

Sensitivity of database solution to earthquake location
For small earthquakes, small change in location can result in drastically different forecast (gray rectangles)

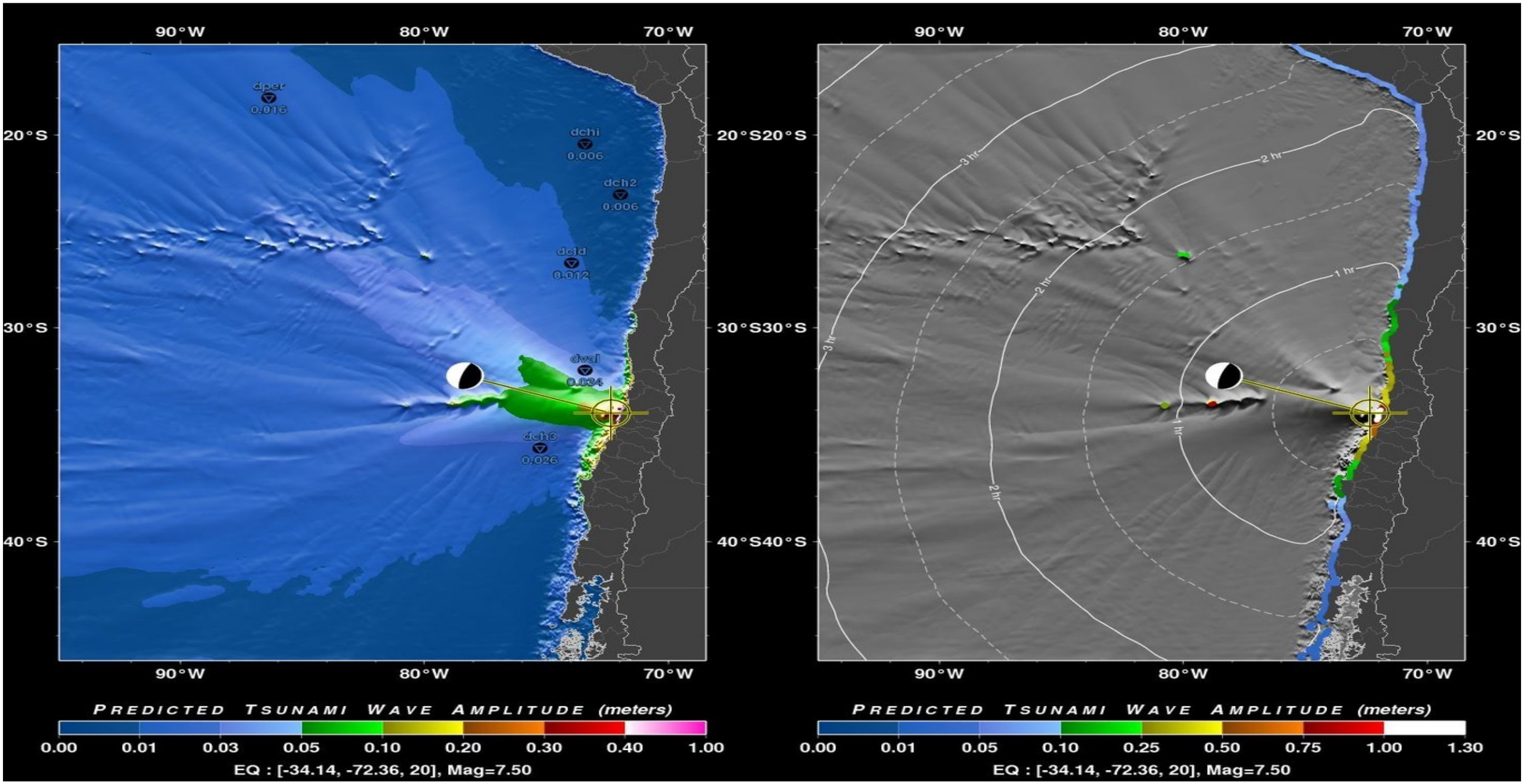
SIFT Unit sources are 50 km x 100 km



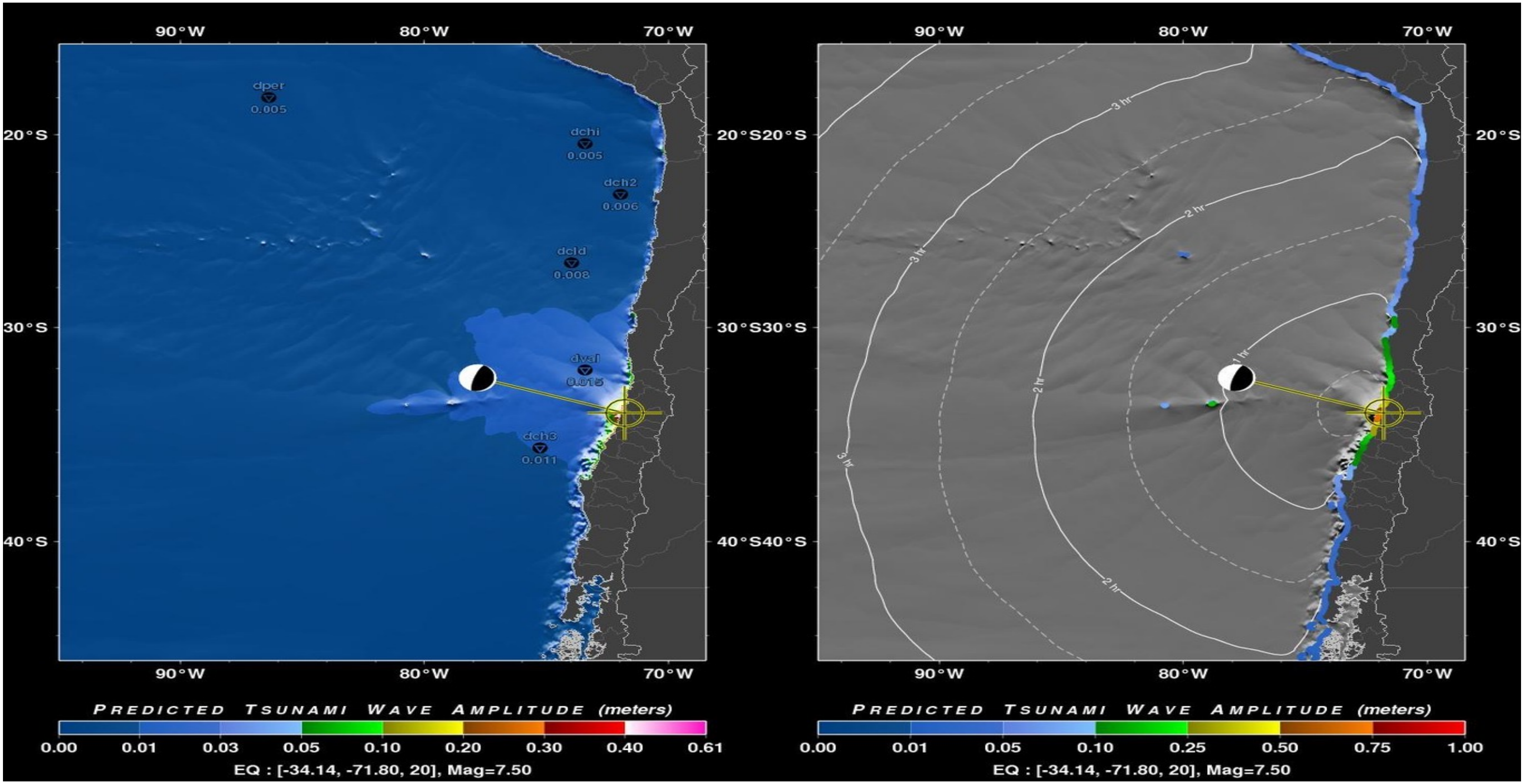
Not a problem for real-time model, because the fault plane is centered at the epicenter/centroid, not the nearest unit-source in the data base.

This is not a major problem for mega-thrust earthquakes however, when the fault plane covers several unit sources.

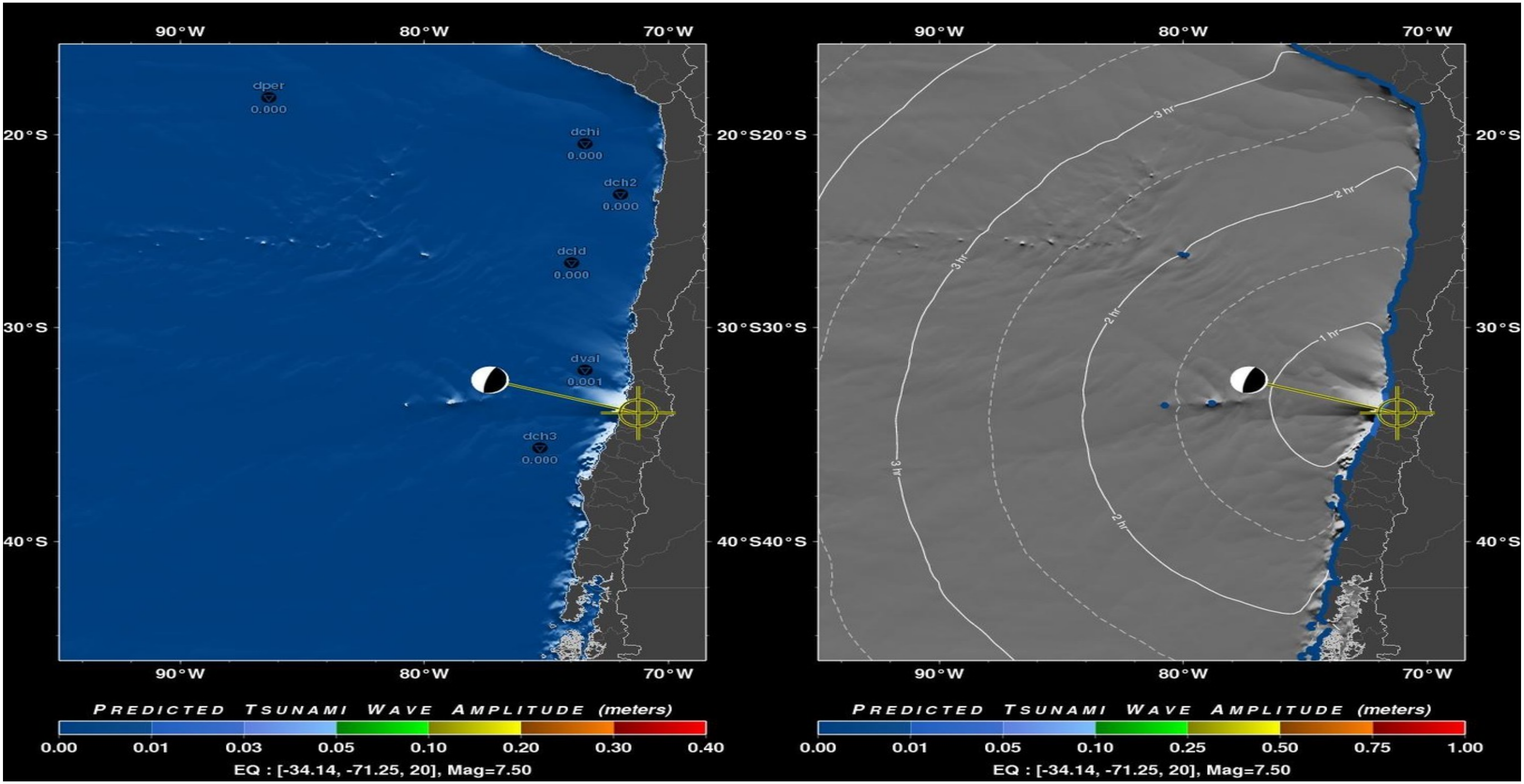
Epicenter offshore, max amp=1.3 m



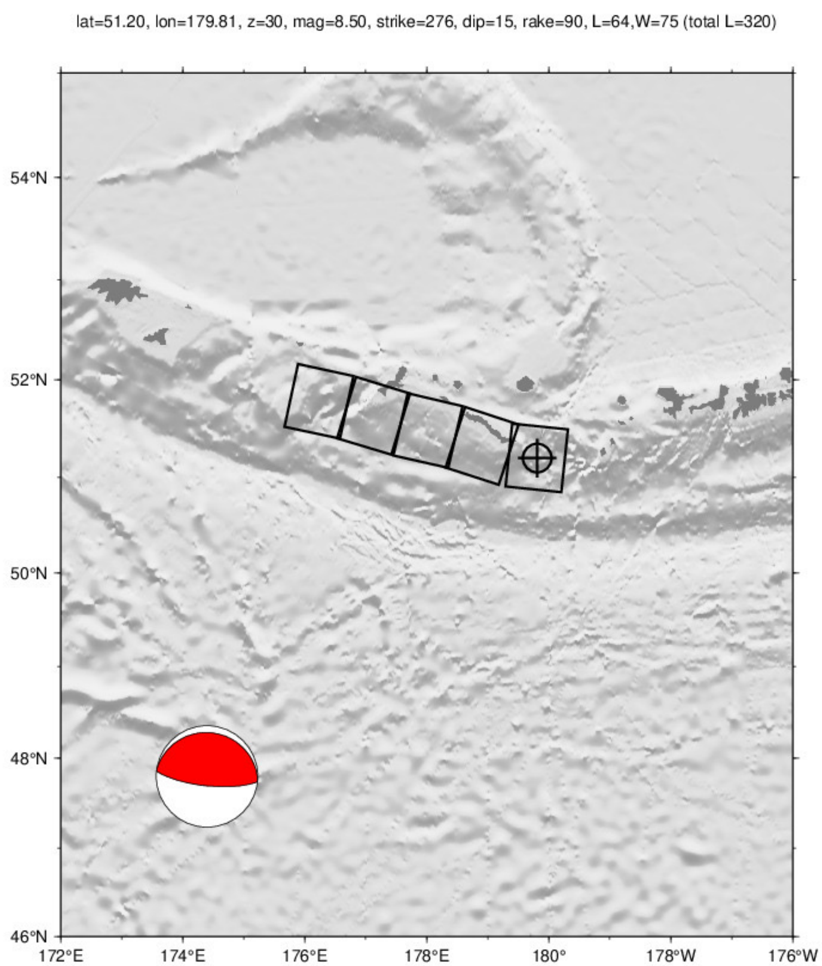
Epicenter shifted 50 km towards land (15 km inland), Max coastal amp: 0.70 m

