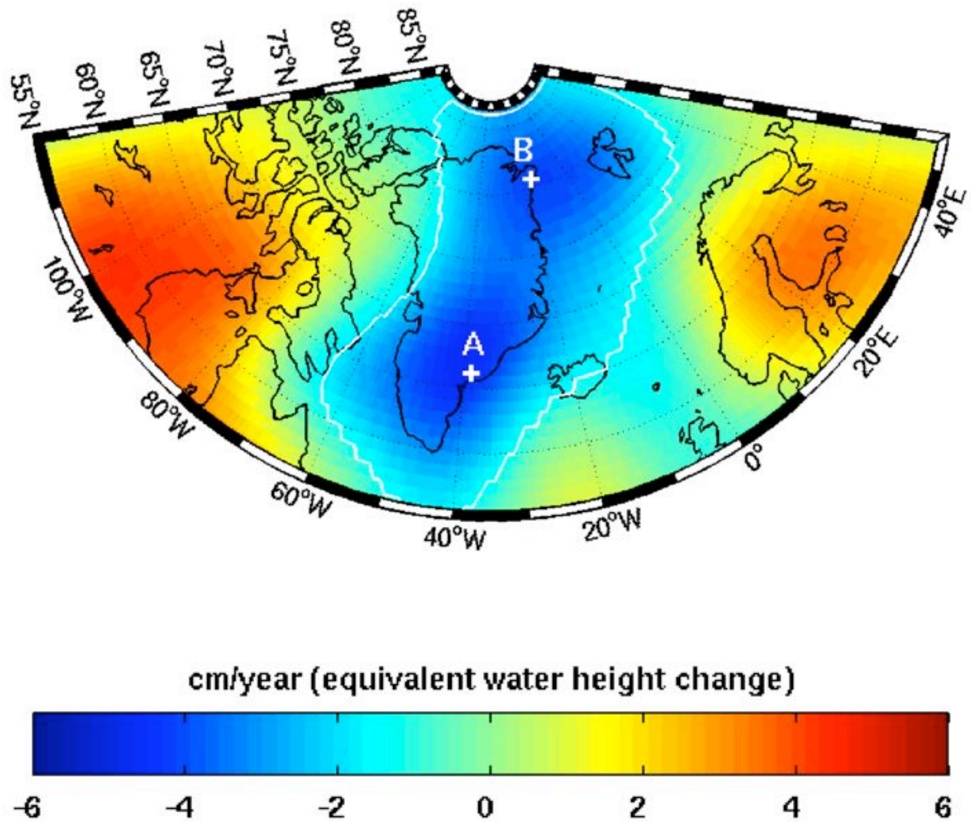
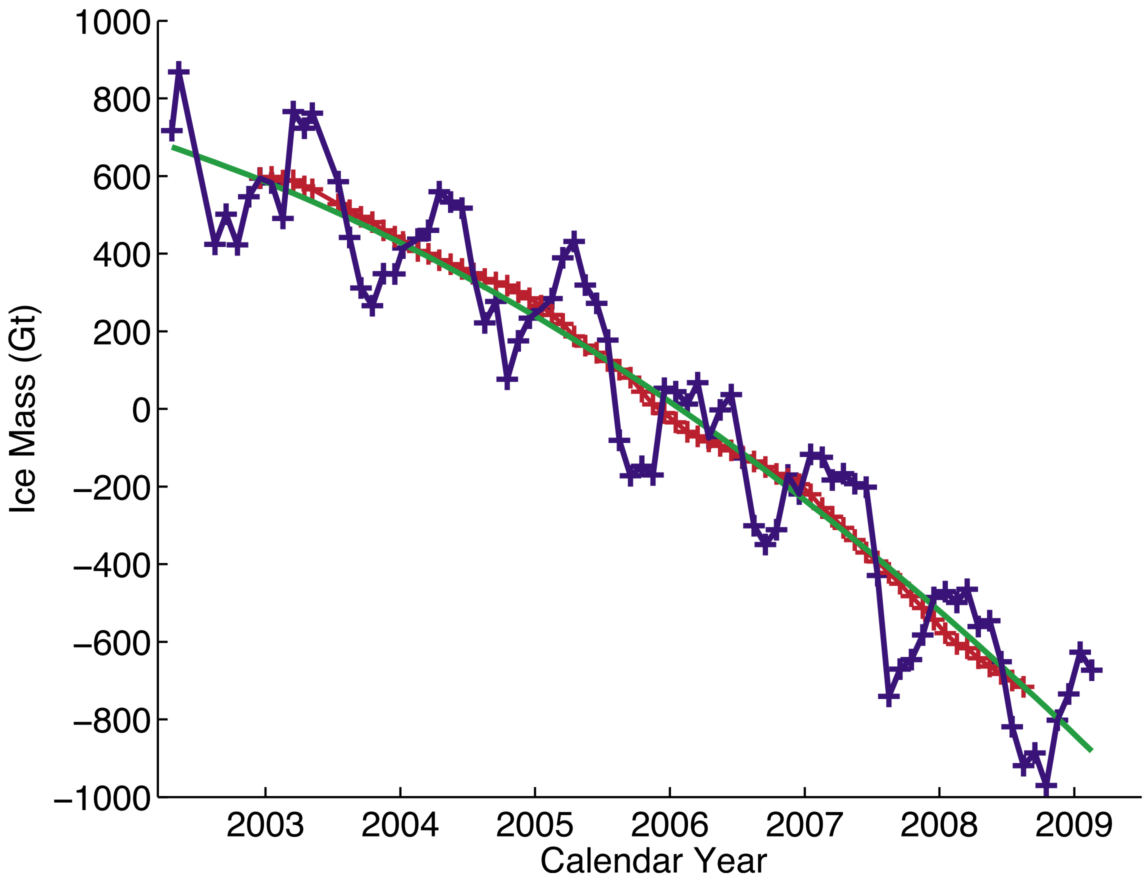
GRACE Gravity Change



