Lecture course on

Sea level variations
and global geodynamics

Charles University in Prague

November 7–11, 2011
Department of Geophysics
V Holešovičkách 2 (12th floor)
Prague 8

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Lecture course on

Sea level variations and global geodynamics
November 7–11, 2011

1. Introductory notes about sea level and geodynamics
   (November 7, start 12:20)

2. Loading problems and rheological models
   (November 8, start 12:20)

3. The sea level equation, theory and applications
   (November 9, start 13:10)

4. Secular sea level variations
   (November 10, start 15:40)

5. Greenland uplift and regional sea level changes
   (November 11, start 10:40)

Approximate length of a lecture: 2 hours
Lecture course on

Sea level variations and global geodynamics
Prague, November 7–11, 2011

General “philosophy” of these lectures:

- classical topics (e.g., the sea level equation),
- special topics (e.g., “new” techniques of Laplace inversion),
- work in progress (e.g., Greenland, etc.), ...

... a basic knowledge of SE geophysics and math-phys is assumed
- technical issues are minimized in the discussion
- Questions and discussions are encouraged
Lecture course on
Sea level variations and global geodynamics

1. Introductory notes about sea level and geodynamics
(November 7, start 12:20)

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Charles University in Prague, Department of Geophysics
November 7–11, 2011
Outline

Discussion of (and speculations on) sea level variations observed during the last 21,000 yrs (the LGM) and at present time

Stress on variability, extent, global character - but regional importance - of sea-level variations.

Is it possible to explain the spatio-temporal variability of sea level change by a simple law? (in spite of apparent complexity)
Does an “equation for sea level” exist?

Theory (“the equation”) vs Holocene RSL observations: are they compatible?

Sea level change during the era of “global warming” and a look into the future
is sea level *rising* or *falling* currently?

(a major environmental problem indeed)
Sea level rise from tide gauges “viewpoint of the solid Earth”

Rate is ~ 20 cm/century
Sea Level rise between 1993 and 2010 by satellite ALTIMETRY

Sea level is rising (by altimetry)
“viewpoint of space”

1993-2010

Sea level will be rising (IPCC scenarios)

**Figure 11.12:** Global average sea level rise 1990 to 2100 for the SRES scenarios. Thermal expansion and land ice changes were calculated using a simple climate model calibrated separately for each of seven AOGCMs, and contributions from changes in permafrost, the effect of sediment deposition and the long-term adjustment of the ice sheets to past climate change were added. Each of the six lines appearing in the key is the average of AOGCMs for one of the six illustrative scenarios. The region in dark shading shows the range of the average of AOGCMs for all 35 SRES scenarios. The region in light shading shows the range of all AOGCMs for all 35 scenarios. The region delimited by the outermost lines shows the range of all AOGCMs and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition. Note that this range does not allow for uncertainty relating to ice-dynamical changes in the West Antarctic ice sheet. See 11.5.4.3 for a full discussion. The bars show the range in 2100 of all AOGCMs for the six illustrative scenarios.
~ 70% of coasts are subject to erosion today

Figure 1. One trillion dollars is the assessed value of coastal real estate in Florida between Miami and Palm Beach. Pompano Beach, shown here, is roughly halfway between the two.

Figure 2. The local recession rate of the Delmarva coast is plotted on the left as a function of shoreline position (transect number). The areas highlighted in yellow correspond to those sections of beach where the assumptions of Bruun’s model apply. There, the average rate of shoreline retreat was 0.2 meters per year. (Adapted from ref. 1.)
Coastal erosion ... ...and land loss
Coastal erosion ... ...and land loss

\[ \sum_{\text{coasts}} \text{Sea level change} = \text{a lot of} \, \$ \]
Figure 8.1 The coastal zone is increasingly becoming a collision course.

