

# LECCIONES Y APRENDIZAJES EN 12 AÑOS

**Patricio Catalán**

Rafael Aránguiz, Roberto Benavente, Rodrigo Cienfuegos,  
Jorge Crempien, Juan González, Gabriel González,  
Alejandra Gubler, Paula Navarrete, Jorge León,  
Patricio Winckler, Natalia Zamora, y muchos más (CIGIDEN)  
Ca

March 30 2010

**Las Últimas Noticias**

3207 Regeneración, L.I., XI 2010 y 2.V: \$400 • Año CML • N.º 33.639 • Martes día 30 de marzo de 2010

# ¿Por qué el tsunami nos pilló tan desprevenidos?

7-3

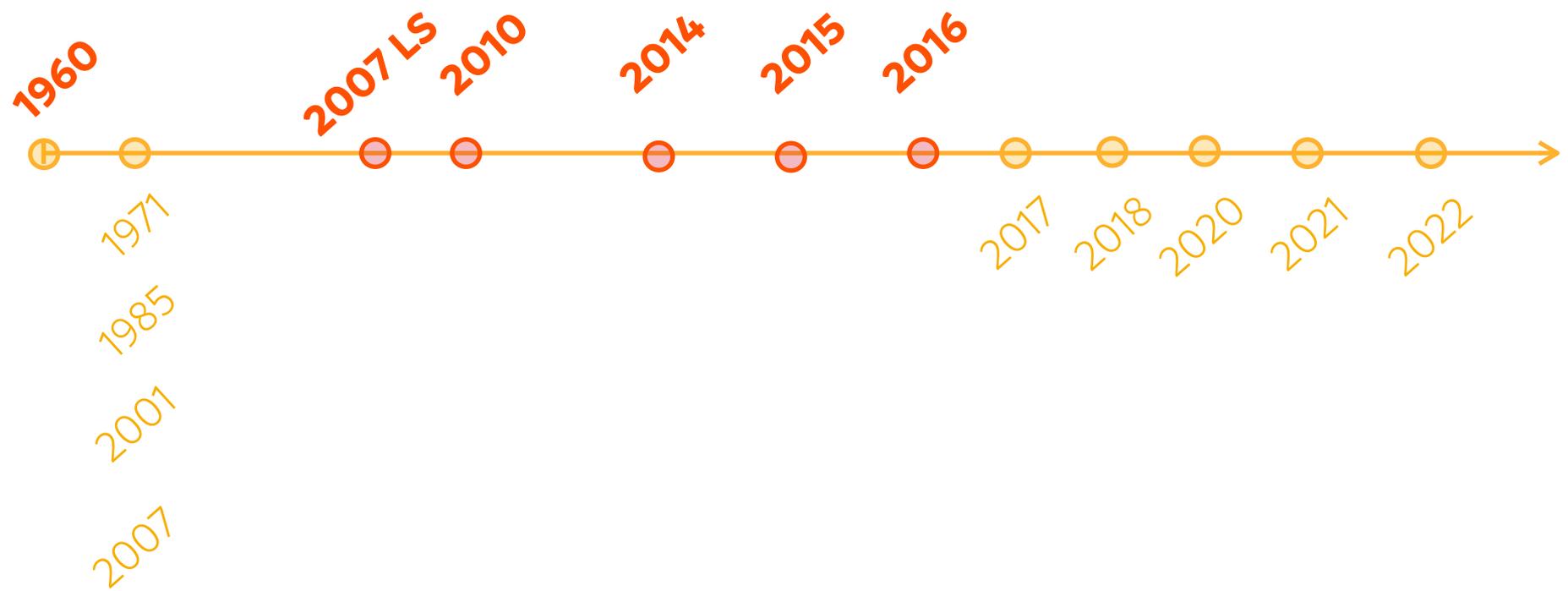
La madrugada del maremoto no hubo bengalas ni sirenas que avisaran del peligro. Una niña que alertó a la Isla Juan Fernández o policías y hombres que actuaron por iniciativa propia fueron más efectivos que la Dnami y el Sheca.

Arrollador éxito del joven que cuenta chistes en YouTube **32**

La U le agió la fiesta a la UC en la Libertadores **20**

La casa de Cata Palacios quedó sin cimientos **34**

# A Little History of ...





# Challenges for the Hazard Assessment

- It has to cover a very large domain
  - 4300 km of coast, plus several Pacific Islands and Archipelagos
  - Well exposed to tsunamis in the Pacific, though most of the time we are the culprits
  - Catalog is huge
  - High computational cost ?
- It has to consider a wide range of tsunami behaviors
  - Large first arrivals ( PTHA? )
  - Large late arrivals ( PTHA? )
  - Long lasting activity
  - Multiple inundation phases ( PTHA? )
  - Landslides ?
  - Energy funneling (fjords, estuaries, bays)
  - Energy trapping (resonance, edge waves)

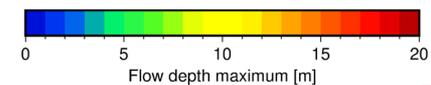
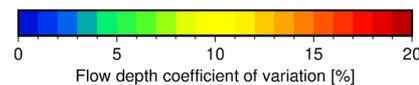
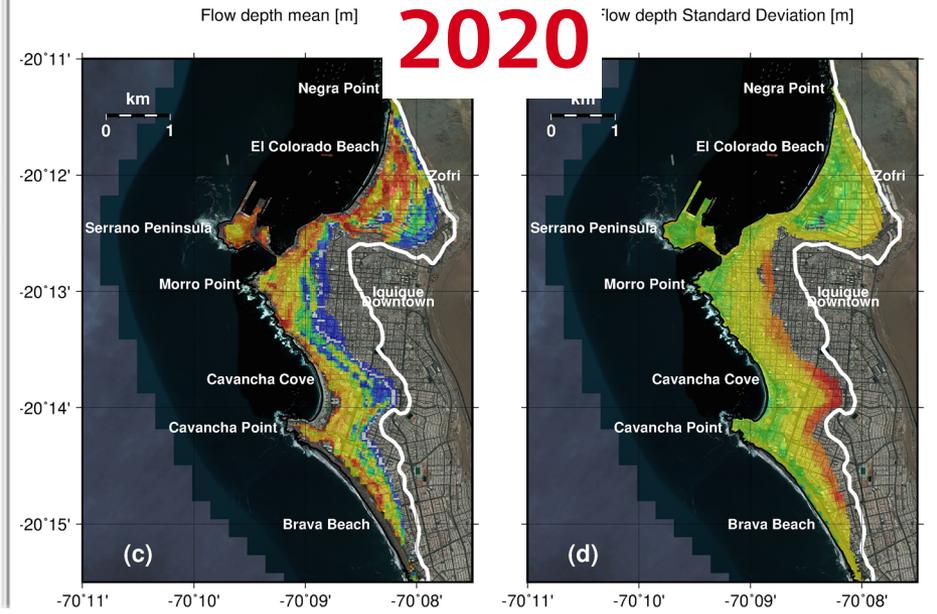
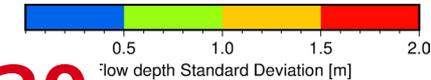
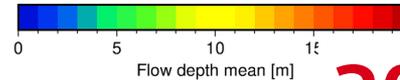
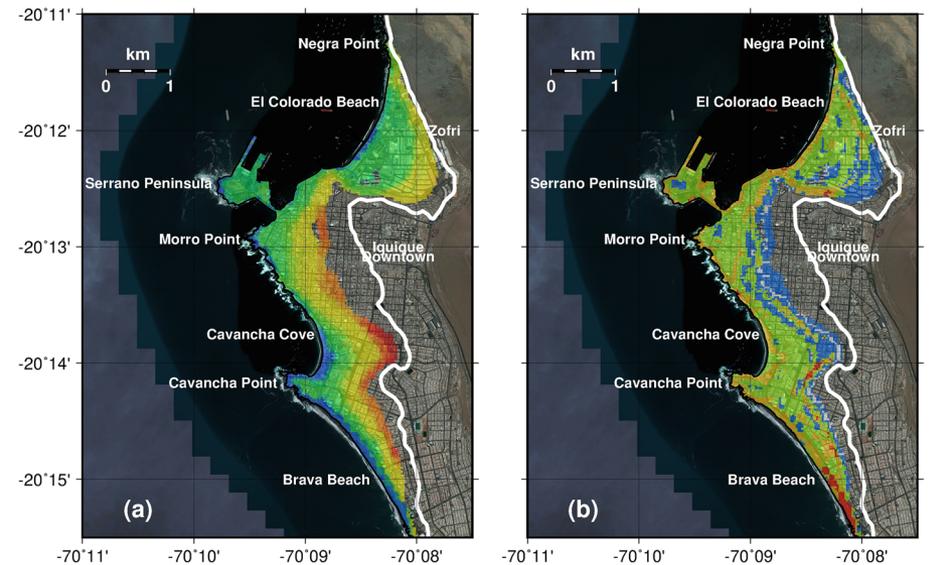
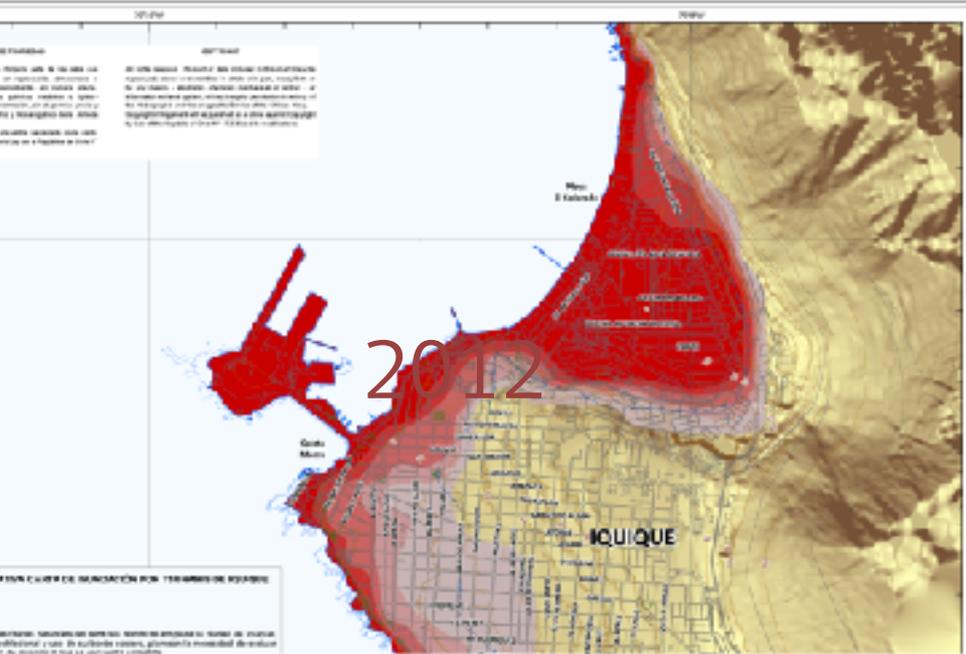
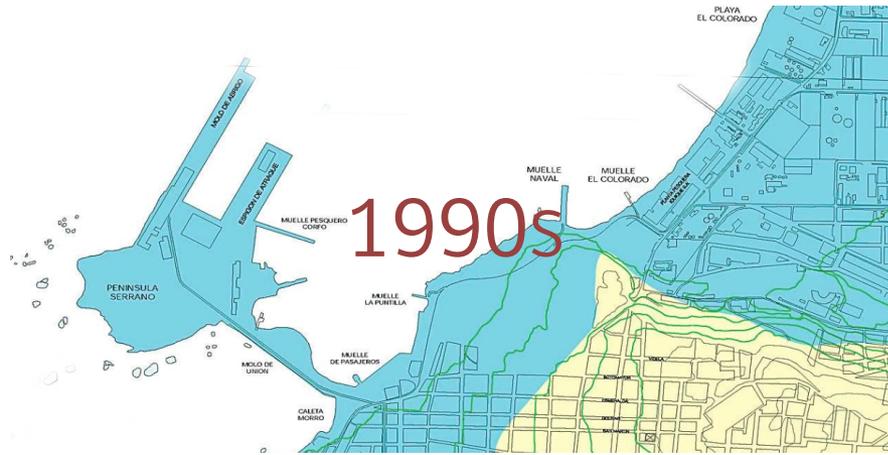
# Amenaza, Peligro

- Evolución desde modelos deterministas
- Recurrencia
- Incertidumbre
- Cuáles son nuestros objetivos



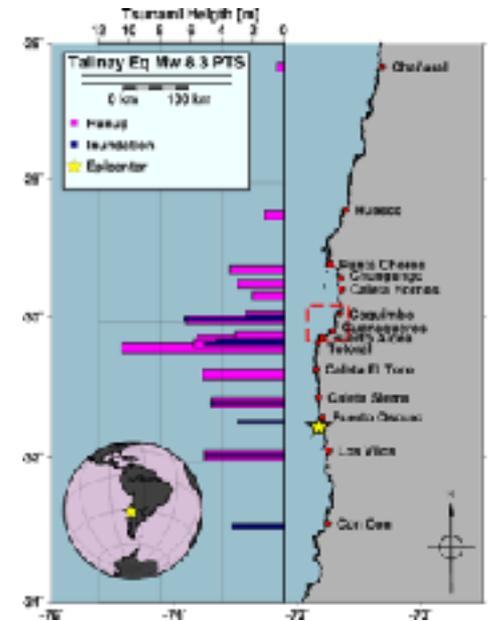
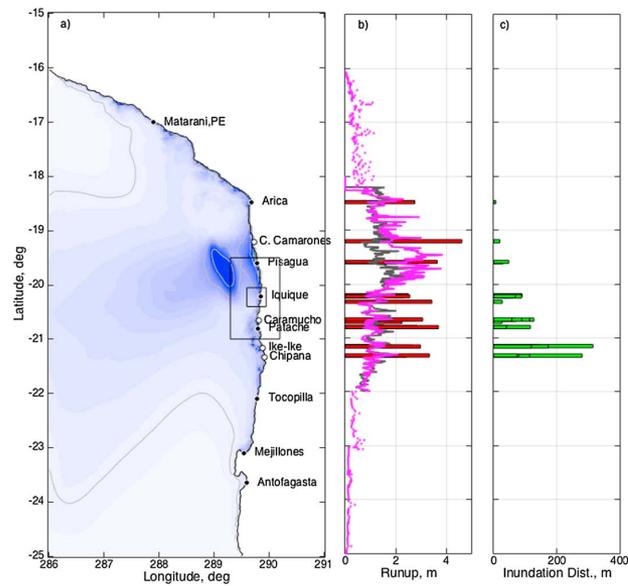
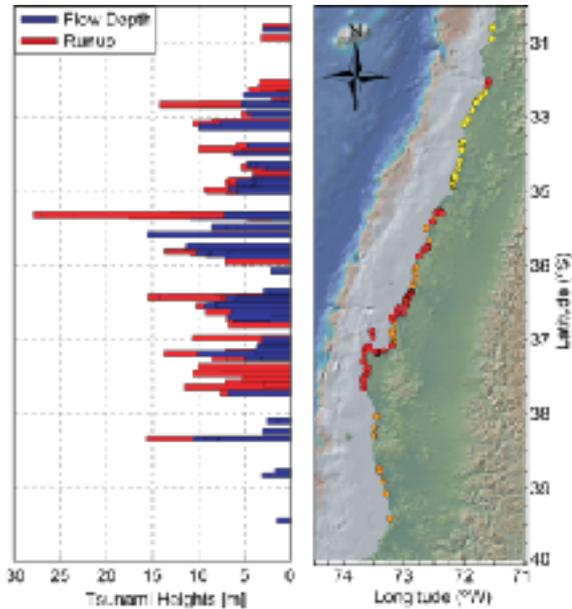
## Guía para la Estimación de Peligro de Tsunami