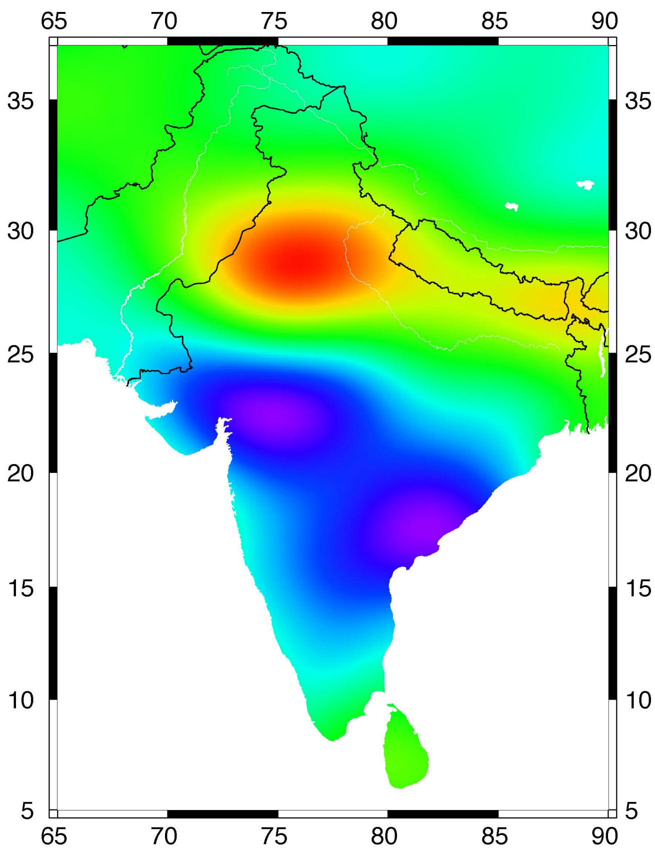
From J.L. Chen, U. Texas

Greenland Mass Change Trend



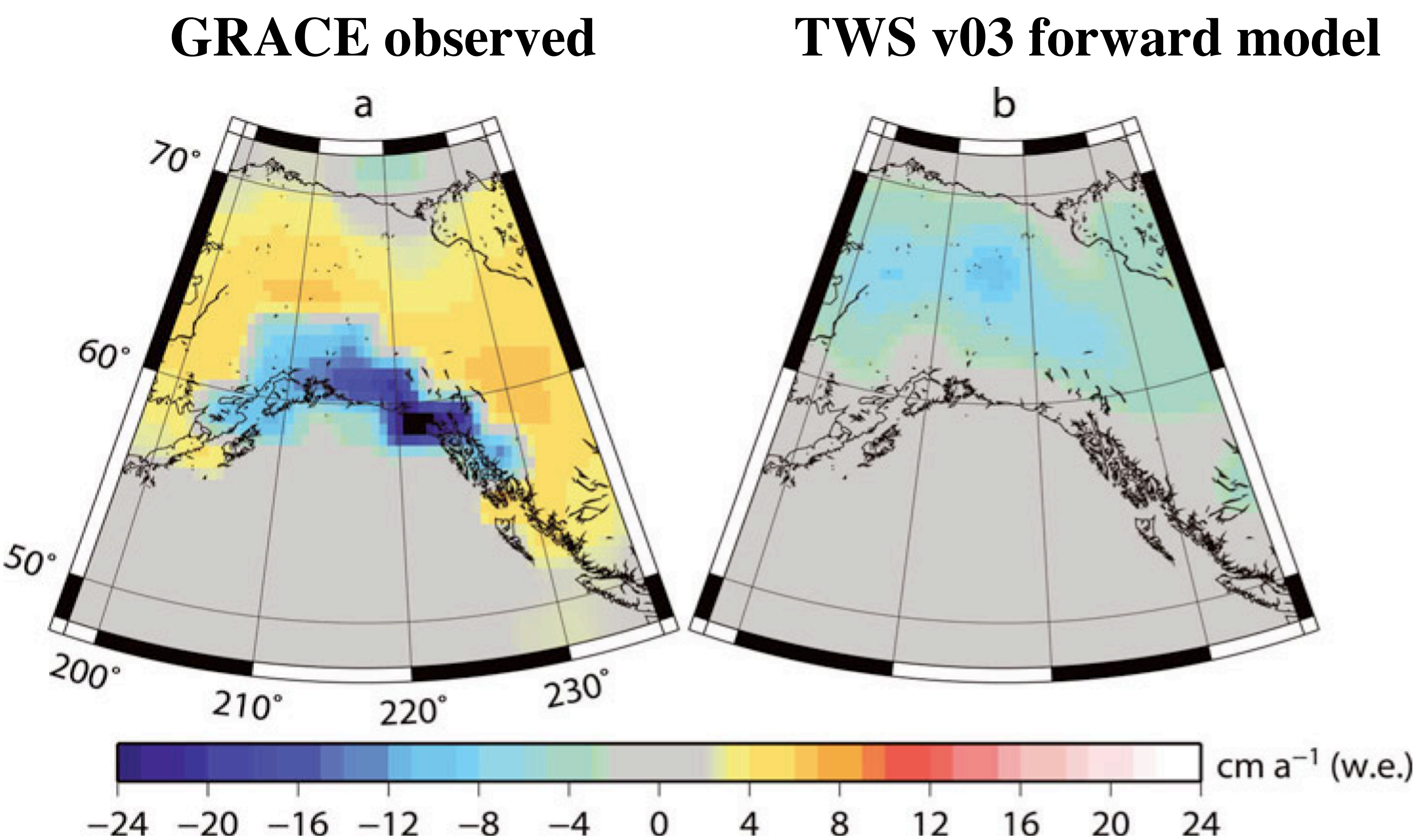
Velicogna (2009)

Groundwater Extraction in India



- From Rodell et al. (2009)
- Same basic procedure as used for measuring ice mass variations.

