Lecture 23: Tides and Sea Level Change

GEOS 655 Tectonic Geodesy
Jeff Freymueller
Topics Today

• Tides
• Tide Gauges and Measurement of Tides and sea level variations  
  – Tide surveys and tidal benchmark surveys  
  – Long-term tidal records
• Sea level history
• The Sea level equation and ocean function
Tides as a Measure of Changing $g$

- Tides are the most obvious change in gravity, caused by the attraction of the moon and sun.
  - Solid earth deforms due to changing tidal gravitational potential (*solid earth tide*)
  - Ocean water flows around due to changing potential (*ocean tides*)
  - Solid earth deforms due to changing load of ocean tides (*ocean tidal loading*)

- Tidal bulge is two-sided because of earth rotation, and because Earth is orbiting about CM of Earth-Moon system

- *Tidal potential* (gravitational potential) varies with position of Moon and Sun relative to Earth.

- Tidal variations generally described as a sum of harmonic terms.
Tidal Friction

- Earth’s tidal bulge gets ahead of Moon position because of rotation of Earth
  - Tidal friction slows Earth rotation and increases orbital radius of Moon
  - Length of day has increased ~10% since Devonian, present rate of change about 0.002 sec/year
- Geodetic observations of change in length of day reflect mostly exchange of angular momentum between solid earth and hydrosphere.
Tidal Potential

From the Law of Cosines:

\[ b^2 = R^2 + r^2 - 2Rr \cos \Psi \]

- We can compute the tidal potential at any point on the Earth’s surface from basic physics

\[ U_M = -\frac{GM_m}{b} \]
\[ U_M = -\frac{GM_m}{r \left[ 1 + \frac{R^2}{r^2} + 2 \frac{R}{r} \cos \Psi \right]^{1/2}} \]
\[ U_M = -\frac{GM_m}{r} \left[ 1 + \frac{R}{r} \cos \Psi + \frac{R^2}{r^2} \left( \frac{3}{2} \cos^2 \Psi - \frac{1}{2} \right) + \ldots \right] \]
Tidal Potential Terms

- First order approximation: distance to Moon is constant.
- First term is constant
- Second term relates to orbit of Earth around CM of Earth-Moon system
- Third and following terms are *tidal potential.*
- We’ll look at that third term in more detail.

\[
U_{M(1)} = -\frac{GM_m}{r}
\]

\[
U_{M(2)} = -\frac{GM_m R}{r^2} \cos \Psi
\]

\[
U_{M(3)} = -\frac{GM_m}{r} \left[ \frac{R^2}{r^2} \left( \frac{3}{2} \cos^2 \Psi - \frac{1}{2} \right) + \ldots \right]
\]
Relation of $\Psi$ to Lat-Long

- The angle $Y$ is measured in the plane defined by the vectors $\mathbf{p}$ and $\mathbf{m}$,
- Define $(\theta, \phi)$ as co-latitude + logitude of $P$
- Define $(\theta_m, \phi_m)$ as co-latitude + longitude of Moon (varies)
- Longitude changes by $2\pi$ per day (non-rotating coordinate system)

$$\cos \Psi = \cos \theta \cos \theta_m + \sin \theta \sin \theta_m \cos(\phi - \phi_m)$$

$$\frac{1}{2} (3\cos^2 \Psi - 1) = \left( \frac{3\cos^2 \theta - 1}{2} \right) \left( \frac{3\cos^2 \theta_m - 1}{2} \right) + \frac{3}{4} \sin^2 \theta \sin^2 \theta_m \cos 2(\phi - \phi_m) + \frac{3}{4} \sin 2\theta \sin 2\theta_m \cos(\phi - \phi_m)$$
Periods of these terms

• **Semi-diurnal tide** \( \frac{3}{4} \sin^2 \theta \sin^2 \theta_m \cos 2(\varphi - \varphi_m) \)
  
  – Undergoes a complete cycle every time \( 2(\phi - \phi_m) \) changes by \( 2\pi \), roughly twice a day
  
  – Amplitude varies over course of lunar month

• **Diurnal tide** \( \frac{3}{4} \sin 2\theta \sin 2\theta_m \cos(\varphi - \varphi_m) \)
  