# Ejemplos



# What we know now (12 years and several tsunamis in between)

- The tsunamis
  - Large variability of Tsunami Intensity Metrics among events



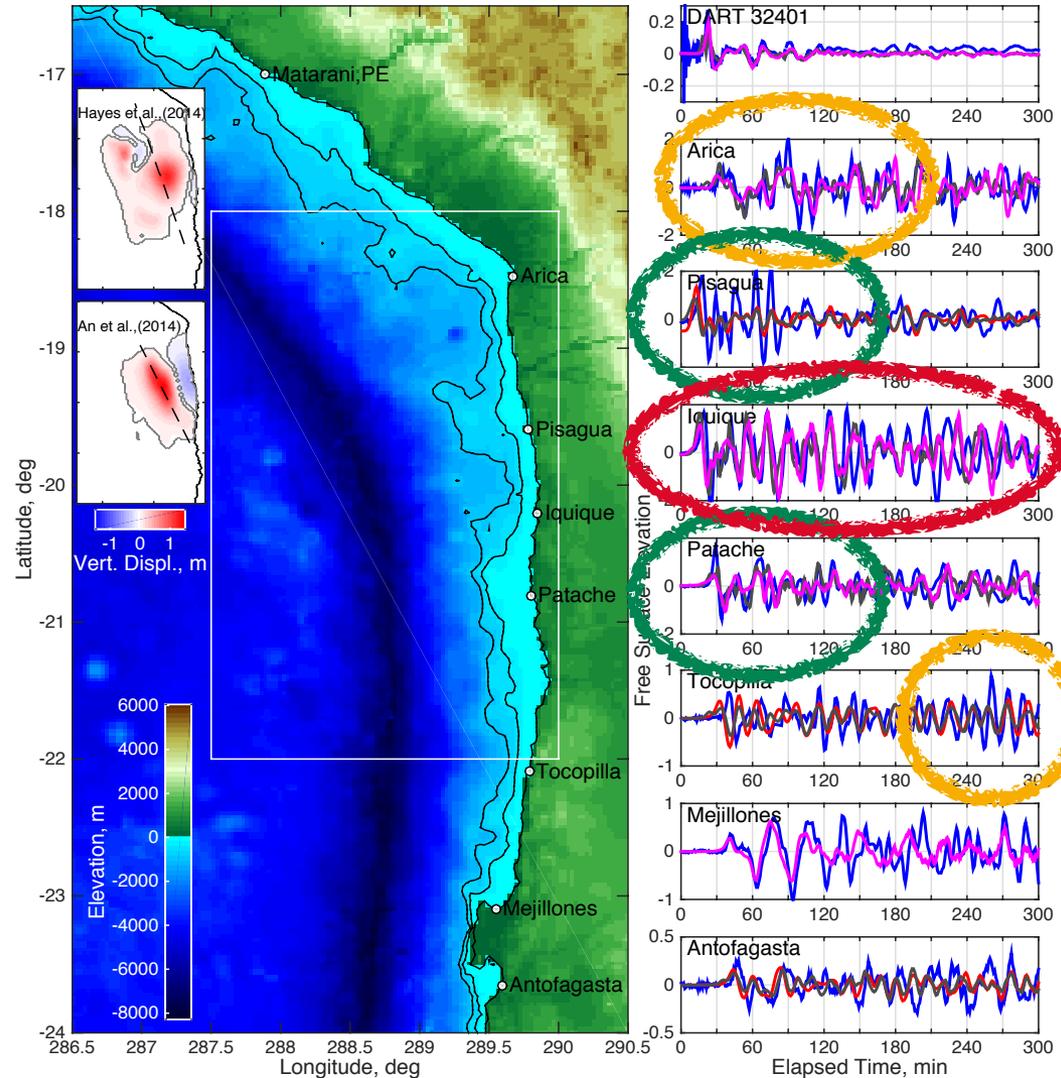
Mw 8,8

Mw 8,2

Mw 8,4

# What we know now (12 years and several tsunamis in between)

- The tsunamis
  - Very different behavior even for the same event among neighboring locations



# Contexto – Las Preguntas Clave

**Dónde**

se producirá el siguiente terremoto

**Cómo**

será el terremoto?  
Magnitud, distribución de deslizamiento

**Generará**

un tsunami ?

**Cómo**

será el tsunami?  
Dónde puede ser peligroso?



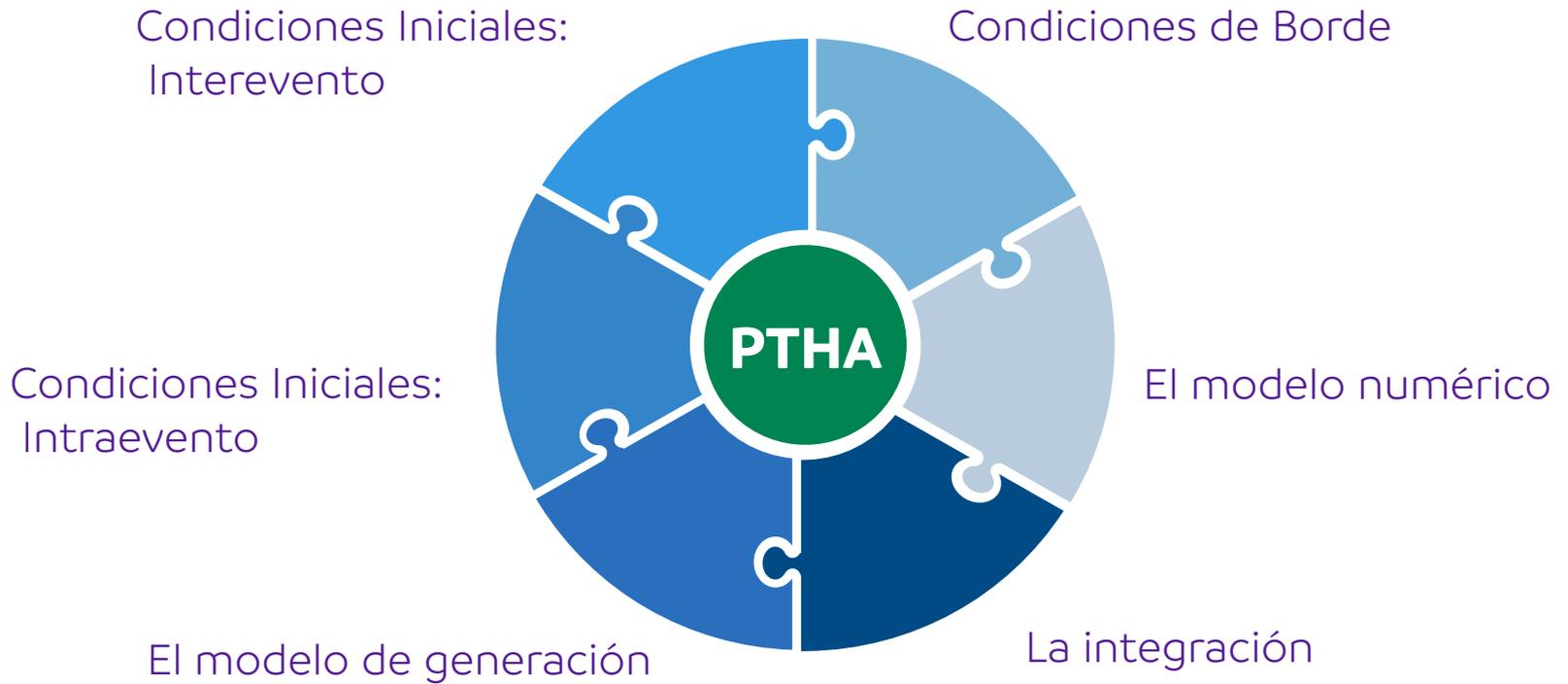
PTHA

¿falta mucho?

# ¿Estamos listos?

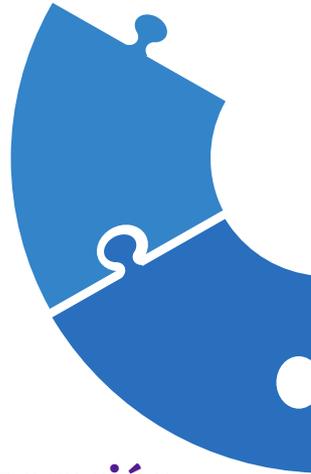


# Partes y piezas



# Partes y piezas

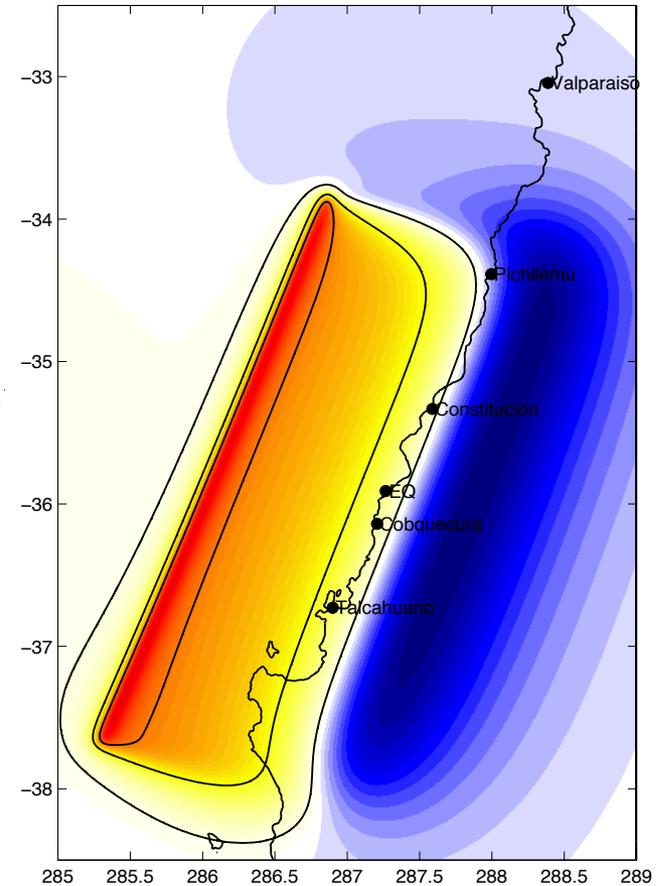
**Condiciones Iniciales:**  
Intraevento



**El modelo de generación**

# Condición Inicial: EQ Subducción : Inter variabilidad

- Mucho aprendizaje
  - Complejidad y rol de la fuente
  - Catálogos más completos
  - Modelos simples ya no se usan “tanto”



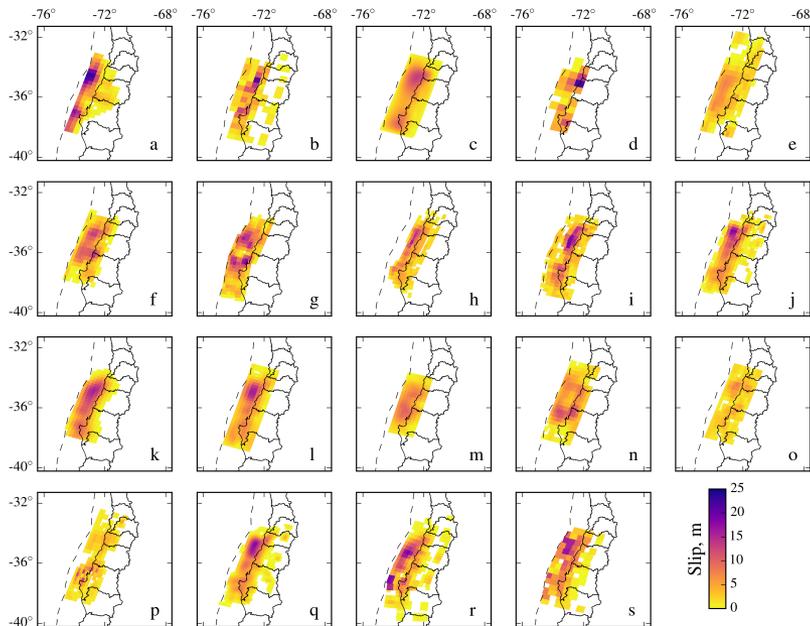
# What we know now (12 years and several tsunamis in between)



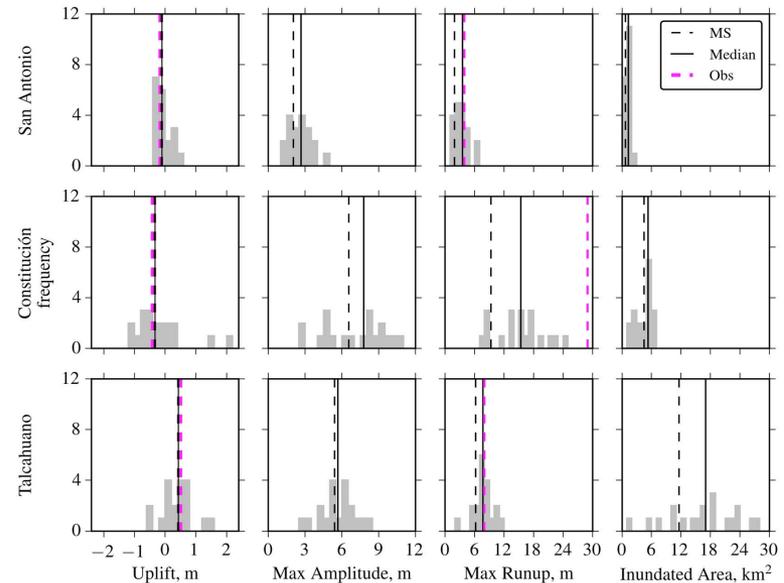
**Key Points:**  
 • We provide an empirical assessment of the variability of finite fault inversions and its consequences for rapid tsunami hazard mapping  
 • The variability in modeled tsunami

Rodrigo Cienfuegos<sup>1,2</sup>, Patricio A. Catalán<sup>1,3,4</sup>, Alejandro Urrutia<sup>1</sup>, Roberto Benavente<sup>1</sup>, Rafael Aránguiz<sup>1,5</sup>, and Gabriel González<sup>1,6</sup>

- The EQ source:
- **Even with time, estimations of EQ slip are not certain enough for tsunami characterization.**



**Figure S2.** Slip distributions for each rupture model used in this study. Labels indicate corresponding entries in Table S2.



**Figure 3.** Histograms for coseismic vertical deformation and tsunami intensity variables at the three locations. (first column) Coseismic vertical deformation. (second column) Maximum amplitude tsunami waves in coastal waters. (third column) Maximum tsunami runup. (fourth column) Maximum inundated area. Black solid lines represent the median values ( $P_{50\%}$ ) of forecast variables. Black dashed lines represent forecast values estimated from propagating the MS source. Magenta dashed lines represent observed values when available (for uplift and maximum runup). MS = median surface.





