# Practical handling sea surface height data from tide gauge

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**Table of Contents**



"busan_tide.mat" incldue 10 years sea surface height (sea level) observations at the Busan tide guage station off the coast of south Korea.

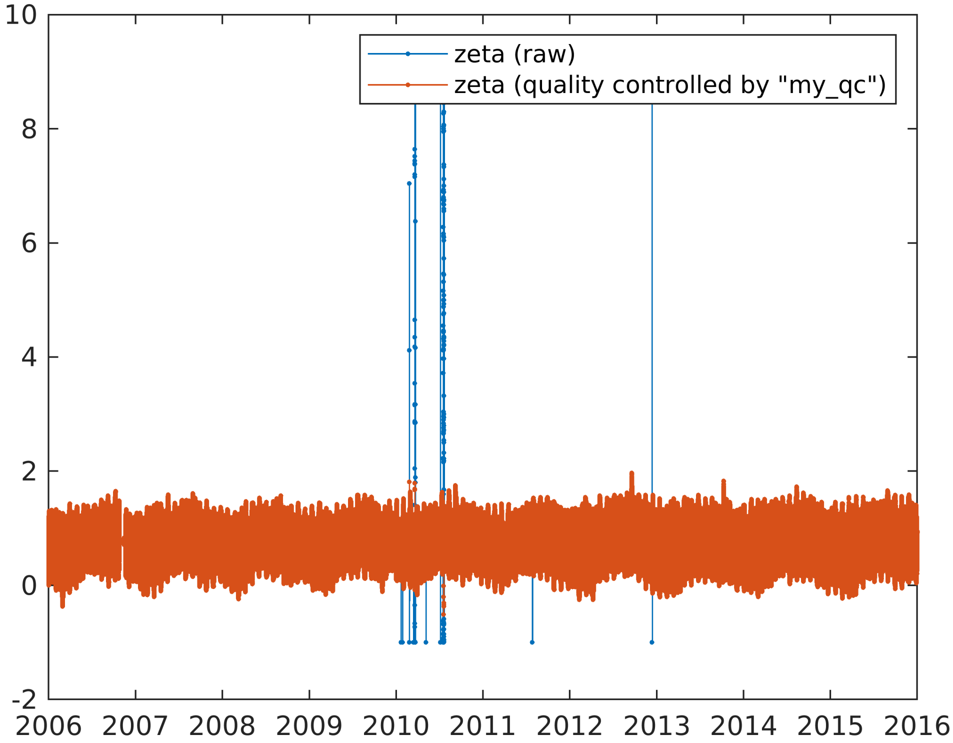
```
clc;clear;
load busan_tide.mat
% t (days): time in MATLAB date-format
% zeta (cm): raw sea level data from tide gauge
% zeta_qc (m): quality-controlled sea level data
plot(t,zeta,'.-')
datetick
```

## 1. Quality control

Unfortunately, many real time tide gauge dataset is not quality controlled. It is usually reauired for the users to do quality control. Useful guidance for quality control is provided by Integrated Ocean Observing System (IOOS; https://ioos.noaa.gov/project/qartod/). I recommend to do gross-range test, spike test, and flat line test to use tide gauge datasets off the coast of the Korea. The "my_qc.m" is an example code for quality control programming

