Tides and the Earth's Climate

or

As above, so below

Chris W. Hughes

University of Liverpool, and National Oceanography Centre

UNIVERSITY OF LIVERPOOL

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

A STORY IN THREE CHAPTERS

in which

Scientists from Merseyside

feature heavily.

Chapter 1: *Jeremiah Horrocks*

Jeremiah Horrocks

(1618 – 1641), Toxteth

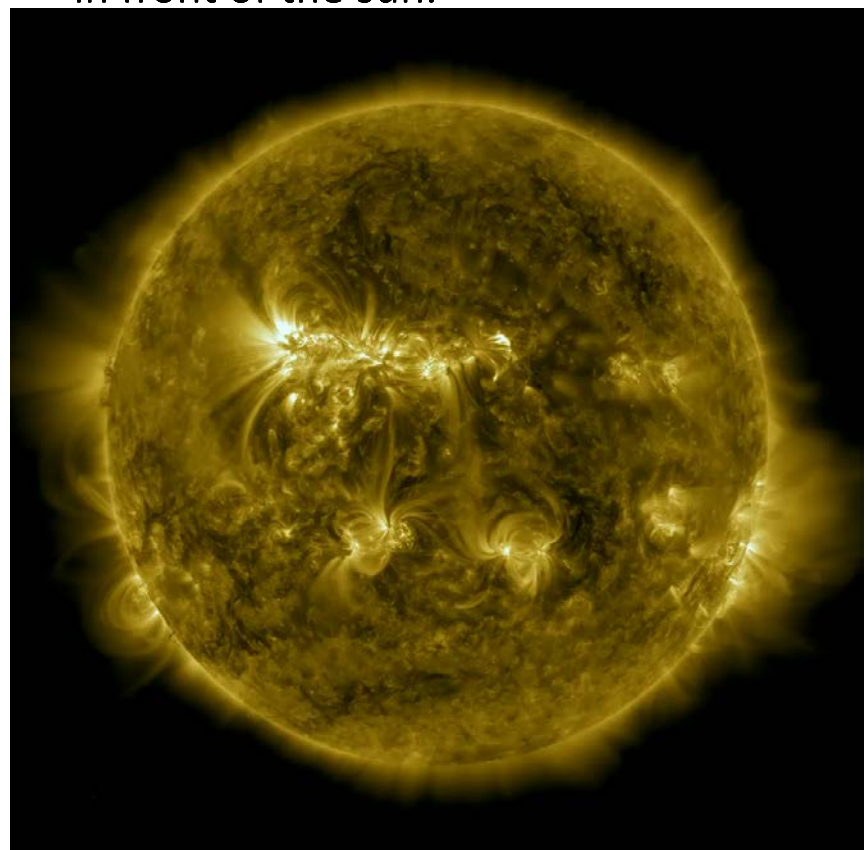
- The first person (with his Manchester friend, William Crabtree) to see a "transit of Venus" – the planet passing in front of the sun.

Transits happened in

1631	1639
1761	1769
1874	1882
2004	2012

The next pair will be in

2117	2125



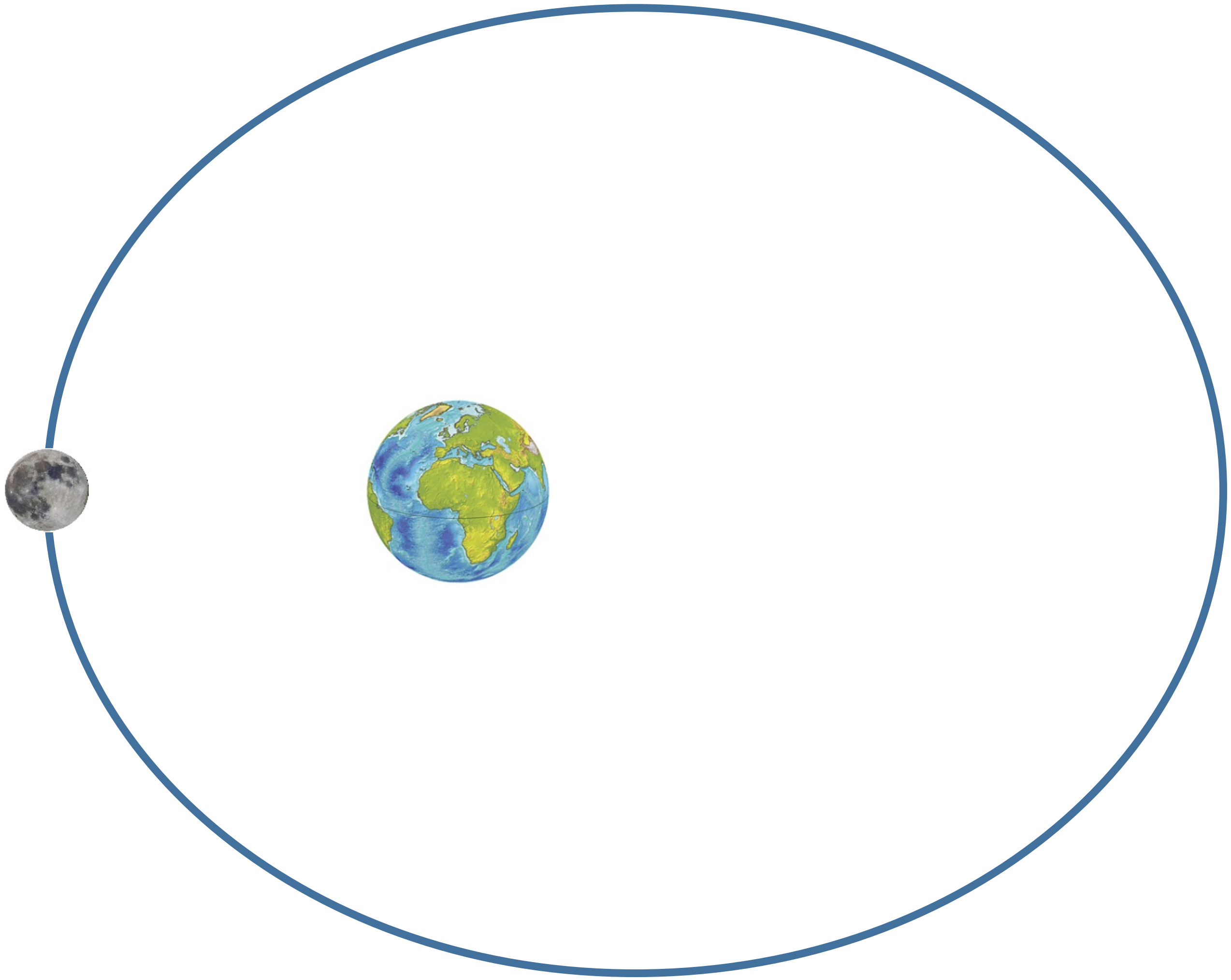
NASA Solar Dynamics Observatory 2012
(click here for movie)

This was before Newton was born, and while Galileo was arguing that the moon had nothing to do with tides.

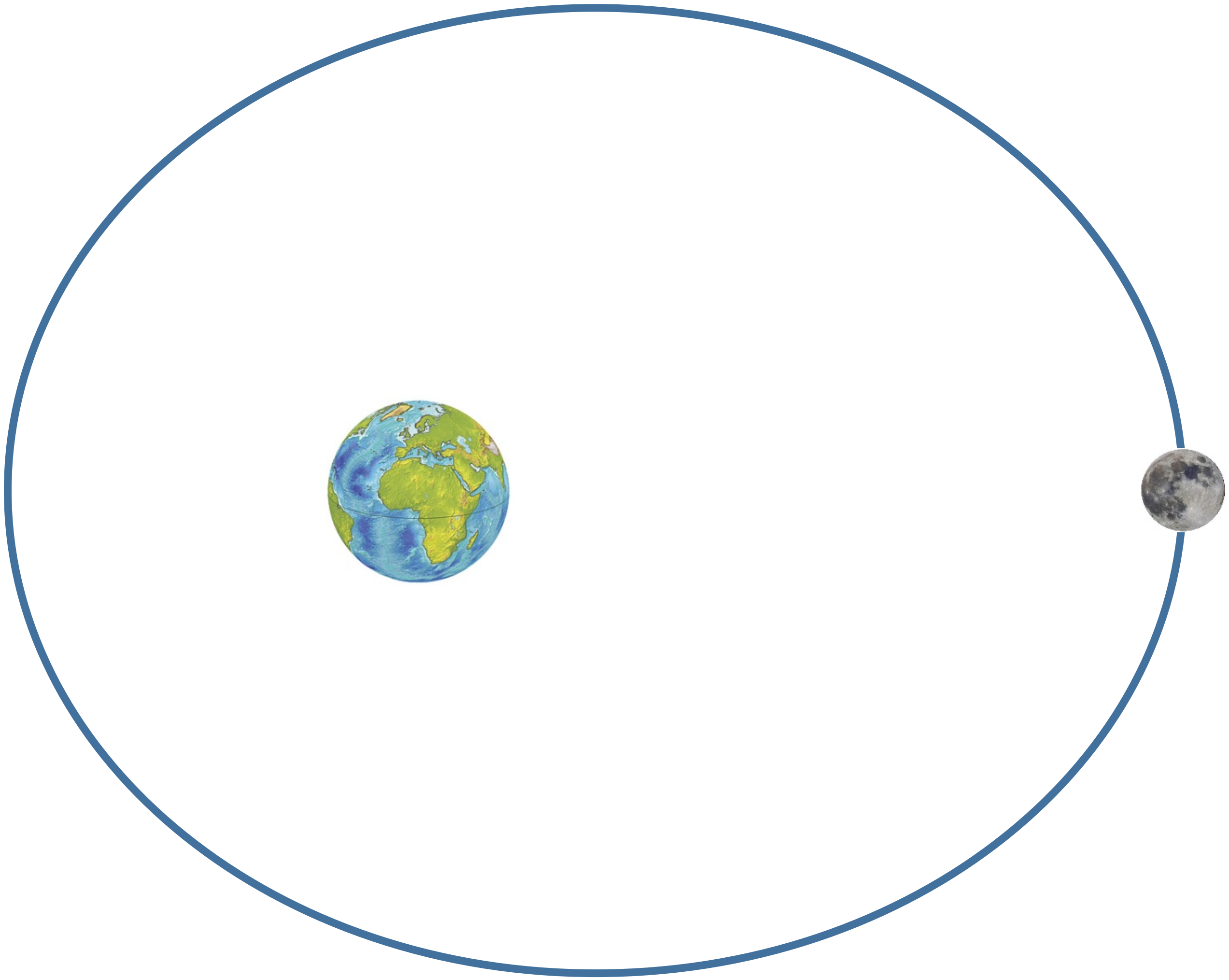
Jeremiah Horrocks (1618 – 1641)

- Used the transit, and other measurements, to estimate the size of the solar system (he was about 1.6 × too small, but the accepted number was about 20 × too small!)
- Theorized about comets, planetary orbits, gravity and motion.
- Made accurate observations of the moon's orbit, showing that the ellipse it moves in stretches, shrinks, and oscillates in direction.
- Had a big influence on the early years of the Royal Society (1660s, after his death).
- Was later praised by Newton in his Principia for the accuracy of his lunar theory.
- Suggested that Saturn and Jupiter influenced each other's orbits.
- Suggested that subtleties in the tides might reflect subtleties in the moon's orbit, and set about measuring them in the Mersey.

Perigean tides (when moon is at perigee, its closest approach to the Earth).



Tides are bigger than normal, so if this coincides with full or new moon (spring tides) it means the tides can be very large (perigean springs).
This situation has recently become known as a "supermoon", for full moon.

