National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

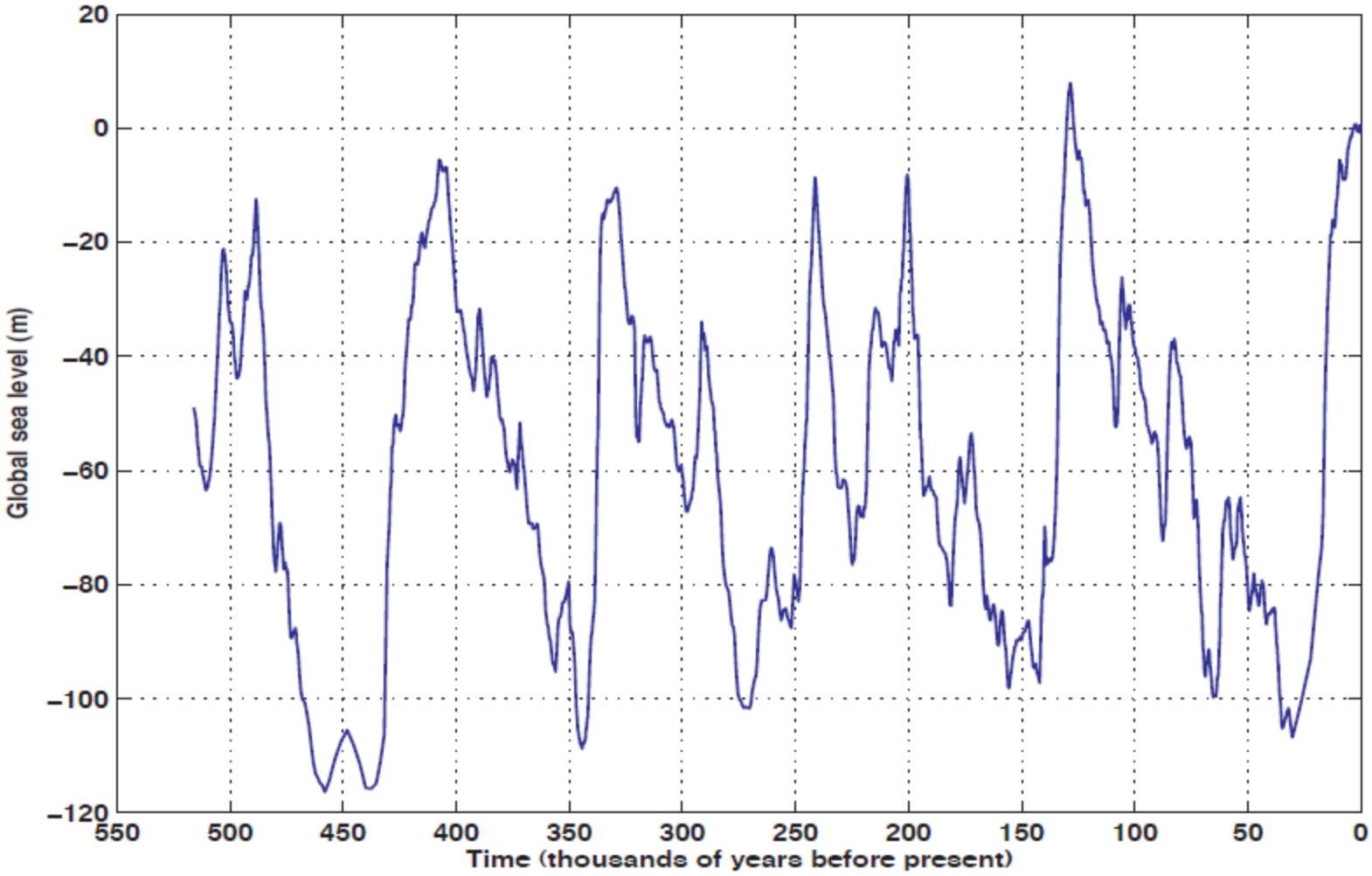
Measuring Long Term Mean and Extreme Sea Level Rise

Philip L. Woodworth
National Oceanography Centre, Liverpool

University of São Paulo, 1 November 2011

This is a Big Subject – Some Things Discussed Today

- How do we measure sea level change?
- How much has sea level changed?
- Do we understand why it has changed?
- Have extreme sea levels changed at the same rate as mean sea levels?
- Look to the future in various ways.



Sea level has always gone up and down but I will focus on the “instrumental era” i.e. the last 100 years or so.

How Do We Measure Sea Level?

Tide Gauges at the Coast

- Float and Stilling-Well Gauges
- Pressure gauges
- Acoustic Gauges
- Radar Gauges

Satellite Radar Altimetry from Space

Classical Float Gauge (from about 1832)

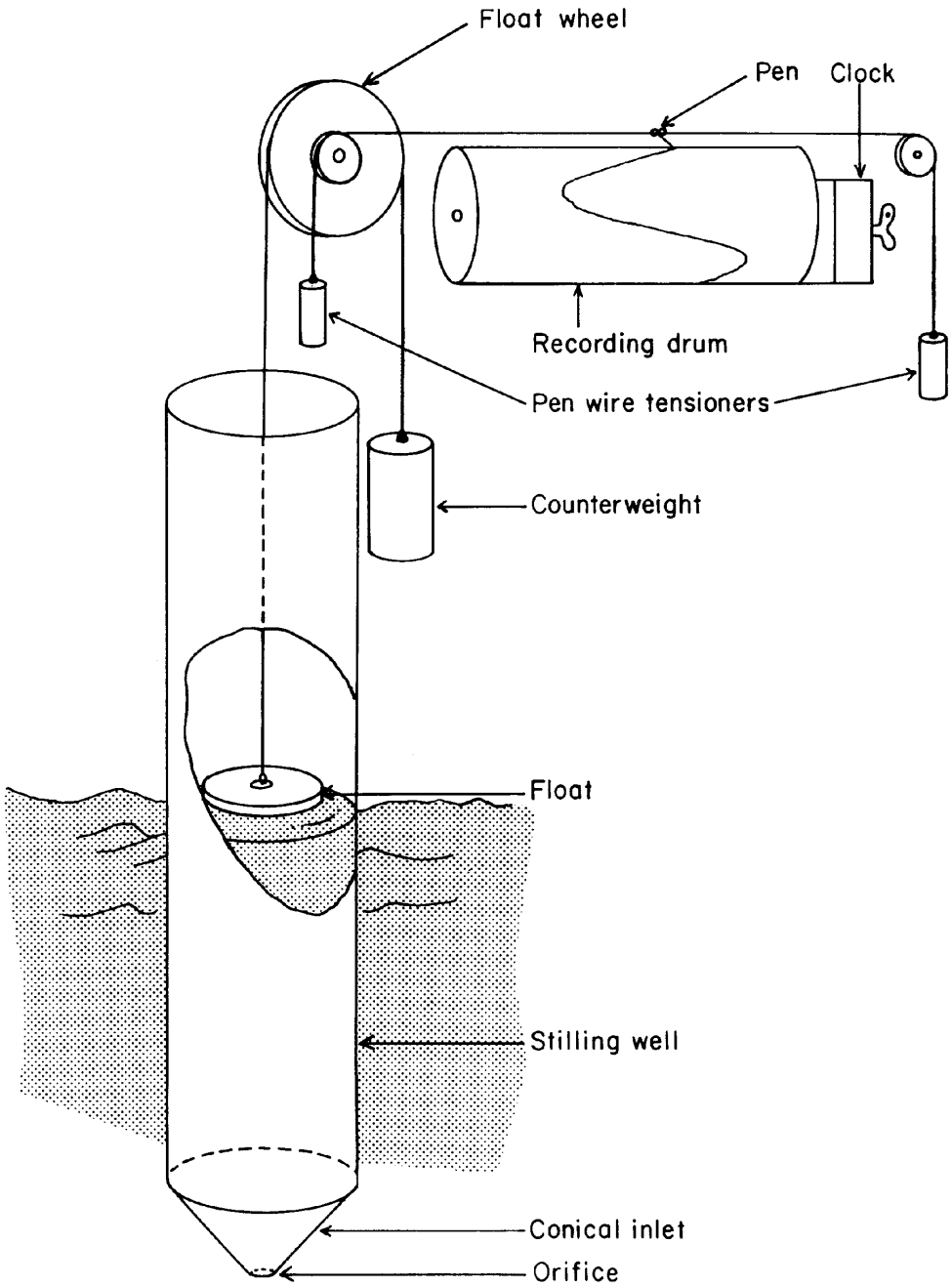


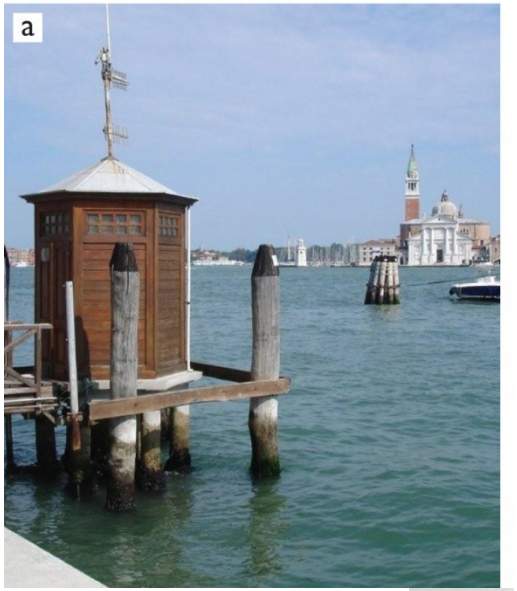
Figure 3.1

UK Float Gauges and Stilling Wells at Holyhead, UK

Cananeia Tide Gauge Station

Float Gauge,
Antarctica

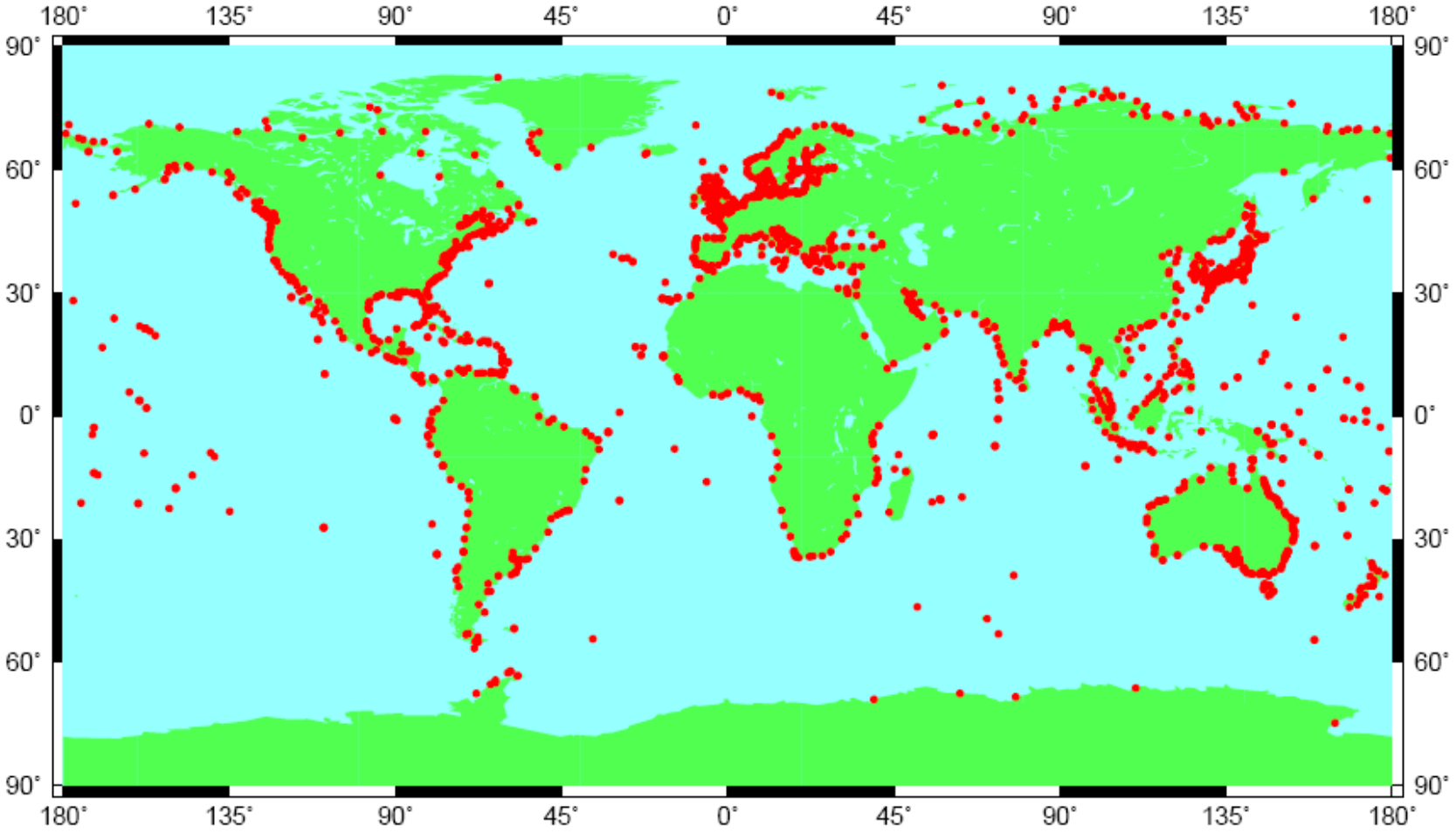
Radar Gauge,
Liverpool



Float Gauge,
Venice

Acoustic Gauge,
Australia

Distribution of PSMSL Stations



1987: 27000 station-years of data

2011: 60000 station-years of data

PSMSL

1933 75th Anniversary 2008

Search

PSMSL Permanent Service for Mean Sea Level

About Us | Data | Products | Training & Information | Links

home >

News

- Changes to the PSMSL Data Files
- PSMSL Launches New Website
- PSMSL Updates Backend Database
- More News ...

Explore the Dataset

Browse dataset in Google Earth

Welcome to the Permanent Service for Mean Sea Level (PSMSL)

Established in 1933, PSMSL is the global data bank for long term sea level change information from tide gauges and bottom pressure recorders.

About Us:

Learn about PSMSL, contact us, read news items and annual reports

Data:

Obtain and submit tide gauge and bottom pressure data

Products:

Browse the data set via GoogleEarth or obtain derived products, view regional commentaries and author archives

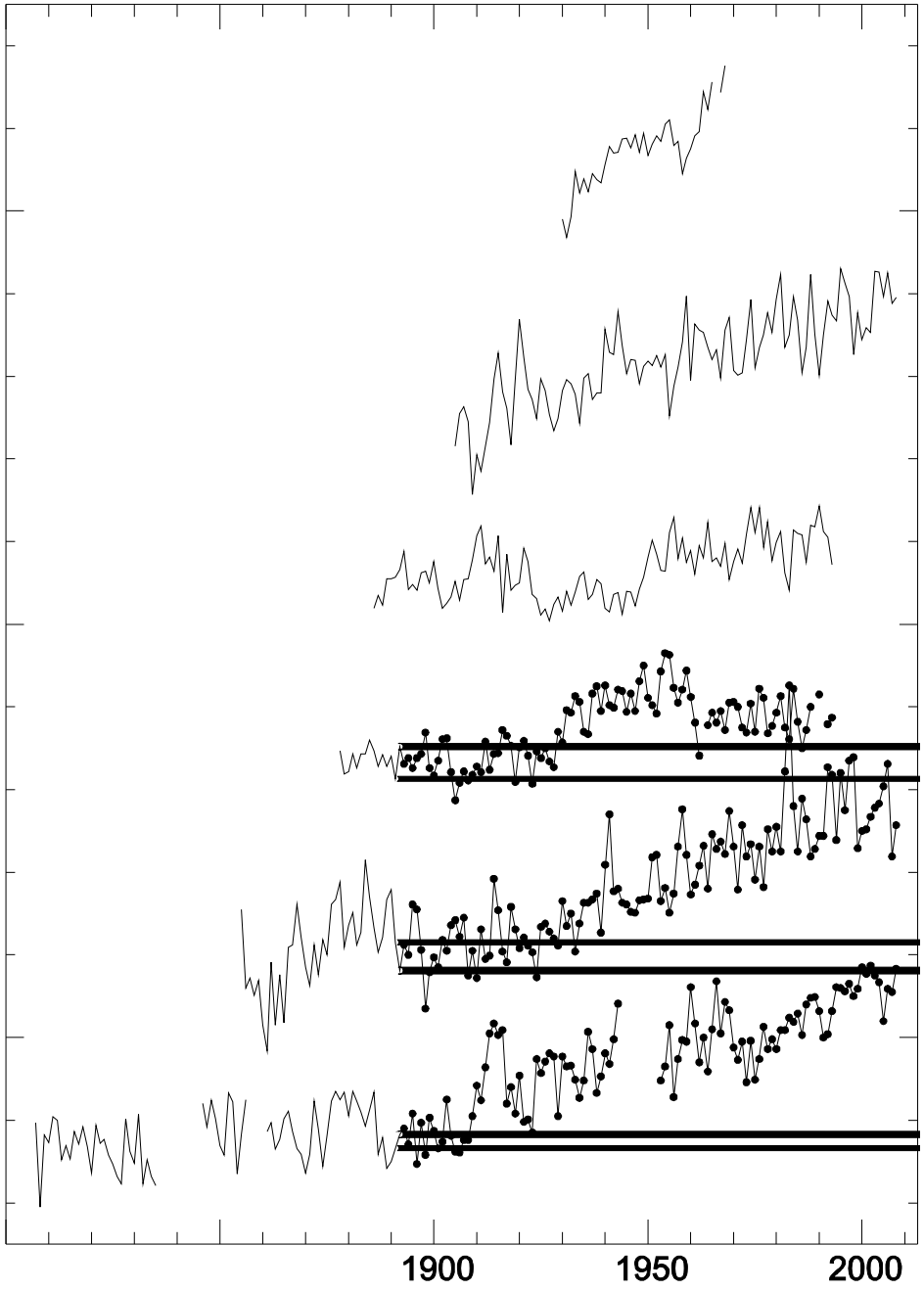
Training & Information:

A wide variety of FAQs, training and software documentation, information on non-oceanographic signals in tide gauge records (e.g., glacial isostatic adjustment, atmospheric pressure, etc.)

