Visualization of Crescent City tsunami inundation ¶

This notebook illustrates how to make some simple plots of geodata using the matplotlib (http://matplotlib.org/index.html) package. See the matplotlib gallery (http://matplotlib.org/gallery.html) for many other examples of how to do things.

The sample data comes from a tsunami simulation of a hypothetical tsunami arising from an earthquake on the Cascadia Subduction Zone hitting Crescent City, CA. The data set used shows the maximum depth of water at each point on a grid covering part of the harbor during the course of the simulation.

Many simulations like this are done in order to perform probabilistic tsunami hazard assessment (PTHA). A set of Jupyter notebooks illustrating how this is done were prepared for a workshop last autumn and also contain some other examples of how to plot data. These can be found in the Github repository https://github.com/rjleveque/ptha_tutorial (https://github.com/rjleveque/ptha_tutorial).

The following "magic" command makes makes the `matplotlib` plots show up right in the notebook. If you instead give the command `%matplotlib notebook` then it is also possible to interact with plots, e.g. to zoom.
See Jupyter documentation (http://ipython.readthedocs.io/en/stable/interactive/plotting.html)

In [1]:
```
%matplotlib inline
```

```
/opt/conda/lib/python2.7/site-packages/matplotlib/font_manager.py:273: UserWarn
ing: Matplotlib is building the font cache using fc-list. This may take a momen
t.
  warnings.warn('Matplotlib is building the font cache using fc-list. This may
 take a moment.')
```

Import numpy and matplotlib:

In [2]:
```
import numpy as np
import matplotlib.pyplot as plt
```

So that this notebook runs with either a Python 2 or Python 3 kernel, use the Python 3 print function rather than the Python 2 print statement:

In [3]:
```
from __future__ import print_function # in case of Python 2
```

Function to read a file in asc format:

There are many tools available in various packages to read geodata in a variety of formats. Here we provide a simple function to read a file in ESRI ASCII raster format (http://resources.esri.com/help/9.3/arcgisengine/java/GP_ToolRef/spatial_analyst_tools/esri_ascii_ras which consists of a header describing the grid followed by values on the grid.

Note: The data_tools.py (data_tools.py) file in this directory contains the same `read_asc_file` function, so we could have just imported from there. Also, GDAL has a way to do this more efficiently but for this exercise, a function was created to read in needed asc data.

In [4]:
```
def read_asc_file(file_path, verbose=True):
    import numpy as np
    asc_file = open(file_path, 'r')

    tokens = asc_file.readline().split()
    ncols = int(tokens[1])

    tokens = asc_file.readline().split()
    nrows = int(tokens[1])

    tokens = asc_file.readline().split()
    xllcorner = float(tokens[1])

    tokens = asc_file.readline().split()
    yllcorner = float(tokens[1])

    tokens = asc_file.readline().split()
    cellsize = float(tokens[1])

    tokens = asc_file.readline().split()
    nodata_value = float(tokens[1])

    if verbose:
        print( "ncols = %i" % ncols)
        print( "nrows = %i" % nrows)
        print( "xllcorner = %g" % xllcorner)
        print( "yllcorner = %g" % yllcorner)
        print( "cellsize = %g" % cellsize)
        print( "nodata_value = %g" % nodata_value)

    # read in all the data, assumed to be on ncols lines,
    # each containing nrows values

    asc_file.close()  # close file so we can load array
    asc_data = np.loadtxt(file_path, skiprows=6)  # skip header

    # reshape
    values = asc_data.reshape((nrows,ncols))

    # flip in y because of data order
    values = np.flipud(values)

    x = xllcorner + cellsize * np.arange(0,ncols)
    y = yllcorner + cellsize * np.arange(0,nrows)

    X,Y = np.meshgrid(x,y)

    asc_data_dict = {'ncols': ncols, 'nrows': nrows, 'xllcorner':xllcorner, \
                     'yllcorner':yllcorner, 'cellsize':cellsize, 'nodata_value':n
                     'X': X, 'Y':Y, 'values': values}
    return asc_data_dict
```

Read in the data files for this example

First the file containing the maximum water depth hmax:

In [5]:
```
hmax_file = '../geoclaw_output/hmax_CC.asc'
hmax_data_dict = read_asc_file(hmax_file)
```

```
ncols = 146
nrows = 128
xllcorner = -124.215
yllcorner = 41.7349
cellsize = 0.000277793
nodata_value = -9999
```

Unpack the dictionary that is returned, extracting the grid and `hmax` values:

In [6]:
```
hmax = hmax_data_dict['values']
X = hmax_data_dict['X']
Y = hmax_data_dict['Y']
```

Do the same for the file containing topography values. These values `topo` are the height of the topography at each point relative to some `vertical datum`, in this case Mean High Water (MHW) since this data came from a database of topography DEMs for tsunami inundation. [Add link!]