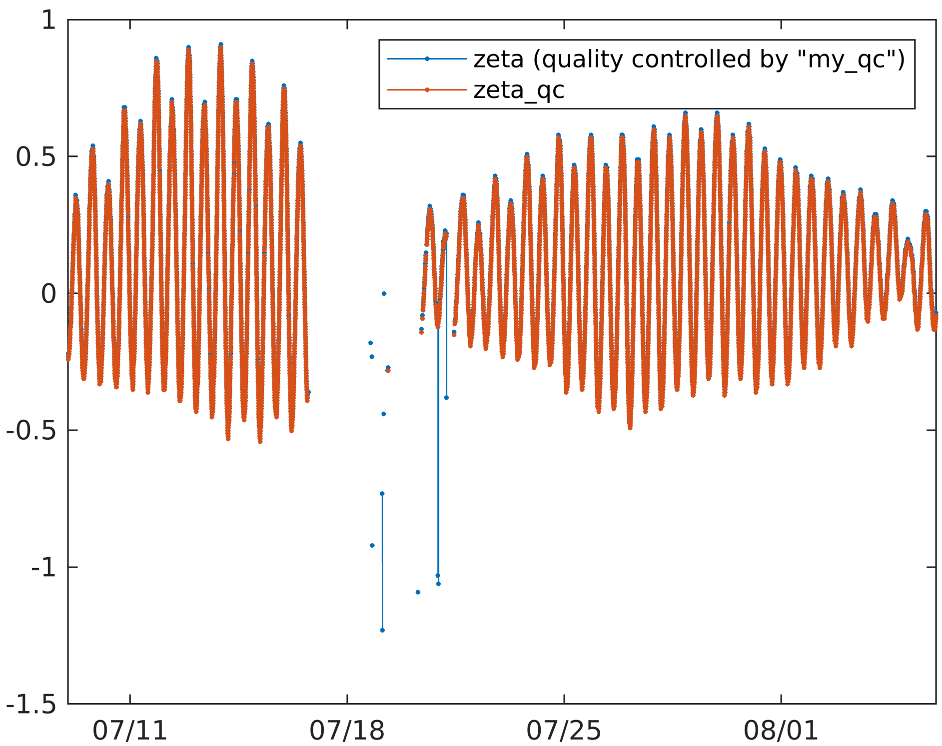
```
% Quality control
% Note that three-standard devidation is frequnetly considered as
% reasonable choice of threshold.
dat_min=nanmean(zeta)-3*nanstd(zeta);
dat_max=nanmean(zeta)+3*nanstd(zeta);
spk_trsd=3*nanstd(conv(zeta,[0.5 0 0.5],'valid'));
flt_n=5;
flt_eps=0.001;
flag=my_qc(zeta,dat_min,dat_max,spk_trsd,flt_n,flt_eps);
% suspect data will be flagged by '4'
hold on

zeta(flag==4)=nan;
plot(t,zeta,'.-')
legend('zeta (raw)','zeta (quality controlled by "my\_qc")')
```




Note that most quality control programs, including "my_qc.m", is imperfect so it may be required to check the data manually. Variable "zeta_qc" is manually quality controlled data where apparently suspect data (e.g., undected spike and abnormal discontinuity) are subjectively removed.

```
figure
plot(t,zeta-nanmean(zeta),'.-')
hold on
plot(t,zeta_qc,'.-')
xlim([734328 734356])
datetick('x','keeplimits')
legend('zeta (quality controlled by "my\_qc")','zeta\_qc')
```




## 2. Tide analysis

Freqeuntly, predominant component in the sea level observations off the shallow coastal region is tides. The tidal component can be obtained by finding  mode having modes having specific freqeunce which corresonds with tides. There are toolboxes for the tidal anaysis:

T_Tide: https://www.eoas.ubc.ca/~rich/

UTide: http://www.po.gso.uri.edu/~codiga/utide/utide.htm

Here, T_Ttide will be used. It is worth noting that demo problem is provided by T_Tide ("t_demo.m").

```
%% Tide analysis using T_Tide
[tidestruc,zeta_tide]=t_tide(zeta_qc,...
'interval',mean(diff(t))*24, ...      % time step (hour)
'start',t(1),...                      % start time is datestr(tuk_time(1))
'latitude',lato,...                   % Latitude of obs
'error','linear',...                  % coloured boostrap CI
'synthesis',1);                       % Use SNR=1 for synthesis.
```

```
   number of standard constituents used: 68
   Points used: 3739300 of 5258880
   percent of var residual after lsqfit/var original:  7.08 %
   Greenwich phase computed with nodal corrections applied to amplitude
 and phase relative to center time
   Using linearized error estimates
   Generating prediction with nodal corrections, SNR is 1.000000
   percent of var residual after synthesis/var original:  7.11 %
-----------------------------------
```