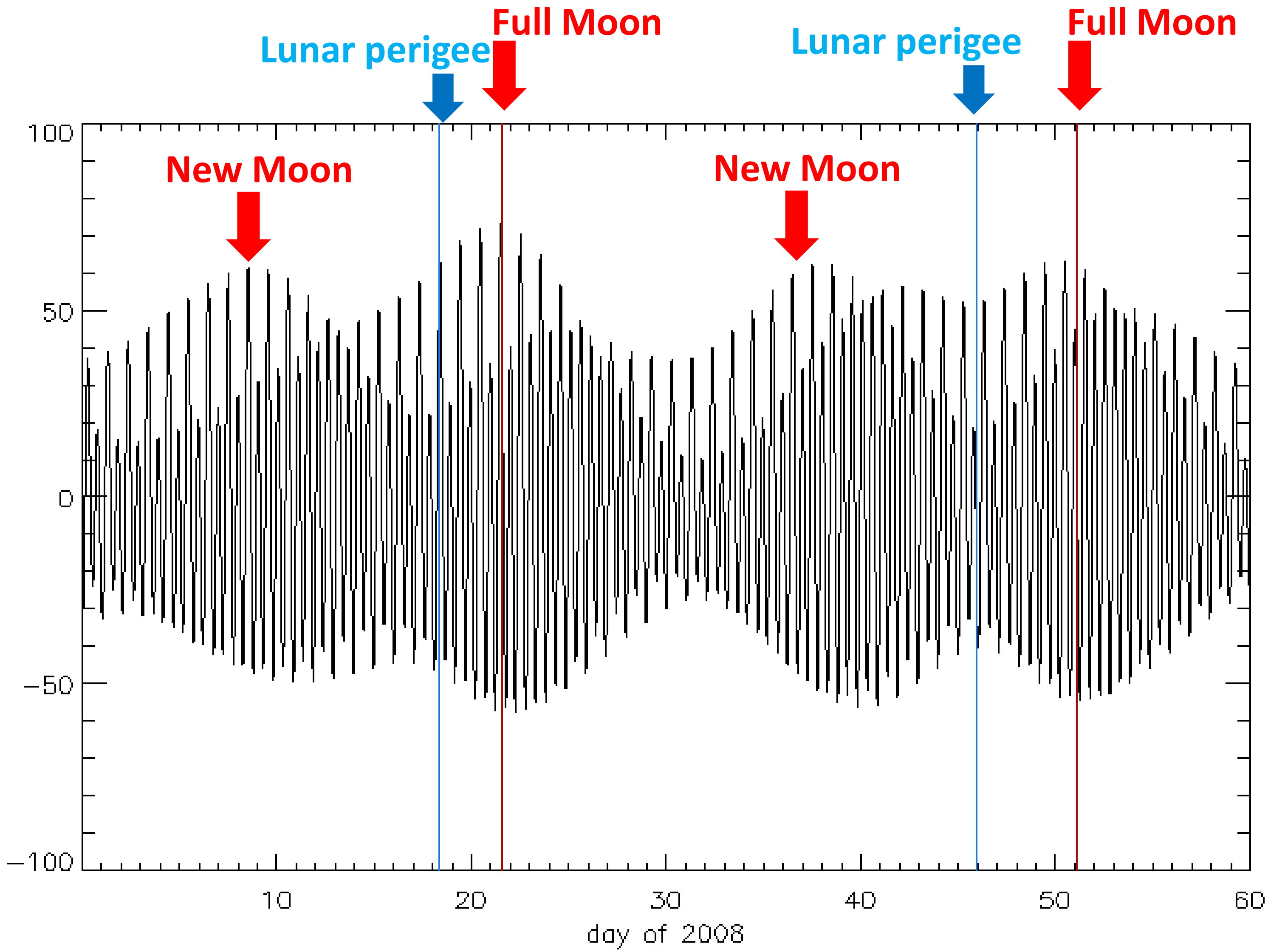


A couple of weeks after a supermoon, it is new moon (spring tides again), but now the moon is at its furthest point (apogee), so these spring tides are less high than usual springs.

How the moon appears from Earth, either side of a supermoon

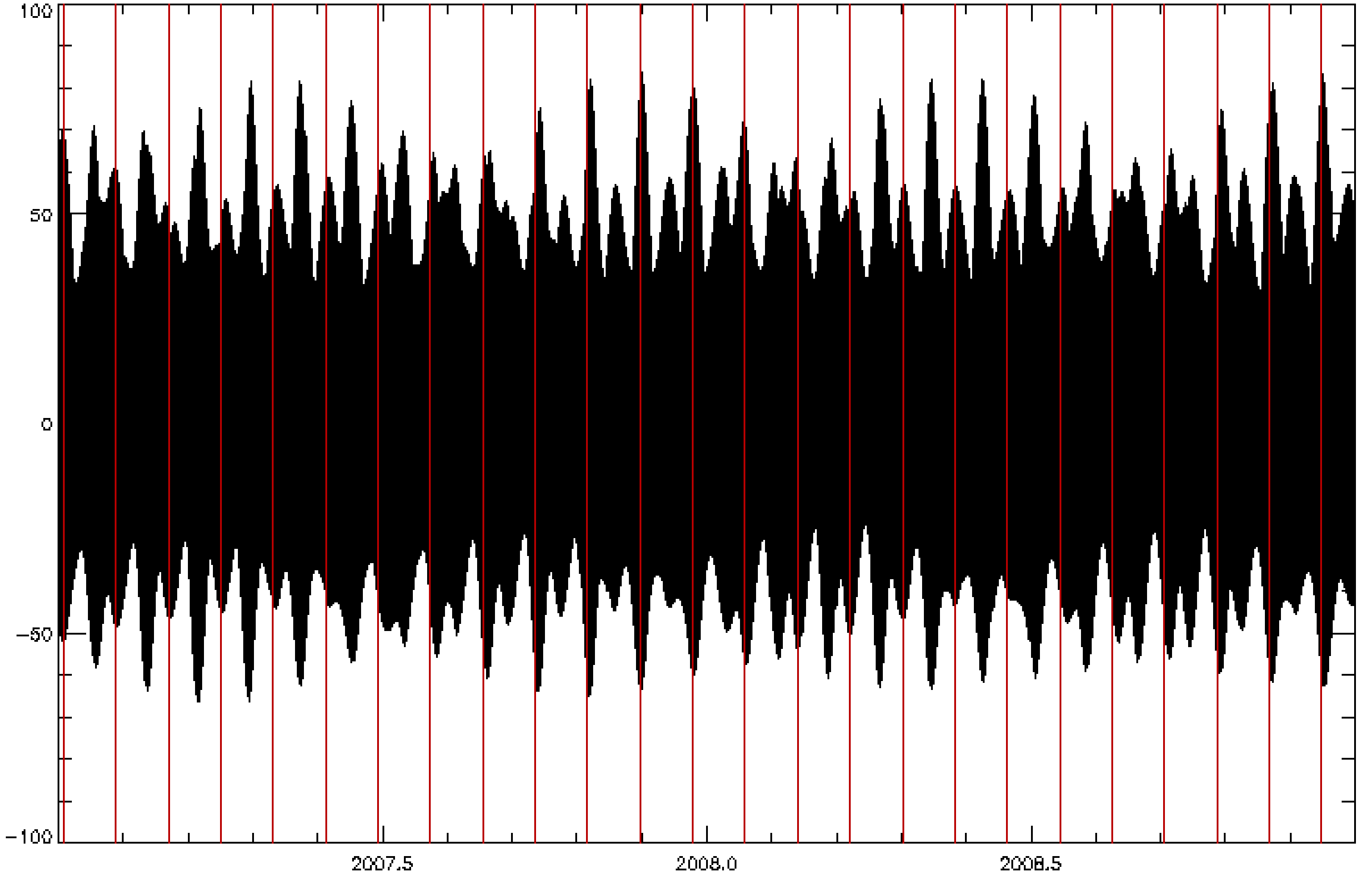
Animation: Tomruen (wikipedia).
(click here for movie)

The tide at a spot off the coast near Boston



Spring-neap cycle (largest tides at full and new Moon)

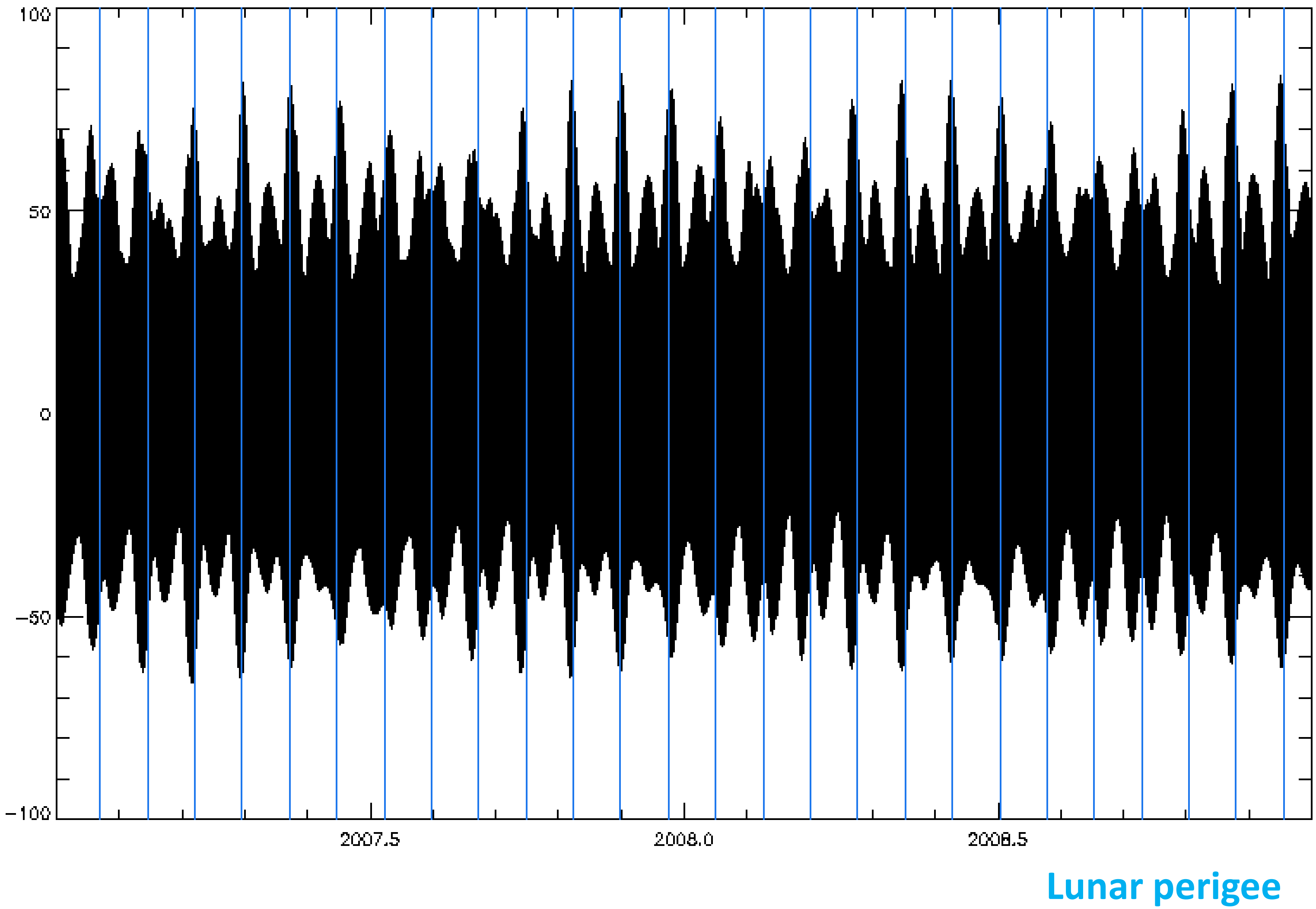
The tide at a spot off the coast near Boston



Full Moon

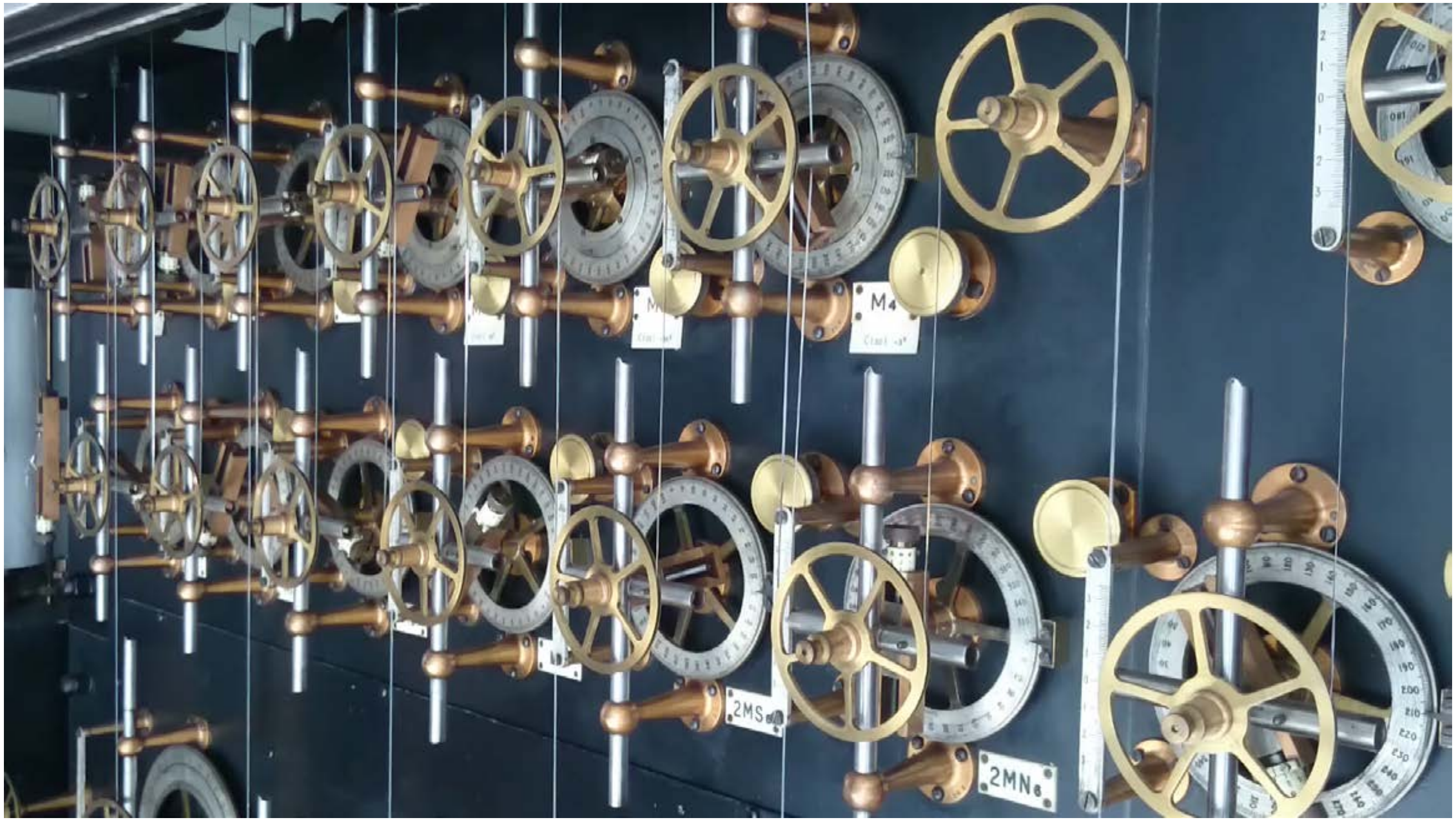
Highest tides each month are near either full moon (red lines) or new moon (half way between red lines)

The tide at a spot off the coast near Boston



The higher of the two spring tides each month occurs for the full or new moon which occurs closest to lunar perigee. When perigee falls half way between full and new moon, both sets of springs have similar size, but neither is very high.

click here for video



Horrocks was right – the changing shape and orientation of the moon's orbit affect the tides, and are reflected in the many constituents we now use to represent the tide, as used in this Liverpool mechanical tide predicting machine.

