Interpreting the noisy historical and geological records of ancient sea level changes: What can the past tell us about the future?

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Collaborators:
Jerry Mitrovica, Carling Hay, Eric Morrow (Harvard)
Frederik Simons, Adam Maloof, Michael Oppenheimer (Princeton)
• Humans are shifting the Earth’s climate into a state novel for our species, though familiar to the planet.

• The potential sea level hazard from melting grounded ice is large but geographically variable.

• The sea level risk for ice sheets is difficult to model; geological and historical records provide a complementary approach.

• But to leverage these records, we must see through a host of uncertainties.
Humans are shifting the Earth’s climate into a state novel for our species, though familiar to the planet.
About 1.2 billion metric tons of fossil carbon dioxide have been released by human activities since 1800.

Datas Sources: CDIAC, Etheridge et al. (1996), GISS
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About 1.2 billion metric tons of fossil carbon dioxide have been released by human activities since 1800.

As a consequence, CO$_2$ concentrations have risen by about 40% over the last two centuries.

Global temperatures today are ~0.8°C warmer than in 1880-1900.
MIT IGSM projections for 2041-2050 and 2091-2100
(“Business-as-usual” no policy case)

CO₂

Surface Temperature

Red: Emissions Uncertainty
Green: Climate and Carbon Cycle Uncertainty
Blue: Combined Uncertainty

Sokolov et al. (2009)
The basic outlines have been known for quite some time

Fig. 6. Projections of global temperature. The diffusion coefficient beneath the ocean mixed layer is 1.2 cm$^2$ sec$^{-1}$, as required for best fit of the model and observations for the period 1880 to 1978. Estimated global mean warming in earlier warm periods is indicated on the right.

Hansen et al. (1981)
The basic outlines have been known for quite some time

van Oldenborgh and Haarsma (realclimate.org, 2 April 2012)

Hansen et al. (1981)
The potential sea level hazard from melting grounded ice is large but geographically variable.
Dominant factors in global sea level rise:

1. Thermal Expansion

Compare observed thermal expansion of about 1.0 mm/yr from 1983-2003 (Domingues et al., 2008)
Dominant factors in global sea level rise:
II. Glacier and ice sheet melt

**Total Hazard**

<table>
<thead>
<tr>
<th>Region</th>
<th>Hazard (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-polar glaciers and ice caps</td>
<td>$0.26 \pm 0.11$ m</td>
</tr>
<tr>
<td>Greenland &amp; W. Antarctic glaciers and ice caps</td>
<td>$0.46 \pm 0.17$ m</td>
</tr>
<tr>
<td>Greenland Ice Sheet</td>
<td>7 m</td>
</tr>
<tr>
<td>West Antarctic Ice Sheet</td>
<td>5 m</td>
</tr>
<tr>
<td>East Antarctic Ice Sheet</td>
<td>52 m</td>
</tr>
</tbody>
</table>

Maps by P. Fretwell (British Antarctic Survey)

Lemke et al. (2007); Bamber et al. (2001); Lythe et al. (2001)
Global Sea Level change is not the same as local sea level change

- Short-term: Dynamic effects
- Short to medium term: Gravitational, elastic and rotational effects
- Long term: Isostasy and tectonics
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\[ M_E - M_I \]

\[ a \]

\[ a + \varepsilon(\theta) \]

n.b. \( \varepsilon(\theta) = 0 \) at \( \theta \sim 2 \arcsin \left( \frac{.5 (\rho_E + 3 \rho_w)}{3 \rho_w} \right) \sim 30^\circ \)

Farrell & Clark (1976), after Woodward (1888)
Global Sea Level change is not the same as local sea level change

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\[ \text{and so wavelength } 2\pi\alpha \sim 7000 \text{ km} \]
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Gravitational-Elastic-Rotational Fingerprints of Greenland and WAIS melting, per meter GSL rise
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The sea level risk for ice sheets is difficult to model; geological and historical records provide a complementary approach.
IPCC AR4 projections for the 21st century

Figure 10.33. Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099 (relative to 1980 to 1999) for the six SRES marker scenarios. The projected sea level rise assumes that the part of the present-day ice sheet mass imbalance that is due to recent ice flow acceleration will persist unchanged. It does not include the contribution shown from scaled-up ice sheet discharge, which is an alternative possibility. It is also possible that the present imbalance might be transient, in which case the projected sea level rise is reduced by 0.02 m. It must be emphasized that we cannot assess the likelihood of any of these three alternatives, which are presented as illustrative. The state of understanding prevents a best estimate from being made.
IPCC estimates likely fall at the low end of the probability distribution.