  – Undergoes a complete cycle every time \( (\phi - \phi_m) \) changes by \( 2\pi \), roughly once a day
  
  – Amplitude varies over course of lunar month

• **Fortnightly tide** \( \left( \frac{3\cos^2 \theta - 1}{2} \right) \left( \frac{3\cos^2 \theta_m - 1}{2} \right) \)
  
  – Undergoes a complete cycle twice per lunar month

• Plus higher order terms from ellipticity of Moon’s orbit.
Solar Tides

• Solar tides come from the same causes as lunar tides.
  – Magnitude \( \sim 0.42 \) of lunar tides due to ratio of masses and ratio of distances cubed.
• Solar tides include semi-diurnal and diurnal, but vary with year rather than lunar month
• Solar tidal components may be out of phase with lunar components
Tidal Components are Named

- Only major tidal components listed here

- Lunar tides
  - Semi-diurnal M2
  - Diurnal K1, O1
  - Elliptical J1, L1, K2, L2

- Solar Tides
  - Semi-diurnal S2
  - Diurnal P1
  - Elliptical R2, T2


The M2 tide is very large in Alaska due to a resonance in the Gulf of Alaska.
Predicting Tides

• The periods of the tidal harmonic components are known.

• Tides can be predicted forward in time by fitting amplitudes and phases for each harmonic component based on some data.

• Non-tidal components include:
  – Storms and storm surges
  – Variations in currents/salinity
  – El Niño/La Niña
  – Pacific Decadal Oscillation and other basin-scale variations
  – Some of the non-tidal components repeat seasonally
Oldest continuous tide gauge site: Amsterdam, since 1700
Classical Float Gauge (from about 1832)
Float gauges are still important and can be made into digital gauges with the use of encoders.
Example: Kodiak Tide Station
Sample Tide Data

NOAA/NOS/CO-OPS
Verified Water Level vs. Predicted Plot
9457292 Kodiak Island, AK
from 2009/02/25 - 2009/02/26
A month of Tide Data

NOAA/NOS/CO-OPS
Verified Water Level vs. Predicted Plot
9457292 Kodiak Island, AK
from 2009/01/01 - 2009/02/01
# Tidal Harmonic Components

**Twenty largest harmonic components at Kodiak Island**

<table>
<thead>
<tr>
<th>Const#</th>
<th>Name</th>
<th>Amplitude</th>
<th>Phase</th>
<th>Speed (°/hour = 360/period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M2</td>
<td>3.192</td>
<td>308.1</td>
<td>28.9841042 ( = 12.4 hours)</td>
</tr>
<tr>
<td>4</td>
<td>K1</td>
<td>1.306</td>
<td>288.6</td>
<td>15.0410686 ( = 23.93 hours)</td>
</tr>
<tr>
<td>2</td>
<td>S2</td>
<td>1.066</td>
<td>341.4</td>
<td>30.0000000</td>
</tr>
<tr>
<td>6</td>
<td>O1</td>
<td>0.850</td>
<td>273.0</td>
<td>13.9430356</td>
</tr>
<tr>
<td>3</td>
<td>N2</td>
<td>0.659</td>
<td>284.2</td>
<td>28.4397295</td>
</tr>
<tr>
<td>30</td>
<td>P1</td>
<td>0.413</td>
<td>284.4</td>
<td>14.9589314</td>
</tr>
<tr>
<td>35</td>
<td>K2</td>
<td>0.295</td>
<td>332.8</td>
<td>30.0821373</td>
</tr>
<tr>
<td>22</td>
<td>SA</td>
<td>0.256</td>
<td>262.1</td>
<td>0.0410686 ( = 1 year)</td>
</tr>
<tr>
<td>26</td>
<td>Q1</td>
<td>0.154</td>
<td>264.8</td>
<td>13.3986609</td>
</tr>
<tr>
<td>11</td>
<td>NU2</td>
<td>0.128</td>
<td>284.2</td>
<td>28.5125831</td>
</tr>
<tr>
<td>33</td>
<td>L2</td>
<td>0.079</td>
<td>321.0</td>
<td>29.5284789</td>
</tr>
<tr>
<td>14</td>
<td>2N2</td>
<td>0.079</td>
<td>258.9</td>
<td>27.8953548</td>
</tr>
<tr>
<td>19</td>
<td>J1</td>
<td>0.075</td>
<td>297.9</td>
<td>15.5854433</td>
</tr>
<tr>
<td>13</td>
<td>MU2</td>
<td>0.072</td>
<td>277.1</td>
<td>27.9682084</td>
</tr>
<tr>
<td>24</td>
<td>MF</td>
<td>0.066</td>
<td>165.2</td>
<td>1.0980331 ( = 13.6 days)</td>
</tr>
<tr>
<td>27</td>
<td>T2</td>
<td>0.062</td>
<td>329.5</td>
<td>29.9589333</td>
</tr>
<tr>
<td>20</td>
<td>MM</td>
<td>0.062</td>
<td>191.7</td>
<td>0.5443747</td>
</tr>
<tr>
<td>23</td>
<td>MSF</td>
<td>0.049</td>
<td>51.5</td>
<td>1.0158958</td>
</tr>
<tr>
<td>21</td>
<td>SSA</td>
<td>0.049</td>
<td>151.7</td>
<td>0.0821373</td>
</tr>
<tr>
<td>18</td>
<td>M1</td>
<td>0.046</td>
<td>293.2</td>
<td>14.4966939</td>
</tr>
</tbody>
</table>
Tidal Benchmark Surveys