This has little to do with climate, but it's the start of an idea that does: Understand the moon's motion, and you understand something about the oceans.

Chapter 2: Longitude of the moon

In 1695, Edmond Halley (the comet man, and much besides) wrote a paper about the Syrian city of Palmyra:

III. *Some Account of the Ancient State of the City of* Palmyra, *with ſhort Remarks upon the Inſcriptions found there.* By E. Halley.

poſe. And if any curious Traveller, or Merchant reſiding there, would pleaſe to obſerve, with due care, the *Phaſes* of the *Moons Eclipſes* at *Bagdat*, *Aleppo* and *Alexandria*, thereby to determine their Longitudes, they could not do the Science of *Aſtronomy* a greater Service: For in and near theſe Places were made all the Obſervations whereby the Middle Motions of the *Sun* and *Moon* are limited: And I could then pronounce in what Proportion the *Moon*'s Motion does Accelerate; which that it does, I think I can demonſtrate, and ſhall (God

(God willing) one day, make it appear to the Publick.

… he never did, but it was the start of a long investigation

Through the 18th century, observations and theory developed dramatically.

Richard Dunthorne estimated lunar longitude to be accelerating at 10 arcseconds per century per century.

In 1787, Laplace showed that this could be explained purely in terms of solar system dynamics, and was associated with slow changes in the Earth's orbit.

In 1853, John Couch Adams improved on Laplace's calculation, and showed that in fact it did not explain the observed acceleration. This took a few years to be accepted, but in the end it was agreed.

So what was missing?

In 1754, the philosopher Immanuel Kant wrote a prize essay suggesting the answer:

Examination of the Question

whether

the Rotation of the Earth on its Axis

by which it

Brings About the Alternation of Day and Night

has Undergone any Change Since its Origin

and

How One Can be Certain of This,

which

was set by the Royal Academy of Sciences in Berlin

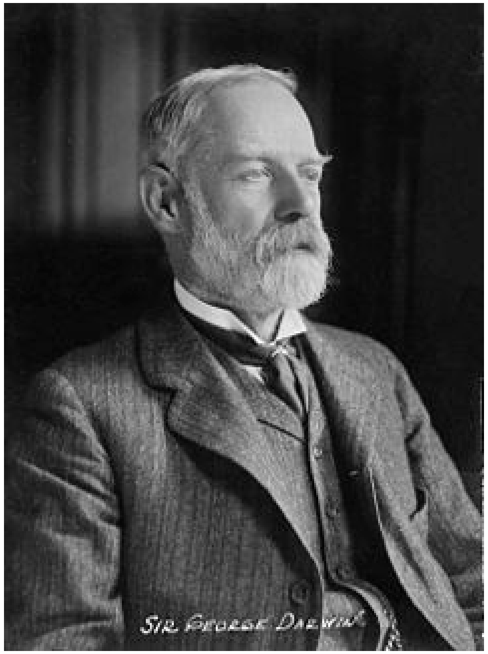
as the Prize Question

for the Current Year.

Kant argued that:

> some change in the rotation. The attraction of the Moon, which has the greatest part in this effect, keeps the waters of the ocean[s] in constant upward motion, whereby the water endeavours to flow to and rise at the points immediately beneath the Moon both on the side facing it and also on the opposite side; and because these points of high water move from east to west, they impart a constant current in this direction to all the water of the world's oceans. The experience of sailors has long since removed any doubt concerning this general motion, and it is observed most clearly in straits and bights where the water increases its speed because it has to pass through a narrow passage. Since this current is exactly opposite to the direction of the Earth's rotation, we have a cause which we surely rely on ceaselessly to weaken and reduce this rotation as much as is in its power.

Wrong, but the right idea: tidal friction must be extracting energy from the Earth's rotation, slowing it down – the moon isn't accelerating, the Earth is slowing.



A lot of this was reconciled in the late 19th century by George Darwin (son of Charles)

He showed that the Earth's rotation is the energy source of the tides: any friction in the tide means the Earth must slow down, and days get longer.

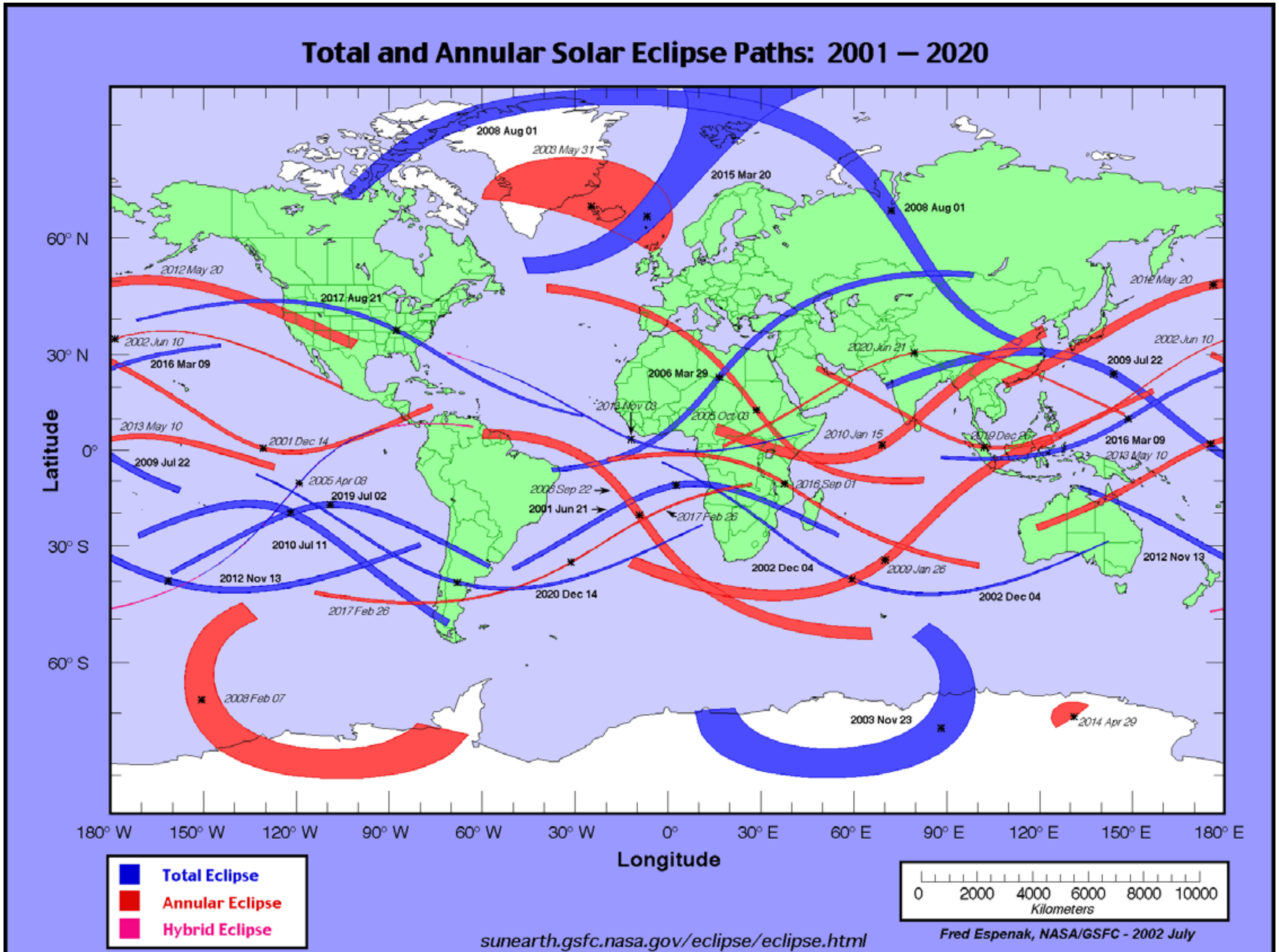
At the same time, angular momentum must be conserved: if the Earth spins more slowly, the moon must gain angular momentum.

It turns out, that higher orbits have more angular momentum, so the moon must be drifting away.

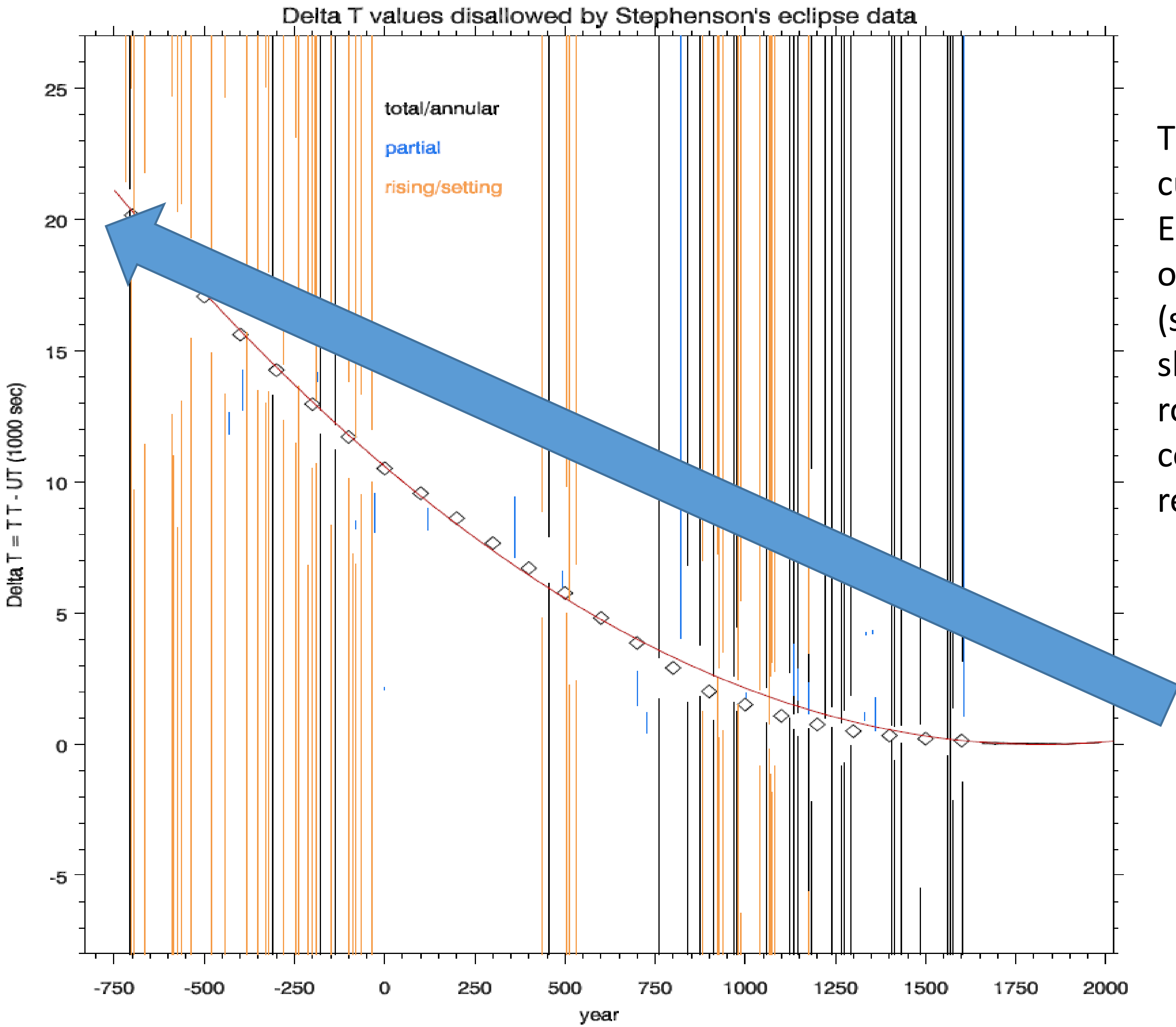
The rate of slowing of the Earth, and of recession of the moon, are both ways to measure the energy dissipated by the tide.

How can we check this?

