Operational Tsunami Forecast and Warning

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Australian Government
Bureau of Meteorology

The Centre for Australian Weather and Climate Research
A partnership between CSIRO and the Bureau of Meteorology

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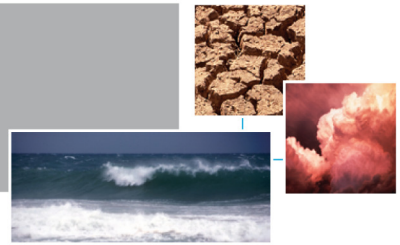
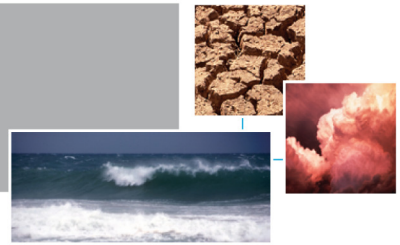
Outline



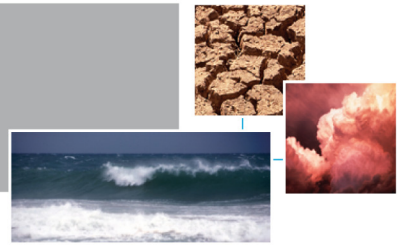
- Introduction
- Operational tsunami warning systems
- Tsunami prediction
  - T2 scenario database
- Tsunami warning decisions
- Case studies
- Closing remarks

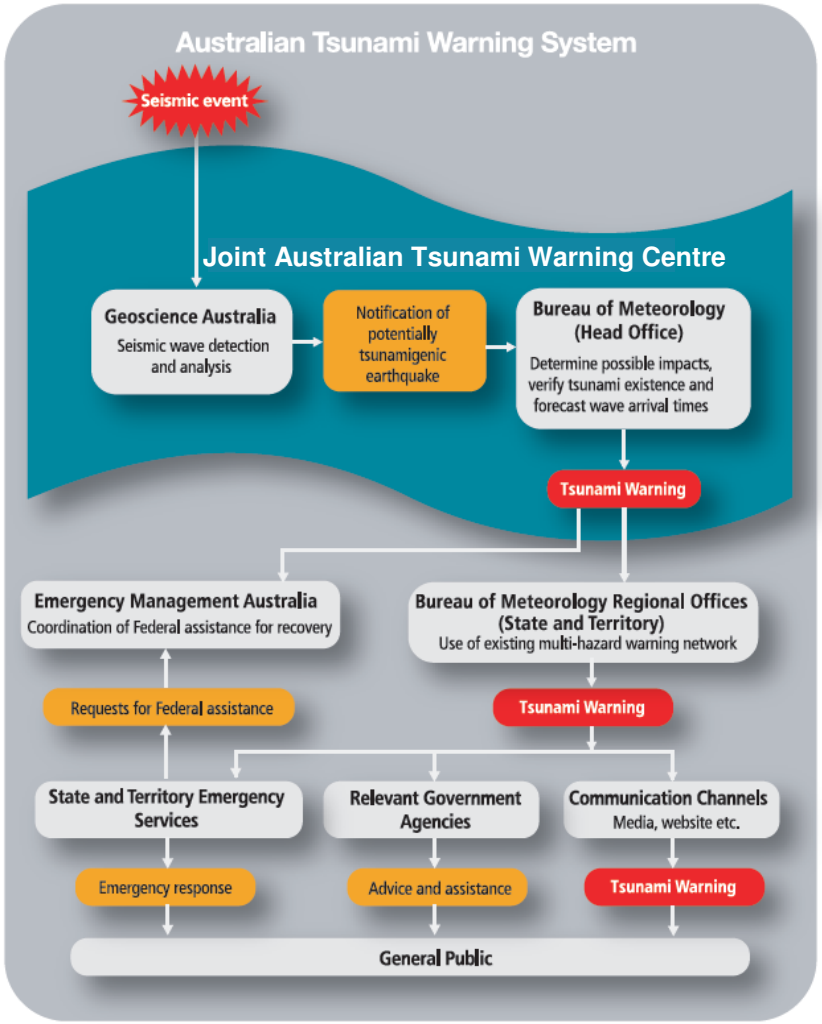
Introduction

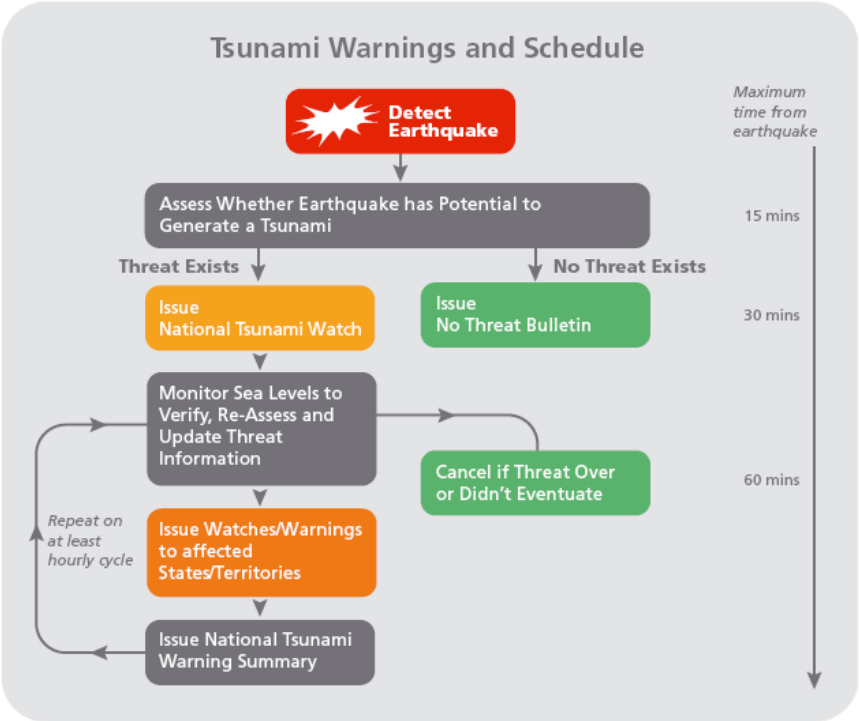


- Centre for Australian Weather and Climate Research (CAWCR)
  - Research branch of the Bureau of Meteorology
  - Five research programs
- Before 2004, little or no tsunami modelling or warning capability
- After Indian Ocean Tsunami of 26th December 2004, the Australian Tsunami Warning System (ATWS) was established.
- ATWS was an AU$68.9M 4-year project: July 2005 – June 2009
- Jointly managed by the Bureau, Geoscience Australia (GA) and Emergency Management Australia (EMA)
- Main objective: To provide a comprehensive tsunami warning system for Australia
- Joint Australian Tsunami Warning Centre (JATWC)

Operational tsunami warning systems







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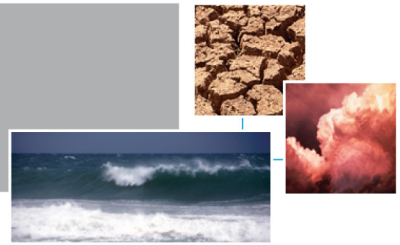
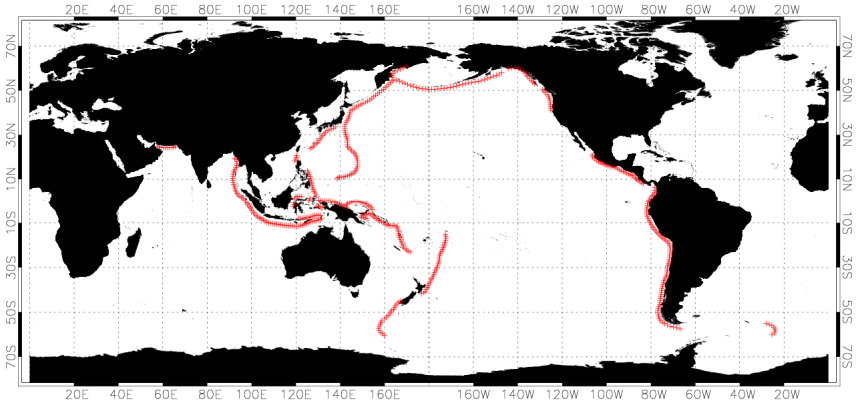
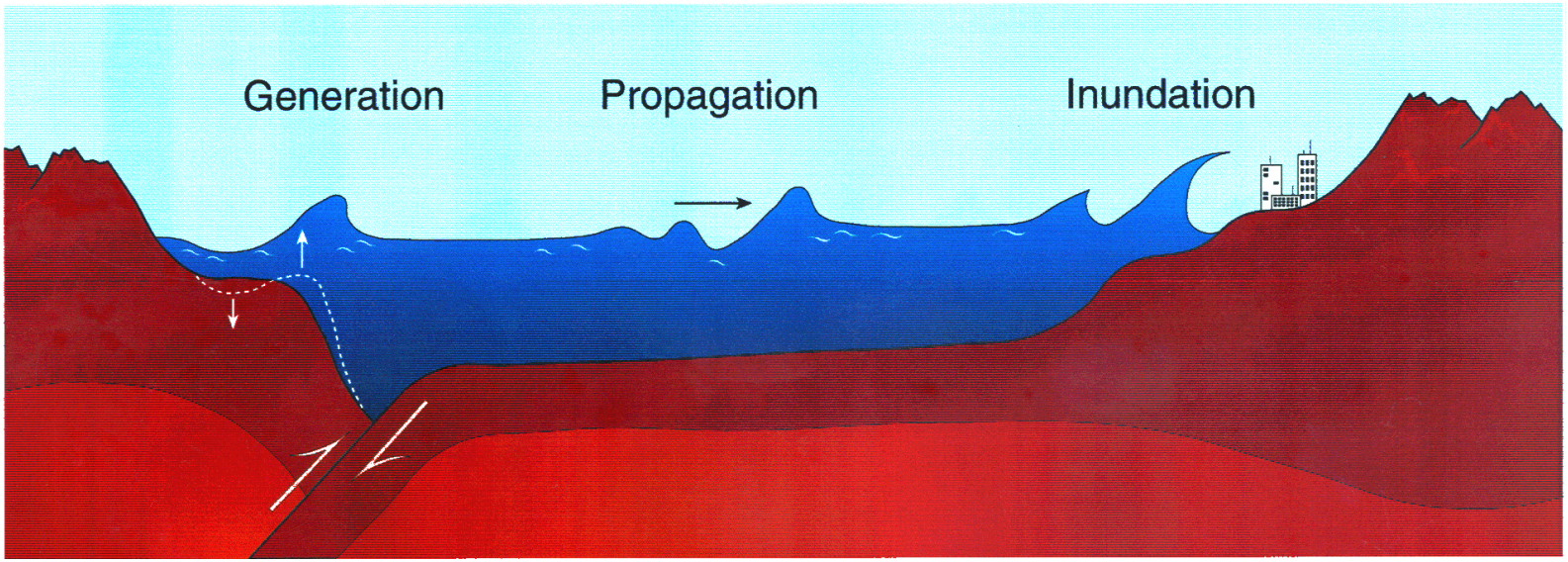
Operational tsunami warning systems



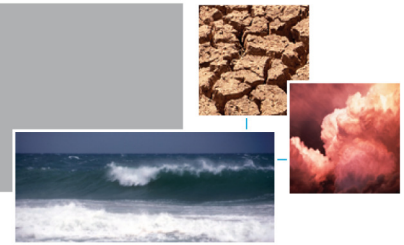
- State-of-the-art tsunami warning systems assess potential tsunami impact based on numerical models
- Real-time tsunami predictions
  - Dynamical real-time forecasts not currently feasible
  - Operational systems based on scenario databases
  - Pre-computed tsunami scenarios representing “all” possible events
  - In an event, extract closest scenario
- National warning systems:
  - Japan, USA, Australia, India, Indonesia…