date: 13-Jan-2023
nobs = 5258880,  ngood = 3739300,  record length (days) = 3652.00
start time: 01-Jan-2006
rayleigh criterion = 1.0
Greenwich phase computed with nodal corrections applied to amplitude \n and phase relative to center time

x0= -0.00474, x trend= 0

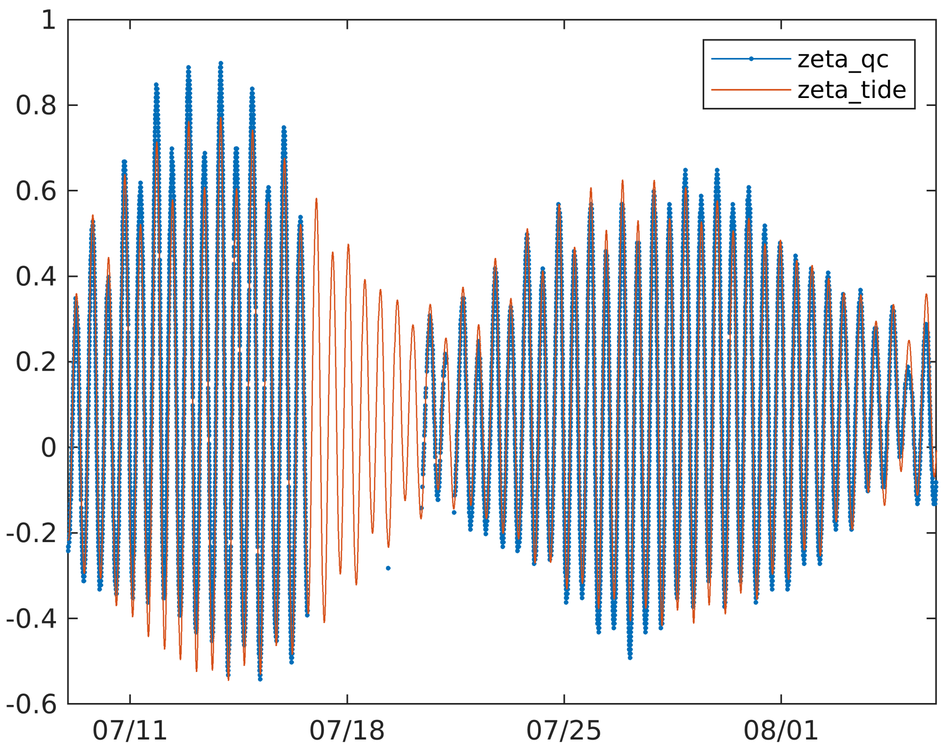
var(x)= 0.10119   var(xp)= 0.093995   var(xres)= 0.0071934
percent var predicted/var original= 92.9 %