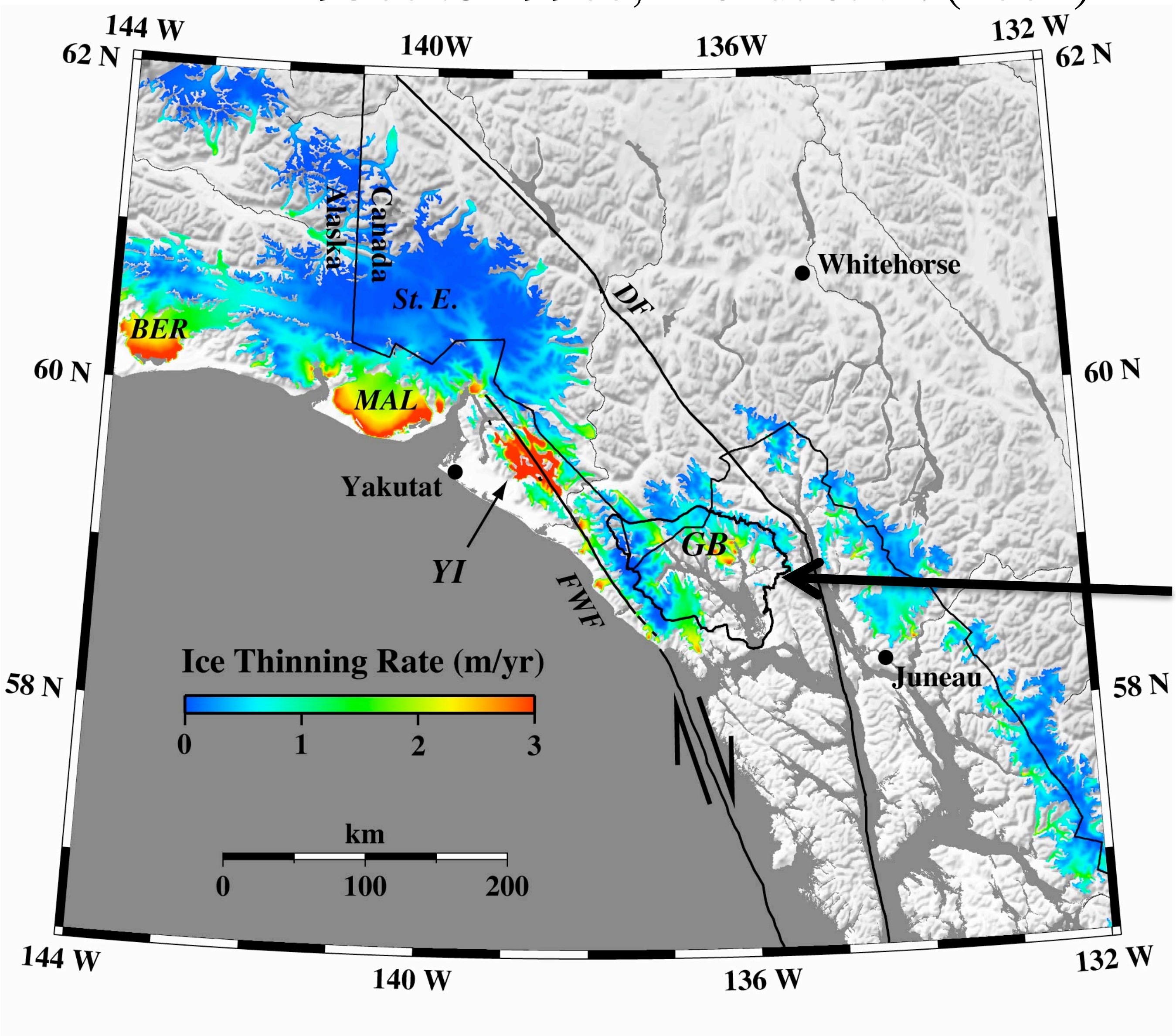
Present Mass Loss from GRACE



Luthcke et al. (2008)

Average Regional Thinning Rate

1950s to 1990s, Arendt et al. (2002)