Tsunami prediction



Tsunami prediction

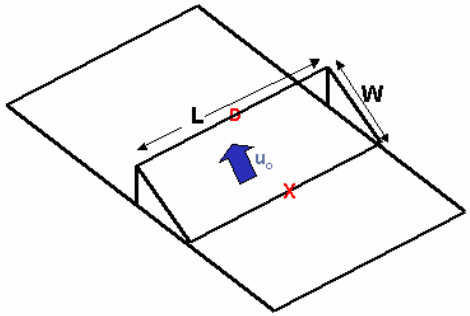


- Generation of initial condition
  - Double-couple-model earthquake source Gusiakov (1972), Okada (1985)
  - Assume undersea earthquake triggers instantaneous deformation of the seafloor
  - Required parameters:
    - Epicentre location (lat. lon.)
    - Length (L), width (W), depth
    - Strike, dip, rake (degrees)
    - slip (u_o)

$$M_o = \mu L W u_o$$

$$M_w = \frac{2}{3}\left(\log_{10} M_o - 9.1\right)$$

  - M_w = moment magnitude, M_o = seismic moment, μ = rigidity of earth's crust
  - Deformation of sea-floor imposed directly on sea-surface

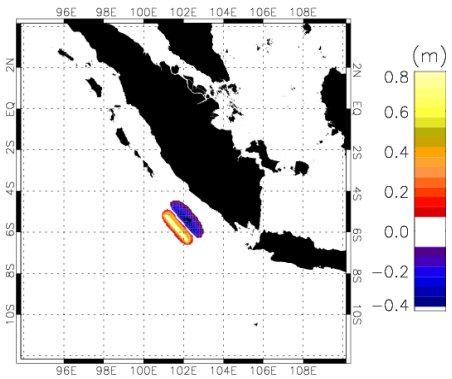


e.g. L = 100 km

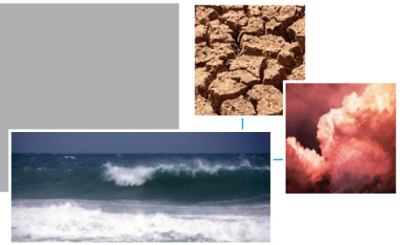
W = 50 km

u_o = 1 m

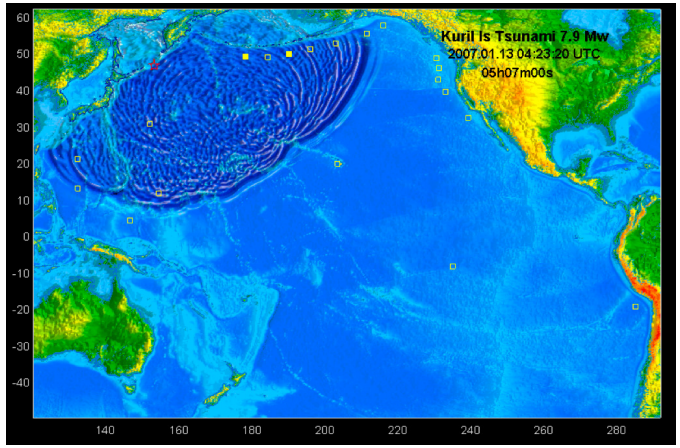
M_w = 7.5



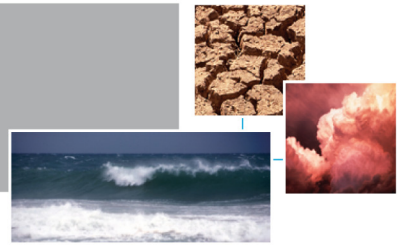
Tsunami prediction



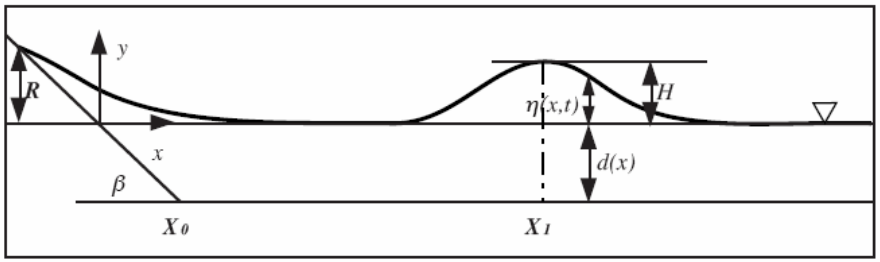
- Propagation + inundation
  - Majority of tsunami models are based on non-linear shallow water equations
  - Propagation ("deep" ocean)
    - linear shallow water equations
  - Inundation/run-up
    - Still long waves, but processes include wave breaking, overland flows, etc.
    - non-linear shallow water equations
    - Applicability of depth-averaging?
  - Dispersion may be important for trans-ocean tsunamis
    - Boussinesq models; or use numerical dispersion in place of physical dispersion
    - Near-field tsunamis are not affected much by dispersion because of their short propagation distances
- Numerous tsunami models
  - MOST,TUNAMI, FUNWAVE,….



MOST model



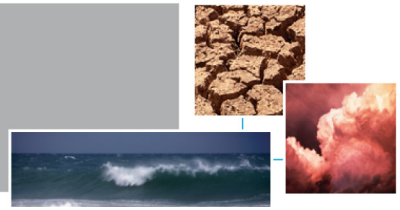
- Method Of Splitting Tsunamis (MOST)
  - Titov and Synolakis (1998)
- Initial condition
  - Gusiakov (1972), Okada (1985)
- Non-linear shallow water equations
- No bottom friction
  - No consensus on roughness coefficients
  - avoids ad hoc parameterisation



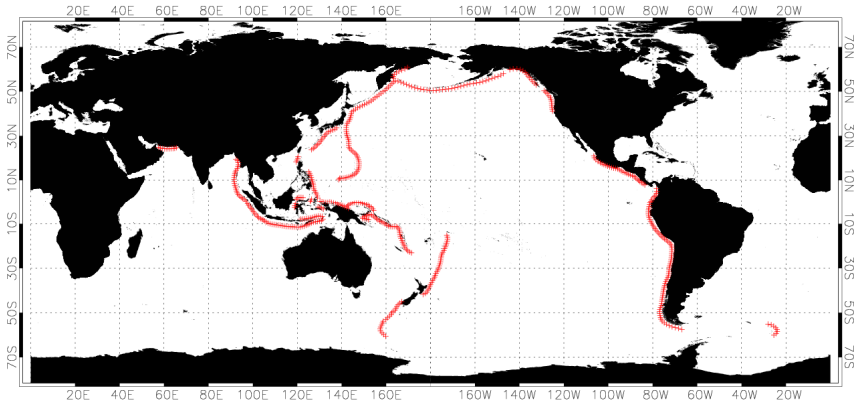
$$h(x,y,t) = \eta(x,y,t) + d(x,y,t)$$

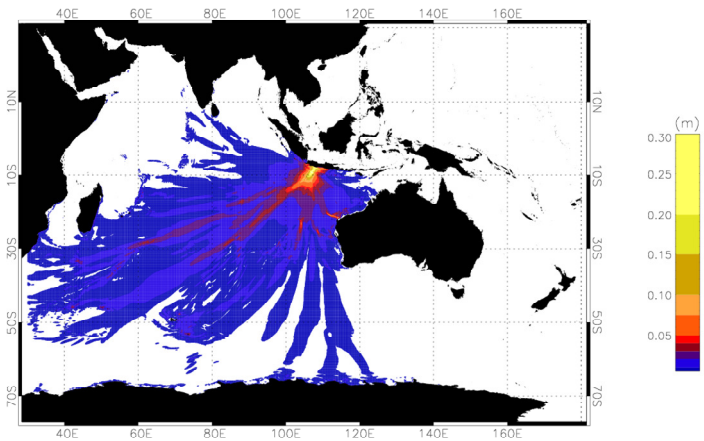
$$\begin{aligned} h_t + (uh)_x + (vh)_y &= 0 \\ u_t + uu_x + vu_y + gh_x &= gd_x \\ v_t + uv_x + vv_y + gh_y &= gd_y \end{aligned}$$

T2 Scenario database

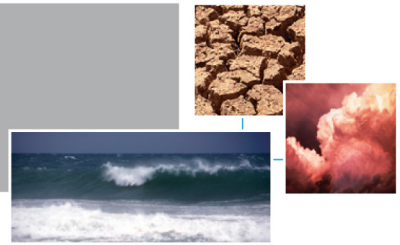


- 522 individual locations
- Up to 5 scenarios of different magnitude at each location
- > 2,000 scenarios
- Scenario details:
  - Epicentre location (lat. lon.)
  - Length (*L*), width (*W*), depth
  - Strike, dip, rake (degrees)
  - slip (u_o)
- Other generic details:
  - 24-hour model run
  - 4 arc min resolution
  - Output (*u, v, h*) saved every gridpoint and every 2 minutes
  - h_{max} calculated every time step
  - Each scenario ~72GB
  - Entire database ~140TB





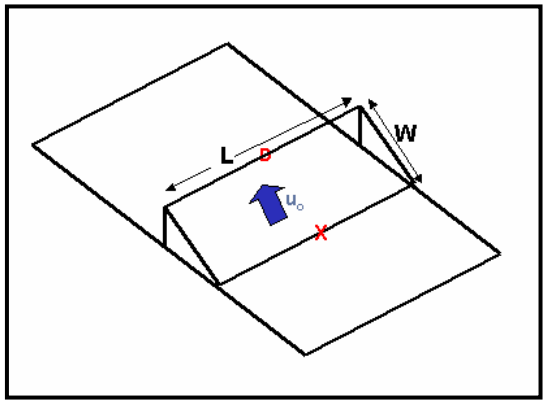
T2 Scenario database

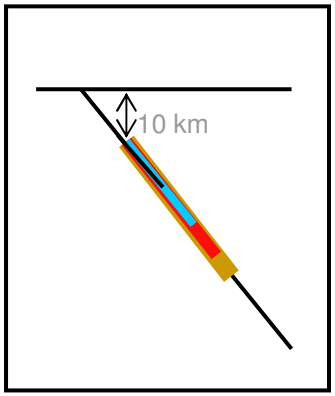


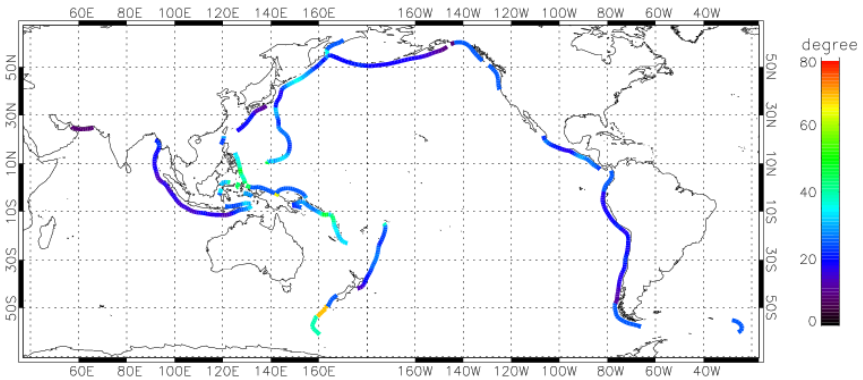
- Scenario details:
  - Epicentre location (lat. lon.)
  - Length (L), width (W), slip (u_o)
  - Depth
  - Strike, dip, rake (degrees)