tidal amplitude and phase with 95% CI estimates

| tide | freq | amp | amp_err | pha | pha_err | snr |
|---|---|---|---|---|---|---|
| *SA | 0.0001141 | 0.1045 | 0.006 | 221.40 | 3.17 | 3.3e+02 |
| *SSA | 0.0002282 | 0.0075 | 0.006 | 337.69 | 44.11 | 1.7 |
| MSM | 0.0013098 | 0.0048 | 0.006 | 12.58 | 68.61 | 0.7 |
| MM | 0.0015122 | 0.0028 | 0.006 | 75.51 | 118.45 | 0.23 |
| MSF | 0.0028219 | 0.0038 | 0.006 | 8.18 | 87.95 | 0.42 |
| *MF | 0.0030501 | 0.0106 | 0.006 | 214.32 | 31.33 | 3.3 |
| *ALP1 | 0.0343966 | 0.0006 | 0.000 | 169.52 | 34.67 | 2.6 |
| 2Q1 | 0.0357064 | 0.0004 | 0.000 | 254.38 | 59.10 | 0.88 |
| *SIG1 | 0.0359087 | 0.0012 | 0.000 | 172.62 | 18.80 | 8.9 |
| *Q1 | 0.0372185 | 0.0019 | 0.000 | 86.57 | 11.71 | 23 |
| RHO1 | 0.0374209 | 0.0003 | 0.000 | 117.01 | 78.83 | 0.55 |
| *O1 | 0.0387307 | 0.0164 | 0.000 | 109.81 | 1.37 | 1.7e+03 |
| *TAU1 | 0.0389588 | 0.0010 | 0.000 | 224.76 | 22.62 | 5.8 |
| BET1 | 0.0400404 | 0.0002 | 0.000 | 16.52 | 138.49 | 0.16 |
| *NO1 | 0.0402686 | 0.0013 | 0.000 | 179.14 | 12.27 | 11 |
| CHI1 | 0.0404710 | 0.0001 | 0.000 | 3.29 | 229.22 | 0.058 |
| *PI1 | 0.0414385 | 0.0009 | 0.000 | 200.14 | 24.59 | 5.4 |
| *P1 | 0.0415526 | 0.0136 | 0.000 | 149.90 | 1.70 | 1.1e+03 |
| *S1 | 0.0416667 | 0.0066 | 0.000 | 280.38 | 5.07 | 2.7e+02 |
| *K1 | 0.0417807 | 0.0429 | 0.000 | 152.80 | 0.53 | 1.1e+04 |
| *PSI1 | 0.0418948 | 0.0011 | 0.000 | 246.87 | 20.28 | 8 |
| *PHI1 | 0.0420089 | 0.0016 | 0.000 | 189.94 | 14.11 | 15 |
| *THE1 | 0.0430905 | 0.0009 | 0.000 | 143.60 | 25.44 | 4.7 |
| *J1 | 0.0432929 | 0.0029 | 0.000 | 204.56 | 7.77 | 52 |
| *SO1 | 0.0446027 | 0.0026 | 0.000 | 283.04 | 8.57 | 43 |
| *OO1 | 0.0448308 | 0.0015 | 0.000 | 210.81 | 12.51 | 13 |
| UPS1 | 0.0463430 | 0.0004 | 0.000 | 255.47 | 50.94 | 0.93 |
| OQ2 | 0.0759749 | 0.0009 | 0.002 | 176.64 | 125.64 | 0.2 |
| *EPS2 | 0.0761773 | 0.0049 | 0.002 | 203.05 | 23.77 | 5.8 |
| *2N2 | 0.0774871 | 0.0101 | 0.002 | 216.83 | 11.38 | 25 |
| *MU2 | 0.0776895 | 0.0189 | 0.002 | 229.95 | 6.15 | 87 |
| *N2 | 0.0789992 | 0.0735 | 0.002 | 233.19 | 1.57 | 1.3e+03 |
| *NU2 | 0.0792016 | 0.0121 | 0.002 | 231.99 | 9.53 | 36 |
| *GAM2 | 0.0803090 | 0.0041 | 0.002 | 241.08 | 31.91 | 4.2 |
| *H1 | 0.0803973 | 0.0131 | 0.002 | 95.05 | 8.67 | 42 |
| *M2 | 0.0805114 | 0.3787 | 0.002 | 242.70 | 0.31 | 3.5e+04 |
| *H2 | 0.0806255 | 0.0131 | 0.002 | 0.20 | 8.82 | 42 |
| *MKS2 | 0.0807396 | 0.0032 | 0.002 | 289.42 | 34.78 | 2.6 |