# Initial Condition: “Un” evento

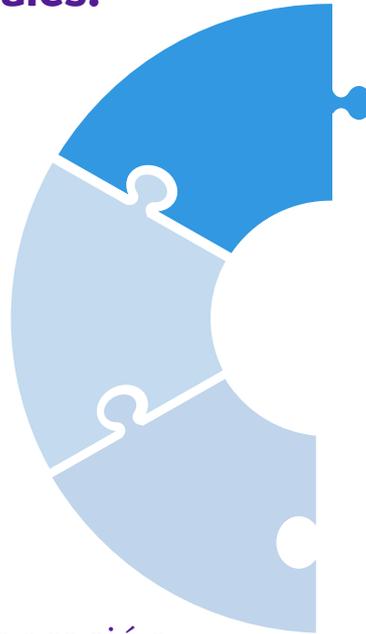
- Asumiendo se puede modelar el terremoto...hay que tomar otras decisiones
  - Cómo modelar la Interface
    - Slab 1.0, 2.0, Aproximado
    - Qué modulus de corte 30 GPa
  - Límite inferior de la zona de generación
    - (Berryman et al, m 2015)
  - Largos de Correlación
  - Qué leyes de escalamiento
  - Se limita el máximo slip?
    - Goda, Davies, Lavalle, Hayes?

# Partes y piezas

## Condiciones Iniciales:

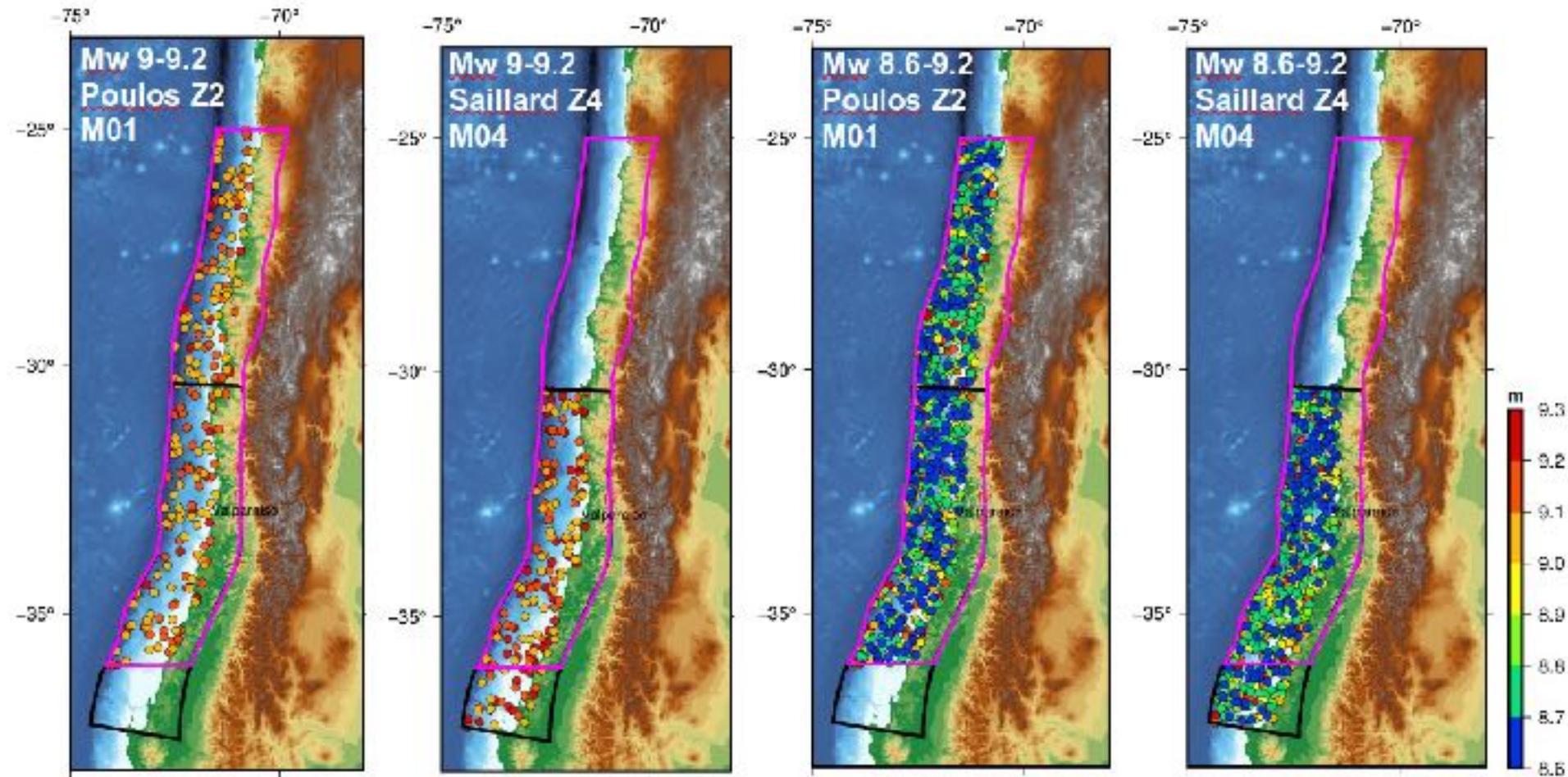
Interevento

Condiciones Iniciales:  
Intraevento

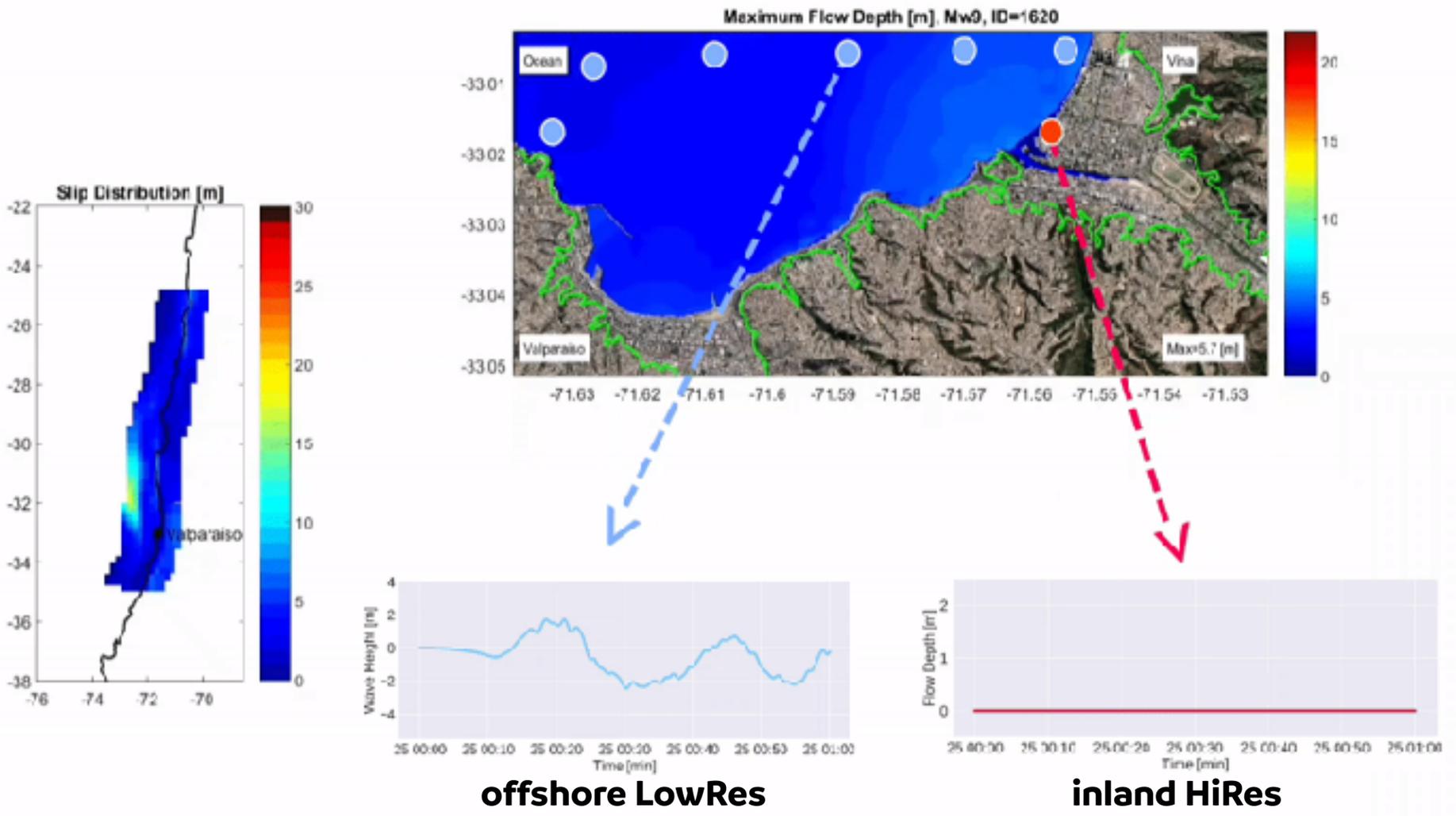


El modelo de generación

# Zonificación: Recurrencia de largo plazo

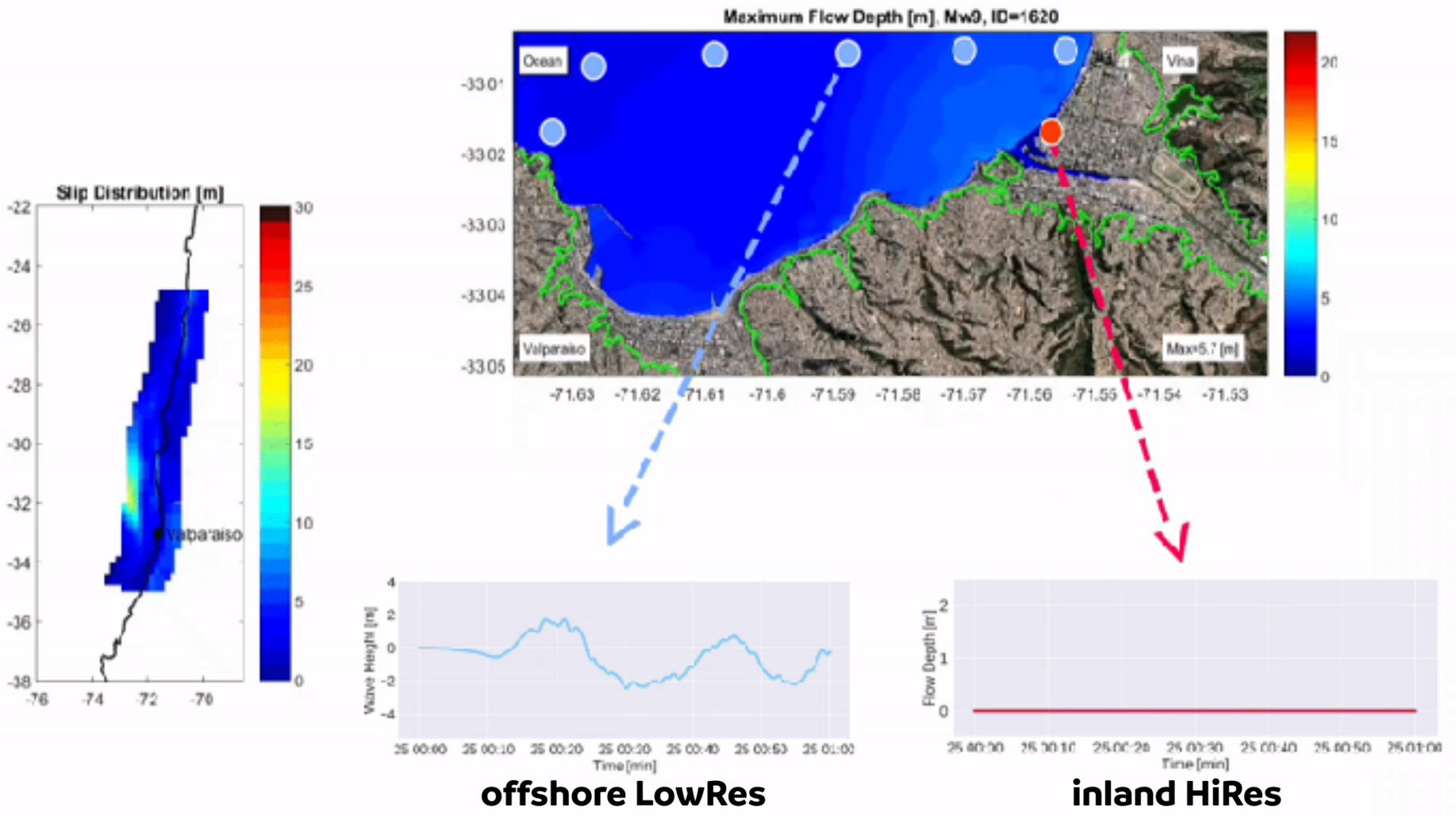


# Modeling: Tsunami HySEA (Macias et al., 2017)



Sample: Viña del Mar

# Modeling: Tsunami HySEA (Macias et al., 2017)

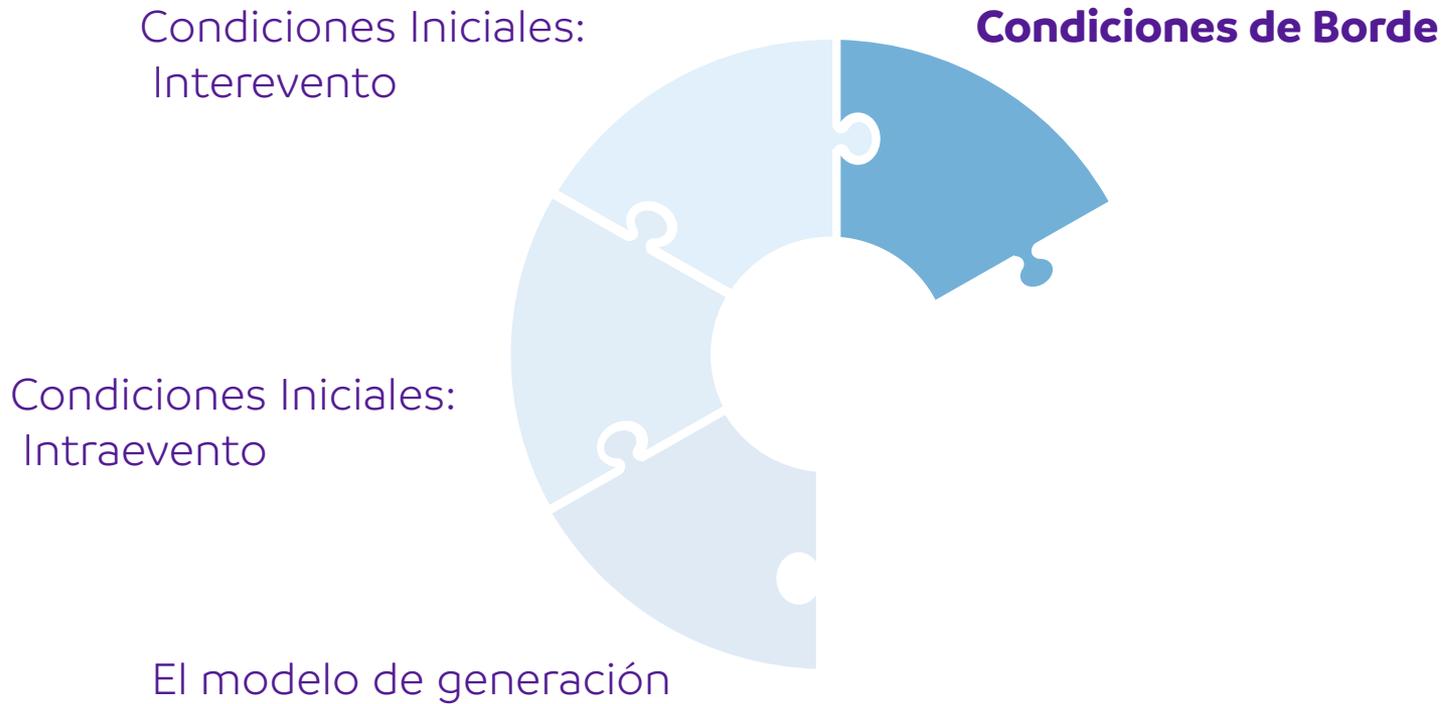


# Condiciones Iniciales: La variabilidad de largo plazo



- Como incluirla a bajo costo
  - ◉ FAUS was the preferred model of choice (VAUS is tempting)
  - ◉ HS full swing
    - ◉ *Long Term*
    - ◉ Karhunen-Loeve (Leveque et al., 2016)
    - ◉ Cholesky-expansion (\*, Crempien et al., 2020)
    - ◉ (there are others...)
    - ◉ *Emergency*
    - ◉ Phase Variation (\*, unpublished)

