CLIVAR Summer School, Qingdao, China

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Vertical land movement, GIA and sea-level practical

Background

Sea level rise, one of the clear and measurable consequences of global climate change has been identified as one of the major challenges facing humankind in the current century (Church et al., 2013). Historically, sea level has been observed and monitored by tide gauges. These have provided long, but sparse records confined to the coastlines, and typically biased towards the northern hemisphere around Europe and the United States. More recently, the tool of choice to provide near global coverage of sea level is the satellite altimeter. The so called 'precision-era' of modern altimetry began more recently in comparison with the longer tide gauge records - TOPEX/Poseidon was launched in late 1992, followed by Jason-1 in 2001, OSTM/Jason-2 in 2008 and Jason-3 in 2016.

Tide gauges and satellite altimeters are two very different but equally important geodetic tools used to observe changes in sea level. Both sample sea level in very different ways; tide gauges sample very frequently (high temporal resolution) but provide data at point locations (poor spatial resolution). Sea level observed from a tide gauge is also a measurement *relative* to the land on which the gauge is attached. If that land is subsiding, then *relative to the land*, sea level is rising. Satellite altimeters on the other hand, provide near global coverage (high spatial resolution) in an *absolute* reference frame, with slightly less frequent sampling (slightly lower temporal resolution).

Task Overview and Learning Objectives

Data links and code snippets are provided for each task. Please read the question carefully and ask questions if you don't understand what is required.

This assessment addresses learning objectives 1, 2, 3 and 4.

TASK 1 – Spatial variations in sea level, and effect of vertical land motion on sea level

Overview:

This task uses observations from a tide gauge, satellite altimetry and a model of vertical land motion (VLM) to explore the questions:

- Why does relative sea level (from a tide gauge) differ from absolute sea level (from an altimeter)?
- Why are changes in regional sea level different from the global average?

Suggested Readings:

Wöppelmann and Marcos (2016): Read this paper published in *Reviews of Geophysics*.
Church et al. (2013): Read the FAQ 13.1 on page 1148.

Data:

This task requires you to download some tide gauge data. The tide gauge data comes from the Permanent Service for Mean Sea Level (PSMSL).

You will also download a vertical land motion (VLM) estimate for the tide gauge location computed from a Glacial Isostatic Adjustment (GIA) model. GIA refers to the ongoing response of the solid Earth induced by significant changes in past mass loads. During the last ice age, northern Europe was mostly covered by a large ice sheet known as the Fennoscandian Ice Sheet. The weight of this ice sheet loaded the crust, displacing the viscous mantle deep in the Earth. Following the melting of that ice sheet, the crust is rebounding as the mantle flows in return. This process is one driver of VLM at the tide gauge site.

1) Download monthly mean sea level data from the tide gauge located in Forsmark, Sweden, from the Permanent Service for Mean Sea Level (PSMSL) website:
   Site information: http://www.psmsl.org/data/obtaining/stations/2103.php
   Data: http://www.psmsl.org/data/obtaining/rlr.monthly.data/2103.rlrdata Note this data is provided as monthly estimates of mean sea level.

2) Download the VLM estimate for the Forsmark tide gauge from the ICE6G GIA model (note this file contains VLM estimates for all tide gauges in the PSMSL archive – you will need to extract the correct line for the Forsmark gauge:
   http://www.atmosp.physics.utoronto.ca/~peltier/datasets/Ice6G_C_VM5a_O512/drad.PSMSL.ICE6G_C_VM5a_O512.txt

Preparation:

- Download the data indicated above. Open the data in a text editor (or in Matlab) to get a sense of what you will be working with.
- Create a new m-file in Matlab and assemble the code examples given below. *You will need to modify the code.*

Analysis Requirements:

Your analysis tasks focus on comparing relative sea level (observed using a tide gauge) to absolute sea level (observed from a satellite altimeter). Write an appropriately commented Matlab m-file to undertake the following:

- Load the tide gauge data downloaded from the PSMSL. The following code may be useful to load the data.

```
% Load RLR data - ignoring QAQC flags for this site
%  1975.6250;  7048; 5;000
%  1975.7084;  7141; 0;000
fid = fopen('../data/2103.rlrdata.txt');
data = textscan(fid,'%f%f%f%f','Delimiter',';');
time = data{1};  % Time vector (years)
ssh = data{2};   % Monthly mean sea level (mm)
```