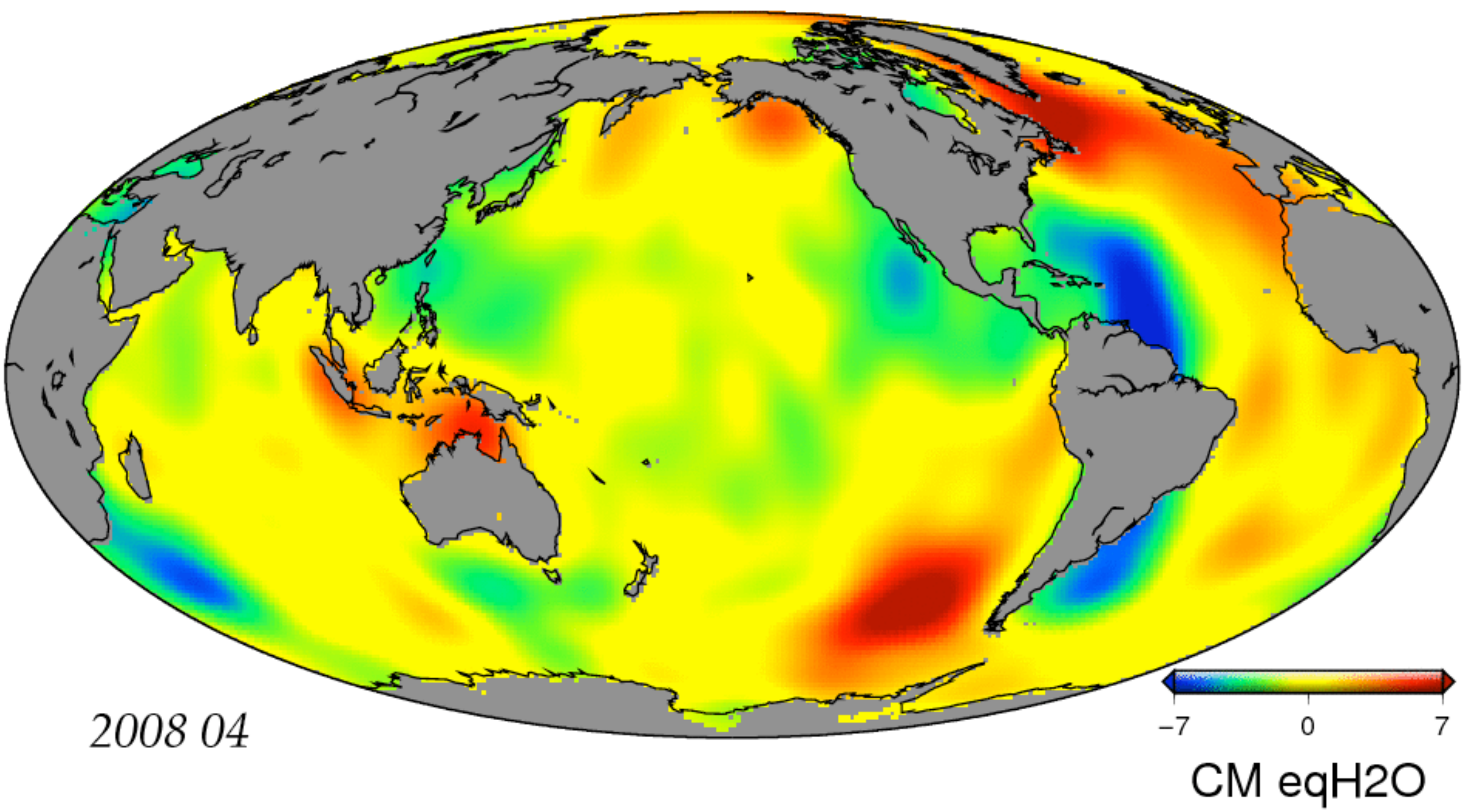
Regional: 5800 km^3 lost in 20th century. May be underestimated by a factor of 2 (Larsen et al., 2007)

Glacier Bay: 3000 km^3 lost in 19th century (Larsen et al., 2005)

How Are These Determined?

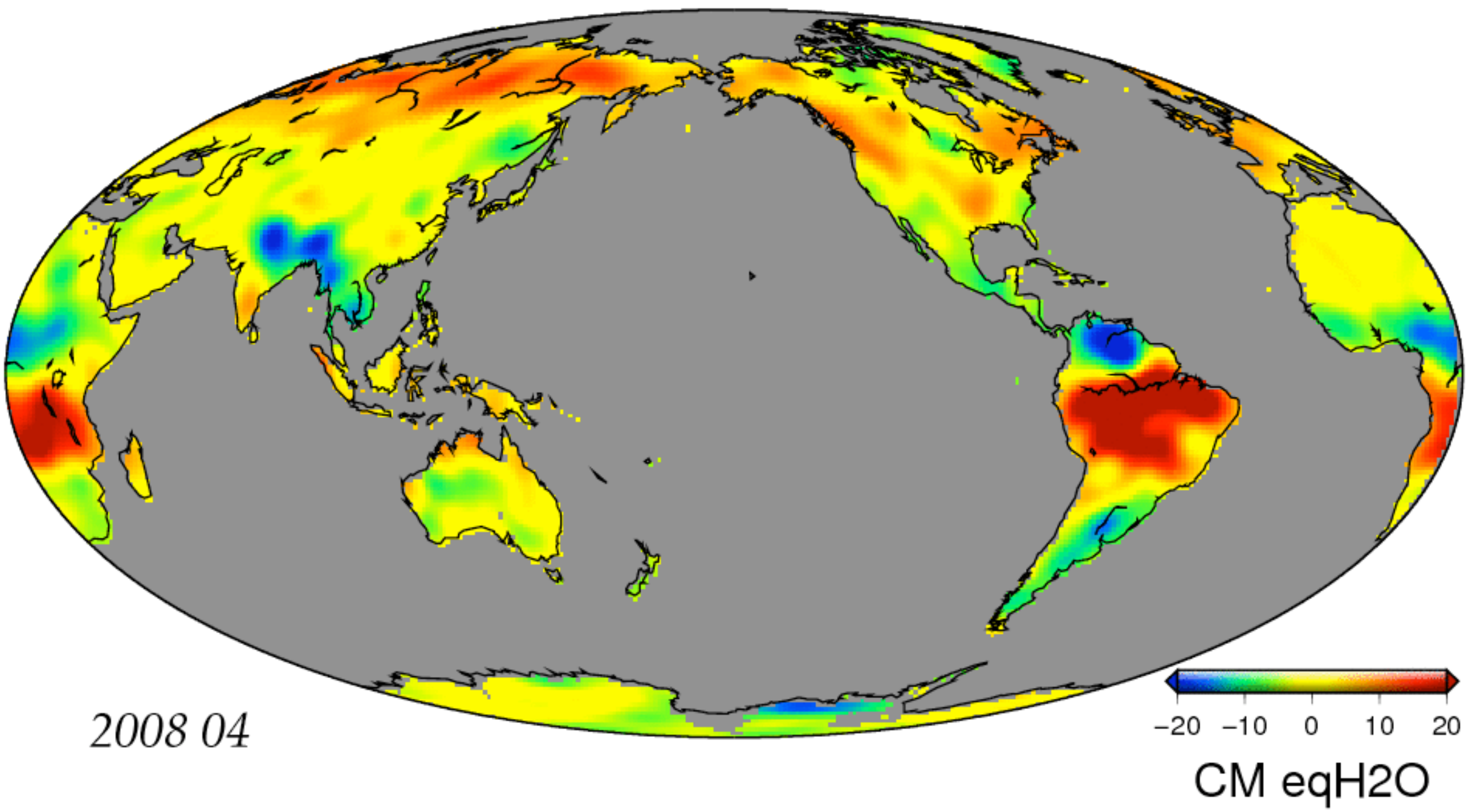
- The critical data from the GRACE satellites is the range rate measurement between the satellites (relative velocity along-track)
- The GRACE mission team provides these data and also monthly solutions for the gravity field in terms of spherical harmonic coefficients
- There are also other ways to parameterize gravity change or mass variations (e.g., mascons).