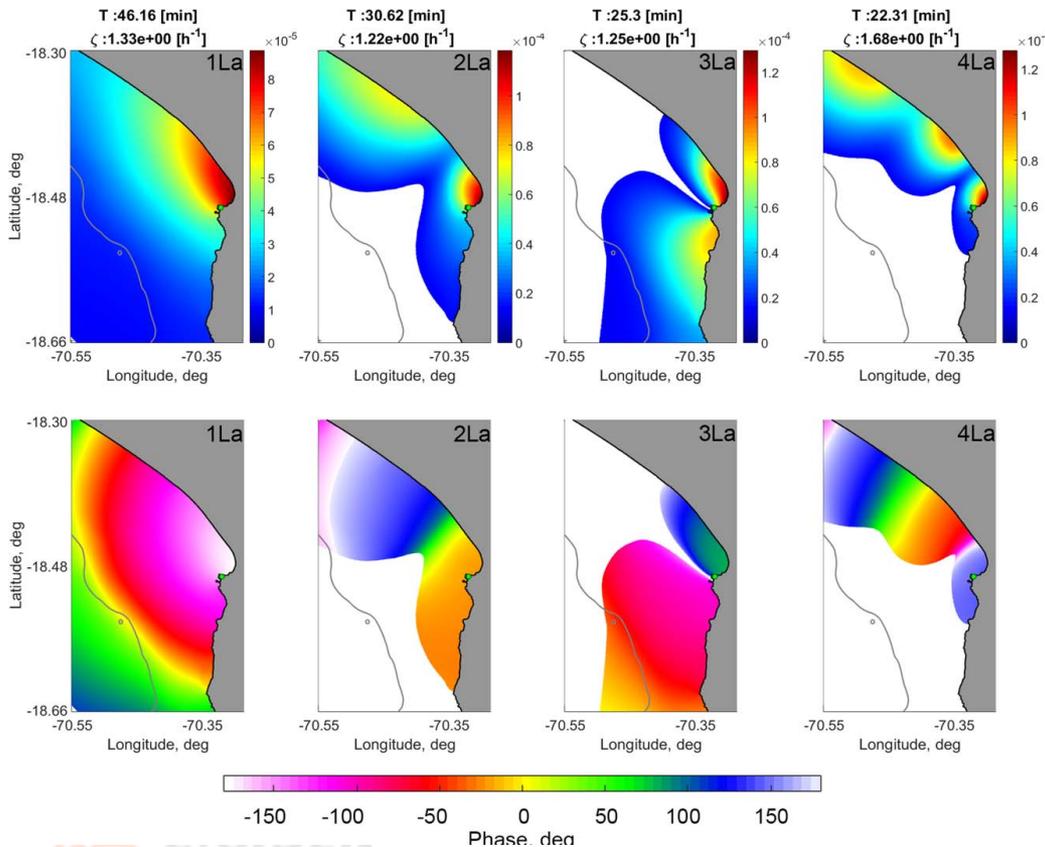
# Partes y piezas



# What we know now (12 years and several tsunamis in between)

- Causes: Resonance, Edge Waves, Bathymetric control

## FREE OSCILLATION MODELS



## DATA DRIVEN

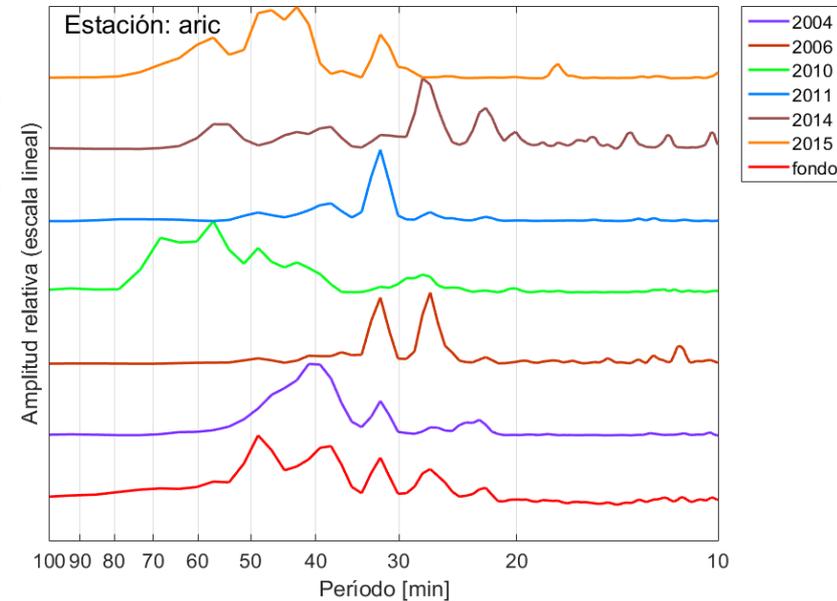
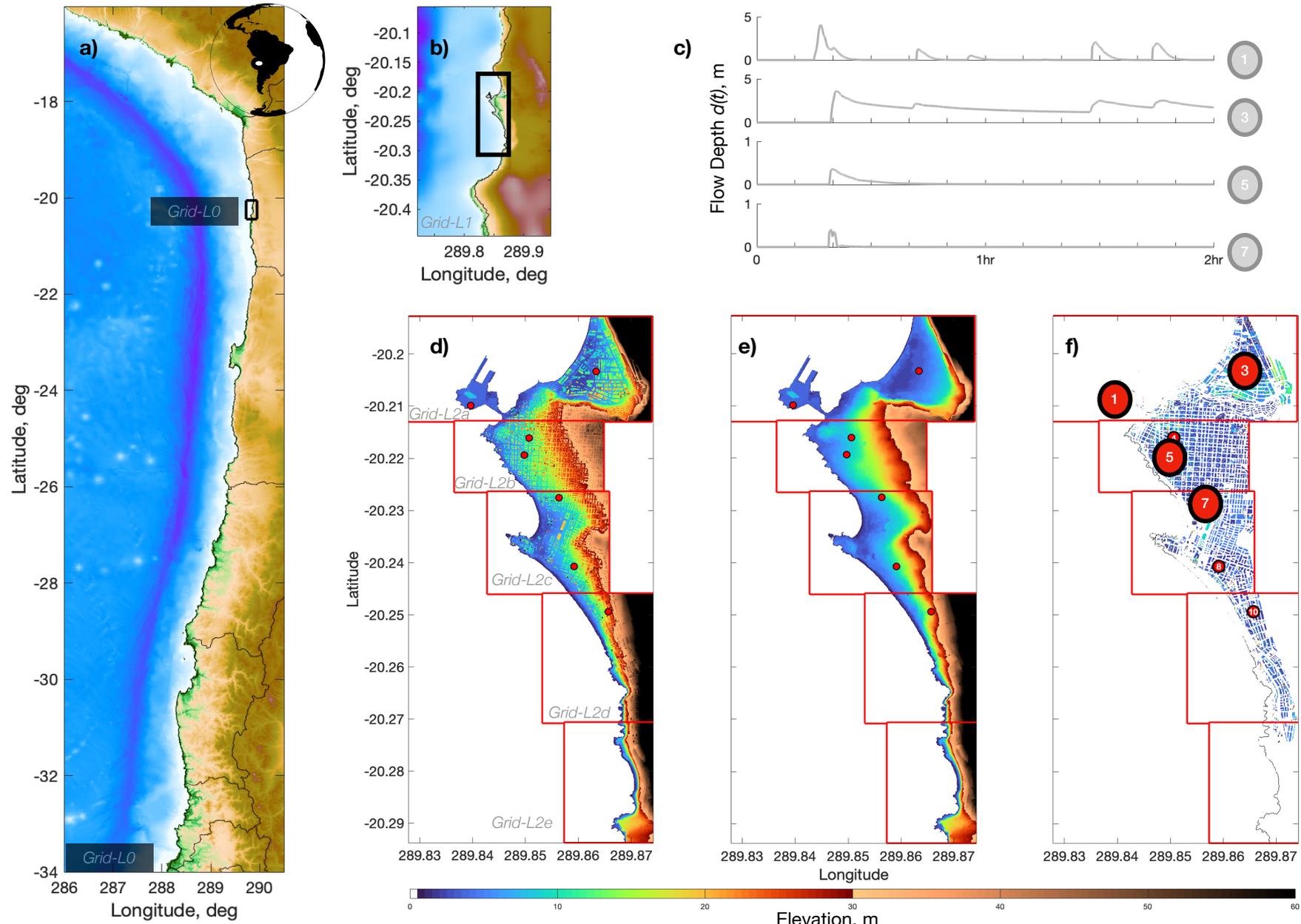


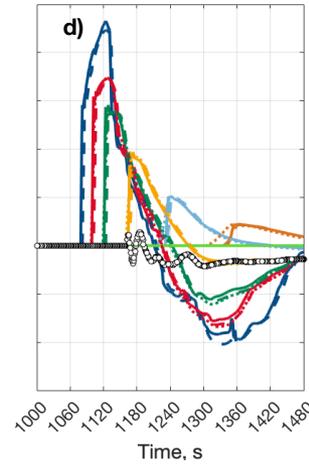
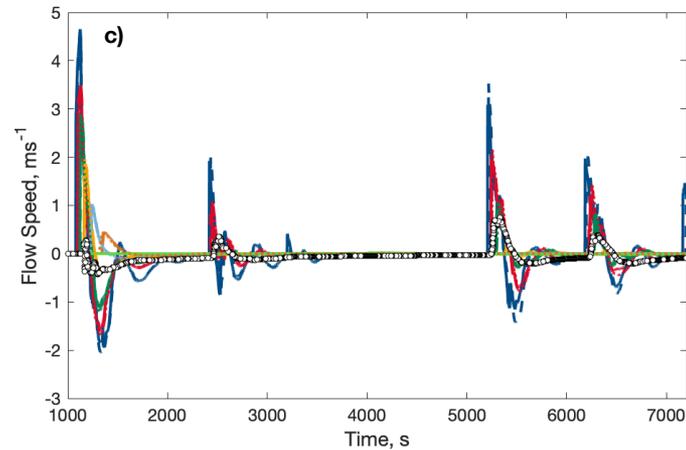
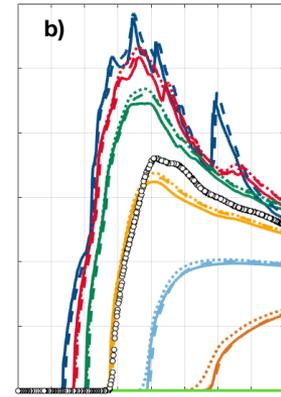
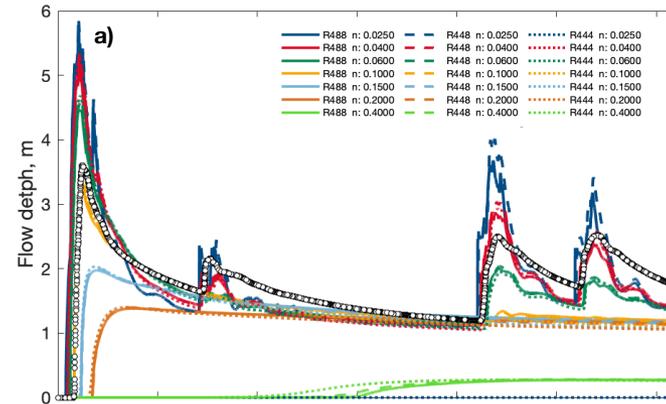
Figura 3.-Espectros normalizados para Arica.