• In addition to permanent tide gauges, there are many tidal benchmarks, which have been surveyed relative to tide level.

• Good tidal benchmark surveys include 2-3 months of temporary tide gauge surveys to measure major tidal components.

• Shorter tidal benchmark surveys use nearby permanent tide gauges or even tide tables.
Sea Level Monitoring

• Each country operates its own tide gauges, data coordinated through international organizations
  – PSMSL = Permanent Service for Mean Sea Level
    • Under ICSU
    • Archives tide gauge data from almost 2000 global stations
  – GLOSS = Global sea Level Observing SyStem
    • Under WMO
    • The main component of GLOSS is the 'Global Core Network' (GCN) of 290 sea level stations around the world for long term climate change and oceanographic sea level monitoring.
    • Also Long-term trends network fed to IPCC, etc.
Measuring Sea Level Changes

Tide Gauge (float)

Altimeter System

Bottom Pressure Gauge

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html
Sea-Level Changes

Different Time-Scales
- Momentary changes due to tsunamis
- Daily changes due to tides and surges
- Seasonal changes
- Interannual changes e.g. due to ENSO
- Long term changes due to climate change

Causes of Sea Level Change
- Local processes in river/coastal regimes
- Ocean circulation changes
- Regional and global climate changes
- Geological processes

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html
Long Term Changes in Sea Level

Past 100 years

- Most records show evidence for rising sea levels during the past century
- IPCC concluded that there has been a global rise of approximately 10-20 cm during the past 100 years

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html
Long Term Changes in Sea Level

Next 100 years

- a rise between 9 and 88 cm
- a central value of 48 cm
- a rate of approx. 2.2 - 4.4 times that of the past 100 years

Projected sea level rise, IPCC 2001

http://www.pol.ac.uk/psmsl/programmes/gloss.info.html
Present GLOSS Core Network
All PSMSL Tide Stations
PSMSL with >40 years records
Lower 48 Sea Level Trends
Alaska Sea Level Trends
Global Mean Sea Level

Nicholls and Cazenave (2011)

Observations

Projections

Trend = +3.26 mm/year

Time (year)

Sea level (cm)

Date (years)
Regional Sea Level Trends
1992-2009

Nicholls and Cazenave (2011)
Absolute Sea Level Variation

- Most of the variation in this figure is oceanographic – redistribution of water
  - Thermal expansion of surface waters
  - El Niño/La Niña
  - Other oscillatory shifts in currents
- Some long-term trends are buried in this figure
Addition of water to Oceans

- Melting glaciers are the main contributor of water to the oceans
- Continental water storage (groundwater, reservoirs) has been largest source of uncertainty
- Addition of water to reservoirs has reduced rate of sea level rise (Chao et al., 2008)
Global Scale Variations

- Measure all mass redistribution using data from the NASA GRACE satellite mission
  - Solve “sea level equation” (Farrell and Clark, 1976)
Mean Sea Surface from multi-mission altimetry
Sea level variability
The up and down of the ocean tides

