*The Florida Advanced Technological Education (FLATE) Center wishes to make available, for educational and non-commercial purposes only, materials relevant to the "EST1830 Introduction to Alternative/Renewable Energy" course comprised of images, texts, facilitator's notes, and other demonstration materials.*

*This instructional resource forms part of FLATE's outreach efforts to facilitate a connection between students and teachers throughout the State of Florida. We trust that these activities and materials will add value to your teaching and/or presentations.*

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# Introduction to Alternative and Renewable Energy

EST1830

FESC Florida Energy Systems Consortium

FLATE FLORIDA ADVANCED TECHNOLOGICAL EDUCATION CENTER
A National Science Foundation Regional Center For Advanced Technological Education

# 3. Energy Production

3.1 Renewable Energy Technologies

3.1.4 Hydro Energy

3.1.4.1 Tide Energy

3.1.4.2 Wave Energy

3.1.4.3 Other Hydro Energy

# Hydro Energy

Energy exists in the ocean in several forms -- as salinity, temperature differential, currents, tidal, and wave.

We will first cover Tidal and Wave Energy

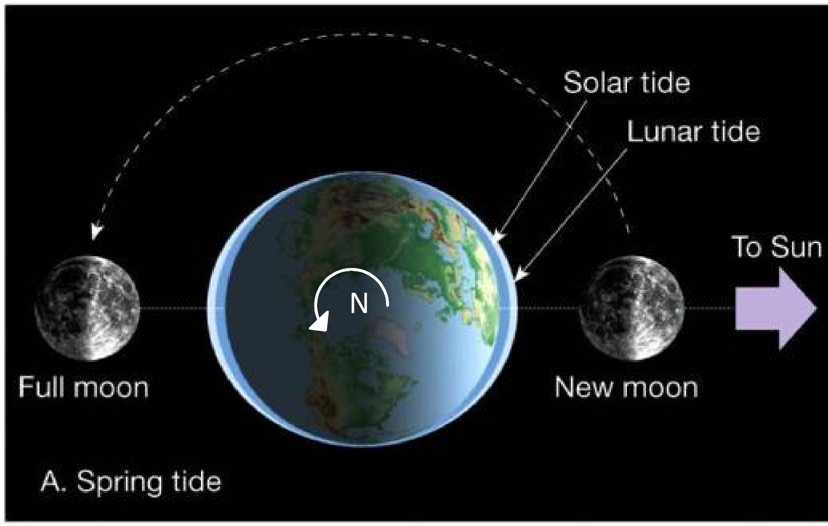
# 3.1.4.1 Tide Energy

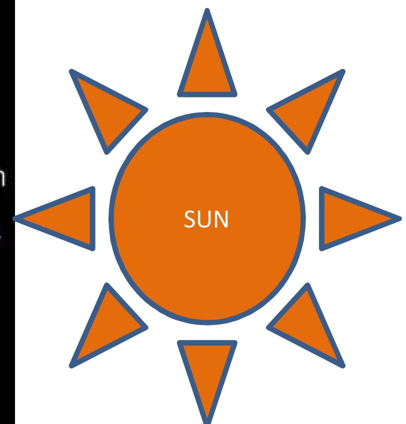
# 3.1.4.1 Tide Energy

**Tide energy is different than Wave energy**

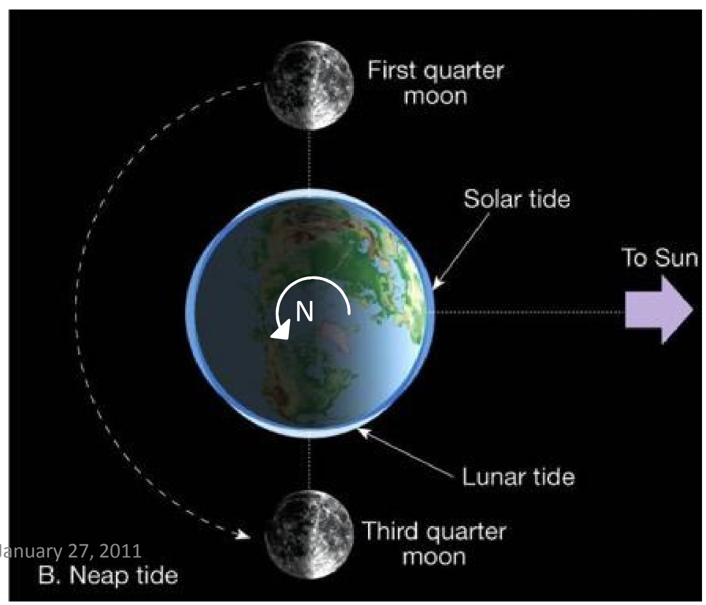
- Ordinary waves are caused by the action of wind over water (a type of solar heating).
  - Could be thought of as solar power
- Tide energy is obtained by the twice-daily ebb and flow of tides.
  - Result of the interaction of gravitational pull of the moon on the seas (and to a lesser extent also pull from the sun).

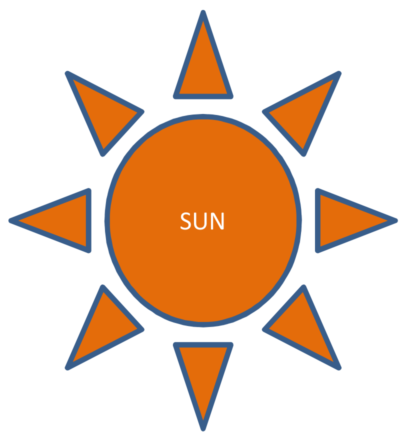
# Neap and Spring Tides




When the sun and moon pull together (in line), whether both puling on the same side of the earth or on opposite sides, the result is the very high **spring tides.** We say that lunar and solar forcings are in phase.



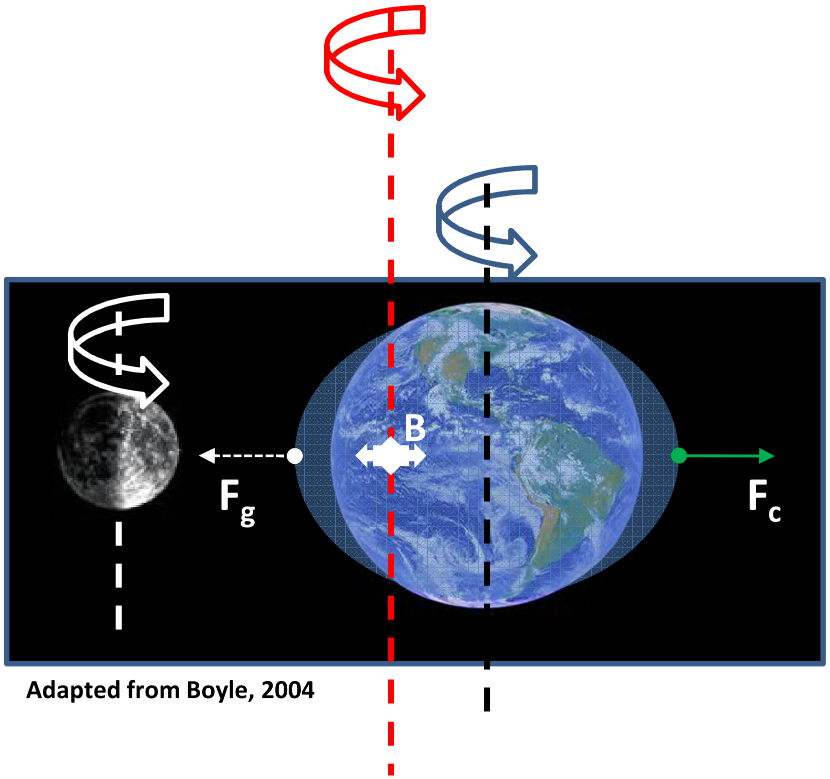




When the sun and moon are at 90º to each other, the result is the lower **neap tides.** We say that lunar and solar forcings are out of phase.

http://scienceray.com/astronomy/

# Earth-Moon System

**The effects of forces acting in the earth-moon system will here be discussed, with the recognition that a similar force complex exists in the earth-sun system.**




**Adapted from Boyle, 2004**

The tide-raising forces at the earth's surface result from a combination of two basic forces:

(1) the force of gravitation exerted by the moon upon the earth; and
(2) centrifugal forces produced by the revolutions of the earth and moon around their common center-of-gravity (mass) or barycenter (B).

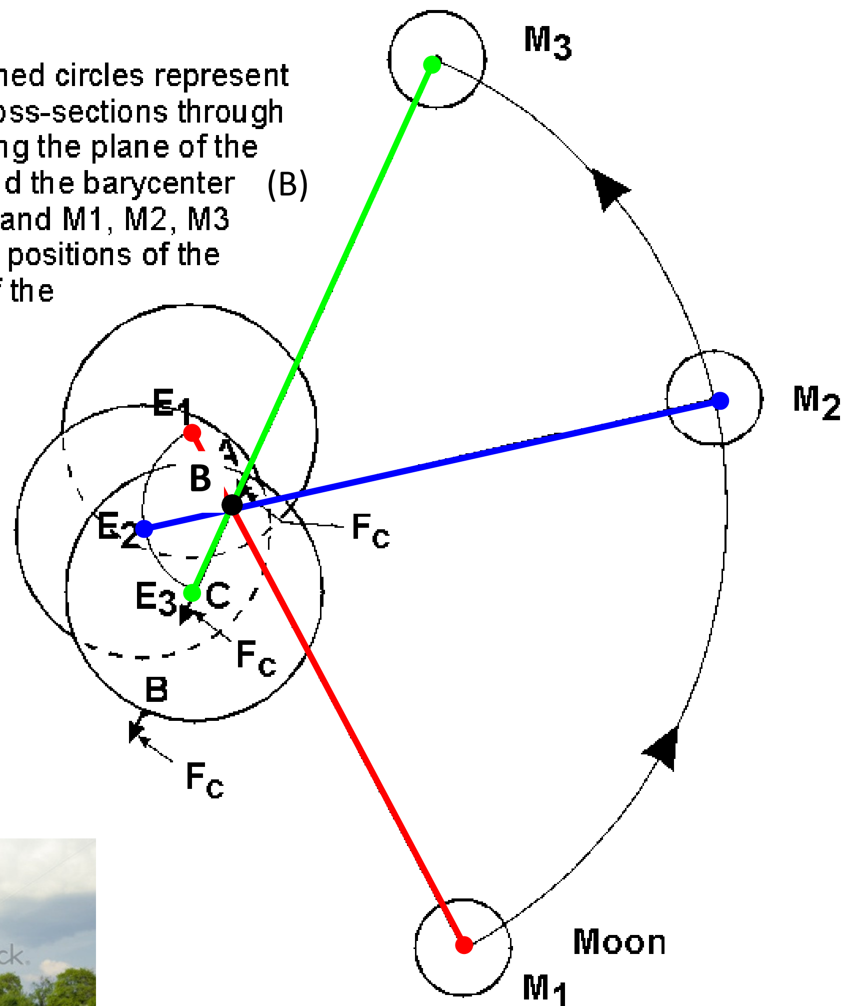
With respect to the center of mass of the earth or the center of mass of the moon, the above two forces always remain in balance (i.e., equal and opposite). This results in the orbits familiar to us. **However, at local points on, above, or within the earth, these two forces are not in equilibrium, and oceanic, atmospheric, and earth tides are the result.**



http://co-ops.nos.noaa.gov/restles3.html

# Earth-Moon System

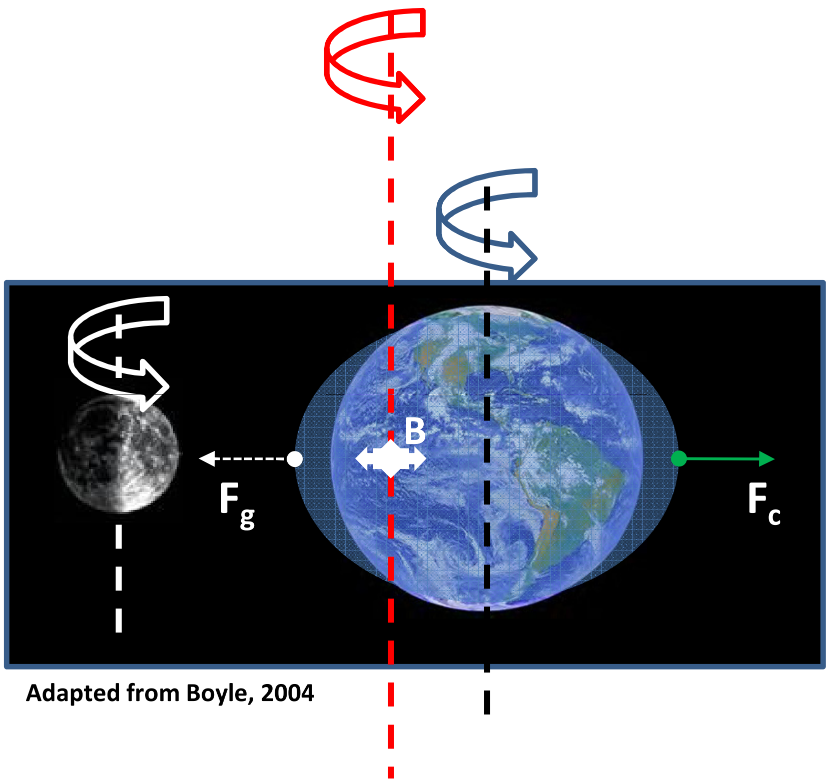
The solid and dashed circles represent near-equatorial cross-sections through the earth, containing the plane of the Moon's orbit around the barycenter (B) Points E1, E2, E3 and M1, M2, M3 are corresponding positions of the centers of mass of the Earth and Moon respectively.