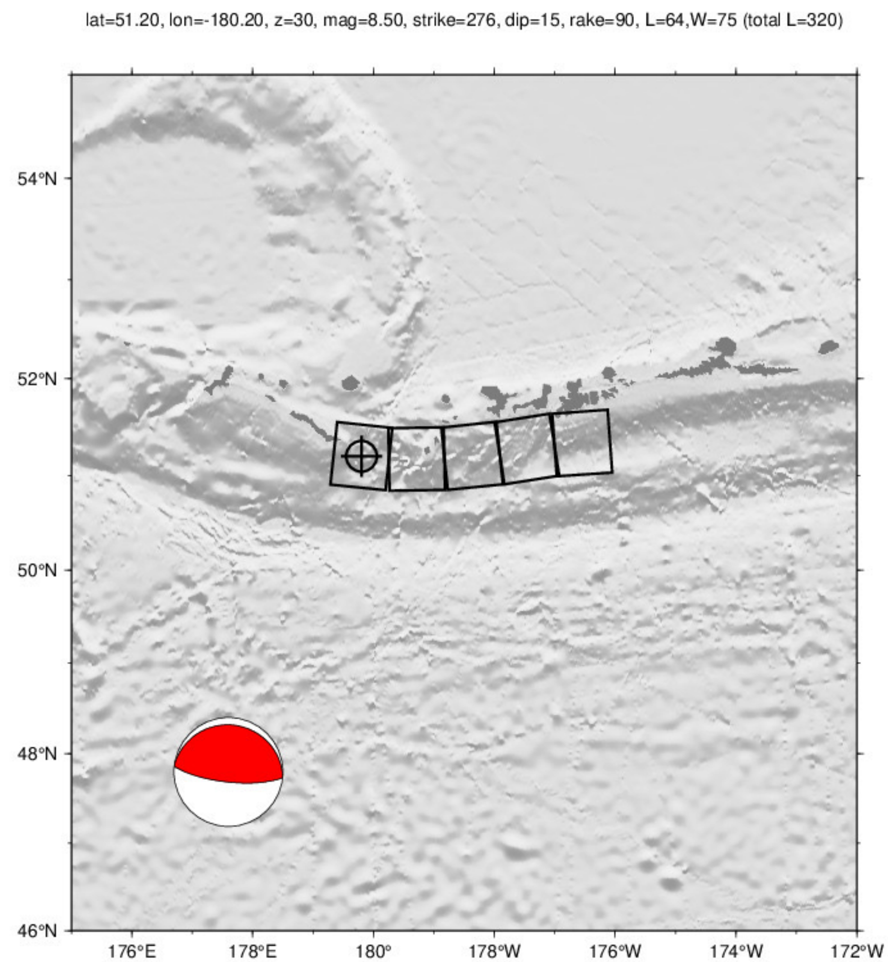


Epicenter shifted 100 km towards land (60 km inland), Max coastal amp: 0.03 m

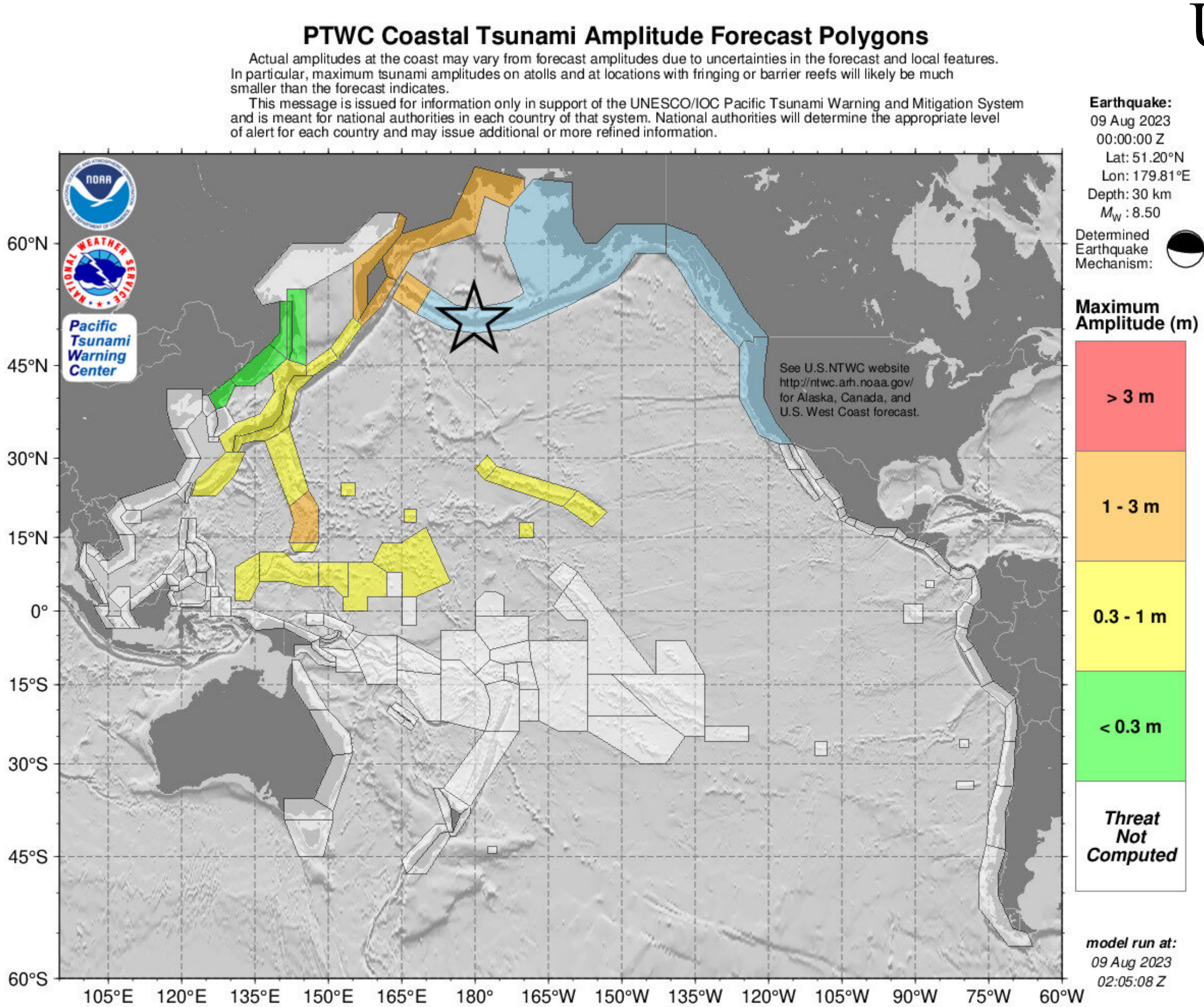


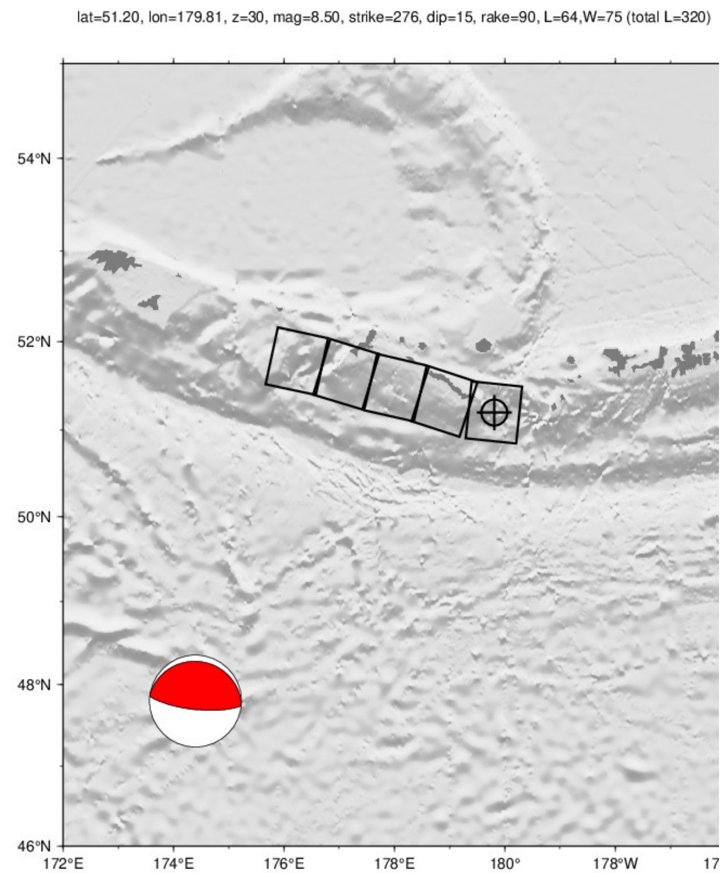
Effect of unilateral rupture. Aleutians



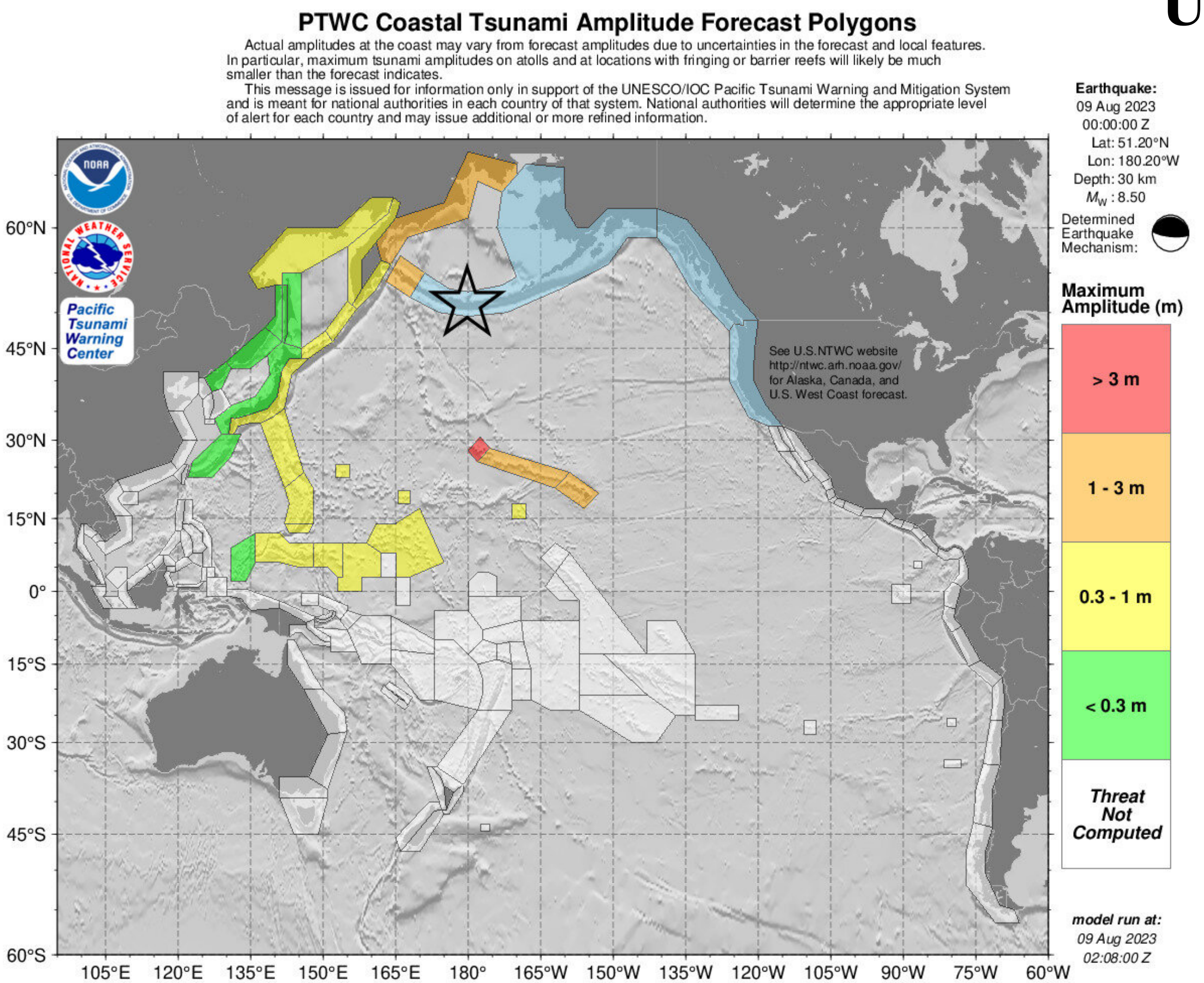


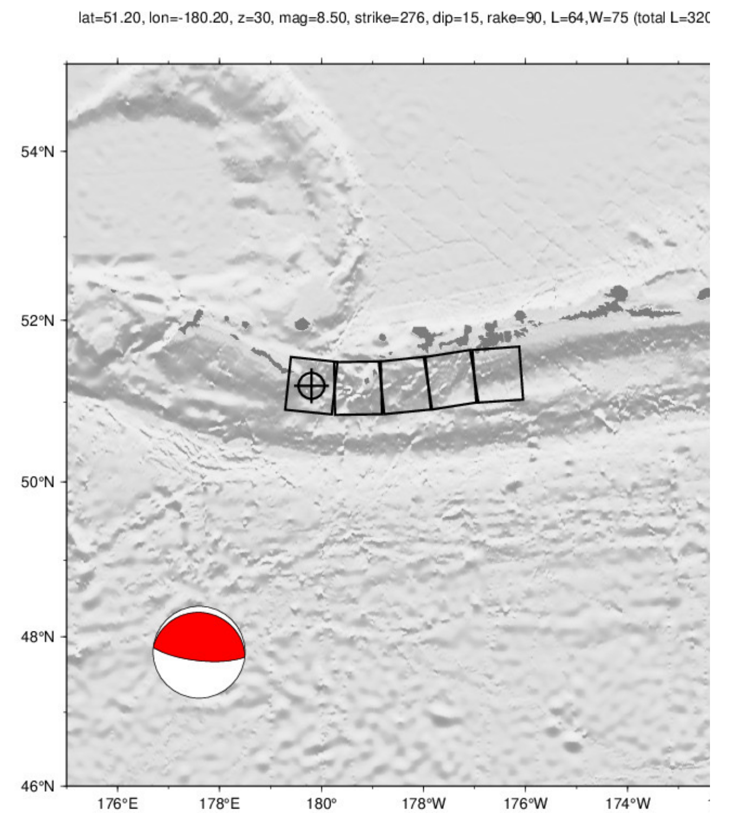
Uni-lateral rupture right





Uni-lateral rupture left





3. Case studies

Ensemble/composite statistics are based on these events

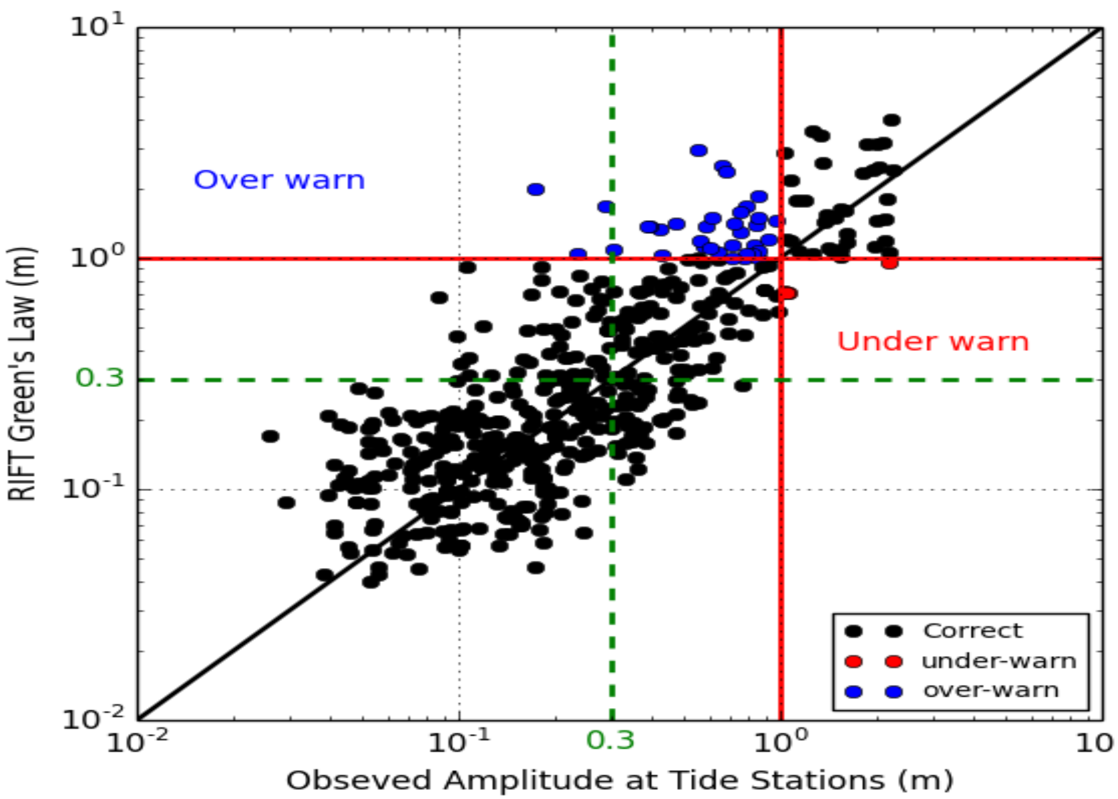
- **Kuril M8.3, Nov. 15, 2006 (GCMT)**
- **Kuril M8.1, Jan. 13, 2007   (GCMT)**
- **Samoa M8.0, Sep. 29, 2009 (USGS WCMT)**
- **Chile M8.8, Feb. 27, 2010 (USGS WCMT)**
- **Tohoku M9.0, Mar. 11, 2011 (PTWC WCMT)**
- **Haida Gwaii, M7.7, Oct. 28, 2012 (USGS WCMT)**
- **Solomon Islands, M8.0, Feb. 6, 2013, M8.0 (PTWC WCMT)**
- **Northern Chile M8.2, Apr. 1, 2014 (USGS WCMT)**

RIFT runs were forced with W-phase CMTs or Global CMTs (when W-phase CMT was not available).