Atlantic Ocean

South Indian Ocean

Pacific Ocean

Gascogne Gulf

New Amsterdam

Funafuti

Cophase lines drawn with a 30° interval (0° phase has a larger drawing)

Centimeters

Source: IMG/LEGI, Grenoble 1995
Annual Cycle of Sea Level Height (TOPEX/POSEIDON, cy:1-157)
Long Term Sea Level Changes

• We know from geologists that sea level has changed over many 1000s of years largely as a result of the exchanges of water between the ocean and ice caps

• So we should not be too surprised if sea level is still changing
How is water redistributed?

- If water is added to the oceans (from melting glaciers, for example), how is it distributed?
  - **Small changes**
    - Added to present ocean areas, not land. Distribution of ocean described by *ocean function*.
  - **Large Changes**
    - For the melting of large amounts of ice (Greenland or Antarctica), you have to account for the changes in bathymetry of oceans due to GIA, and also the changes in ocean area as sea level rises onto coastal plains.
Ocean Function

white = 1; green = 0
15K BP
9K BP
Two Main Problems with the Present ‘Global’ Sea Level Data Set

- Coverage is not uniform around the globe.
- ‘Sea Level’ measurements are relative to land level. Land level may be changing, too.

SOLUTION (to #2) ➔ Measure Land Levels using new geodetic techniques such as GPS and Absolute Gravity
Two Main Geodetic Tools for Measuring Land Level Changes

GPS

Absolute Gravity
Questions and Answers

Q. Has global sea level risen during the 20th century?

A. Yes. By 10-20 cm.

There are many references, see the IPCC Fourth Assessment Report for a review.
<table>
<thead>
<tr>
<th>Region, VLM</th>
<th>Rate ± s.e. (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gornitz and Lebedeff (1987)</td>
<td>Global, Geological 1.2 ± 0.3</td>
</tr>
<tr>
<td>Peltier and Tushingham (1989, 1991)</td>
<td>Global, ICE-3G/M1 2.4 ± 0.9c</td>
</tr>
<tr>
<td>Trupin and Wahr (1990)</td>
<td>Global, ICE-3G/M1 1.7 ± 0.13</td>
</tr>
<tr>
<td>Nakiboglu and Lambeck (1991)</td>
<td>Global decomposition 1.2 ± 0.4</td>
</tr>
<tr>
<td>Shennan and Woodworth (1992)</td>
<td>NW Europe, Geological 1.0 ± 0.15</td>
</tr>
<tr>
<td>Gornitz (1995)d</td>
<td>NA E Coast, Geological 1.5 ± 0.7c</td>
</tr>
<tr>
<td>Mitrovica and Davis (1995),</td>
<td>Far field, PGR Model 1.4 ± 0.4c</td>
</tr>
<tr>
<td>Davis and Mitrovica (1996)</td>
<td>NA E Coast, PGR Model 1.5 ± 0.3c</td>
</tr>
<tr>
<td>Peltier (1996)</td>
<td>NA E Coast, ICE-4G/M2 1.9 ± 0.6c</td>
</tr>
<tr>
<td>Peltier and Jiang (1997)</td>
<td>NA E Coast, Geological 2.0 ± 0.6c</td>
</tr>
<tr>
<td>Peltier and Jiang (1997)</td>
<td>Global, ICE-4G/M2 1.8 ± 0.6c</td>
</tr>
<tr>
<td>Douglas (1997)d</td>
<td>Global, ICE-3G/M1 1.8 ± 0.1</td>
</tr>
<tr>
<td>Lambeck et al. (1998)</td>
<td>Fennoscandia, PGR Model 1.1 ± 0.2</td>
</tr>
<tr>
<td>Woodworth et al. (1999)</td>
<td>UK &amp; N Sea, Geological 1.0 ± 0.2</td>
</tr>
</tbody>
</table>

N.B. All these analyses use the same PSMSL data set
Questions and Answers

Q. Do we understand why it has risen?

A. Yes. (Or at least ‘more or less’)
Why has sea level risen?

Main driver has been the

**0.6 °C global temperature change during the past century**

but there have been many contributors to the sea level change.