$$M_w = \frac{2}{3}\left(\log_{10} M_o - 9.1\right)$$

$$M_o = \mu L W u_o$$

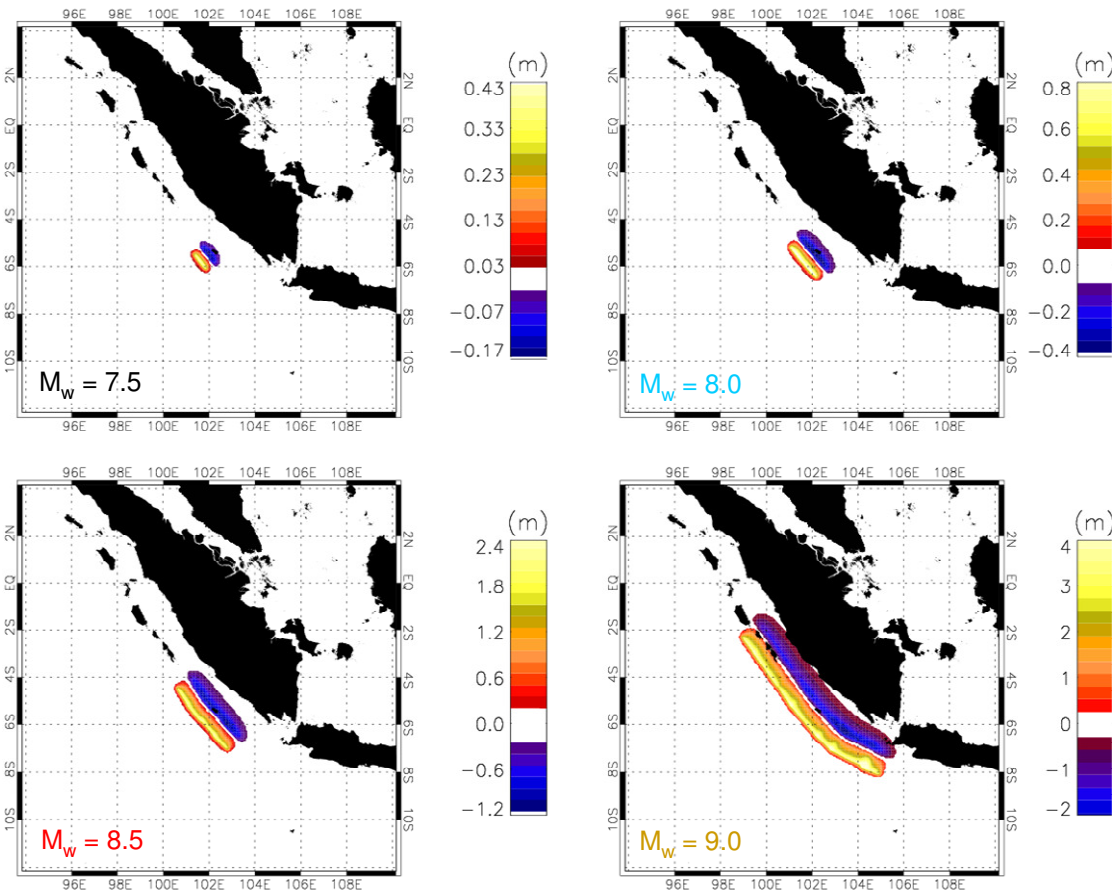






M_w	W (km)	L (km)	u_o (m)
7	35	50	0.5
7.5	50	100	1
8	65	200	2.2
8.5	80	400	5
9	100	1000	8.8

T2 Scenario database



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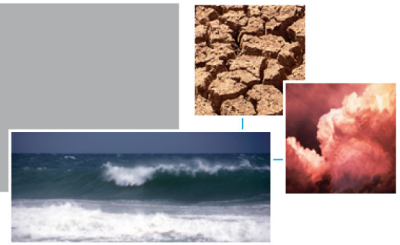
T2 Scenario database

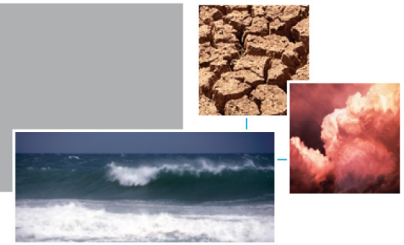


- We need to be able to provide guidance for events of intermediate magnitude, i.e., M_w = 8.1, M_w = 7.6 etc.
- Tsunami generation and propagation can be assumed linear in deep ocean
  - T2 scenarios > 20m depth
- h_{max} from intermediate event is linear function of h_{max} from closest magnitude scenario
- Assume L and W constant and vary u_o

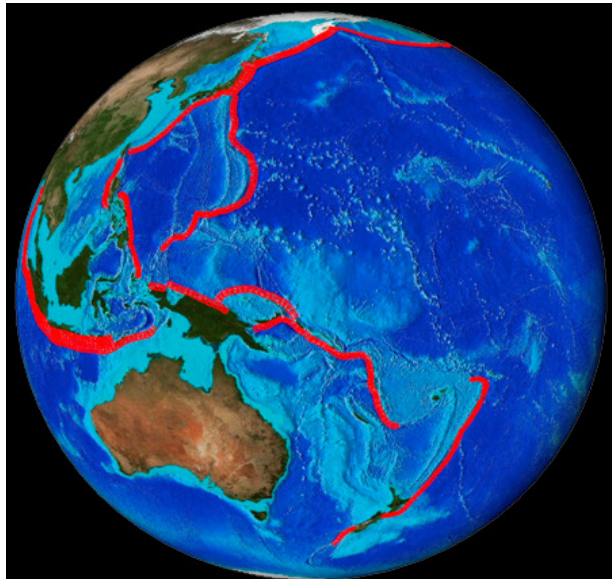
$$F_s = 10^{\frac{3}{2}\left(M_{w(new)} - M_w\right)}$$

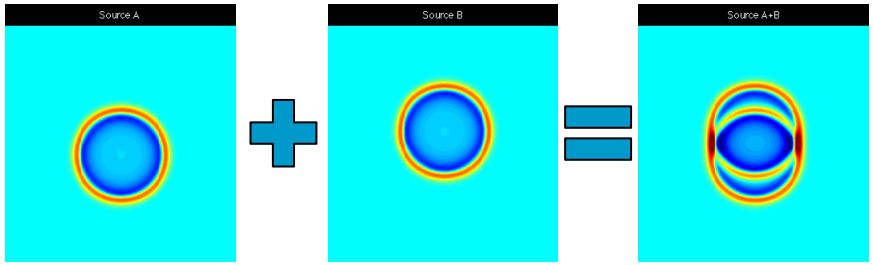
$M_{w(new)}$	Existing M_w	F_s	$F_s u_o$ (m)	W (km)	L (km)
7.3	7.5	0.50	0.50	50	100
7.4	7.5	0.71	0.71	50	100
7.5	**7.5**	**1.00**	**1.00**	**50**	**100**
7.6	7.5	1.41	1.41	50	100
7.7	7.5	1.90	1.90	50	100
7.8	8.0	0.52	1.14	65	200
7.9	8.0	0.71	1.56	65	200
8.0	**8.0**	**1.00**	**2.20**	**65**	**200**
8.1	8.0	1.41	3.10	65	200
8.2	8.0	1.90	4.18	65	200
8.3	8.5	0.52	2.60	80	400
8.4	8.5	0.71	3.55	80	400
8.5	**8.5**	**1.00**	**5.00**	**80**	**400**
8.6	8.5	1.41	7.05	80	400
8.7	8.5	1.90	9.50	80	400
8.8	9.0	0.53	4.66	100	1000
8.9	9.0	0.71	6.25	100	1000
9.0	**9.0**	**1.00**	**8.80**	**100**	**1000**
9.1	9.0	1.41	12.41	100	1000
9.2	9.0	2.00	17.60	100	1000

Unit source method



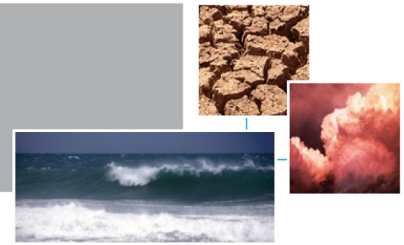
- Unit source method (NOAA/NCTR) takes advantage of linear propagation
- Define unit sources, $M_w = 7.5$
- Combine and scale to create larger (or smaller) magnitude events
  - Based on seismic magnitude
  - Inversion based on observations