| *LDA2 | 0.0818212 | 0.0028 | 0.002 | 185.07 | 42.04 | 1.9 |
| *L2 | 0.0820236 | 0.0128 | 0.002 | 227.15 | 12.30 | 40 |
| *T2 | 0.0832193 | 0.0176 | 0.002 | 288.05 | 6.57 | 76 |
| *S2 | 0.0833333 | 0.1768 | 0.002 | 279.07 | 0.65 | 7.7e+03 |
| *R2 | 0.0834474 | 0.0089 | 0.002 | 248.70 | 10.50 | 19 |
| *K2 | 0.0835615 | 0.0476 | 0.002 | 279.26 | 2.37 | 5.5e+02 |
| MSN2 | 0.0848455 | 0.0017 | 0.002 | 24.14 | 66.17 | 0.75 |
| *ETA2 | 0.0850736 | 0.0033 | 0.002 | 308.35 | 32.68 | 2.7 |
| *MO3 | 0.1192421 | 0.0068 | 0.000 | 72.27 | 3.56 | 2.5e+02 |
| *M3 | 0.1207671 | 0.0110 | 0.000 | 344.41 | 2.23 | 6.6e+02 |
| *SO3 | 0.1220640 | 0.0039 | 0.000 | 83.19 | 6.23 | 81 |
| *MK3 | 0.1222921 | 0.0047 | 0.000 | 100.36 | 5.18 | 1.2e+02 |
| *SK3 | 0.1251141 | 0.0050 | 0.000 | 155.91 | 4.78 | 1.4e+02 |

```
*MN4  0.1595106    0.0042    0.001   220.39     8.20        49
*M4   0.1610228    0.0089    0.001   246.97     3.90  2.2e+02
*SN4  0.1623326    0.0011    0.001   221.12    32.35       3.1
*MS4  0.1638447    0.0031    0.001   313.90    11.23        26
*MK4  0.1640729    0.0016    0.001   259.71    20.53       7.4
 S4   0.1666667    0.0006    0.001   335.88    57.55      0.99
*SK4  0.1668948    0.0010    0.001   327.50    32.07         3
*2MK5 0.2028035    0.0002    0.000   230.04    28.48       3.9
*2SK5 0.2084474    0.0003    0.000   110.41    22.02       6.5
*2MN6 0.2400221    0.0010    0.000   348.73     6.91        69
*M6   0.2415342    0.0015    0.000   352.03     4.59  1.6e+02
*2MS6 0.2443561    0.0024    0.000    41.49     2.92  3.9e+02
*2MK6 0.2445843    0.0004    0.000    82.24    17.19        11
*2SM6 0.2471781    0.0008    0.000   117.20     8.88        42
*MSK6 0.2474062    0.0005    0.000   214.18    12.53        20
*3MK7 0.2833149    0.0005    0.000    63.56     8.40        45
*M8   0.3220456    0.0004    0.000    95.91    11.60        25
```

```
% tidestruc.name: name of tidal harmonic constituents
% tidestruc.freq: frequency of tidal harmonic constituents
% tidestruc.tidecon(:,1): amplitude of the harmonic constituents
% tidestruc.tidecon(:,2): amplitude error (95% confident interval)
% tidestruc.tidecon(:,3): phase (degrees) of the harmonic constituents
% tidestruc.tidecon(:,4): phase error (95% confident interval)
figure
plot(t,zeta_qc,'.-')
hold on
plot(t,zeta_tide,'-')
legend('zeta\_qc','zeta\_tide')
xlim([734328 734356])
datetick('x','keeplimits')
```