Sea level rise: history and consequences

Di Bruce C. Douglas, Michael S. Kearney, Stephen P. Leatherman
Sea level rise: +12 m

Europe
N. America
S. America
Africa
SE. Asia
China & Japan
Australia
Sea level rise: +12 m

Europe  N. America  S. America  Africa  SE. Asia  China & Japan  Australia

http://flood.firetree.net/?ll=48.3416,14.6777&z=13&m=7

Bologna  Venezia  my village ~ 12 m

sea level + 12 m
“How did we get here?”
The last few millennia
Northern hemisphere glaciation during the last ice ages. The setup of 3 to 4 km thick ice sheets caused a sea level lowering of about 120 m.
Minimum (interglacial, black) and maximum (glacial, grey) glaciation

http://en.wikipedia.org/wiki/Ice_age
Paleogeography: the changing face of the Earth

Australia mainland linked to New Guinea and Tasmania
Paleogeography: the changing face of the Earth

Java and Borneo linked to the Asian mainland

Australia mainland linked to New Guinea and Tasmania
Paleogeography

the changing face of the Earth

BERINGIA - a bridge between Alaska and Siberia -

Java and Borneo linked to the Asian mainland

Australia mainland linked to New Guinea and Tasmania
Paleo-environmental Atlas of Beringia

Ice sheets


ICE5G thickness until 21 kyrs BP

ICE-5G thickness (m)

The Last Glacial Maximum (LGM)

Friday, November 11, 2011
Ice sheets

the LAST GLACIAL MAXIMUM (LGM)

Equivalent Sea Level (m)

Total ESL = 127.40 m

\[ ESL = \frac{\rho_i V}{\rho_w A_o} \]

time BP (kyrs)

today

LGM

CRE’s?
Consequences of melting?

**Reasonable assumptions:**

1. The Earth is a strong (*) body and ice has a low density (~ that of water). *Ice load has negligible effects.*

2. The amount of water filling the basins was huge: ~130 m of sea level equivalent. *Details of water load and its loading effects are not so important.*

3. *Gravity is a weak force* (Newton constant is small $10^{-11}$ SI units). Small influence [?] upon the *changes of shape of the Earth and of the oceans*...

Hence, we expect - to a first approximation - *a uniform sea level variation*. In the views of Suess...

(*) See George Darwin argument about the rigidity of the Earth, in comparison to steel.
Reasonable assumptions:

1) Rigid Earth: “Love numbers” are zero,

2) no gravitational interactions: Newton constant is zero.

Sea level variations are “EUSTATIC”, from “eustatism” a word coined by the English geologist Eduard Suess (1903):

$$S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o}$$

Eduard Suess

Evidence from the Holocene (in 6 examples)
Evidence from the Hudson Bay
Evidence from the Hudson Bay

Raised beach
Evidence from the Hudson Bay

Raised beach
Evidence from the Hudson Bay
Evidence from the Hudson Bay

Former sea level

Raised beach
Evidence from the Hudson Bay
A qualitative RELATIVE SEA LEVEL curve for the Hudson bay based on raised shorelines.
Evidence from the Pacific (Malden Island) ...

Kapapa Island (Ohau), Hawaiian Islands
Evidence from the Pacific

Kapapa & Malden Island

A qualitative RELATIVE SEA LEVEL curve for the Pacific Islands based on recently raised shorelines - Marine terraces

Evidence of a Late-Holocene high-stand
Evidence from "remote sites" e.g. Barbados

Evidence from Barbados coral records in the "far field": monotonous sea level rise
Evidence from “remote sites”

Isle of the Dead

The Ross-Lempriere sea level benchmark on the ‘Isle of the Dead’, ca 1841

A proposal by Baron Von Humboldt to the British Colonial Secretary...

... that mean sea level marks should be struck on newly discovered coasts and islands....

The Ross-Lempriere sea level benchmark on the ‘Isle of the Dead’, ca 1841

A stationary sea level in the last ~ 1.5 centuries?