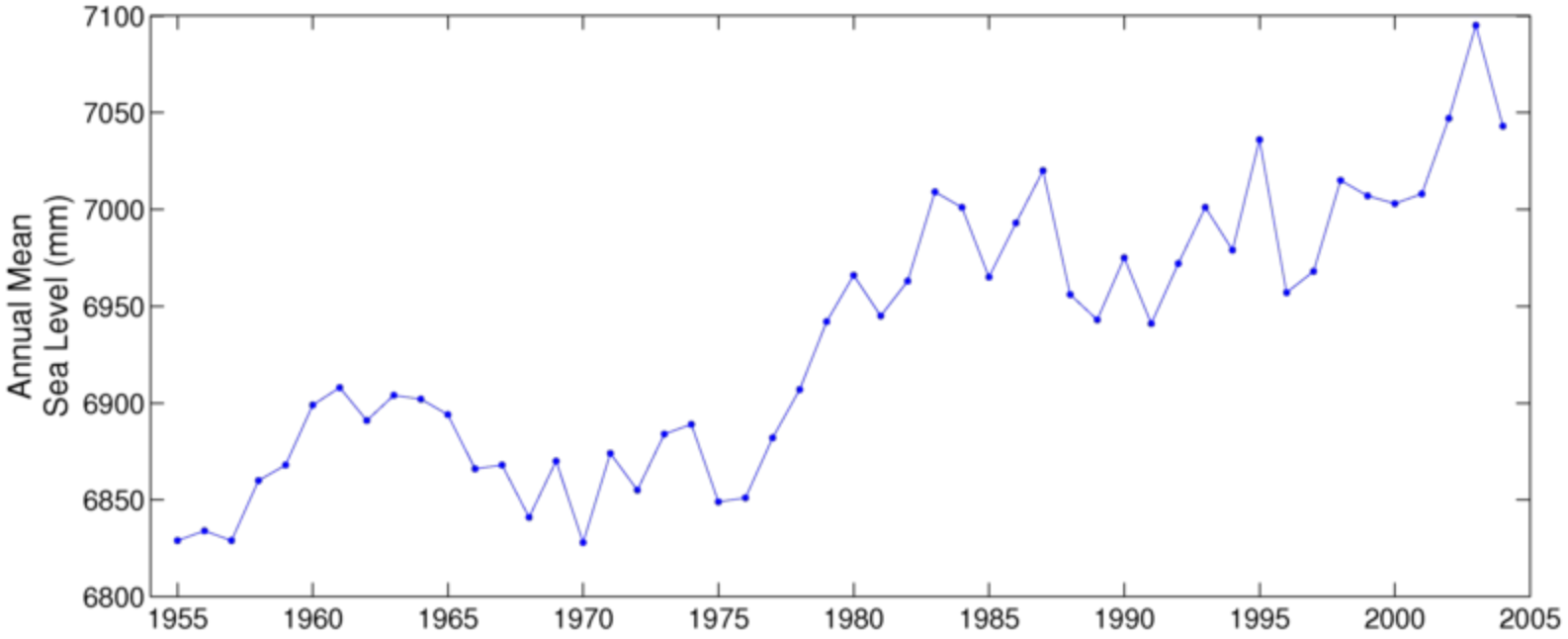
Links:

Links to other networks and programs, as well as international sea level contacts

www.psmsl.org



Long sea level records from the PSMSL



Cananeia Mean Sea Level Change (data from PSMSL)

Chapter 66

New analysis of a 50 years tide gauge record at Cananéia (SP-Brazil) with the VAV tidal analysis program

B. Ducarme
Chercheur Qualifié FNRS, Observatoire Royal de Belgique, Av. Circulaire 3, B-1180, Bruxelles, Belgique.

A.P. Venedikov
Geophysical Institute & Central Laboratory on Geodesy, Acad. G. Bonchev Str., Block 3, Sofia 1113

A.R. de Mesquita, C.A. de Sampaio França
Instituto Oceanográfico da Universidade de São Paulo, SP, Brasil.

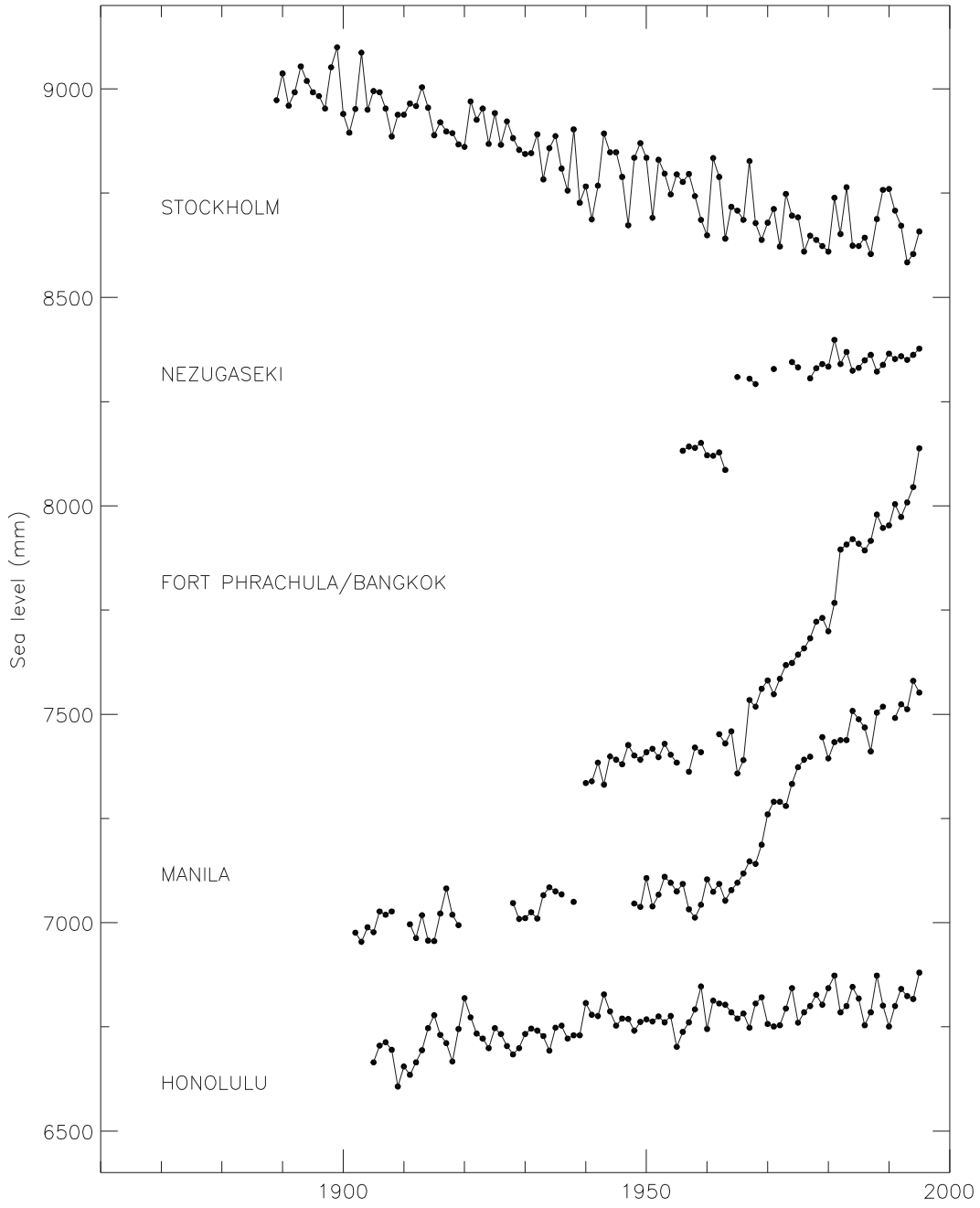
GIA/PGR

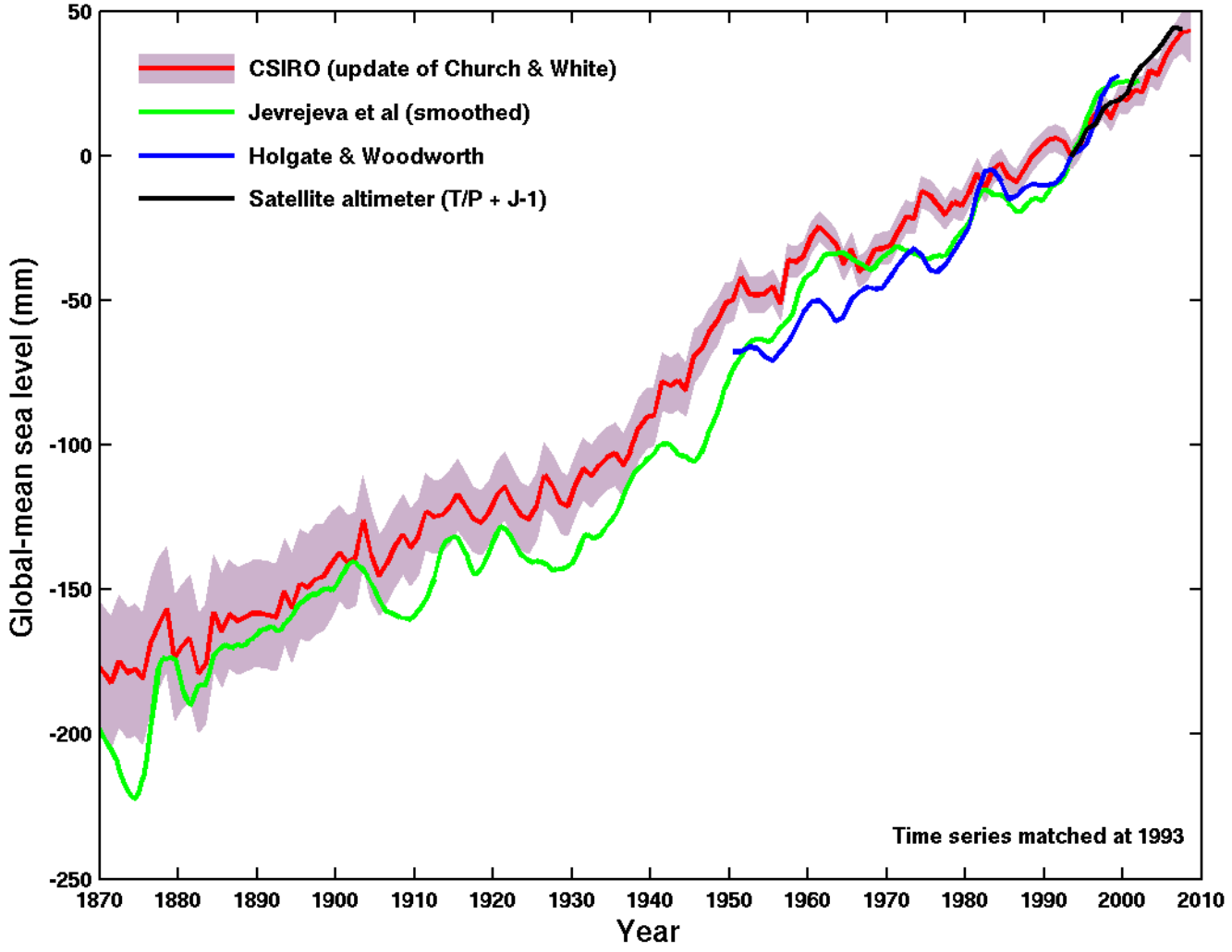
Earthquake

Ground-water pumping

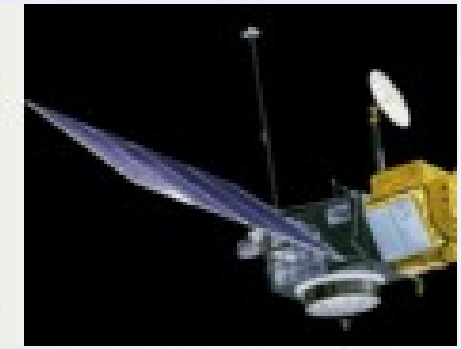
Harbour development/
Sedimentation

For comparison:
Hot spot (normal?)





‘Global’ Sea Curves from Different Authors
All analyses use the PSMSL data set



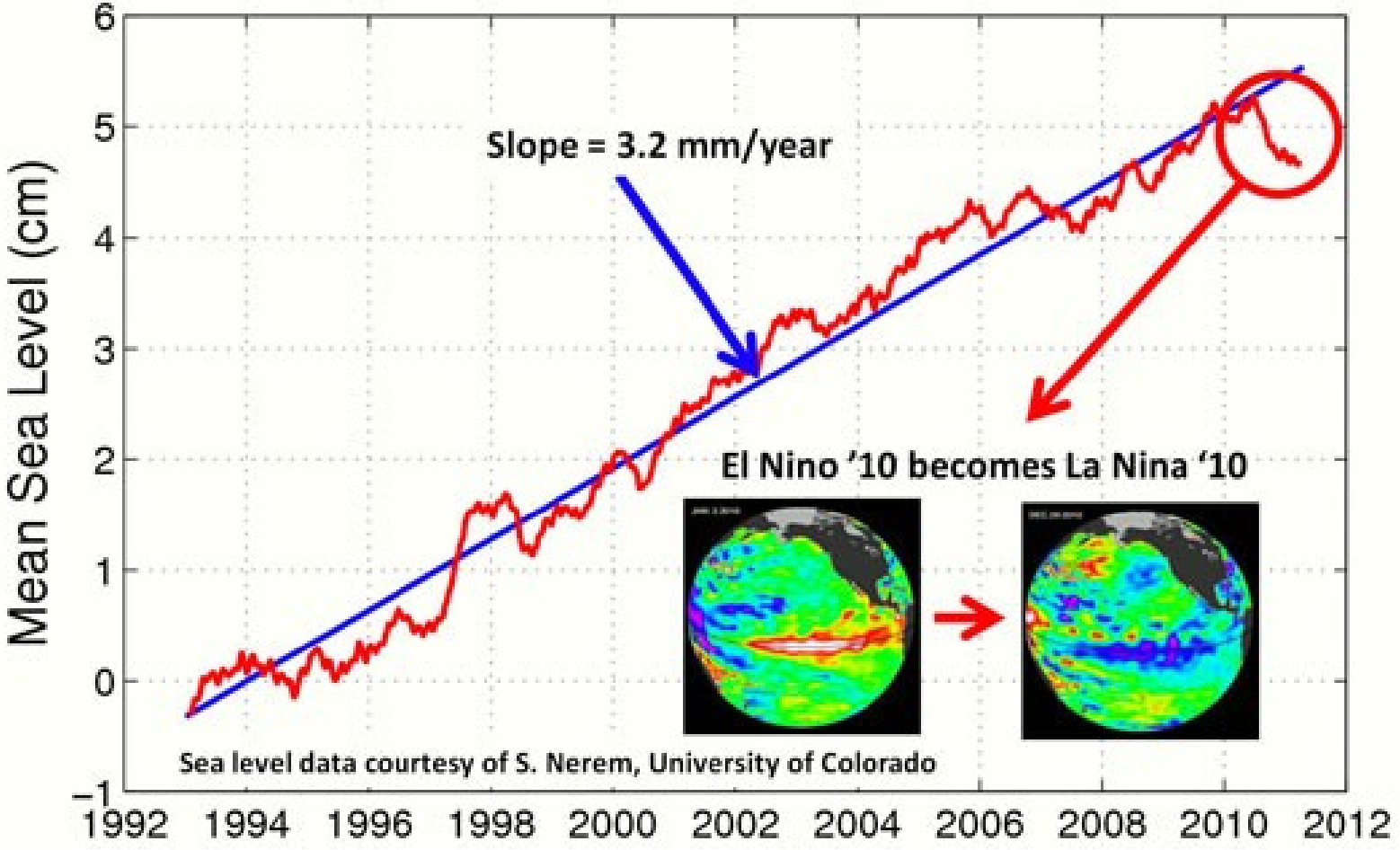
TOPEX/POSEIDON
(1992)

Jason-1
(2001)

OSTM/Jason-2
(2008)

Jason-3
(2013?)