In [7]:
```
topo_file = '../geoclaw_output/topo_CC.asc'
topo_data_dict = read_asc_file(topo_file, verbose=False)

topo = topo_data_dict['values']
```

Plot contours of topography

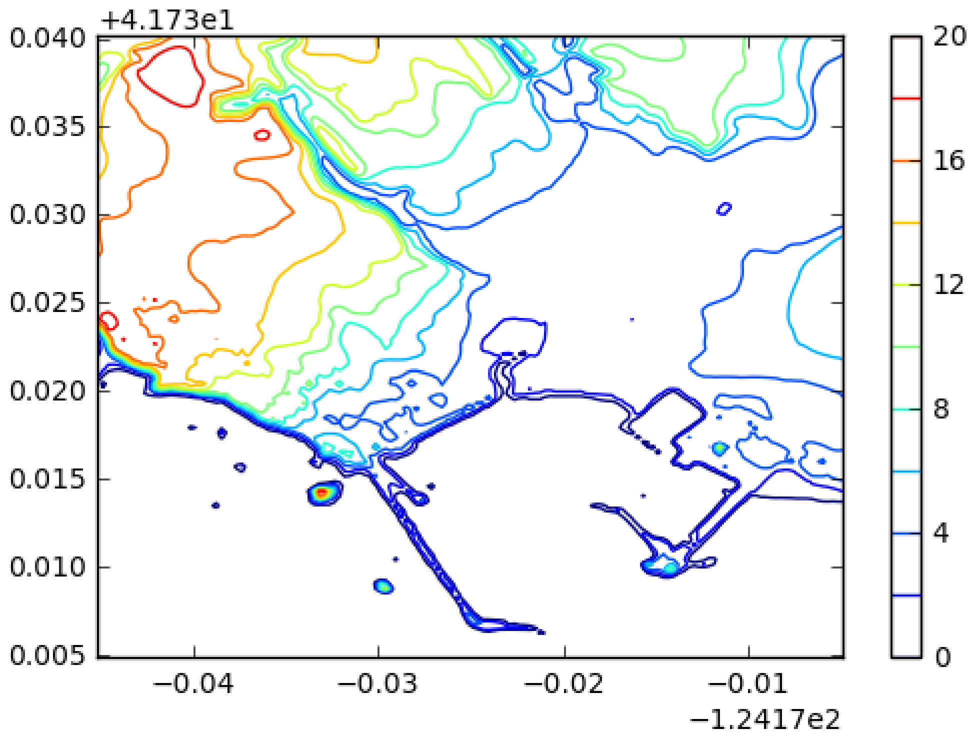
The `X,Y` arrays for the `topo` are the same as for `hmax` (one should check this!)

We can do a quick and dirty plot of contours of topography:

In [8]:
```
topo_contour_levels = np.arange(0, topo.max()+1, 2)  # 2 meter increments
print( "Contour levels: %s" % topo_contour_levels)
plt.contour(X,Y,topo, topo_contour_levels)
plt.colorbar()
```

```
Contour levels: [  0.   2.   4.   6.   8.  10.  12.  14.  16.  18.  20.]
```