What about the ~20 cm/century suggested by IPCC?
1. Mallorca

University of South Florida USA

2. SE Tunísia

Liverpool University UK
MIUR project

3. Cyclades

Remote Sensing Laboratory University of Athens
Delft University of Technology, Delft, NL

European collaboration
COST ES0701

4. Tyrrhenian
Mallorca

Evidence from encrusted stalagmites

Mallorca
“Encrusted stalagmites” are nowadays growing at present sea level (see image). The age of these bulbous calcite is 2800 years in the inner part and 0 at surface (forming now). The mean sea level corresponds to the thickest section of the stalagmite. These samples (dated by U/Th method) are 2800 years old or younger, which means the sea level basically remained stable around Mallorca over the last ~3000 years (+/- the tide effect).

~ stable sea level (since 3 ka)
A late-Holocene high-stand in SE Tunisia? possibly unique in the northern hemisphere (also confirmed by recent beach rock field evidence, possibly unique in the Mediterranean).
recent sea level RISE

San Vito lo Capo, NW Sicily

0 0.5

~0.5 m

time BP (ka)

Evidence from Dendropoma patreum (gasteropode)
monotonous sea level rise

A case study the Mediterranean Sea
A case study: recent sea level rise in the Mediterranean Sea. Evidence from Dendropoma patreum (gasteropode) showing a monotonous sea level rise of approximately 0.5 m at San Vito lo Capo, NW Sicily.
recent sea level RISE

San Vito lo Capo, NW Sicily

Evidence from Dendropoma patreum (gasteropode) monotonous sea level rise

time BP (ka)

0 0.5

0 ~0.5 m

RSL

A case study the Mediterranean Sea
A case study the Mediterranean Sea

0.0 +/- 0.2 m

Archaeological evidence (ancient pool):
stable sea level since 2 ka

Haifa, Israel

date unknown!
RSL observations

Fig. 2. Observed spatial variability of sea level change since the time of the LGM from tectonically stable areas or areas where the tectonic rate is known and has been removed from the observed signal. (A) Ångermanland, Gulf of Bothnia, Sweden (13). (B) Andøya, Nordland, Norway (12). (C) South of England (14). (D) Hudson Bay, Canada (4). (E) Barbados (16–18). (F) Bonaparte Gulf, northwest Australia (27). (G) Orpheus Island, North Queensland, Australia (23) and unpublished Australian National University data. (H) Sunda Shelf, southeast Asia (15). Note the different time and amplitude scales. In the examples illustrated, all observed depths or elevations of the sea level indicators have been reduced to mean sea level. All time scales are in calendar years.

Sea Level Change Through the Last Glacial Cycle
Kurt Lambeck, et al.
Science 292, 679 (2001);
DOI: 10.1126/science.1059549
Evidence from field data

To summarize, from these examples:

1. ... we observe sea level rise, sea level fall, high-stands, rapid changes, stationary sea levels... in different parts of the world, even in “tectonically stable” areas,

2. There is no evidence of a globally uniform sea level rise since the LGM. This contrasts with intuition that suggests a uniform filling of basins during melting,

3. A variety of sea level curves is also observed across relatively narrow basins (e.g. the Mediterranean),

4. Possible explanation (i): errors in data, misinterpretation, ...

5. Possible explanation (ii): data are OK, but we need a valid “theory of glacio-isostatic adjustment” (GIA).
GLOBAL Relative Sea Level (RSL) observations

Relative Sea Level (RSL) sites
from file sealevel.dat – NRSL = 392

T/P database
http://gcmd.nasa.gov/records/GCMD_EARTH_LAND_NGDC_PALEO_SEALEVEL1.html

can we explain the data?

RSL data from file: sealevel.dat
Is it possible to write a simple “equation” for sea level?
the "Sea Level Equation" is: \[ S = N - U \]
A couple of difficulties:

1. $N$ and $U$ both depend on $S$ itself!