# Comportamiento varía mucho

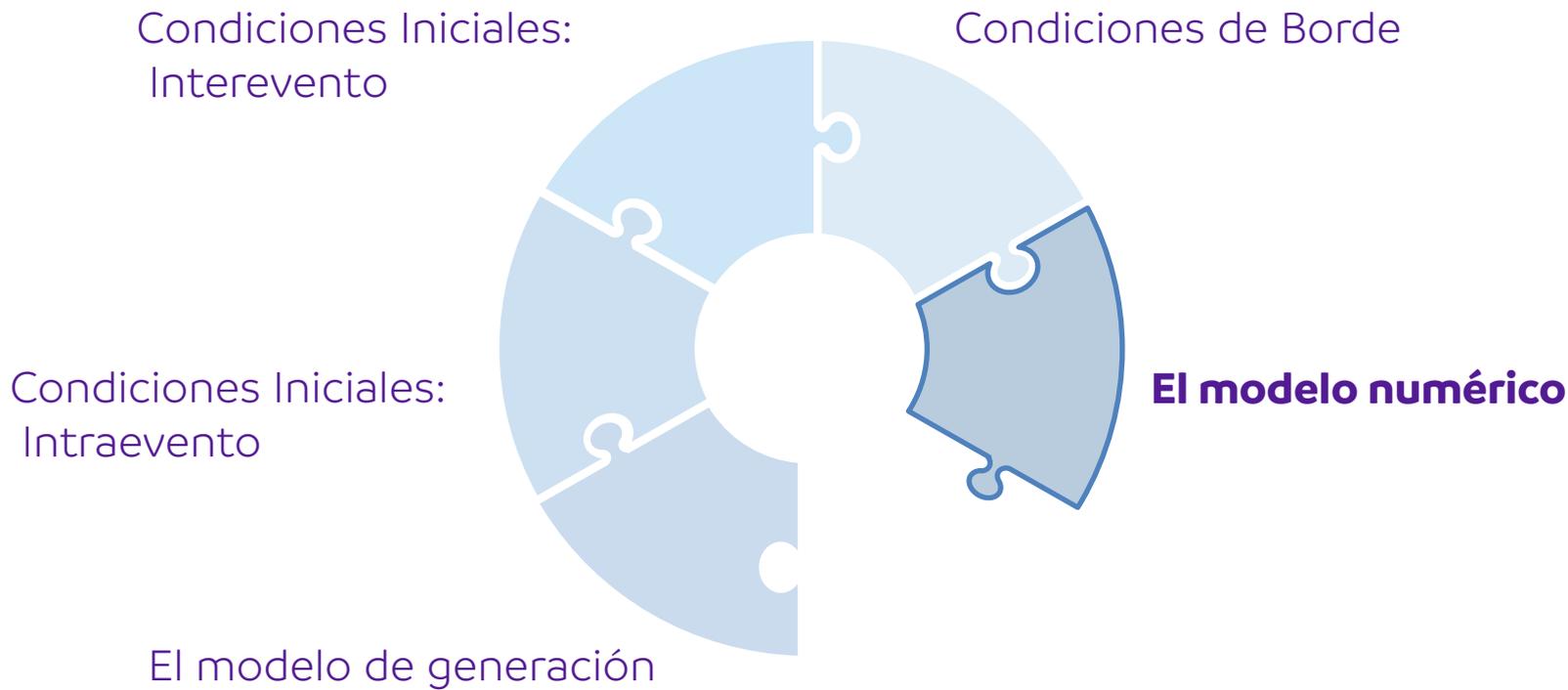


# Condiciones de Borde: Topobatimetría

- Calidad de la batimetría
  - Sepúlveda et al, 2020
- Qué usar? DEM, DTM
  - Gibbons et al, 2021, Kaiser et al, 2011, Gayer et al, 2010
- Cómo modelar la fricción,
  - CRM, ERM, DEM
- Mareas?
- RSLR:
  - Largo plazo



# Partes y piezas





**Precisión**

**Datos**

**Fácil comprensión**

**Tiempo calculo**

**\$\$\$\$**

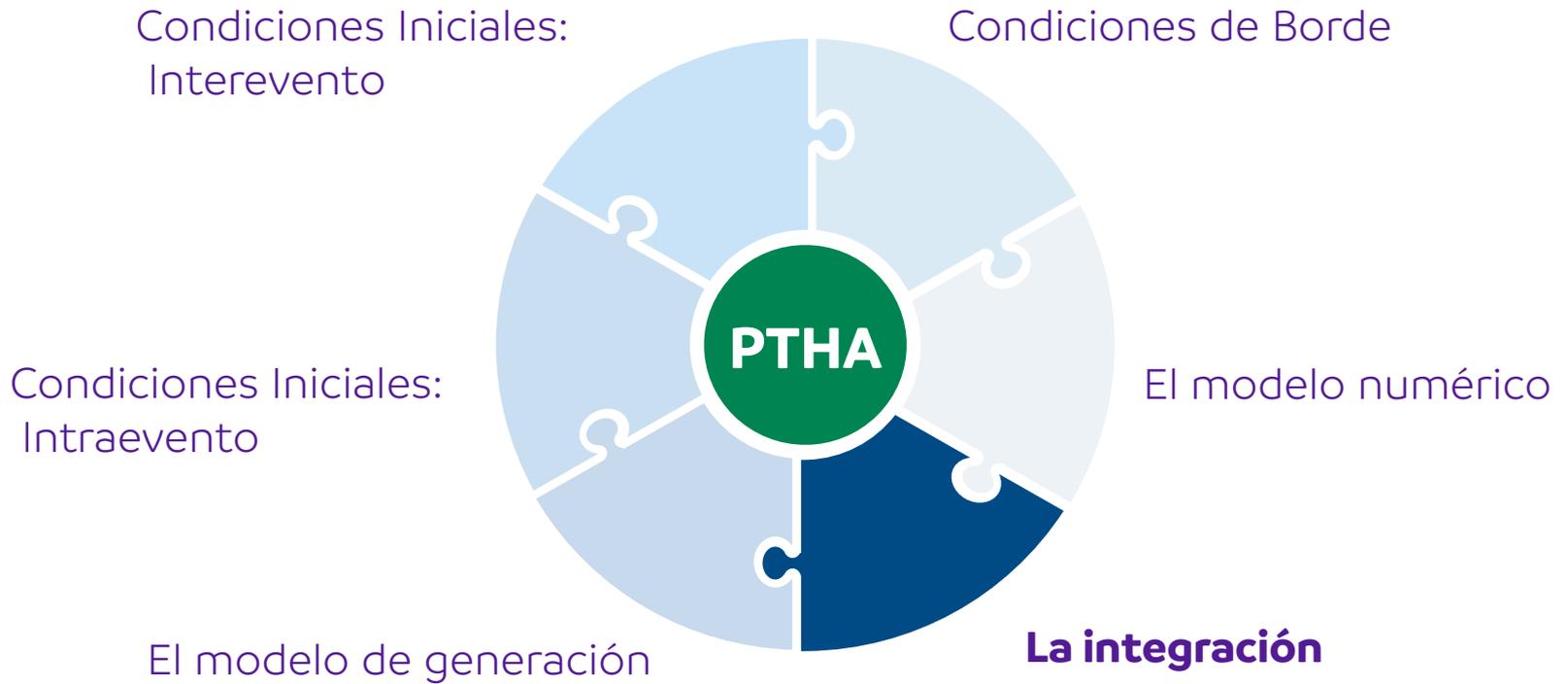
**Rapidez**



# Modelo numérico

- Dependencia en el modelo
  - ◉ LSWE, NLSWE, Boussinesq
- ◉ Dependencia del Algoritmo
  - ◉ Modelo en sí mismo
- ◉ Resolución de las celdas
- ◉ Capacidad de modelar corrientes
- ◉ Cuanto modelar

# Partes y piezas





# La integración

- Qué fuentes
    - ◉ Locales, regionales, telesísmicas
  - ◉ Qué procesos
    - ◉ subduction, deslizamientos, volcanes
  - ◉ Cuanto modelar?
    - ◉ Todo, SROM, etc.
- Qué queremos modelar
    - ◉ ¿Altura, corrientes?
  - ◉ **¿Para qué?**
    - ◉ **Vidas**
    - ◉ **Evacuación**
    - ◉ **Infraestructura**

# VALPARAISO-VIÑA

una historia difícil

# ¿PUEDEN HABER TSUNAMIS EN VALPARAÍSO?



# Un caso: Valparaíso 1906

- Un terremoto que causó mucho daño en la ciudad puerto de Valparaíso, y fue considerado por mucho tiempo el terremoto más grande que ha afectado dicha zona
- No generó un tsunami que causara daño!

# Ejemplo: Valparaíso 1906



**Journal of Geophysical Research: Solid Earth**

**RESEARCH ARTICLE**  
10.1002/2016JB013269

**Key Points:**

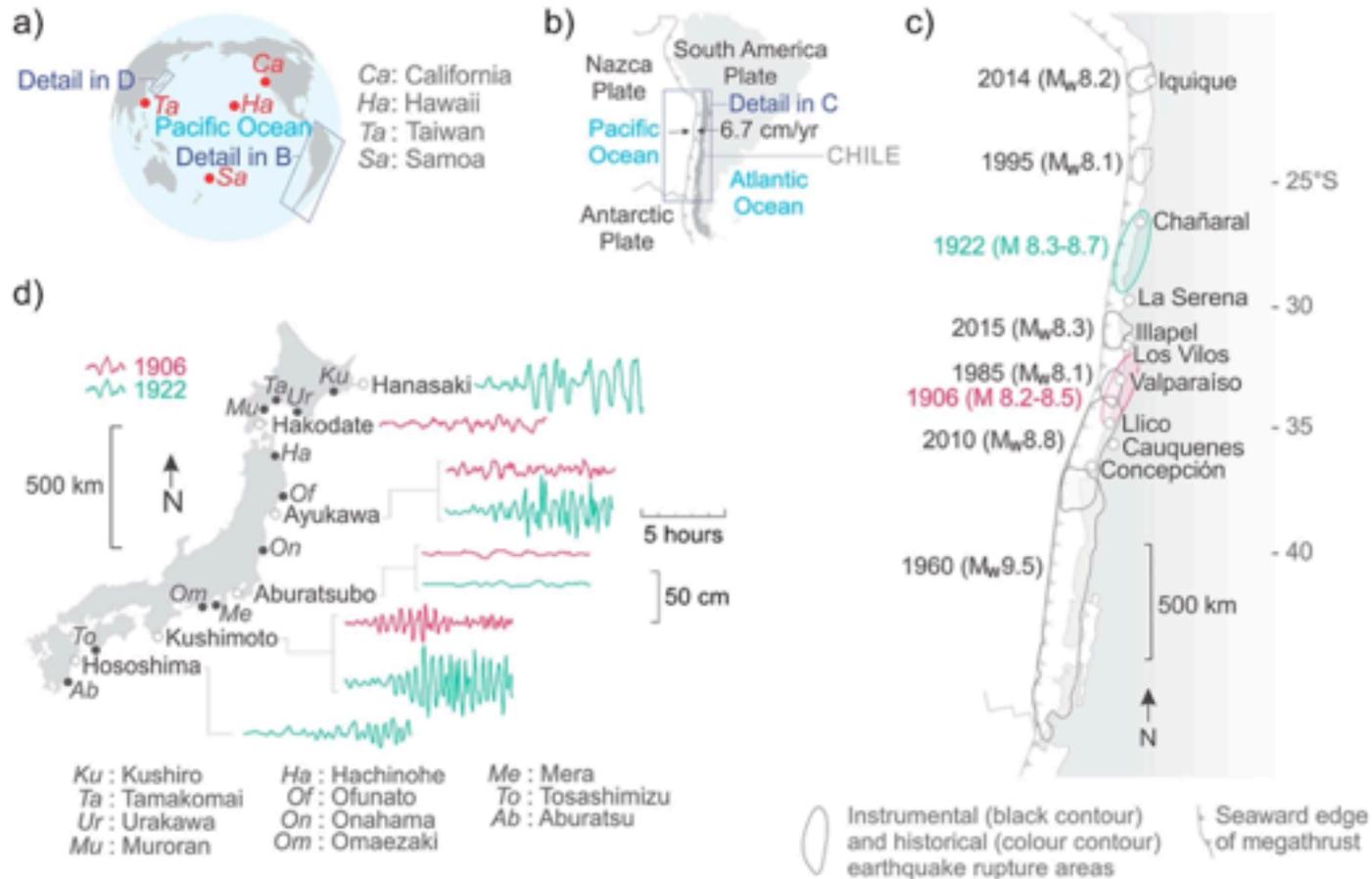
- Far-field tsunami amplitudes gauged in Japan provide both magnitude and source depth constraints on the Chilean 1906 and 1922 earthquakes
- Peak tsunami amplitudes in Japan scale consistently with the moment magnitude for Chilean earthquakes that occur at typical source depths
- While the 1922 tsunami amplitudes in Japan indicate a typical source depth, those for 1906 point to a deeper than average source

**Reexamination of the magnitudes for the 1906 and 1922 Chilean earthquakes using Japanese tsunami amplitudes: Implications for source depth constraints**

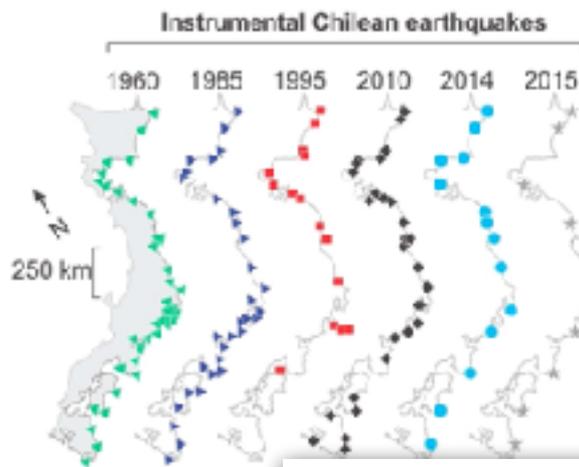
**M. Carvajal<sup>1</sup>, M. Cisternas<sup>2</sup>, A. Gubler<sup>3,4</sup>, P. A. Catalán<sup>3,4,5</sup>, P. Winckler<sup>6</sup>, and R. L. Wesson<sup>7</sup>**

<sup>1</sup>Programa Magister en Oceanografía, Escuela de Ciencias del Mar, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile, <sup>2</sup>Escuela de Ciencias del Mar, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile, <sup>3</sup>Departamento de Obras Civiles, Universidad Técnica Federico Santa María, Valparaíso, Chile, <sup>4</sup>Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales, CIGIDEN, Santiago, Chile, <sup>5</sup>Basal Project FB021, Centro Científico Tecnológico de Valparaíso, Valparaíso, Chile, <sup>6</sup>Escuela de Ingeniería Civil Oceánica, Universidad de Valparaíso, Valparaíso, Chile, <sup>7</sup>U.S. Geological Survey, Denver, Colorado, USA

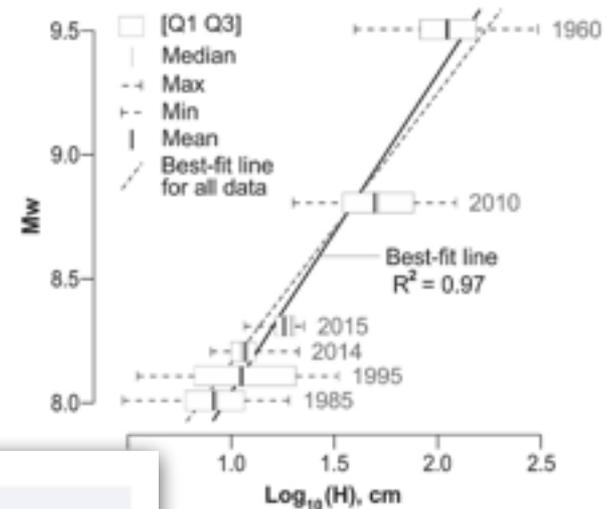
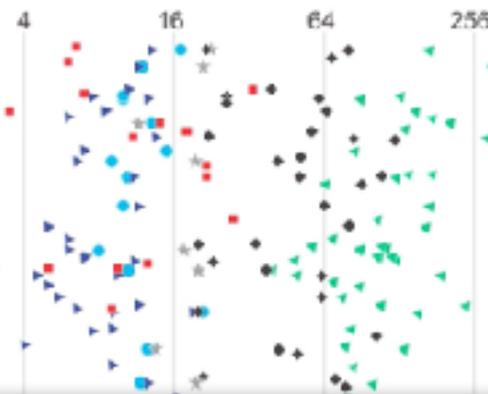
- Sabemos de otros tsunamis originados en Chile que causaron daño en Japón
- Se puede inferir a partir de ellos



**Figure 2.** Index maps. (a) Locations of studied sites on the Pacific Ocean. (b) Tectonic setting of Chile. The paired arrows indicate the plate convergence at 6.7 cm/yr [Altamimi et al., 2007]. (c) Rupture areas of instrumental [Moreno et al., 2009; Comte et al., 1986; Chlieh et al., 2004; Moreno et al., 2012; Yagi et al., 2014; Tilmann et al., 2016] and historical (modified from Kelleher [1972]) earthquakes. (d) Japanese tsunami records from the 1906 (crimson) and 1922 (green) earthquakes.