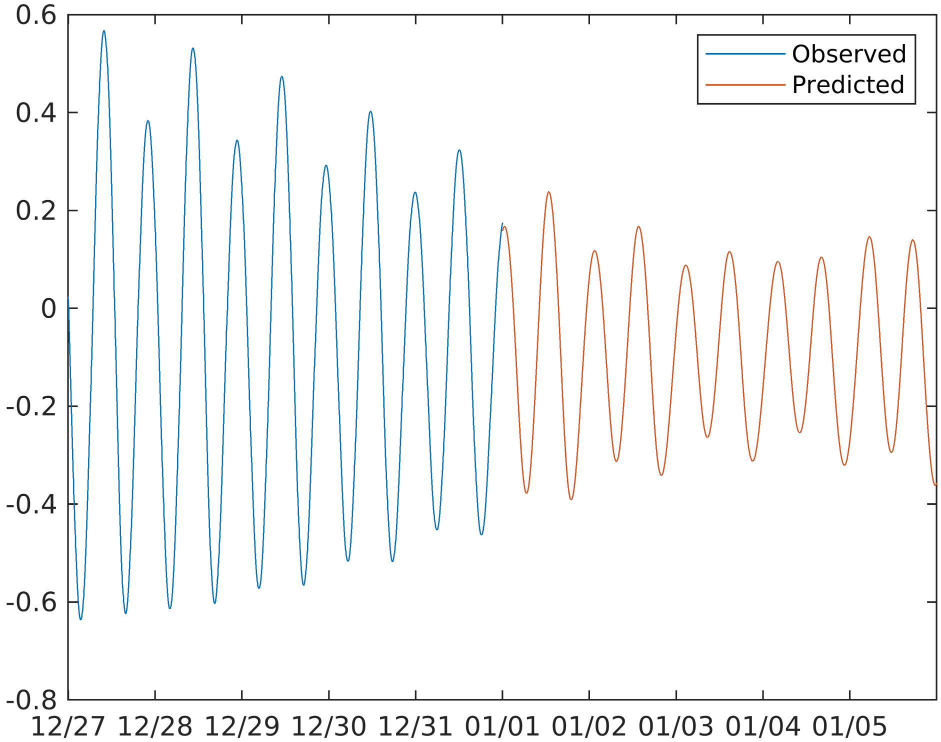

The squared correlation between the origial sea level time and tidal component is 0.93, that means tides explain 93% of variance of sea level.

```
R2_tide=nancorr(zeta_qc,zeta_tide)^2
```

```
R2_tide = 0.9289
```

Using the analyzed tidal constituents, tidal component can be easily predicted by "t_predic".

```
t_p=t(end):nanmean(diff(t)):(t(end)+5);
zeta_tide_predic=t_predic(t_p,tidestruc,...
    'latitude',lato,...
    'synthesis',1);
figure
plot(t,zeta_tide)
hold on
plot(t_p,zeta_tide_predic)
xlim([t(end)-5 max(t_p)])
datetick('x','keeplimits')
legend('Observed','Predicted')
```




## 3. Inverted barometer component

The inverted barometer component indicate sea level fluctuation component caused by atmospheric pressure. It is well known that 1 cm sea level decrease as 1 hPa atmospheric pressure increase (0.0001 m decrease as 1 Pa), governed by

$$\eta_I = -\frac{P_{atm} - P_0}{\rho_0 g}$$

where $P_{atm}$ is atmospheric pressure, $P_0$ is reference pressure, $\rho_0$ is constant density, and $g$ is gravitational acceleration. The reference pressure usually indicates spatially avaeraged global atmospheric pressure over the entire ocean but ocassionally assumed as constant. This equation is obtained by hydrostatic equation with constant density and continuity equation given by

$$0 = -\frac{1}{\rho_0}\frac{\partial P}{\partial z} - g \quad (1)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial (hu)}{\partial x} = 0 \quad (2).$$

For simplicity, let's consider one-dimensional ocean (in $x$) where both west ($x = 0$) and east boundaries ($x = L$) are closed. The former equation (1) can be solved for $P$ by the vertical integration:

$$P(\eta) - P(z) = -\rho_0 g(\eta - z)$$

where $P(\eta) = P_{atm}$ can be used as surface boundary condition and $z = 0$ can be induced to discuss values at the surface.

$P_{atm} - P(0) = -\rho_0 g \eta$ (3)

The $P(0)$ can be determined by the vertical integrated continuity equation (2). Note that the continuity equation can be rewritten as mass (volume) conservation equation by the closed boundary condition. To be specific, sptial averaging (2) for the domain yields

$$\frac{\partial}{\partial t}\left(\int_0^L \eta\, dx\right) - \left(hu|_{x=L} - hu|_{x=0}\right) = 0$$