Ocean Mass Variations



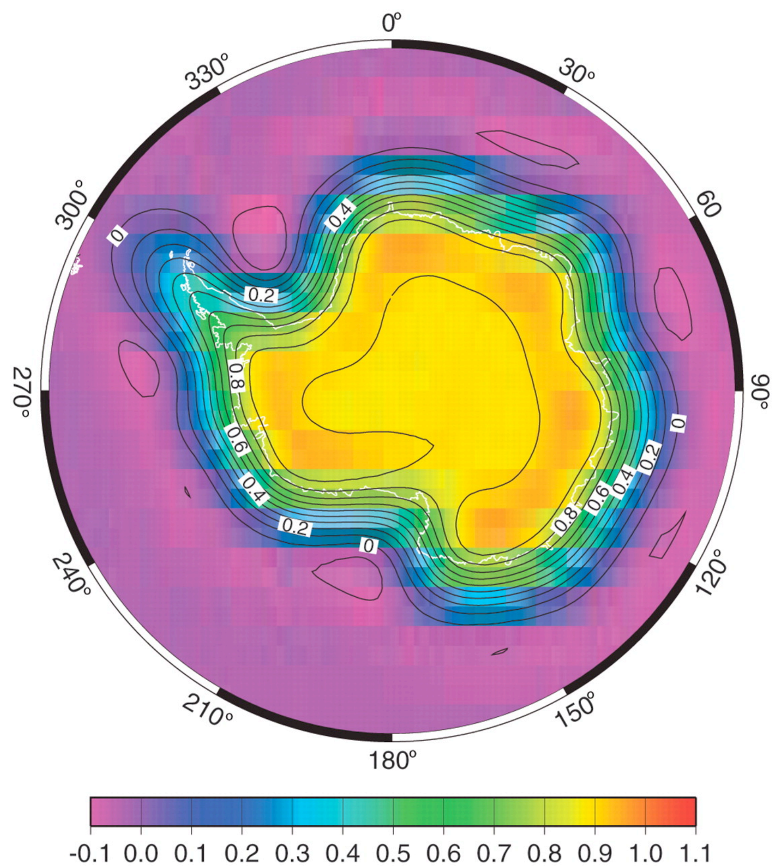
Source: GRACE Tellus website, JPL

Surface Mass Variations



Source: GRACE Tellus website, JPL

Estimating Greenland + Antarctica Mass Variations



Velicogna et al. (2006)

- Remove effects of post-glacial rebound from spherical harmonic coefficients.
- Remove land hydrology model from coefficients.
- Compute an 'averaging function' that relates integrated surface mass variations to the spherical harmonic coefficients (Wahr et al., 2008).


Tides

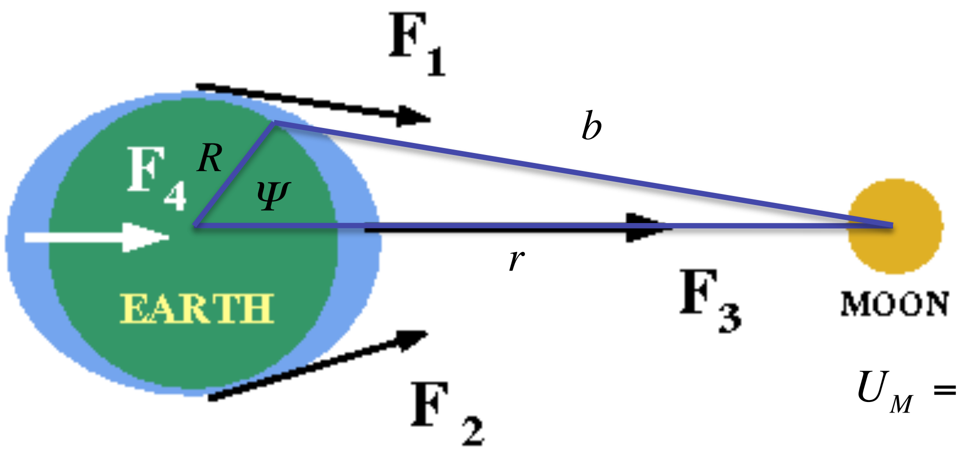
Response of Fluid

- Fluids can’t maintain “topography”, flow to equalize pressure
  - Fluid flows from high gravitational potential to lower potential (== “downhill”)
  - In real ocean, this flow takes time, so tides are not a perfect match to potential because of tidal currents
    - Tidal modeling involves solving fluid flow equations subject to changing potential.
    - We’ll ignore these details.