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Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf
31 Jan. 2002
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

17 Feb. 2002

http://earthobservatory.nasa.gov/IOTD/view.php?id=2288
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

23 Feb. 2002

http://earthobservatory.nasa.gov/IOTD/view.php?id=2288
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

5 Mar. 2002

http://earthobservatory.nasa.gov/IOTD/view.php?id=2288
Poorly captured by models: buttressing and rapid collapse

Larsen B Ice Shelf

7 Mar. 2002

http://earthobservatory.nasa.gov/IOTD/view.php?id=2288

~40 km
Poorly captured by models: hydrology and lubrication

Poorly captured by models: hydrology and lubrication

http://www.gsfc.nasa.gov/gsfc/earth/pictures/20020606greenland/figure1m.jpg
How can historical records help?

Possible forcing parameters

- Temperature
  - Global mean
  - Polar air
  - Circumpolar marine
- Insolation (intensity, duration)
  - Northern Hemisphere
  - Southern Hemisphere
- Ice sheet configuration

Model parameters (including stochasticity)

Proxy data/Observations

Model Structures

<table>
<thead>
<tr>
<th>Complexity →</th>
<th>Global semi-empirical</th>
<th>Process semi-empirical</th>
<th>I-D</th>
<th>3-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal resolution ↓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Equilibrium”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hindcast

Model likelihood
How can historical records help?

Sea level rise rate

**Figure 3 | Long-term SLR.** a, Rate of SLR and b, SLR calculated from temperature reconstructions\(^2^8\) for 1000–2006 and from climate-model projections 1860–2300. For comparison, observed and proxy reconstructions for SLR are given as well from refs 2,2,2,29. 90% uncertainty ranges are shown for only two scenarios for reasons of readability, focusing on the lowest and highest temperature-goal scenarios. Error bars on the right-hand side as in Fig. 2.

\[
dH/dt = a_1 [T(t) - T_{0,0}] + a_2 [T(t) - T_0(t)] + b dT/dt
\]

with \[
dT_0/dt = \tau^{-1} [T(t) - T_0(t)]
\]

**Global semi-empirical, transient estimate (1000-2300 CE)**

**Global mean temperature as only forcing parameter**

Schaeffer et al. (2012)
### Complexity →

<table>
<thead>
<tr>
<th></th>
<th>Global semi-empirical</th>
<th>Process semi-empirical</th>
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<tr>
<td>&quot;Equilibrium&quot;</td>
<td>e.g., Gasson et al. (2012)</td>
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<td>e.g., Applegate et al. (2012)</td>
<td>e.g., Pollard et al. (2009)</td>
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<td>e.g., Applegate et al. (2012)</td>
<td>e.g., Goelzer et al. (2012)</td>
</tr>
</tbody>
</table>

**Temporal resolution ↓**
For the last 2 My, the Earth has oscillated between glacials and interglacials...

(a) The global benthic oxygen isotope stack of Lisiecki and Raymo (2005), which is a convolved record of global ice volume change and benthic temperature change, (b) summertime insolation at 65°N latitude (Berger and Loutre, 1991), and some paleoclimatic proxies that might be related to ice sheet changes – (c) the deuterium-derived temperature record from Dome C in East Antarctica (Joulez et al, 2007), and (d) alkenone-derived sea surface temperature records from ODP 1090 from Agulhas Ridge in the South Atlantic (red: Marinez-Garcia et al., 2009) and ODP 982 from the Rockall Plateau in the North Atlantic (blue: Lawrence et al., 2009).
...with pacing sets by change’s in Earth orbit

Zachos et al. (2003)
The Last Interglacial stage

Figure 1. Long-term variations of eccentricity, precession, obliquity, summer solstice insolation at 65°N (Berger, 1978) and atmospheric CO₂ concentration (Petit et al., 1999) from 200 kyr BP to 130 kyr AP.
But to leverage these records, we must see through a host of uncertainties.
A forward model for historical SL observations

This gives us $P(s \mid X_i, x_v, X_d, U, \Delta s)$.