See IPCC 4AR for a review.
Variations of the Earth's surface temperature: 1000 to 2100.

1000 to 1861, N.Hemisphere, proxy data; 1861 to 2000 Global, Instrumental; 2000 to 2100, SRES projections.
Melting Low Latitude Glaciers (Alaska etc.)

Figure 2.18: A collection of 20 glacier length records from different parts of the world. Curves have been translated along the vertical axis to make them fit in one frame. [Data from the World Glacier Monitoring Service (http://www.geo.unizh.ch/wgms/) with some additions from various unpublished sources].
20th Century Sea Level Rise - IPCC 2001

- Thermal expansion
- Glaciers
- Greenland (present)
- Antarctica (present)
- Ice sheets (long term)
- Permafrost
- Sedimentary deposits
- Continental waters

TOTAL OBSERVATIONS

Continental waters

-1.0 -0.5 0.0 0.5 1.0 1.5 2.0 mm/year

-1.0 -0.5 0.0 0.5 1.0 1.5 2.0 mm/year
Progress in Understanding Budget

• IPCC 2001 underestimated several factors
  – Steric (thermal expansion)
  – Contribution from melting glaciers.

• Recent work by Steve Nerem (U. of Colorado) suggests that sea level budget closes fairly well, and consistent with present altimeter rate of >3 mm/yr.

• Chao et al. (2008) estimated water storage in dams and concluded that sea level rate averaged 2.5 mm/yr post-WW2, partially masked by impoundment of water in reservoirs.
Questions and Answers

Q. Is the rate of rise increasing?

A. **Yes.** On basis of study of long records spanning 18\textsuperscript{th} to 20\textsuperscript{th} centuries.

A. **Not clear.** On basis of 20\textsuperscript{th} century tide gauge data alone.

A. **Yes.** On basis of altimeter and tide gauge from the 1990s.
Sea level change contains an acceleration of sea level rise from the 19th to the 20th centuries probably due to climate change.
Predicted Global Average Sea Level

Vermeer and Rahmstorf (2009)

Sea Level Change (cm)

Year

1950  2000  2050  2100

IPCC AR4

A1FI

A2

B1

AR4
IPCC AR4 Underestimates Rise

- Present observed rate of sea level rise is at the upper envelope of IPCC predictions.
- Why?
  - IPCC AR4 assumed no input to sea level from glacier ice.
  - Because the uncertainty in the future response of glaciers was large
- IPCC AR4 estimates are almost certainly a lower bound on future sea level rise.

Allison et al. (2009)
Predicted Global Average Sea Level

Vermeer and Rahmstorf (2009)

Pfeffer et al. (2008)

IPCC AR4
Hay et al. (2015) Reconstruction

- Reconstruct 20th century sea level change while attributing mass changes
- Inverse problem including gravitationally self-consistent “fingerprints”
Example Data Fits

Hay et al. (2015, Nature)
Results

Hay et al. (2015, Nature)

Church and White (2011)
Questions and Answers

Acceleration in the 1990s?

• Look at altimetry

• Look at tide gauge records.

• Look at IPCC-type models.

Answer:

• Yes
Altimeter Sea Level Change

http://sealevel.colorado.edu
Questions and answers

Q. How much might sea level rise in the 21\textsuperscript{st} century?

A. 9-88 cm with central value of 48 cm based on 35 emission scenarios and 7 AOGCMs (IPCC Third Report).
Predicted Global Average Sea Level

Vermeer and Rahmstorf (2009)

Sea Level Change (cm)

Year

1950  2000  2050  2100
Questions and Answers

Q. How important will the 21st century changes be?

A. When MSL (or water depth) changes, and when also there are coupled changes in regional meteorology, there will be changes in storm surges, tides, waves and extreme water levels.
It is important to keep in mind that these rising Sea Levels sooner or later lead to changes in Extreme Levels and often to local flooding. (This is not only a ‘Scientific’ exercise.)
Floods in the Irish Sea 2002

Douglas

"the worst in living memory"

Many £M’s damage in few hours

Ramsey
Tuvalu Floods 2002

Poor infrastructure

Typical coral island

Erosion

Plant damage
New Orleans 2005
New Orleans 2005