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

$$U_M = -\frac{GM_m}{b}$$

$$U_M = -\frac{GM_m}{r\left[1 + \frac{R^2}{r^2} + 2\frac{R}{r}\cos\Psi\right]^{1/2}}$$

$$U_M = -\frac{GM_m}{r}\left[1 + \frac{R}{r}\cos\Psi + \frac{R^2}{r^2}\left(\frac{3}{2}\cos^2\Psi - \frac{1}{2}\right) + \cdots\right]$$

Tidal Potential Terms

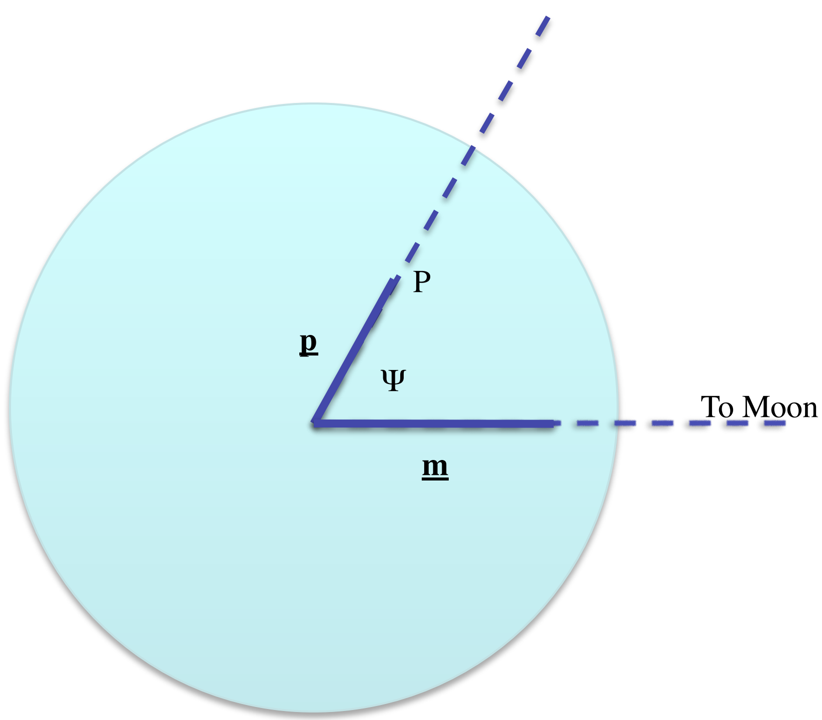
$$U_{M(1)} = -\frac{GM_m}{r}$$

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

$$U_{M(3)} = -\frac{GM_m}{r}\left[\frac{R^2}{r^2}\left(\frac{3}{2}\cos^2\Psi - \frac{1}{2}\right) + \cdots\right]$$

- 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.

Relation of Ψ to Lat-Long



$$\cos\Psi = \cos\theta\cos\theta_m + \sin\theta\sin\theta_m\cos(\varphi-\varphi_m)$$

- The angle Y is measured in the plane defined by the vectors **p** and **m**,
- Define (θ,ϕ) as as co-latitude + logitude of P
- Define (θ_m,ϕ_m) as co-latitude + longitude of Moon (varies)
- Longitude changes by 2π per day (non-rotating coordinate system)

$$\frac{1}{2}\left(3\cos^2\Psi-1\right) = \left(\frac{3\cos^2\theta-1}{2}\right)\left(\frac{3\cos^2\theta_m-1}{2}\right) + \frac{3}{4}\sin^2\theta\sin^2\theta_m\cos2(\varphi-\varphi_m) + \frac{3}{4}\sin2\theta\sin2\theta_m\cos(\varphi-\varphi_m)$$

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 2π, 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 2π, 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 ~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

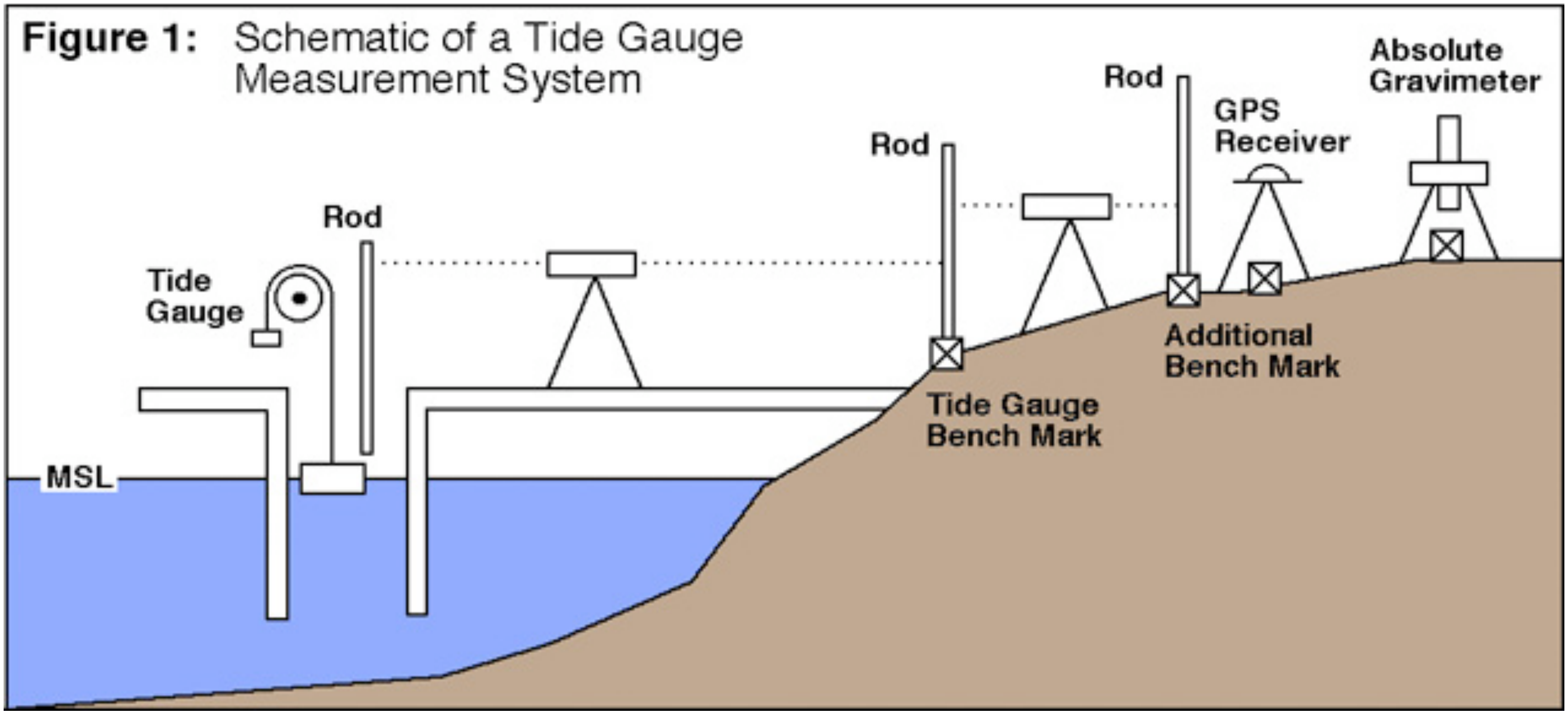
The M2 tide is very large in Alaska due to a resonance in the Gulf of Alaska