Global Sea Level Drops 6 mm in 2010

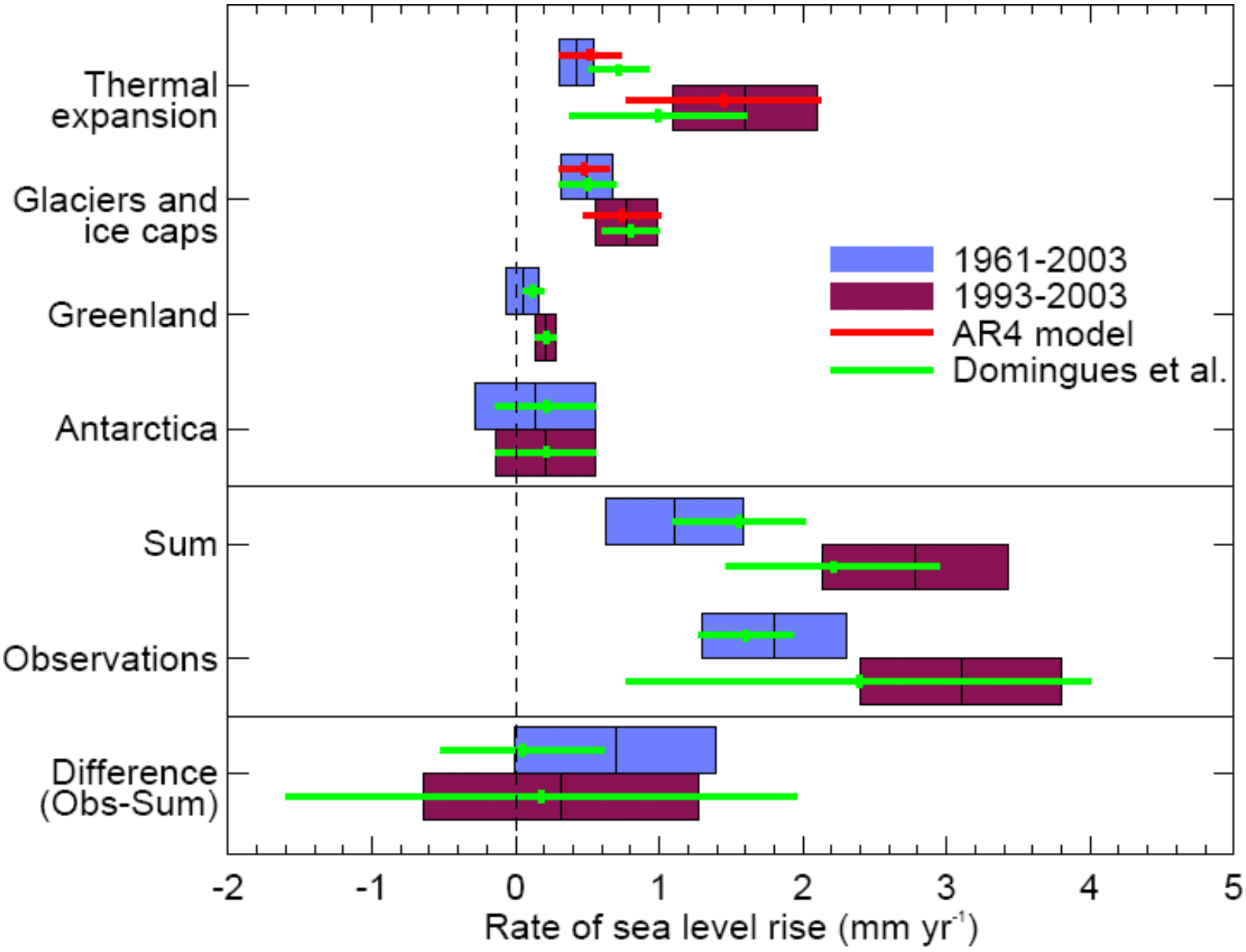


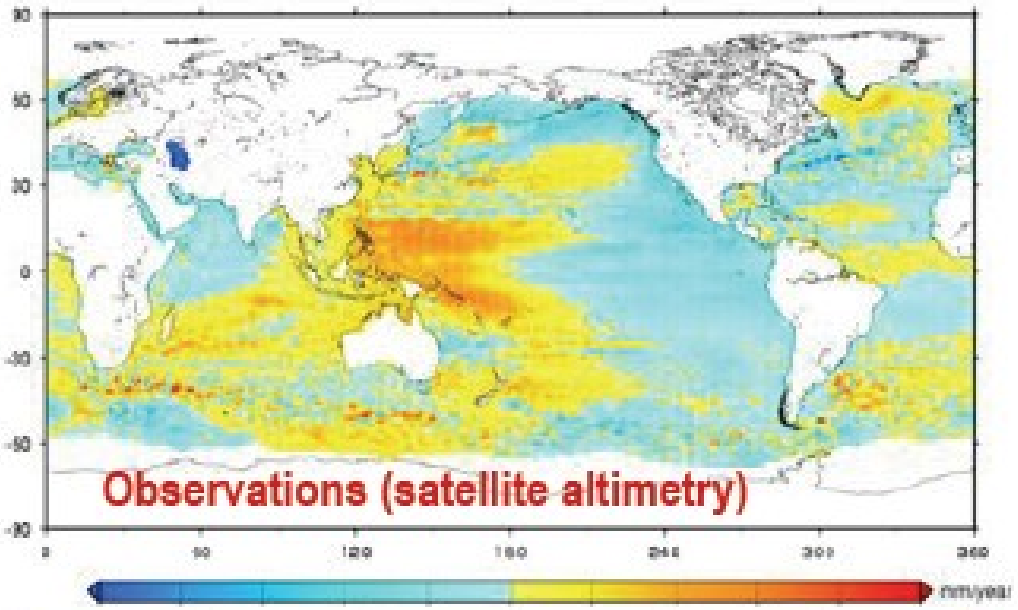
Do We Understand Sea Level Change in the 20th century?

Updates since the IPCC AR4

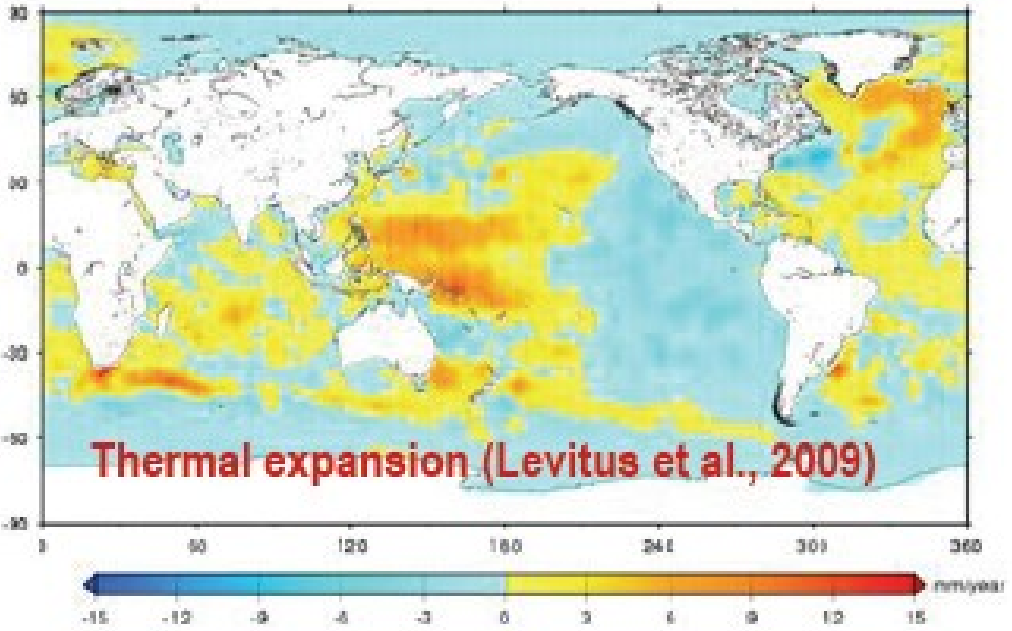
- Anny Cazenave, Oceanobs'09, (www.oceanobs09.net)
- Catia Domingues et al, 2008, Nature
- John Church et al, 2010, Wiley-Blackwell book
- Church et al, 2011, Geophysical Res. Lett.

Accounting for observed sea-level rise (IPCC AR4)