Need to add newer events in future studies.

Composite comparison of RIFT's Green's law with tide station observations from eight basin crossing tsunamis.

All tide stations, including "hidden" tide stations but excluding tide stations are many km from the open ocean (e.g., Craig tide station in Alaska). Tide stations with 6-min. sampling intervals were also excluded.



At individual locations, model results can be easily off by a factor of 3!!

Mean Error = 71%
Mean Model/Obs Ratio=1.5

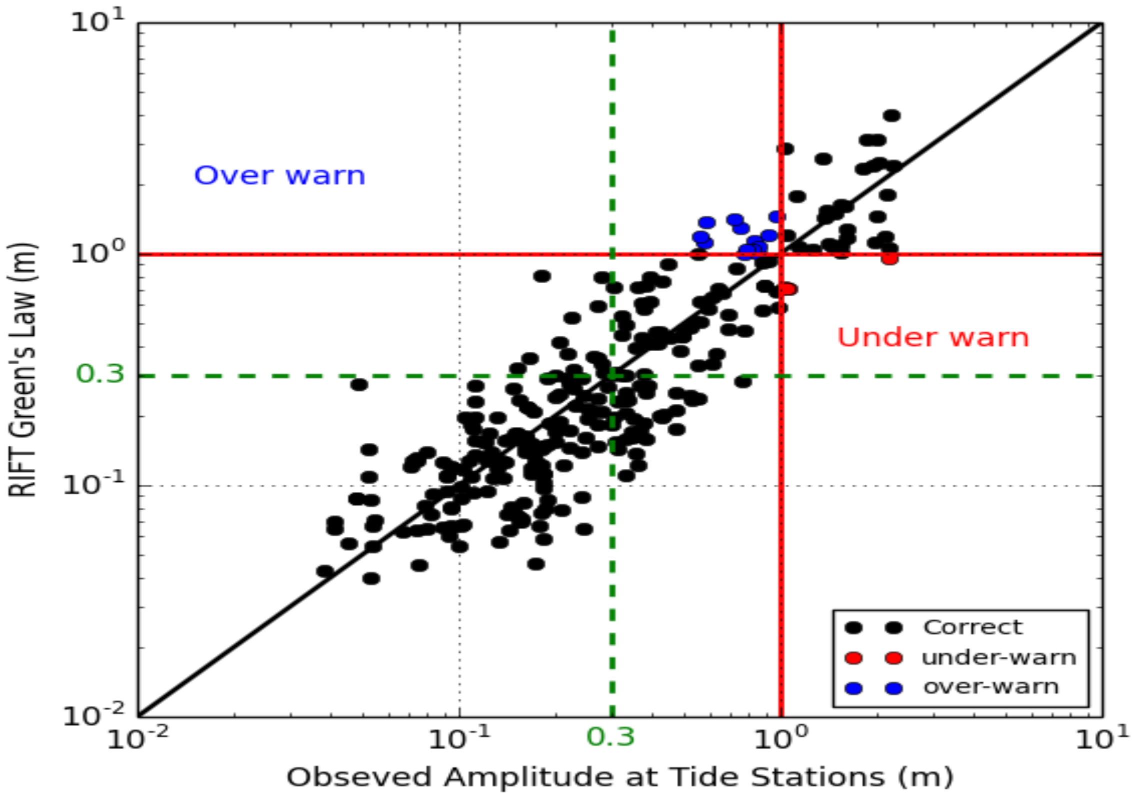
The mean ratio of 1.5 means there is a systematic upward bias in the model results, partly due to the inclusion of so-called "hidden" tide stations.

Still, the model results are within a factor of two of the observations on average, despite significant scatter at individual locations, especially at lower amplitudes.

Using 1-m as warning threshold:
under-warns: 1% of total
over-warns: 7% of total
correct: 92% of total

Composite comparison of RIFT's Green's law with tide station observations from eight basin crossing tsunamis.

"Open ocean" tide stations: excluding tide stations on atolls, islands with barrier or fringing reefs, small islands, and tide stations in well protected harbors or are too far from the open ocean.



Mean Error = 41%
Mean Mod/Obs Ratio=1.1

Model result is well within a factor of two of the observations on average.

Note that upward bias is greatly reduced when only "open ocean" tide stations are included in the error analysis, which is a more meaningful assessment of the efficacy of the Green's law.

Using 1-m as warning threshold: :
under warns: 1% of total
over warns: 5% of total
correct: 94% of total

Observations	NoThreat < 0.3 m		MarineThreat 0.3 - 1.0 m		LandThreat > 1.0 m	
	%	(mobs,mmod)	%	(mobs,mmod)	%	(mobs,mmod)
Model NoThreat	91	(0.1,0.1)	35	(0.4,0.2)	0	(0.0,0.0)
Model MarineThreat	9	(0.2,0.4)	51	(0.5,0.6)	12	(1.3,0.8)
Model LandThreat	0	(0.0,0.0)	14	(0.8,1.2)	79	(1.6,1.6)
Model MajorLandThreat	0	(0.0,0.0)	0	(0.0,0.0)	9	(2.0,3.4)

mobs: mean of observed amplitudes for given bin
Mmod: mean of model amplitudes for the same bin

The numbers inside the parentheses are mean values of observations (mobs) and model results (mmod) for the same set of tide stations that are binned according to the observational values: < 0.3, 0.3-1.0, and > 1.0 meters. Red, green, and blue numbers are percentages of model underestimating, being correct, and overestimating, respectively, for the same set of observation points.

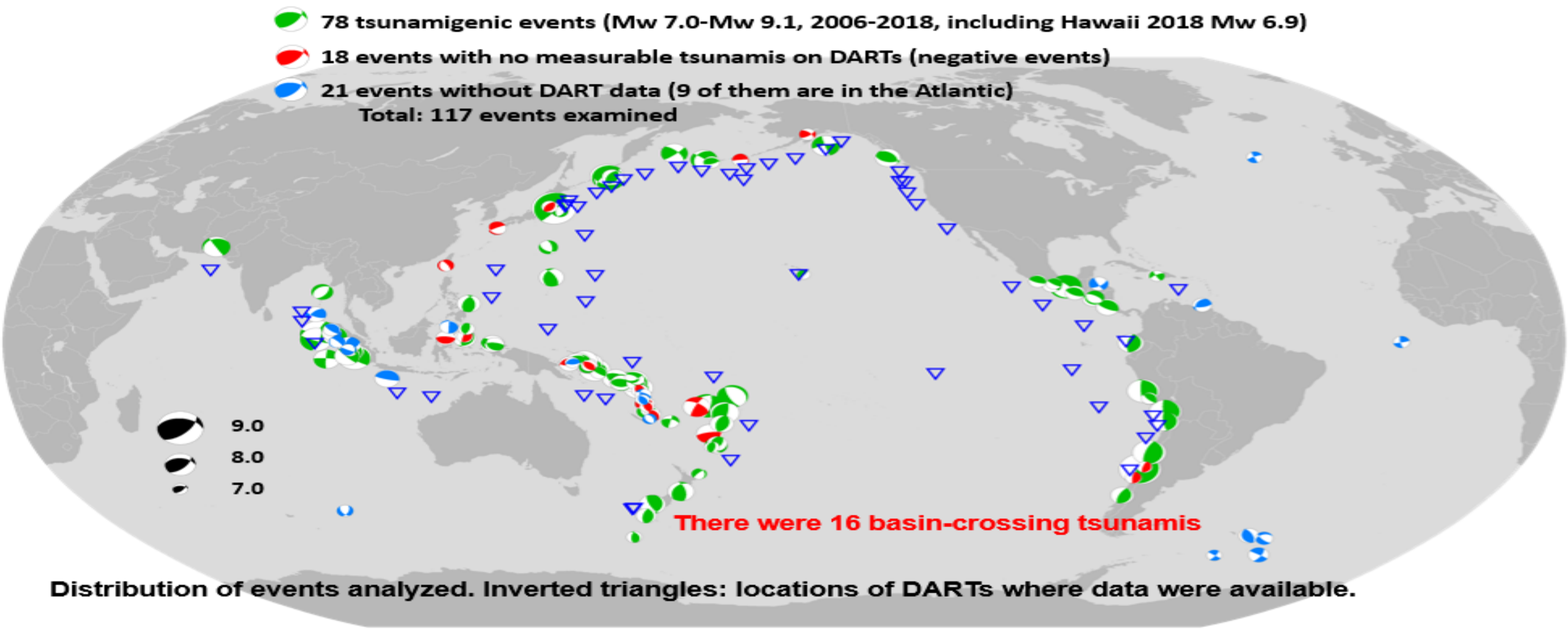
When the observation showed no-threat (<0.3 m), the model showed no-threat for 91% of those points. Both observations and model results have the same mean value 0.1 m. At 9% of the no-threat observation points, the model showed marine threat. Note however, the mean value for those model points is 0.4 m, close to the no-threat level of <0.3 m.

For the observational points that showed marine-threat (0.3 to 1 m), 35% of the corresponding model points showed no threat. Although this is a large percentage, the mean observation value 0.4 m is close to the no-threat threshold of <0.3 m. About 14% of the model points showed land-threat. Note that the mean observation value 0.8 m (compared to the model mean value 1.2 m), is also close to the land-threat threshold of 1.0 m, than to the lower boundary 0.3 m of marine -threat.

For the observational points that showed land threat (amp > 1 m), 12% of the corresponding points showed only marine-threat. This is undesirable. Still, the mean model value of 0.8 m is not far from the land threat level 1m.

RIFT for 117 events

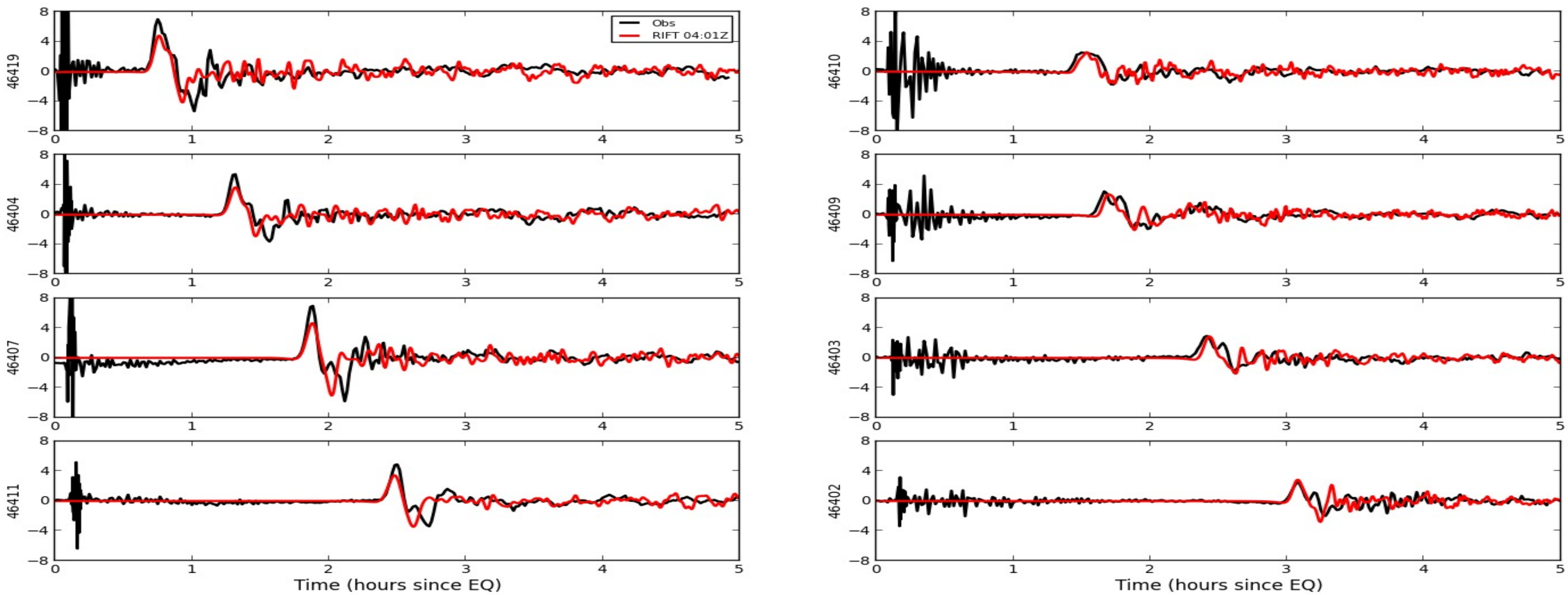
RIFT results: maximum wave amplitude of all negative events: 2.6 mm,
average of maximum wave amplitude: 1.0 mm



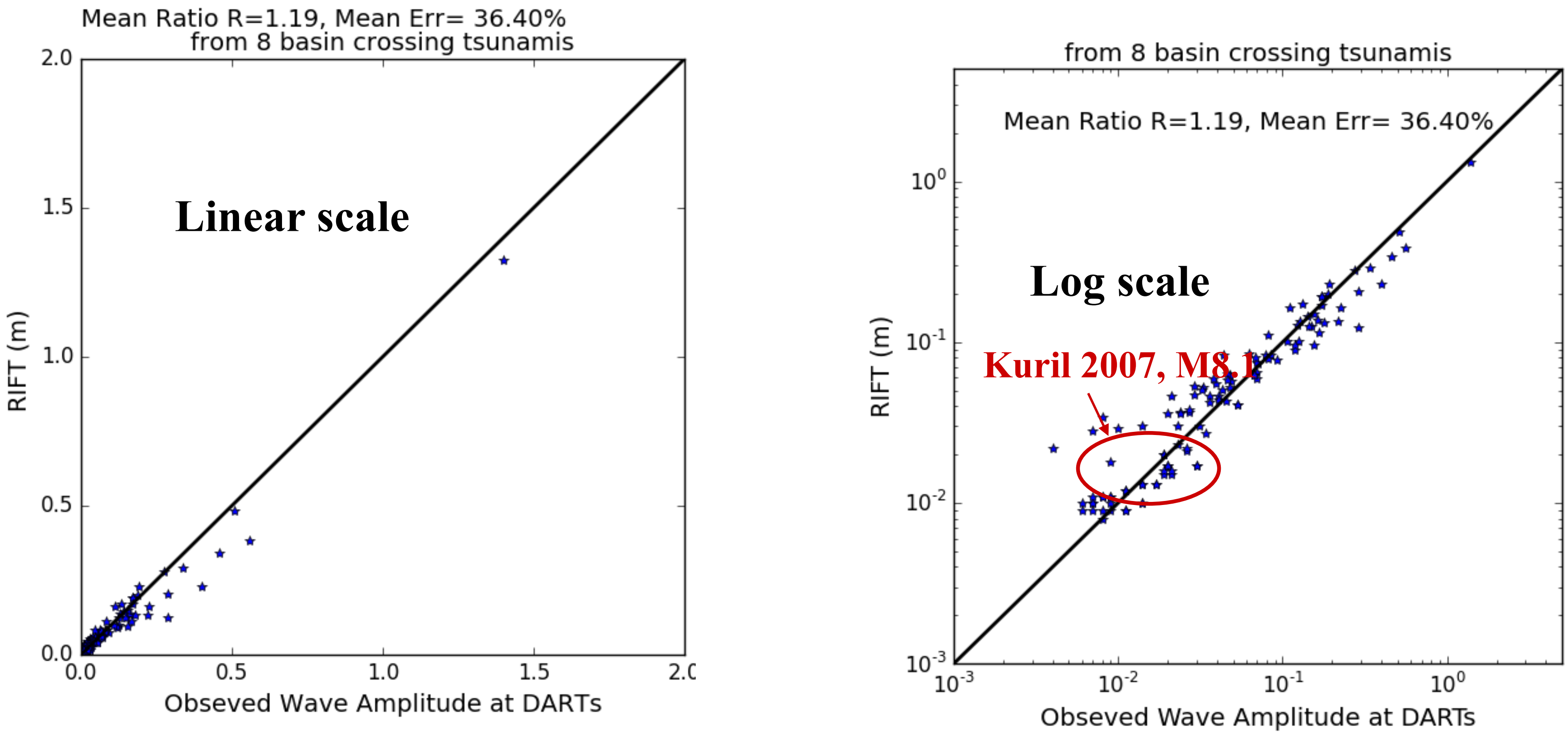
Distribution of events analyzed. Inverted triangles: locations of DARTs where data were available.