- Solar Tides
  - Semi-diurnal S2
  - Diurnal P1
  - Elliptical R2, T2
- See http://en.wikipedia.org/wiki/Theory_of_tides

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

Example Tide Gauge Site



Oldest continuous tide gauge site: Amsterdam, since 1700

Classical Float Gauge (from about 1832)

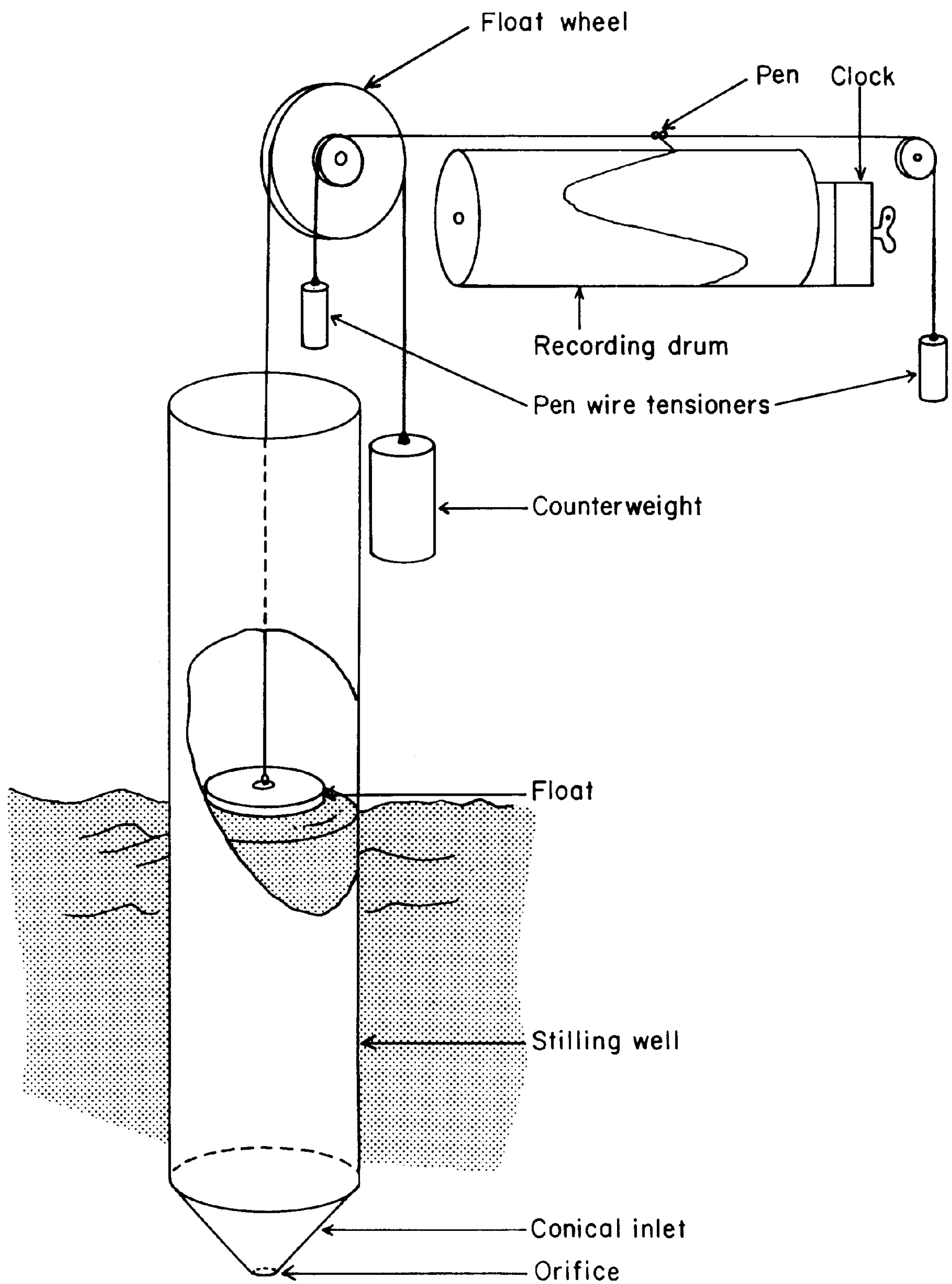