The center of revolution around the barycenter (B) lies at a point approximately 1,068 miles beneath the earth's surface.


http://co-ops.nos.noaa.gov/restles3.html

# Earth-Moon System

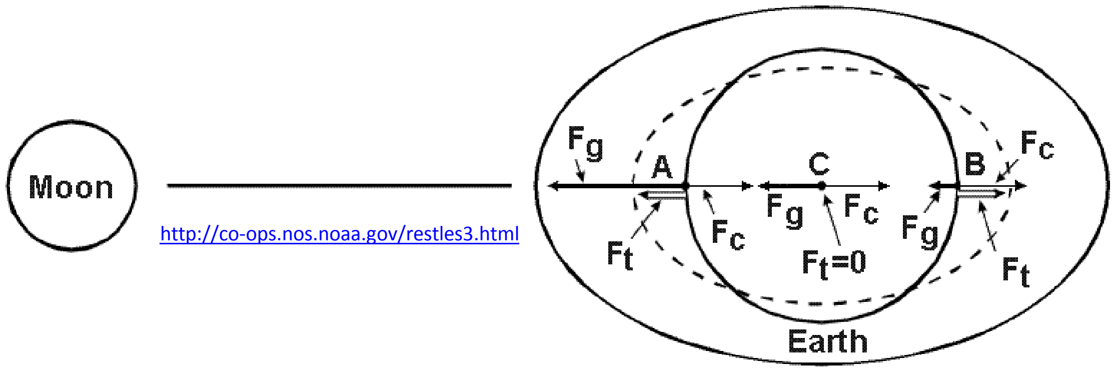



Adapted from Boyle, 2004

1. **Gravitational effect:** This relates to the gravitational pull of the moon, which draws the seas on the side of the earth nearest to the moon into a "bulge" towards the moon, whilst the seas farthest from the moon experience a reduced lunar pull.

2. **Centrifugal effect:** The mutual rotation around the barycenter produces a relatively large outward centrifugal force acting on the seas on the side of the earth farthest from the moon, bunching them into a "bulge". There is also a smaller centrifugal force directed towards the moon that acts on the seas facing the moon (but it is smaller since at this point the distance from the earth's surface to the barycenter is smaller).

# Earth-Moon System




http://co-ops.nos.noaa.gov/restles3.html

**COMBINED EFFECT**

**Facing the moon:** There is a small centrifugal force **($F_c$)** and an increased lunar pull **($F_g$)** acting on the seas facing the moon.

**Other side of moon:** There is a larger centrifugal force **($F_c$)** and a decreased lunar pull **($F_g$)** acting on the seas on the other side of the earth.

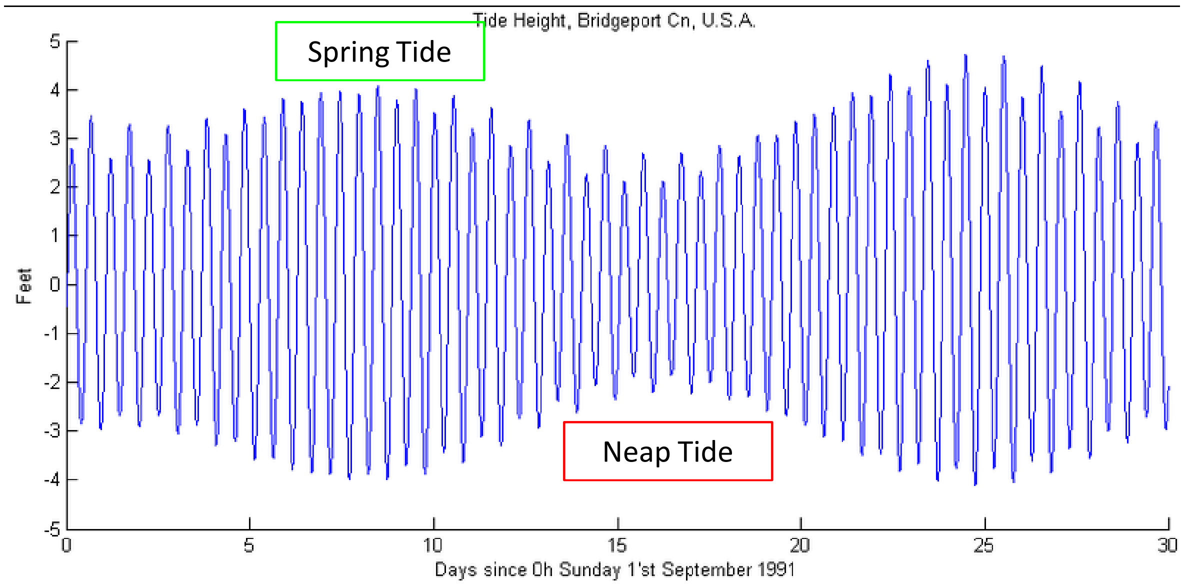
**Combined effect:** The result is essentially a rough symmetry of forces, small and large, on either side of the earth, producing tidal bulges of roughly the same size on each side of the earth.

The two high tide configurations will be drawn around the globe as the earth rotates, giving at any particular point on earth, two tides per day. More accurately, **two tides in every 24.8-hour period occurring about 12.4 hours apart**. Since the moon orbits around the earth, the timing of these high tides at any particular point will vary , occurring approximately 50 minutes later each day.

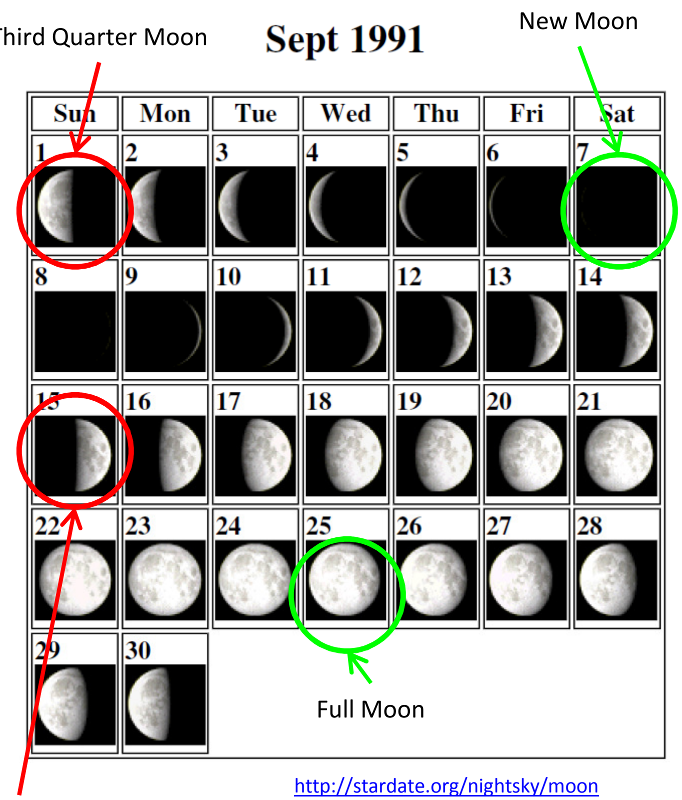
**Adapted from Boyle, 2004**

# Tidal Characteristics

Tidal record shows regular vertical movements of the water surface relative to an average level.  This record is over a month period.

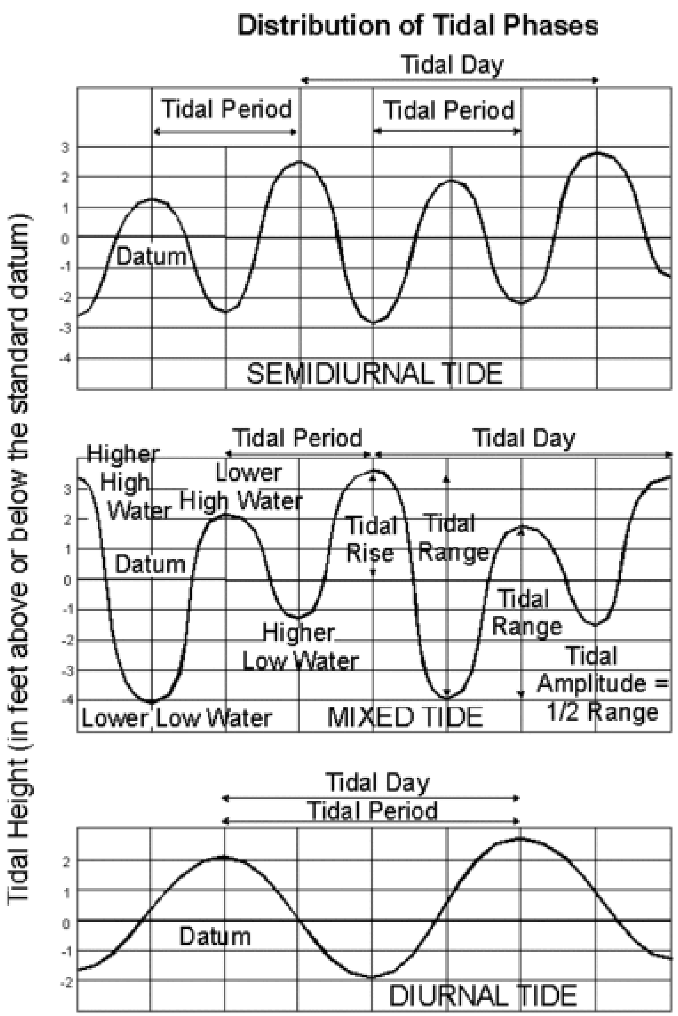



Thirty days of tide heights at Bridgeport Connecticut U.S.A. as calculated from the Harmonic Constituent data aligned with 0h Sunday 1'st September 1991 http://en.wikipedia.org/wiki/Tide




http://stardate.org/nightsky/moon

# Tidal Characteristics




Tide changes proceed via the following stages:

1. Sea level rises over several hours, covering the intertidal zone; flood tide.
2. The water rises to its highest level, reaching high tide.
3. Sea level falls over several hours, revealing the intertidal zone; ebb tide.
4. The water stops falling, reaching low tide.

Tides produce oscillating currents known as tidal streams.

- The moment that the tidal current ceases is called slack tide.
- The tide then reverses direction and is said to be turning.

Tides are most commonly ***semidiurnal*** (two high waters and two low waters each day), or ***diurnal*** (one tidal cycle per day). The two high waters on a given day are typically not the same height (the daily inequality); these are the *higher high water* and the *lower high water* in tide tables. Similarly, the two low waters each day are the *higher low water* and the *lower low water*. The daily inequality is not consistent and is generally small when the Moon is over the equator.

When there are two high tides each day with different heights (and two low tides also of different heights), the pattern is called a ***mixed semidiurnal tide***.

# Tide Comparison

Oct 22 2010 10:31 ELEVATIONS ON STATION DATUM
National Ocean Service (NOAA)

Station: 8418150 T.M.: 0 W
Name: PORTLAND, CASCO BAY, ME Units: Feet
Status: Accepted Epoch: 1983-2001

| Datum | Value | Description |
|---|---|---|
| MHHW | 18.46 | Mean Higher-High Water |
| MHW | 18.02 | Mean High Water |
| DTL | 13.51 | Mean Diurnal Tide Level |
| MTL | 13.46 | Mean Tide Level |
| MSL | 13.49 | Mean Sea Level |
| MLW | 8.90 | Mean Low Water |
| MLLW | 8.55 | Mean Lower-Low Water |
| GT | 9.91 | Great Diurnal Range |
| MN | 9.12 | Mean Range of Tide |
| DHQ | 0.44 | Mean Diurnal High Water Inequality |
| DLQ | 0.34 | Mean Diurnal Low Water Inequality |
| HWI | 3.59 | Greenwich High Water Interval (in Hours) |
| LWI | 9.75 | Greenwich Low Water Interval (in Hours) |
| NAVD | 13.81 | North American Vertical Datum |
| Maximum | 22.68 | Highest Water Level on Station Datum |
| Max Date | 19780207 | Date Of Highest Water Level |
| Max Time | 10:30 | Time Of Highest Water Level |
| Minimum | 5.10 | Lowest Water Level on Station Datum |
| Min Date | 19551130 | Date Of Lowest Water Level |
| Min Time | 17:18 | Time Of Lowest Water Level |

To refer Water Level Heights to a Tidal Datum, apply the desired Datum Value.

Casco Bay- Portland, ME

Hillsborough Inlet, FL

Oct 22 2010 10:30 ELEVATIONS ON STATION DATUM
National Ocean Service (NOAA)

Station: 8722862 T.M.: 75 W
Name: HILLSBORO INLET OCEAN, FL Units: Feet
Status: Accepted Epoch: 1983-2001

| Datum | Value | Description |
|---|---|---|
| MHHW | 4.86 | Mean Higher-High Water |
| MHW | 4.72 | Mean High Water |
| DTL | 3.45 | Mean Diurnal Tide Level |
| MTL | 3.46 | Mean Tide Level |
| MSL | 3.46 | Mean Sea Level |
| MLW | 2.21 | Mean Low Water |
| MLLW | 2.04 | Mean Lower-Low Water |
| GT | 2.82 | Great Diurnal Range |
| MN | 2.52 | Mean Range of Tide |
| DHQ | 0.13 | Mean Diurnal High Water Inequality |
| DLQ | 0.17 | Mean Diurnal Low Water Inequality |
| HWI | 0.77 | Greenwich High Water Interval (in Hours) |
| LWI | 7.01 | Greenwich Low Water Interval (in Hours) |
| NAVD | 4.48 | North American Vertical Datum |
| Maximum | | Highest Water Level on Station Datum |
| Max Date | | Date Of Highest Water Level |
| Max Time | | Time Of Highest Water Level |
| Minimum | | Lowest Water Level on Station Datum |
| Min Date | | Date Of Lowest Water Level |
| Min Time | | Time Of Lowest Water Level |

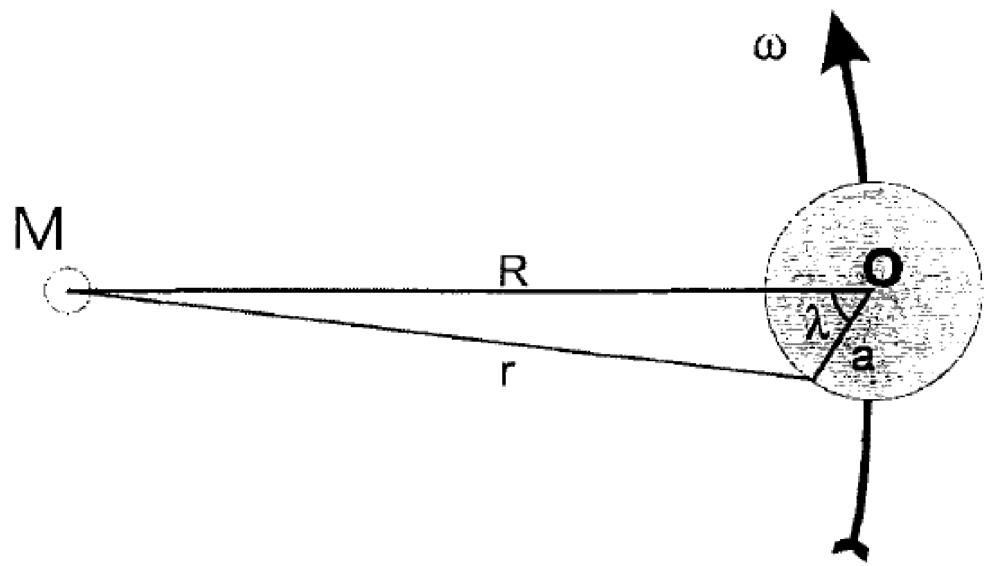
To refer Water Level Heights to a Tidal Datum, apply the desired Datum Value.

