VI CARIBE EWS SHORT COURSE ON SEA LEVEL STATION INSTALLATION, MAINTENANCE AND LEVELING, QUALITY CONTROL AND DATA ANALYSIS
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Overview of Oceanographic Concepts/Types of Sea Level Variability

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Oceanographic Concepts

Sea levels respond to a number of key natural processes:

\[ H_T = H_t + H_b + H_w + H_s + H_e + H_g \]

- \( H_T \) **Total sea level height** =
- \( H_t \) Height due to **tides** +
- \( H_b \) Response to **barometric pressure** +
- \( H_w \) **Wind**-driven component +
- \( H_s \) **Steric** contribution +
- \( H_e \) **Eustatic** (mass) component +
- \( H_g \) **Geological** effects (volume of the ocean basins)
$H_t$ Height due to Tides (astronomical forcing)

Periodic movements which are directly related in amplitude and phase to variations of the tidal gravitational potential on the surface of the earth, caused by regular movements of the Moon-Earth and Earth-Sun systems.
$H_b$ Height due to barometric pressure

The inverse barometer effect
Variations in surface atmospheric pressure usually cause sea level to change at a rate of -1 cm/hPa. High (low) atmospheric pressure corresponds to low (high) sea level.
The wind exerts a force on the sea surface, that is proportional to the square of the wind speed.

- Most of the transferred energy results in waves
- Some results in wind driven currents, injecting momentum into the upper layer (Ekman layer) of the ocean.
- This layer moves at 90° to the wind direction due to Earth’s rotation (the Coriolis Force).
- Ekman transport acts right (left) of the wind in the northern (southern) hemisphere.
- Sea Surface is tilted
$H_w$ Height due to wind stress

In the open ocean, Ekman transport also produces convergences and divergences of surface water, causing hills and valleys in sea level, which then produce a horizontal gradient of pressure.

Hills (valleys) have an outward (inward) directed pressure gradient, which is also deflected by the Coriolis force, creating a current acting in the same direction as the wind.
$H_s$ Height due to steric effects

Thermal expansion of water

Sea level rise due to water over 1 km warming 1°C
\[ \Delta h = \alpha \Delta TH \]
\[ = 2 \times 10^{-4} \text{ °C}^{-1} \times 1 \text{ °C} \times 10^3 \text{ m} \]
\[ = 20 \text{ cm} \]

Sea level rise due to freshening water over 1 km by 0.1 psu
\[ \Delta h = \beta \Delta SH \]
\[ = 7.5 \times 10^{-4} \text{ psu}^{-1} \times 0.1 \text{ psu} \times 10^3 \text{ m} \]
\[ = 7.5 \text{ cm} \]
Land-based ice melting

Meltwater from ice sheets and glaciers running into the sea will increase sea level by adding into the total amount of water in the ocean.

Melting of sea ice does not change sea level!

$H_e$ Eustatic (mass) component

Same water level
$H_g$ Geological effects e.g.

Sea floor spreading

Mountain building

Destructive boundaries

(bgs.ac.uk)
Sea level is a fantastic parameter to study because…….

It responds to

- Astronomical, geological and meteorological forcings on many different timescales
- So, it is a good indicator of changes in the Earth system

But what does a sea level record look like?
Characteristics of a sea level record

Sea levels vary on different time scales and for different reasons:

- Wind generated waves (<20s)
- Tsunamis (10s of minutes to an hour)
- Seiches (minutes to hours)
- Tides (diurnal, semi-diurnal, mixed)
- Storm surges (few days)
- Seasonal cycle (annual, semiannual)
- Mean sea level changes (months – millennia)

Sampling intervals:
- 1 min sampling or less
- 5 min - hourly sampling
- >hourly sampling
Tides

Periodic movements which are directly related in amplitude and phase to variations of the movements of the Moon-Earth and Earth-Sun systems.