Out[8]:
```
<matplotlib.colorbar.Colorbar at 0x7fd7a1f33210>
```

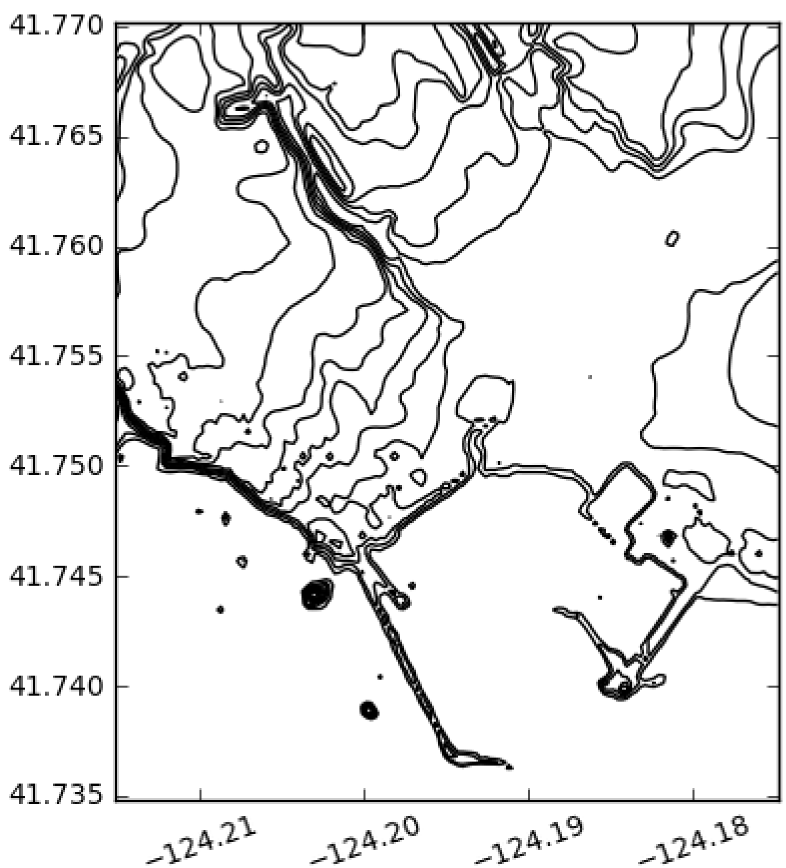


There are several things about this plot that we might want to fix:

- The ticklabels show only an offset rather than the full latitude longitude,
- The aspect ratio is not correct. At latitude theta, one degree of longitude is shorter than one degree of latitude by a factor of $cos(\theta)$.
- For plotting data on top of the contour plot, we might want all the contour lines to be the same color, say black (which is denoted by `'k'`).

In [9]:
```
# Create a figure of the desired size:
fig = plt.figure(figsize=(5,5))
ax = plt.axes()

plt.contour(X,Y,topo, topo_contour_levels, colors='k') #instead of one color, cou
#if you want an array of colors

# set the aspect ratio, converting 41.7 degrees to radians
ax.set_aspect(1./np.cos(41.7*np.pi/180.))

# get rid of the offsets:
ax.ticklabel_format(format='plain',useOffset=False)

# rotate the xtick labels so they are readable:
plt.xticks(rotation=20);   # semi-colon to suppress a message
```

```
/opt/conda/lib/python2.7/site-packages/matplotlib/axes/_base.py:1210: UnicodeWa
rning: Unicode equal comparison failed to convert both arguments to Unicode - i
nterpreting them as being unequal
  if aspect == 'normal':
/opt/conda/lib/python2.7/site-packages/matplotlib/axes/_base.py:1215: UnicodeWa
rning: Unicode equal comparison failed to convert both arguments to Unicode - i
nterpreting them as being unequal
  elif aspect in ('equal', 'auto'):
```