   In fact, $U$ is determined by the ice load BUT also by the water load, whose amplitude is related with variations of the water column, e.g., from sea level change itself, $S$. Hence:

   $$U = U(S,I) \text{ and } N = N(S,I)$$

   $$S = S(U,N,I) = \text{Implicit function of } S \text{ itself.}$$

2. What about Earth rheology? What is the response to loads?
3. Which \textbf{rheology} for the Earth’s mantle?

- Forward “Creep problem” (theoretical viscoelasticity)

  \textit{Given the “LOAD” + Rheology, then} compute the system response (e.g. strain)

- Inverse “Creep problem” (real world)

  \textit{Given some (imperfect) knowledge about the “load” (ice sheets), obtained by glaciology, geology and geomorphology,}

  \textit{and given imperfect knowledge about the response (e.g. sea level change, from indirect evidence during the Holocene),}

  \textit{then, infer mantle rheology.}

(*) In a “creep experiment”, a load is applied instantaneously.
The sea level equation (SLE) - basic ideas

Adapted from Clark & Lingle, 1979
The sea level equation (SLE) - basic ideas

Adapted from Clark & Lingle, 1979

Degree 0 and 2 deformations

INERTIA
Angular Momentum Conservation

INERTIA

Degree 0 and 2 deformations

ROTATION

Angular Momentum Conservation

Adapted from Clark & Lingle, 1979

The sea level equation (SLE) - basic ideas
The sea level equation (SLE) - basic ideas

Adapted from Clark & Lingle, 1979

Degree 0 and 2 deformations

Angular Momentum Conservation

Centrifugal Potential

Inertia

Rotation

Load

Mass Attraction

Attraction

G

Ice

Earth

Ocean
The sea level equation (SLE) - basic ideas

Adapted from Clark & Lingle, 1979

Degree 0 and 2 deformations

Centrifugal Potential

Angular Momentum Conservation

INERTIA

ICE

LOAD

Mass Attraction

LOAD

Attraction

G

EARTH

OCEAN

ROTATION
Farrell (1976) has shown that the “original” SLE:

\[ S = N - U \]

can be transformed into:

\[
S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} G_s \otimes_i I - \frac{\rho_w}{\gamma} G_s \otimes_o S
\]

with:

- \( S \) = sea level change
- \( m_i \) = ice mass variation
- \( \rho_i, \rho_w \) = ice and water density
- \( A_o \) = area of the oceans
- \( G_s \) = sea level Green function
- \( \otimes_i, \otimes_o \) = 3(2+1)D convolutions
- \( I \) = ice thickness variation
- \( (\ldots) \) = ocean average

The sea level equation (SLE) - basic ideas
About the SLE

\[ S = \frac{\rho_i}{\gamma} G_s \otimes i I + \frac{\rho_w}{\gamma} G_s \otimes o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} G_s \otimes i I - \frac{\rho_w}{\gamma} G_s \otimes o S \]

The SLE is a **linear, integral equation**, since the unknown \( S \) also appears within convolution integrals.

Sea level change at one point \( \omega \) and time \( t \) depends on sea level change at any point \( \omega' \) and at any time \( t' \leq t \).

the problem of sea level change cannot be reduced to a regional scale
About the SLE

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The sea level equation (SLE) - basic ideas

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the problem of sea level change cannot be reduced to a regional scale
The sea level equation (SLE) - basic ideas

**Exercise #1**: Dropping some terms in the SLE.

\[
S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} G_s \otimes_i I - \frac{\rho_w}{\gamma} G_s \otimes_o S
\]

Eustatic solution!

\[
S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o}
\]

solves the SLE in the very special case:

- the EARTH is RIGID
- Newton constant is =0
Exercise #1: Dropping some terms in the SLE.

\[ S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} G_s \otimes_i I - \frac{\rho_w}{\gamma} G_s \otimes_o S \]

Eustatic solution!