http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Datums

# Tidal Forcing

Assumptions:

1. Neglect earth declination
2. Consider only forces along equator
3. Same derivation can be used for Sun-Earth System separately (all three simultaneously would be a difficult three body problem)




| quantity | value | units |
|---|---|---|
| $G$ | $6.67 \times 10^{-11}$ | $Nm^2kg^{-2}$ |
| $M$ | $7.30 \times 10^{22}$ | kg |
| $R$ | $3.82 \times 10^{8}$ | m |
| $a$ | $6.38 \times 10^{6}$ | m |
| $g$ | $9.78$ | $ms^{-2}$ |

λ - Longitude relative to earth's surface
R - Distance from Moon to center of earth
r – distance to the earth's surface at λ from M
a - Earth's radius
ω – orbital angular velocity of earth
M=Moon
G= Gravitational constant
g= average gravity on earth

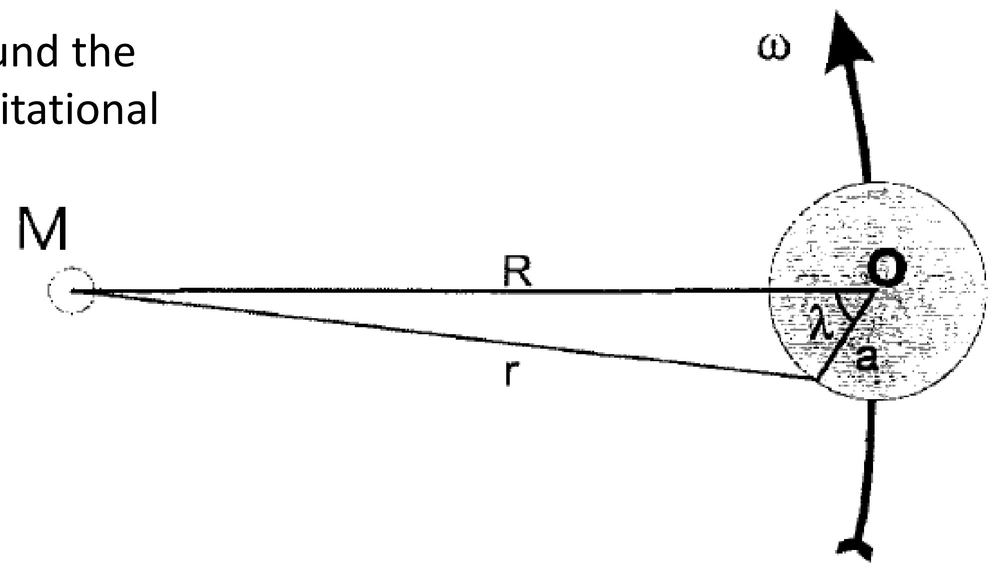


Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Tidal Forcing

The net variation in Tidal Potential around the equator is given by the sum of the gravitational potential plus the centrifugal potential.

$$\Phi_T = \Phi_G + \Phi_C$$




Tidal Potential

Gravitational Potential

Centrifugal Potential

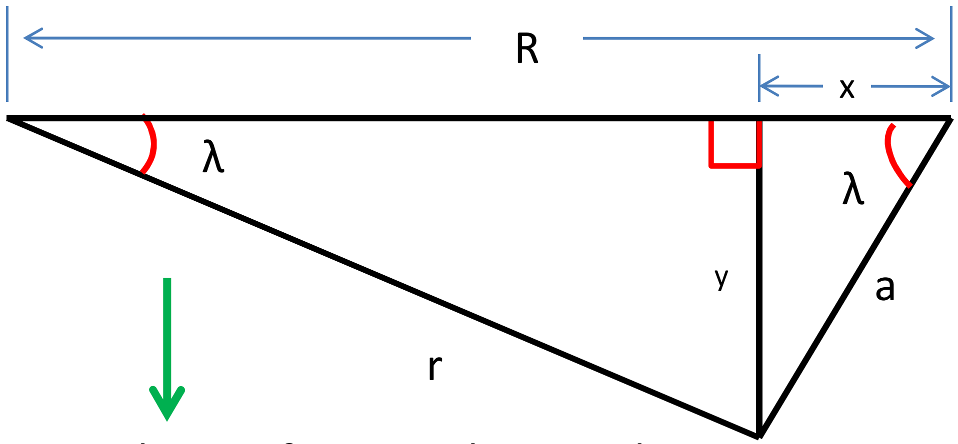
$$\Phi_T = \Phi_g = -\frac{GM}{r} + \Phi_C = -\frac{1}{2}\omega^2 r^2$$

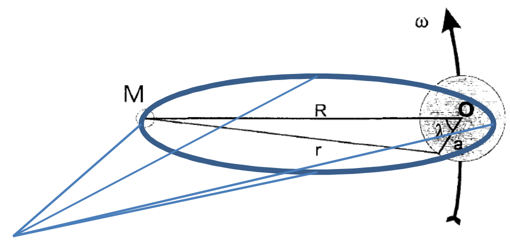


Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Gravitational Tidal Forcing

Find r in terms of R and λ



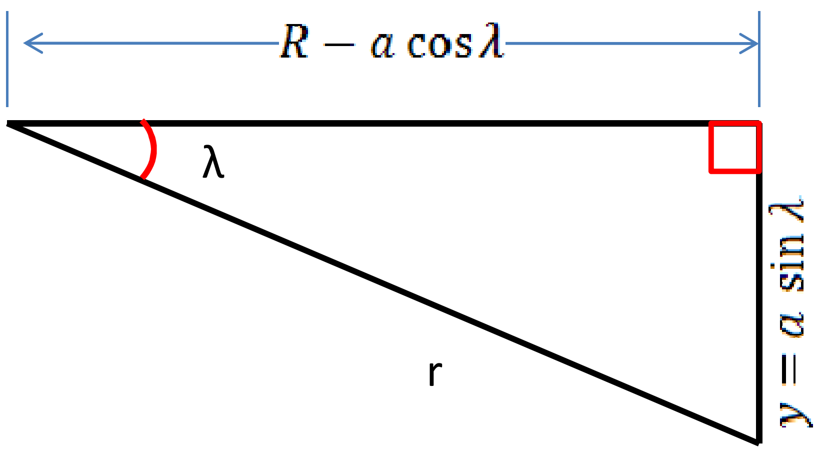




Let

$x = a \cos\lambda$

$y = a \sin\lambda$

Using relations from a right triangle….




So we can solve for r using the Pythagorean Theorem

$$r^2 = (a\sin\lambda)^2 + (R - a\cos\lambda)^2$$

# Gravitational Tidal Forcing

Now we expand this relation............

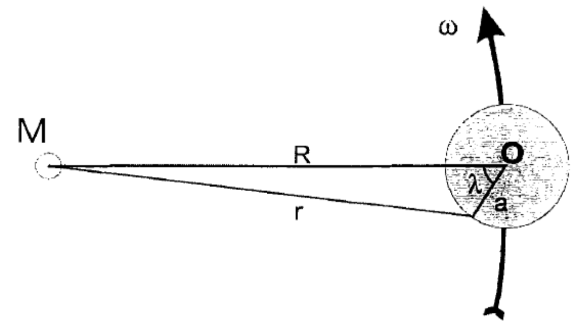
$$r^2 = (a \sin\lambda)^2 + (R - a\cos\lambda)^2$$

$$= a^2(\sin\lambda)^2 + R^2 - 2aR\cos\lambda + a^2(\cos\lambda)^2$$

$$= a^2[(\sin\lambda)^2 + (\cos\lambda)^2] + R^2 - 2aR\cos\lambda$$

1

$$= a^2 + R^2 - 2aR\cos\lambda$$




So that............

$$r^2 = a^2 + R^2 - 2aR\cos\lambda$$

Which is the same as......

$$r^2 = R^2 - 2aR\cos\lambda + a^2$$ And...... → $$r = \sqrt{R^2 - 2aR\cos\lambda + a^2}$$

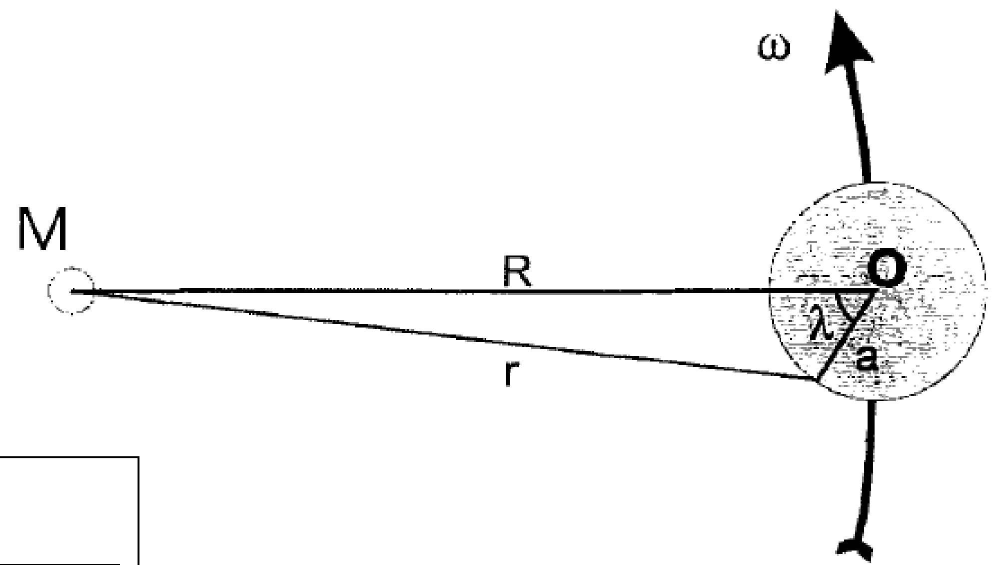
So now we can substitute r into the relation for gravitational potential

$$\Phi_g = -\frac{GM}{r}$$

# Gravitational Tidal Forcing

With

$$r = \sqrt{R^2 - 2aR\cos\lambda + a^2}$$




Gravitational potential at λ relative to M on earth's surface due to M

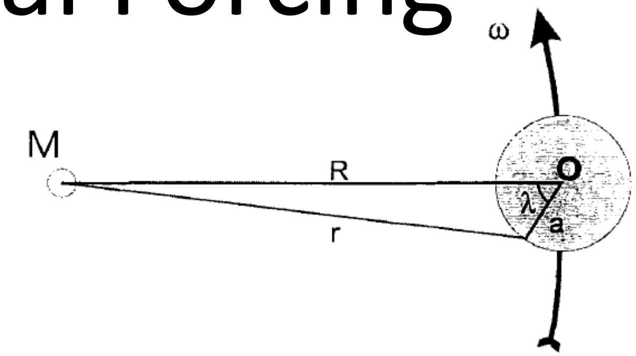
$$\Phi_g = -\frac{GM}{r} = -\frac{GM}{\sqrt{R^2 - 2aR\cos\lambda + a^2}}$$

λ - Longitude relative to earth's surface
R - Distance from Moon to center of earth
r – distance to the earth's surface at λ from M
a - Earth's radius
ω – orbital angular velocity of earth
M=Moon



Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Gravitational Tidal Forcing




Extracting R from $r = \sqrt{R^2 - 2aR\cos\lambda + a^2}$

We get $r = \sqrt{R^2\left(1 - \frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}\right)}$

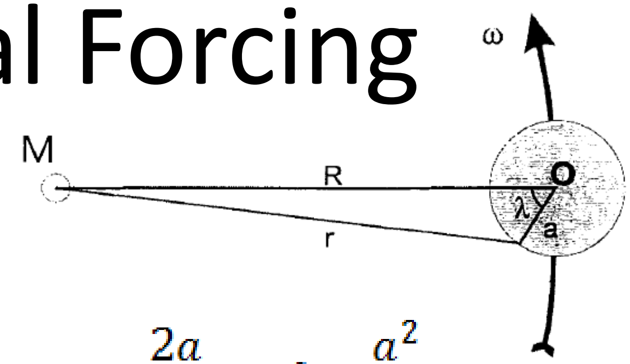
$$r = R\sqrt{1 - \frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}} \longrightarrow r = R\left[1 - \frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}\right]^{\frac{1}{2}}$$

So, $\Phi_g = -\frac{GM}{r}$ becomes $\Phi_g = -\frac{GM}{R\left[1 - \frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}\right]^{\frac{1}{2}}}$

Or equivalently……

$$\Phi_g = -\frac{GM}{R}\left[1 - \frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}\right]^{\frac{-1}{2}}$$

# Gravitational Tidal Forcing




*Using a Taylor Series expansion of the form….*

$$(1+x)^{\frac{-1}{2}} = 1 - \frac{1}{2}x + \frac{3}{8}x^2 + \ldots\ldots.$$

And letting $x = -\frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}$

One can approximate the gravitational potential from this……..

$$\Phi_g = -\frac{GM}{R}\left[1 - \frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}\right]^{\frac{-1}{2}}$$

ignoring terms higher than….. $\frac{a^2}{R^2}$

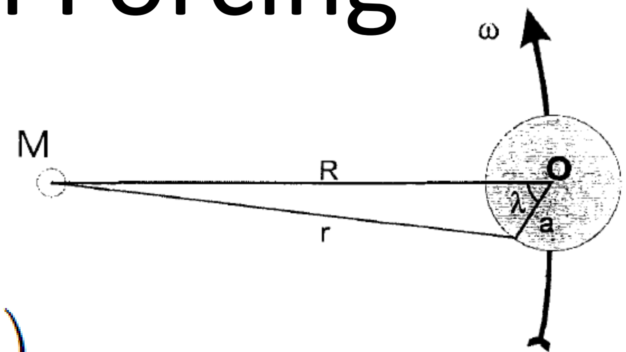
**….to this……**

$$\Phi_G \approx -\frac{GM}{R}\left(1 + \frac{a}{R}\cos\lambda - \frac{a^2}{2R^2}\left(1 - 3\cos^2\lambda\right)\right)$$



Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Centrifugal Tidal Forcing




Centrifugal Potential

$$\Phi_C = -\frac{1}{2}\omega^2 r^2$$

With

$$r^2 = R^2 - 2aR\cos\lambda + a^2$$
$$= R^2\left(1 - \frac{2a}{R}\cos\lambda + \frac{a^2}{R^2}\right)$$