Total solar eclipses have very narrow tracks. If the Earth turned a bit more slowly over time, then they would be visible in quite different places – back to Halley and Palmyra

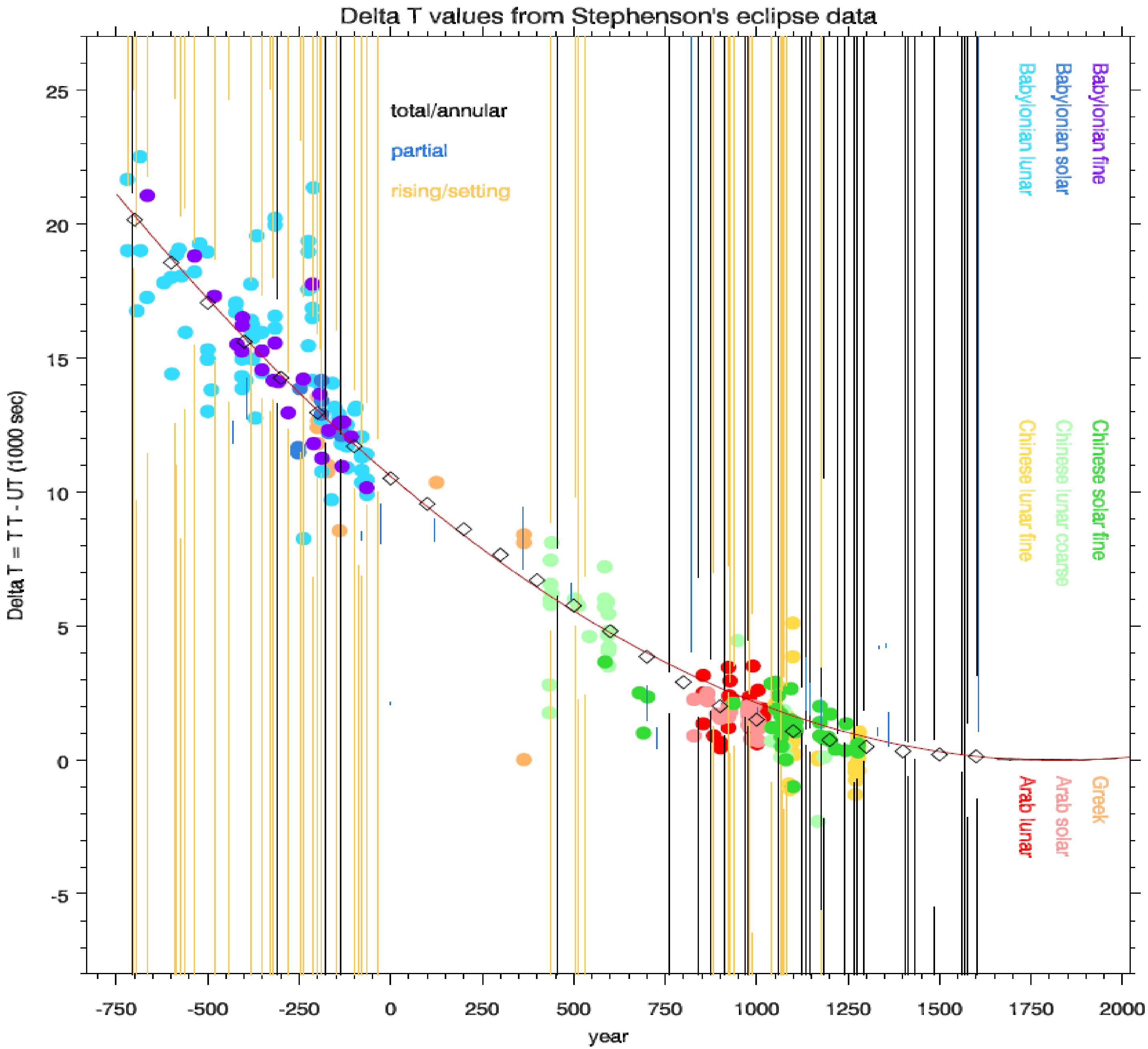


Richard Stephenson has looked at hundreds of ancient records of eclipses, and worked out how much the Earth must have slowed since they occurred



The smooth curve shows how Earth has slowed over time (steeper slope shows faster rotation, compared to recently)

20,000 seconds is 5.556 hours, during which time the Earth has turned through 83.333 degrees.



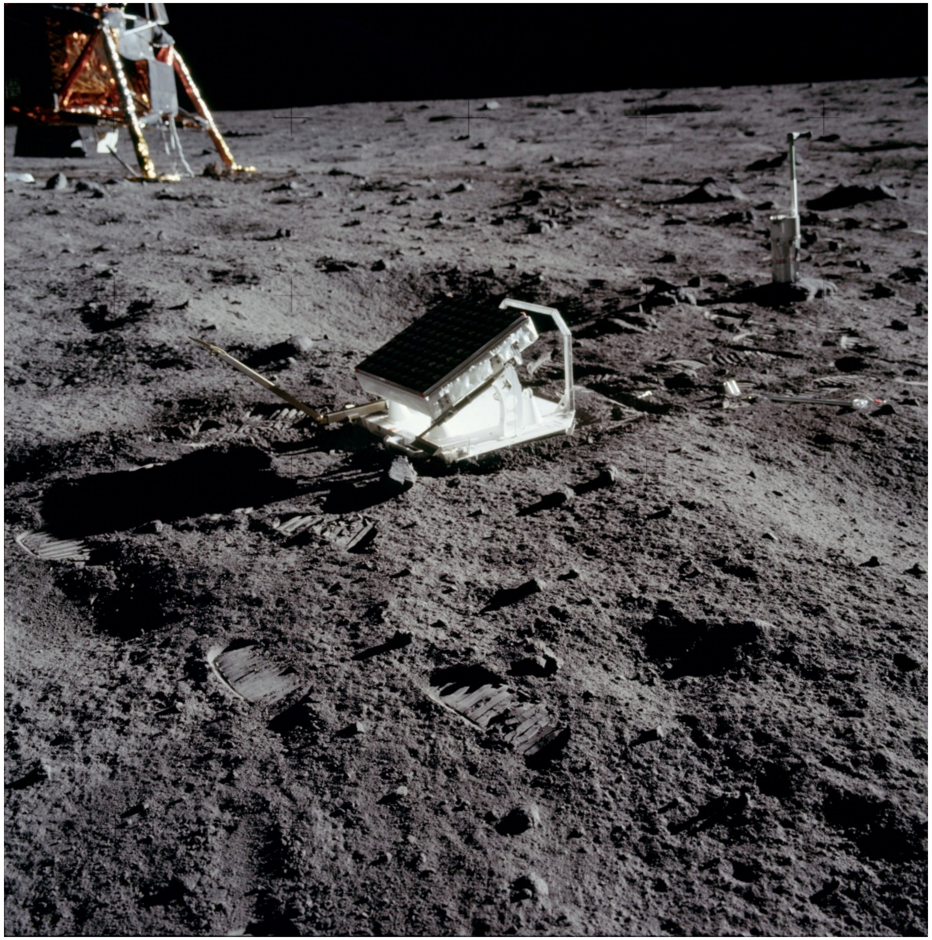
Adding in lunar eclipses shows that it is all consistent.

How about distance to the moon?

There are 5 of these on the moon, left by Apollo 11, 14 and 15, and the Soviet Luna 17 and 21.

They are retroreflectors – they bounce light back to where it came from.

Laser ranging to the moon has now established that it is drifting away at 3.8 cm per year.



Put together, we find:

- The length of day is increasing by 2 milliseconds per century.
- This implies the tides are dissipating energy at a rate of 3.5 TW (a terawatt is 10^{12} watts, or 1000 gigawatts).
- The moon is drifting away at 3.8 cm per year.
- This implies that the lunar tides are dissipating energy at a rate of 2.5 TW.
- More recently, satellite orbits and accurate maps of the tides have allowed us to confirm these numbers in several other ways.
- By looking at the moon, we can measure how much energy is dissipated by the tides, throughout the entire ocean.

Chapter 3: What does that energy do in the ocean?

The Dissipation of Energy in the Tides in Connection with the Acceleration of the Moon's Mean Motion.

By R. O. STREET, M.A., The University, Liverpool.

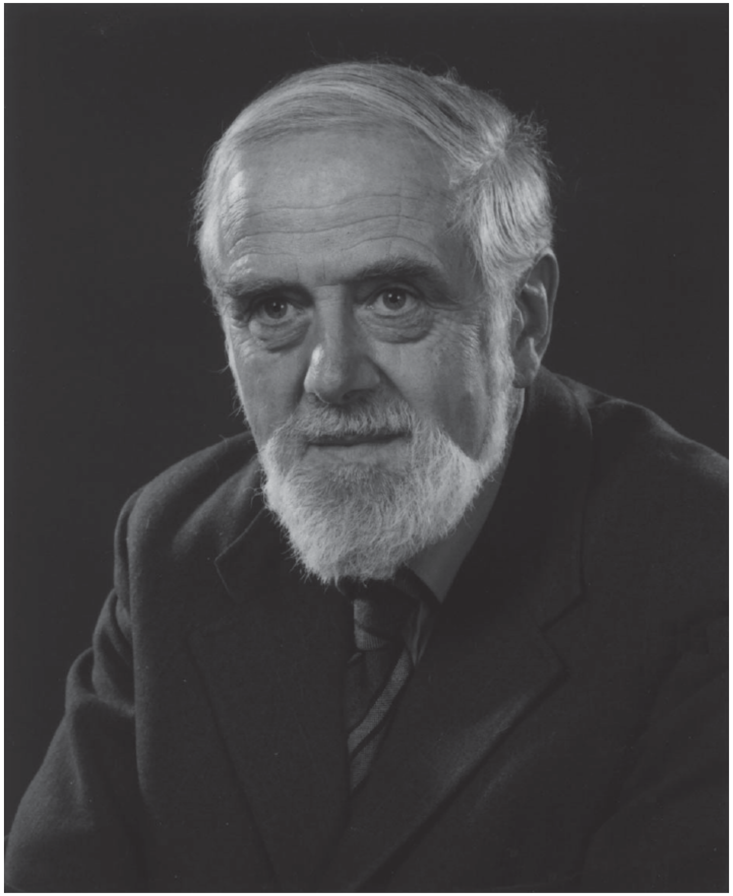
(Communicated by Sir Joseph Larmor, F.R.S. Received February 12, 1917.)

Reginald Street asked the question: Can friction in shelf seas provide the dissipation needed to explain the astronomical observations.

In this first paper, the answer was "not unless we assume the flow is turbulent".

His intention was to move onto calculations of the turbulent case, but war intervened.

By the time he returned, the Cambridge scientists G. I. Taylor and Harold Jeffreys had done the calculation, and concluded "yes", but with huge uncertainties.



Prof David Cartwright FRS

Head of the Bidston Observatory branch of the Institute of Oceanographic Science (IOS)

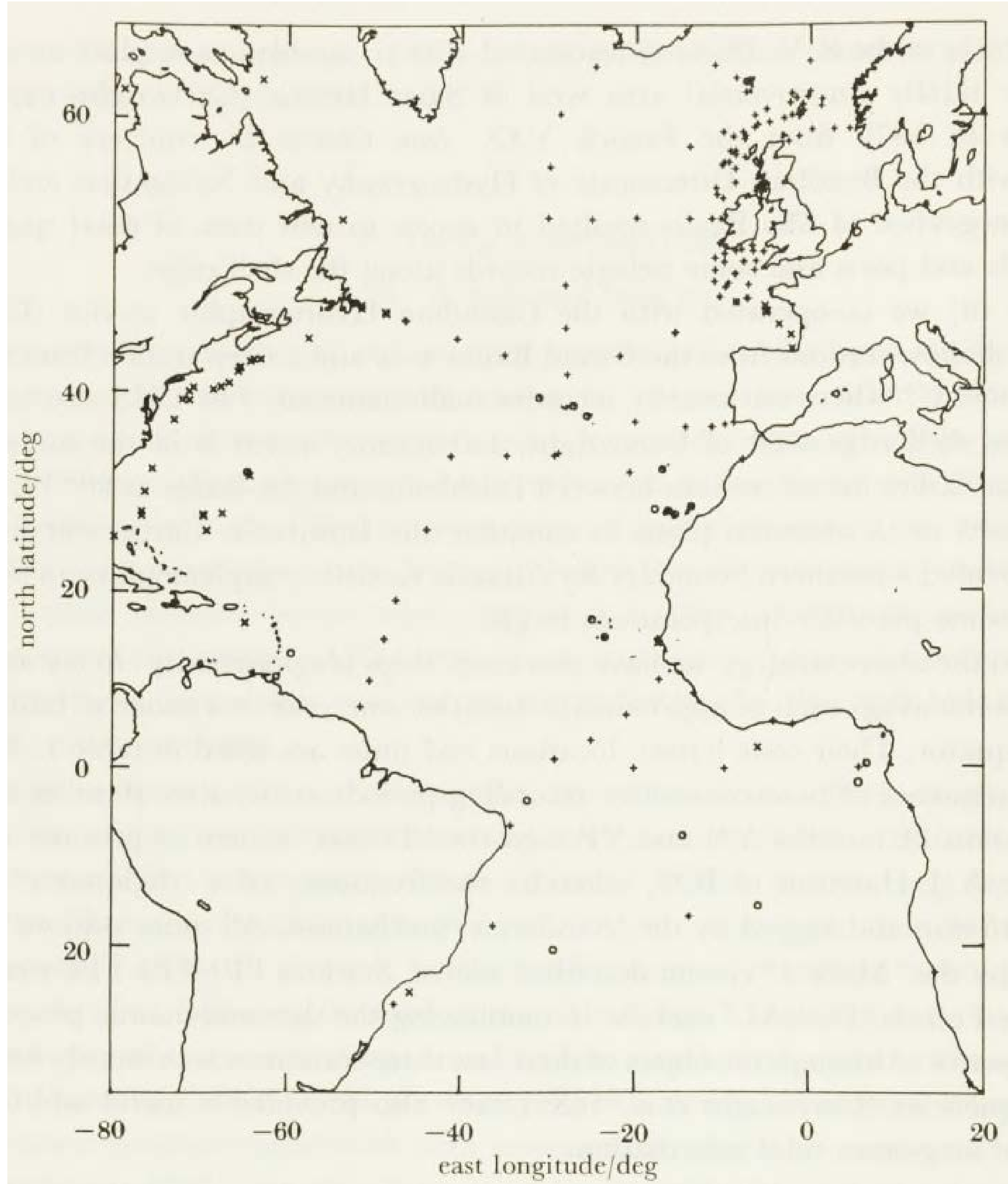
Oversaw a wide range of observations to improve knowledge of the tides

Developed (with Walter Munk and Richard Ray) methods of analysis suited to short time series or satellite observations

Made a large contribution to reducing those uncertainties.