Comparison of RIFT real-time forecast during the event with DARTs for the 2012 Haida Gwaii tsunami.

2012 Haida Gwaii M7.8 tsunami: RIFT (USGS WCMT) vs DART Obs
RIFT results were obtained before the closest DART recorded a full wave

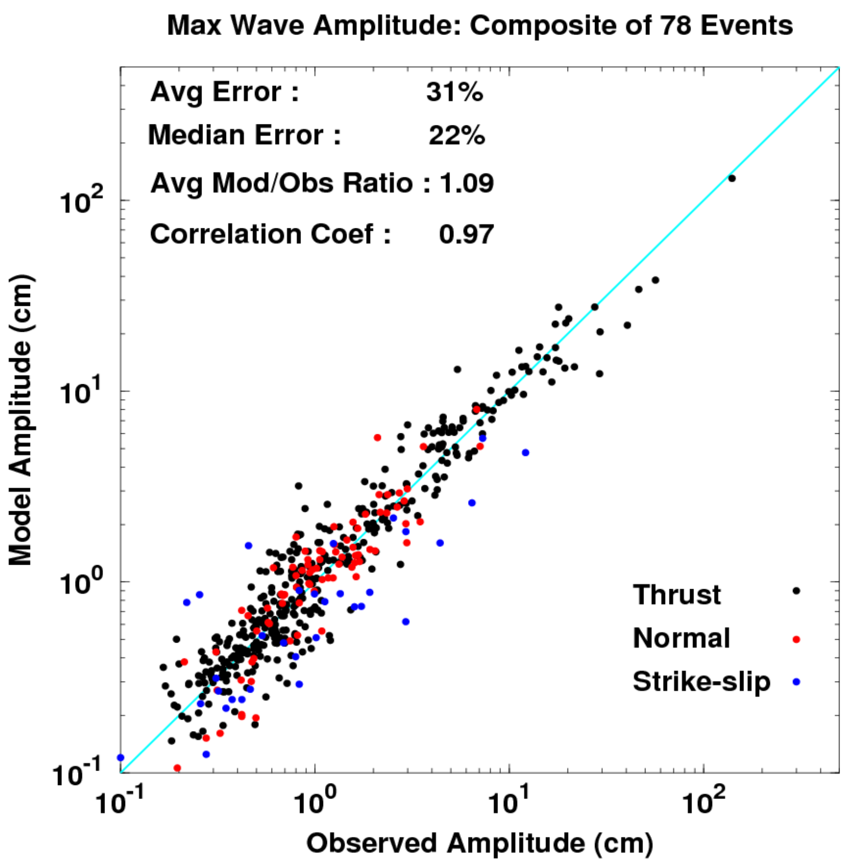


Composite comparison of RIFT vs. DART obs (8 tsunamis)

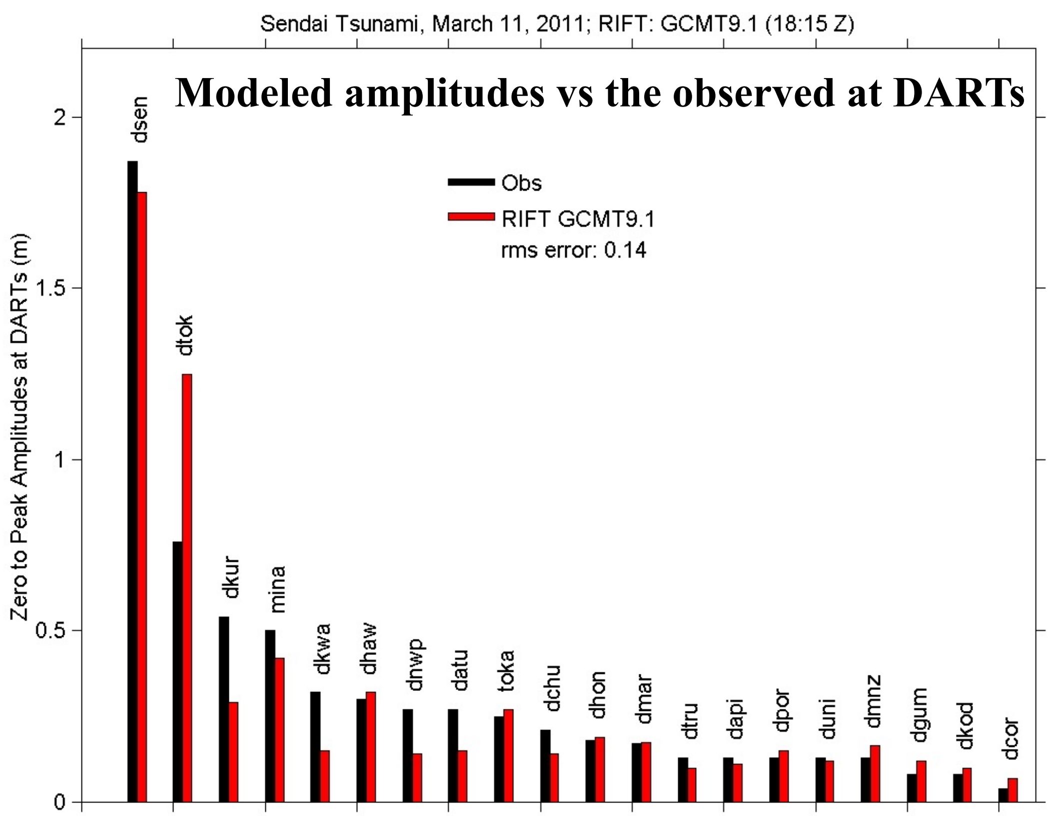


Typically, RIFT results agree better with DARTs than with tide observations, because propagation in the deep ocean is well resolved and DART records are usually free of local bathymetric effects.

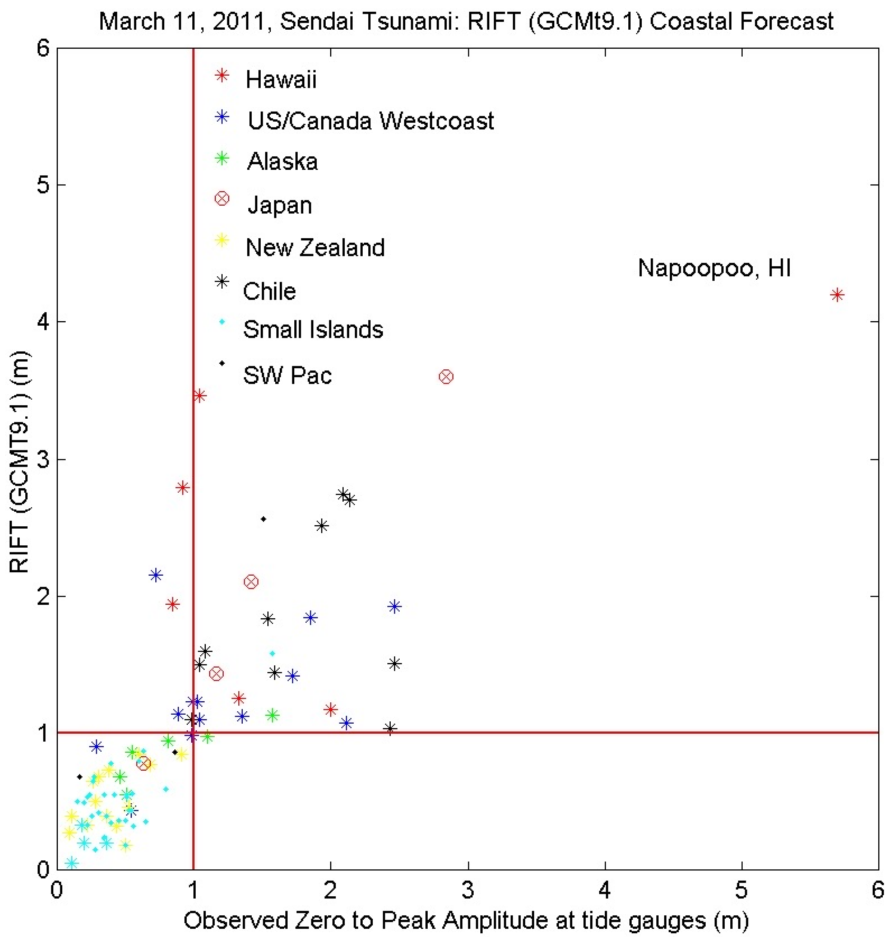
Comparison of RIFT with observations at DARTs for 78 events. Earthquakes with magnitudes ≥ 7, between 2006 and 2018, that generated a tsunami recorded at least one DART



RIFT results for 2011 Tohoku Tsunami, using Global CMT Mw 9.1
Earlier results using w-phase CMTs not good (there was a good W-phase CMT solution at the time but known to us during the event).

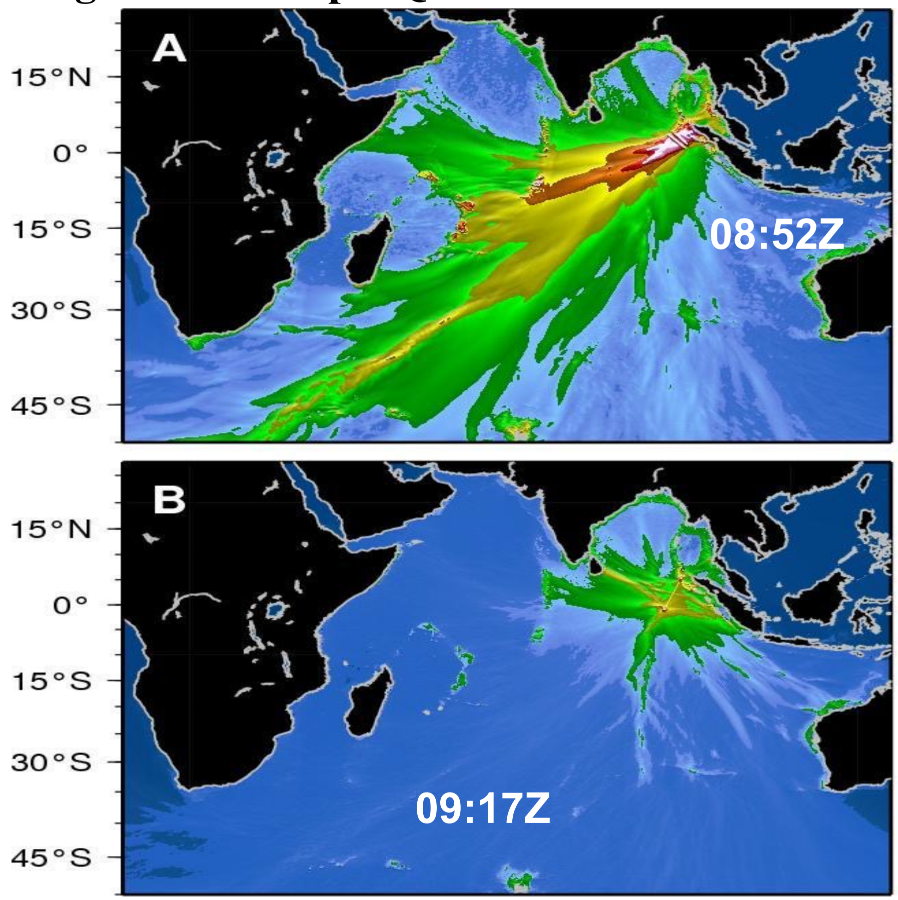


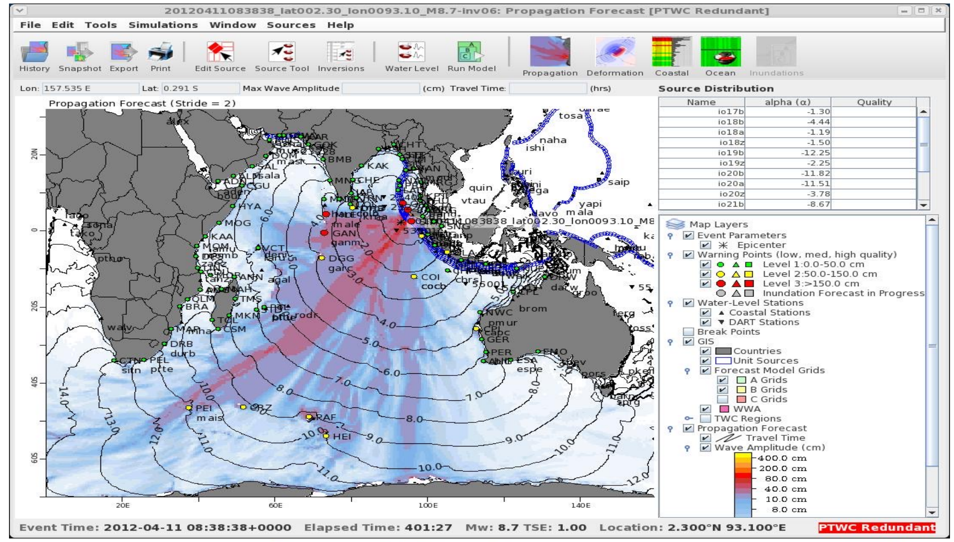
RIFT results for 2011 Tohoku Tsunami, using Global CMT Mw 9.1