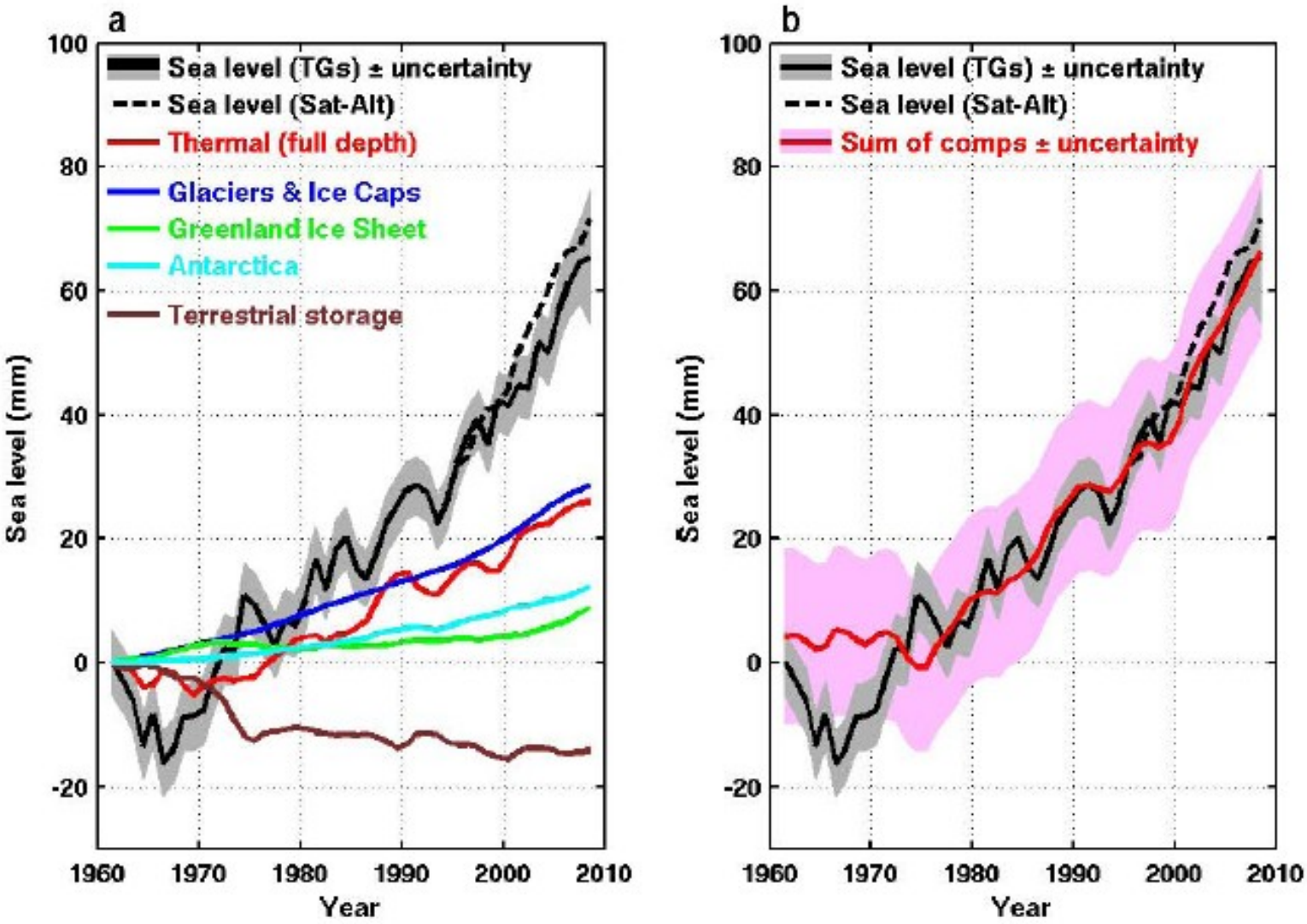


Spatial variations in sea level rise from satellite altimetry 1992-2008



Thermal expansion over the same period from ocean instruments

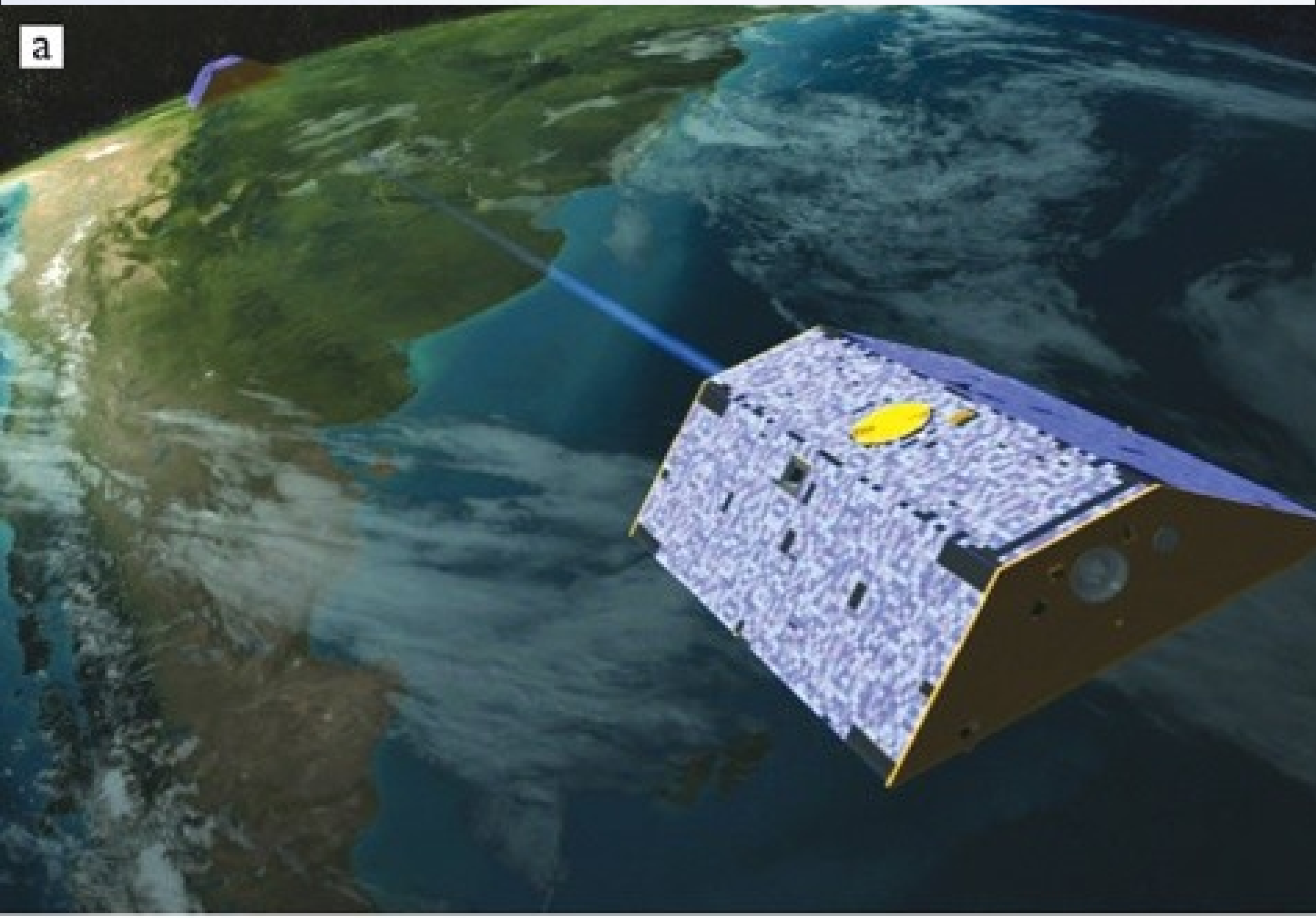
Rhone Glacier 1900 and 2008

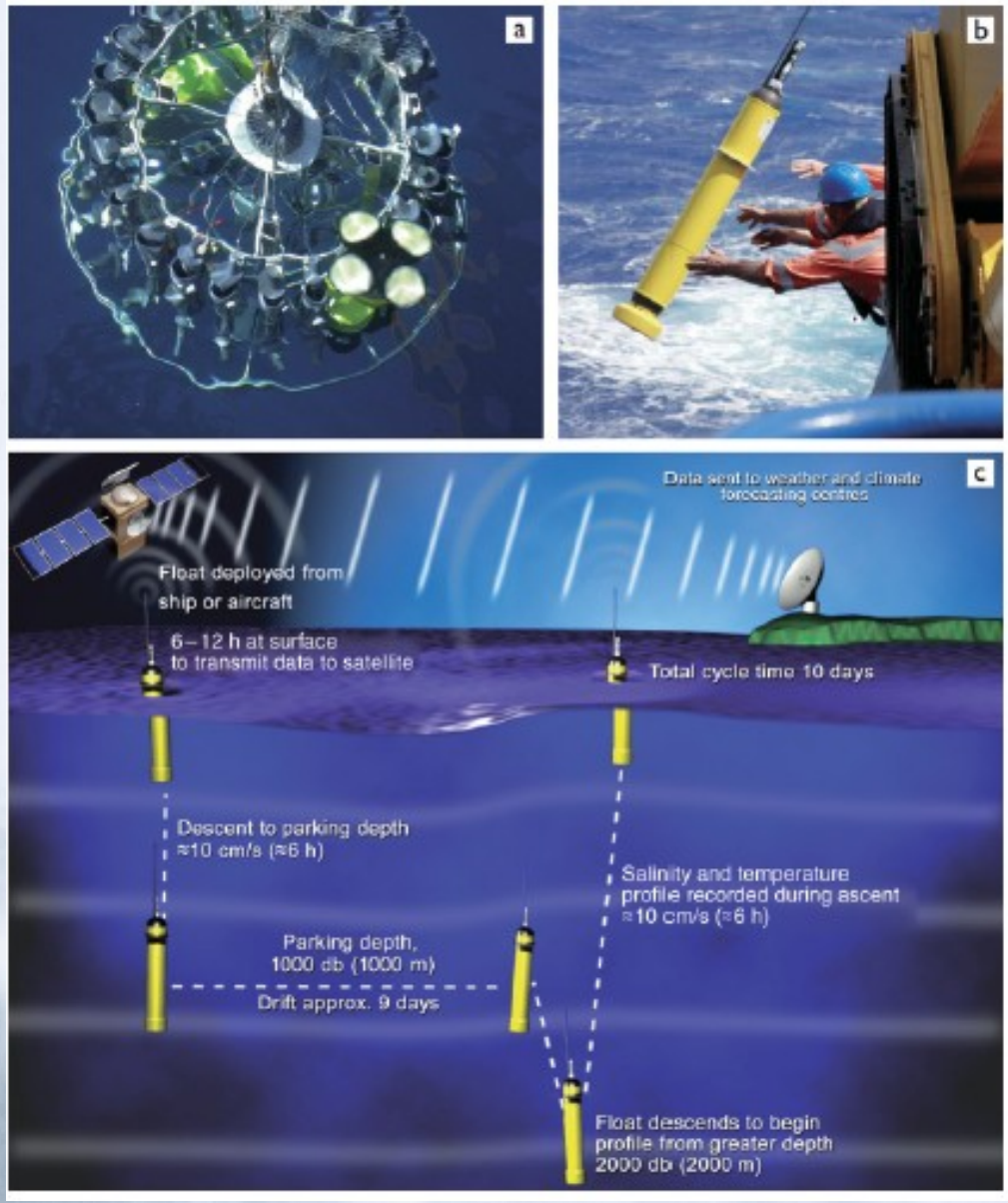


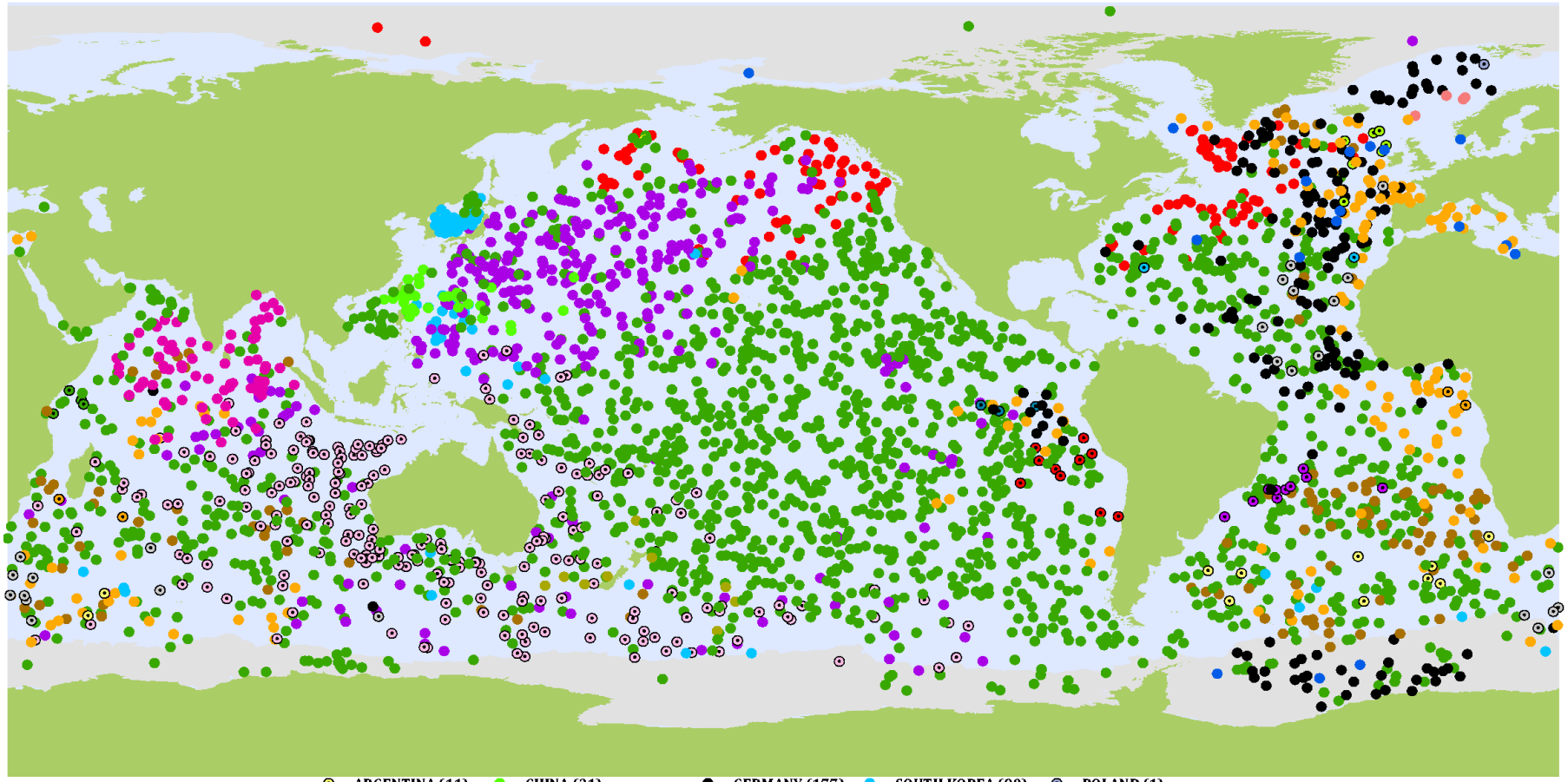
Church et al. 2011 (Geophysical Research Letters)

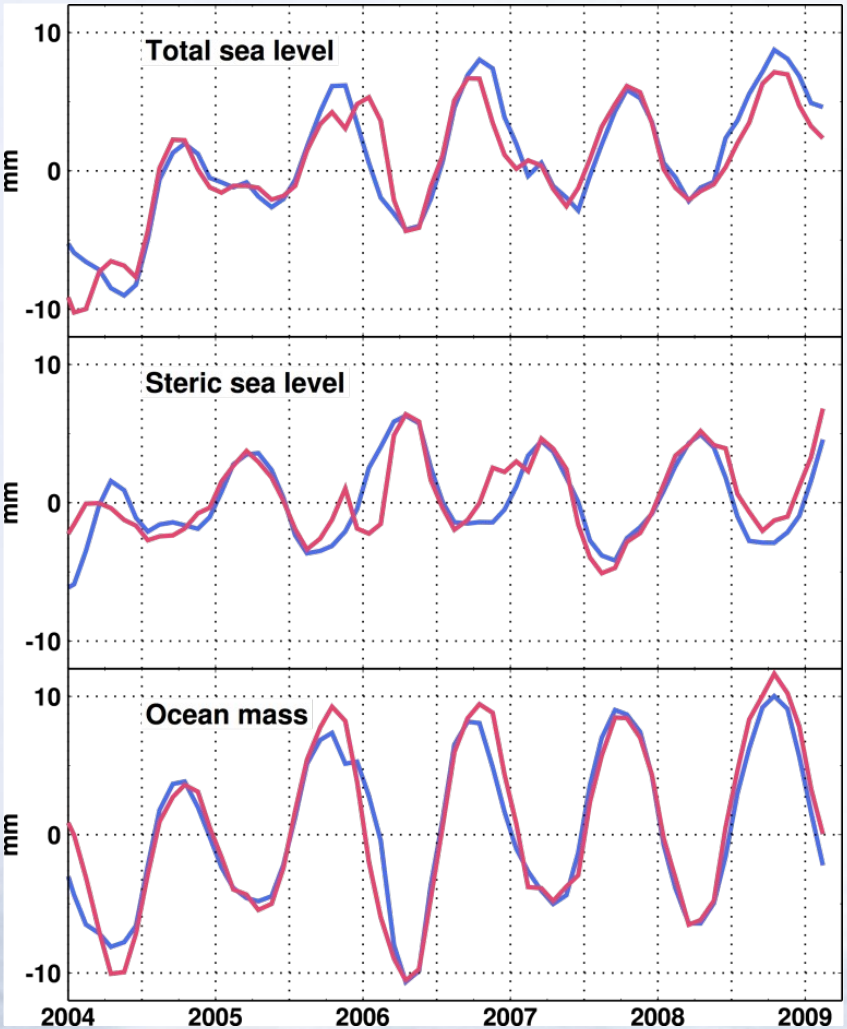
Do We Understand Sea Level Change in the well-instrumented recent years?

- Continuous satellite altimetry
- Continuous space gravity from GRACE
- Continuous monitoring of ocean temperatures and salinities with ARGO


a


a
b
c
Data sent to weather and climate forecasting centres
Float deployed from ship or aircraft
6–12 h at surface to transmit data to satellite
Total cycle time 10 days
Descent to parking depth ≈10 cm/s (≈6 h)
Salinity and temperature profile recorded during ascent ≈10 cm/s (≈6 h)
Parking depth, 1000 db (1000 m)
Drift approx. 9 days
Float descends to begin profile from greater depth 2000 db (2000 m)


3261 Argo Floats
ARGENTINA (11)
AUSTRALIA (224)
BRAZIL (10)
CANADA (118)
CHILE (10)
CHINA (31)
ECUADOR (3)
EUROPEAN UNION (17)
FRANCE (156)
GABON (2)
GERMANY (177)
INDIA (72)
IRELAND (7)
JAPAN (320)
KENYA (4)
SOUTH KOREA (90)
MAURITIUS (2)
NETHERLANDS (25)
NEW ZEALAND (9)
NORWAY (4)
POLAND (1)
RUSSIAN FEDERATION (2)
SPAIN (2)
UNITED KINGDOM (115)
UNITED STATES (1849)
September 2009
jcommops



Total sea level
TOPEX/Poseidon/Jason

Steric sea level
Argo

Ocean mass change
GRACE

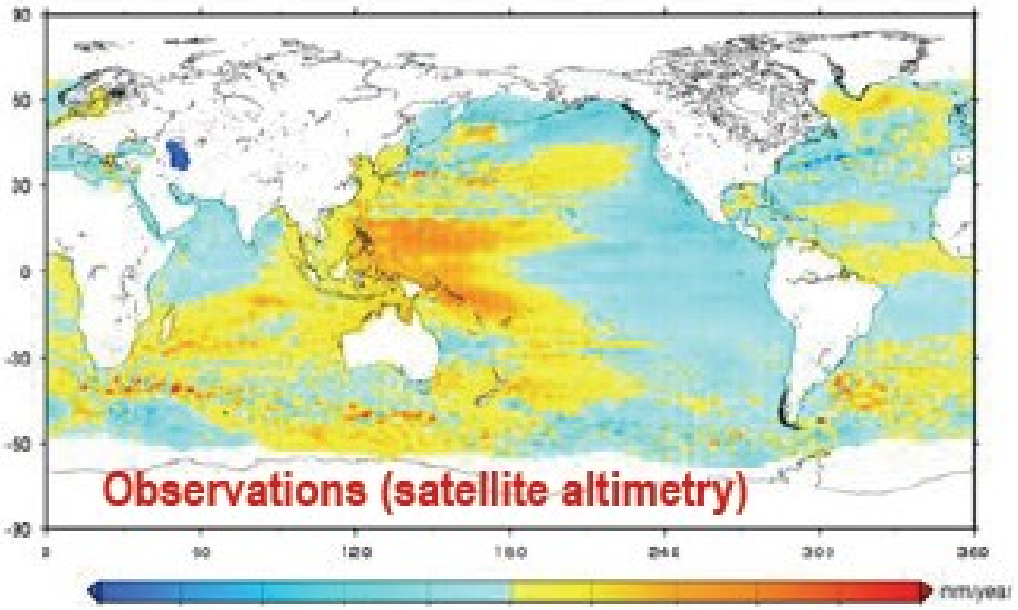
Leuliette and Miller, 2010

Blue = observed values. Red = inferred values from the other two.

Importance of Spatial Variations

- In the ocean - constantly readjusting to changes in heat and salt on many timescales
- In the geosphere - readjusting to changing loads on the solid earth

Understanding spatial variations is important for people studying impacts of sea level changes on regional basis



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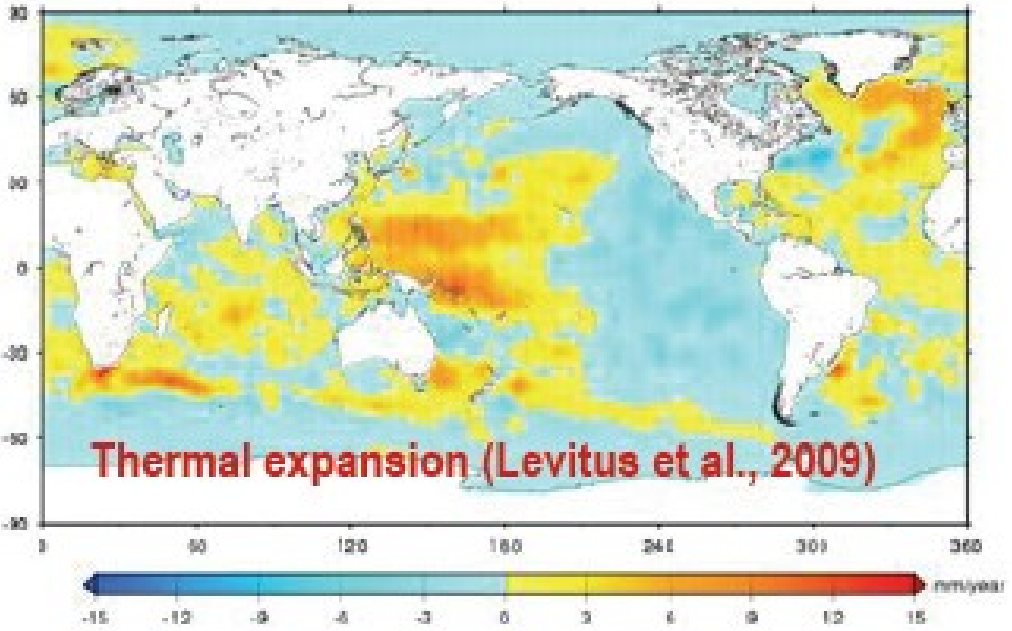

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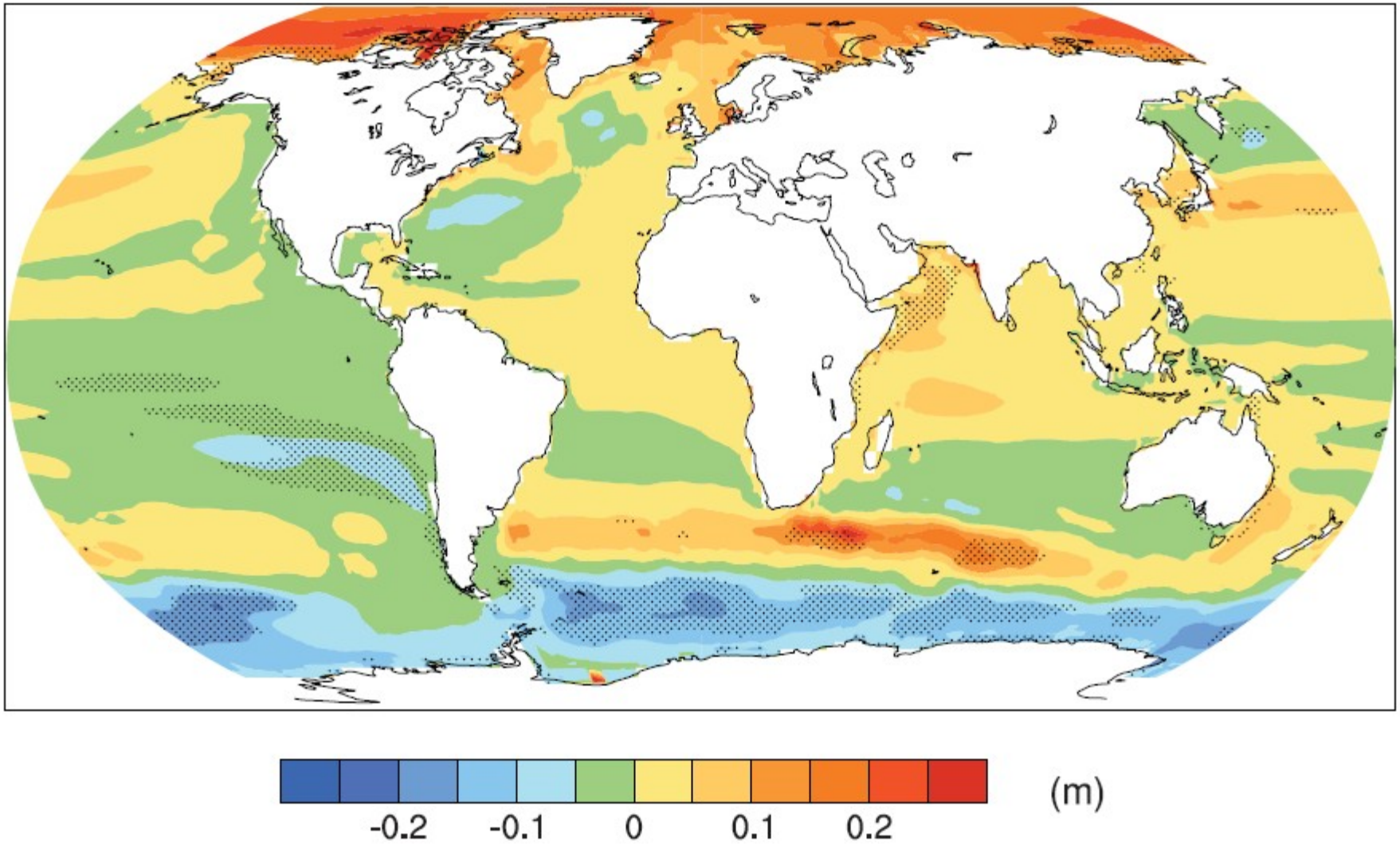