We want to find $P(X_i, x_v, X_d \mid s, U, \Delta s)$. 
A forward model for geological sea level proxies

This gives us $P(s,t | X_i, x_v, U, g, H_s, H_T)$.

We want to find $P(F, g | s, t, U, H_s, H_T)$
[and ideally $P(X_i, x_v, X_d | s, t, U, H_s, H_T)$]
It's possible to generate high LSL without high GSL

Far from
Laurentide Ice Sheet

In this model, GSL from 135 to 120 ka is the same as today!

Closer to
Laurentide Ice Sheet

Lambeck & Nakada (1992)
Goal: Given database, assess the probability distribution of sea level through space and time

- Geomorphological, sedimentological, and isotopic sea level proxy observations
- Physical model of the relationship between ice sheet melt, local sea level, and global sea level

Statistical integration

Posterior probability distribution for past global and local sea level
Goal: Given database, assess the probability distribution of sea level through space and time

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Statistical integration

Posterior probability distribution for past global and local sea level
Database of sea level observations

Sites with at least one LIG Sea Level Indicator

Indicator Nature – $\Delta$: isotopic; $\odot$: reef terraces; $\triangle$: coral biofacies; $\Box$: sedimentary facies and non-coral biofacies; $\Diamond$: erosional

# Observations – 1, 2, 3, $\geq$4

Kopp et al. (2009)
Key Characteristics of Observations

Sea Level ($s$)
- Heteroscedastic, some non-Gaussian
- Some are platykurtic
- Some are censored

Ages ($t$)
- Heteroscedastic
- Some have strong ordering constraints
- Some have relative ages better known than absolute ages
Sea Level Database

Example 1: Cockburn Town Reef, San Salvador, Bahamas

http://www.mnstate.edu/leonard/G390BPHOTOS.html

Chen et al. (1991)
Reef terrace dominated by *Acropora palmata*

Altitude of $1.5 \pm 1.0$ m

Composite U/Th age of $128.4 \pm 8.0$ ka

Depositional range based on assemblages: 0-5 m below MLTL

Subsidence rate estimate: 1-2 cm/ky
Goal: Given database, assess the probability distribution of sea level through space and time

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Statistical integration

Posterior probability distribution for past global and local sea level
Prior covariance within $F$ calculated from SL model

*Effects included:*
- Gravitational, elastic, rotational, isostatic, shoreline migrations

Gravitational and elastic response

Isostatic response
With prior for total ice volume from $\delta^{18}O$ record

$\delta^{18}O$ data from Lisiecki & Raymo (2005)

2σ ranges

Cartoon from: http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml
With prior for total ice volume from $\delta^{18}O$ record

$\delta^{18}O$ data from Lisiecki & Raymo (2005)

$\Delta \delta^{18}O$

Global Ice Loss (m esl)

Age (ka)

Ice Volume

Temperature

Glacial Ice (-30%)

(0%)

High Sealevel

Permanent Ice

Low Sealevel (+1%)

0°C  5°C  10°C

2σ ranges

Cartoon from: http://earthguide.ucsd.edu/virtualmuseum/climatechange2/01_1.shtml
Prior probability distributions for GSL and ice sheets over time (inferred from global benthic foram $\delta^{18}$O stack)

![Graphs showing changes in GSL, Laurentide, Greenland, Europe, WAIS, EAlS, NH Glaciers, SH Glaciers, and Steric SL over time.](image-url)
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Statistical integration

Posterior probability distribution for past global and local sea level
altitudes \((z)\)
depositional ranges \((D)\)
uplift rates \((u)\)
ages \((t)\)

RSL \((z')\)

uplift \((u \cdot g)\)

LSL \((s)\)

LSL \((f)\)

ages \((g)\)

Algorithmic steps
1: measurement correction
2: Gauss. proc. regression
3: Markov ch. Monte Carlo

observables
internal vars.
posterior dist. samples

Kopp et al. (2009)
Probability of **local sea level observations**, conditional on:

- altitudes,
- meanings,
- uplift rates,
- “true” ages

---

**Algorithmic steps**

1: measurement correction
2: Gauss. proc. regression
3: Markov ch. Monte Carlo

---

**Statistical Integration Algorithm**

- **altitudes** (z)
- **depositional ranges** (D)
- **uplift rates** (u)

---

- **RSL** (z')
- **uplift** (u•g)

---

- **LSL** (s)

---

- **LSL** (f)
- **ages** (g)

---
Probability of **“true” local sea level**, conditional on:

- local sea level observations,
- “true” ages,
- and the physical prior.