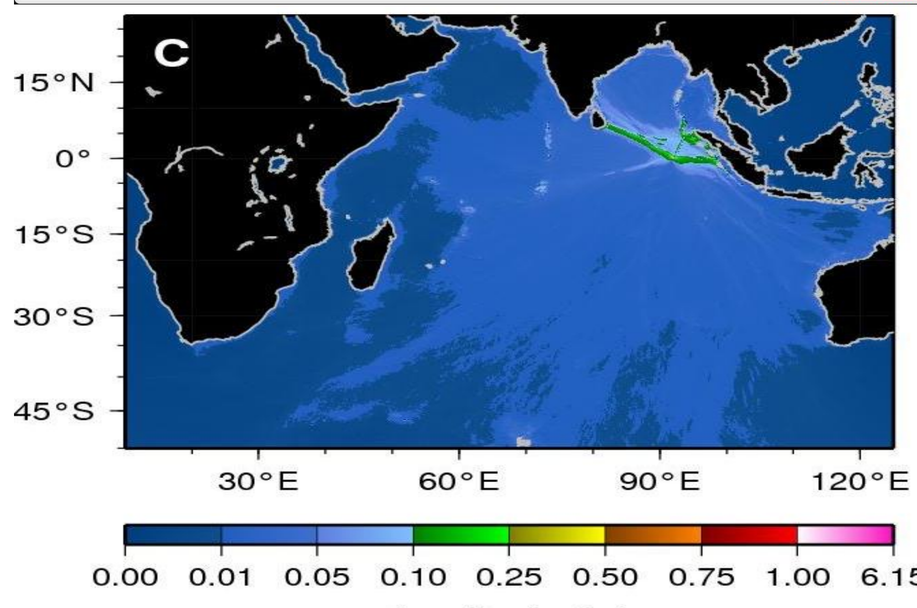


Modeled amplitudes vs the observed at tide gauges

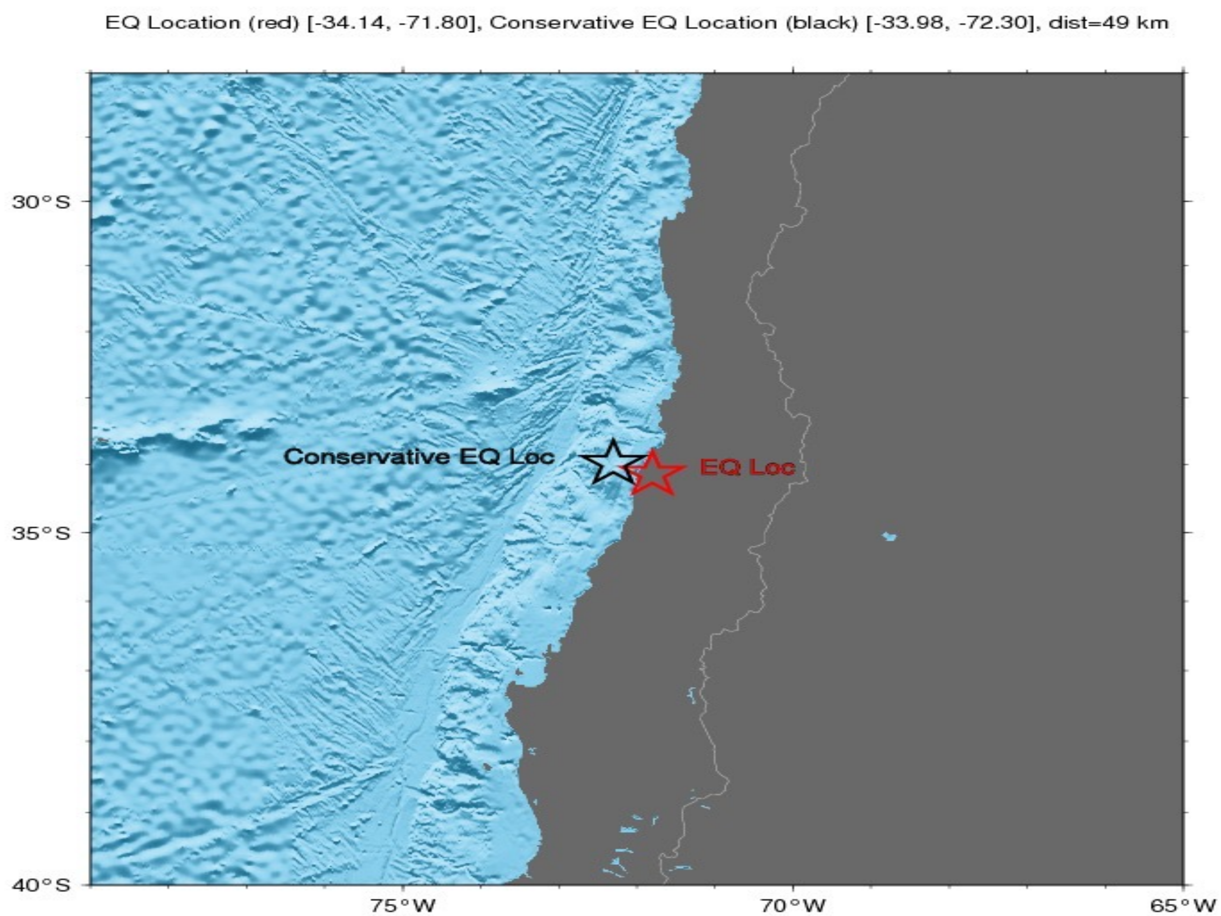
Wang et al. 2012, (Geophy. Res. Lett.)
Sumatra 2012 M8.6, Strike slip EQ
Largest strike-slip EQ on record





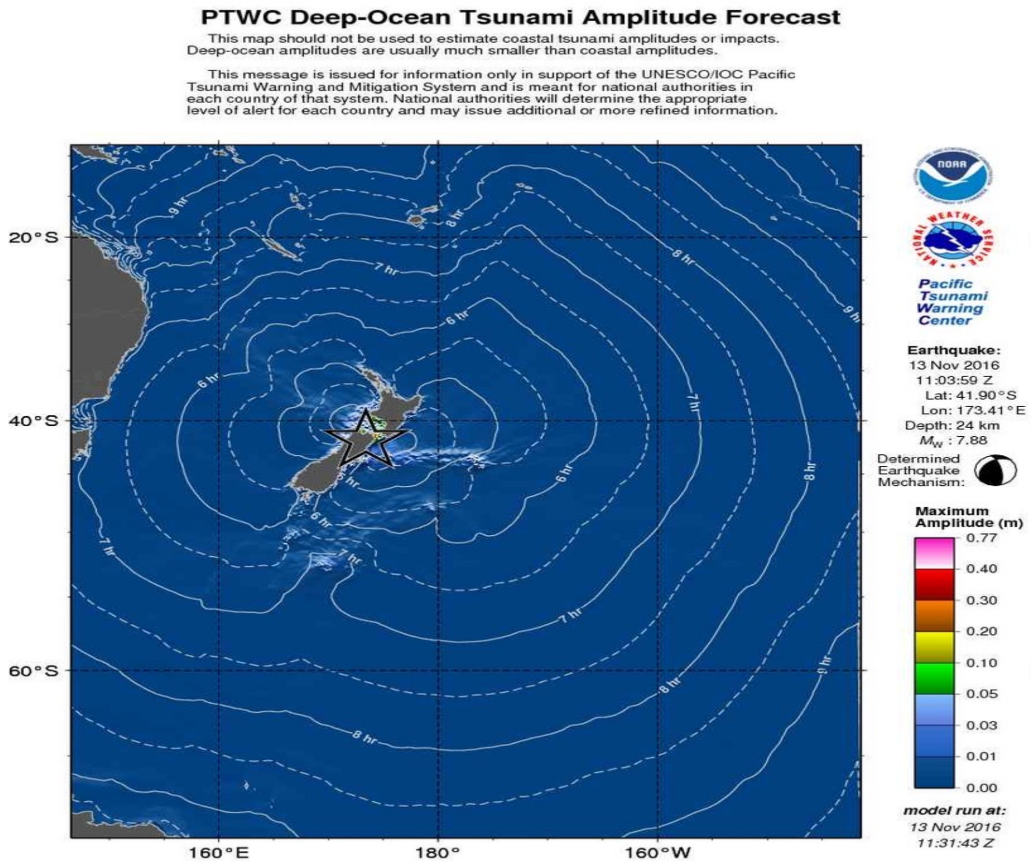


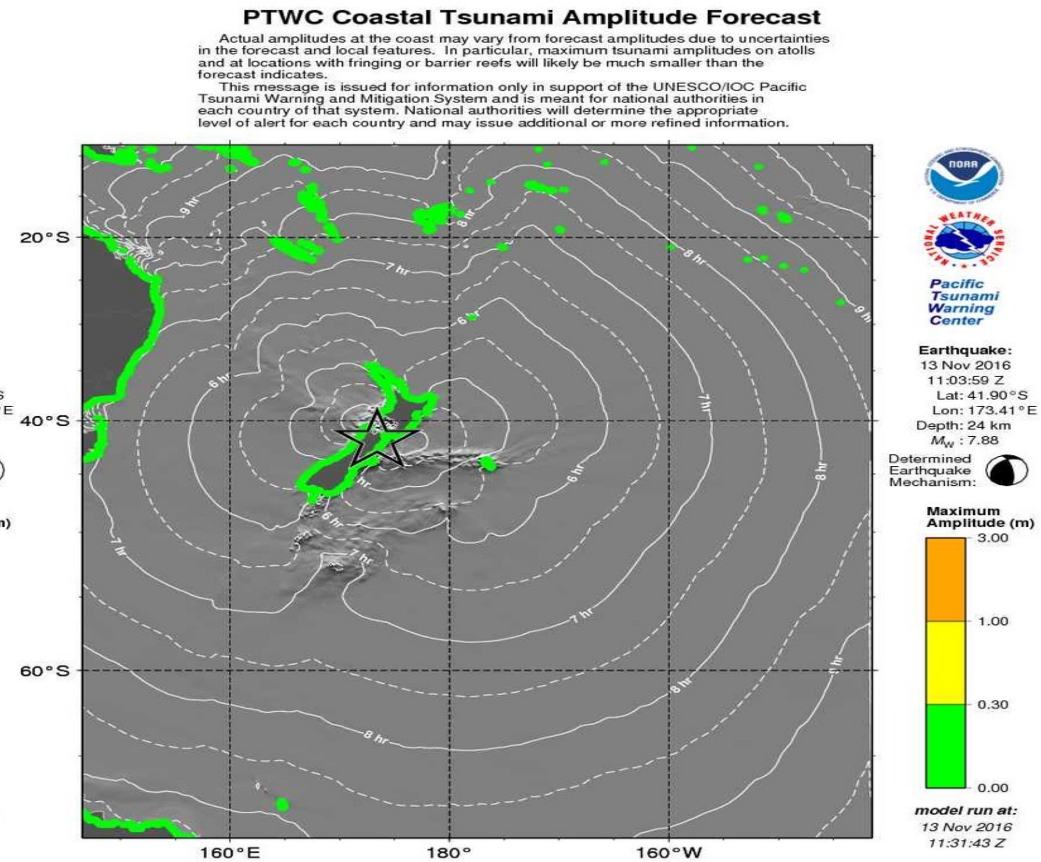
The operator of RIFT can choose to use a conservative (or the worst case) EQ location, i.e., moving the EQ location offshore or to over deeper water.



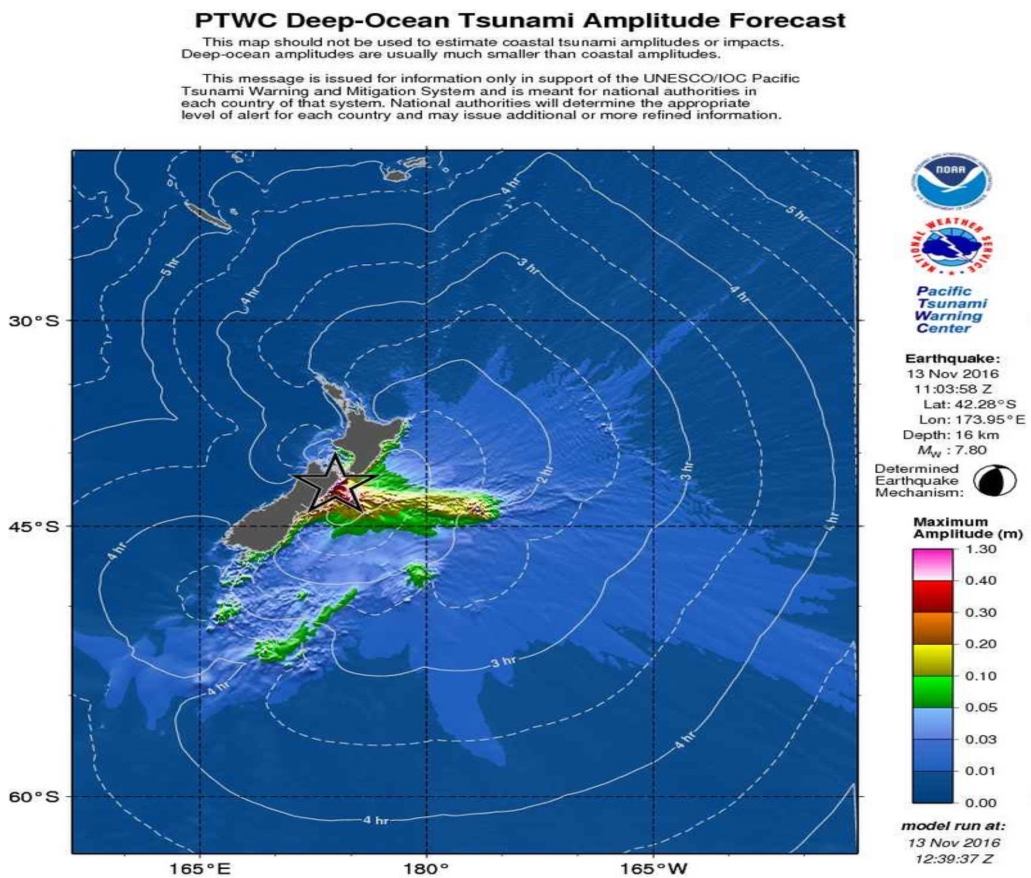
W-phase CMT based Forecast can also fail!!

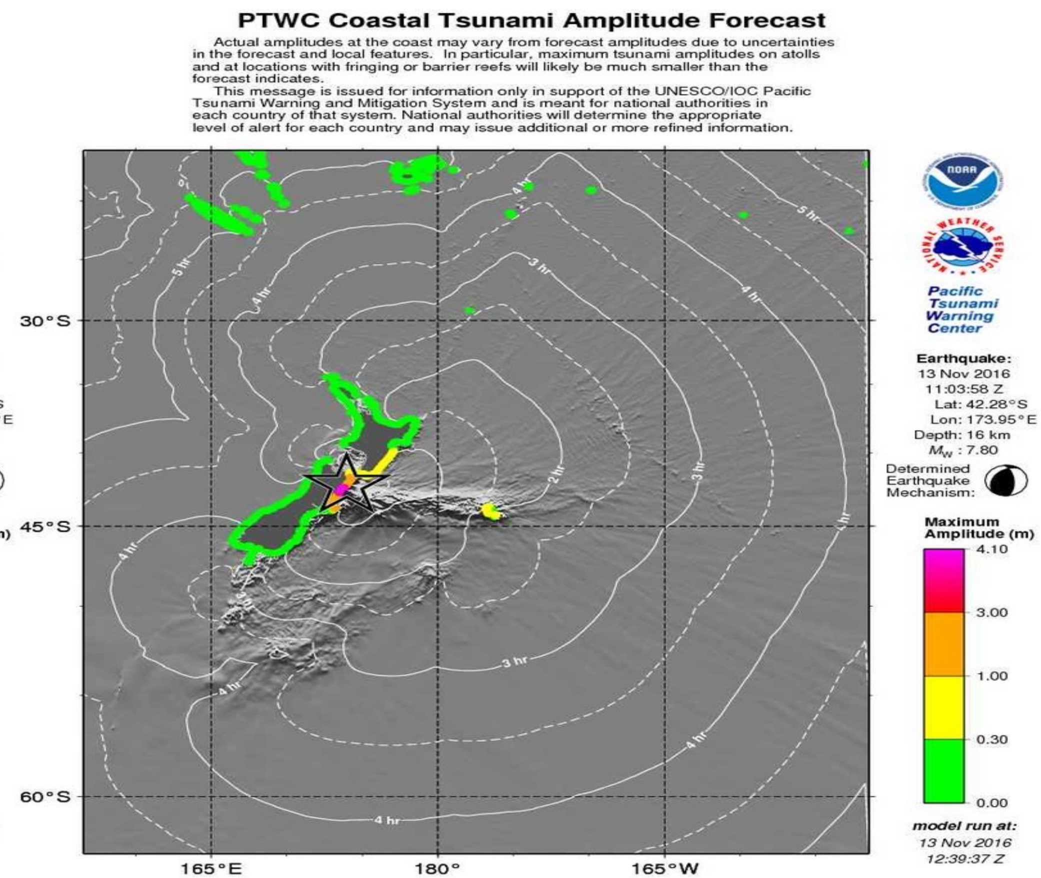
Nov. 13, 2016, Mw 7.8 New Zealand Tsunami