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solves the SLE in the very special case:

the EARTH is RIGID

and

Newton constant is =0
The sea level equation (SLE) -

**Exercise #1:** Dropping some terms in the SLE.

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S = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \frac{\rho_i}{\gamma} G_s \otimes_i I - \frac{\rho_w}{\gamma} G_s \otimes_o S
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\[
S = \rho_i G_s \otimes_i I + \rho_w G_s \otimes_o S - \frac{m_i}{\rho_w A_o} - \rho_i G_s \otimes_i I - \frac{\rho_w}{\gamma} G_s \otimes_o S
\]

Eustatic solution!

\[
S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o}
\]

solves the SLE in the very special case:

- the EARTH is RIGID
- Newton constant is \( = 0 \)
The sea level equation (SLE) - basic ideas

**Exercise #1:** Dropping some terms in the SLE.

\[ S = \frac{\rho_i G_s \otimes_i I}{\gamma} + \frac{\rho_w G_s \otimes_o S}{\gamma} - \frac{m_i}{\rho_w A_o} - \frac{\rho_i G_s \otimes_i I}{\gamma} - \frac{\rho_w G_s \otimes_o S}{\gamma} \]

Eustatic solution!

\[ S = S^E(t) = -\frac{m_i(t)}{\rho_w A_o} \]

solves the SLE in the very special case:

the EARTH is RIGID and

Newton constant is =0
Exercise #2: Taking the ocean-average of the SLE.

\[
\overline{S} = \frac{\rho_i}{\gamma} G_s \otimes_i I + \frac{\rho_w}{\gamma} G_s \otimes_o S + S^E - \frac{\rho_i}{\gamma} G_s \otimes_i I - \frac{\rho_w}{\gamma} G_s \otimes_o S
\]

Hence:

\[
\overline{S} = S^E
\]

(regardless of rheology, actual shape of shorelines...).

“the ocean-averaged sea level change coincides with the sea level change we would observe in eustatic conditions”.

A consequence:
If the ice masses do not vary, the ocean-averaged sea level change is ZERO (and vice-versa).
HOW to solve the SLE?

A few ideas here ...

The SLE "looks like" a "inhomogeneous integral Fredholm equation of the 2nd type", where the unknown occurs both inside and outside the integral, and the integration interval is fixed (fixed shorelines, in our language), which in 1D sounds like:

$$\varphi(x) = f(x) + \lambda \int_{a}^{b} K(x, x') \varphi(x') dx',$$

The problem can be solved by "iteration" of a first-guess solution:

0. Assume \( \varphi(x) = \varphi^{(0)} \)

1. This gives \( \varphi^{(1)}(x) = f(x) + \lambda \int_{a}^{b} K(x, x') \varphi^{(0)} dx' \)

... ... ...

n. At step "n": \( \varphi^{(n)}(x) = f(x) + \lambda \int_{a}^{b} K(x, x') \varphi^{(n-1)}(x') dx' \)

... ... ...

and continue until some convergence criterion is met...
The sea level equation (SLE) - do it yourself!

**SELEN 3.0**

A source free, pesudo-spectral Sea Level equation solver


* NEW features under development * (helped by Florence Colleoni CMCC BO) *

**TABOO (~ 1997)**

A source-free Post-glacial rebound solver


**ALMA (2008)**

A Love number (Green function) calculator


Theory vs Holocene RSL observations
Relative Sea Level (RSL) sites
from file sealevel.dat – NRSL = 392
Convergence test for the SLE - Ungava Pen.

Model vs RSL observations

Hudson Bay

Relative Sea Level (m)

RSL (m)

0  120  180  240  300  360

(a)

time Before Present (kyr)

10  8  6  4  2  0

0  2  4  6  8  10  12  14

-60 -120 0

RSL data

S MAX=0

1 2 3 4 5

data

Convergence test for the SLE - Ungava Pen.
Model vs RSL observations

Convergence test for the SLE - Ungava Pen.

Relative Sea Level (m)

time Before Present (kyr)

RSL data
S MAX=0
1
2
3
4
5

step #0 (eustatic)

data

(a)
Convergence test for the SLE - Ungava Pen.

Model vs RSL observations

RSL (m)

60° 60° 60°
264° 276° 288°

(a) RSL data

SMAX=0
1
2
3
4
5

data

#1

Relative Sea Level (m)

Relative Sea Level (m)

0 120 180 240 300 360

time Before Present (kyr)

14 12 10 8 6 4 2 0

step #0 (eustatic)

Convergence test for the SLE - Ungava Pen.