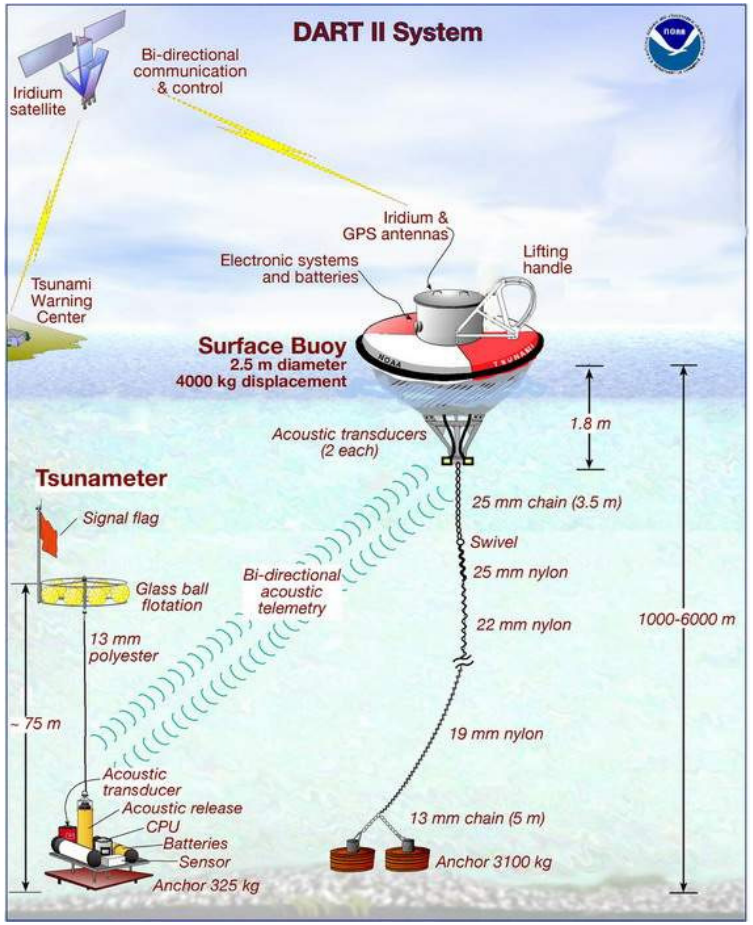


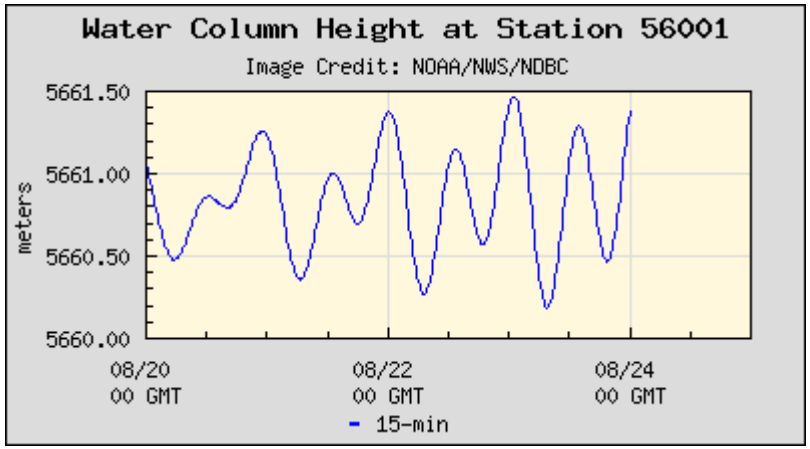


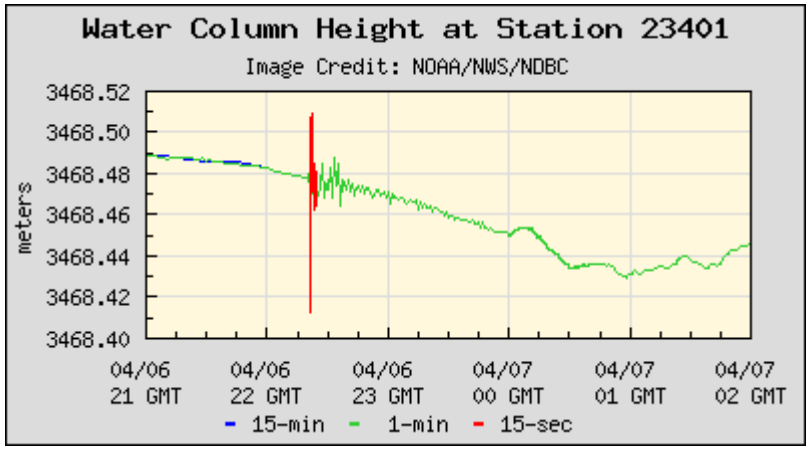
M_w	W (km)	L (km)	u_o (m)
7.5	50	100	1

Tsunameters

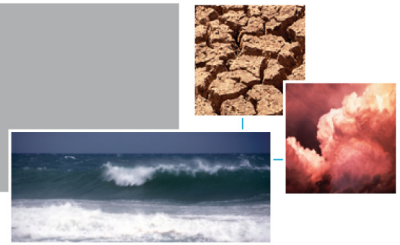


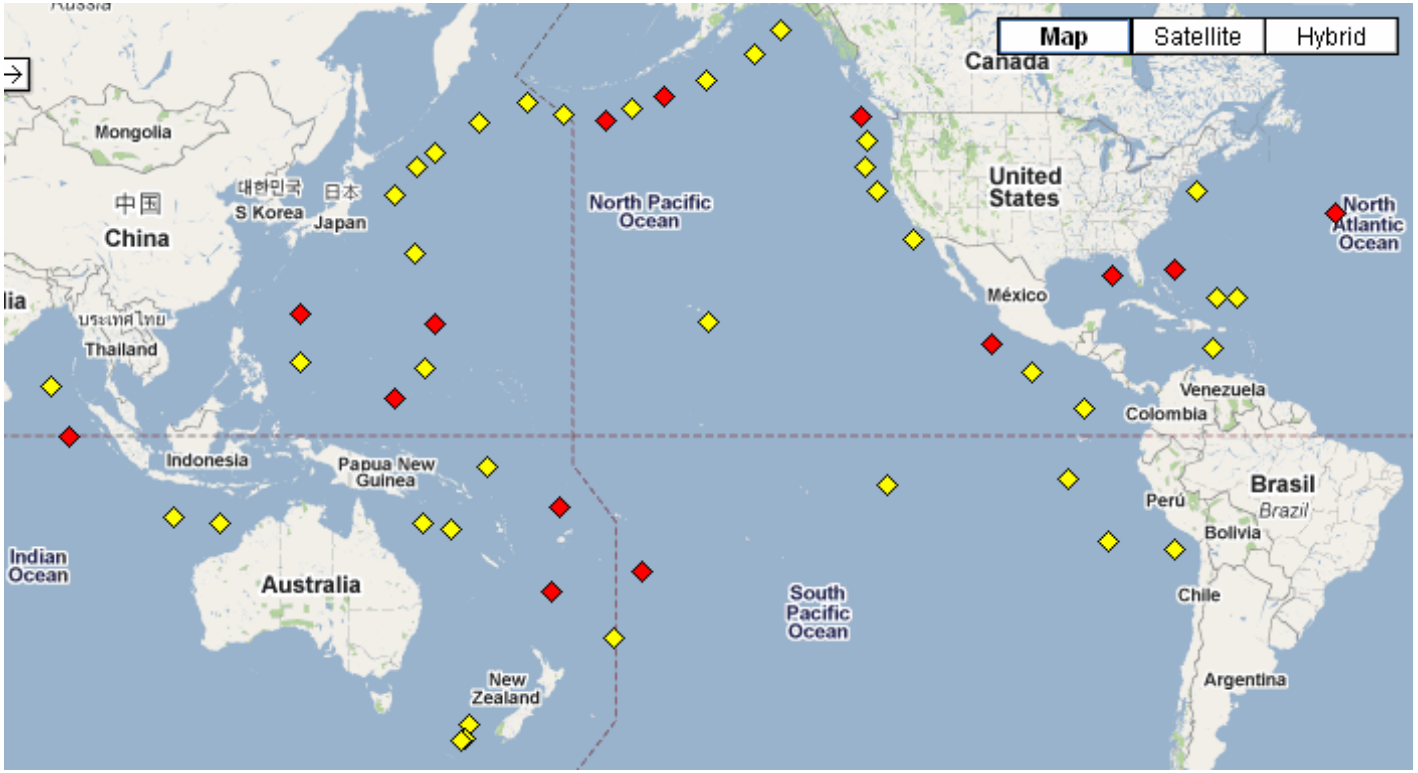






Tsunameters





US National Data Buoy Center

http://www.ndbc.noaa.gov/

As at June 9th, 2011

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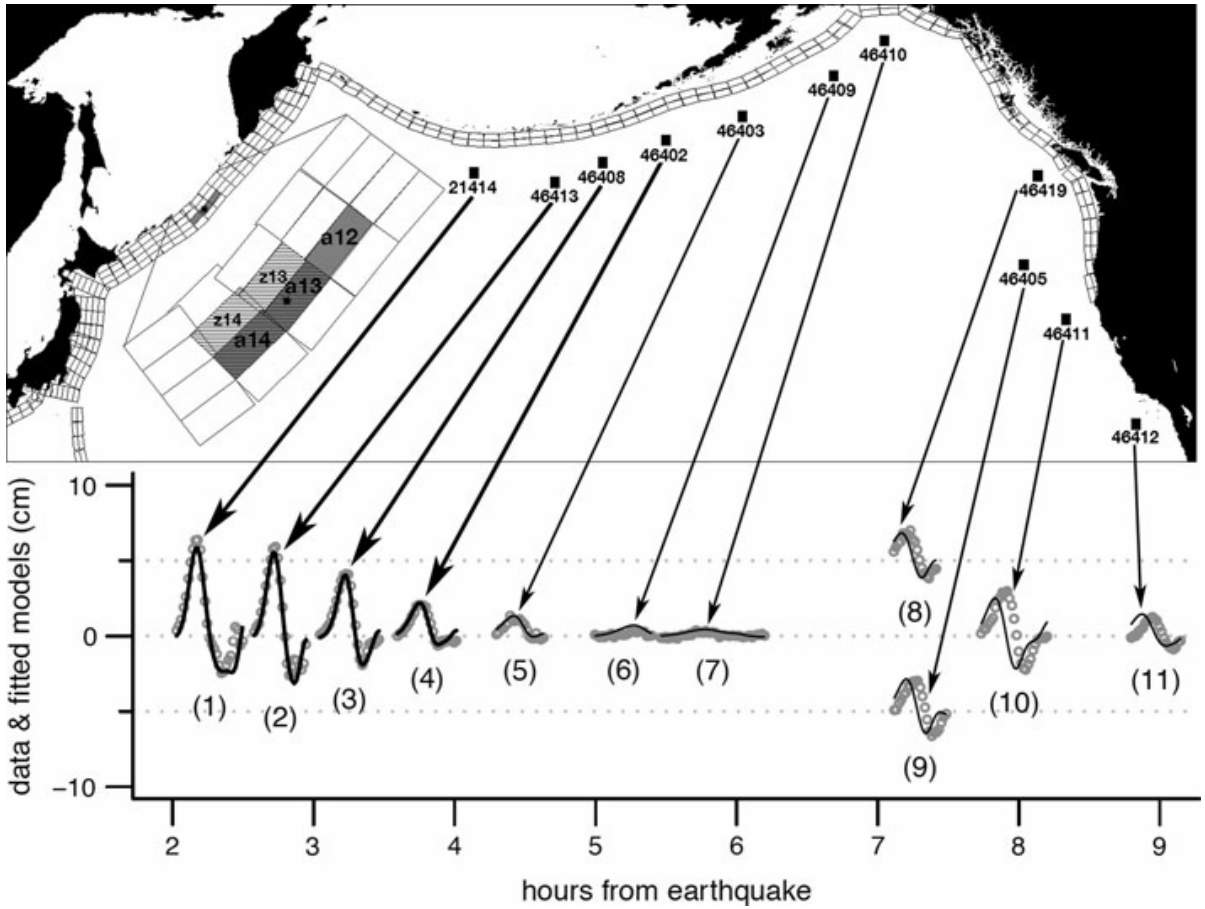
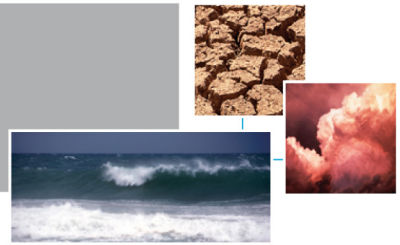
Unit source method

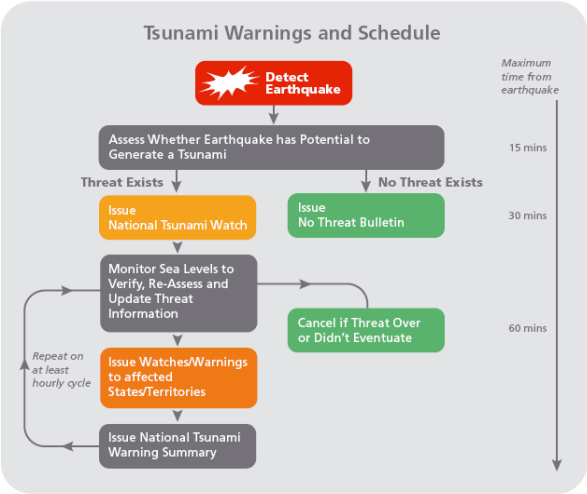


Percival et al., (2010)

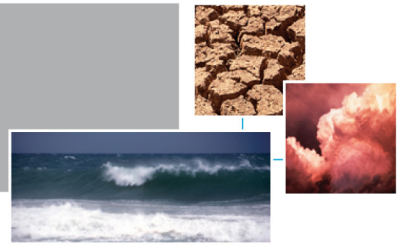
Unit source method



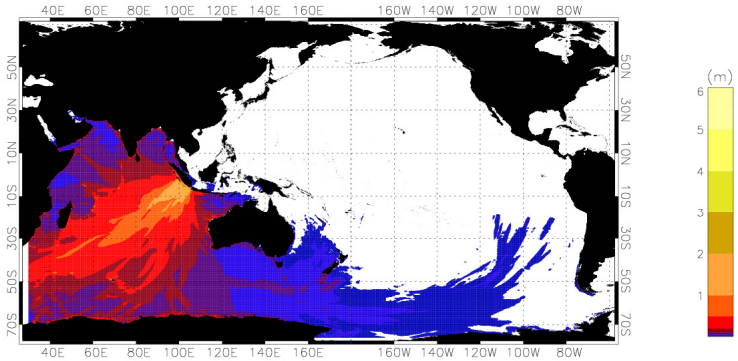
- Unit source method
  - Flexible rupture dimensions
    - Can reproduce complex earthquakes
  - Complex data inversion process
    - Takes time
    - Relies on observations
- T2 method
  - Fixed rupture dimensions
  - Simple procedure
    - Instant warning guidance
    - Given a location and magnitude, warnings can be issued instantaneously