Gives

$$\Phi_C = -\frac{1}{2}\omega^2 r^2 = -\frac{1}{2}\omega^2 R^2\left(1 - 2\frac{a}{R}\cos\lambda + \frac{a^2}{R^2}\right)$$

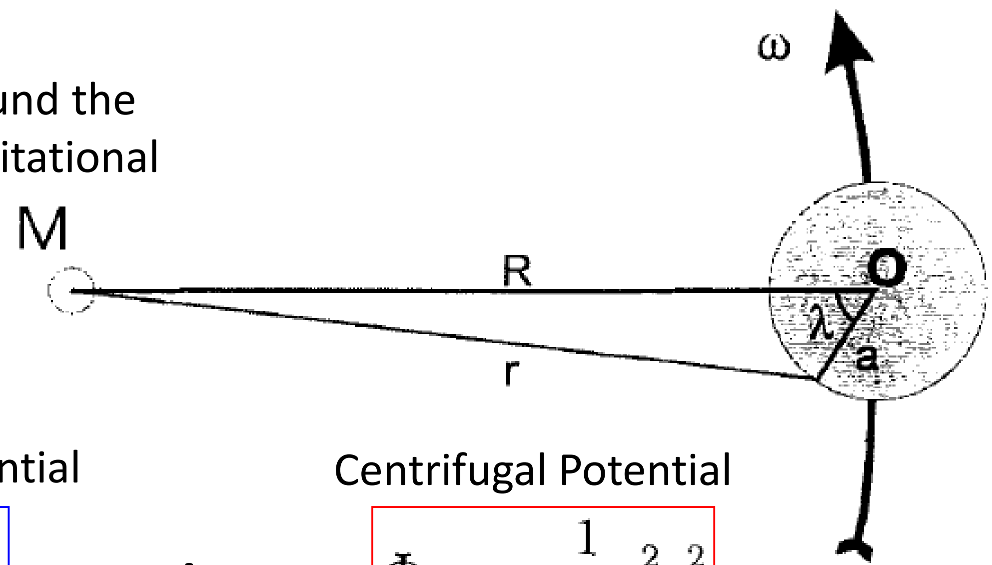
λ - Longitude relative to earth's surface
R - Distance from Moon to center of earth
r – distance to the earth's surface at λ from M
a - Earth's radius
ω – orbital angular velocity of earth
M=Moon



Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Tidal Forcing

The net variation in Tidal Potential around the equator is given by the sum of the gravitational potential plus the centrifugal potential.




$$\Phi_T = \Phi_G + \Phi_C$$

Tidal Potential | Gravitational Potential | Centrifugal Potential

$$\Phi_T = \Phi_g = -\frac{GM}{r} + \Phi_C = -\frac{1}{2}\omega^2 r^2$$

To a rough approximation, the two components of force balance at the earth's center, so that

$$\omega^2 R = \frac{GM}{R^2}$$

And this becomes….

$$\Phi_T = \Phi_G + \Phi_C = -\frac{3GM}{2R} - \frac{3GMa^2}{4R^3}(1 + \cos 2\lambda)$$





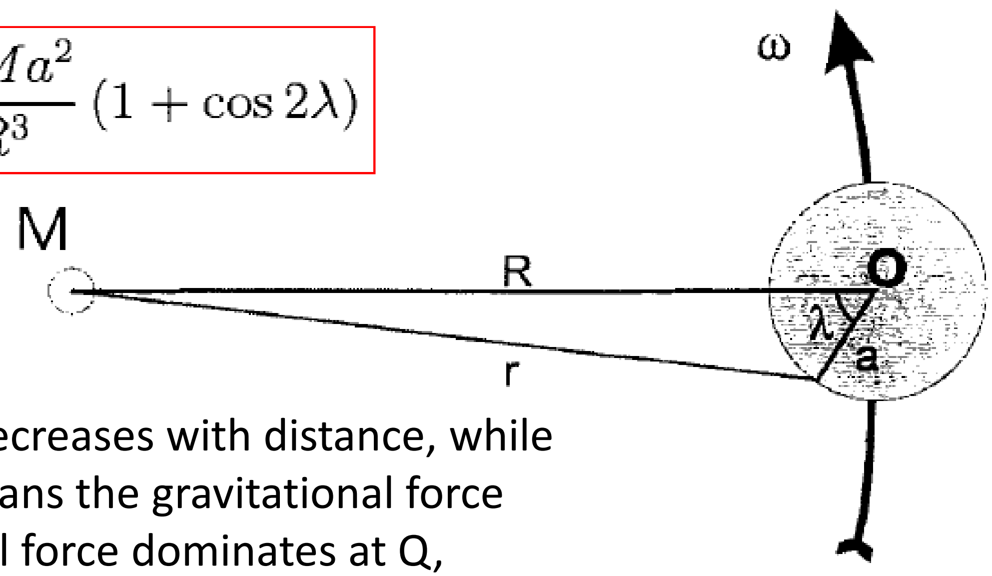
Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Tidal Forcing

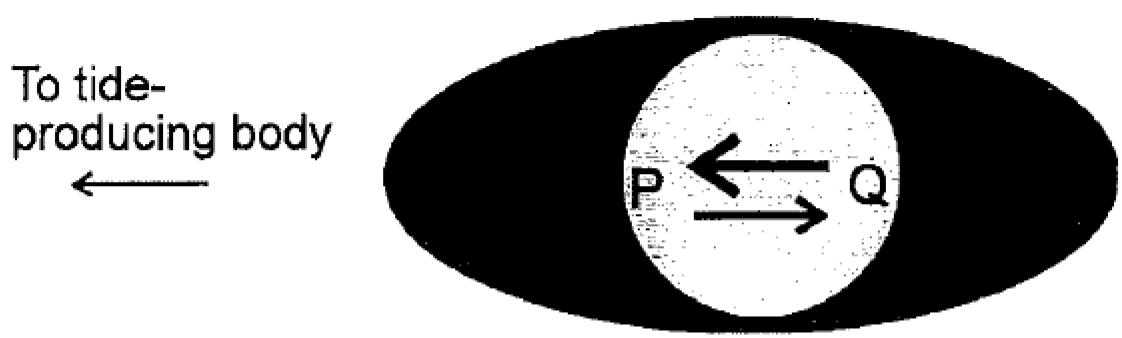
$$\Phi_T = \Phi_G + \Phi_C = -\frac{3GM}{2R} - \frac{3GMa^2}{4R^3}(1+\cos 2\lambda)$$

longitude

$0 \leq \lambda \leq 180^o$




So we see that the gravitational force decreases with distance, while the centrifugal force increases. This means the gravitational force dominates at point P and the centrifugal force dominates at Q, which was previously explained qualitatively.






Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Tidal Forcing

$$\Phi_T = \Phi_G + \Phi_C = -\frac{3GM}{2R} - \frac{3GMa^2}{4R^3}(1 + \cos 2\lambda)$$

| quantity | value | units |
|---|---|---|
| $G$ | $6.67 \times 10^{-11}$ | $Nm^2kg^{-2}$ |
| $M$ | $7.30 \times 10^{22}$ | kg |
| $R$ | $3.82 \times 10^8$ | m |
| $a$ | $6.38 \times 10^6$ | m |
| $g$ | $9.78$ | $ms^{-2}$ |

Plugging in all these constants we get….

$$\Phi_T = -19119.5 - 5.3(1 + \cos 2\lambda) \text{ J/kg}$$

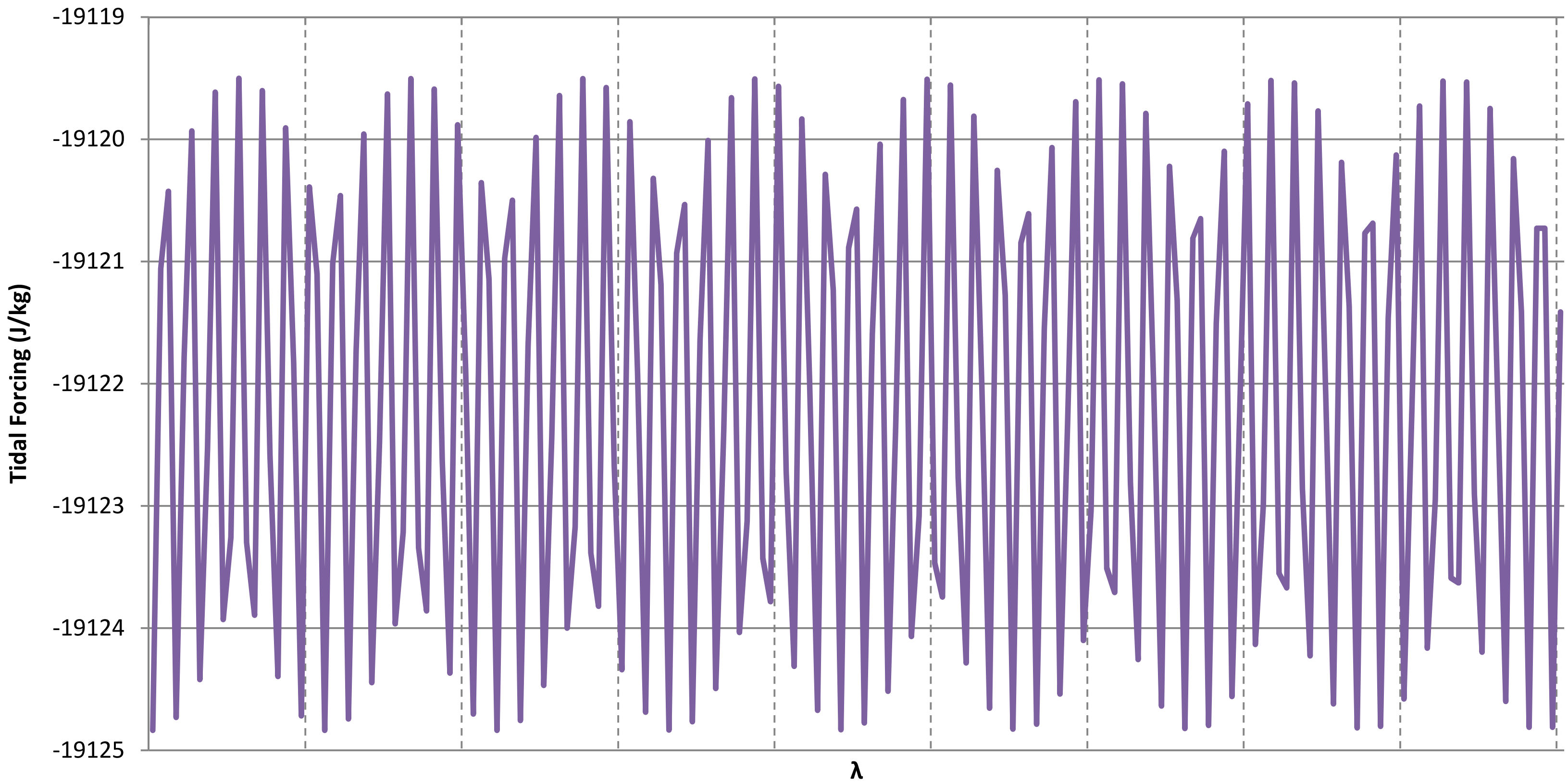
So we can generate a graph for $0 \leq \lambda \leq 180^o$



Adapted from http://ocw.mit.edu/courses/earth-atmospheric-and-planetary-sciences/12-333-atmospheric-and-ocean-circulations-spring-2004/

# Tidal Forcing

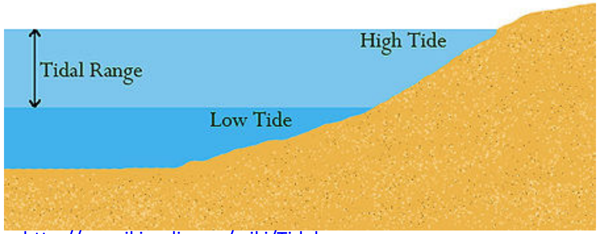
$$\Phi_T = -19119.5 - 5.3(1 + \cos 2\lambda)$$ J/kg




$0 \le \lambda \le 180^{o}$

# Tidal Energy/Power Available

**Barrages**



http://en.wikipedia.org/wiki/Tidal_range

$$E = \frac{1}{2} A \rho g h^2$$

where:

*h* is the vertical tidal range,
*A* is the horizontal area of the barrage basin,
*ρ* is the density of water = 1025 kg per cubic meter (seawater varies between 1021 and 1030 kg per cubic meter) and
*g* is the acceleration due to the Earth's gravity = 9.81 meters per second squared.