Apply the closed boundary conditions ($hu|_{x=L} = 0$ and $hu|_{x=0} = 0$) removes second terms of left hand side, that yields spatially integrated (summed) sea level is constant in the time. Applying initial condition $\eta|_{t=0} = 0$ determines the constant is zero, so the equation is given by

$$\int_0^L \eta\, dx = 0$$

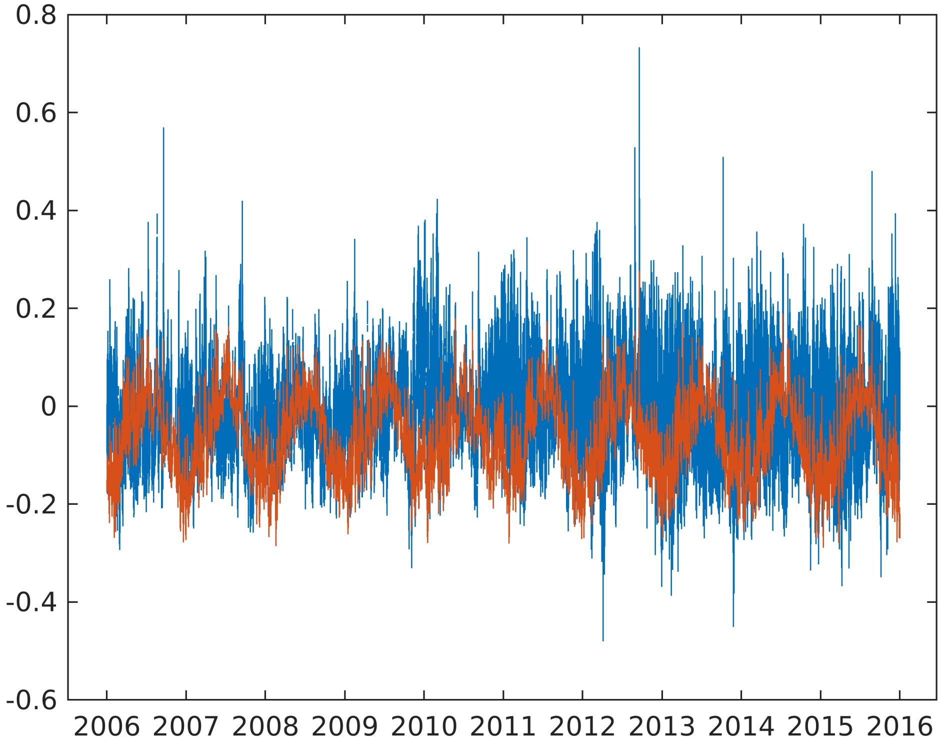
Substituting (3) to the above equation with assuming $P(0)$ is constant in space and the rearranging for $P(0)$ yields

$$P(0) = \frac{1}{L}\int_0^L P_{atm}\, dx$$

The left hand side indicates spatially averaged atmospheric pressure over entire domain. If observation is located at the closed basin, the reference pressure need to be spatial-averaged over the basin (Le Traon and Gauzelin, 1997). If it is semi-closed, a bit complex approach may be required (Le Traon and Gauzelin, 1997; Inazu et al., 2006; Lee et al., 2022).

"pair_ref" includes time series for atmospheric pressure from ECMWF ERA5 reanalyiss dataset.

```
load('pair_ref.mat')
% tpair (days): time of atmospheric pressure data
% pair_global (Pa): global averaged atmospheric pressure over entire ocean
% pair (Pa): mean local atmospheric pressure over south coast of the Korea
g=9.8;
rho0=1025;
zeta_ib=-(pair-pair_global)/rho0/g;
zeta_detide=zeta_qc-zeta_tide;
figure
plot(t,zeta_detide)
hold on
plot(tpair,zeta_ib)
datetick('x','keeplimits')
```




```
zeta_ibi=interp1(tpair,zeta_ib,t);
nancorr(zeta_detide,zeta_ibi)^2
```