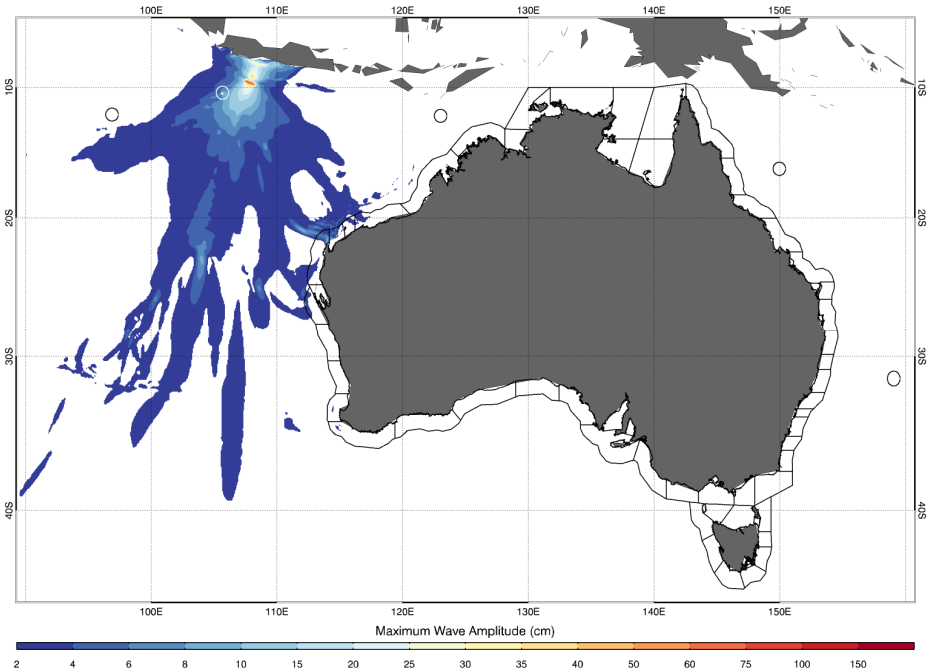
JATWC tsunami warnings

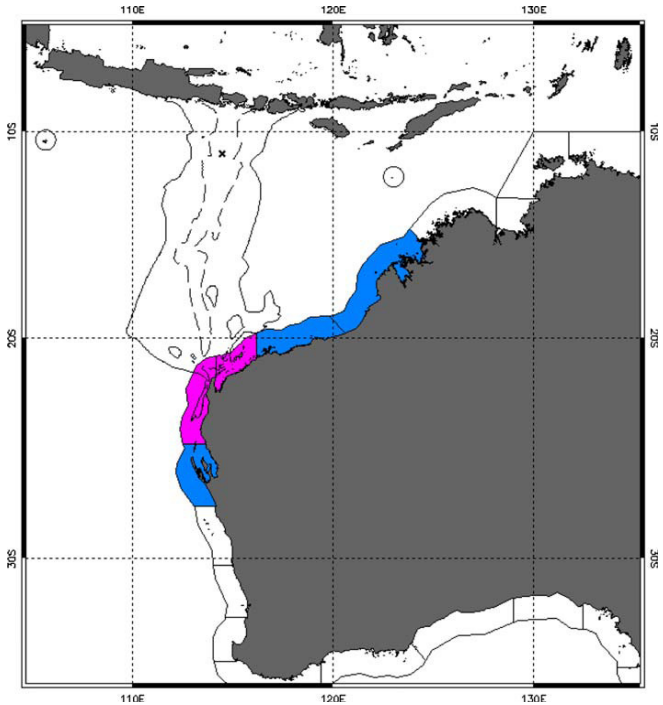


- Want to issue tsunami warnings based on model output
  - In absence of detailed inundation modelling
- Use h_{max} from scenario database as a proxy for coastal impact
- Look at values of h_{max} within coastal zones
- Three levels of warning
  - No threat
  - Marine threat
    - Warning of potentially dangerous waves, strong ocean currents in the marine environment and the possibility of only some localised overflow onto the immediate foreshore.
  - Land threat
    - Warning for low-lying coastal areas of major land inundation, flooding, dangerous waves and strong ocean currents.



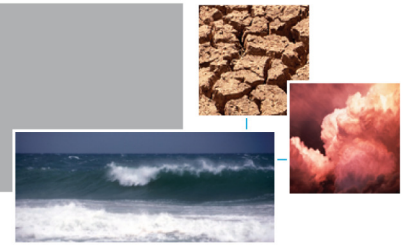
JATWC tsunami warnings





What values of h_{max} should trigger warnings?

JATWC tsunami warnings



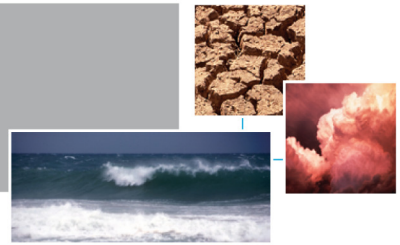
- One option:
  - Use observed relationships between tsunami amplitude at tide gauges and impact
    - Amplitude > 0.5 m = “dangerous” tsunami (Whitmore, 2003)
  - Use simple shoaling arguments to convert offshore h_{max} to amplitude at hypothetical tide gauge
  - If > 0.5m → warning!

- Issues
  - Green’s law assumptions

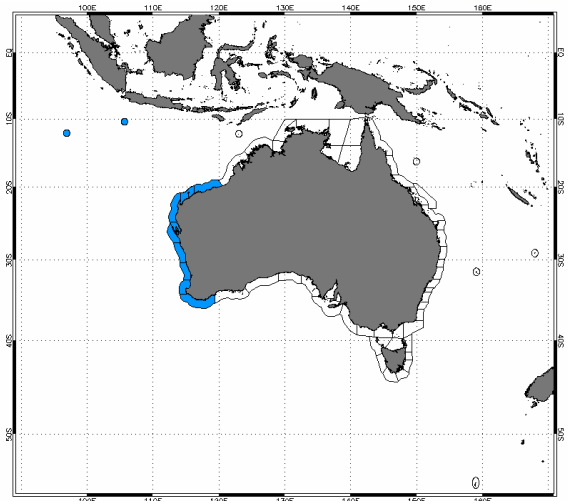
$$\frac{h_s}{h_d} = \left(\frac{H_D}{H_S}\right)^{\frac{1}{4}}$$

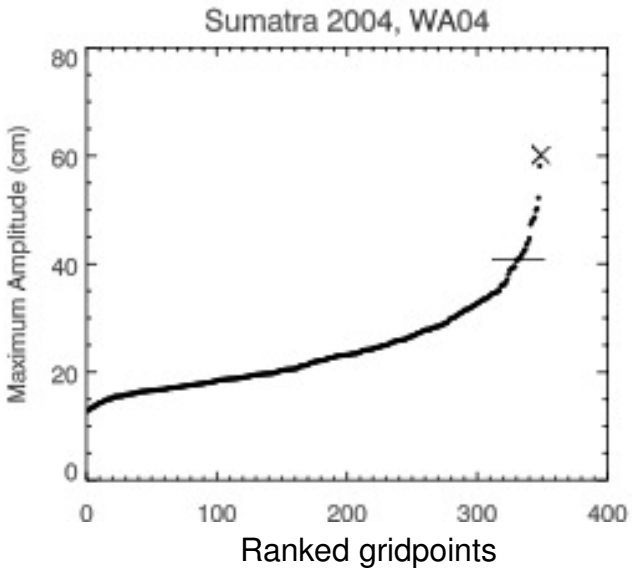
  - Modelled h_{max} is not necessarily wave amplitude, but likely superposition of a number of waves

JATWC tsunami warnings

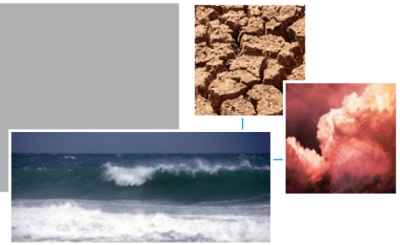


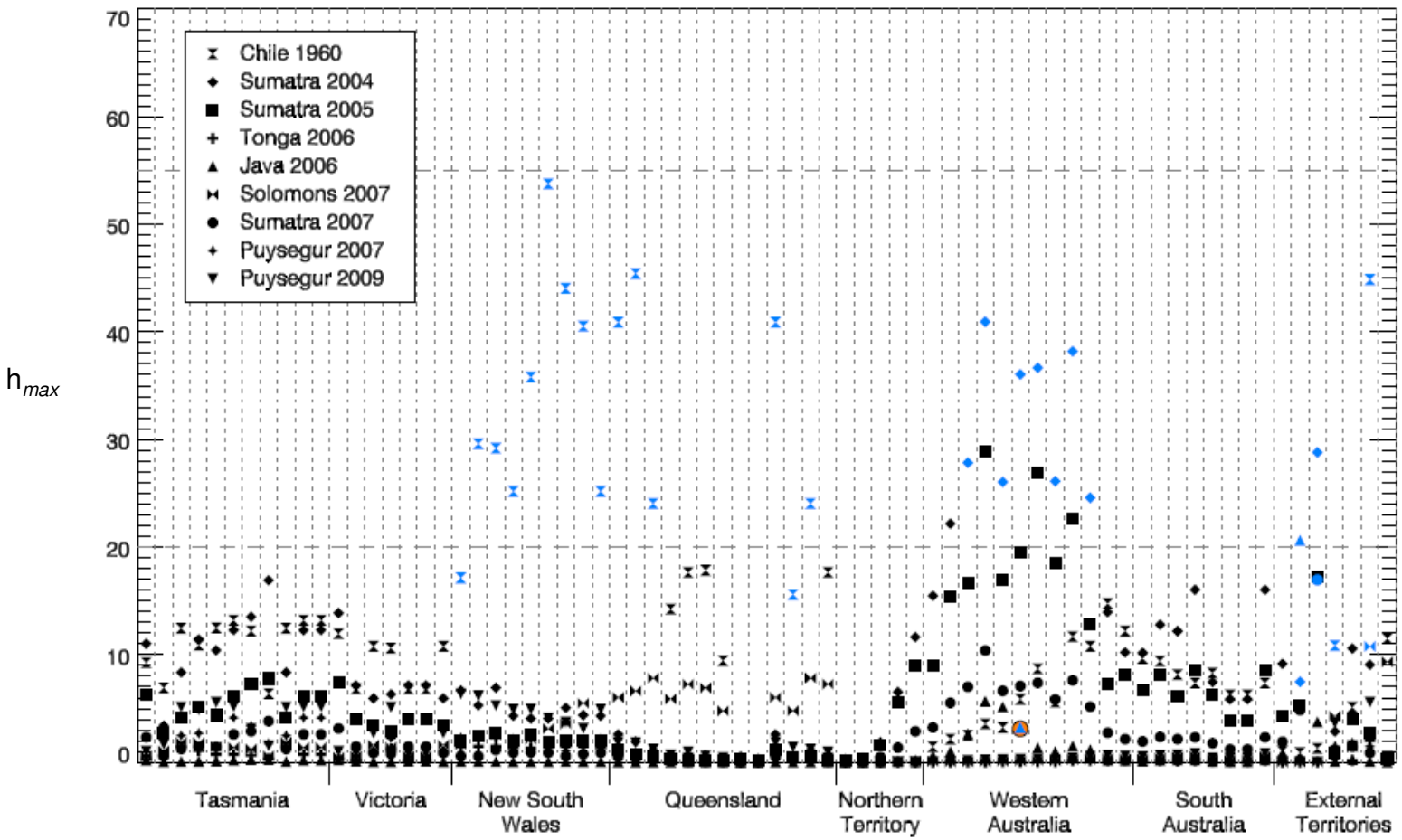
- Empirical-statistical method to derive thresholds
- Design “ideal” warning schemes for past events based on known impacts
  - e.g. Indian Ocean, December 26 2004
- For each event, find the relevant T2 scenario
- From the T2 scenario, extract h_{max} values within coastal zones
- Determine 95th percentile value of h_{max} in each coastal zone
- Assign appropriate warning level to the 95th percentile





JATWC tsunami warnings





Allen and Greenslade (2010)

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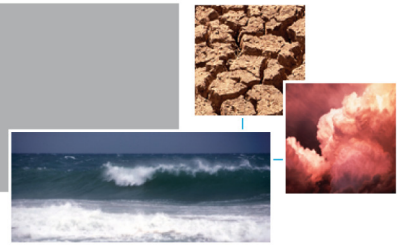
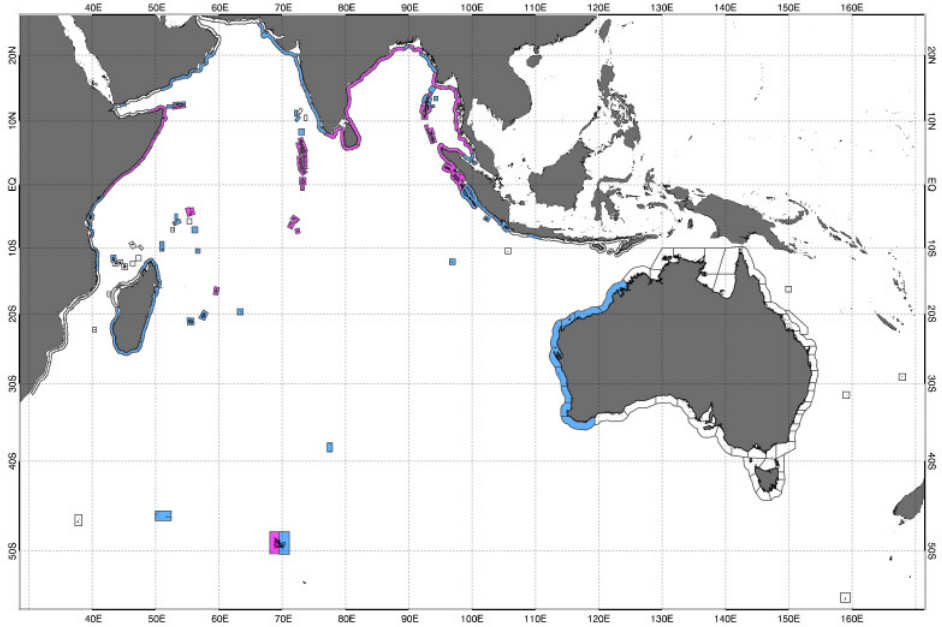
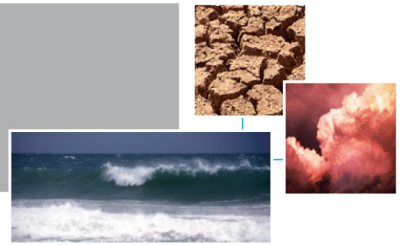
JATWC tsunami warnings