Figure 3.1

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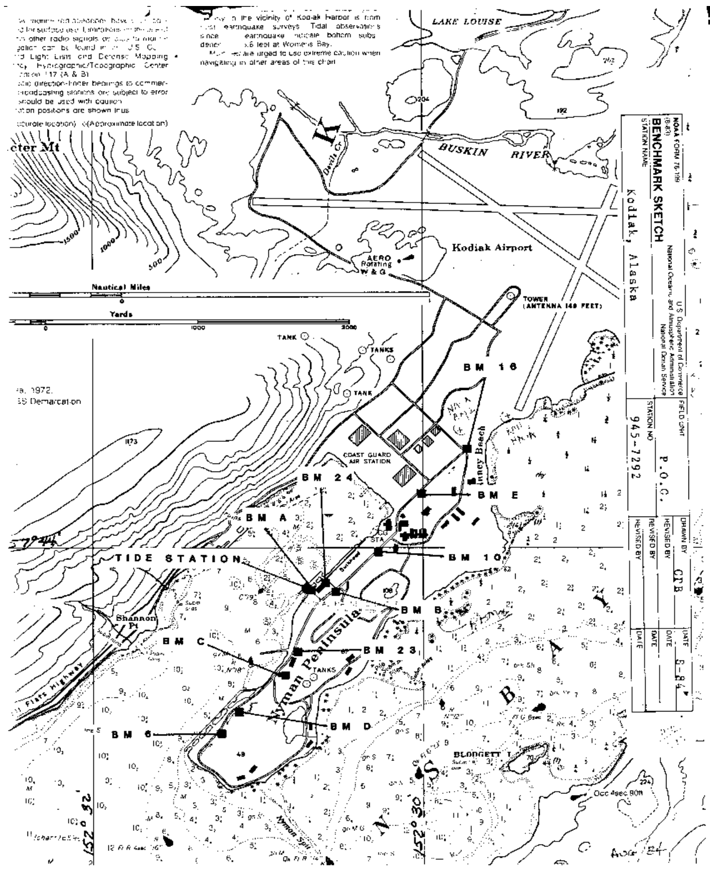
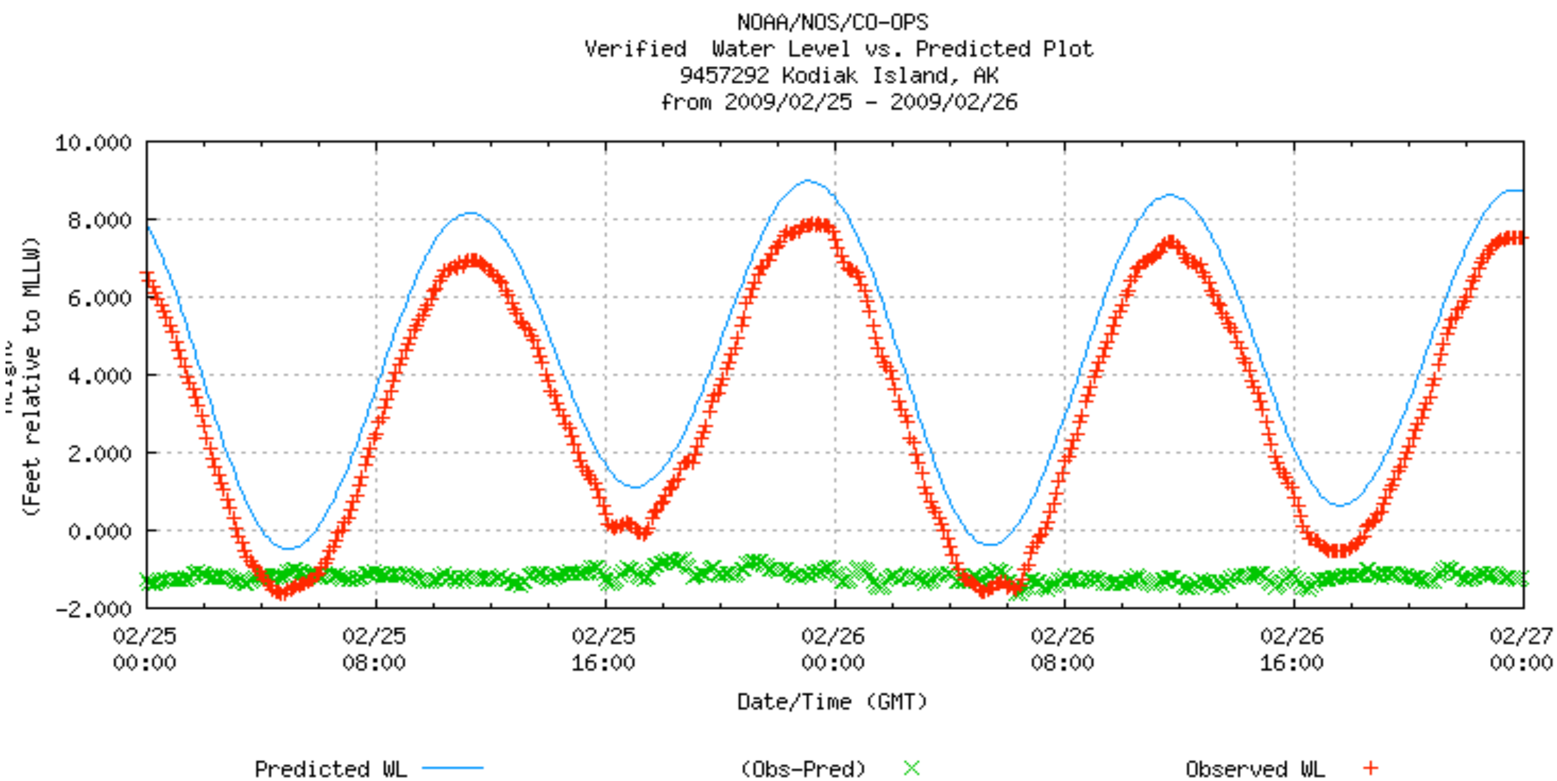
UK Float Gauge at Holyhead

Float gauges
are still important
and can be made
into digital gauges
with the use of
encoders

Example: Kodiak Tide Station



Sample Tide Data



A month of Tide Data