(a) RSL data

SMAX=0
1
2
3
4
5

data

#1

Relative Sea Level (m)

Relative Sea Level (m)

0 120 180 240 300 360

time Before Present (kyr)

14 12 10 8 6 4 2 0

step #0 (eustatic)

Convergence test for the SLE - Ungava Pen.
Convergence test for the SLE - Ungava Pen.

Model vs RSL observations

Hudson bay

Relative Sea Level (m)

Convergence test for the SLE - Ungava Pen.

RSL data
SMAX=0
1
2
3
4
5

data

step #0 (eustatic)

Relative Sea Level (m)

time Before Present (kyr)

108  62.0  -75.0  7 UNGAVA PEN. QUE.

Convergence test for the SLE - Ungava Pen.

RSL data
SMAX=0
1
2
3
4
5

data

step #0 (eustatic)

Relative Sea Level (m)

time Before Present (kyr)

108  62.0  -75.0  7 UNGAVA PEN. QUE.

Convergence test for the SLE - Ungava Pen.

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step #0 (eustatic)

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data

step #0 (eustatic)

Relative Sea Level (m)

time Before Present (kyr)

108  62.0  -75.0  7 UNGAVA PEN. QUE.
Convergence test for the SLE - Ungava Pen.

Relative Sea Level (m)

step #0 (eustatic)

#1

#2

#5: convergence!

data

RSL data

SMAX = 0

Convergence test for the SLE - Ungava Pen.
Model vs RSL observations

Sea level 2 kyrs BP (relative to present day datum)

-Ice model: ICE5G –LMAX=72 –RES=18 –ALMA rheology: ./VSC/vsca_BENCH.dat –MODE=1 –ITER=3
Evidence from the Mediterranean

The Tyrrhenian coast

Diagram showing a plan view of a structure with labeled sections marked A, B, C, D, etc. The text on the diagram reads:

TAV. VII
16. P. della Vipera – Pianta della peschiera
(Da GIACOPLI et al., 1994)
Evidence from the Mediterranean

The Tyrrhenian coast

TAV. V
13. Valdaliga – Pianta della peschiera (Da GIACOPINI et alii, 1994)

TAV. VIII
17. Evo Guardiolo
Sopra: Pianta della peschiera principale e dei relativi moli esterni di protezione (Da GIACOPINI et alii, 1994).
Sotto: Pianta della peschiera minore alla foce del fosso.
Evidence from the Mediterranean

The Tyrrhenian coast
Evidence from the Mediterranean

The Tyrrhenian coast

Fig. 2: Part of La Mattonara fish tank.
**Fig. 6.** Ice- and ocean-load induced components of RSL for the site of Djerba (see map of fig. 3a) obtained using model ICE5G (VM1).
Evidence from the Mediterranean

**Fig. 6.** Ice- and ocean-load induced components of RSL for the site of Djerba (see map of fig. 3a) obtained using model ICE5G (VM1).

**Fig. 8.** Contributions to RSL due to individual components of ICE5G (VM1) at the site of Djerba (see fig. 3a).
Sea level in the last century

the era of tide gauges:
DIRECT observation
Radar gauge
Sea Level trends

nature of tide gauge observations

All PSMSL tide gauges (~ 1200)

All PSMSL tide gauges with T > 60 years (~ 140)
Rate of vertical displacement today
- Ice model: ICE5G
- ALMA rheology: ./VSC/vsca_BENCH.dat

All PSMSL tide gauges (~ 1200)

All PSMSL tide gauges with $T > 60$ years (~ 140)

Most (all?) tide gauges are in regions of considerable GIA disequilibrium

Present sea levels

tide gauges

Friday, November 11, 2011
Can you see the 2 mm/yr sea level rise proposed by the IPCC?
Short period: Many noisy data

Long period: A few, inconsistent, data.

Average (weighted) rate: $1.01 \pm 0.78 \text{ mm/yr}$
The GLOBALLY AVERAGED RATE of SEA LEVEL RISE is estimated using long series of T/G data after GIA correction!