---

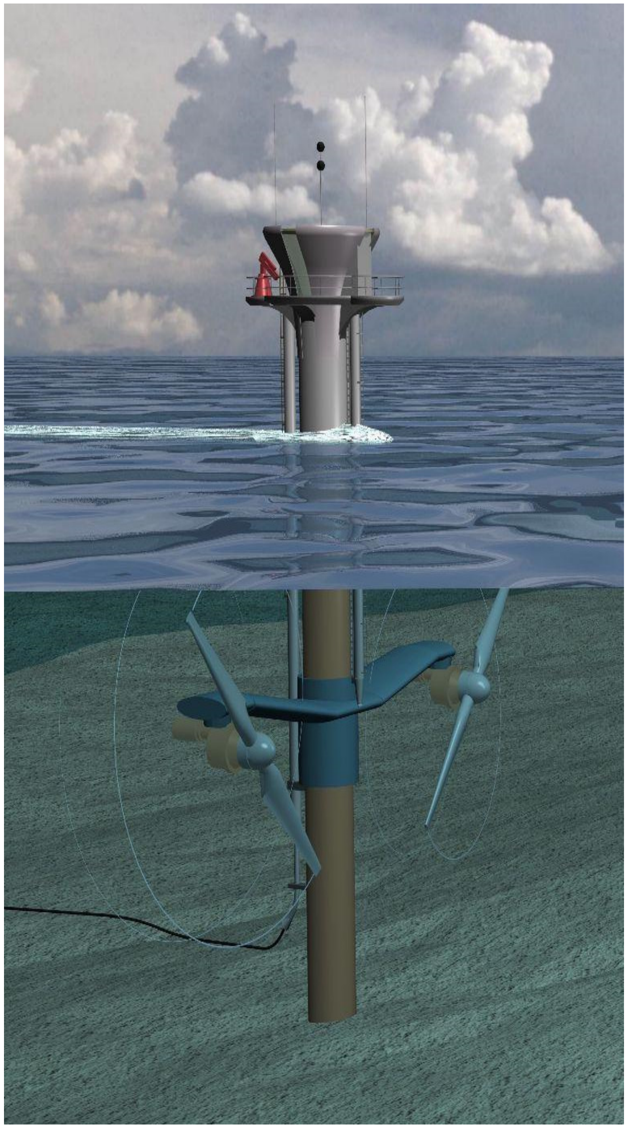
**Tidal turbines**

$$P = \frac{\xi \rho A V^3}{2}$$

where:

ξ = the turbine efficiency
*P = the power generated (in watts)*
ρ = the density of the water (seawater is 1025 kg/m³)
*A = the sweep area of the turbine (in m²)*
*V = the velocity of the flow*

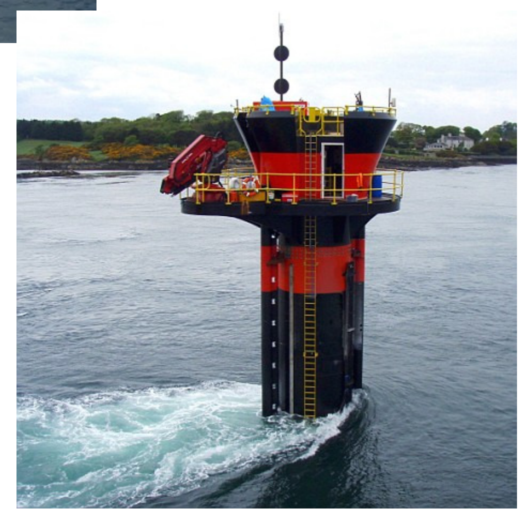
# Tidal Turbine




## **SeaGen**

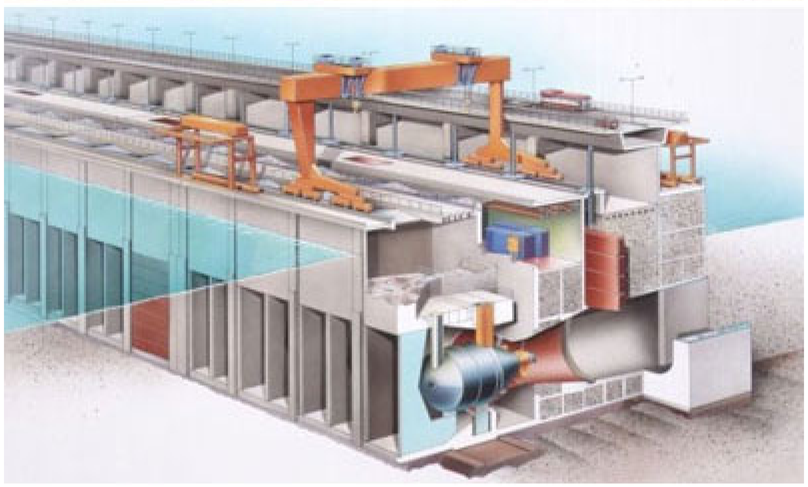
Marine Current
Turbines Ltd

The first commercial scale tidal turbine was positioned at Strangford Lough in Northern Ireland. Built in Belfast, the Sea Gen Turbine has a capacity of 1.2 megawatts and can generate enough electricity to power 1,140 homes.



http://www.seageneration.co.uk/default.asp

# Tidal Barrage

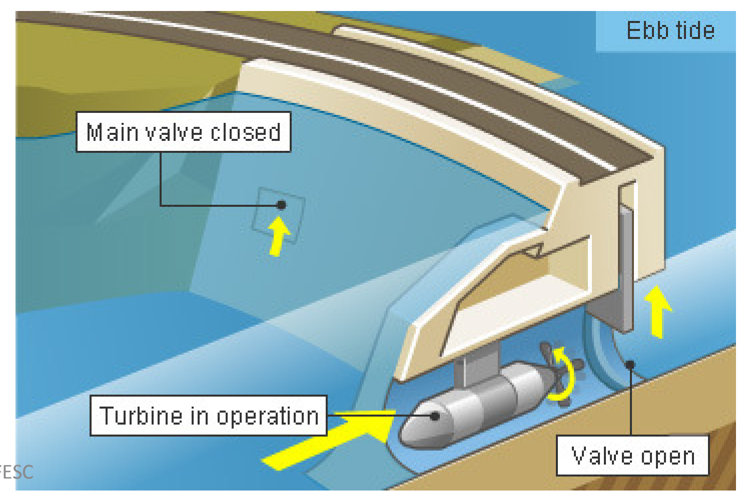


Rance Tidal Power Station, on the Rance river, in France, which has been operating since 1966, and generates 240MW

[http://www.tidalenergy.eu/tidal_barrages.html](http://www.tidalenergy.eu/tidal_barrages.html)

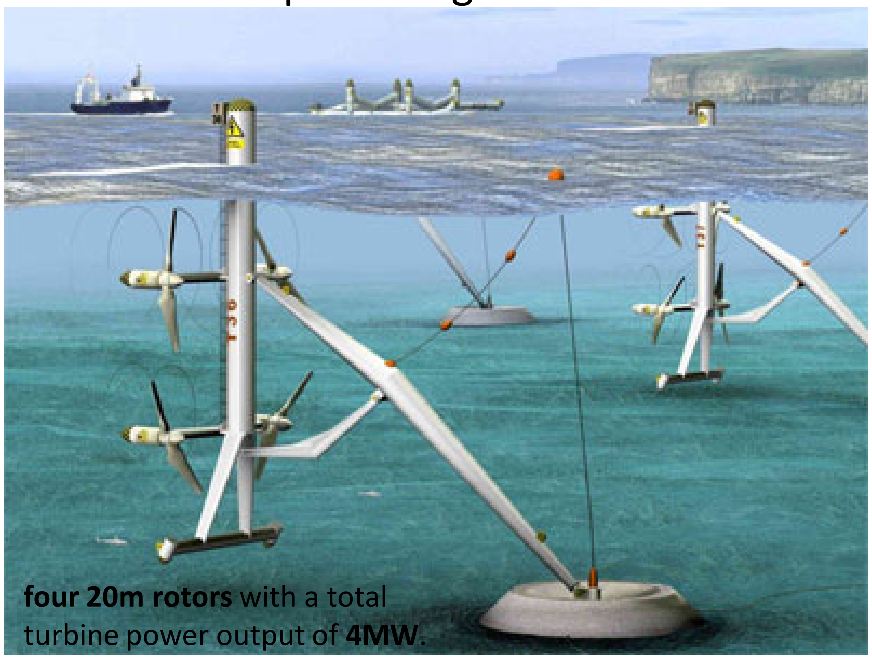
**Tidal Barrages** utilize the potential energy from the difference in height between high and low tides. A dam with a sluice is constructed spanning a tidal inlet, or a section of a tidal estuary creating a reservoir. At high tide sea water flows into the reservoir through a one way gate. The gate closes when the tide began to fall and when the tide is low enough, the stored water is released at pressure through turbines, back into the sea. The rotation of these turbines generates electricity.

The viability of Barrage systems has been questioned due to high civil infrastructure costs and environmental issues. There are only a few potential sites across the globe and there are only three functioning plants worldwide (Rance River, Bay of Fundy and Kislaya Guba).



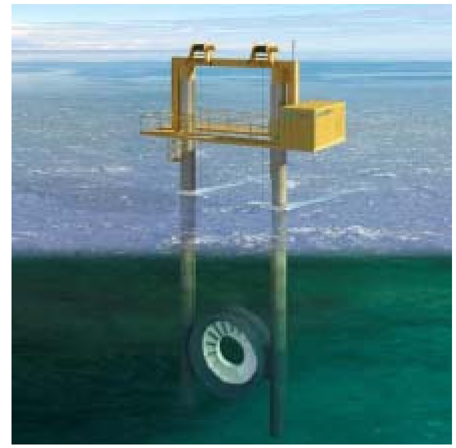
# Other Tidal Energy Options

Still in conceptual stage Tidal Stream Ltd




**Tidal stream systems** utilise the kinetic energy from water currents to turn turbines, in the same way that wind mills use air currents.

http://www.johnarmstrong1.pwp.blueyonder.co.uk/Home.htm



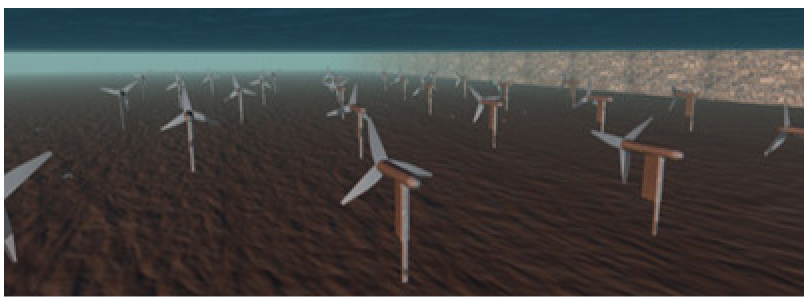
The Open-centre turbine is an innovative turbine designed by the Open Hydro Group. A prototype was installed at the European Marine Energy Centre in Orkney in 2006. In May 2008 it became the first tidal turbine to contribute to the UK grid.
The OpenHydro machine is a large underwater turbine, resembling a jet engine, fixed to the sea floor. OpenHydro is built by Cantick Head Tidal and will harness the firth's fierce tides at a 200MW site south of Orkney.

http://www.tidalenergy.eu/openhydrogroup_opencentre.html

# Other Tidal Energy Options

The project involved a set of six submerged turbines designed to capture energy from the East River's tidal currents. The three-bladed turbines, which are five meters in diameter and resemble wind turbines, are made by Verdant Power of Arlington, VA.

http://verdantpower.com/

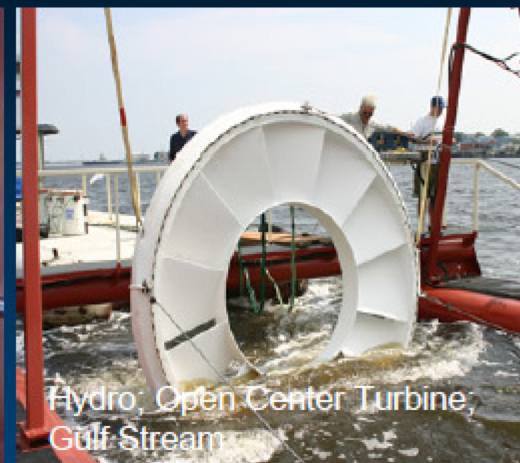
The system delivered 70 megawatt hours of grid-connected energy from the tides of the East River to NYC customers with no power quality problems.

# In-Stream Tidal Technology Examples

http://ocsenergy.anl.gov/guide/wave/index.cfm


Verdant; Horizontal Axis; East River, NY


Gorlov Helical Vertical Axis; Merrimack River,


Hydro; Open Center Turbine; Gulf Stream


Lunar Energy, Rotech Tidal Turbine

Underwater Electric Kite; Merrimack River,


MCT SeaFlow Experimental Test

# 3.1.4.2 Wave Energy

# 3.1.4.2 Wave Energy

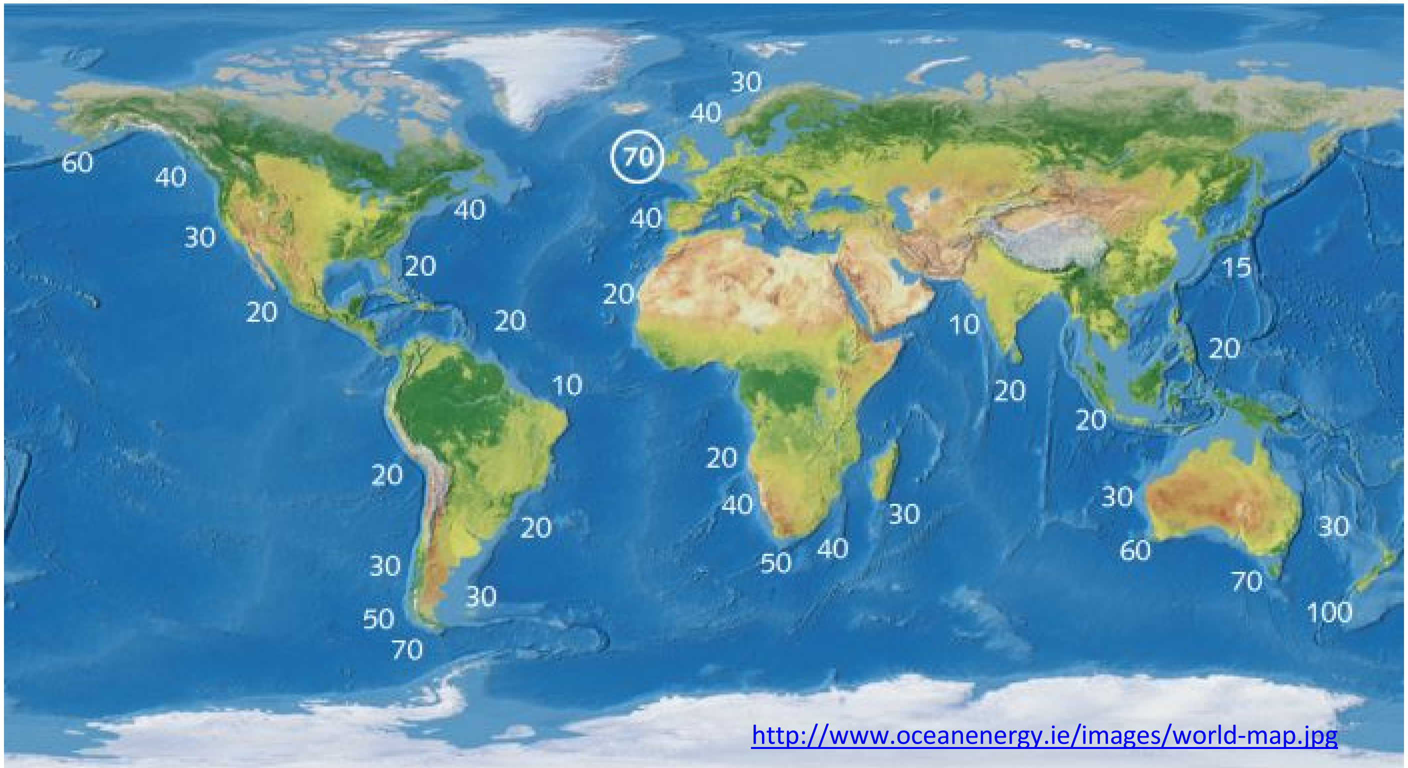
**Tide energy is different than Wave energy**

- Ordinary waves are caused by the action of wind over water (a type of solar heating).
  - Could be thought of as solar power
- Tide energy is obtained by the twice-daily ebb and flow of tides.
  - Result of the interaction of gravitational pull of the moon on the seas (and to a lesser extent also pull from the sun).
- Explanation of Thermohaline Circulation: http://www.youtube.com/watch?v=x59MptHscxY&feature=player_embedded

# Waves

- Because wind is generated by uneven solar heating, wave energy can be considered a concentrated form of solar energy.
  - Incoming solar radiation levels that are on the order of 100 $W/m^2$ are transferred into waves with power levels that can exceed 1,000 kW/m of wave crest length.
- The transfer of solar energy to waves is greatest in areas with the strongest wind currents (primarily between 30° and 60° latitude), near the equator with persistent trade winds, and in high altitudes because of polar storms.
- **Wave power devices** extract energy directly from the surface motion of ocean waves or from pressure fluctuations below the surface.
  - Wave power **varies considerably** in different parts of the world so wave energy can't be harnessed effectively everywhere.
  - Wave-power rich areas of the world include the western coasts of Scotland, northern Canada, southern Africa, Australia, and the **northwestern coasts of the United States**.