Maximum tsunami amplitude, cm



18 Range

**Table 1.** Regression Results and Regressed Moment Magnitudes for the 1906 and 1922 Earthquakes<sup>a</sup>

					1906		1922	
Tsunami data analyzed	$\alpha$	$\beta$	$R^2$	RMSE	$H$ (cm)	$M_w$	$H$ (cm)	$M_w$
Event-averaged amplitudes	1.27	6.79	0.97	0.11	-	8.07	-	8.54
All amplitudes	1.09	7.06	0.83	0.26	-	8.17	-	8.57
Individual-site amplitudes								
<i>Hanasaki</i>	1.24	6.62	0.97	0.13	-	-	60	8.45
<i>Kushiro</i>	1.00	7.02	0.99	0.10	-	-	-	-
<i>Urakawa</i>	1.08	7.03	0.96	0.17	-	-	-	-
<i>Tamakomai</i>	1.26	6.82	0.98	0.12	-	-	-	-
<i>Muroran</i>	1.08	7.31	0.92	0.24	-	-	-	-
<i>Hakodate</i>	1.06	7.02	0.97	0.15	24	8.17	-	-
<i>Hachinohe</i>	1.02	6.93	0.98	0.12	-	-	-	-
<i>Ofunato</i>	0.79	7.33	0.66	0.21	-	-	-	-
<i>Ayukawa</i>	1.14	6.92	0.98	0.12	18	8.00	65	8.63
<i>Onahama</i>	1.10	6.94	0.95	0.18	-	-	-	-
<i>Mera</i>	1.24	6.86	0.94	0.21	-	-	-	-
<i>Aburatsubo</i>	-	-	-	-	5	-	5	-
<i>Omaezaki</i>	1.12	6.96	0.98	0.10	-	-	-	-
<i>Kushimoto</i>	1.51	6.20	0.97	0.13	35	8.08	70	8.53
<i>Tosashimizu</i>	1.19	6.90	0.98	0.11	-	-	-	-
<i>Hososhima</i>	-	-	-	-	-	-	39	-
<i>Aburatsu</i>	1.54	6.39	0.98	0.13	-	-	-	-
Mean	1.16	6.88	0.95	0.15	21	8.08	48	8.54
Maximum	1.54	7.33	0.99	0.24	35	8.17	70	8.63
Minimum	0.79	6.20	0.66	0.10	5	8.00	5	8.45
Standard deviation	0.19	0.30	0.08	0.04	13	0.09	27	0.09

<sup>a</sup>The  $\alpha$  and  $\beta$  are the slope and intercept for the best model fit.  $R^2$  and RMSE are the coefficient of determination and root-mean-square error.  $H$  (cm) is the maximum tsunami crest-to-trough height recorded in Japan for the 1906 and 1922 earthquakes.  $M_w$  is the regressed moment magnitude for the 1906 and 1922 earthquakes. Mean, maximum, minimum, and standard deviation are for individual sites only (shown in italic font).

... results showing data with box plot diagrams. The black intercept of 1.26 and 6.8, respectively, represents the (7) between the logarithm of the average of the maximum amplitudes in Japan (cm) and the  $M_w$  of the parent earthquake. Similarly, the oblique dashed line with slope and 7.1, respectively, represents the best fit line ( $R^2 = 0.83$ ) if analysis is performed on all the tsunami amplitudes plotted in represent the 25th and 75th percentiles, respectively.

# Valparaíso, reanalizado

RESEARCH ARTICLE

10.1002/jgrb.12406

Source of the 1730 Chilean earthquake from historical records: Implications for the future tsunami hazard on the coast of Metropolitan Chile

M. Cervelán<sup>1</sup>, M. Cisternas<sup>2</sup>, and P. A. Cerjakin<sup>3,4</sup>

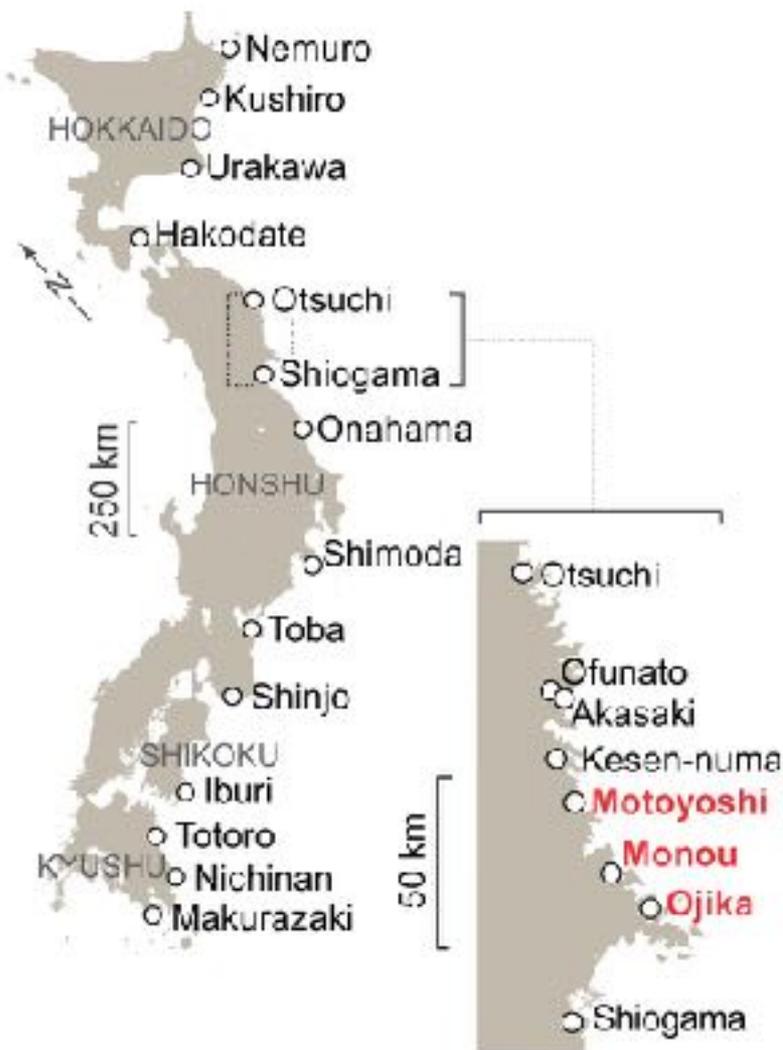
Key Points:

- Historical records of the tsunami triggered by the 1730 Metropolitan Chile earthquake suggest a magnitude in the range of  $M_w$  1–1.8.
- A subduction process of the city system during the rupture area of the 1730 earthquake best explains the tsunami and uplift observations.
- The near-future earthquakes on Metropolitan Chile could involve

<sup>1</sup>Escuela de Ciencias del Mar, Pontificia Universidad Católica de Valparaíso, Valparaíso, Chile; <sup>2</sup>Departamento de Civil, Universidad Técnica Federico Santa María, Valparaíso, Chile; <sup>3</sup>Centro Nacional de Investigación para la Integración de Datos de Naturales, Santiago, Chile; <sup>4</sup>Centro Científico Tsunamiológico de Valparaíso, Valparaíso, Chile

**Abstract:** Historical records of an earthquake that occurred in 1730 affecting Metropolitan Chile

- Datos de inundación histórica en Penco
- Datos de inundación paleotsunami en Quintero
- Datos de mareógrafos en Japón
- Un estudiante motivado

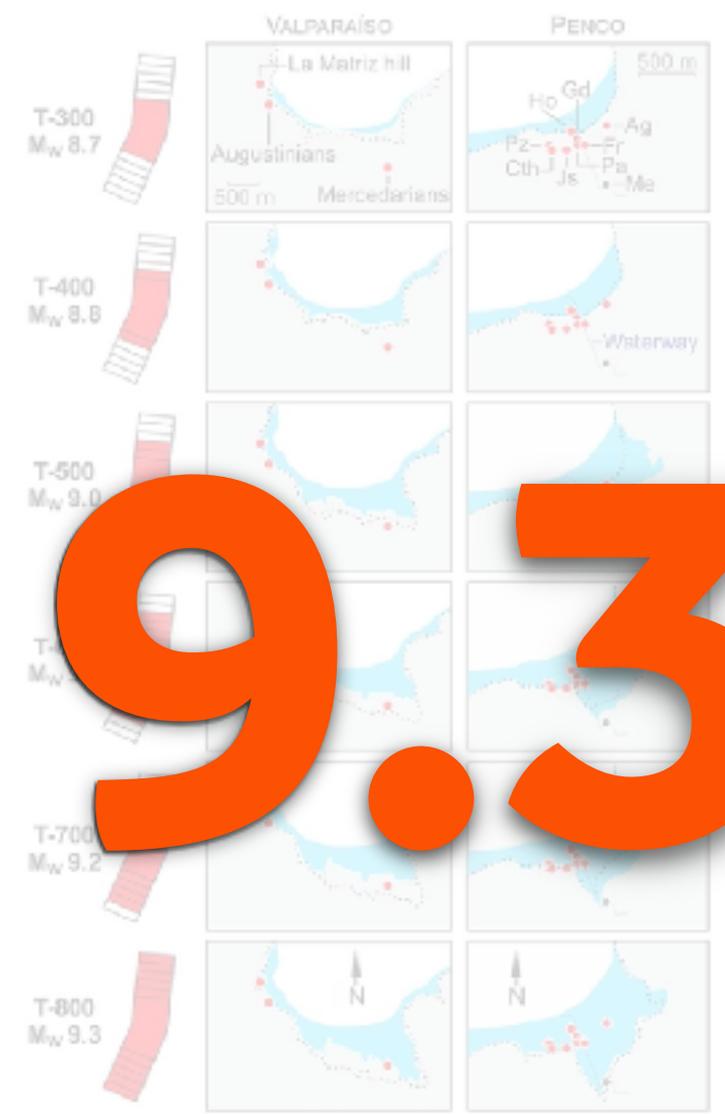
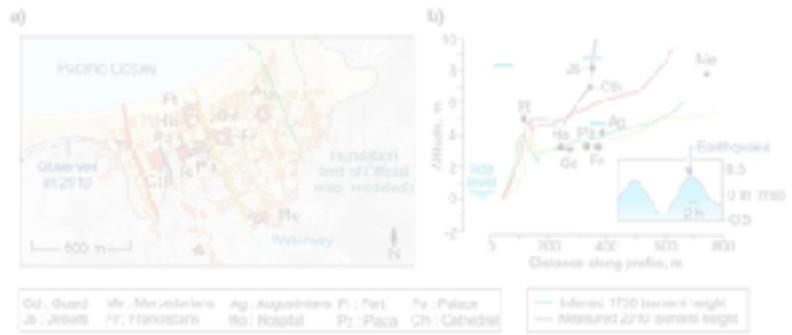


其（東邊史稿）  
 五月二十五日、宮城牡鹿雄生本台諸郡海嘯アリ、  
 對邊ヲ破リ、田島ヲ損ス、

## Kyoho 15 [1730]

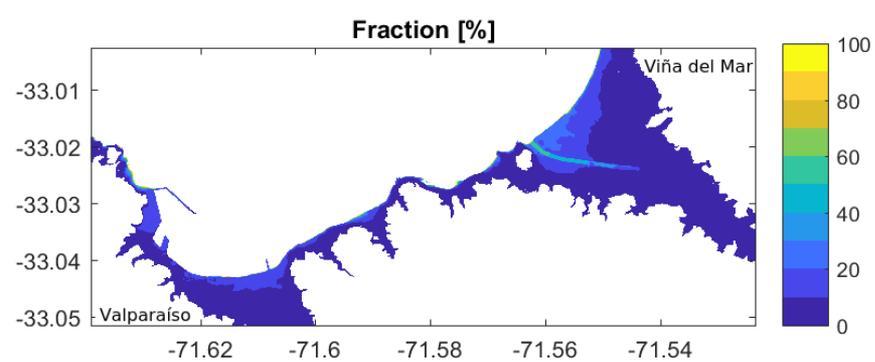
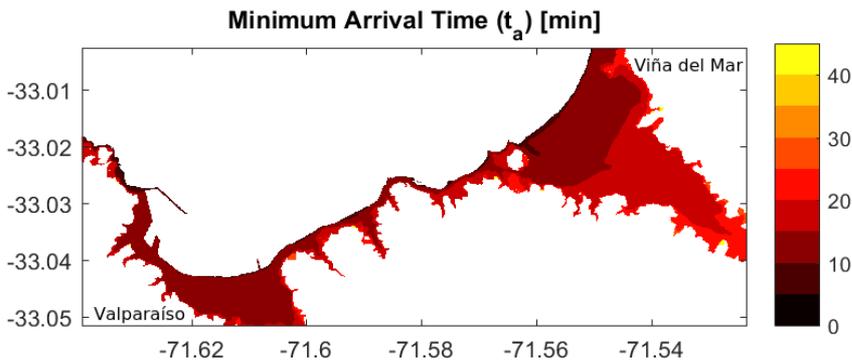
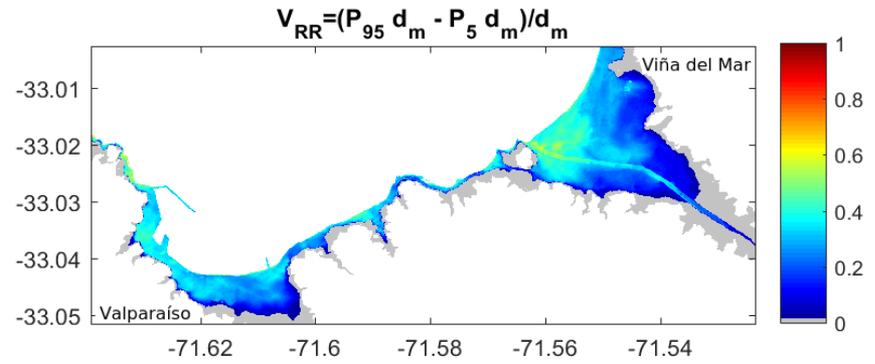
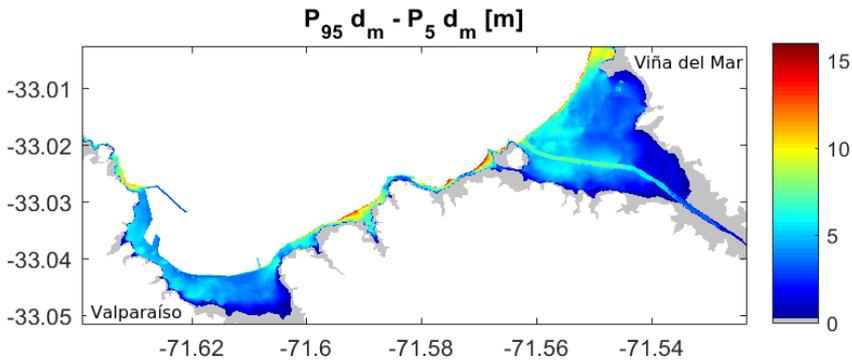
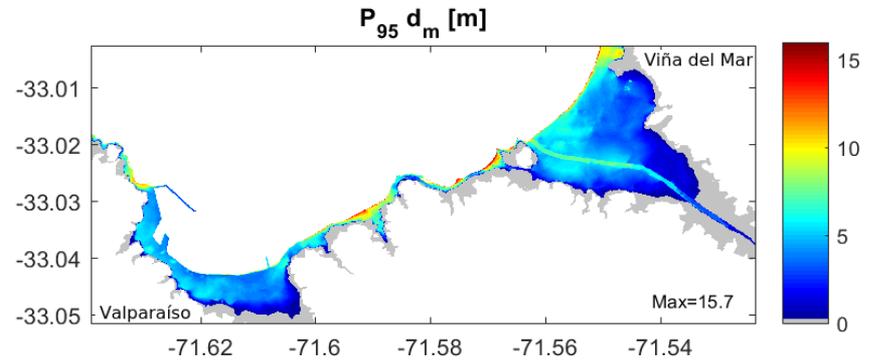
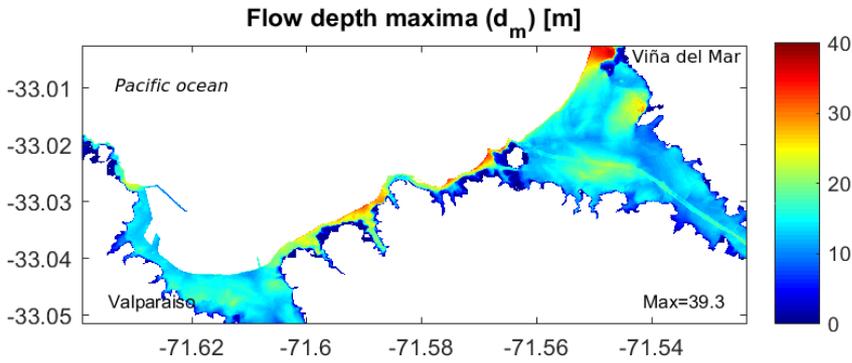
El día 25 del quinto mes [9 de Julio] hubo *kaisho* [tsunami] en los distritos de Miyagi, Ojika, Monou y Motoyoshi [todos en la actual prefectura de Miyagi]. Destruyó cercas y dañó arrozales y cultivos.