- How can we confirm land warning threshold?
  - No events for Australia that would have required “land threats”
- As part of the Indian Ocean tsunami Warning System, coastal zones have being developed for all countries of the Indian Ocean
- Apply this method to Indian Ocean event of 26th December 2004
- Results compare well to observed impacts (Synolakis and Kong, 2006)



Case Studies

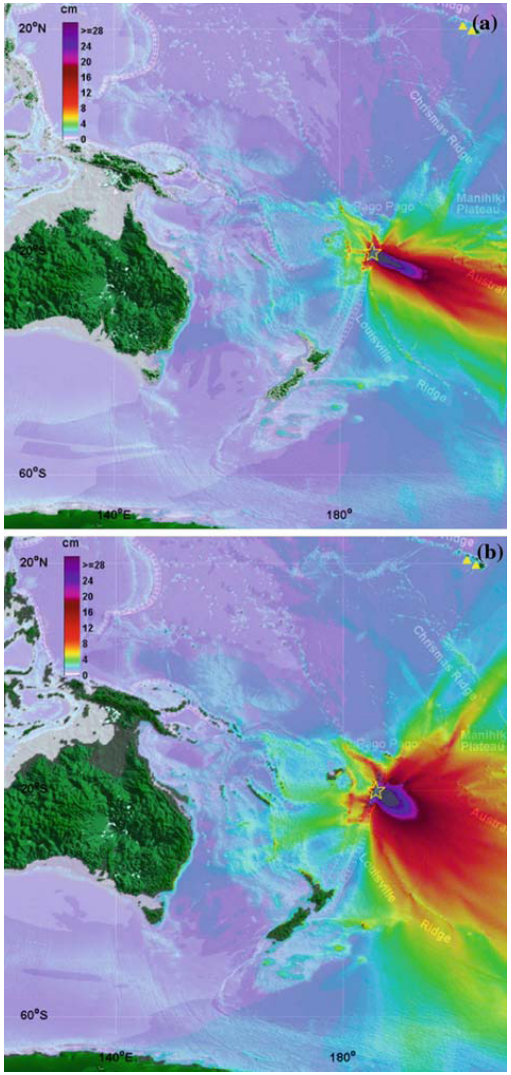


- Tonga 2006
- Chile 2010
- Japan 2011

Tonga 2006

- May 3rd, 2006
- $M_w = 7.9$
- Comparison study (Greenslade and Titov, 2008)
  - High-resolution model for Hilo

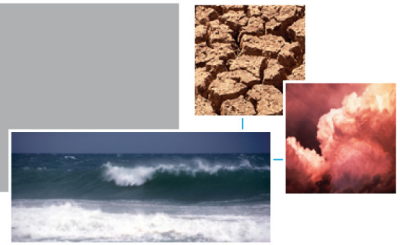
- JATWC: scaled $M_w = 8.0$ scenario
  - "Magnitude" scaling
  - Source 200 km x 65 km
- SIFT: scaled unit source ($M_w = 7.5$)
  - "Observation scaling"
  - Source 100km x 50km



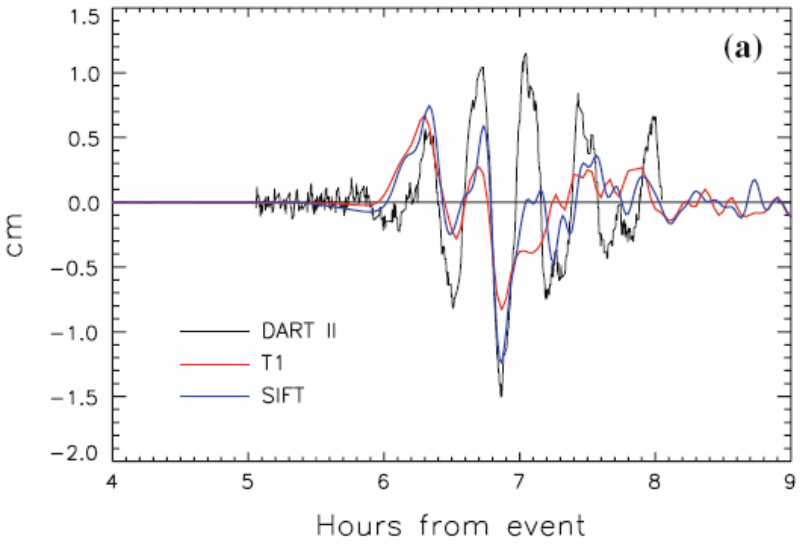
JATWC

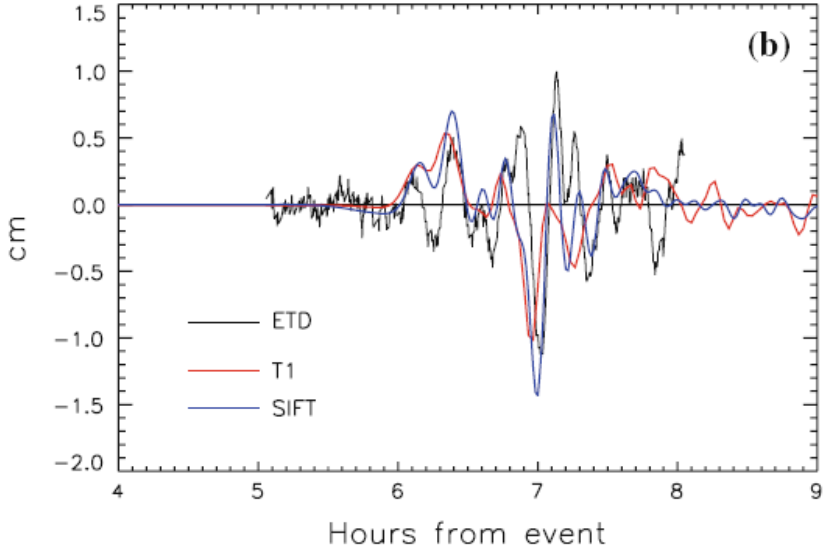
SIFT

Tonga 2006

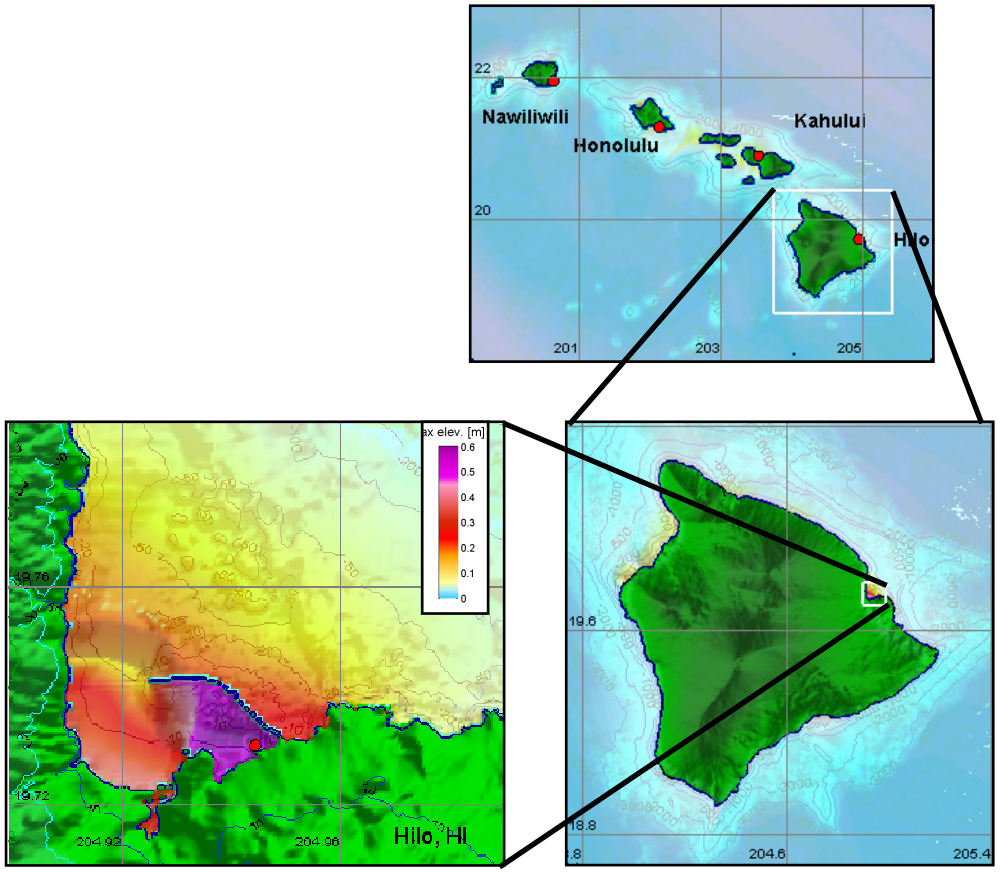


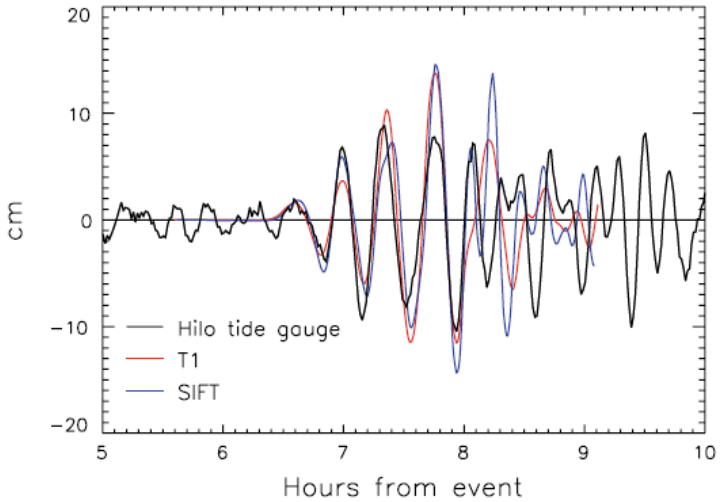
Deep water observations



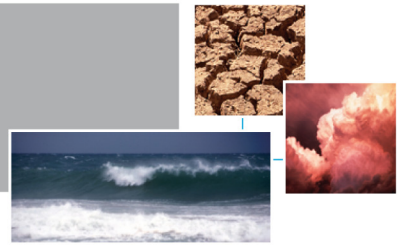


Tonga 2006


Nawiliwili
Honolulu
Kahului
Hilo
22
20
201
203
205
ax elev. [m]
0.6
0.5
0.4
0.3
0.2
0.1
0
19.76
19.72
204.92
204.96
Hilo, HI
19.6
18.8
204.6
205.4