# Wave Resources

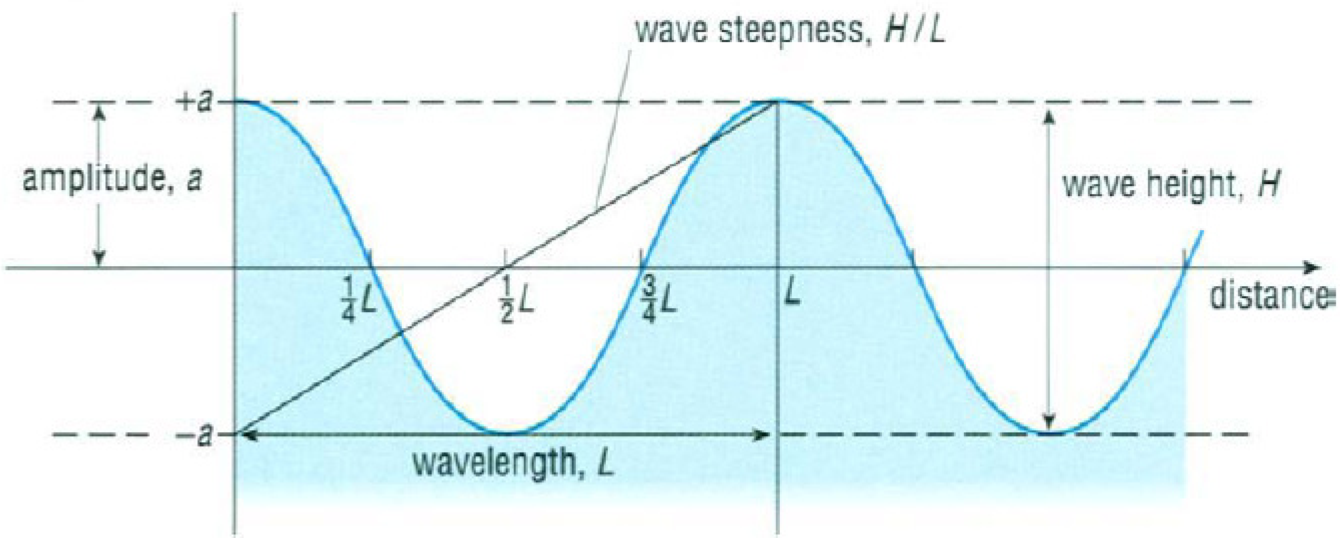



**Annual Wave Power Averages Worldwide in kW/m Wave Front**

The total annual average wave energy off the U.S. coastlines (including Alaska and Hawaii), calculated at a water depth of 60 m has been estimated (Bedard et al. 2005) at 2,100 Terawatt-hours (TWh) (2,100 × 1012 Wh).

# Wave Terminology

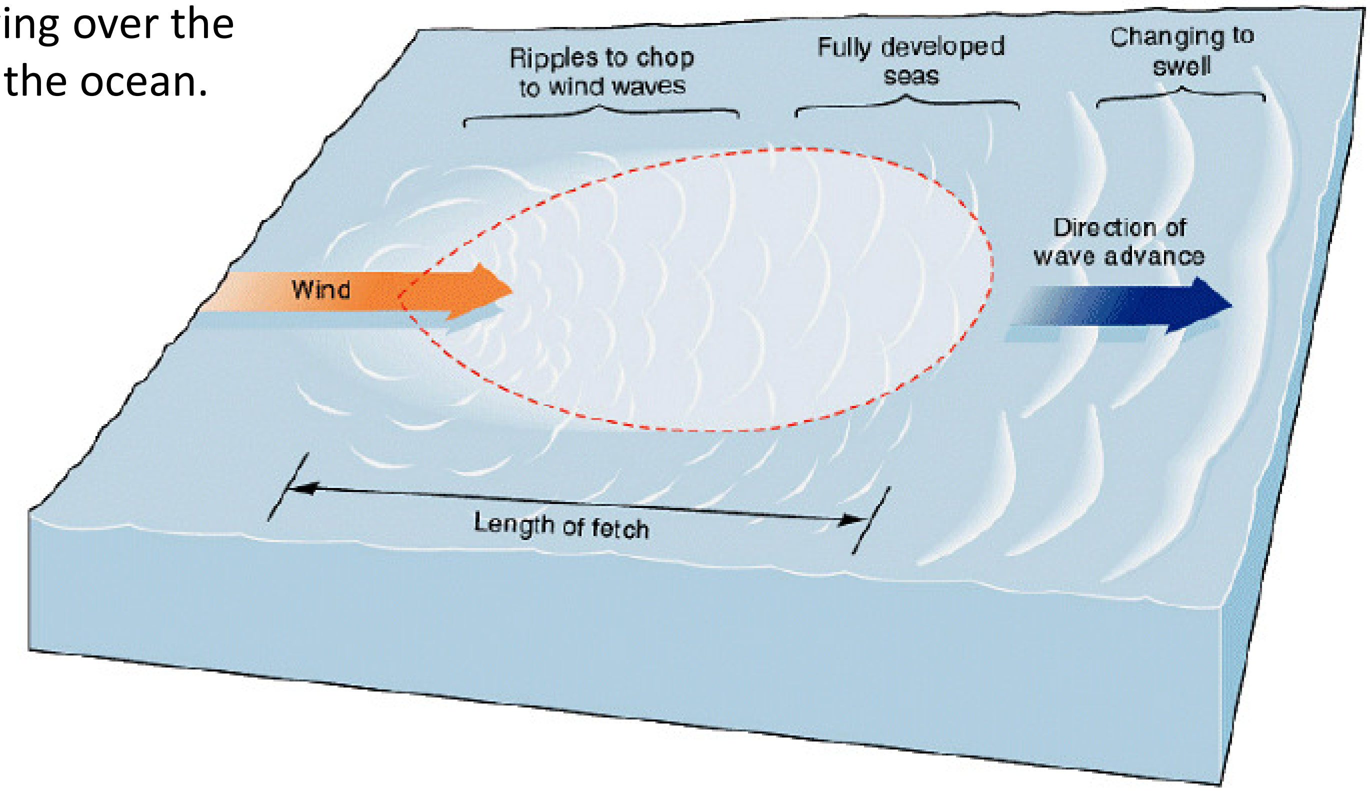
Wave height (H) refers to the overall vertical change in height between the wave crest (or peak) and the wave trough. The wave height is twice the wave amplitude (a). Wavelength (L) is the distance between two successive peaks (or two successive troughs). Steepness is defined as wave height divided by wavelength (H/L).




**THE TIME INTERVAL BETWEEN TWO SUCCESSIVE PEAKS (OR TWO SUCCESSIVE TROUGHS) PASSING A FIXED POINT IS KNOWN AS THE PERIOD (T), AND IS GENERALLY MEASURED IN SECONDS. THE NUMBER OF PEAKS (OR THE NUMBER OF TROUGHS) WHICH PASS A FIXED POINT PER SECOND IS KNOWN AS THE FREQUENCY (F).**

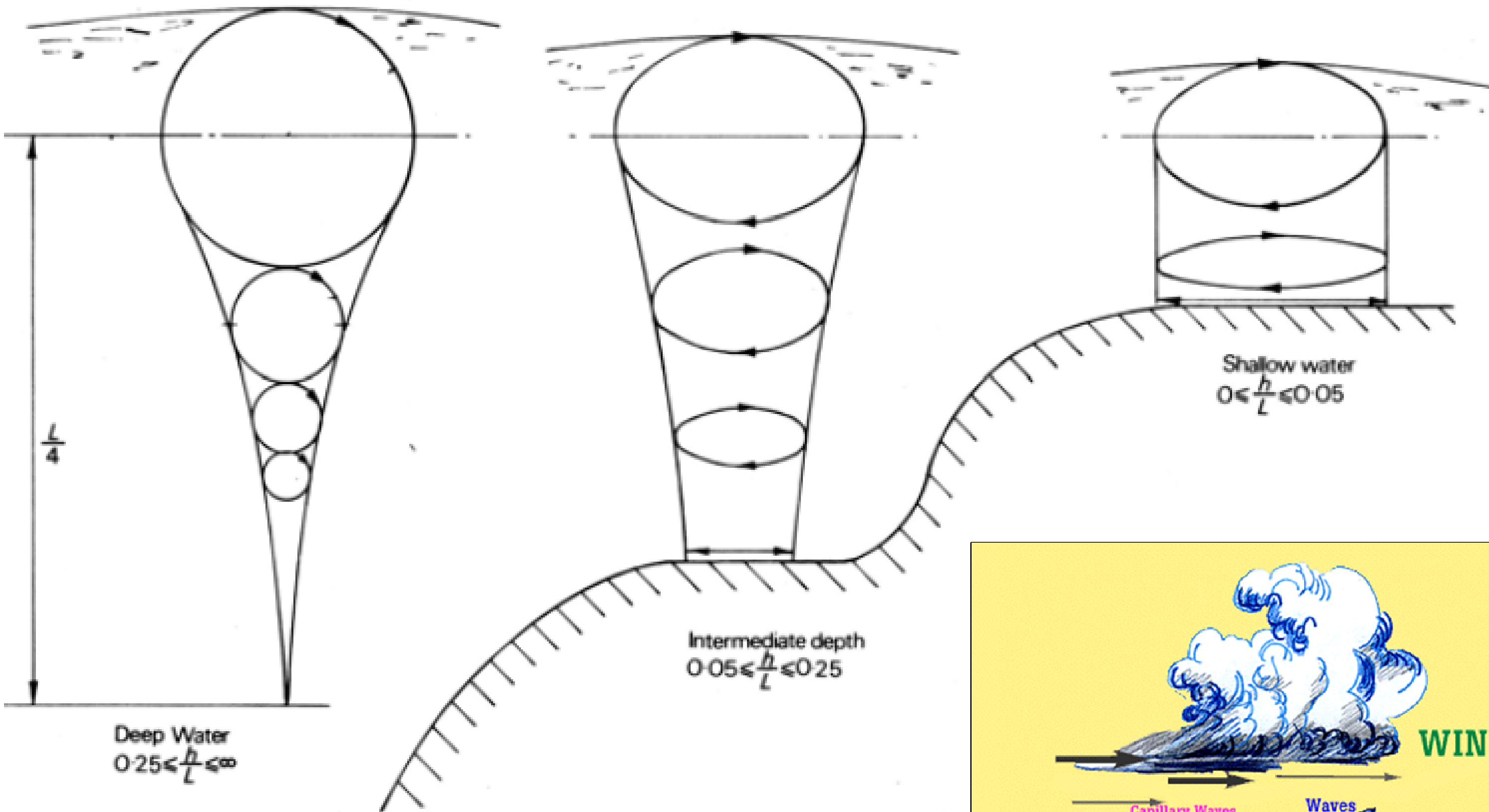
# Waves

Waves are caused by the wind blowing over the surface of the ocean.

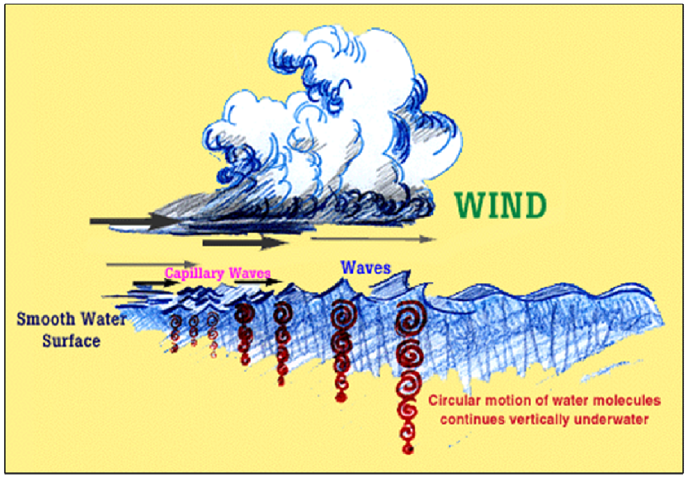



**Wind Blowing Over Fetch of Water Produces Waves**

# Particle Motion in Waves




**Particle Motion in Different Water Depths**




http://senergi.oregonstate.edu/wave-energy

# Wave Power

$$P = \frac{\rho g^2 T H^2}{32\pi}$$

Watts per meter (W/m)

of crest length

(distance along an individual crest)

where:

P= Wave power

$\rho$ = the density of seawater = 1,025 kg/m$^3$,

$g$ = acceleration due to gravity = 9.8 m/s/s,

$T$ = period of wave (s), and

$H$ = wave height (m).


http://ocsenergy.anl.gov/guide/wave/index.cfm, May 2006

# Wave Energy Technologies

**Point Absorber-** A bottom-mounted or floating structure that absorbs energy in all directions. The power take-off system may take a number of forms, depending on the configuration of displacers/reactors

**Oscillating Water Column (OCW)**- Near or offshore, this is a partially submerged chamber with air trapped above a column of water. As waves enter and exit the chamber, the water column moves up and down and acts like a piston on the air, pushing it back and forth. The air is channeled through a turbine/generator to produce electricity.

**Overtopping Terminator-** A floating reservoir structure with a ramp over which the waves topple and hydro turbines/generators through which the water returns to the sea.  A floating structure moves at or near the water surface, typically with reflecting arms to focus the wave energy.