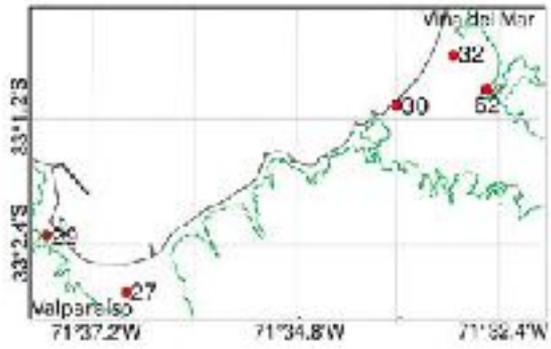
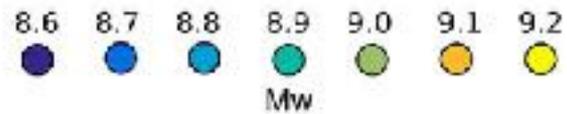
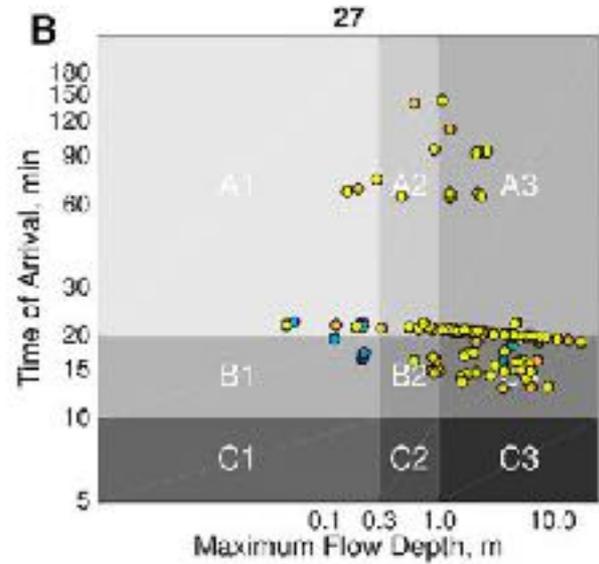
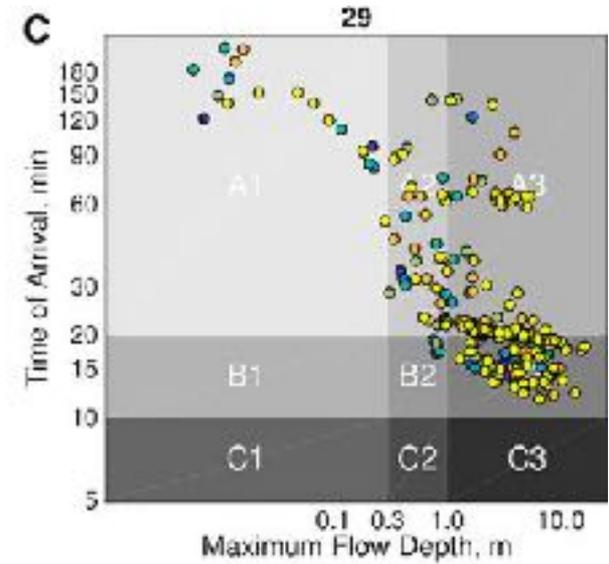
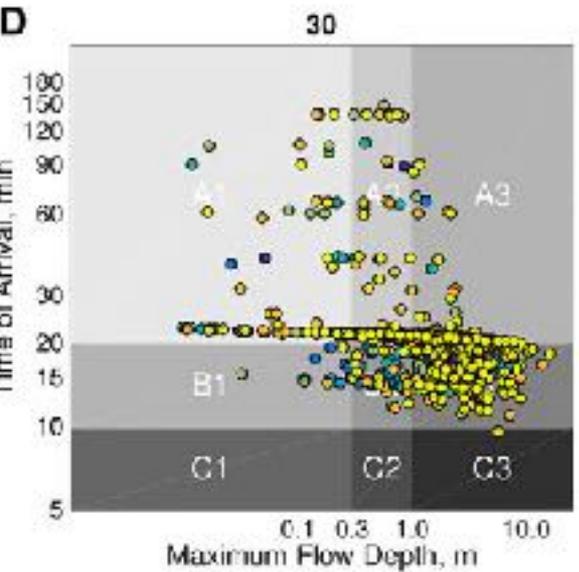
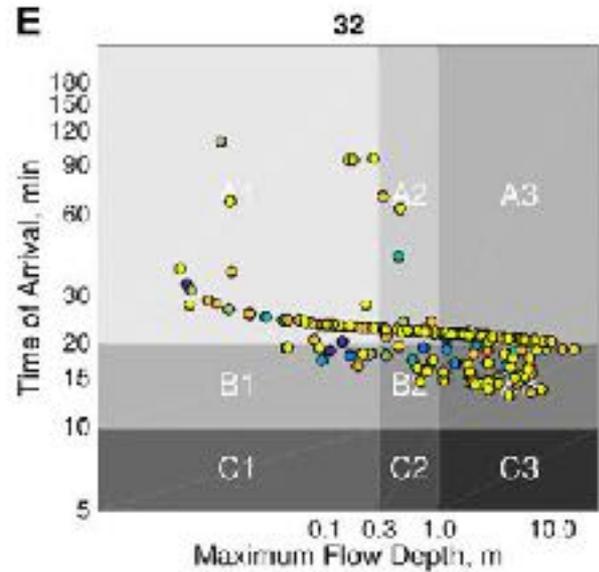
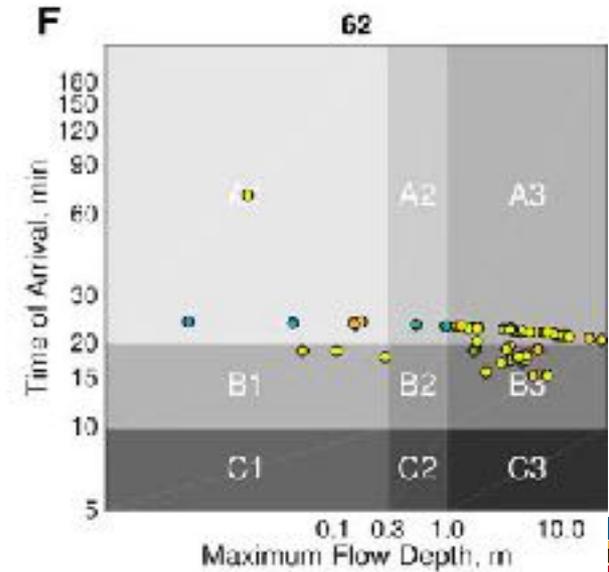
En: Tohan-shikou (Historia del Clan del Este)



Y...¿QUÉ PODRÍA PASAR?

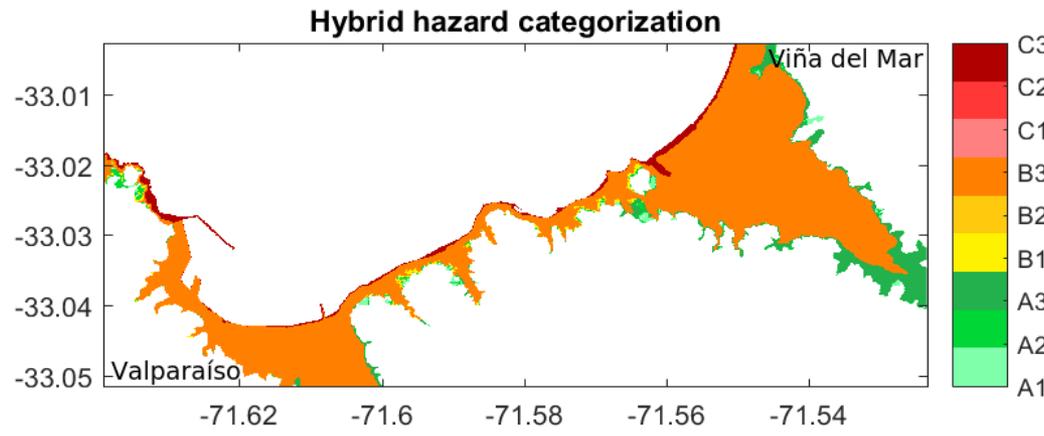
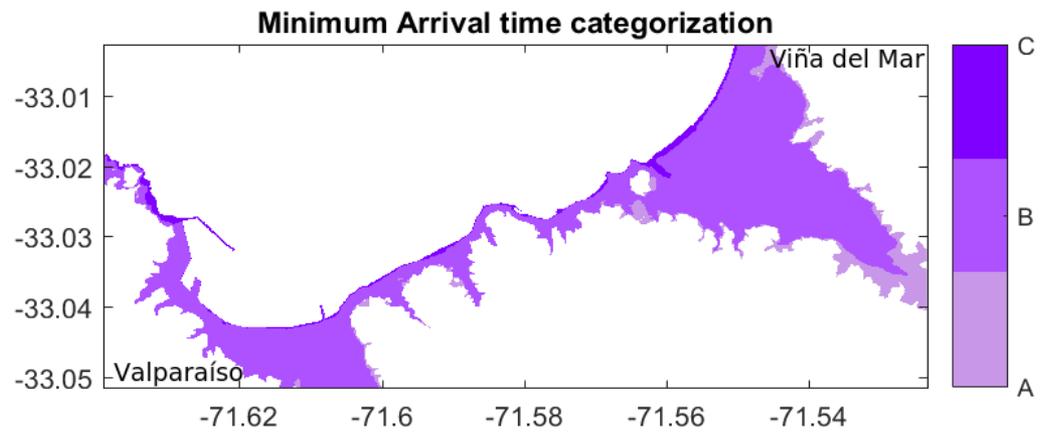
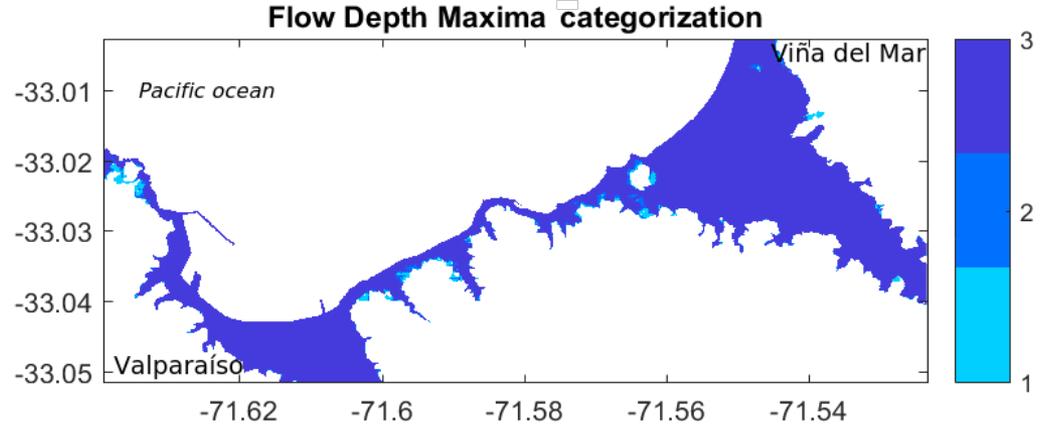
# Ejemplo: Tsunami: Incorporating arrival time



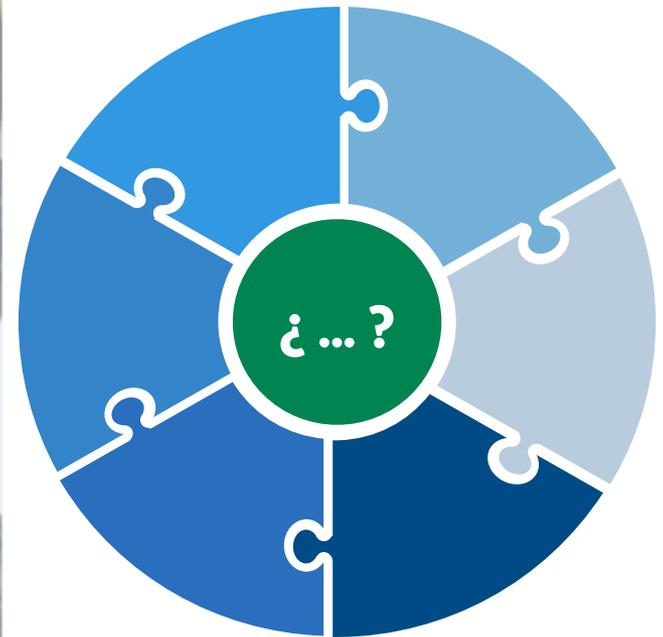
**A****B****C****D****E****F**

# Is simpler better?

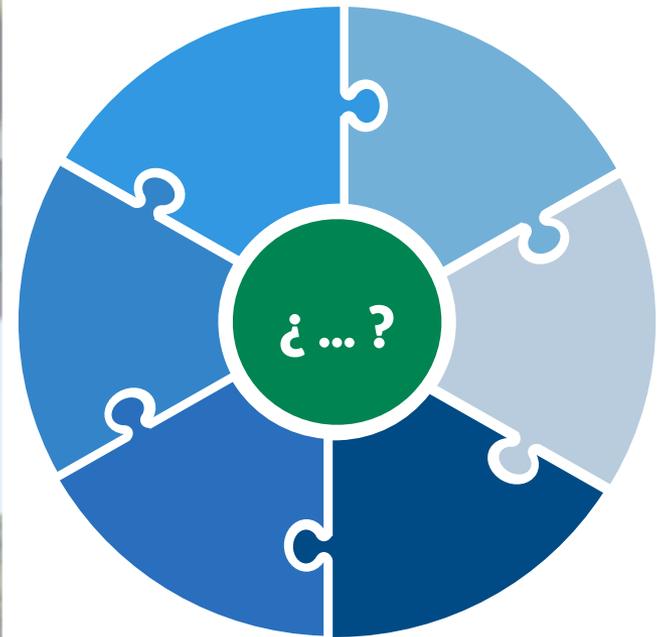
- Two-criteria:
  - flow depth
  - arrival time
- Ej: 2800 scenarios modeled with HySea with magnitudes 8,6-9,2