- Fit a regression solving for offset, linear rate of change and seasonal periodic terms, outputting parameter estimates to the command window. This code may help (you will need to modify it).

```
% Fit a linear model with time, solving for constant and linear rate of change terms
model_obj=fit(time,ssh,'a + b*x');

% To add seasonal periodic terms to the regression model, change the model in 'quotes'.
% As shown below, 4 additional coefficients/parameters are solved for (c, d, e and f).
% These coefficients describe the amplitude (same units as data) and phase (radians)
% of two sinusoids with 1 cycle per unit time (i.e. annual period), and 2 cycles per
% unit time (i.e. semi-annual period). This about what the addition of the semi-annual
% term does to the quality of the fit.
% model_obj=fit(time,gmsl_filtered,'a + b*x + c*sin(2*pi*x*1 + d) + e*sin(2*pi*x*2 + f)');

% Evaluate the model
model = model_obj(time);

% Compute the residual by subtracting the model from the data
residual = ssh-model;

% Display the model parameters to the screen
model_obj

% Extract model coefficients to a vector
coefficients = coeffvalues(model_obj);

% Extract 95% confidence intervals for each coefficient to a vector
% Watch out for the line breaks in the fprintf lines when copied from this PDF
ci = confint(model_obj,0.95);
fprintf('Model "a" coefficient and 95 CI is: %3.1f (%3.2f %3.2f)\n',coefficients(1),ci(:,1));
fprintf('Model "b" coefficient and 95 CI is: %3.1f (%3.2f %3.2f)\n',coefficients(2),ci(:,2));

% Plot the data, model and residual
subplot(2,1,1);
plot(time,ssh,'b-'); hold on;
plot(time,model,'r-');
subplot(2,1,2);
plot(time,residual);
```

- Correct the *relative* sea level change derived in the previous step for the effects of GIA VLM by applying the VLM as extracted from the ICE6G GIA model as downloaded. Output the adjusted linear rate of change to the command window.
- Produce an appropriately annotated and labelled scientific plot. Include two panels. Plot the tide gauge (corrected and uncorrected for GIA VLM). Include your regression model fits and annotate linear rates of change. In the lower panel, show the residual time series, appropriately annotated and labelled using your regression model fits.
- Make the figure look nice so that it portrays the effect of vertical land movement clearly

Bibliography

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S.Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan, (2013). Sea Level Change. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Wöppelmann, G., and Marcos, M. (2016) Vertical land motion as a key to understanding sea level change and variability, *Reviews of Geophysics*, 54,64–92, doi:10.1002/2015RG000502.

TASK 2 – Solid earth response to ice loading changes, and sea level effects

Overview:

The task is to understand:

- the solid Earth and sea level components of GIA
- that these components vary spatially

Essential Readings:

Tamisiea & Mitrovica (2011)

Data:

Present-day sea levels are also affected by ice sheet mass changes that stopped long ago, through glacial isostatic adjustment (GIA). A very widely used computer model of GIA is ICE-6G_C + VM5a. It is available at http://www.atmosp.physics.utoronto.ca/~peltier/data.php. Users can download global grids (in netCDF format) of rates of change of relative sea level or vertical land movement. Download the 1x1 degree grid of relative sea level ("Rate of change of sea-level") and the 1x1 degree grid of radial displacement, that is vertical uplift rates ("Rate of radial displacement (UP)").

Analysis Requirements:

- Load the relative sea level grid into Matlab, noting once read in the matrix containing the grid will need transposing.

```
% get the variable names in the netcdf file
info=ncinfo('./dsea.1grid_O512.nc')
% list the variable names, noting there are variables for each of
latitude,longitude and relative sea level rate (mm/yr)
info.Variables.Name

% load a netcdf variable
%loading the netcdf variable. An example is loading the variable Lat –
%note they are case sensitive
lat_ice6g=ncread('./dsea.1grid_O512.nc','Lat')
%the actual data are in the Dsea_250 grid

% you may need to transpose a matrix
gridtranspose = grid';


% plot a grid from a 2d matrix called 'grid'
mesh(lon,lat, grid); % create a 2d perspective mesh of the grid
view(0,90); % view from above
colorbar % add a color bar scale
caxis([-5 5]); %change the extent of the colour scale to -5mm/yr to +5mm/yr
%see help for xlabel, ylabel and title for how to label axes. See the colorbar
help for how to label the colorbar
```

- Add a map of the world's coastlines

```
% load and plot the world coastline
load coast; %loads variables lat and long which contain coastlines
hold on;
plot(long,lat); %recall that you can specify longitude from -180 to +180 or 0 to
360.
```

- Find coordinates for tide gauges at Hobart, Stockholm and New York using the PSMSL database. Interpolate the ICE-6G grids to determine the rates of relative sea level or land motion at each of these locations

```
% perform interpolation in latitude and longitude on a 2d matrix called 'grid'
interp2(lon,lat,grid,300,-85) % interpolate grid at longitude 300, latitude -85 degrees
```

- Download the tide gauge data from the PSMSL (as for Task 1) for Hobart, Stockholm and New York and compute the rates of sea-level change (as for Task 1)
- Compute the sum of the VLM and RSL ICE-6G grids and consider what this reveals.
- Consider the various geophysical processes which result in sea level varying spatially: recalling that this is a model of present-day GIA and no ocean mass is being introduced or removed (glacier melt ended 4,000 years before present).