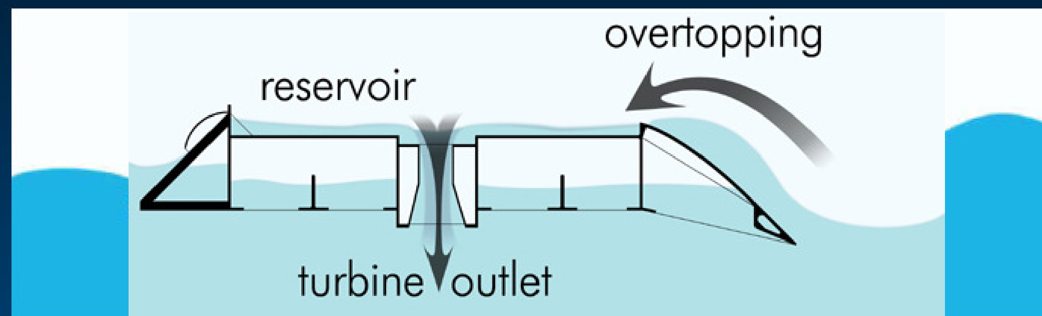
**Attenuator-**One incarnation of the attenuator principle is a long floating structure that is orientated parallel to the direction of the waves. The structure is composed of multiple sections that rotate in pitch and yaw relative to each other. That motion is used to pressurize a hydraulic piston arrangement and then turn a hydraulic turbine/generator to produce electricity

# Wave Energy Extraction Technologies

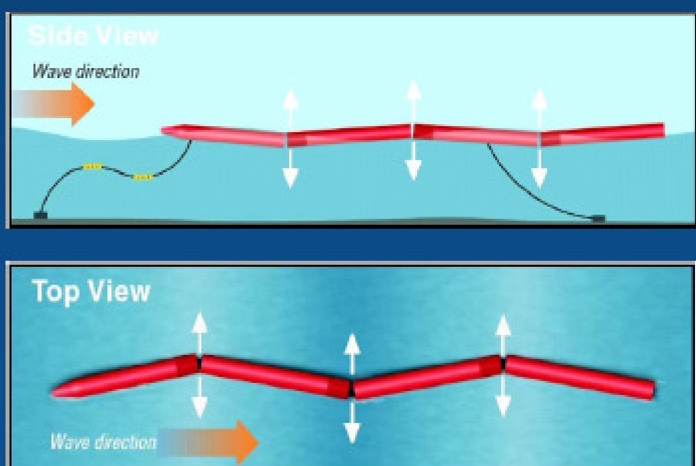
http://ocsenergy.anl.gov/guide/wave/index.cfm

## Point Absorber

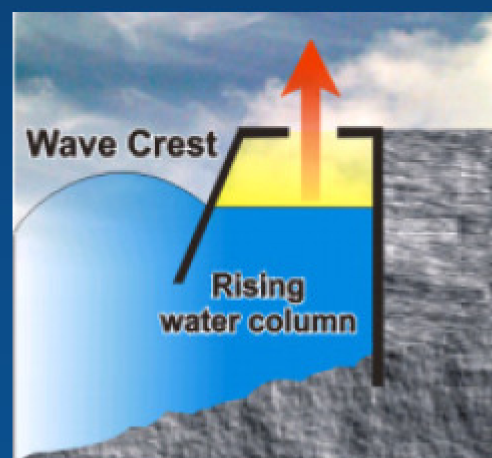
## Overtopping




## Attenuator



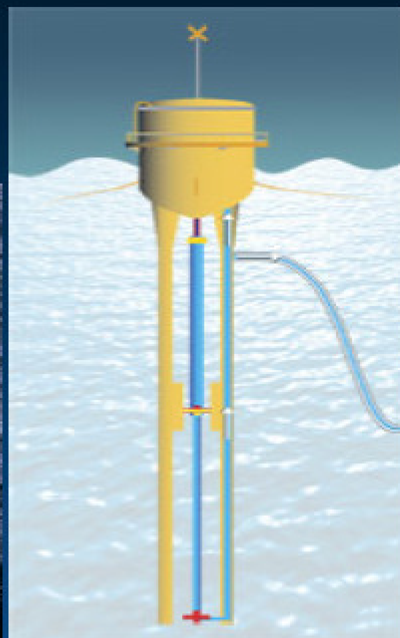

## Terminator OWC



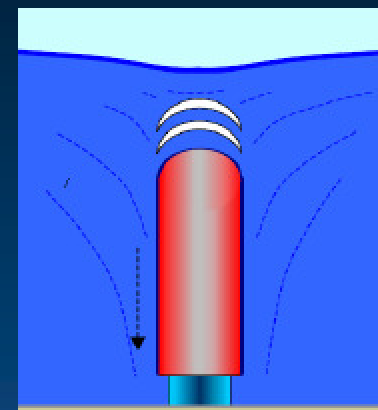

# Wave (Point Absorber) Technology Examples

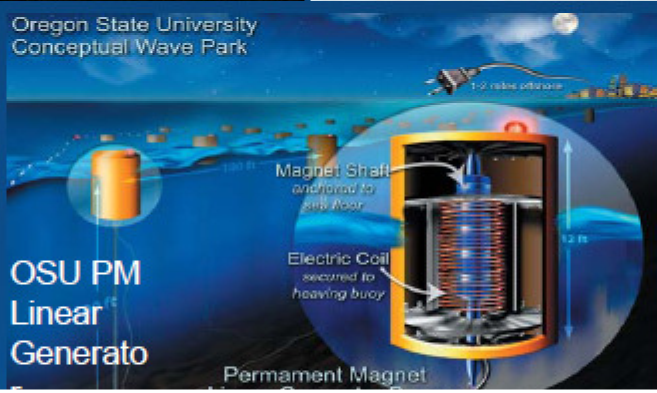
http://ocsenergy.anl.gov/guide/wave/index.cfm

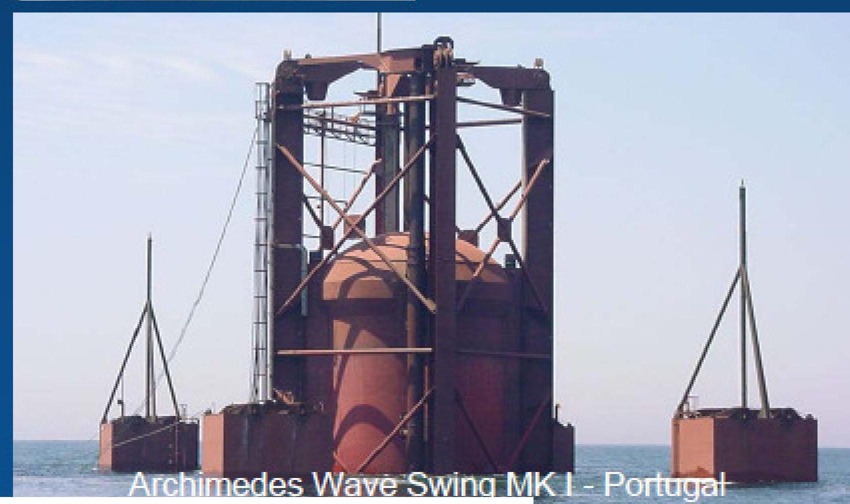
Aquabuoy; AquaEnergy - Makah Bay, WA




PowerBuoy; Ocean Power Technology Oahu, Hawai





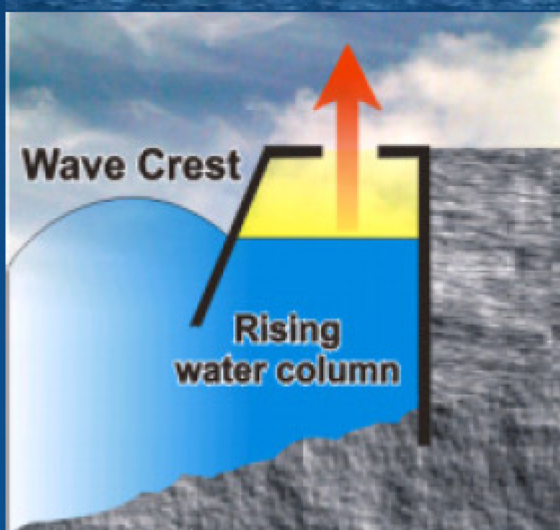

http://seagrant.oregonstate.edu/video/wave_energy/vonjouanne.html

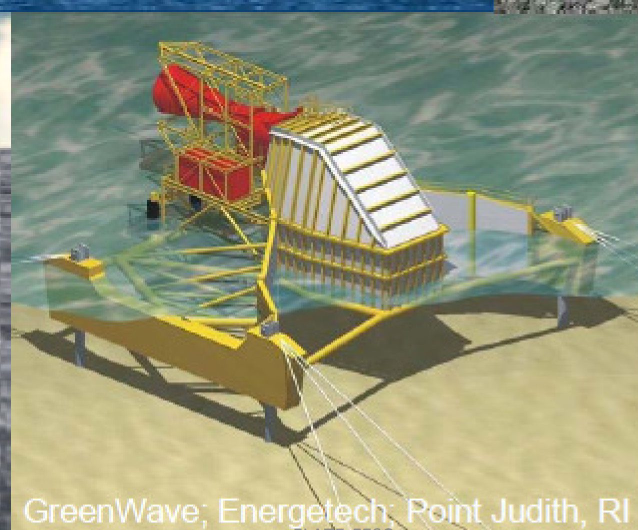
# Oscillating Water Column Technology

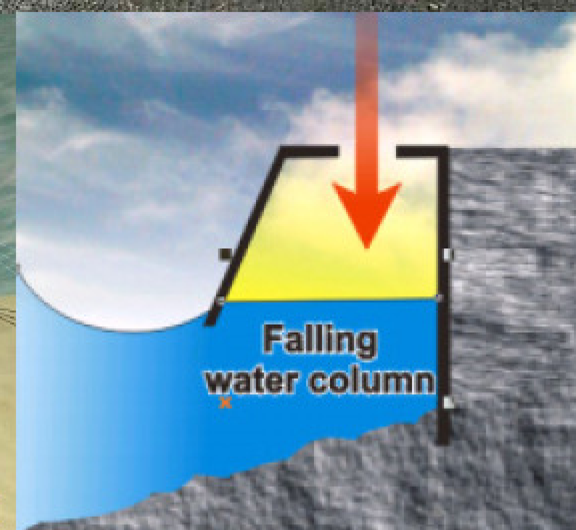
http://ocsenergy.anl.gov/guide/wave/index.cfm


Oscillating Water Column; Energetech; Port Kembla, Australia

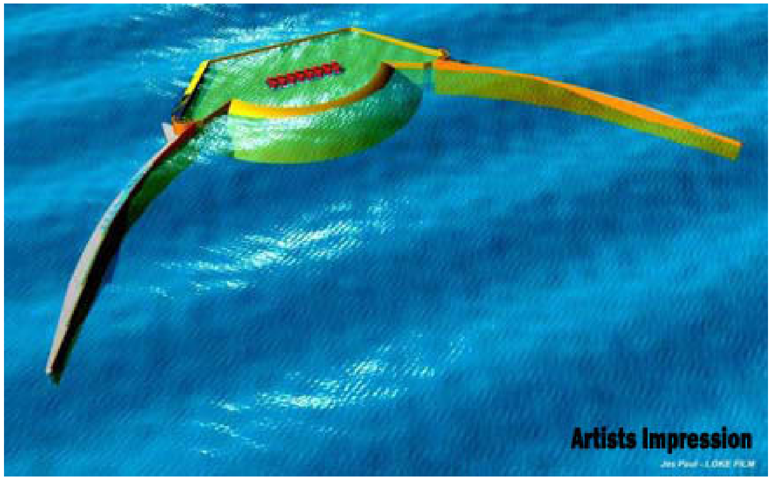

Wave Gen; OWC; Islay, Scotland



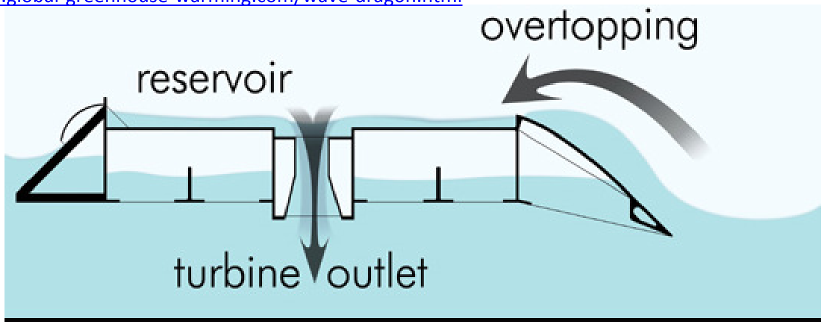


GreenWave; Energetech; Point Judith, RI



# Overtopping Devices




http://www.global-greenhouse-warming.com/wave-dragon.html




Wave Dragon Overtopper

Wave dragon in Action

# Integrator Technology Example

http://ocsenergy.anl.gov/guide/wave/index.cfm

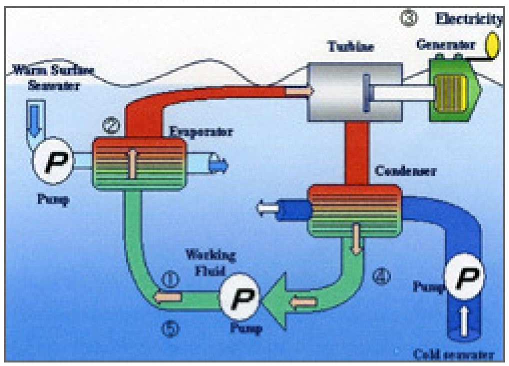

**OPD Pelamis Being Towed to EMEC For Test Trials**

# 3.1.4.3 Other Hydro Energy

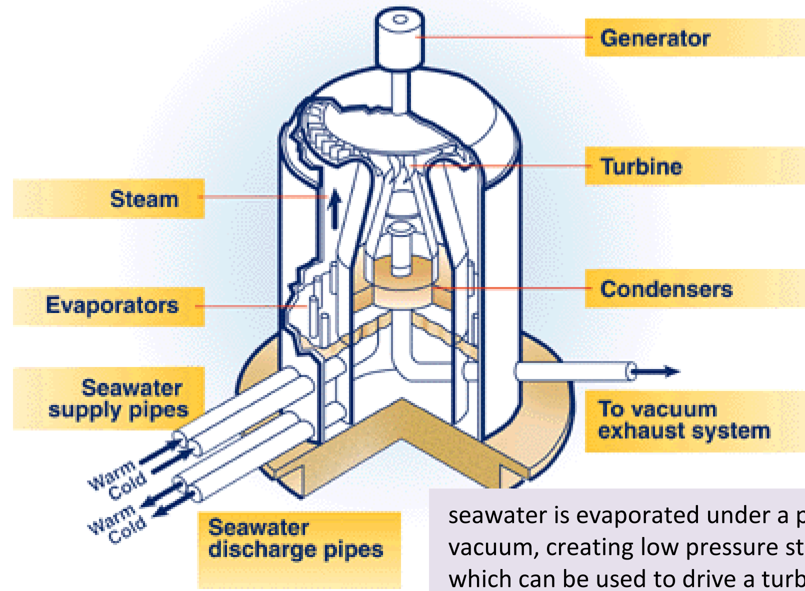
# Ocean Thermal Energy Conversion

The oceans cover a little more than 70 percent of the Earth's surface. This makes them the world's largest solar energy collector and energy storage system.