2100 Steric Sea Level Change from Climate Models (IPCC AR4)

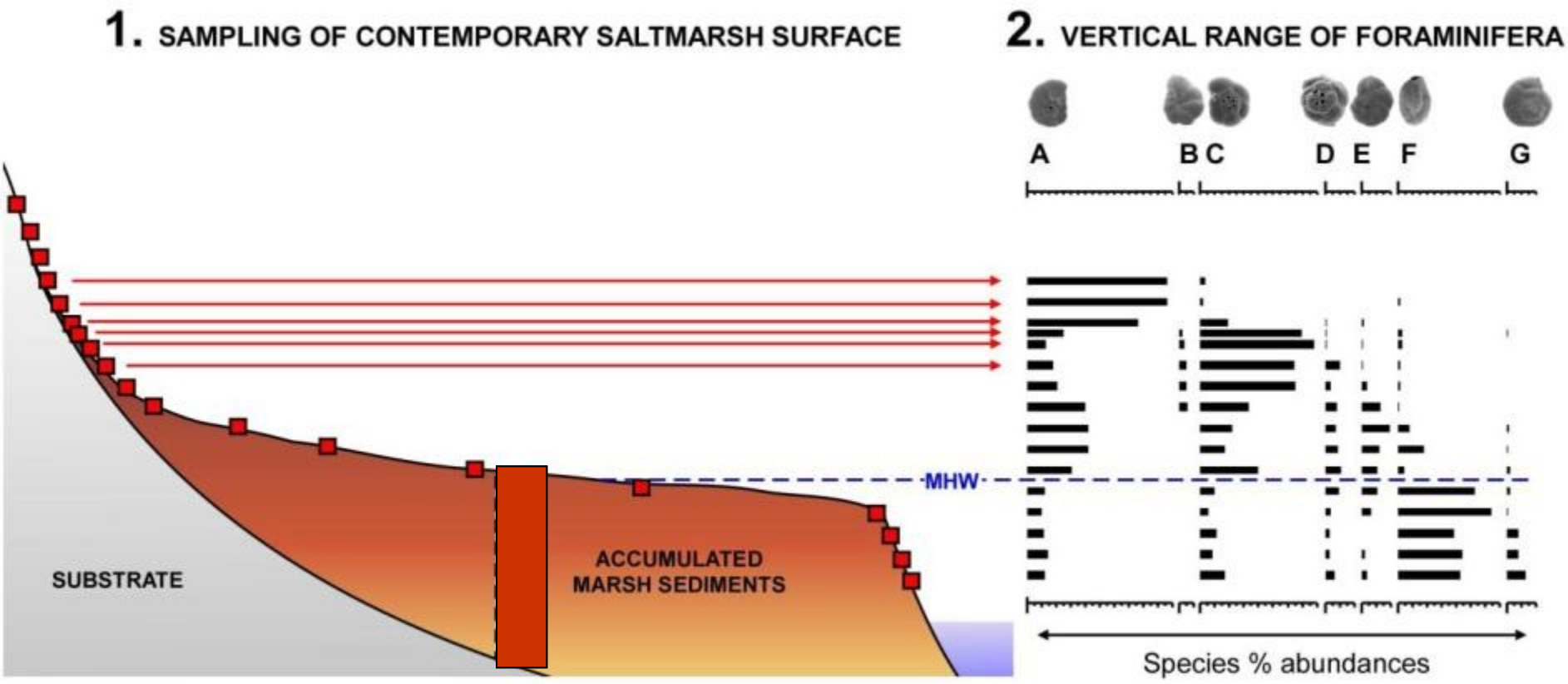
How to Improve the Data Set?

- Tide gauge “data archaeology”
- Development of new methods e.g. saltmarsh data

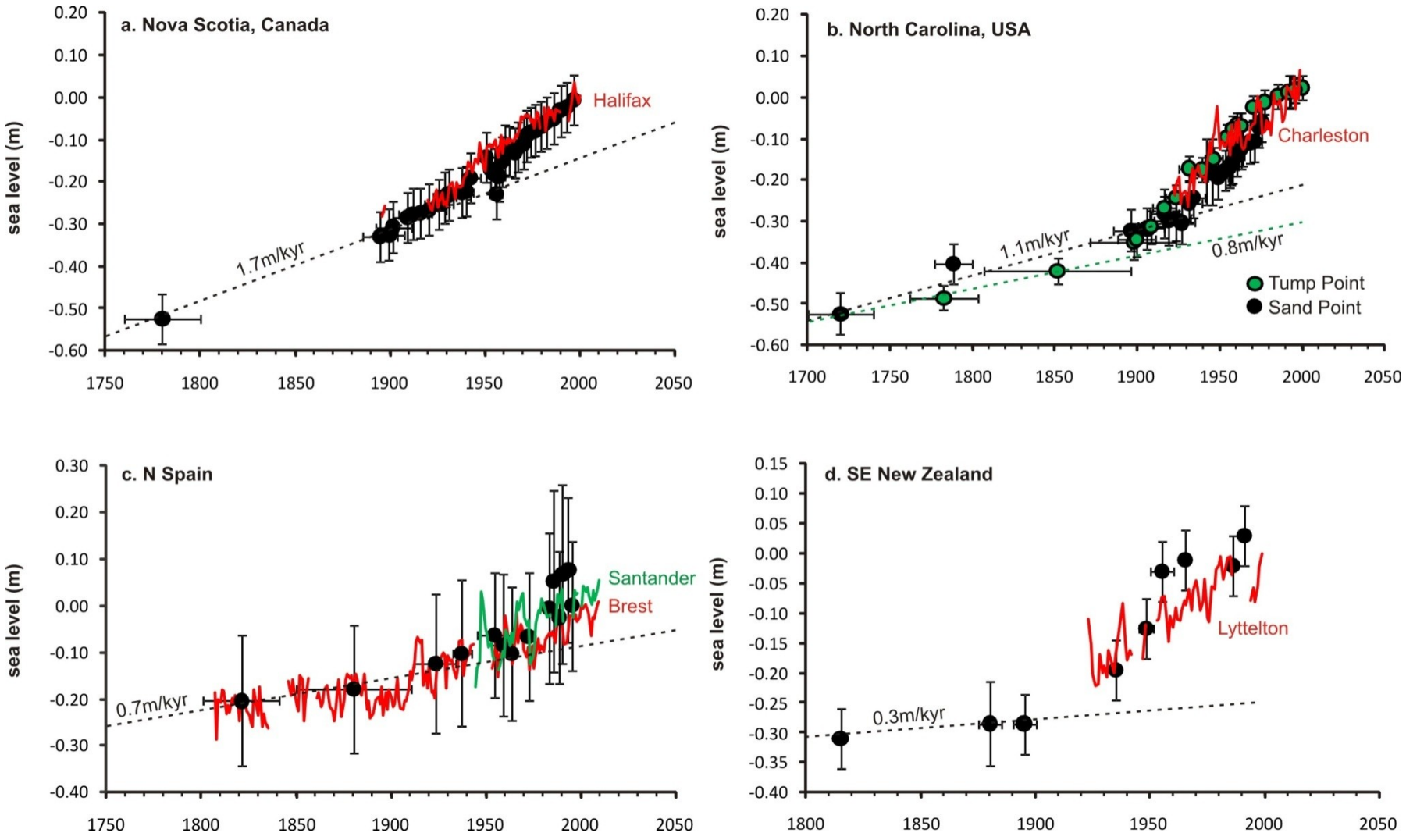
10
20
30
40

Salt-marsh foraminifera: modern distribution

From Roland Gehrels



A '***transfer function***' quantifies the relationship between foram assemblages and
elevation to reconstruct in cores the elevation at which fossil forams lived


a. Nova Scotia, Canada
sea level (m)
Halifax
1.7m/kyr
b. North Carolina, USA
Charleston
1.1m/kyr
0.8m/kyr
Tump Point
Sand Point
c. N Spain
Santander
Brest
0.7m/kyr
d. SE New Zealand
Lyttelton
0.3m/kyr

Does Extreme Sea Level Rise follow MSL Rise?

- **Changes in extremes are less studied than those in MSL but they are of greater practical importance**

- **Data sets of extremes are more difficult to access and analyse than those of MSL**

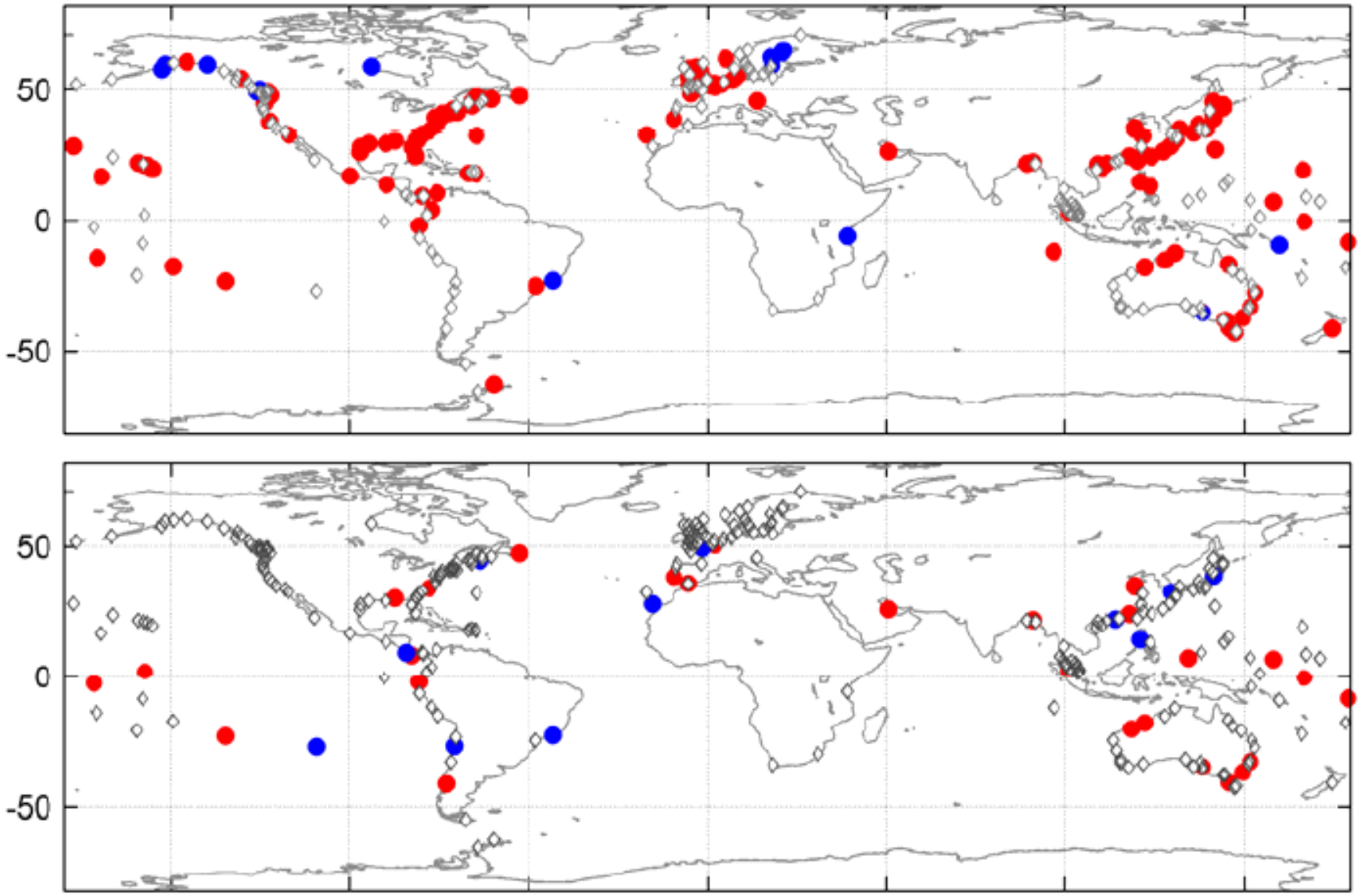

North Norfolk 1953

Galveston 2008 during Hurricane Ike

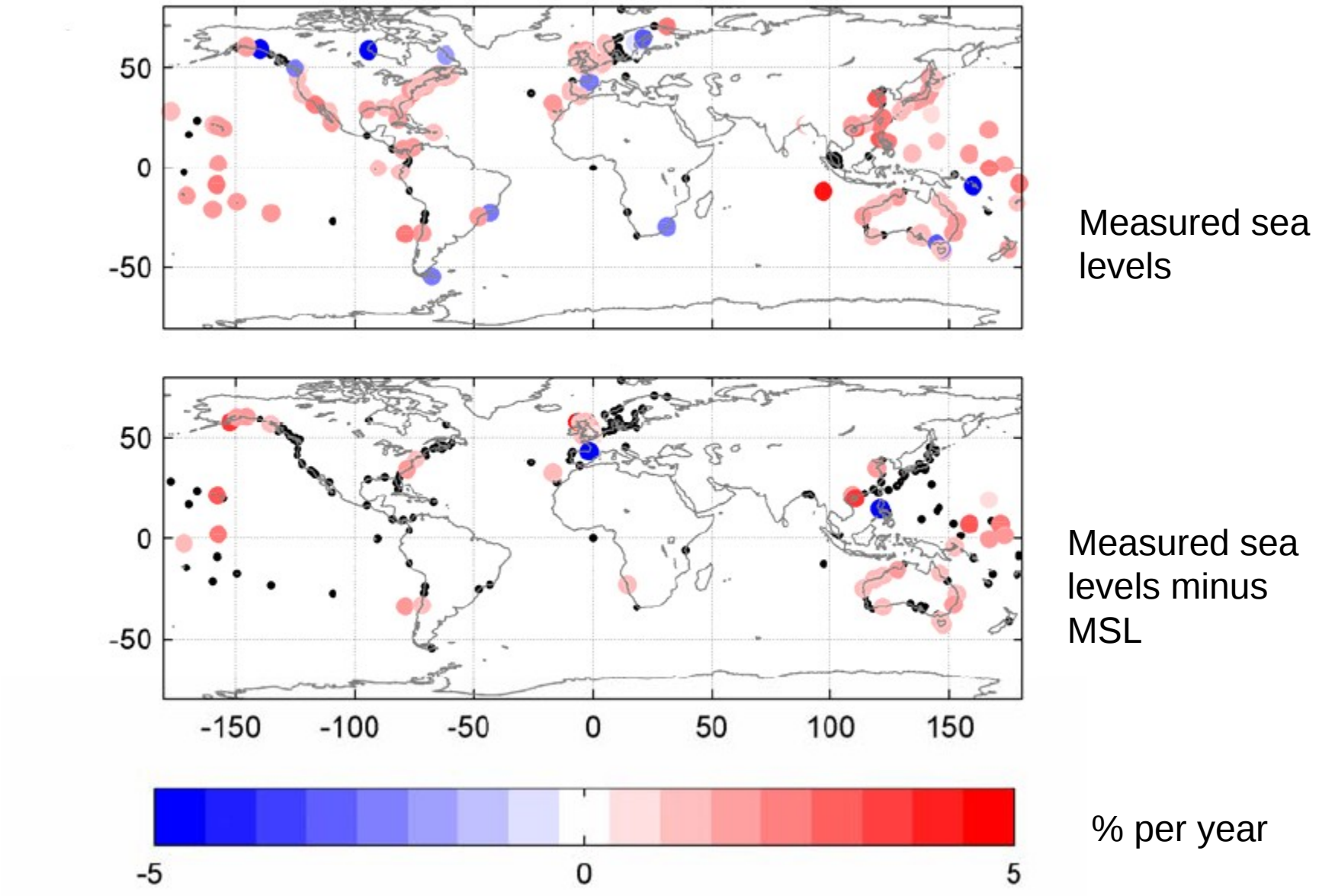
Bangladesh May 2009 after cyclone Aila

Extreme Sea Levels - Questions

- How have the frequency and magnitude of extreme sea levels changed, other than might have been expected from MSL change?
- How might extremes change in the future, aside from that expected from MSL change?