The open ocean tidal measurements before satellites.

+ shows measurements made by IOS (all those on the UK shelf, and most of those far from land)



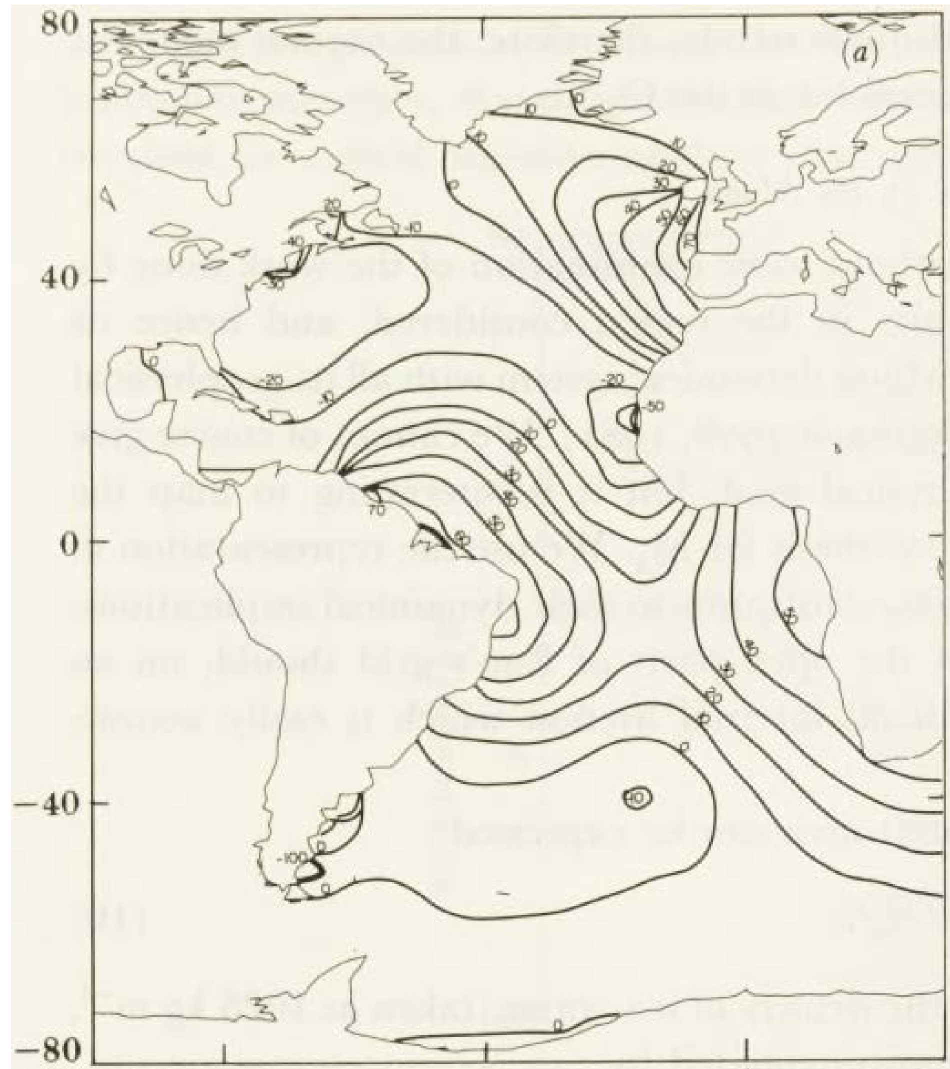
Cartwright et al., Phil. Trans. Roy. Soc. Lond. (1989)

and Cobh (Eire), reproduced in table 3, as definitive, we deduce the following figures for the dissipation in the English Channel and southern part of the Celtic Sea.

Integrals (9): $190.0 - 44.9 - 16.7 = 128.4$ GW;

integrals (10): $183.0 - 45.1 - 16.2 = 121.7$ GW.

The rate of work done by the moon on the M2 tide (kW m^{-2})

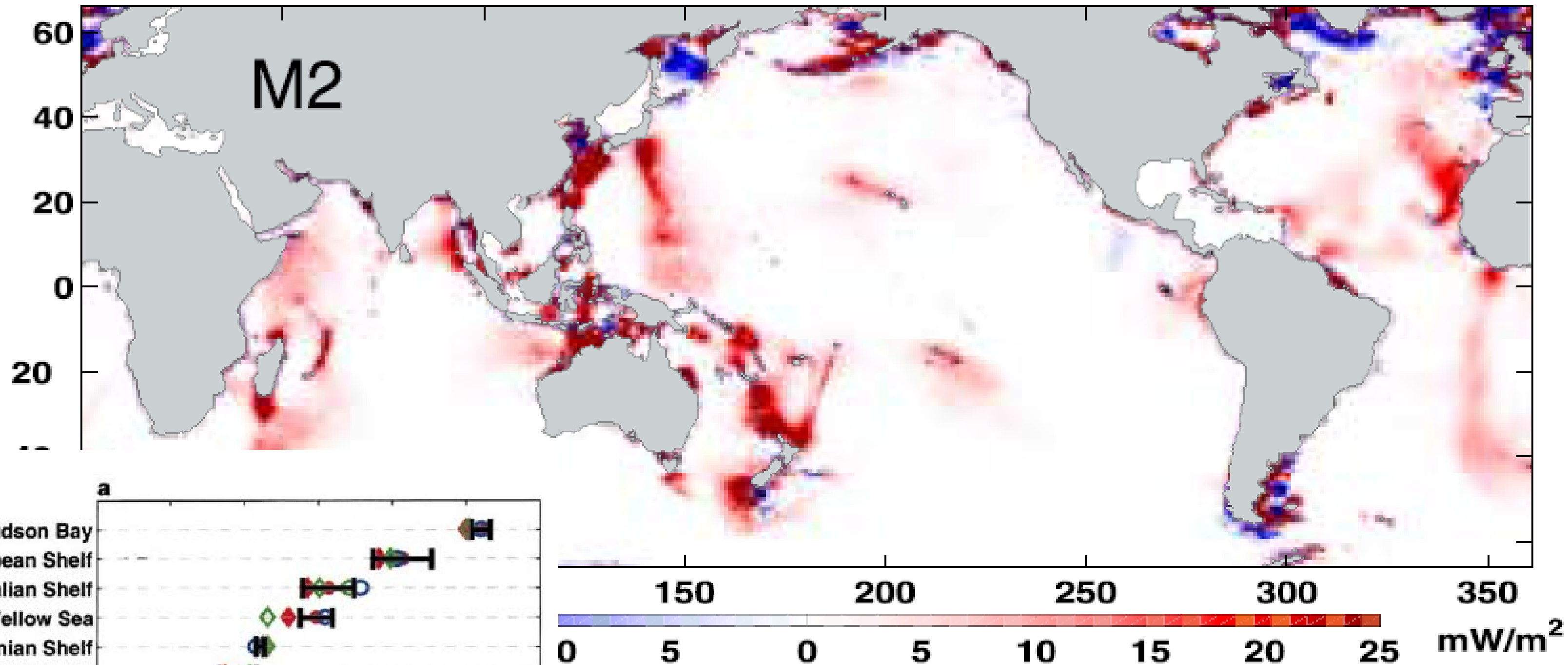


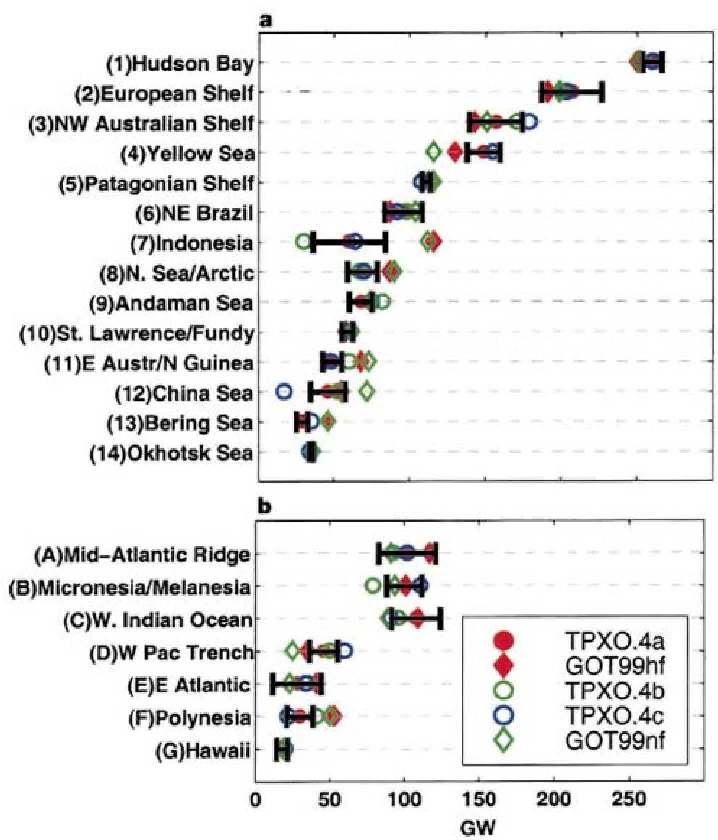
Cartwright et al., Phil. Trans. Roy. Soc. Lond. (1980; 1989)

But, to go further, satellite observations were needed.

Satellite altimetry began with rough measurements in the 1970s, much improved in the 1980s, but really accurate sea level data became available from 1993.

Cartwright, Richard Ray, and Gary Egbert developed techniques to use these measurements to learn about the tidal dissipation.





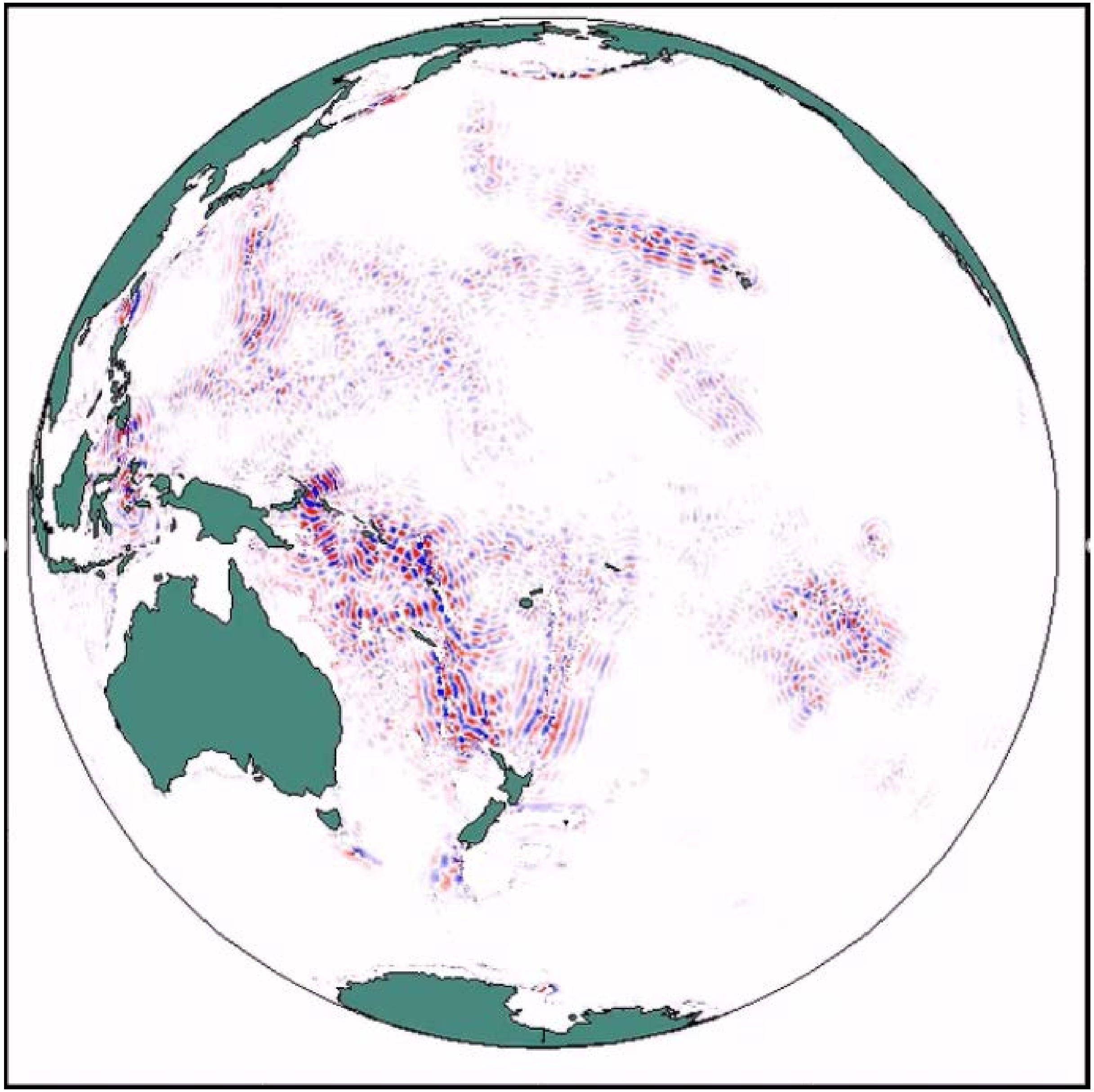
Tidal dissipation:

Total	3.51 TW
Shallow water	2.48 TW
Deep water	1.03 TW

A lot of this "dissipation" of the tide is in fact generation of the internal tide.