# ¿Estamos en condiciones de lanzarnos?



# ¿Estamos en condiciones de lanzarnos?

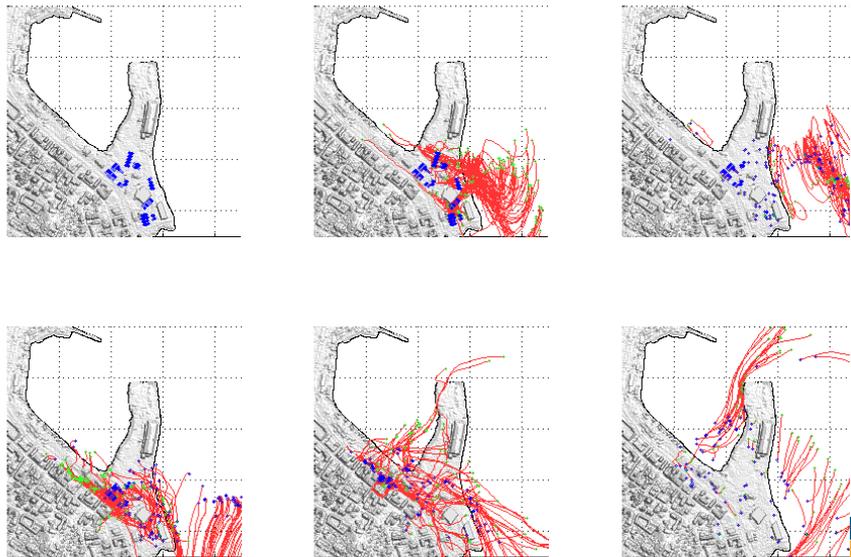
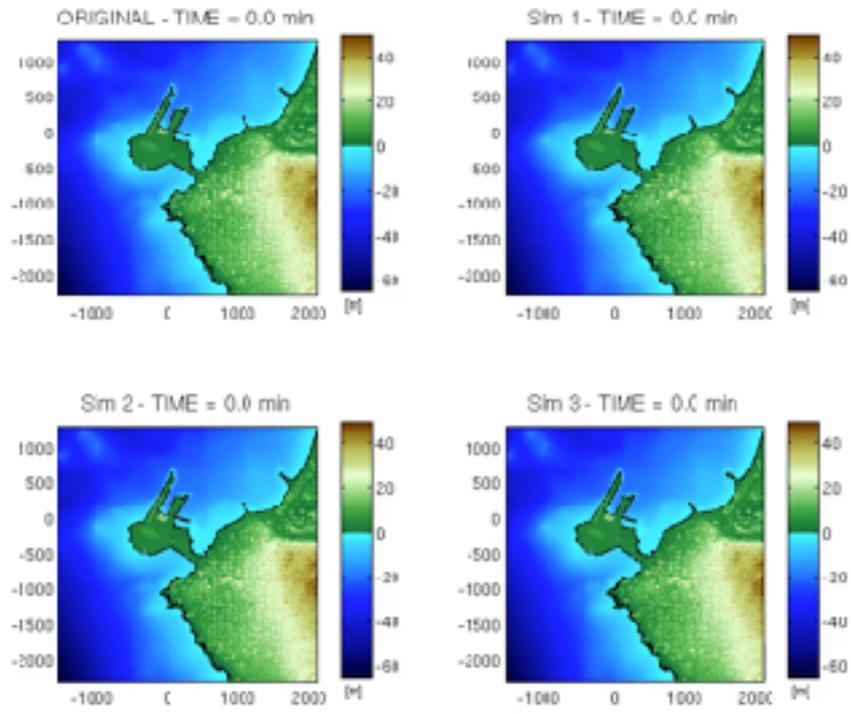




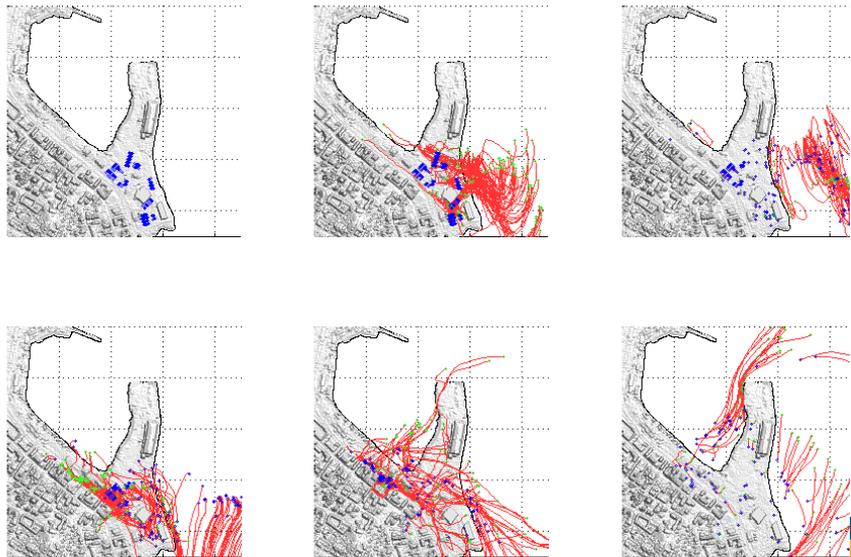
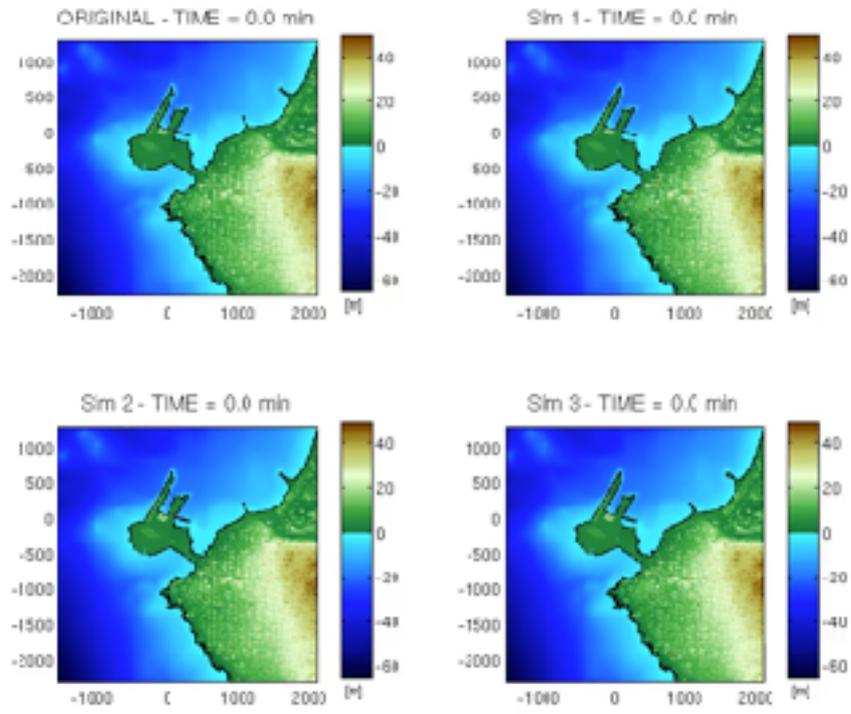
# Resumen

- Hemos avanzado mucho en apenas 10 años
- Pero el progreso y aplicación de las herramientas desarrolladas debe ser cauto, reconociendo que aun hay mucha incertidumbre

# La tentación



# La tentación



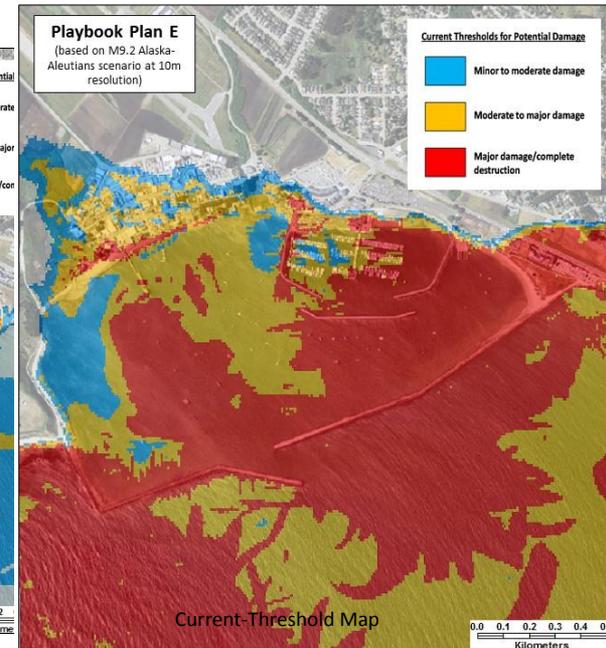
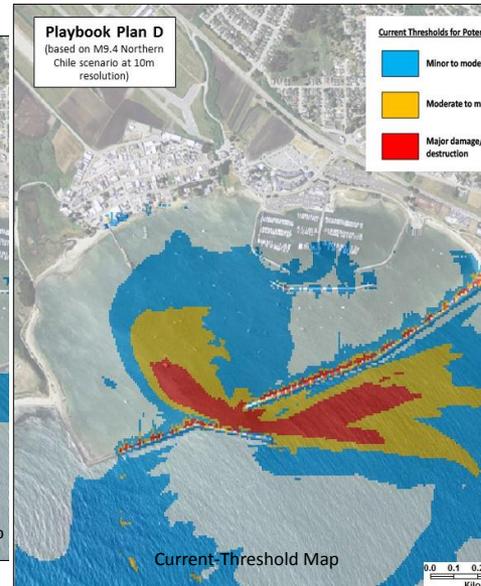
# Puertos...el problema de las corrientes

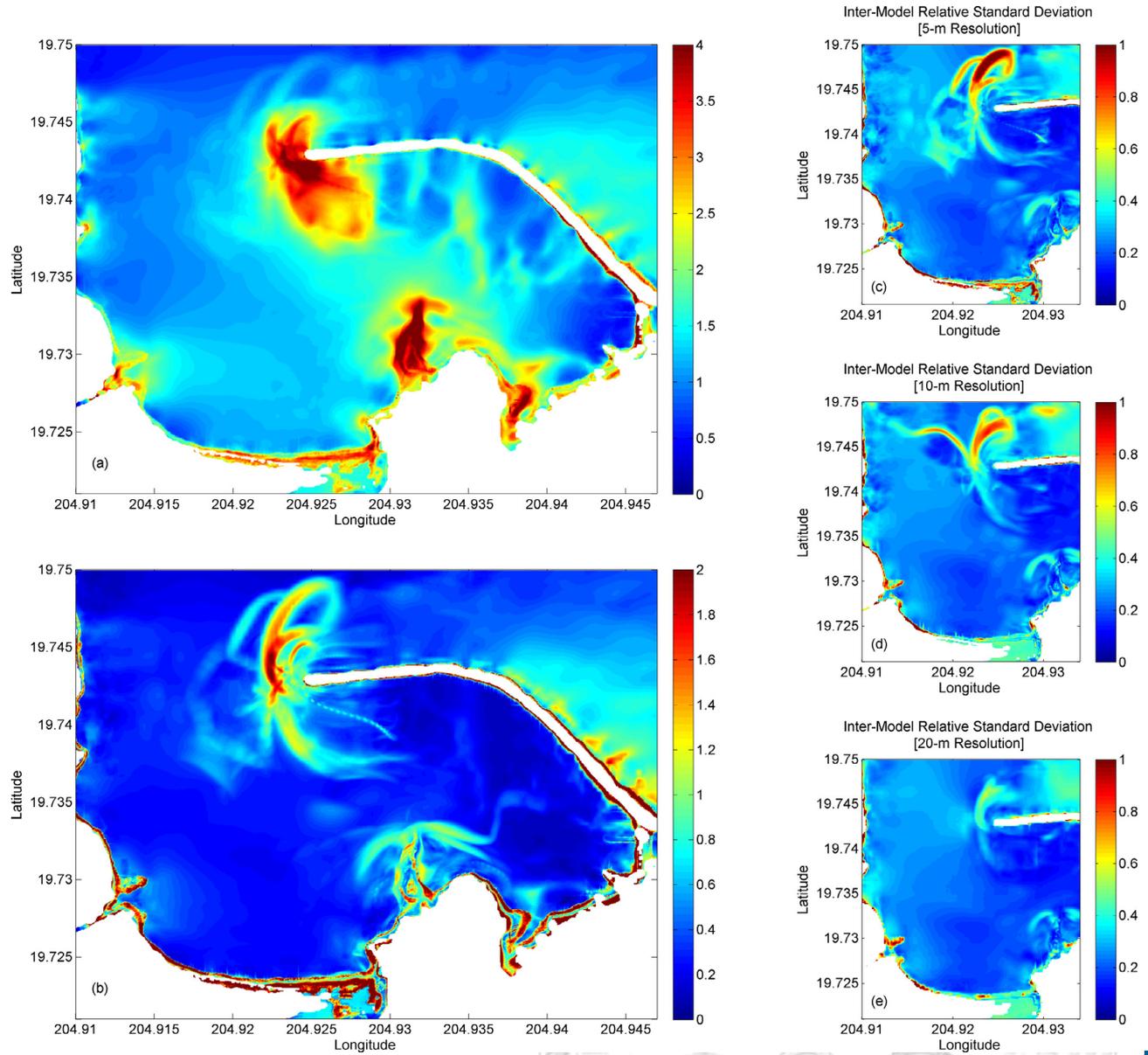
**RELATIONSHIP BETWEEN TSUNAMI CURRENT SPEED AND HARBOR DAMAGE:** Analysis of recent tsunami damage indicates a relationship between current speed and harbor damage. The Damage Index to the right has been used in the analysis to determine the following relationship (see color codes here and on maps):

**CURRENTS = DAMAGE**

- 0-3 knots = No Damage
- 3-6 knots = Minor/Moderate Damage
- 6-9 knots = Moderate/Major Damage
- >9 knots = Major/Complete Damage

Damage Index:	Damage Type:
0	no damage
1	small buoys moved
2	1-2 docks/small boats damaged, large buoys moved
3	Moderate dock/boat damage, mid-sized vessels off moorings
4	Major dock/boat damage, large vessels off moorings
5	Complete destruction





**Fig. 9.** Summary of inter-model spatial statistics. Top left (a): inter-model mean of predicted maximum speed in m/s as taken from the 5-m resolution runs. Bottom left (b): inter-model standard deviation of predicted maximum speed in m/s as taken from the 5-m resolution runs. Right column: inter-model standard deviation of predicted maximum speed scaled by model-mean maximum speed as taken from the 5-m resolution runs (c), 10-m resolution runs (d), and 20-m resolution runs (e).