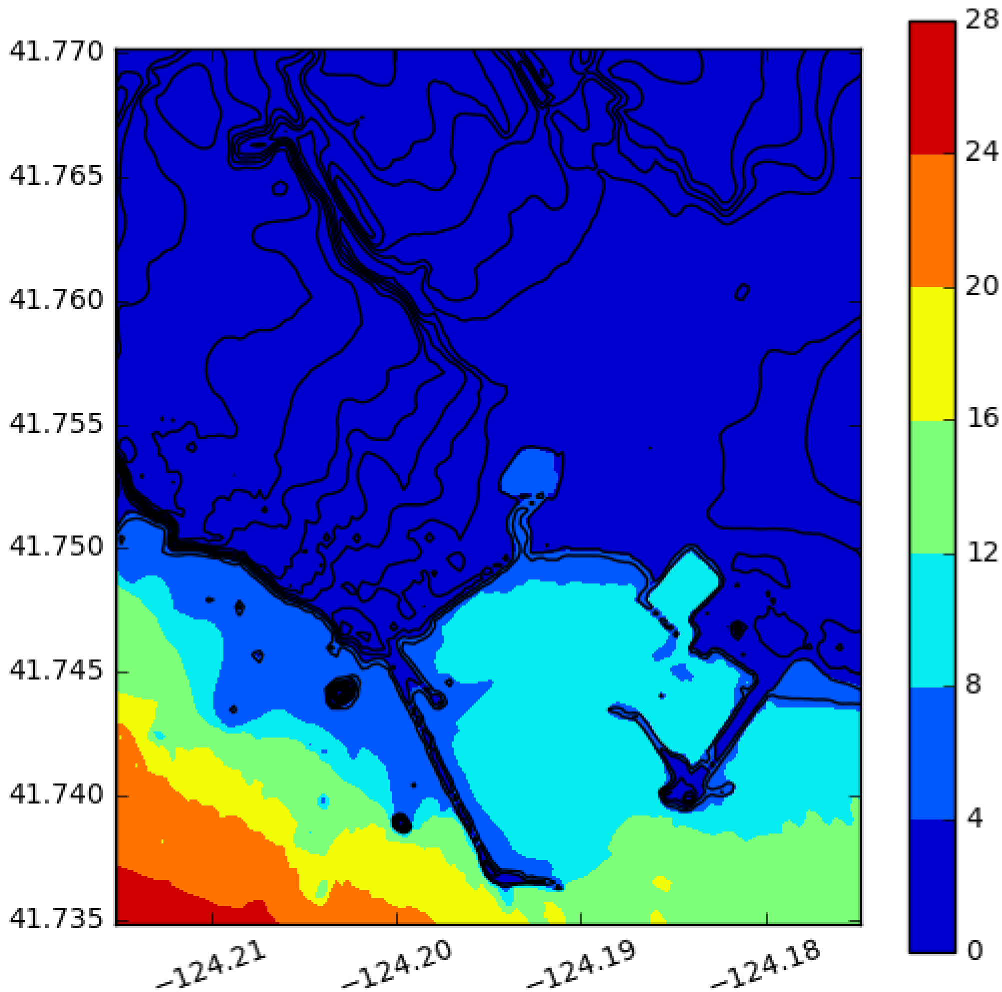


Plot water depth on contour plot

Here's a first attempt a plotting the maximum water depth data on the contour plot:

In [10]:
```
fig = plt.figure(figsize=(6,6))
ax = plt.axes()

plt.contour(X,Y,topo, topo_contour_levels, colors='k')

ax.set_aspect(1./np.cos(41.7*np.pi/180.))
ax.ticklabel_format(format='plain',useOffset=False)
plt.xticks(rotation=20)

# Now plot the data as filled contours:
plt.contourf(X,Y,hmax)
plt.colorbar()
```

Out[10]: <matplotlib.colorbar.Colorbar at 0x7fd7a011c090>



This plot has several problems:

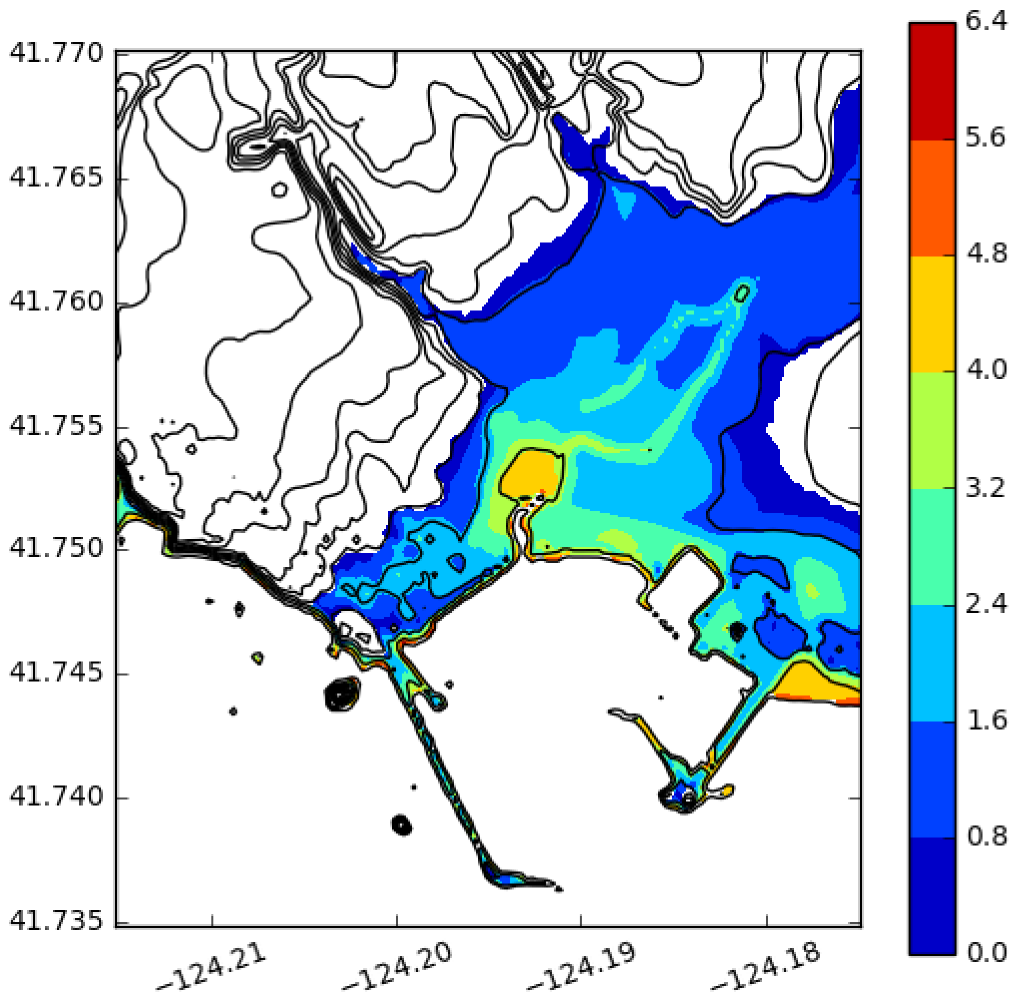
- It is impossible to tell water depth 0 (no inundation) from small depths,
- The colormap and limits were set based on the data, and are revealing deep water offshore, with no information about what's happening onshore.

We can fix this by masking out the `hmax` grid in regions where either the land is dry (e.g. where `hmax < 0.001` meters) and also where `topo < 0`, i.e., anywhere there is water at high tide.

The numpy module `ma` provides masked arrays:

In [11]:
```
from numpy import ma  # masked arrays

# mask out the dry cells (e.g., where depth < 1 mm):
hmax_dry = ma.masked_where(hmax < 0.001, hmax)

# mask out the water region if we only care about onshore:
hmax_onshore = ma.masked_where(topo < 0, hmax_dry)


fig = plt.figure(figsize=(6,6))
ax = plt.axes()

plt.contour(X,Y,topo, topo_contour_levels, colors='k')

ax.set_aspect(1./np.cos(41.7*np.pi/180.))
ax.ticklabel_format(format='plain',useOffset=False)
plt.xticks(rotation=20)

plt.contourf(X,Y,hmax_onshore)
plt.colorbar()
```

Out[11]: `<matplotlib.colorbar.Colorbar at 0x7fd7a00b0710>`



This gives a more useful plot.

Custom color maps

We might want to tweak it further, e.g. by specifying the colormap and/or the depth levels separating colors.

Here's a little function that makes a list of colors (as [R,G,B] values):

In [12]:
```
def discrete_cmap_1(clines):
    """
    Construct a discrete color map for the regions between the contour lines
    given in clines. Colors go from turqouise through yellow to red.
    Good for flooding depth.
    """
    from numpy import floor, linspace, hstack, ones, zeros
    nlines = len(clines)
    n1 = int(floor((nlines-1)/2.))
    n2 = nlines - 1 - n1
    Green = hstack([linspace(1,1,n1),linspace(1,0,n2)])
    Red = hstack([linspace(0,0.8,n1), ones(n2)])
    Blue = hstack([linspace(1,0.2,n1), zeros(n2)])
    colors = zip(Red,Green,Blue)
    return colors
```