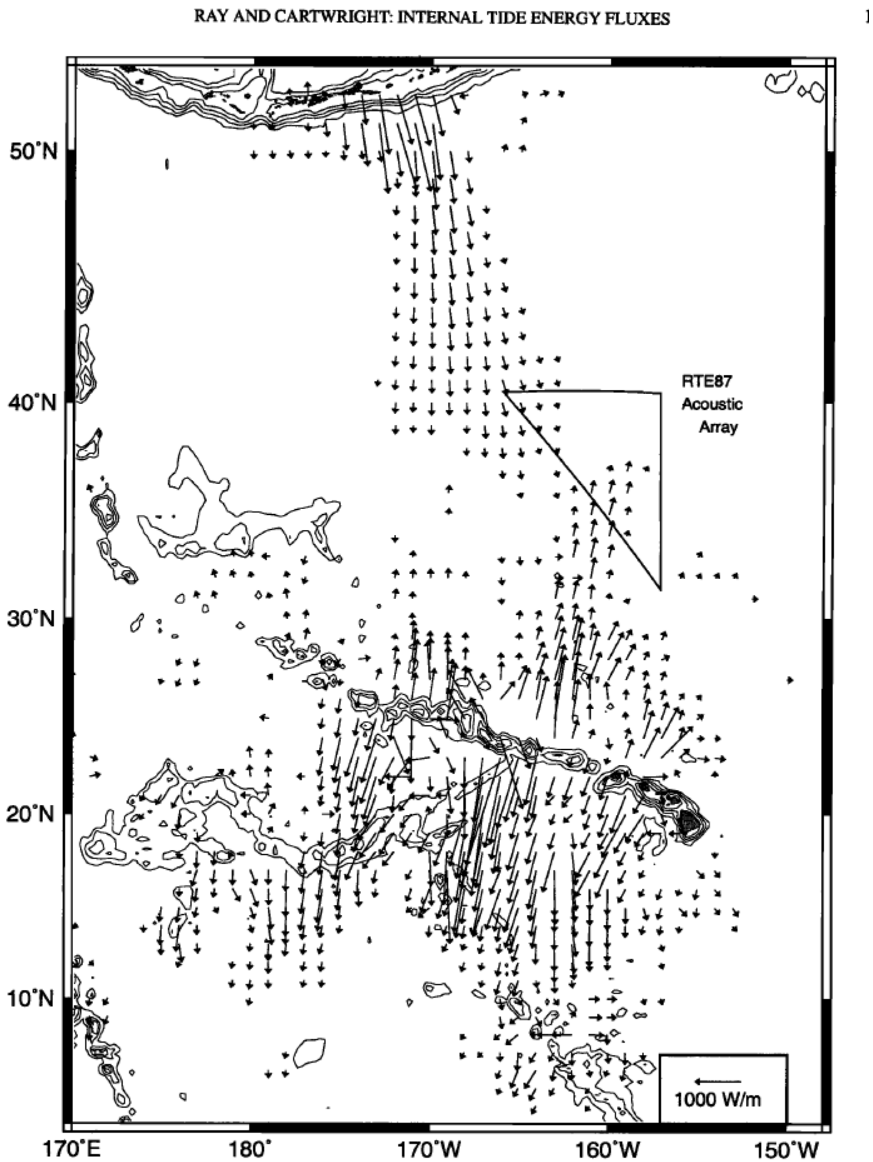
Egbert and Ray, Nature, 2000; GRL 2003

The internal tide in an ocean model, building up after the tides have been turned on



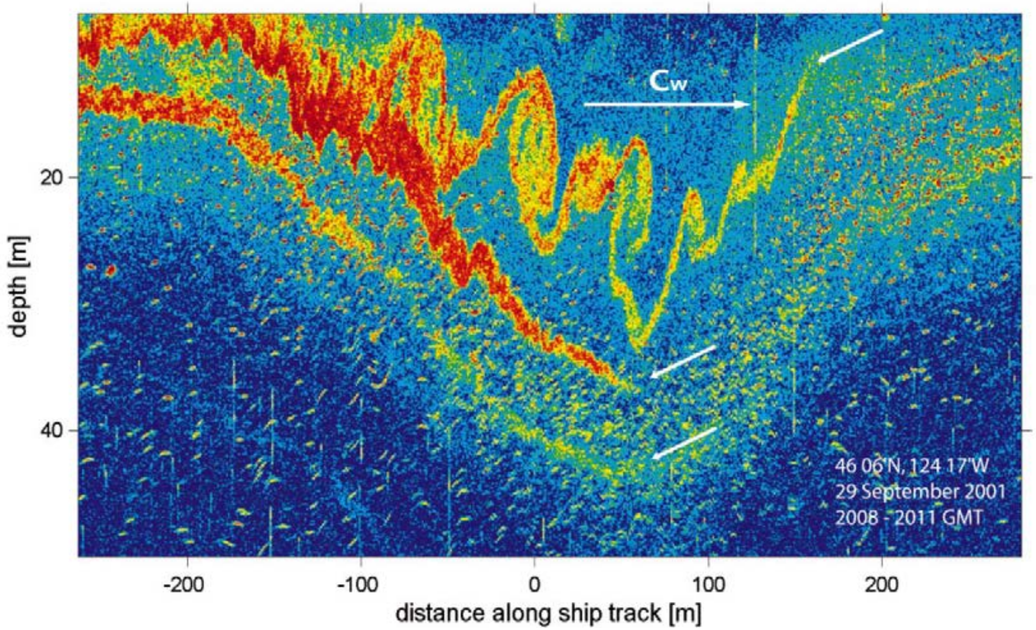
Courtesy Bob Hallberg, GFDL

(movie not available in pdf, please see the video record of the meeting)



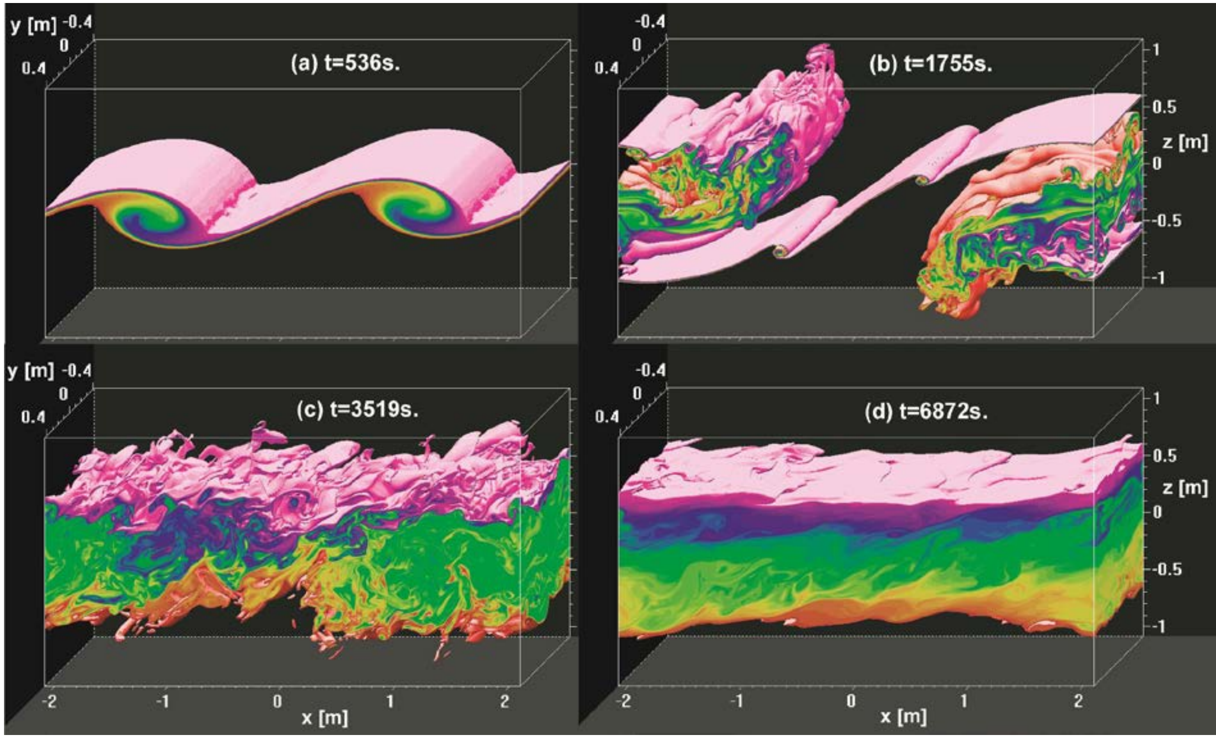
The observed energy flux of internal tides, near Hawai'i.

… but what happens to the internal tide energy?

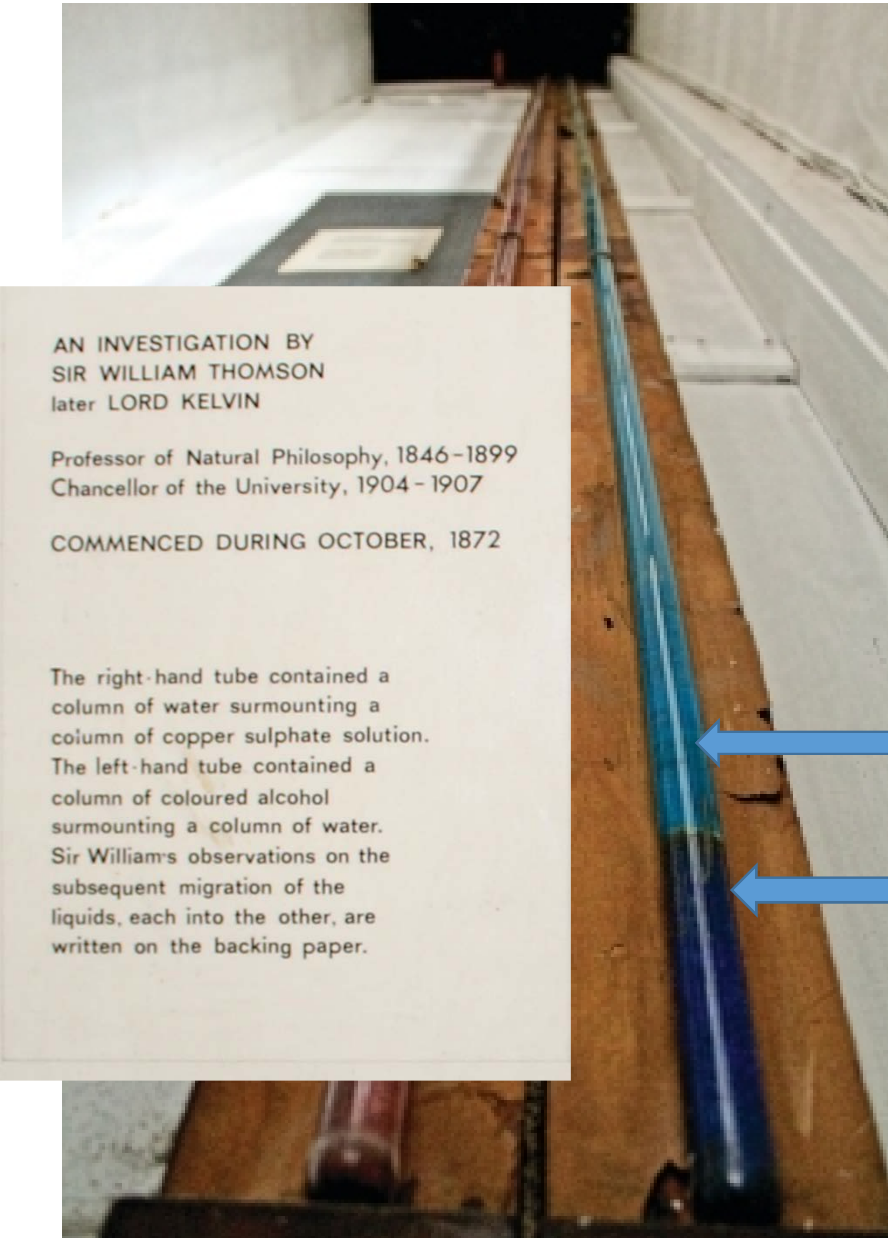


These internal tides are waves that break, and mix the ocean.