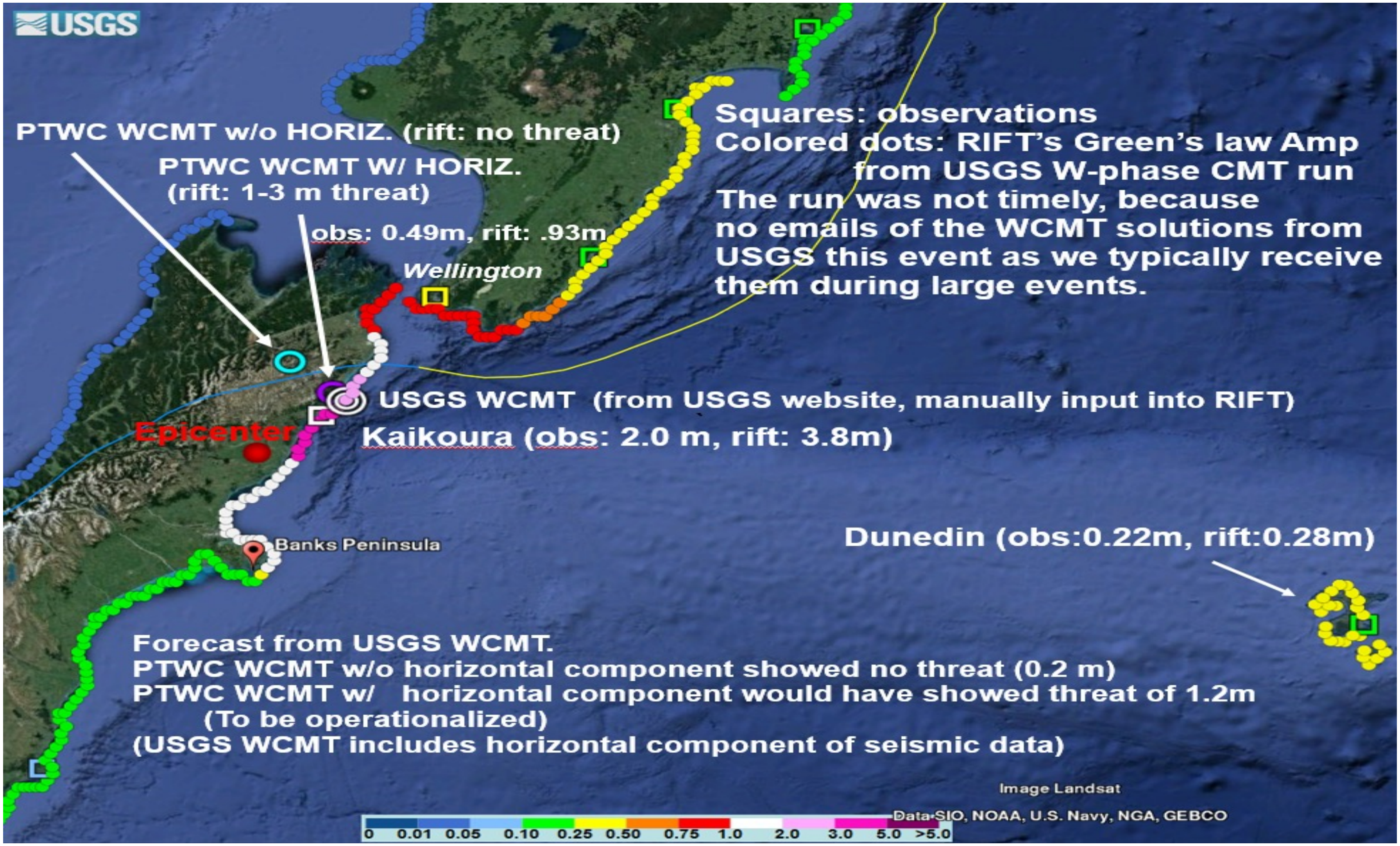
PTWC initial forecast based on PTWC W-phase CMT (no threat)



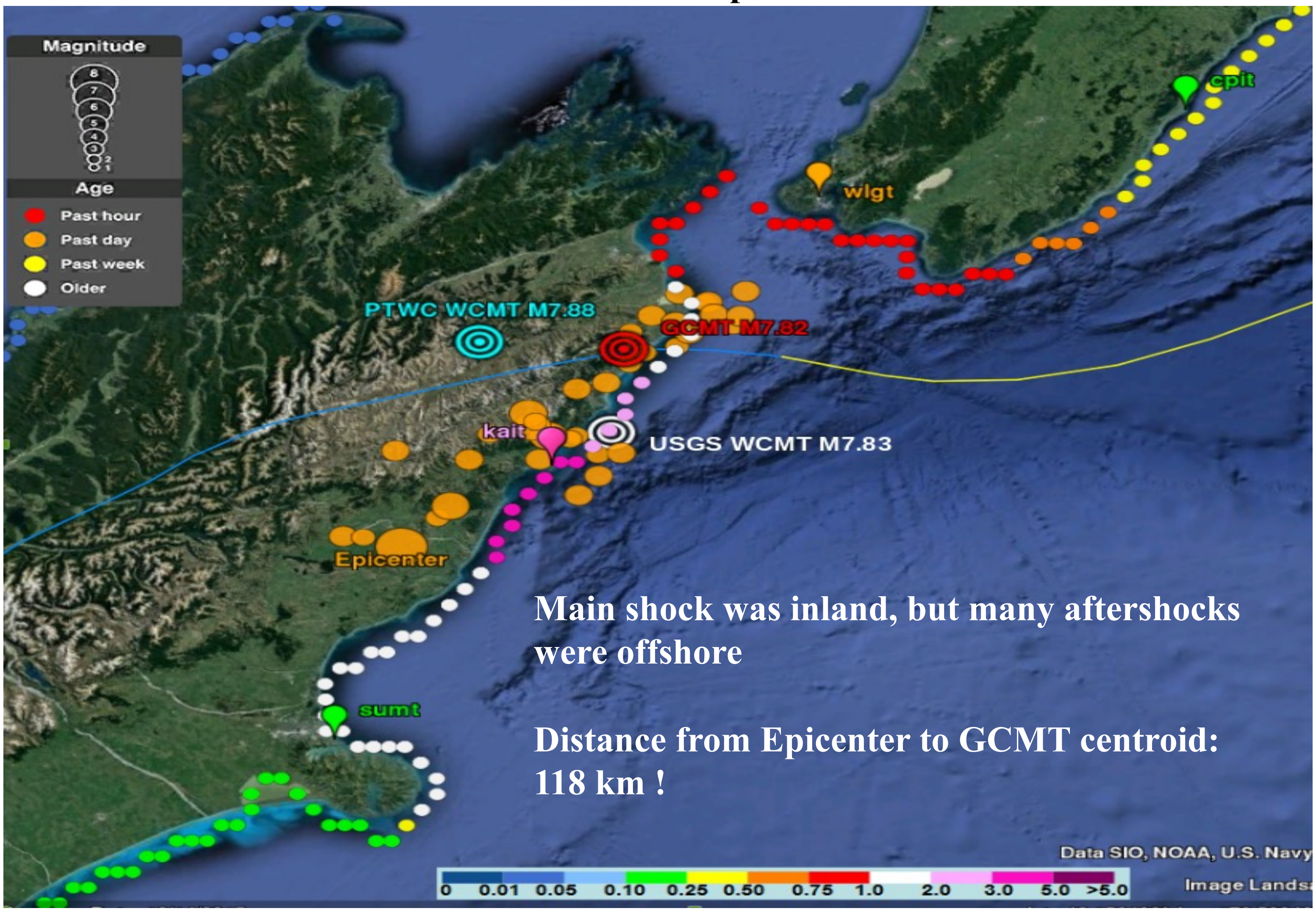


PTWC forecast based on USGS W-phase CMT (land threat)

All CMTs have the same Mw and similar focal mechanisms, but the centroid locations are very different.


USGS
PTWC WCMT w/o HORIZ. (rift: no threat)
PTWC WCMT W/ HORIZ.
(rift: 1-3 m threat)
obs: 0.49m, rift: .93m
Wellington
Squares: observations
Colored dots: RIFT's Green's law Amp
from USGS W-phase CMT run
The run was not timely, because
no emails of the WCMT solutions from
USGS this event as we typically receive
them during large events.
USGS WCMT (from USGS website, manually input into RIFT)
Epicenter
Kaikoura (obs: 2.0 m, rift: 3.8m)
Banks Peninsula
Dunedin (obs:0.22m, rift:0.28m)
Forecast from USGS WCMT.
PTWC WCMT w/o horizontal component showed no threat (0.2 m)
PTWC WCMT w/ horizontal component would have showed threat of 1.2m
(To be operationalized)
(USGS WCMT includes horizontal component of seismic data)
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
0 0.01 0.05 0.10 0.25 0.50 0.75 1.0 2.0 3.0 5.0 >5.0

Results from Global CMT run post event



Lessons

1. Forecast based on initial EQ location and magnitude can be VERY wrong.

2. Even forecast based on W-phase CMTs can also be wrong. Forecast results are very sensitive to centroid location. To be conservative, threat message should be issued for large inland EQs (if not too far inland).

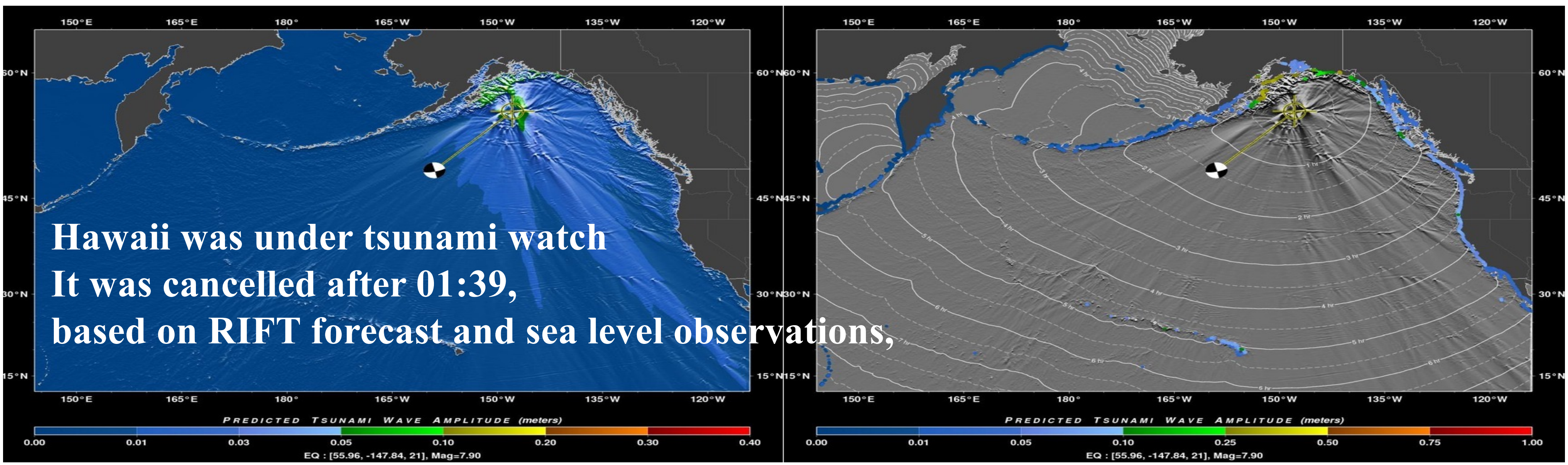
(for the New Zealand M7.8 event, PTWC issued a tsunami information statement (TIS) because of the smaller initial magnitude 7.4 and the inland location)

If the EQ is inland in shallow water, the RIFT GUI will warn the operator if he/she wants to move the epicenter offshore.

Jan. 23, 2018 M7.9 Alaska EQ (strike-slip)

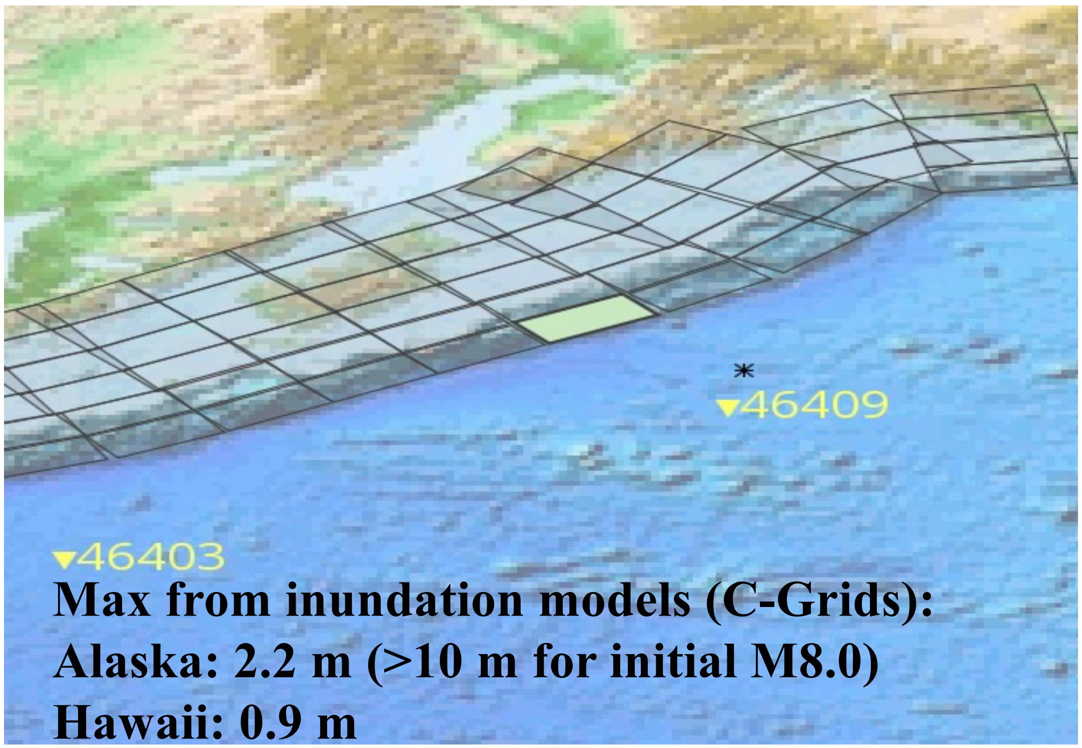
RIFT (27 min. after origin): USGS WCMT M7.9, strike-slip

Max coastal amp for Alaska: 0.33 m (observed: 0.21 m)
Max coastal amp for Hawaii: 0.11 m (observed: 0.18 m)



SIFT and ATFM work well for subduction zone EQs (e.g., Tohoku 2011) but might not work well for EQs outside the subduction zones or EQs of non-thrust types (ATFM does have some non-thrust sources).

Jan. 23, 2018, M7.9 Alaska Earthquake and Tsunami



Max from inundation models (C-Grids):
Alaska: 2.2 m (>10 m for initial M8.0)
Hawaii: 0.9 m

Closest SIFT unit source is more than 100 km from the EQ location and is of thrust type.

The focal mechanism of the earthquake is strike-slip.