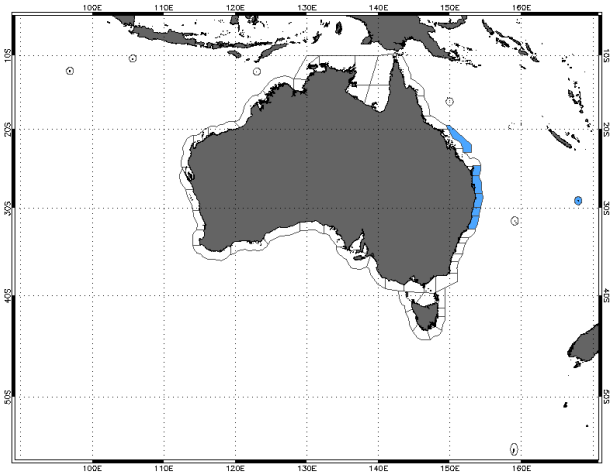

20
10
0
−10
−20
cm
Hilo tide gauge
T1
SIFT
5
6
7
8
9
10
Hours from event

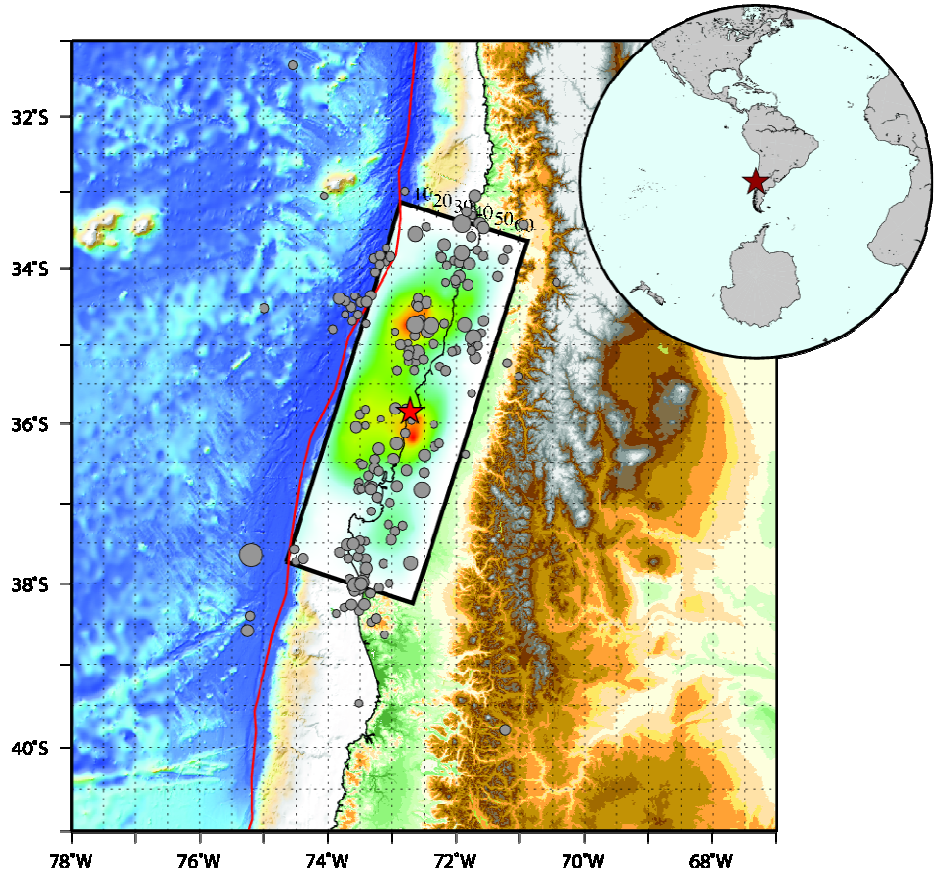
Chile 2010



- February 27th, 2010
- $M_w = 8.8$

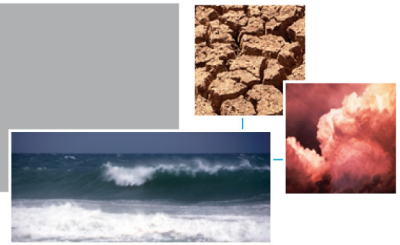
- JATWC operational response:
  - Initial earthquake magnitude: 8.5
    - No threat issued
  - Revised earthquake magnitude: 8.8
    - Marine threats issued
  - Observed amplitudes on east coast tide gauges up to 50cm

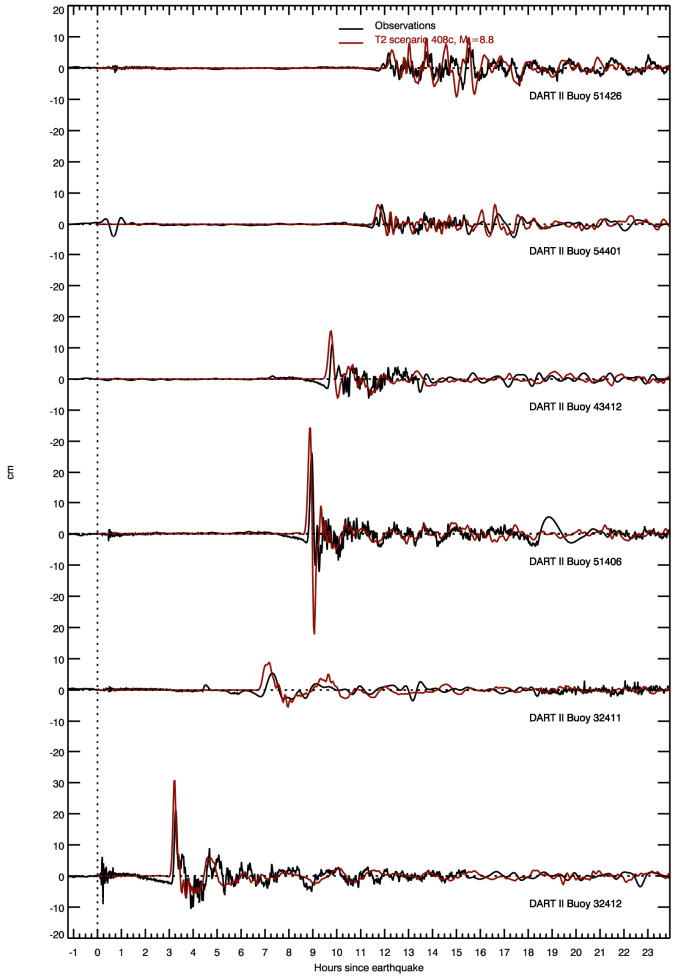


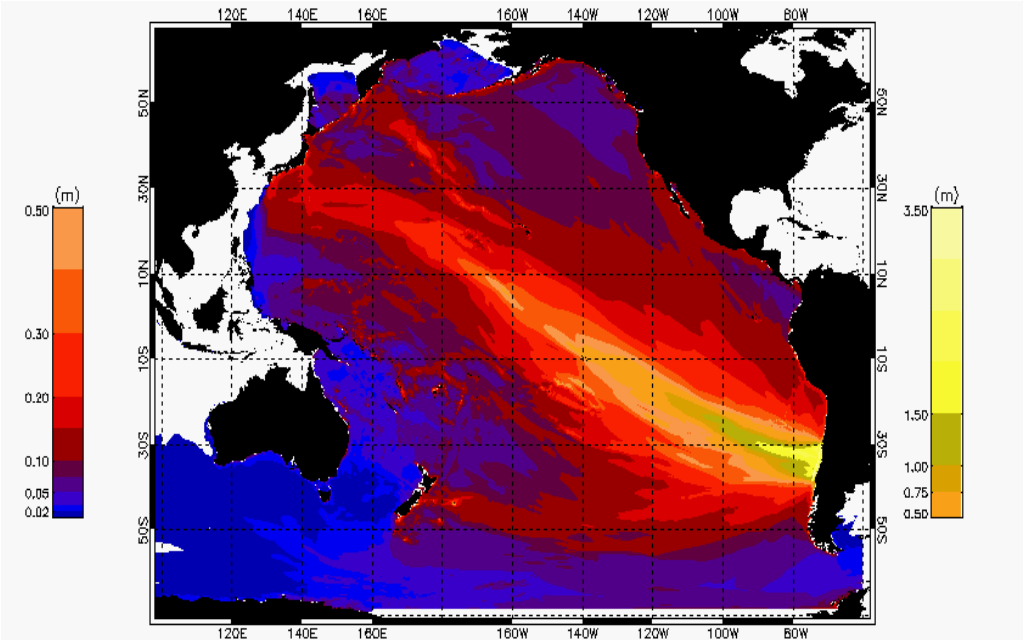


Gavin Hayes, NEIC
http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010tfan/finite_fault.php

Chile 2010







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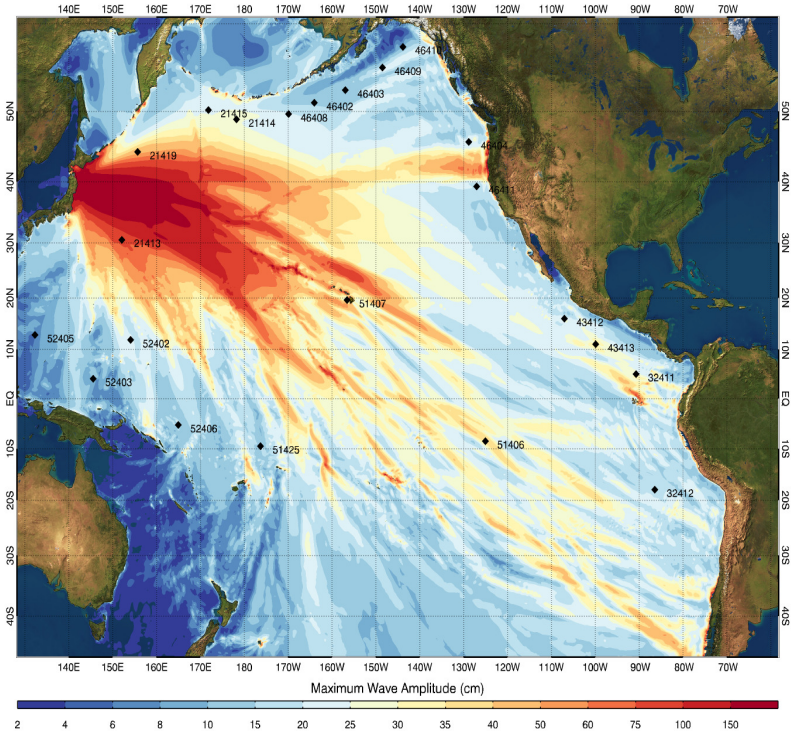
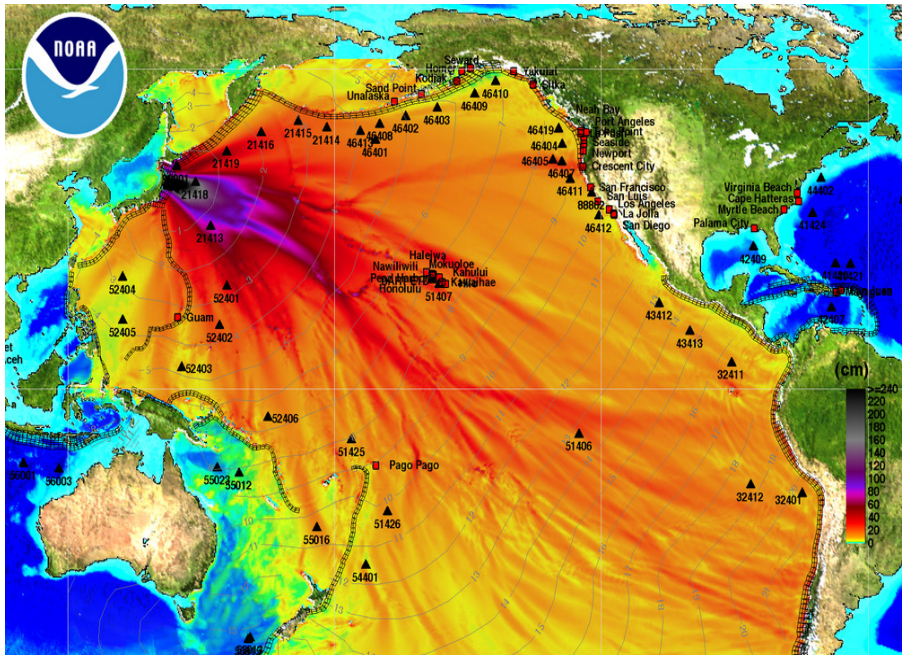
CSIRO