Mixing is important!



Smyth and Moum, TOS, 2012



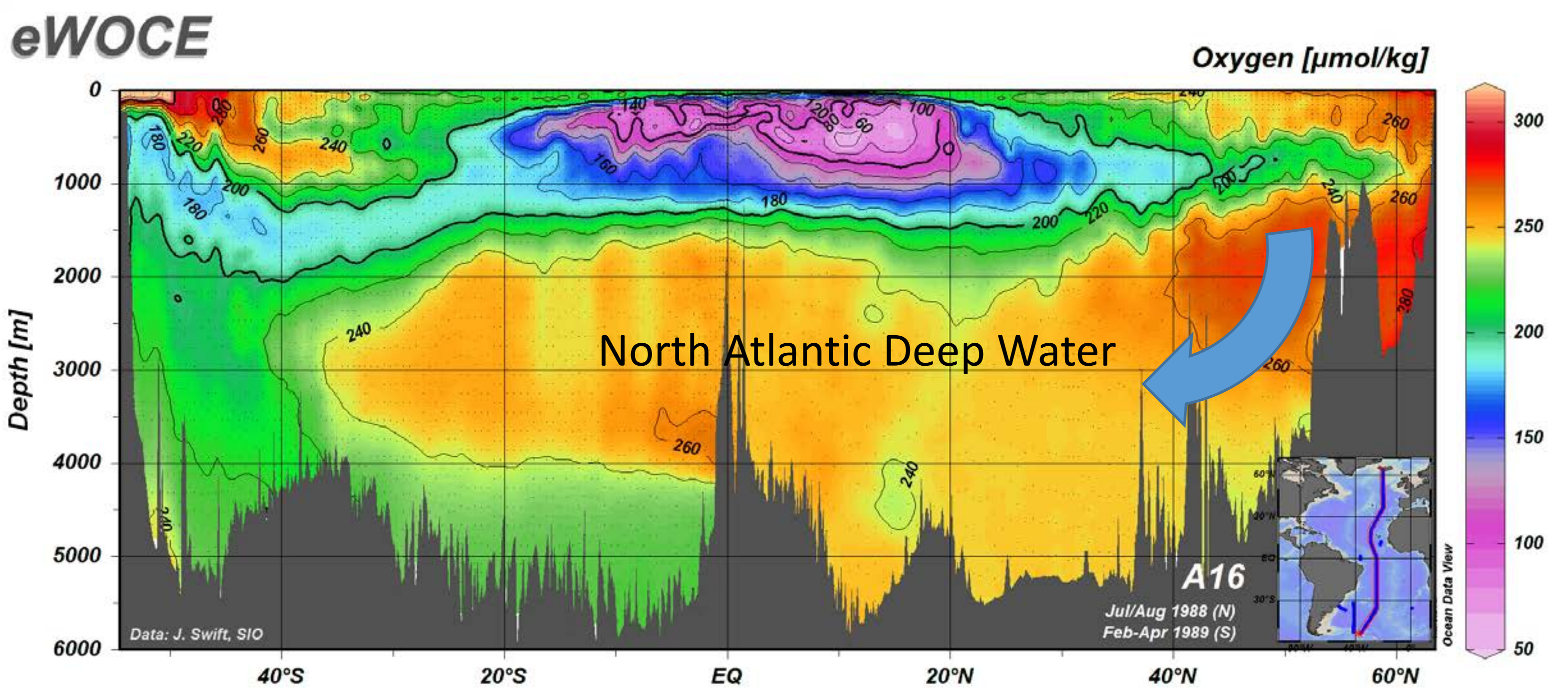
Diffusion experiment started by Lord Kelvin in Glasgow, 1872.

Diffusion is very slow!

To speed it up, we need to mechanically mix the water

Water

Copper Sulfate solution



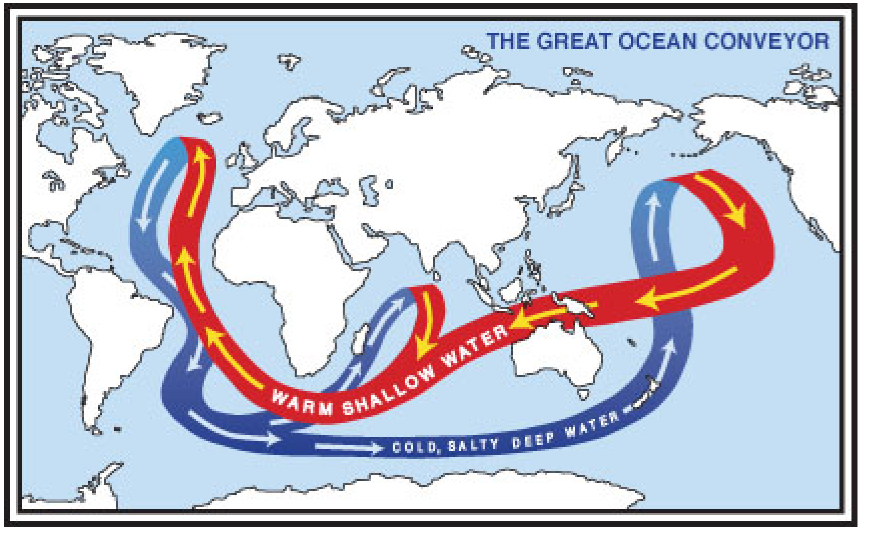
A section across the Atlantic. Red/orange shows water with a lot of oxygen.

Oxygen is high at the surface, due to contact with the atmosphere, and photosynthesis (where there is light) releasing oxygen into the water.

Once the water is below a few hundred metres depth, oxygen is only every used up, by respiration.

High oxygen, means less time since the water was at the surface.

Wally Broeker's famous "ocean conveyor"



A great simplification, but it captures the unique nature of the Atlantic Ocean.

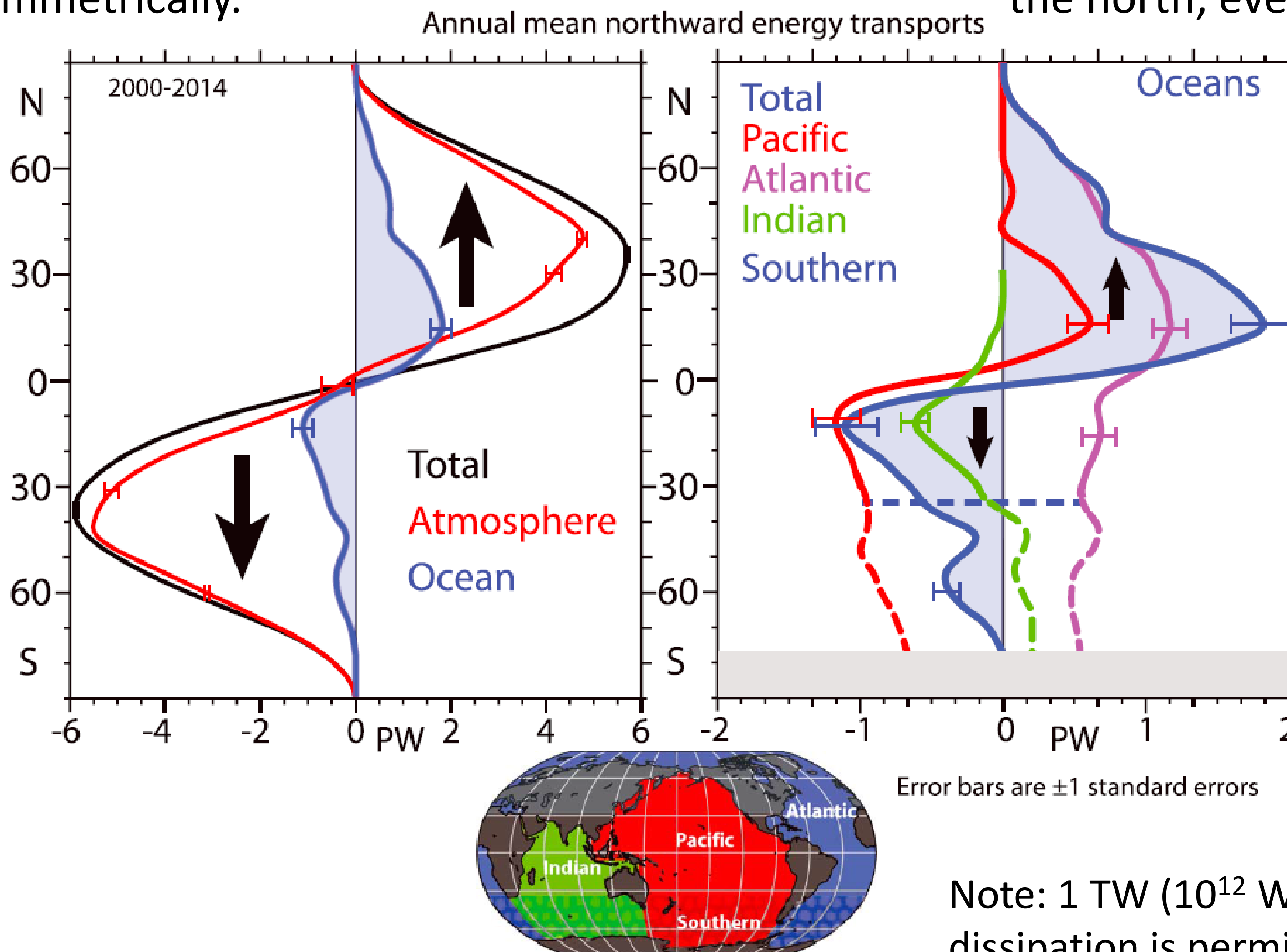
Warm water flows to the north throughout, cools and sinks in the north, then returns as a cold, deep flow (the North Atlantic Deep Water)

For all its simplification, this is a good overall picture of the Atlantic's role in the climate system.

But in order for the water to sink, the cold, deep water must get out of the way – it must warm again, by mixing

The **atmosphere** carries heat away from the equator, toward the poles.
So does the **ocean**, but less symmetrically.

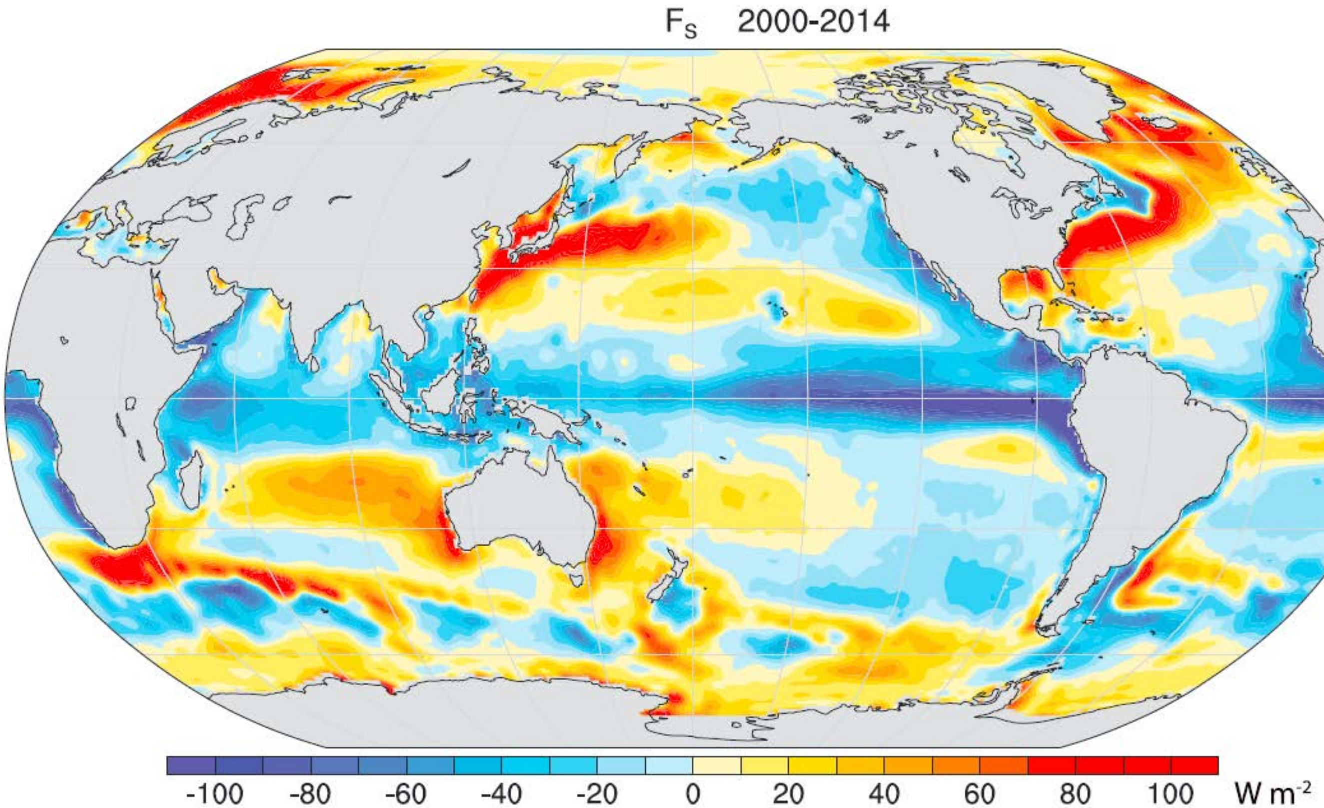
The **Pacific** and **Indian** oceans carry heat away from the equator, toward the poles.
The **Atlantic** carries heat to the north, everywhere



Note: 1 TW (10^{12} W) of tidal dissipation is permitting 1 PW (10^{15} W) of heat transport!