Closed-Cycle OTEC



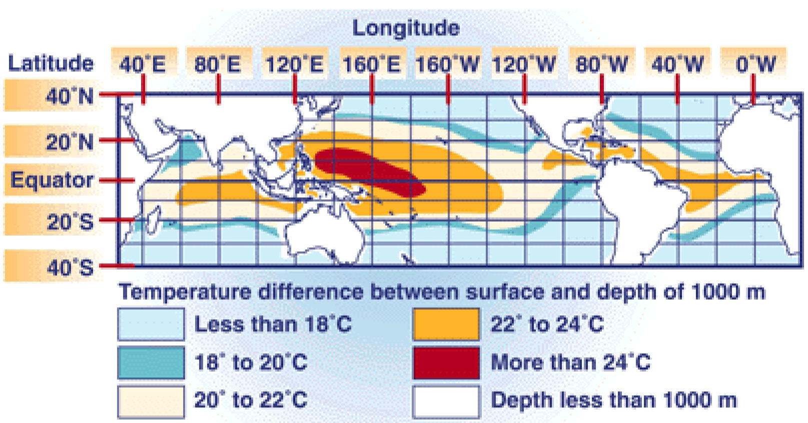

a working fluid with a low boiling point, such as ammonia, which is vaporized using heat extracted from the warm ocean surface water. The heated working fluid is used to turn a turbine to produce electricity




seawater is evaporated under a partial vacuum, creating low pressure steam which can be used to drive a turbine

http://www.nrel.gov/otec/achievements.html

Open-cycle OTEC plant at Keahole Point, Hawaii, produced 50,000 watts of electricity during a net power-producing experiment.



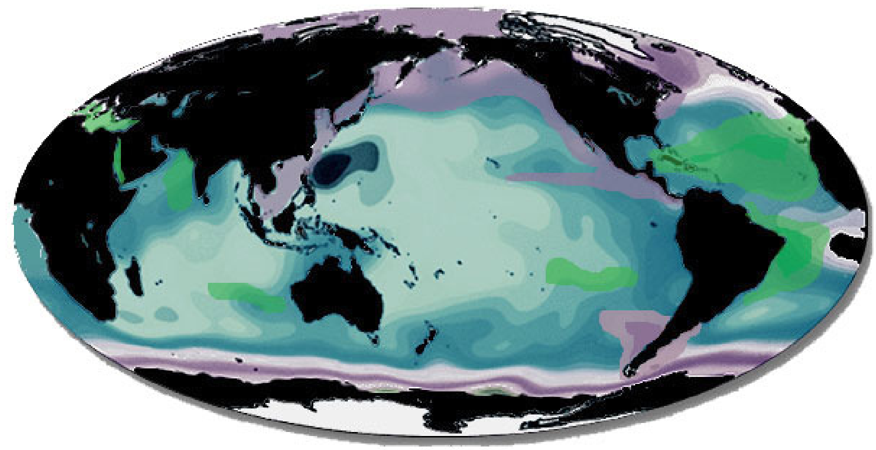

OTEC (ocean thermal energy conversion) systems use the ocean's natural thermal gradient—the fact that the ocean's layers of water have different temperatures—to drive a power-producing cycle. As long as the temperature between the warm surface water and the cold deep water differs by about 20°C (36°F), an OTEC system can produce a significant amount of power.

http://www1.eere.energy.gov/wip/update/2008-01_nelha_roots.html

# Salinity Gradient Power

| Chemical Ion Contributing to Seawater Salinity | Concentration in (parts per thousand) in average seawater | Proportion of Total Salinity |
|---|---|---|
| Chloride | 19.345 | 55.03 |
| Sodium | 10.752 | 30.59 |
| Sulfate | 2.701 | 7.68 |
| Magnesium | 1.295 | 3.68 |
| Calcium | 0.416 | 1.18 |
| Potassium | 0.390 | 1.11 |
| Bicarbonate | 0.145 | 0.41 |
| Bromide | 0.066 | 0.19 |
| Borate | 0.027 | 0.08 |
| Strontium | 0.013 | 0.04 |
| Fluoride | 0.001 | 0.003 |
| Other | less than 0.001 | less than 0.001 |

http://www.marinebio.net/marinescience/02ocean/swcomposition.htm



Salinity map showing areas of high salinity in green, medium salinity in blue , and low salinity in purple.

**Salinity gradient power** is the energy available from the difference in the salt concentration between seawater and river water. Two current practical methods as below:

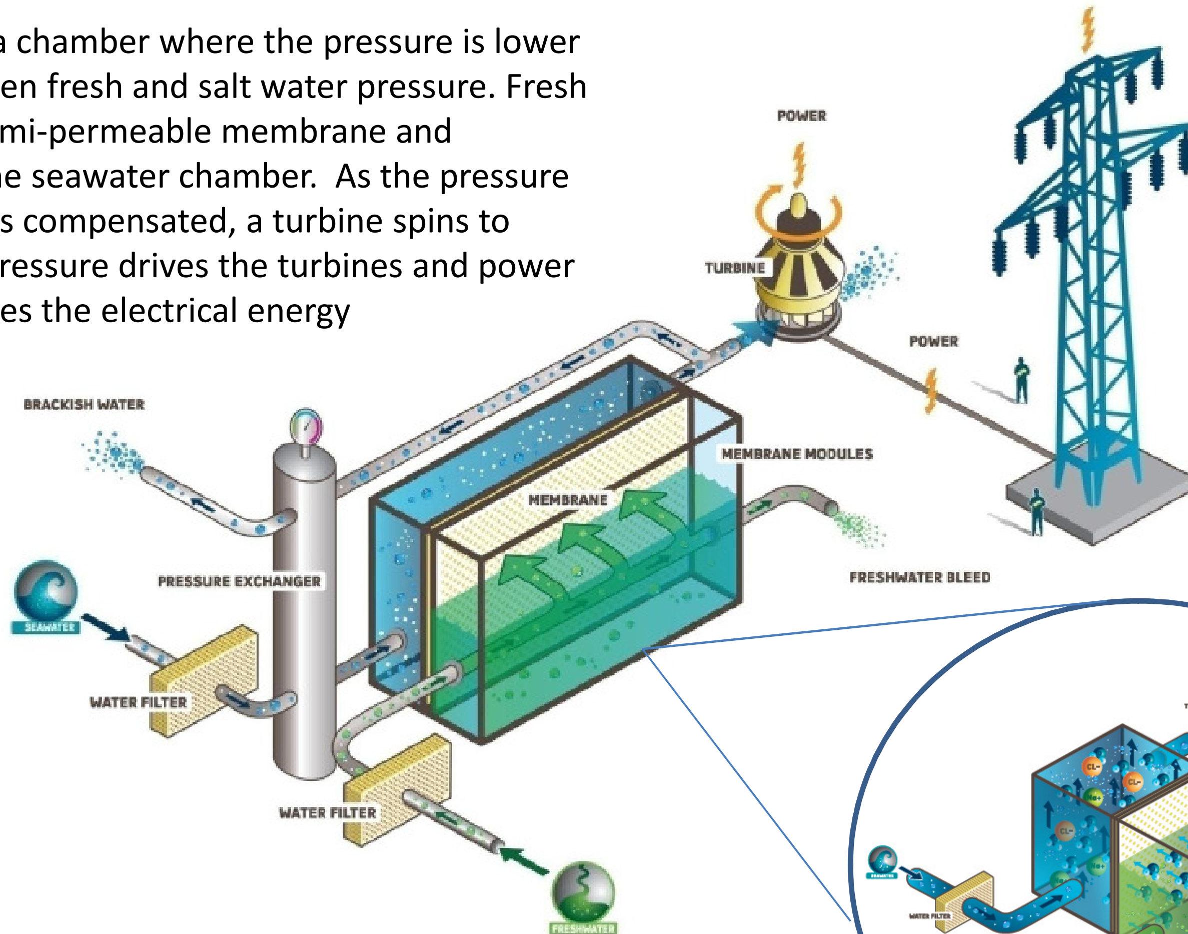
*Clifford Merz, 2010 FESC Summit, http://www.floridaenergy.ufl.edu/?page_id=3657*

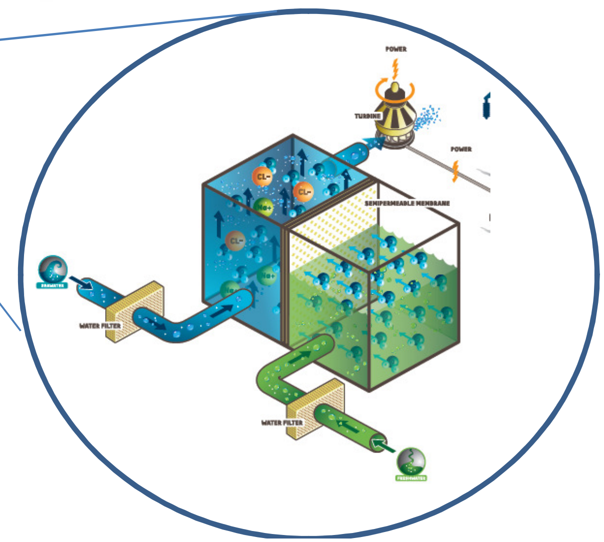
- ✓ Reverse ElectroDialysis (RED) or called Dialytic Batteries, and
- ✓ Pressure-Retarded Osmosis (PRO),

# Salinity Gradient Power

## Pressure Retarded Osmosis (PRO)

Seawater is pumped into a chamber where the pressure is lower than the difference between fresh and salt water pressure. Fresh water moves through a semi-permeable membrane and increases the volume in the seawater chamber.  As the pressure in the seawater chamber is compensated, a turbine spins to generate electricity. The pressure drives the turbines and power the generator that produces the electrical energy



Statkraft

http://www.statkraft.com/

# Salinity Gradient Power

## Reverse ElectroDyalisis (RED)

Blue Energy
http://www.youtube.com/watch?v=UwpY756Qa5U

A salt solution and fresh water are let through a stack of alternating cathode and anode exchange membranes. The chemical potential difference between salt and fresh water generates a voltage over each membrane and the total potential of the system is the sum of the potential differences over all membranes

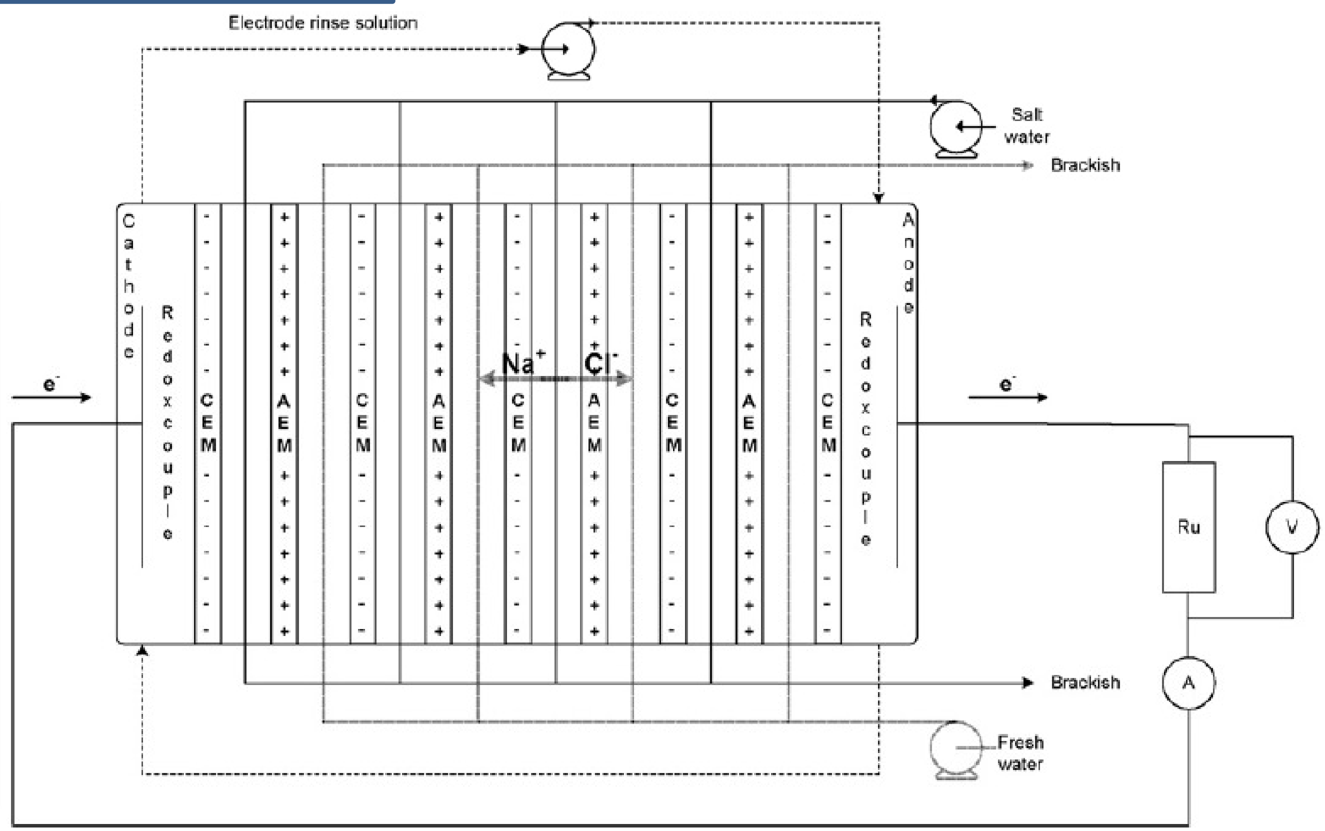



Fig. 1. Schematic representation of a reverse electrodialysis stack with four cells.

*J. Veerman et al. / Journal of Membrane Science 310 (2008) 418–430*