Table 3.1

Recent Determinations of Global Sea Level Rise from Tide Gauge Data

<table>
<thead>
<tr>
<th>Author</th>
<th>Estimate (mm/yr)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peltier and Tushingham (1989, 1991)</td>
<td>2.4 ± 0.9(^a)</td>
<td>Global data</td>
</tr>
<tr>
<td>Barnett (1990)</td>
<td>1-2</td>
<td>Global data</td>
</tr>
<tr>
<td>Nakiboglu and Lambeck (1990)</td>
<td>1.15 ± 0.38</td>
<td>Global data</td>
</tr>
<tr>
<td>Trupin and Wahr (1990)</td>
<td>1.75 ± 0.13</td>
<td>Global data</td>
</tr>
<tr>
<td>Douglas (1991)</td>
<td>1.8 ± 0.1</td>
<td>Global data</td>
</tr>
<tr>
<td>Shennan and Woodworth (1992)</td>
<td>1.0 ± 0.15</td>
<td>U.K. and Europe</td>
</tr>
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<td>Mitrovica and Davis (1995)</td>
<td>1.1–1.6</td>
<td>Global data</td>
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<tr>
<td>Davis and Mitrovica (1996)</td>
<td>1.5 ± 0.3</td>
<td>U.S. east coast</td>
</tr>
<tr>
<td>Peltier (1996)</td>
<td>1.94 ± 0.6(^a)</td>
<td>U.S. east coast</td>
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<tr>
<td>Peltier and Jiang (1997)</td>
<td>1.8 ± 0.6(^a)</td>
<td>U.S. east coast</td>
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<tr>
<td>Douglas (1997)</td>
<td>1.8 ± 0.1</td>
<td>Global data</td>
</tr>
</tbody>
</table>

\(^a\) Standard deviation of trends about their mean. The formal SE is a few tenths.
What is the color of sea level change?

and regional (future) signals

http://www.ice2sea.eu/

Ice2sea is a science programme that is funded by the European Union Framework-7 scheme. Ice2sea will improve projections of the contribution of ice to future sea-level rise.
The mass balance of Greenland since 1990 from various sources

Courtesy of Jonathan Bamber, University of Bristol UK
Recent Sea-Level Contributions of the Antarctic and Greenland Ice Sheets

Andrew Shepherd and Duncan Wingham

Fig. 3. (A) Rate of elevation change of the Greenland Ice Sheet, 1992 to 2003, determined from satellite radar altimetry [from (22)], and (B) time series of elevation change of individual sectors, 2003 to 2005, determined from satellite gravimetry [from (16)]. Also shown (inset) is the ice surface geometry, highlighting areas above (gray) and below (black) 2000 m elevation. Both instruments concur that high elevation areas are growing and low elevation areas are losing mass. According to gravimetry (16) and repeat InSAR measurements of ice discharge (12), the rate of mass loss at low elevations has increased over the past decade (see Table 1).
The mass balance of Antarctica since 1990 from various sources

*Courtesy of Jonathan Bamber, University of Bristol UK*
Identifying the causes of sea-level change
Glenn A. Milne, W. Roland Gehrels, Chris W. Hughes and Mark E. Tamisiea, NATURE GEOSCI 2009

0. Possible causes

1. Thermal expansion

2. Ice melting fingerprints

-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0

mm yr\(^{-1}\)

Greenland

mm yr\(^{-1}\)

Antarctica
Regional sea level change?

Sea level "fingerprint" from the (uniform) melting of Antarctica
Concluding remarks

1. Physical models of glacio-isostatic adjustment are simple to be stated but account for an extremely complex phenomenology - in spite of their linearity - Agreement among scientists difficult to reach (but reachable after some work, see benchmarks...)

2. There are LARGE uncertainties in GIA models, and large error bars in the mass balance models for e.g., Antarctica, Greenland and the small glaciers. Sophisticated GIA theories are useful but probably we need data more than theories.

3. Future sea level rise/fall on a regional scale will be influenced by secular melting of glaciers, but they will be - reminiscent of GIA. So, understanding the effect of ongoing climate change is difficult without information on the solid Earth.