Tides differ from one location to the next. They are large amplitude and tend to dominate other changes in sea level.
Tides

Periodic movements which are directly related in amplitude and phase to variations of the tidal gravitational potential on the surface of the earth, caused by regular movements of the Moon-Earth and Earth-Sun systems.
Tides

Examples:

- Spring-Neap Cycle - 29.53 days (synodic month)
- Eccentricity of lunar orbit – 27.55 days and 8.85y cycle
- Lunar declination – 27.21 day and 18.61 year cycles
Different types of tide:

- **Diurnal**
- **Mixed**
- **Semi-diurnal**
- **Semi-diurnal**
- **Shallow sea distortions**
Non-Tidal Variability

Non-tidal components might include:

- **Storm surges** caused by changes in air pressure and winds
- **Seiches** due to resonant behaviour of harbours and bays
- **Tsunamis** caused by earthquakes, submarine landslides etc.
- **Seasonal** changes due to changes in water density
- **Long-term changes e.g.** due to climate change
Storm surges

Due to a combination of:

1. Low air pressure (1 mbar reduction raises sea level by 1 cm, known as the **Inverse Barometer Effect**)

2. **Wind stress** in shallow water, the surge being proportional to Stress/Depth
UK Storms Surges

Dawlish, Devon coast

New Brighton, Wirral
North Sea storm surge of 1953

Sea Palling, Norfolk (1 Feb 1953)

Thames Barrier

1953 Surge Levels

Diagram shows open sea mathematically modelled surge heights. Local levels recorded may differ from these modelled figures.
New Orleans after the Katrina storm surge
A tide gauge near New Orleans during Hurricane Katrina
Caribbean tide gauges during Hurricane Irma
Seiches are standing waves (a combination of 2 waves travelling in opposite directions)

Due to resonant behaviour in bays, harbours etc.

Fundamental frequency is proportional to $1/\sqrt{\text{depth}}$
Seiches

- Sometimes they can be many decimetres in amplitude and have associated currents that can damage shipping e.g. in the Mediterranean (Rissaga)
- They can be set off by:
  - Rapid meteorological changes
  - Tides
  - Internal waves
  - Earthquakes
  - Landslides
  - Tsunamis
- In practice, they occur in all sea level records and can be readily identified given high frequency sampling.
Seiches in St Lucia triggered by Hurricane Irma
Tsunamis

Caused by undersea earthquakes, submarine landslides, terrestrial landslides, volcanic eruptions, asteroid and comet impacts, man-made explosions.

26 December 2004 Sumatra tsunami
The 26 December 2004 tsunami was observed in tide gauge records on many coastlines.
Longer term trends in Global Mean Sea Level measured by satellite altimetry

Overall trend: 3.10 mm/yr
Altimeter data up to 66° latitude
Corrected for GIA
Annual signal removed
Regional sea level deviates greatly from global MSL

Deviation of the relative sea level trend from the global mean trend as derived from satellite altimetry data (1993-2015)
What causes regional variability in MSL?

Local MSL can deviate significantly from global MSL because:

Ice melting (or any mass redistribution) gives raise to highly non-uniform spatial patterns of sea level by perturbing both the Earth’s gravity field and its crust.

Regional sea level response to land-based ice

Static equilibrium response to meltwater from the Greenland ice sheet (so-called fingerprint)
What causes regional variability in MSL?

Changing winds and surface buoyancy fluxes cause changes in ocean circulation and thus in sea level.

Ocean currents redistribute heat and mass non-uniformly in the ocean, which results in non-uniform sea level changes.
Inverse Barometer Effect

Detrended and deseasoned sea level from the Newlyn tide gauge (black) and the inverse barometer effect (red)
Decadal MSL changes: the response to alongshore wind forcing

Detrended sea level from tide gauges and the integrated alongshore wind

Calafat et al. (2012)
The seasonal cycle of MSL
The seasonal cycle of MSL
Longer Term Changes - Sea level over geological timescales

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.

Changes in sea level during the last 500,000 years.
Sea level is a fantastic parameter to study because……

…..it responds to multiple natural processes in the Earth System and on many different timescales