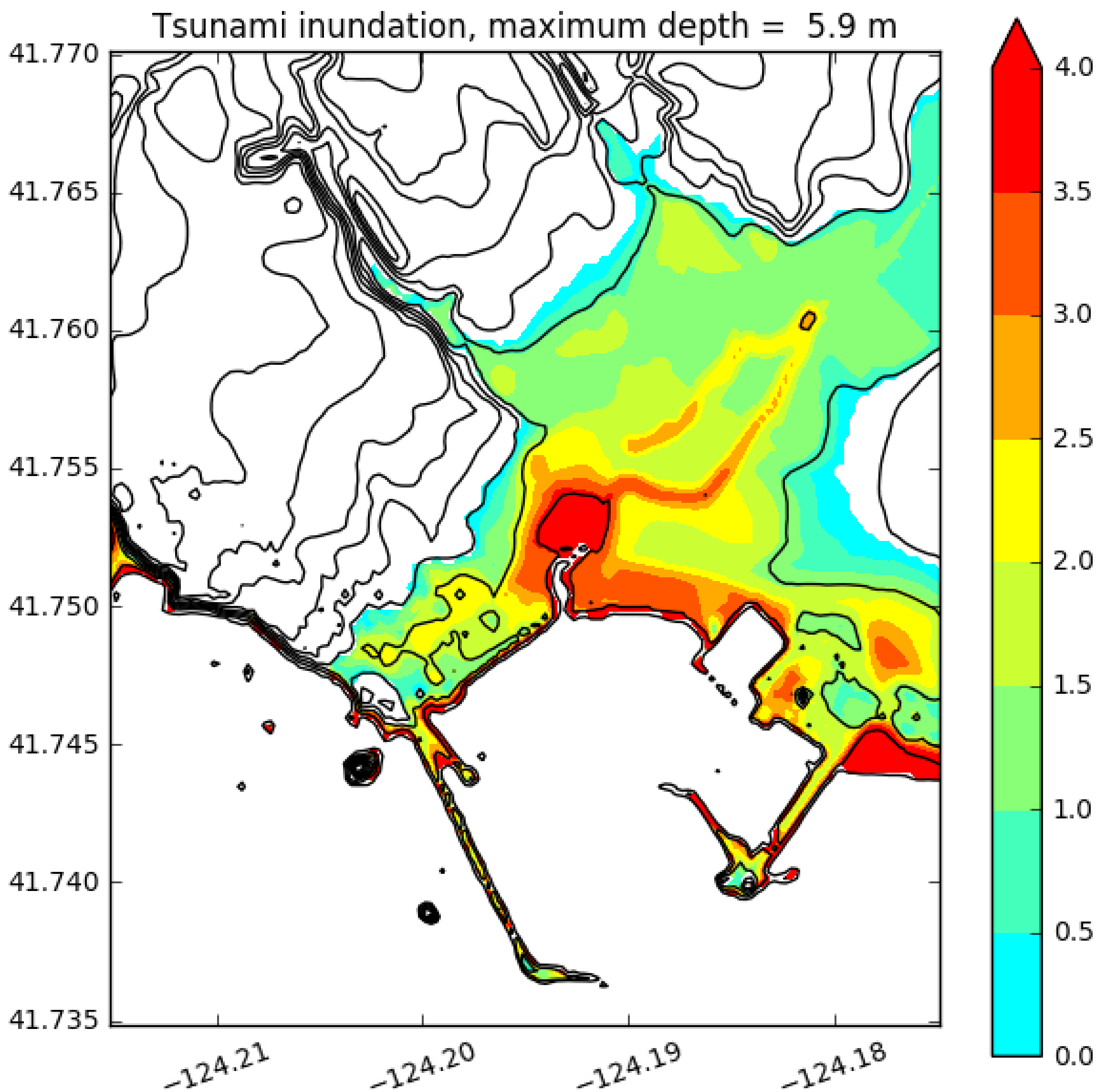
From above we see that the maximum inundation depth is nearly 6 meters, but only in a few regions near the shore. So we will choose contour levels every 0.5 m up to 4 meters (9 values) and then set `depth_colors` to be a list of 8 [R,G,B] values for the color between each.

In [13]:
```
depth_contour_levels = np.arange(0,4.5,0.5)  # every 0.5 m up to 4 m
depth_colors = discrete_cmap_1(depth_contour_levels)

print( "depth_contour_levels = ", depth_contour_levels)
print( "depth_colors = \n",np.array(depth_colors))
```

```
depth_contour_levels =  [ 0.   0.5  1.   1.5  2.   2.5  3.   3.5  4. ]
depth_colors =
 [[ 0.          1.          1.        ]
 [ 0.26666667  1.          0.73333333]
 [ 0.53333333  1.          0.46666667]
 [ 0.8         1.          0.2       ]
 [ 1.          1.          0.        ]
 [ 1.          0.66666667  0.        ]
 [ 1.          0.33333333  0.        ]
 [ 1.          0.          0.        ]]
```

Note that we pass the argument `extend='max'` to `contourf` below so that values above 4m also get painted red (rather than white as they otherwise would). Note that this affects the colorbar as well -- it shows that red extends above 4m. We also add a title telling the actual maximum depth.