Tohoku 2011

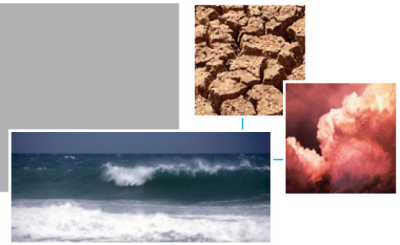


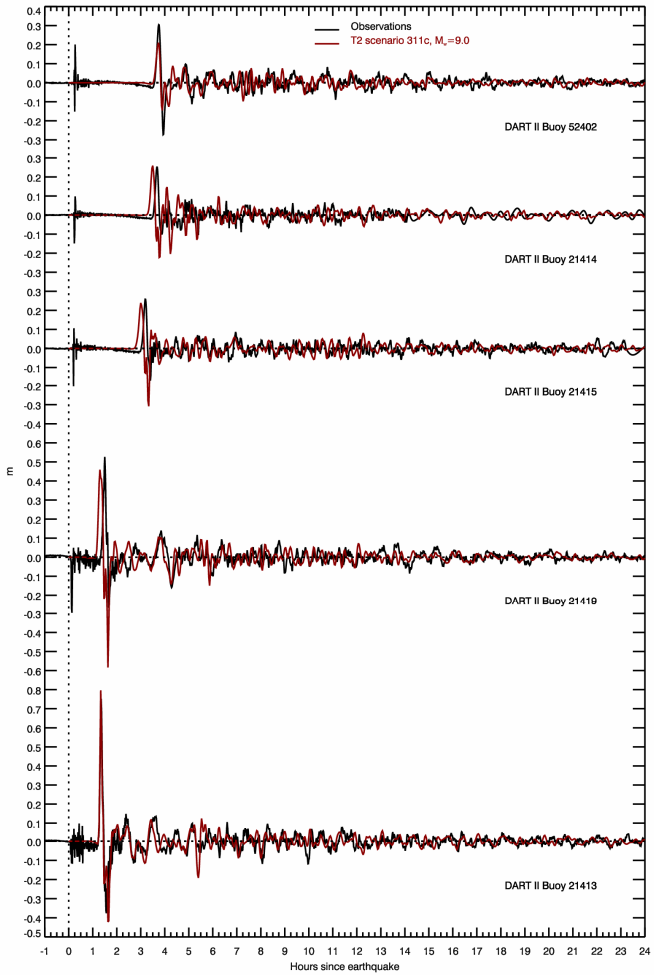
JATWC



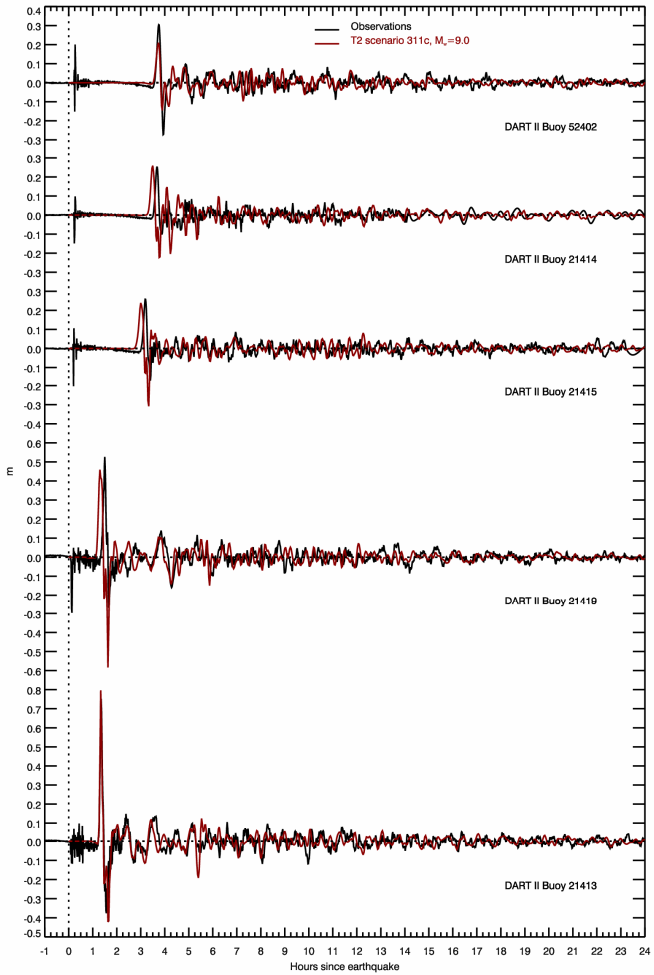
SIFT

Tohoku 2011




Observations
T2 scenario 311c, M_w=9.0
DART II Buoy 52402
DART II Buoy 21414
DART II Buoy 21415
DART II Buoy 21419
DART II Buoy 21413
m
Hours since earthquake

Tohoku 2011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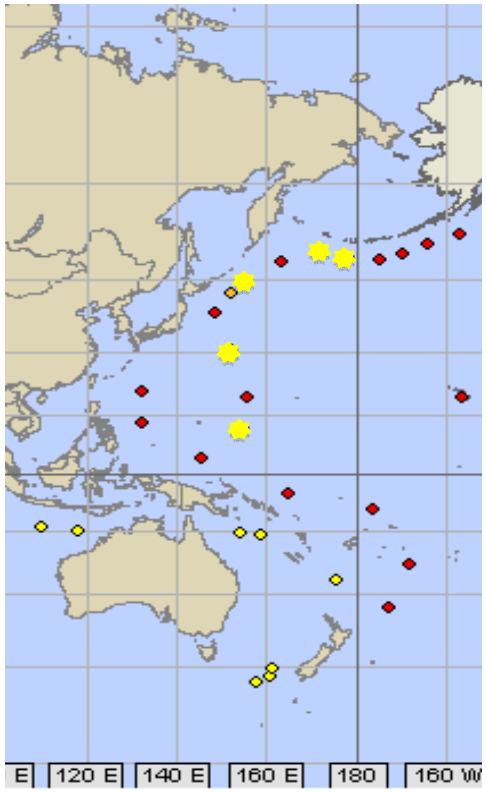
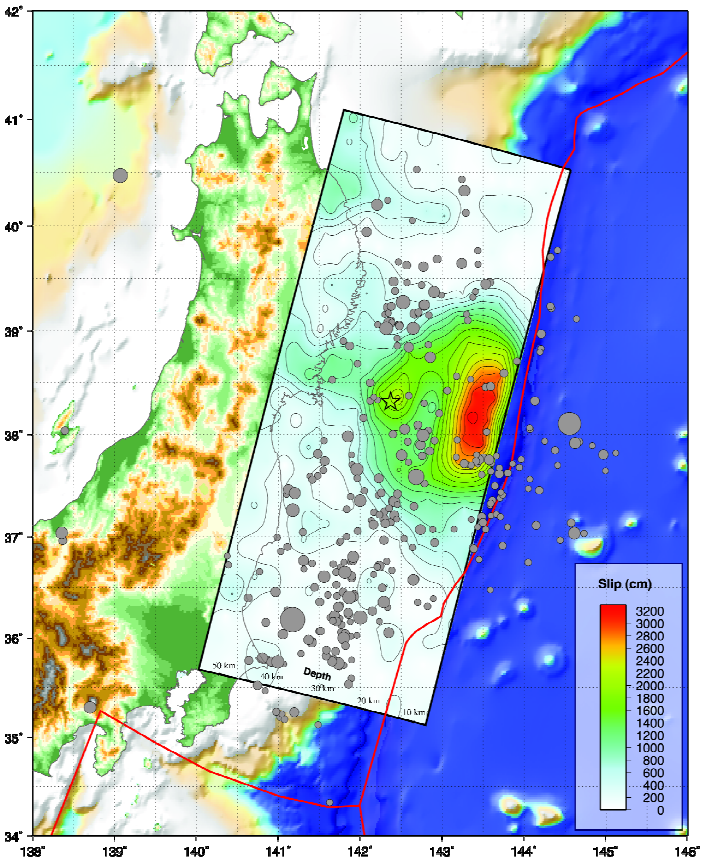
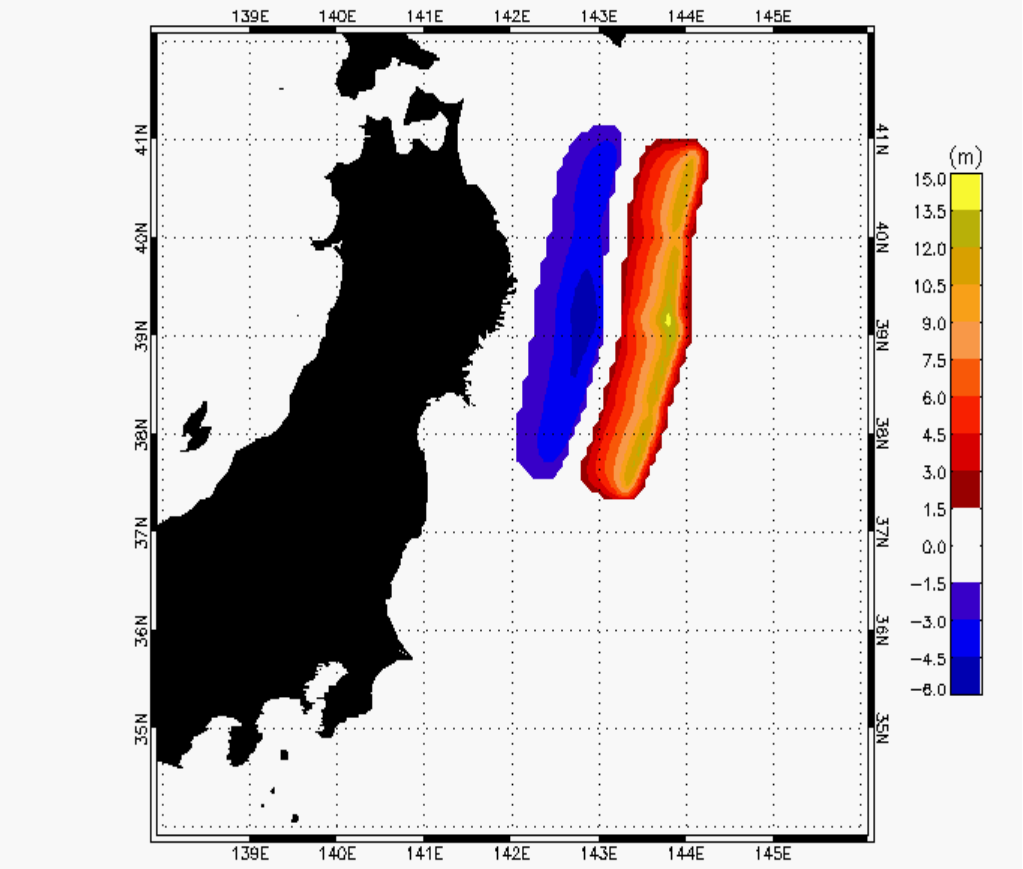

E
120 E
140 E
160 E
180
160 W

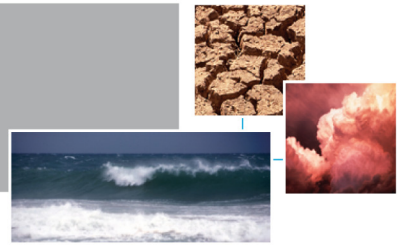
Tohoku 2011



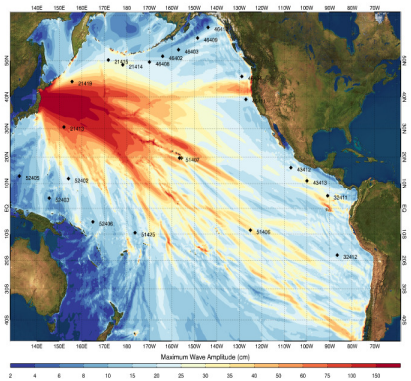


Gavin Hayes, USGS
http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/finite_fault.php

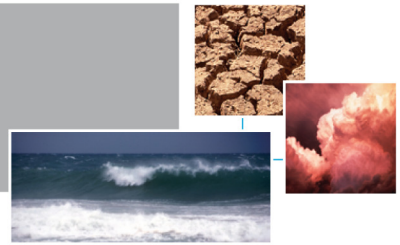
Tohoku 2011



- JATWC
  - No Threat warning issued, based on T2
  - PTWC issued broad tsunami warning
- Observed impacts
  - Tide gauge amplitudes up to ~55 cm
  - Numerous visual observations of unusual tides and currents on NSW coast
  - Several swimmers were washed into a lagoon
  - Despite this, we believe No Threat was warranted…
  - Had this event happened prior to 2004, and the establishment of the JATWC, might have initiated evacuations.



Closing remarks



- Uncertainties/limitations surrounding tsunami prediction
  - Real-time seismic information
    - Can use sea-level observations – but takes time and observations are not always guaranteed
    - Details of the rupture become less important further from the source
  - Availability of accurate and high-resolution bathymetric and topographic data
  - Still somewhat limited by computational capacity and speed
- Compromise to be found between speed of issuing forecast and quality of the forecast

- Quality and accuracy of real-time forecasts, and reliability of warnings has improved significantly since 2004.

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Thank you

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