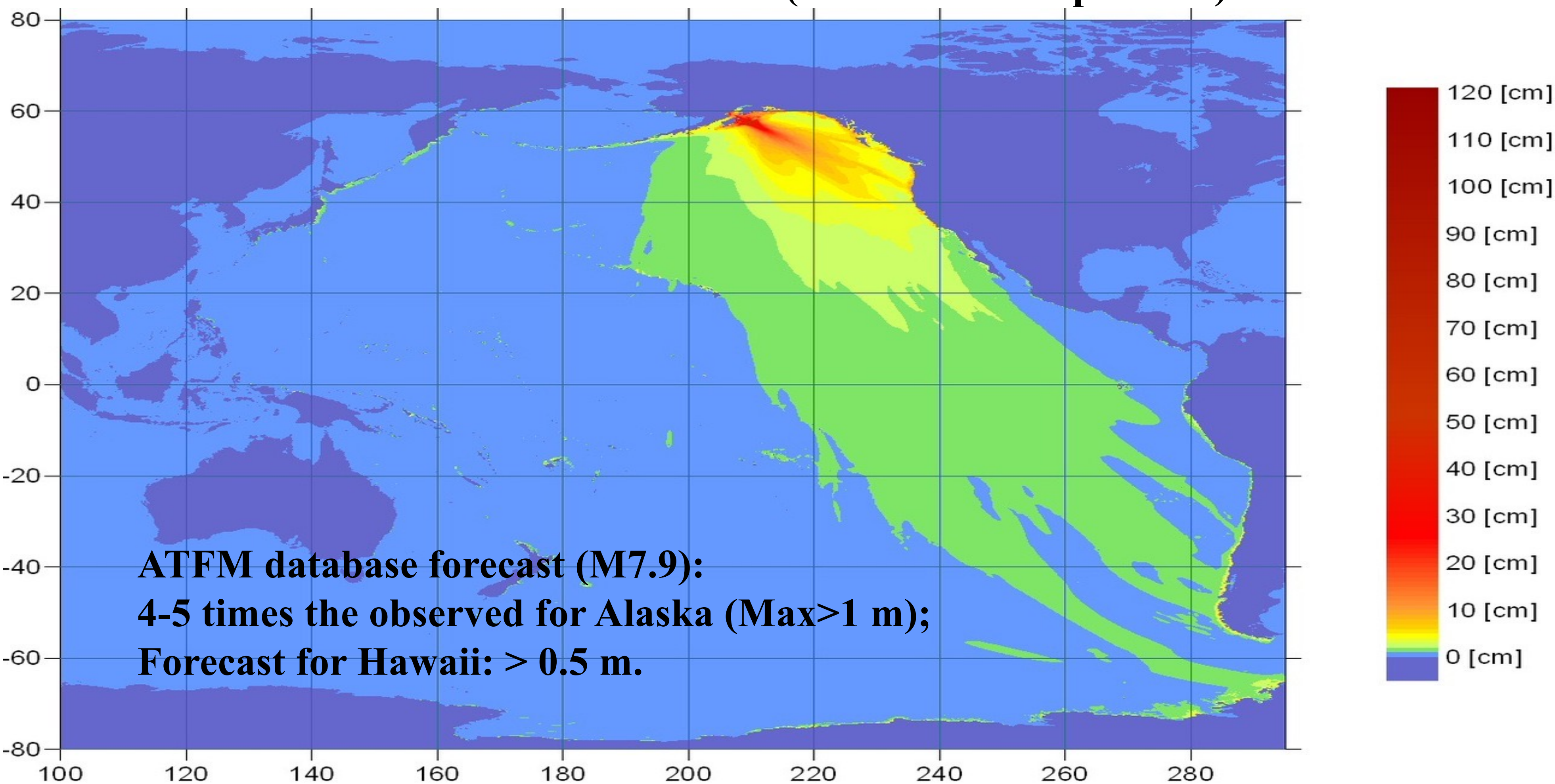
The closest ATFM source is 160 km from the EQ location and is also of thrust type.

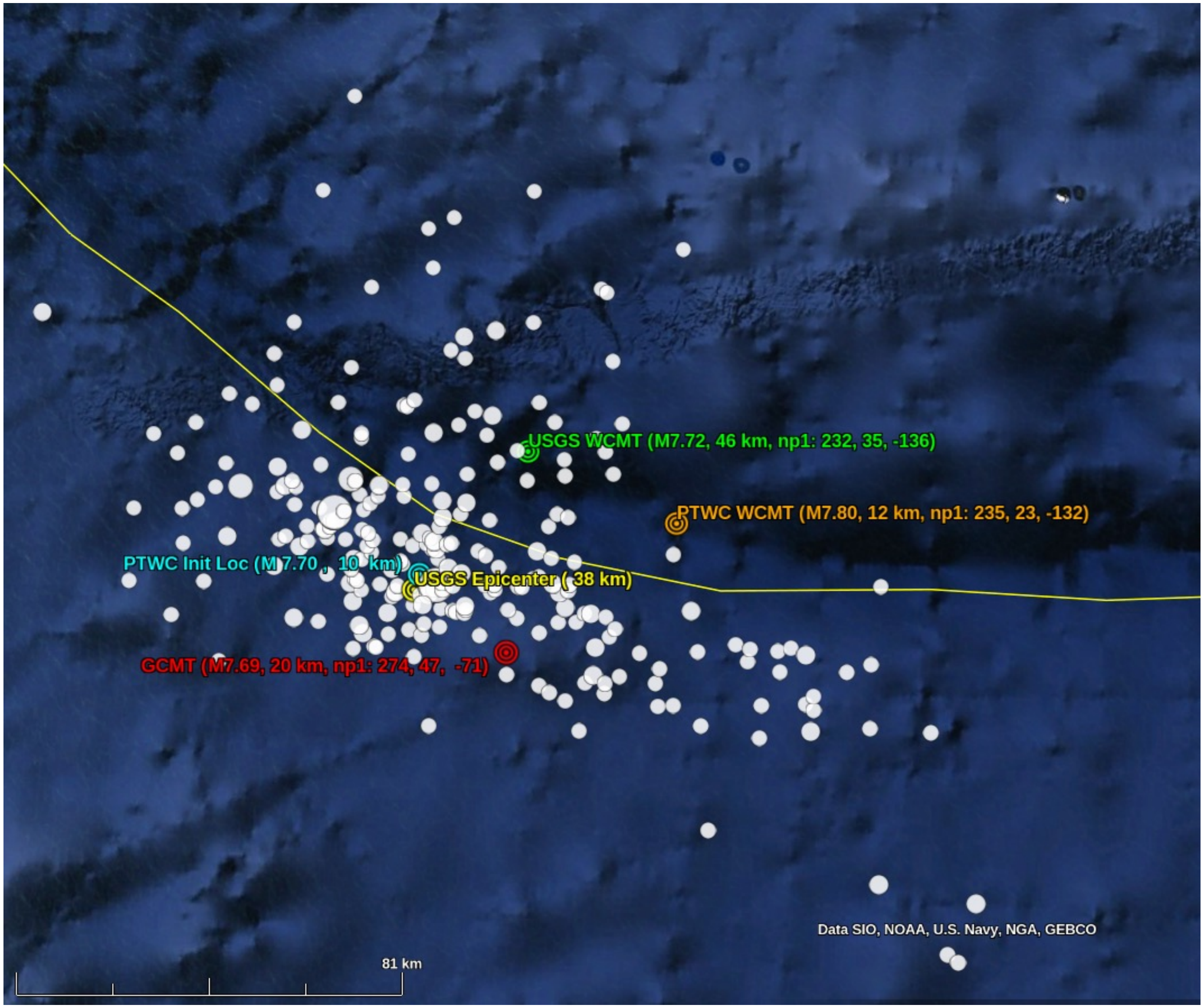
RIFT forecast provided the best results among the three models during the event (still not ideal, though).

PMEL developed the capability of inversion using real-time unit sources generation. It produced good results for this event, but the capability has not been delivered to the TWCs.

Jan. 23, 2018 M7.9 Alaska EQ (strike-slip)

ATFM database closest thrust unit source (>150 km from epicenter)



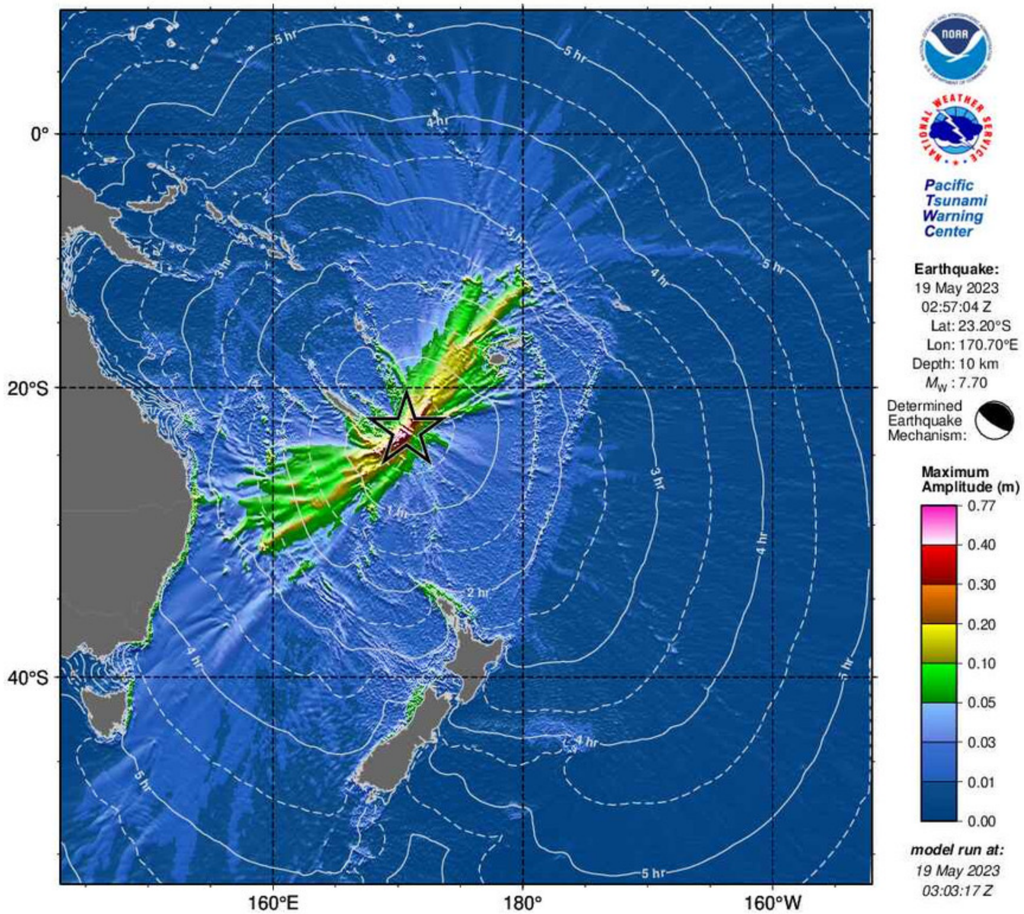


2023.05.19 M7.7 Royalty Islands EQ and Tsunami

PTWC Deep-Ocean Tsunami Amplitude Forecast

This map should not be used to estimate coastal tsunami amplitudes or impacts. Deep-ocean amplitudes are usually much smaller than coastal amplitudes.

This message is issued for information only in support of the UNESCO/IOC Pacific Tsunami Warning and Mitigation System and is meant for national authorities in each country of that system. National authorities will determine the appropriate level of alert for each country and may issue additional or more refined information.



PTWC Coastal Tsunami Amplitude Forecast

Actual amplitudes at the coast may vary from forecast amplitudes due to uncertainties in the forecast and local features. In particular, maximum tsunami amplitudes on atolls and at locations with fringing or barrier reefs will likely be much smaller than the forecast indicates.

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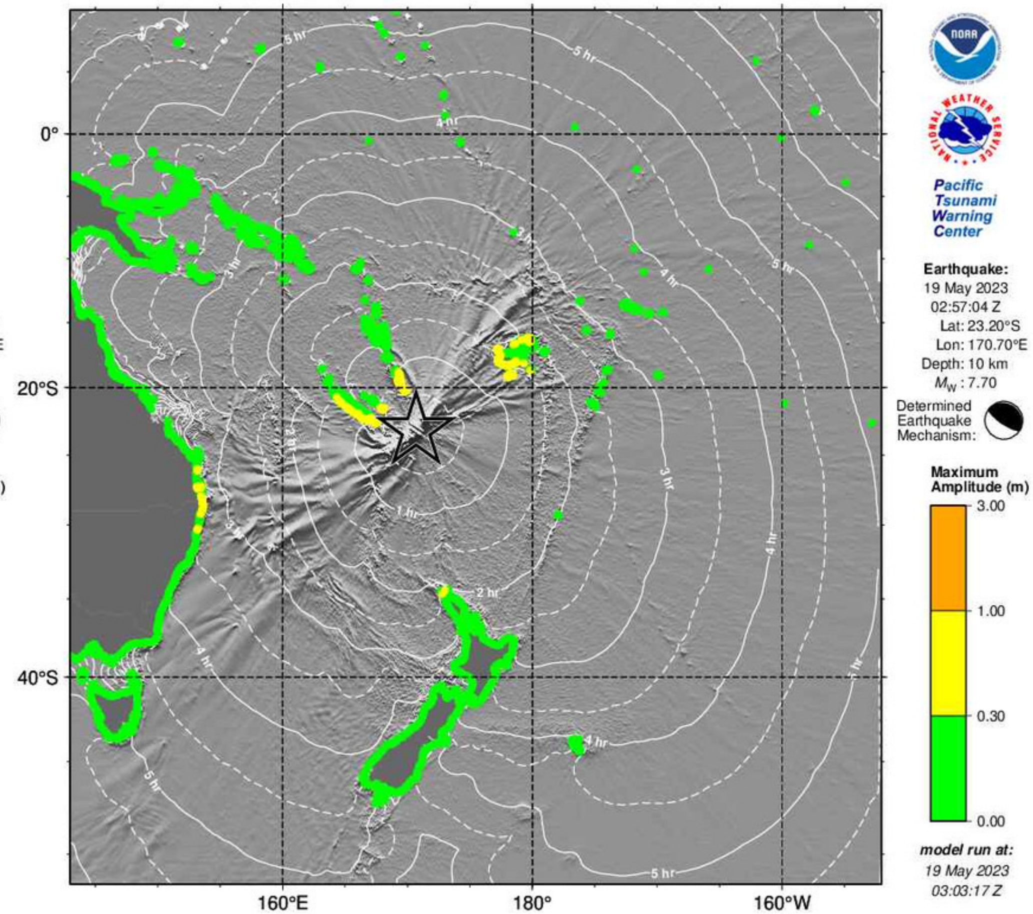
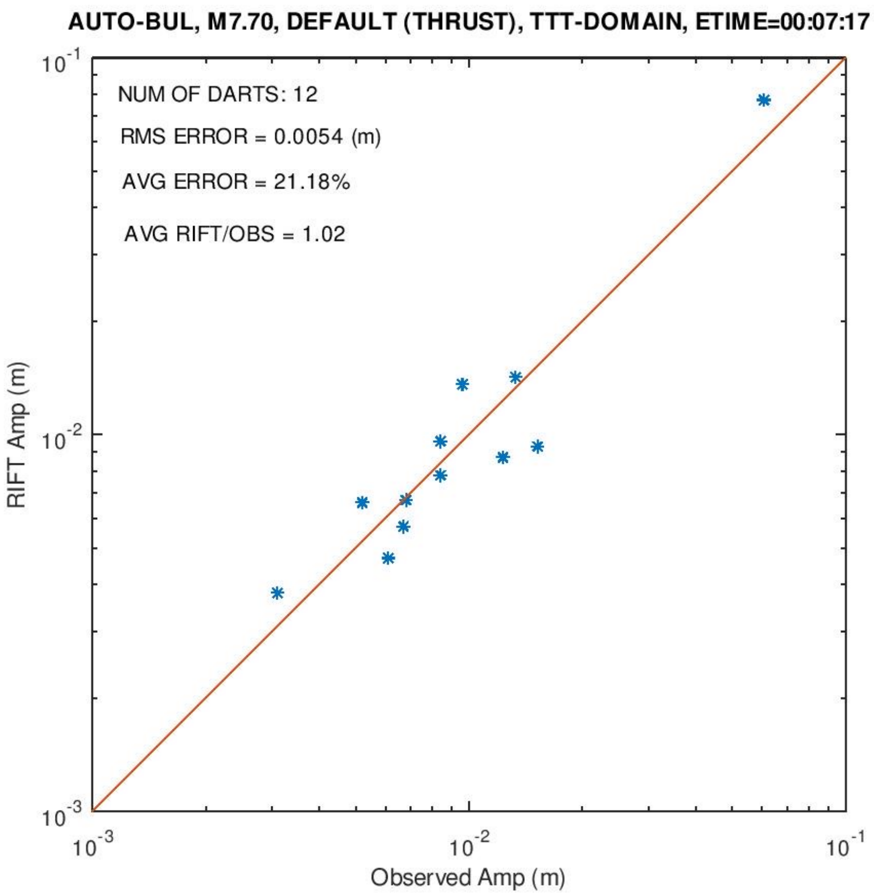
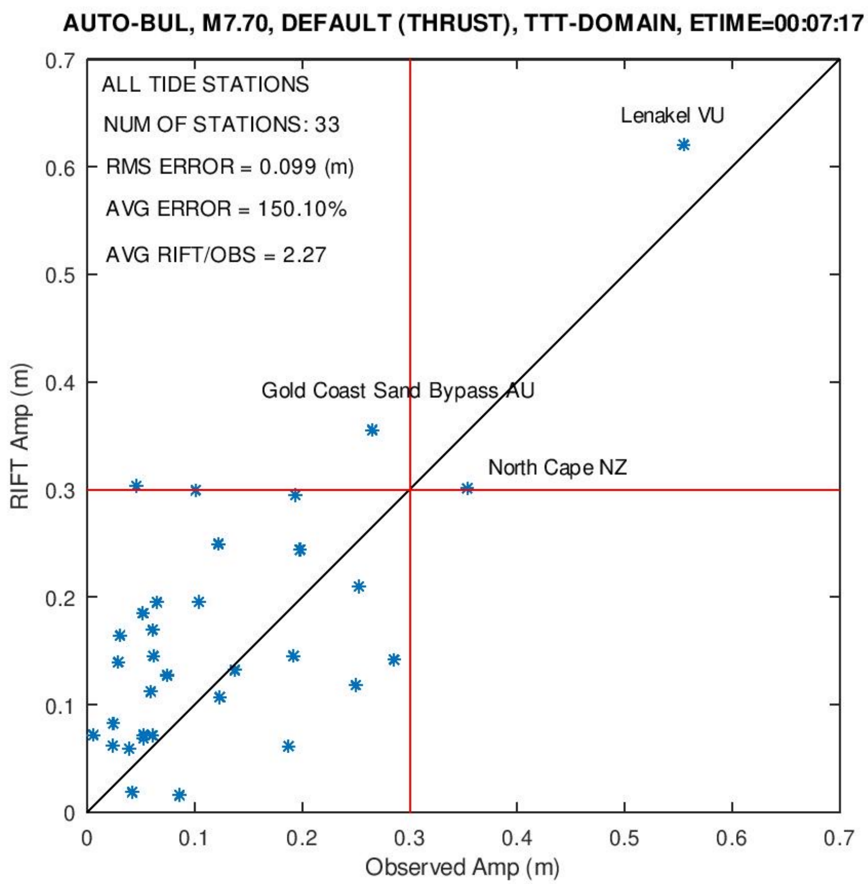