**Statistical Integration Algorithm**

**Algorithmic steps**
1: measurement correction
2: Gauss. proc. regression
3: Markov ch. Monte Carlo
Probability of “true” ages, conditional on:

“true” local sea levels, observed ages, and the physical prior.

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Statistical Integration Algorithm

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Statistical integration

Posterior probability distribution for past global and local sea level
Posterior probability distributions

Kopp et al. (2009)
Posterior exceedance levels

maximum rate at GSL ≥ −10 m (m/ky)

GSL rate

exceedance probability

maximum GSL rise (m) or ice loss (m ESL) in least lossy hemisphere

Kopp et al. (2009)
**Posterior exceedance levels**

Maximum rate at GSL ≥ −10 m (m/ky)

Extremely likely to have exceeded

GSL

rate

GSL
Posterior exceedance levels

maximum rate at GSL ≥ −10 m (m/ky)

GSL rate

GSL

Extremely likely to have exceeded

Likely to have exceeded

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Kopp et al. (2009)
Posterior exceedance levels

maximum rate at GSL ≥ −10 m (m/ky)

- Extremely likely to have exceeded
- Likely to have exceeded
- Unlikely to have exceeded

maximum GSL rise (m) or ice loss (m ESL) in least lossy hemisphere

Kopp et al. (2009)
Posterior exceedance levels

Kopp et al. (2009)
Posterior exceedance levels

Maximum rate at GSL $\geq -10$ m (m/ky)

Extremely likely to have exceeded
6.6 m

Likely to have exceeded
8.0 m

Unlikely to have exceeded

Kopp et al. (2009)
Posterior exceedance levels

Kopp et al. (2009)
Exceedance probability

Maximum rate at GSL ≥ −10 m (m/ky)

Posterior exceedance levels

GSL
rate

Extremely likely to have exceeded
6.6 m
5.6 m/ky

Likely to have exceeded
8.0 m

Unlikely to have exceeded
9.4 m

Kopp et al. (2009)
Posterior exceedance levels

extreme likelihood

Exremely likely
- to have exceeded
  - 6.6 m
  - 5.6 m/ky

Likely
- to have exceeded
  - 8.0 m
  - 7.4 m/ky

Unlikely
- to have exceeded
  - 9.4 m

Kopp et al. (2009)
**Posterior exceedance levels**

![Graph showing exceedance levels for maximum GSL rise or ice loss in least lossy hemisphere.](image)

- **Extremely likely to have exceeded**
  - 6.6 m
  - 5.6 m/ky

- **Likely to have exceeded**
  - 8.0 m
  - 7.4 m/ky

- **Unlikely to have exceeded**
  - 9.4 m
  - 9.2 m/ky

---

Kopp et al. (2009)
How fast did sea level change within the LIG?

Exceedance Probability

Max. Rise Rate (m/ky)

Full
≤ 2 Peaks
Prior

Kopp et al. (in sub.)
How fast did sea level change within the LIG?

Exceedance Probability

- **Full**
- **≤ 2 Peaks**
- **Prior**

**Max. Rise Rate (m/ky)**

- Extremely likely to have exceeded 0 m/ky
- Likely to have exceeded 3 m/ky
- Unlikely to have exceeded 7 m/ky
Conclusions: Last Interglacial Sea Level

- Despite a fairly modest warming with respect to the present (about 3-5°C in the Arctic, as expected with ~1.5-2.5°C globally), peak LIG global sea level was considerably higher than today (likely above 8.0 m).

- Long term (millennial) GSL rise rate was 2-3 times higher than current annual rates, while shorter term rates could have been faster.

- These high sea level were produced with contributions from both NH and SH ice sheet melt.

- Within the LIG, GSL likely rose at a rate between about 3-7 m/ky.

- These results suggest that the equilibrium sea level in a modestly warmer world is significantly higher than today.
One key question: Do internal dynamics vs. external forcing explain interglacial differences?

---

Lisiecki & Raymo (2005)
Berger & Loutre (1991)
Joule et al. (2007)
Martinez-Garcia et al. (2009)
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