Statistically significant trends in annual 99 percentile observed sea levels and sea levels reduced to their annual medians



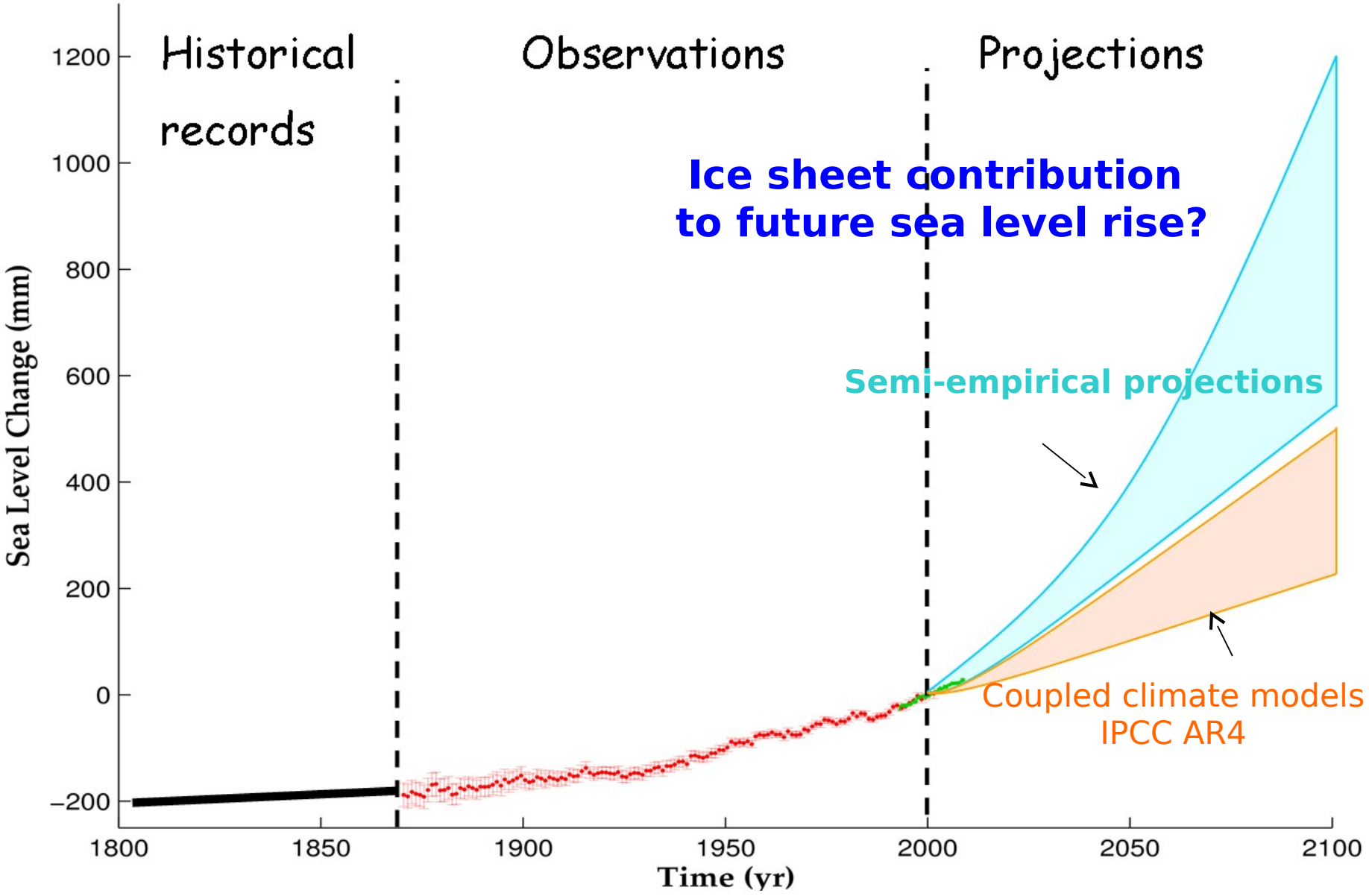
Changes in the frequency of extreme events (Menendez and Woodworth, 2010)

Extreme Sea Levels - Questions

- No convincing evidence for extremes rising faster than MSL
- No evidence for large scale change in the frequency of extreme events when adjusted for MSL

Why is this conclusion so important?

Global mean sea level evolution since 1800



Thames Barrier, London

Maeslantkering Barrier, Rotterdam

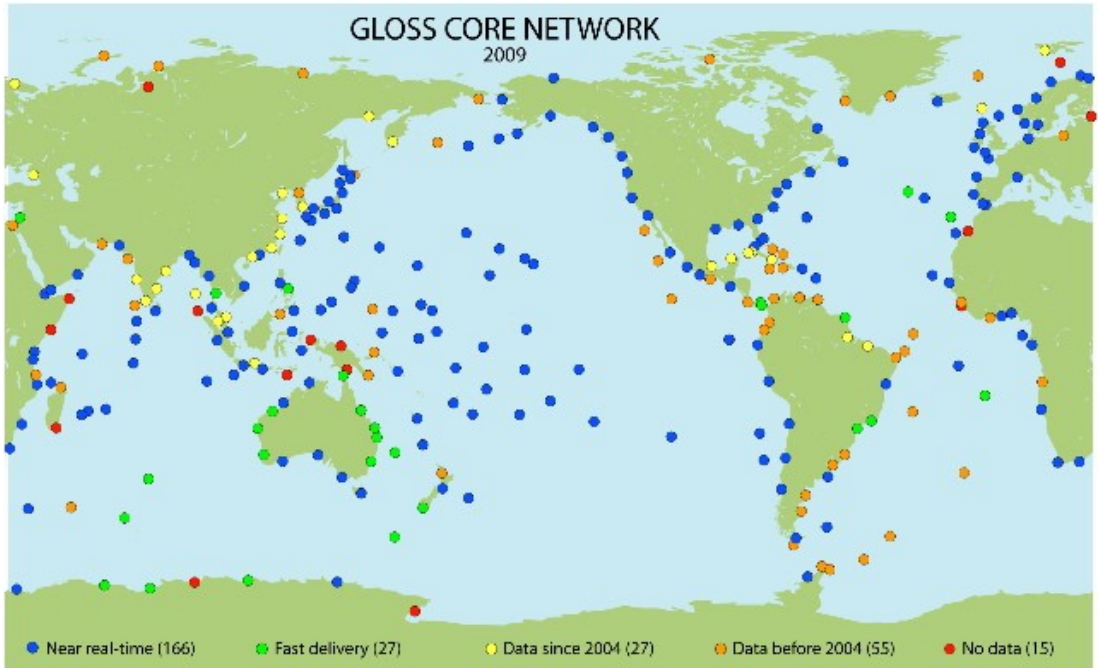
Why is the above so important?

- MSL projection is uncertain enough
- No convincing evidence for extremes levels or frequencies changing faster than one might expect from MSL
- So hopefully engineers may not have to factor in even larger uncertainties when designing coastal infrastructure

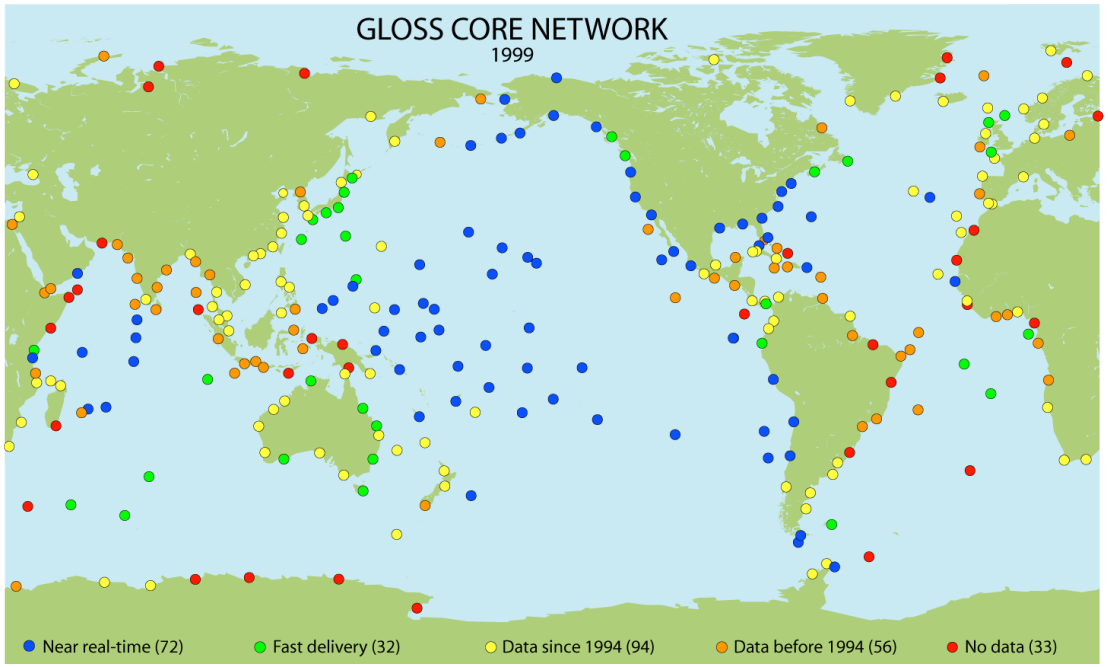
Tremendous recent improvements in the global tide gauge and GPS networks.

This will eventually help us to understand changes in mean and extreme sea levels better.

But there is a lot more to do in some regions e.g. in South America.

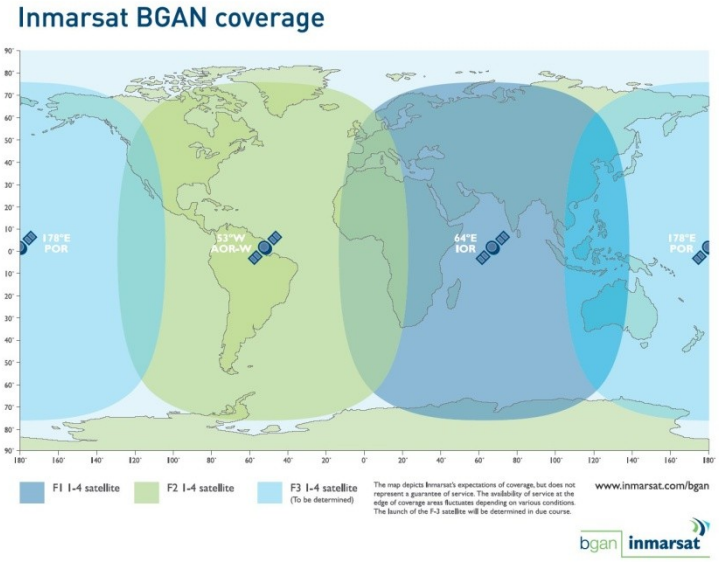

GLOSS CORE NETWORK
2009
Near real-time (166)
Fast delivery (27)
Data since 2004 (27)
Data before 2004 (55)
No data (15)

2009


GLOSS CORE NETWORK
1999
Near real-time (72)
Fast delivery (32)
Data since 1994 (94)
Data before 1994 (56)
No data (33)

1999

BGAN-enabled Tide Gauges



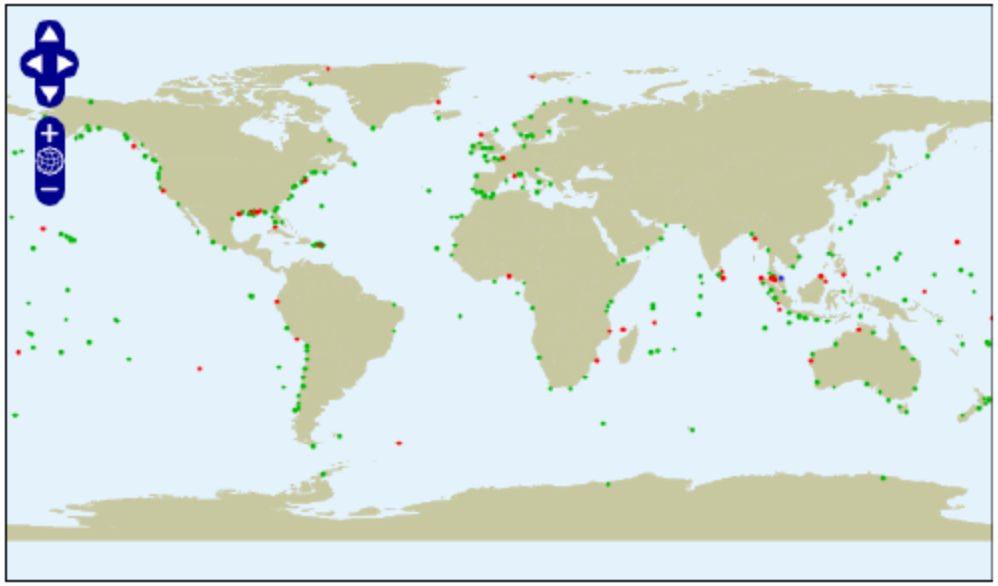
SEA LEVEL STATION MONITORING FACILITY

IOC

Intro | Map | Stations | Database | Metadata

Sealevel stations

Status at 2009-09-07 10:39 GMT



Lat: 16.8 Lon:-109.8

Type: All stations

Legend:

- Station is offline, or data is outdated
- Station is online
- Station is not available at this site

Offline = No data received since 3 times the transmit interval.

The status is checked every 5 minutes.

The quality of the transmitted data is not checked.

- To obtain more details about a station - move mouse over station and click.
- To zoom in - hold down the Shift-key while holding down the mouse button and drawing a rectangle or use the Scroll mouse button, or use the control buttons in upper left part of map.
- To pan - drag the map, or use the control buttons in upper left part of map.

http://www.ioc-sealevelmonitoring.org

NOC (UK) Sea Level Stations in the South Atlantic, Antarctica and Gibraltar

9 Sea Level Stations

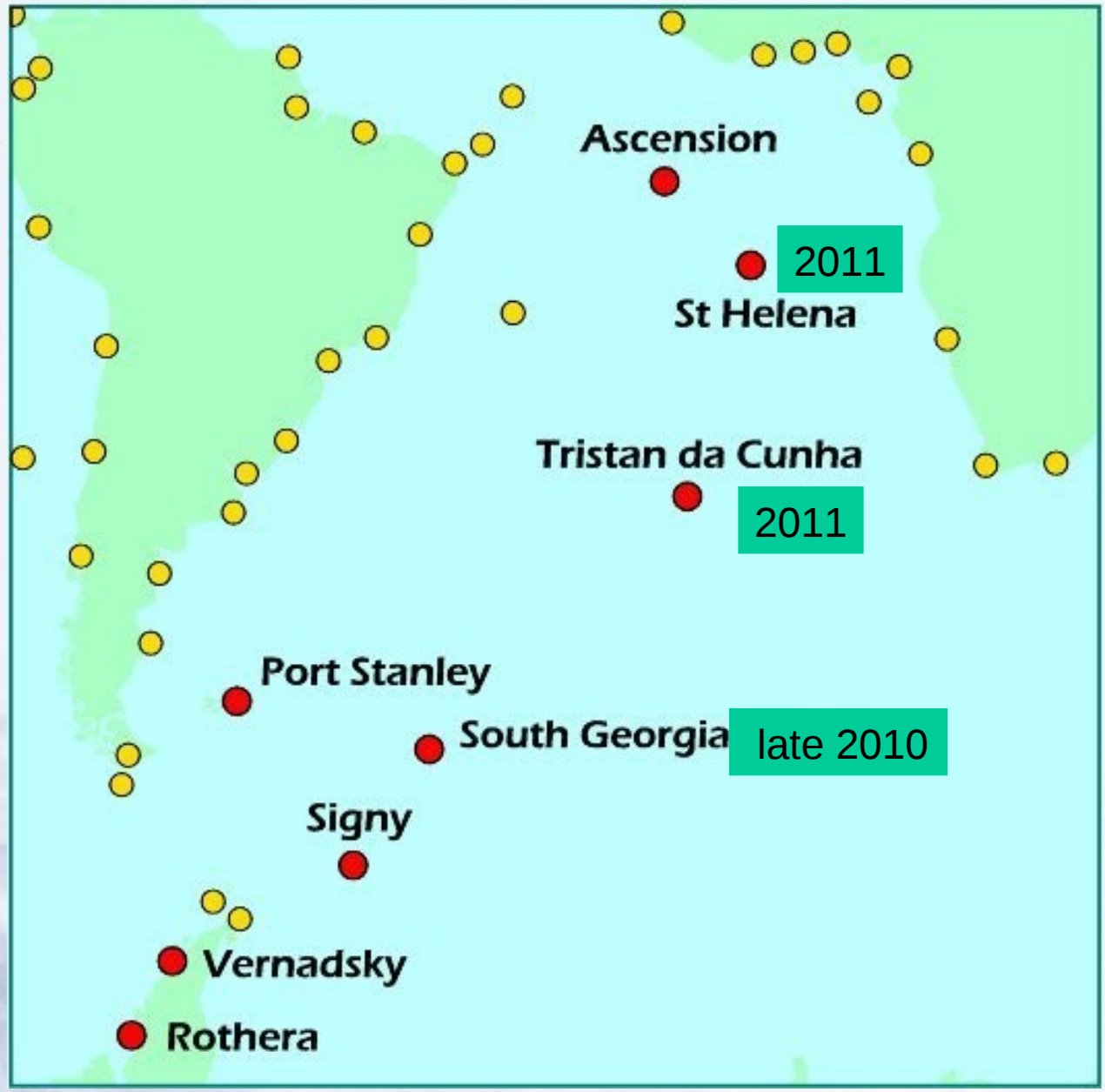
<u>Real time telemetry:</u>

Ascension Island
Saint Helena
Port Stanley
Tristan
Vernadsky (Faraday)
Rothera
Gibraltar

<u>Delayed mode data:</u>

Signy

St.Helena and Tristan recently re-built after storm damage




Ceuta
Melilla
Funchal
Casablanca
Alexandria
Suez
Arrecife
La Gomera
Puerto
de la Luz
Palmeira
Nouakchott
Dakar
Conakry
Djibouti
Hafun
Abidjan
Lagos
Port Sonara
Takoradi
Mogadishu
Sao Tome
Lamu
Pointe Noire
Mombasa
Pointe
La Rue
Zanzibar
Ascension
Mtwara
Agalega
Lobito
Dzaoudzi
Pemba
Nosy Be
St. Helena
Tamatave
Port Louis
In operation
2010
Unknown
Walvis
Bay
Inhambane
Reunion Is.
Fort Dauphin
Durban
Simonstown
Port Elizabeth
Tristan da Cunha
Marion Island
April 2010

NOC (UK) gauge at Alexandria, Egypt

Takoradi, Ghana

Sea Level Changes: Some Conclusions

- We are starting to have a good understanding of what is causing changes in mean and extreme sea levels.
- We are now measuring sea level changes better from tide gauges and using satellites.

- Can these improvements lead to improved predictions of future sea level change?

- I don’t know.