2023.05.19 M7.7 Royalty Islands EQ and Tsunami



2023.05.19 M7.7 Royalty Islands EQ and Tsunami



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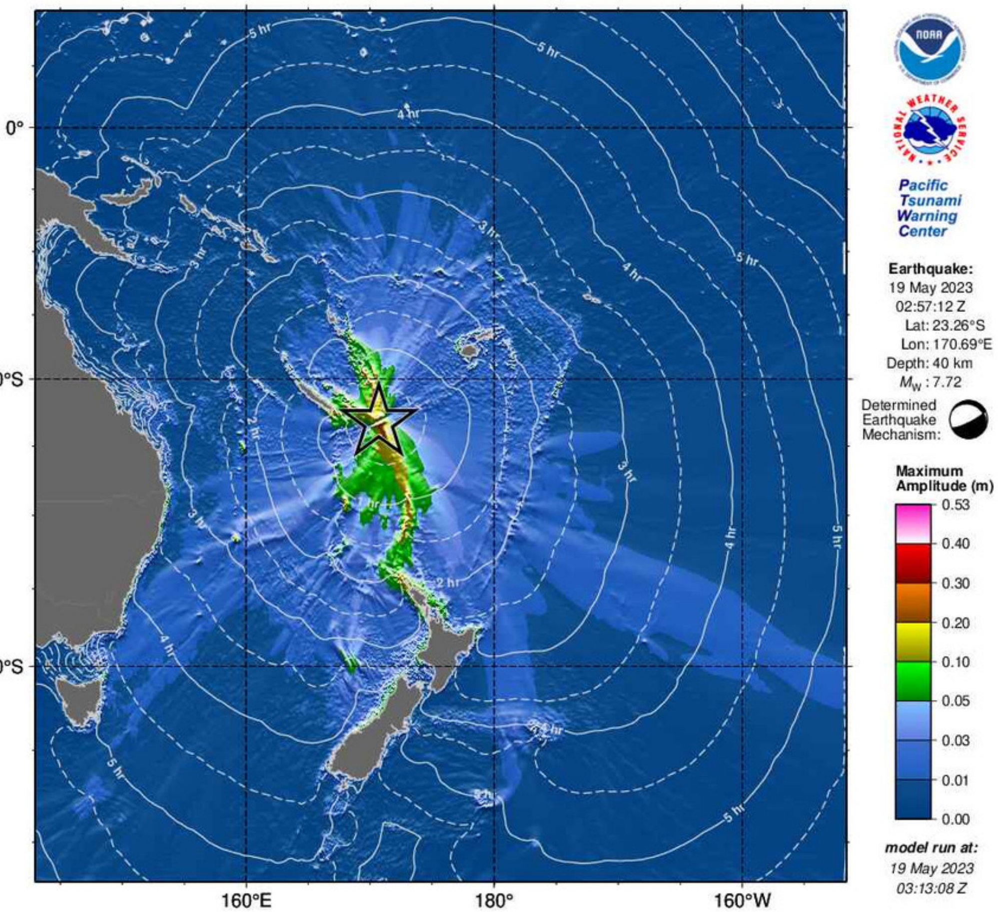

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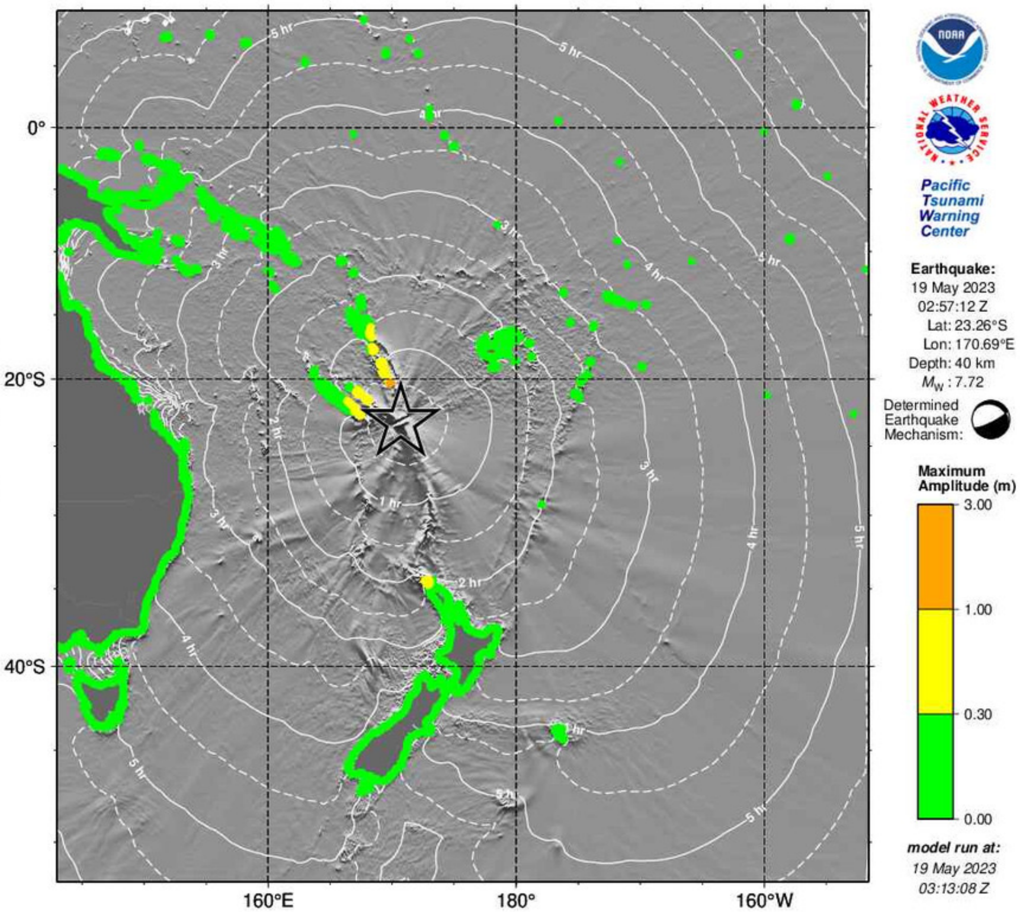
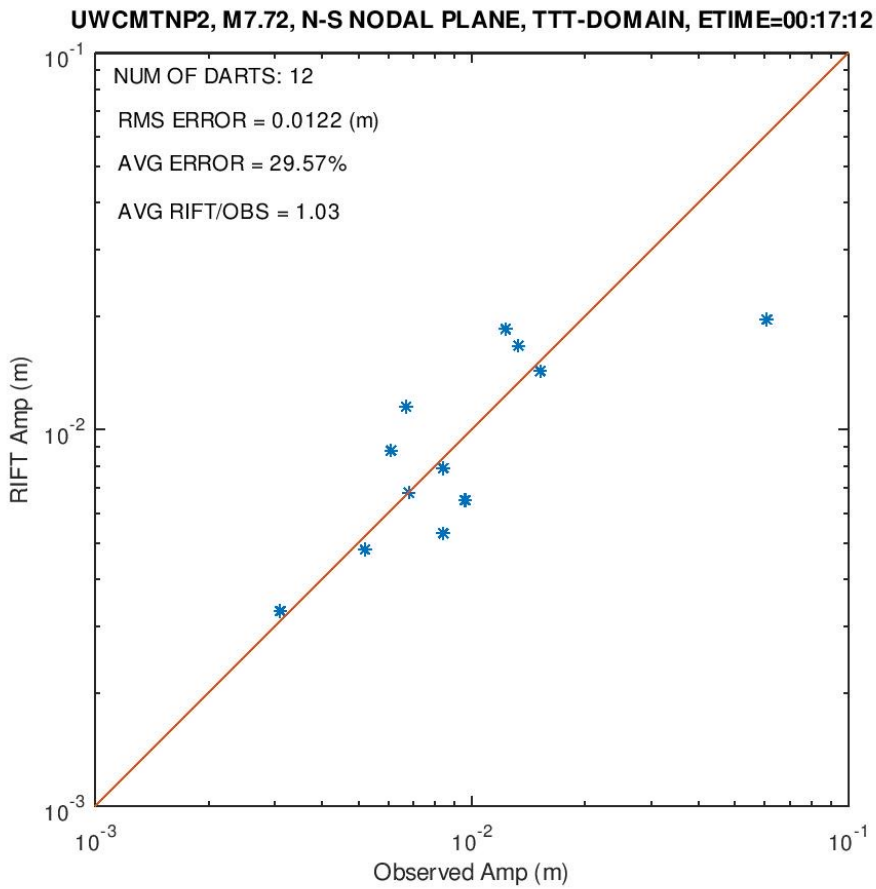
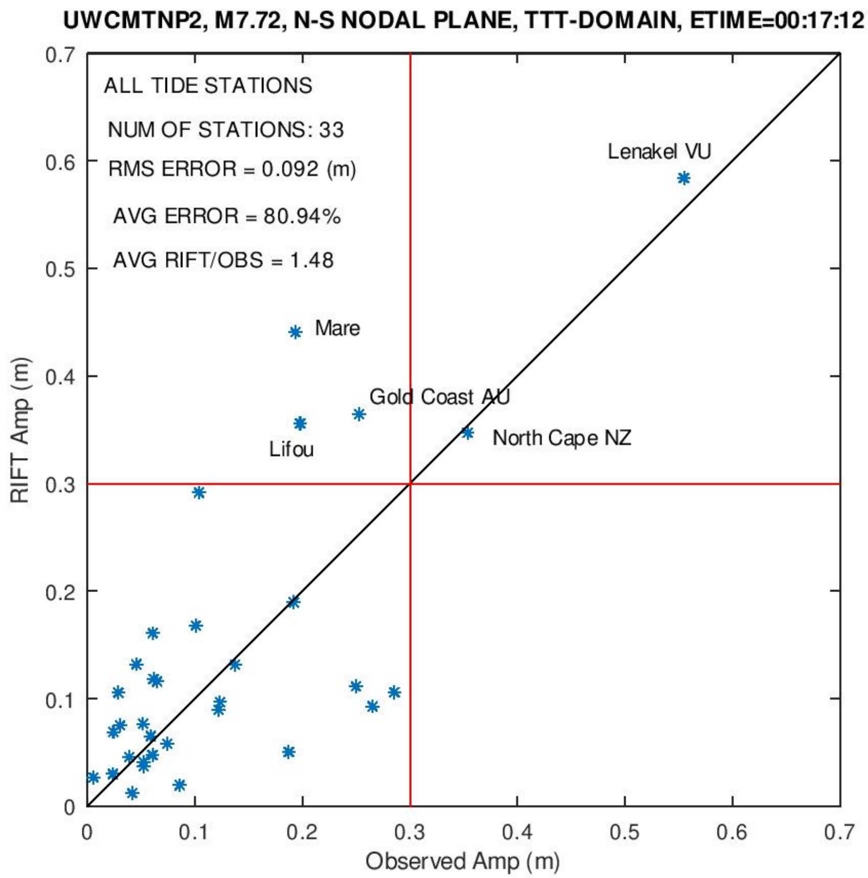


2023.05.19 M7.7 Royalty Islands EQ and Tsunami



2023.05.19 M7.7 Royalty Islands EQ and Tsunami



4. Summary Statement

1. The database approach is fast and robust. It works well if the characteristics of sources are similar to those of the actual earthquakes, especially if good wave-form-fit results are obtained after DART inversion.

2. It is important to have real-time tsunami forecast capability for TWCs to account for all possible earthquakes and focal mechanisms. Forcing a simple real-time model with W-phase CMT worked reasonably well most of the time in PTWC's 10+ years of real-time forecasting experience. However, there were a few exceptions/failures.

3. For local tsunami warning, it is difficult to come up with an accurate forecast quickly because the initial EQ mag can be significantly off and the focal mechanism of the EQ might not be known in a timely fashion.

4. Green's law coastal forecast is an order of magnitude forecast (general level of threat) and is not suitable for evacuation mapping. Inundation models are always preferred over Green's law if the sources used reflect the mechanisms of the earthquakes and there is sufficient time to conduct the inundation model runs during an event.

5. The ultimate goal of tsunami forecasting would be an end-to-end real-time forecast system: from finite fault source generation, to propagation forecasting, and to inundation forecasting. The most difficult part is the real-time finite-fault source generation. There have been some recent promising developments in combining high-rate GPS data and seismology for source characterization, which might provide better sources for real-time forward modeling.

Thank You!