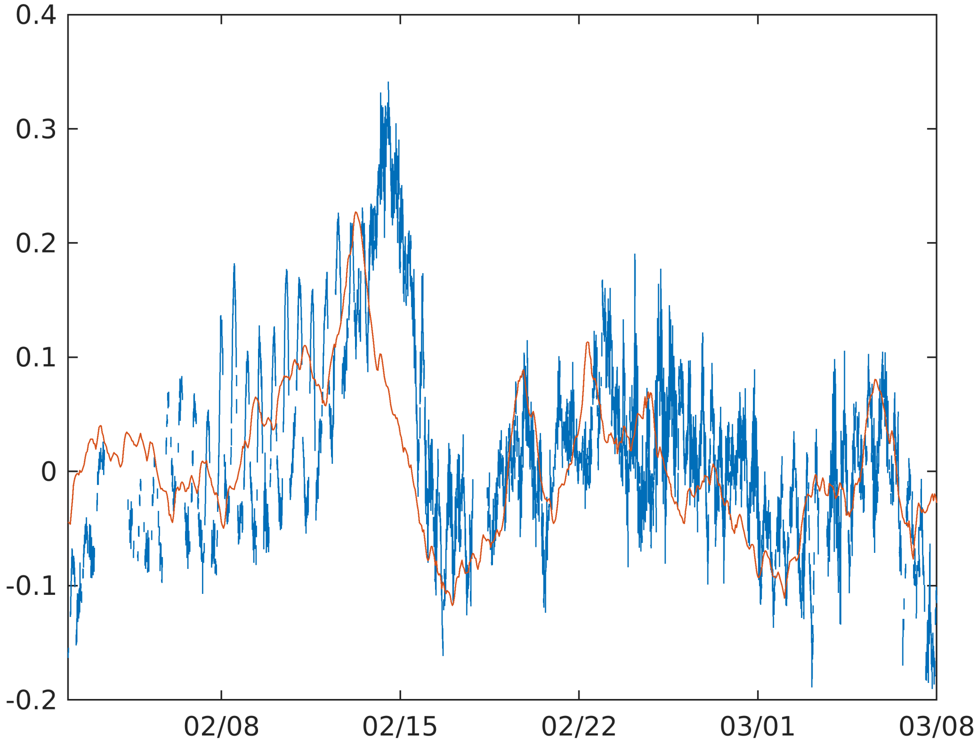
```
ans = 0.0423
```

Calculated inverted barometer component shows predominant seasonality, that is not clearly shown in the observations where tidal signals are removed. The barometer effect is dominant in the intraseasonal so the seasonality need to be removed (Le Traon and Gauzelin, 1997).

```
% SineP=sineFit(tpair,zeta_ib,0); % get seasonal signal via sine fitting
% zeta_ib_seasonal=SineP(1)+SineP(2)*sin(2*pi*SineP(3)*tpair+SineP(4));
zeta_ib_seasonal=smoothdata(zeta_ib,'gaussian',round(90/nanmean(diff(tpair))));

zeta_ib=zeta_ib-zeta_ib_seasonal;

figure
plot(t,zeta_detide)
hold on
plot(tpair,zeta_ib)
xlim([733806 733840])
datetick('x','keeplimits')
```




```
zeta_ibi=interp1(tpair,zeta_ib,t);
nancorr(zeta_detide,zeta_ibi)^2
```

```
ans = 0.1152
```

The squared correlation shows that the inverted barometer components explains about 12% of variation for sea level of which tidal component is removed.

```
zeta_res=zeta_detide-zeta_ibi;
```

The residual component where tidal and inverted barometer components are removed (zeta_res) includes signals which are interested by many geophysical scales (e.g., response to coastal trapped wave and up/downwelling) but it must be noted that the residual inclues not only other signals from unresolved processes (e.g., high frequnecy waves) but also error signals.

## References

Le Traon, P. Y., & Gauzelin, P. (1997). Response of the Mediterranean mean sea level to atmospheric pressure forcing. *Journal of Geophysical Research: Oceans*, *102*(C1), 973-984.

Inazu, D., Hirose, N., Kizu, S., & Hanawa, K. (2006). Zonally asymmetric response of the Japan Sea to synoptic pressure forcing. *Journal of oceanography*, *62*(6), 909-916.

Lee, K., Nam, S., & Park, J. H. (2022). Alongshore Propagation of Subtidal Sea Level Fluctuations Around the Korean Peninsula Over Varying Stratification and Shelf Topography. *Frontiers in Marine Science*, *8*, 2037.