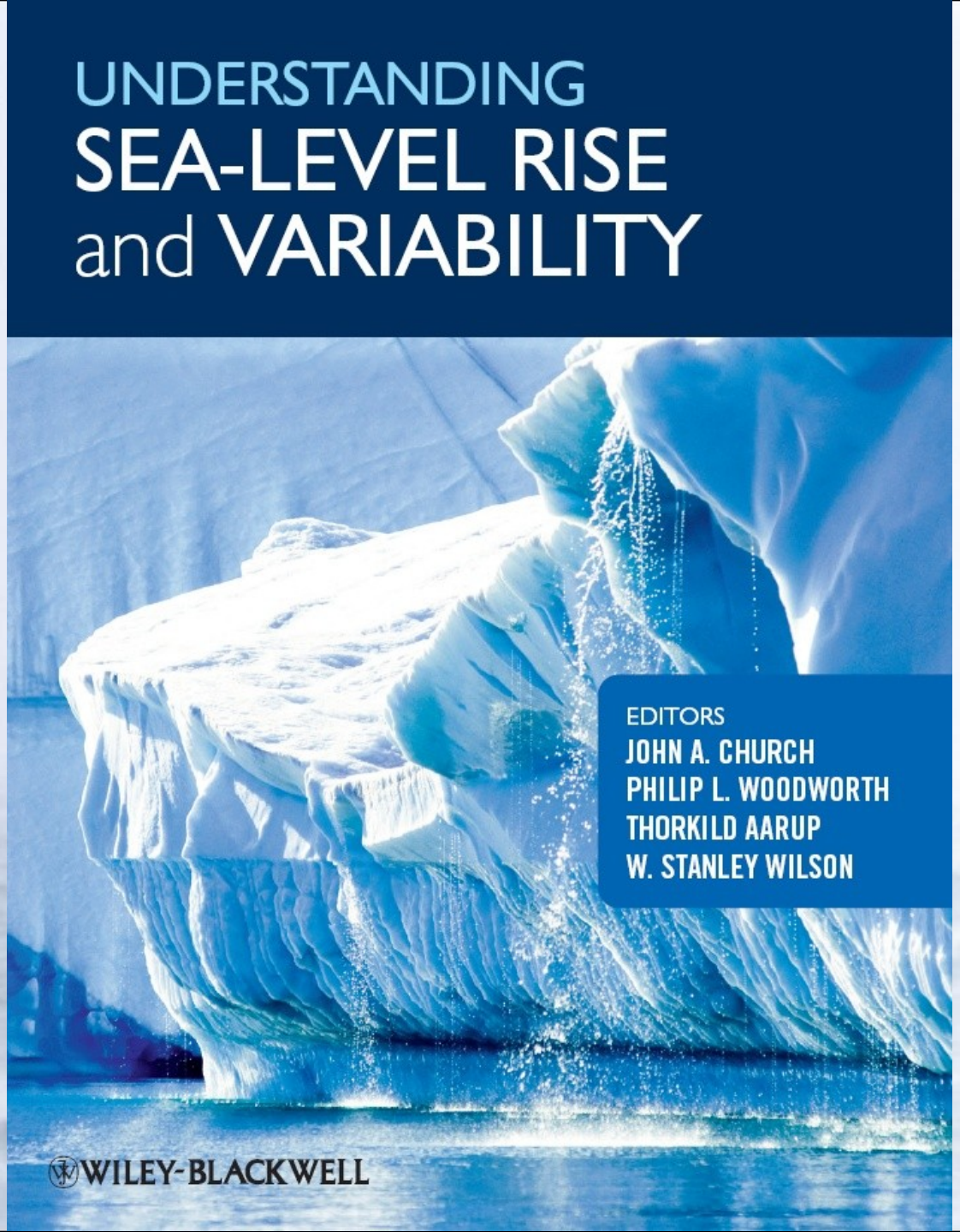
But it is clear that improved understanding will be impossible without:

- continued access to the required good data sets, including tide gauge, GPS, altimeter and space gravity data. (Also monitoring of the deep ocean, cryosphere and hydrosphere.)

- continued programmes of research by excellent scientists.

The Near Future

- The IPCC AR5 is in progress and to be published 2013 – we must engage with that as much as possible
- Much greater emphasis on spatial variations
- Much greater emphasis on extremes



13 chapters of reviews of research in sea level change

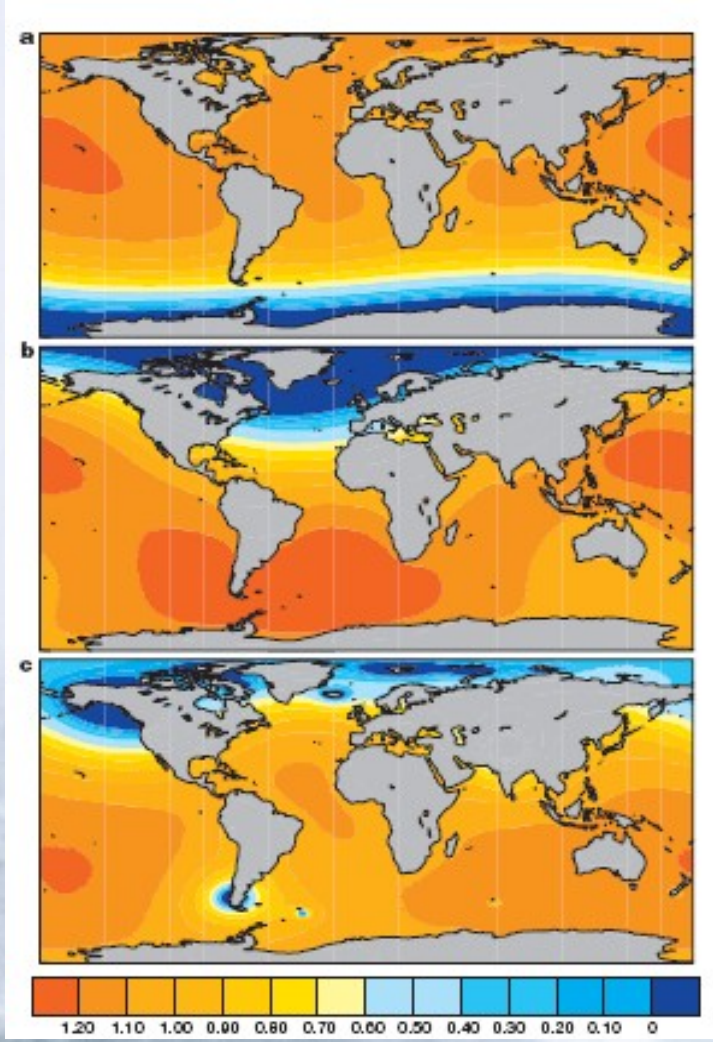
Recommendations for science and monitoring requirements

Thank You For Listening!

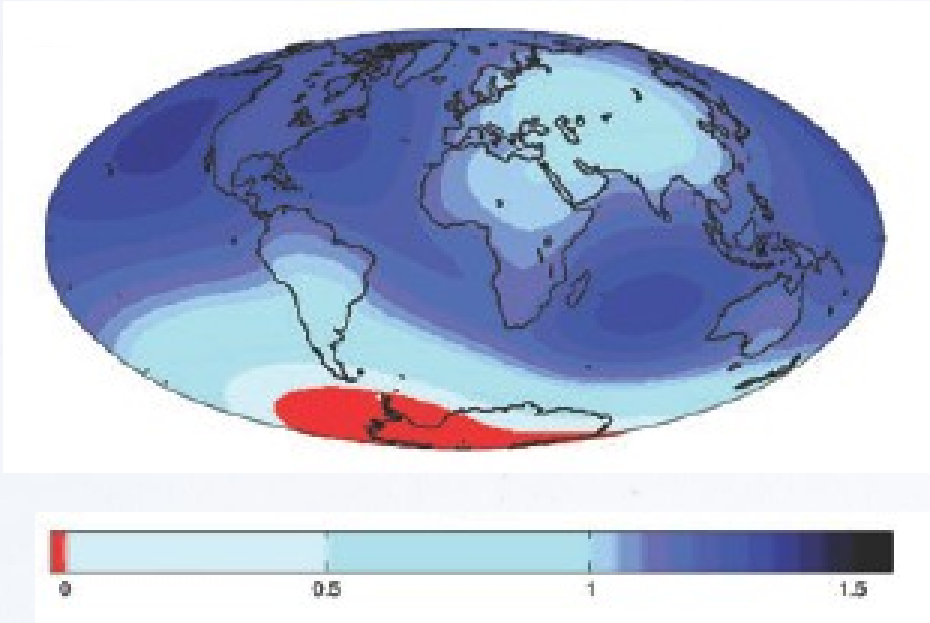
Norfolk Coast England 1998/2007

Gold Coast Australia 1958/2007

Sea Level Fingerprints of Ice Loads



Mitrovica et al., 2001, Nature



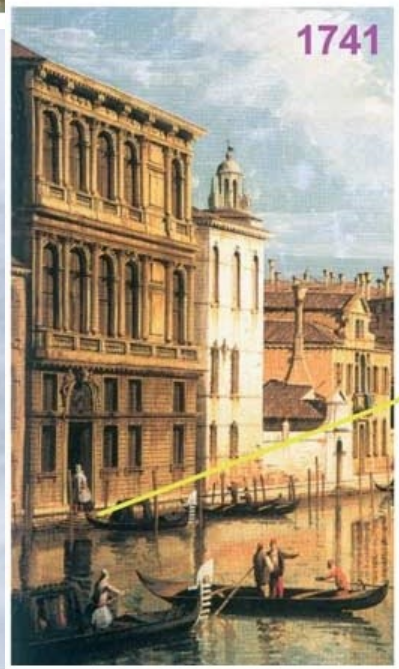
Gomez et al., 2009, GJI

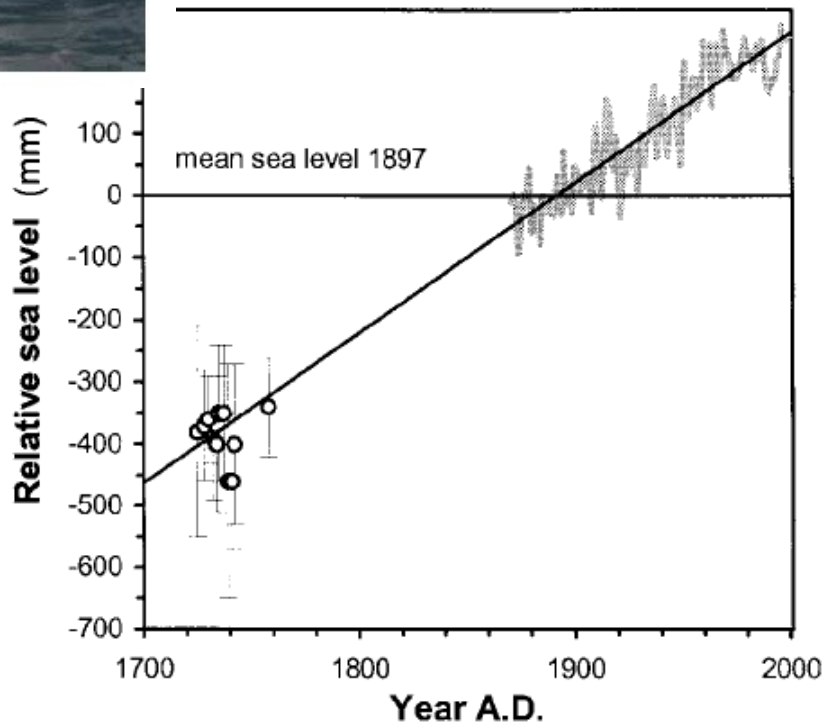
Heritage: Farrell and Clark, 1976, Clark and Lingle 1977 etc.

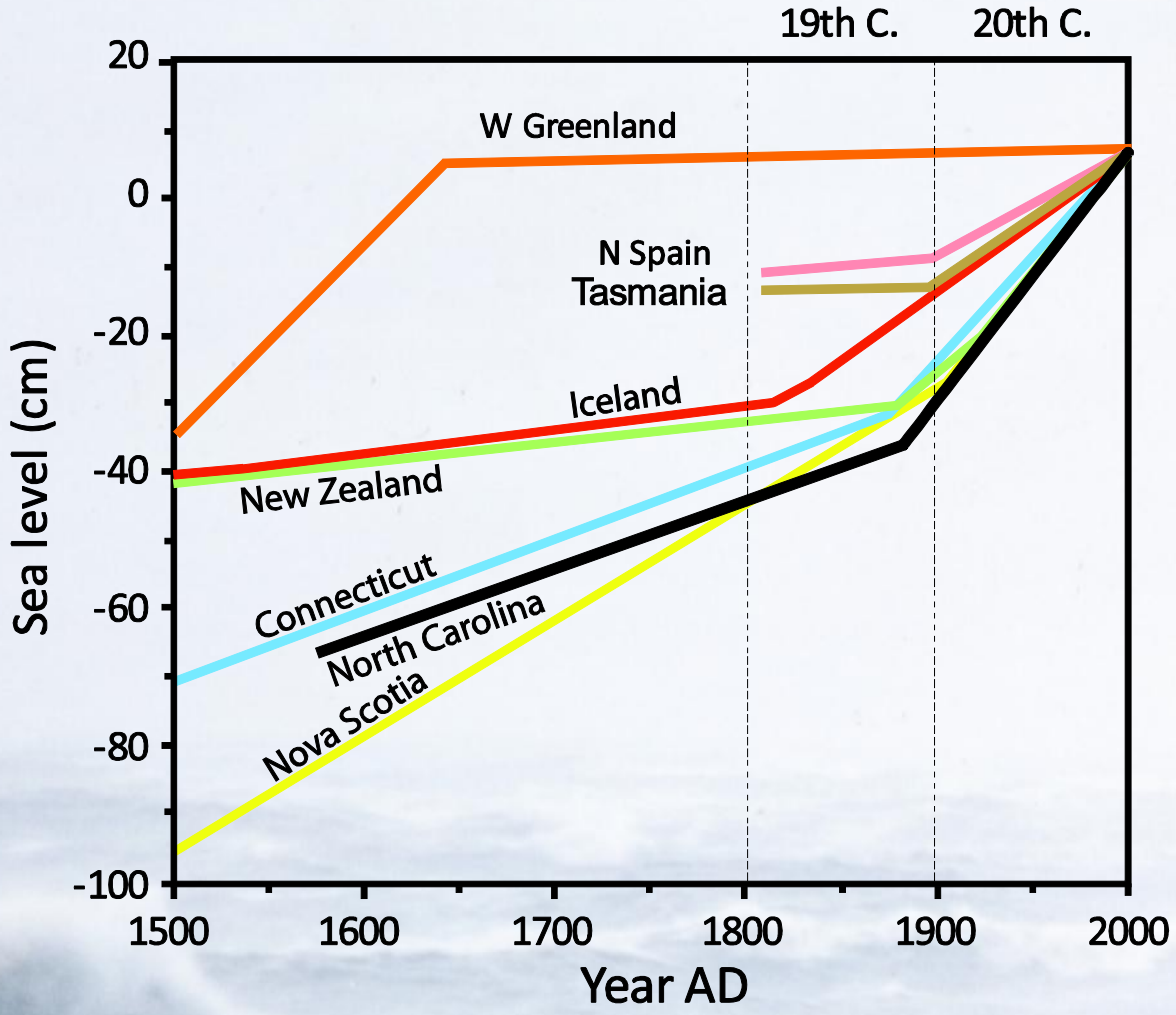
See Mitrovica et al. 2010 for a review

Venice – the use of Canaletto's paintings

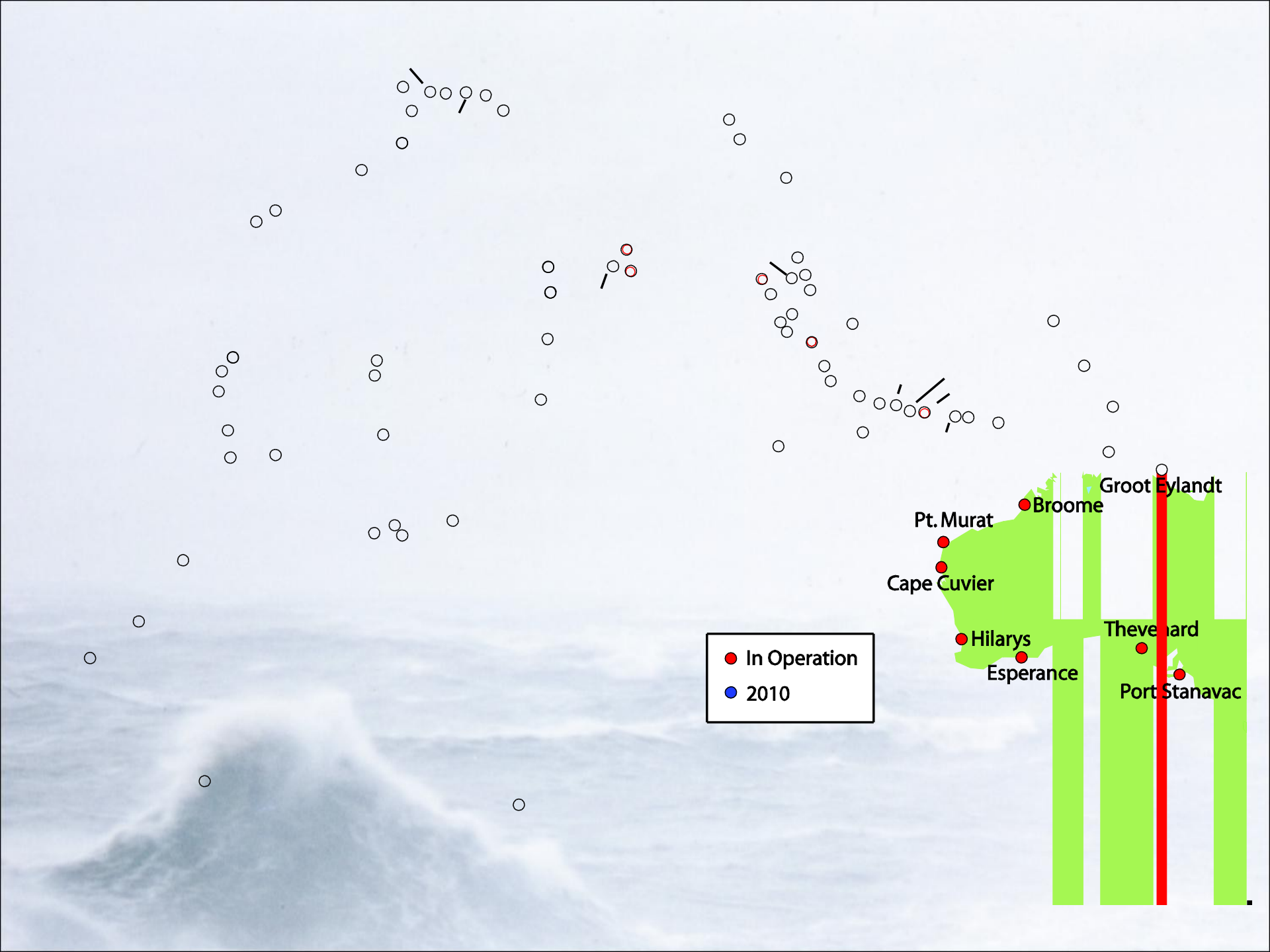
Camuffo and Sturaro 2005







North Atlantic Saltmarsh Sea Level Records


Groot Eylandt
Broome
Pt. Murat
Cape Cuvier
Hilarys
Esperance
Port Stanavac
In Operation
2010