Trenberth and Fassullo, Geophys. Res. Lett. 2017

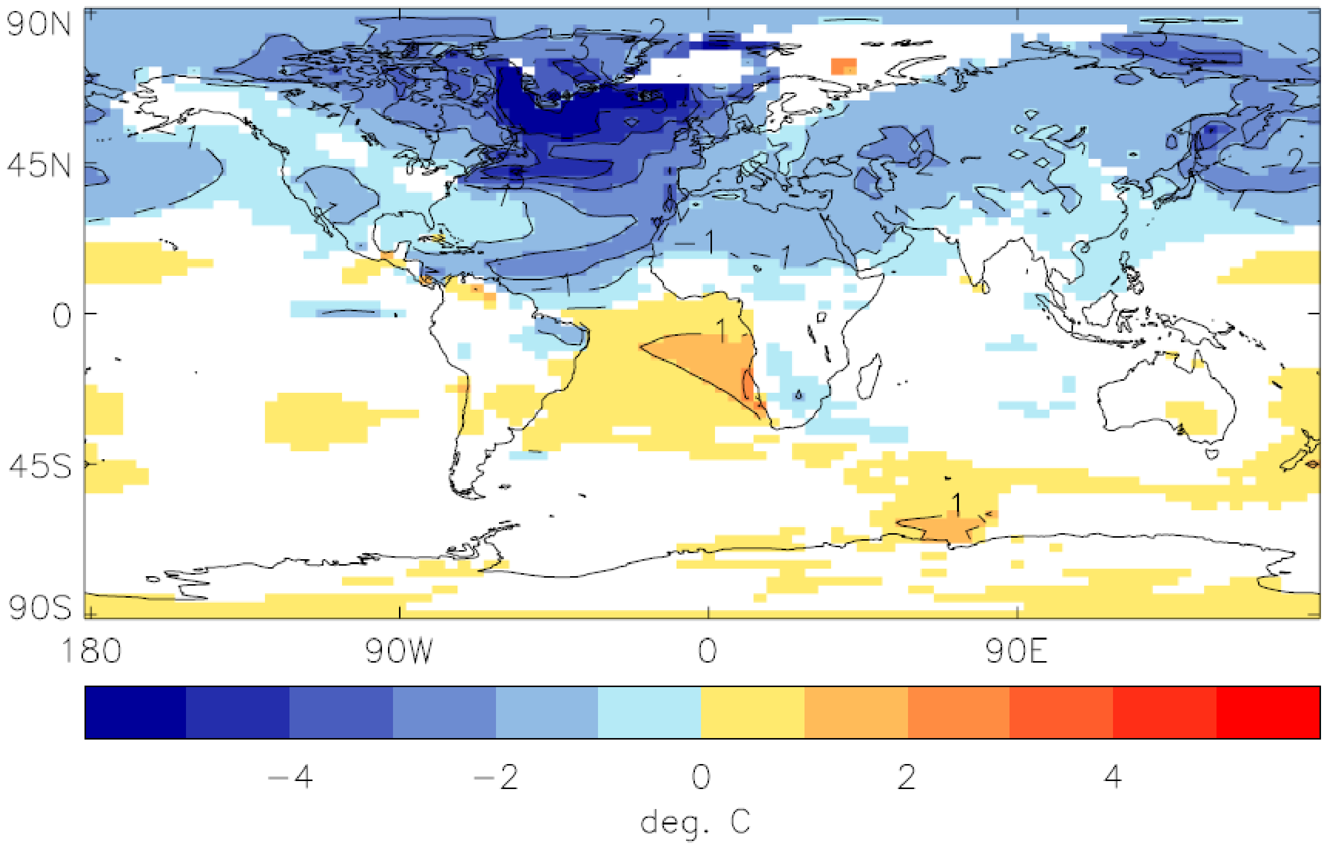
In the North Atlantic, the ocean is giving up heat to the atmosphere.
Red regions are around 100 W m^{-2},
equivalent to having a 100 watt lightbulb on each square metre of the ocean,
heating the winds as they blow towards Europe.
Much of the warming is along the path of the Gulf Stream.



Trenberth and Fassullo, Geophys. Res. Lett. 2017

We are kept warm by the heat brought north by the overturning circulation.
Shutting it down would have a big effect on our climate.

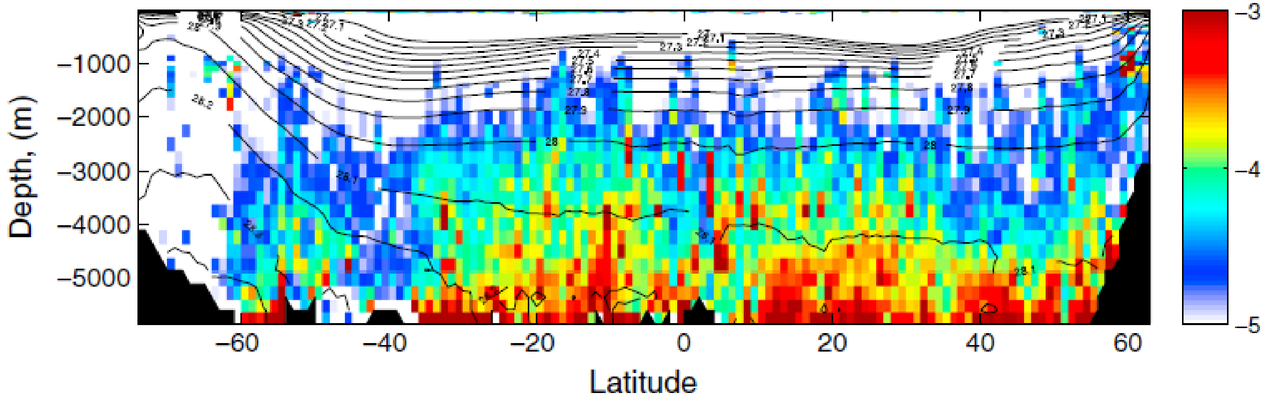
Simulated temperature change, 20-30 years after
a shutdown of the Atlantic overturning circulation



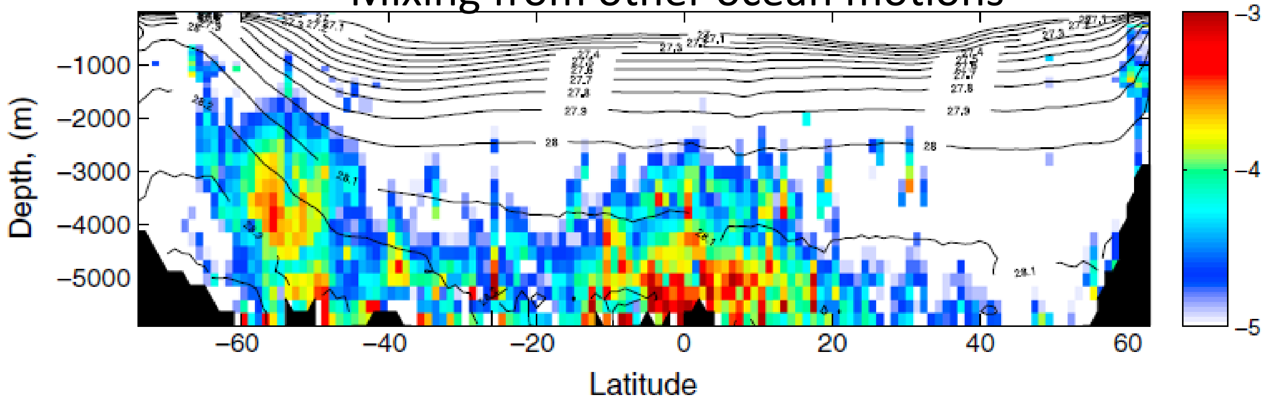
Vellinga and Wood, Climate Change, 2012

Nikurashin and Ferrari, Geophys. Res. Lett. 2013

Mixing from internal tides



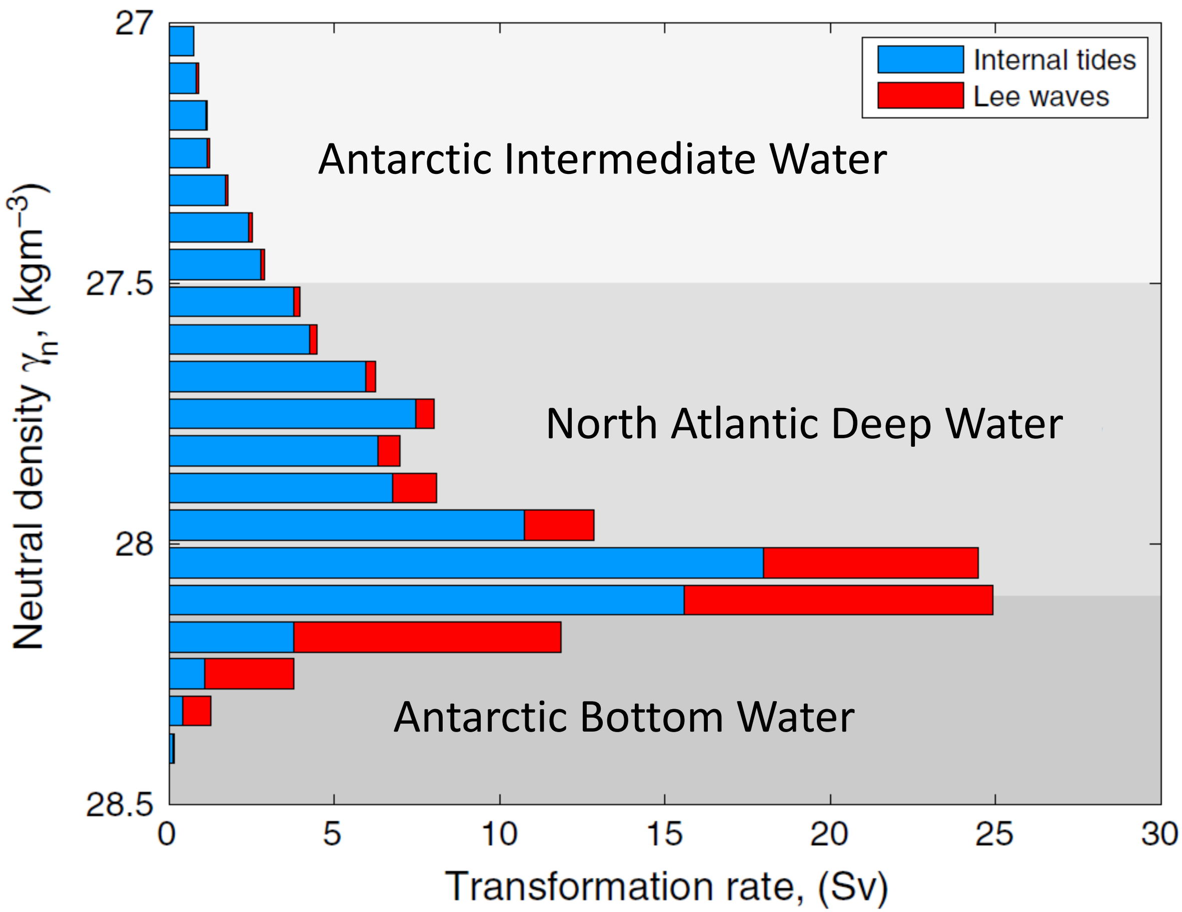
Mixing from other ocean motions



$\log_{10}$ of the diffusion coefficient ($m^2 s^{-1}$)

When water sinks into the deep ocean, it becomes isolated from the surface, and retains its temperature and salinity for many years. If water is sinking somewhere, it must return to the surface elsewhere. This return is limited by mixing: The water has to regain its surface density to return to the surface. Most of this mixing is thought to result from internal tides.

Nikurashin and Ferrari, Geophys. Res. Lett. 2013



Estimates show that most of the mixing, which transforms deep water back to surface waters, comes from the internal tide.

Without that mixing, the overturning circulation would shut down.

Summary

- Space observations (eclipses, rotation of the Earth, distance to the moon, sea level from satellites) allow us to know the total energy dissipated by tides.
- We now know that almost a third of that dissipation happens in the deep ocean, where it causes mixing.
- That mixing is necessary to maintain the Atlantic overturning circulation, which keeps Europe warm.
- The speed of the moon slowly drifting away, and the Earth slowing down, is related to our climate.
- Horrocks was right – we should look at the heavens and the Earth together. Each tells us about the other.