Well Instrumented Era 2003-2009

- Measured sea level change (2.5 mm/yr) = Ocean mass change (1.7) + Steric change (0.7) from Argo
- Ocean mass change from GRACE (1.7) = Land ice contribution (2.0) + small amount from land waters (-0.2)
- This interpretation depends critically on GIA correction applied to GRACE data

(Anny Cazenave, Bern Meeting, March 2010)


Nantucket 1995

International Herald Tribune

SATURDAY-SUNDAY, NOVEMBER 13-14, 2010 THE GLOBAL EDITION OF THE NEW YORK TIMES GLOBAL.NYTIMES.COM

TONY CENICOLA/THE NEW YORK TIMES

The Helheim Glacier in southeastern Greenland is one of a group of glaciers that have shown major changes this decade. The line on the rock behind marks its height a few years ago.

Watching and waiting for the big melt

TASIILAQ, GREENLAND

BY JUSTIN GILLIS

With a tense pilot gripping the stick, the helicopter hovered above the water, a red speck of machinery lost in a wilderness of rock and ice.

To the right, a great fjord stretched toward the sea, choked with icebergs. To the left loomed one of the immense glaciers that bring ice from the top of the Greenland ice sheet and dump it into the ocean.

Hanging out the sides of the craft, two scientists sent a measuring device plunging through a hole in the ice, into the water. Near the bottom, it reported a temperature of just above 4 degrees Celsius, or 39 degrees Fahrenheit. It was the latest in a string of troubling measurements showing that the water was warm enough to melt glaciers rapidly from below.

"That's the highest we've seen this far up the fjord," said one of the scientists, Fiammetta Straneo.

The temperature reading was a new scrap of information in the effort to answer one of the most urgent — and most widely debated — questions facing humanity: How fast is the world's ice going to melt?

Researchers have recently been startled to see big changes unfold in both Greenland and Antarctica. As a result, many scientists now say that sea level is likely to rise perhaps one meter, or just over three feet, by 2100 — an increase

ICE, PAGE 5

G-20 postpones difficult decisions

SEOUL

Leaders vow to address global imbalances, but not before next year

BY SEWELL CHAN AND SHERYL GAY STOLBERG

Leaders of the world's largest economies, after weeks of wrangling leading up to two days of summit meetings, ended up backing a U.S.-led call Friday for curbing "persistently large imbalances" in trade, saving and spending. But under pressure from China and Germany, both export powerhouses, they avoided the thorniest decisions to help fix the problem, deferring any concrete actions until next year at the earliest.

Afterward, President Barack Obama, while saying that progress had been made, directed some of his strongest language yet at Beijing on the fraught topic of China's currency, the renminbi.

"Precisely because of China's success, it's very important that it act in a responsible fashion internationally," Mr. Obama said at a news conference. Its currency "is undervalued," he said, adding that the issue "is one that is an irritant not just to the United States, but is an irritant to a lot of China's trading partners and those who are competing with China to sell goods around the world."

The tough language suggested frustration by the White House at the less-than-rousing conclusion of the meeting of leaders of the Group of 20 economic powers, the fifth such gathering since the financial crisis hit in 2008.

The uneasy compromise reached here fell short of initial U.S. demands for numerical targets on trade surpluses and deficits but reflected a consensus that longstanding economic patterns — in particular, too much consumption by the United States and too little by China — were no longer sustainable.

"Instead of hitting home runs, sometimes we're going to hit singles," Mr. Obama said at a news conference, using a baseball metaphor. "But they're really important singles."

The meeting showed that the United States could still set the agenda for international discussion, even if the result — asking G-20 officials and the International Monetary Fund to define and analyze the imbalances — was far from robust.

The cautious approach, according to several officials from the G-20 powers, reflected the concerns of China, which resisted setting any kind of timetable for currency appreciation, and Germany, which insisted that any approach to the problem include fiscal, monetary

G-20, PAGE 4

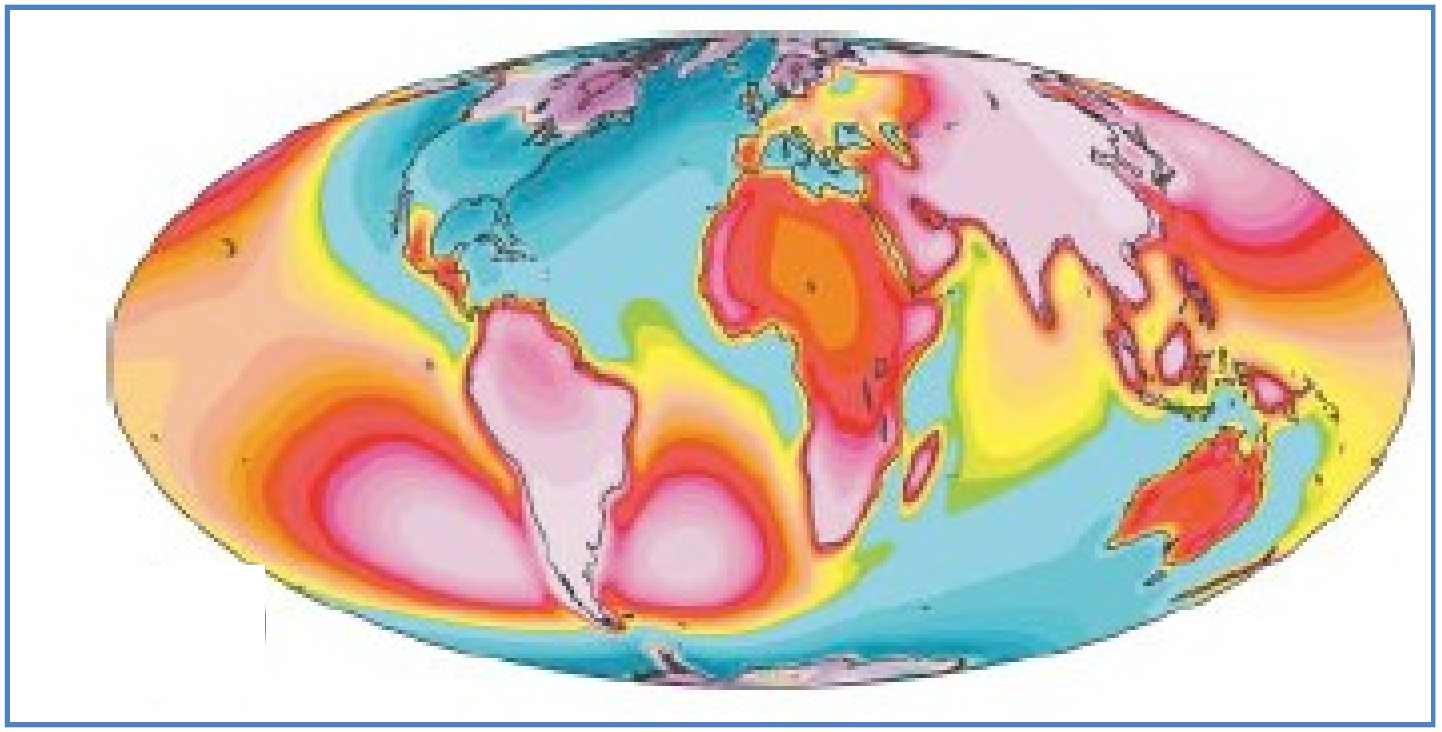
G-20 SEOUL SUMMIT

OBAMA'S LUSTER DIMS ON WORLD STAGE
A G-20 meeting marked by disputes over currency and trade has doused enthusiasm for the U.S. president. PAGE 4

G-20 BACKS TIGHTER BANK REGULATIONS
But the group left open numerous details, including how to deal with the biggest institutions. PAGE 4

A wee tweet blows up into a cause célèbre

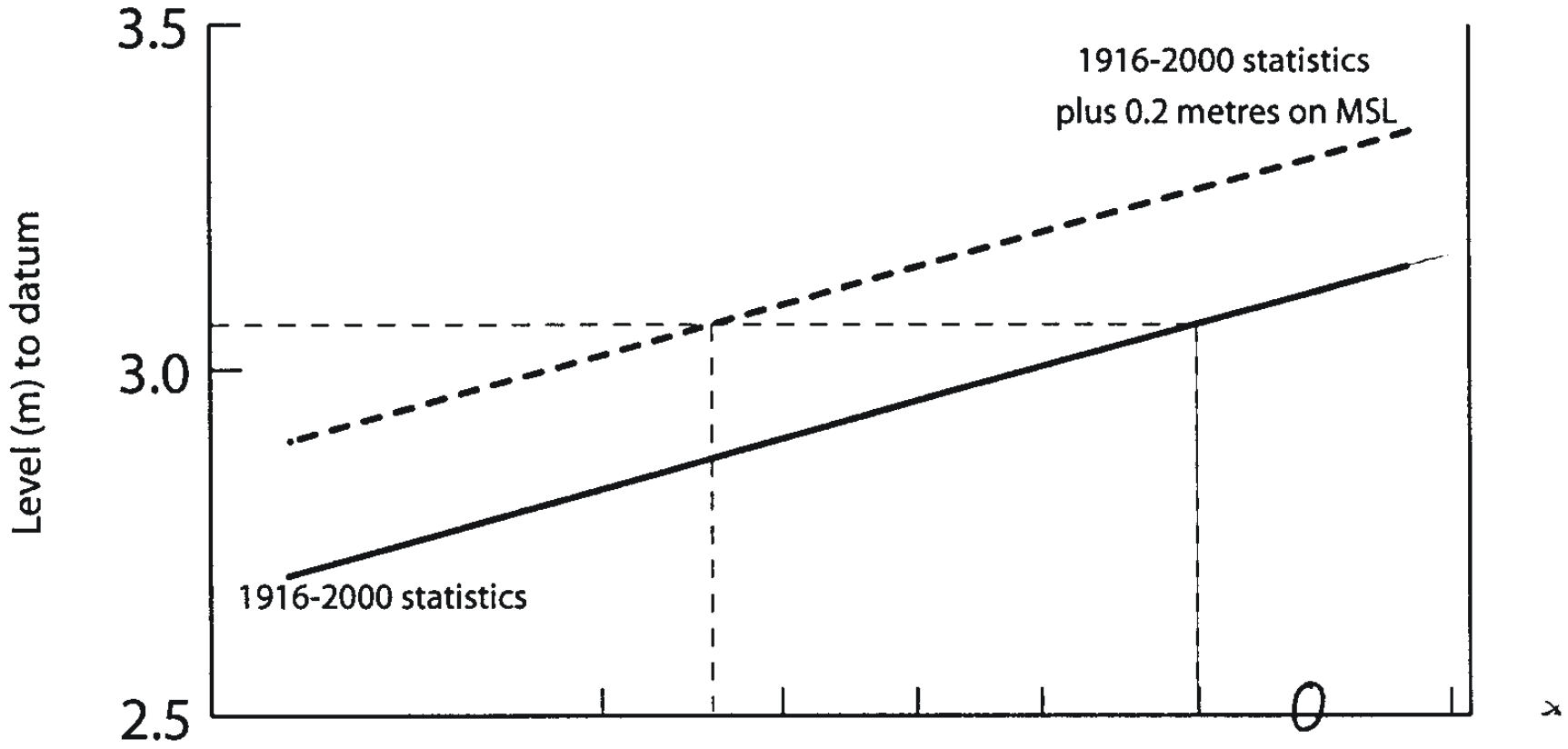
Article also in the New York Times Sunday 14 November



Peltier, 2004

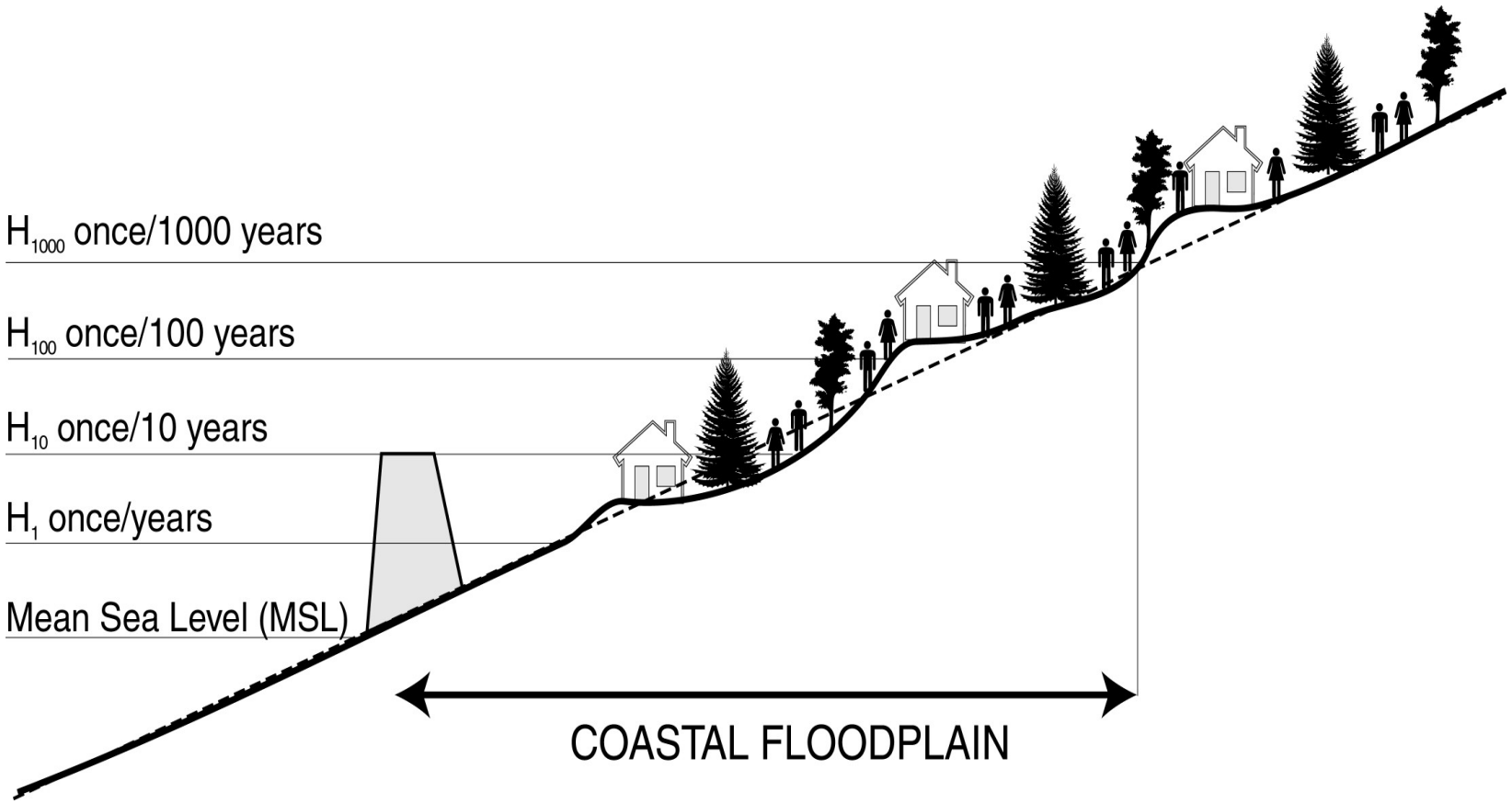
What is the impact of a rise in mean sea level?

- If extreme and mean sea levels rise at the same rate then the change in flood risk from a predicted MSL change can be calculated



Annual exceedance probability Q(z)	0.5	0.2	0.1	0.05	0.02	0.01	0.004
Return period (years)	2	5	10	20	50	100	250

Coastal Flood Plain




c
Tide-gauge


e


d


a


b