In [23]:
```
fig = plt.figure(figsize=(7,7))
ax = plt.axes()

plt.contour(X,Y,topo, topo_contour_levels, colors='k')

ax.set_aspect(1./np.cos(41.7*np.pi/180.))
ax.ticklabel_format(format='plain',useOffset=False)
plt.xticks(rotation=20)

plt.contourf(X,Y,hmax_onshore, depth_contour_levels, \
            colors = depth_colors, extend='max') #the extend = max argument color
#could extend min or extend both as well as desired

plt.colorbar()
plt.title('Tsunami inundation, maximum depth = %4.1f m' \
          % hmax_onshore.max());
```

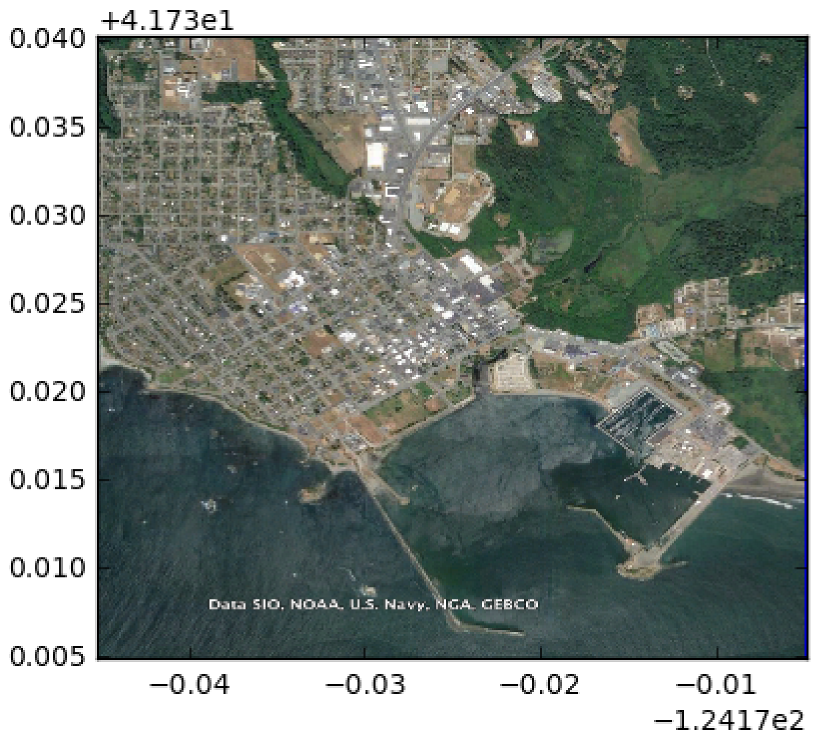


Plotting on top of an image

We can also plot the data on top of an image, in this case a screen shot from Google Earth that was carefully chosen to cover exactly the same region as the data files we are plotting. First we simply read in the image from a png file and show it using `imshow`:

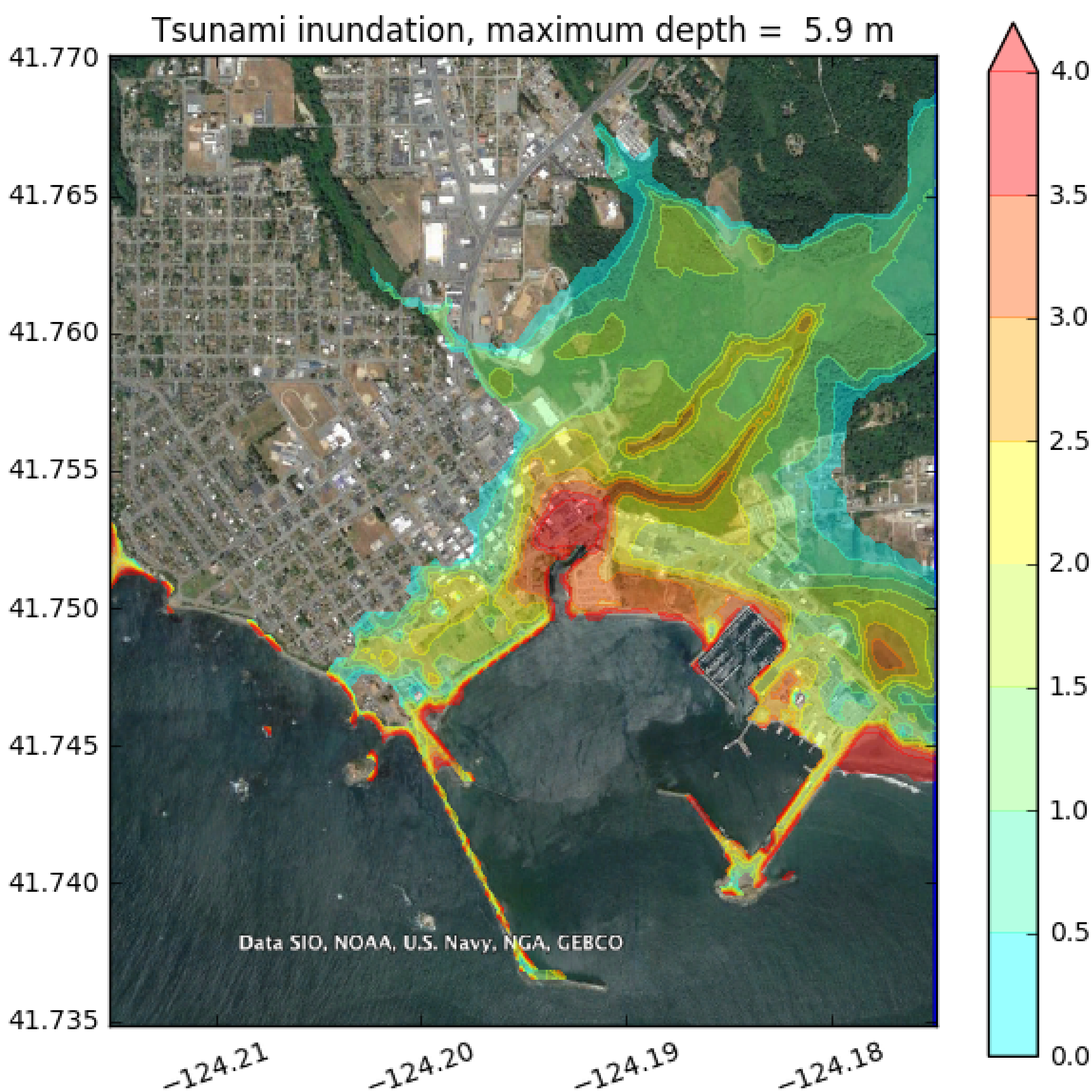
In [15]:
```
CCimage = plt.imread('figures/CC_GE.png')
image_extent = (X.min(),X.max(),Y.min(),Y.max())
plt.imshow(CCimage, extent = image_extent) #last argument helps make sure that yo
```

Out[15]: `<matplotlib.image.AxesImage at 0x7fd79bc51ad0>`



Now we plot the inundation data on this image. Note that `alpha` is a transparency value that can range from 0 (fully transparent) to 1 (opaque), allowing us to see the image beneath the `contourf` plot.

In [16]:
```
fig = plt.figure(figsize=(7,7))
ax = plt.axes()

plt.imshow(CCimage, extent = (X.min(),X.max(),Y.min(),Y.max()))

ax.set_aspect(1./np.cos(41.7*np.pi/180.))
ax.ticklabel_format(format='plain',useOffset=False)
plt.xticks(rotation=20)

alpha = 0.4 #transparency value
plt.contourf(X,Y,hmax_onshore, depth_contour_levels, \
            colors = depth_colors, extend='max', alpha=alpha)
plt.colorbar()
plt.title('Tsunami inundation, maximum depth = %4.1f m' \
          % hmax_onshore.max());
```



pcolor plots

The pcolor (http://matplotlib.org/api/pyplot_api.html#matplotlib.pyplot.pcolor) and imshow (http://matplotlib.org/api/pyplot_api.html#matplotlib.pyplot.imshow) may also be useful for plotting pseudo-color plots of topography or data.

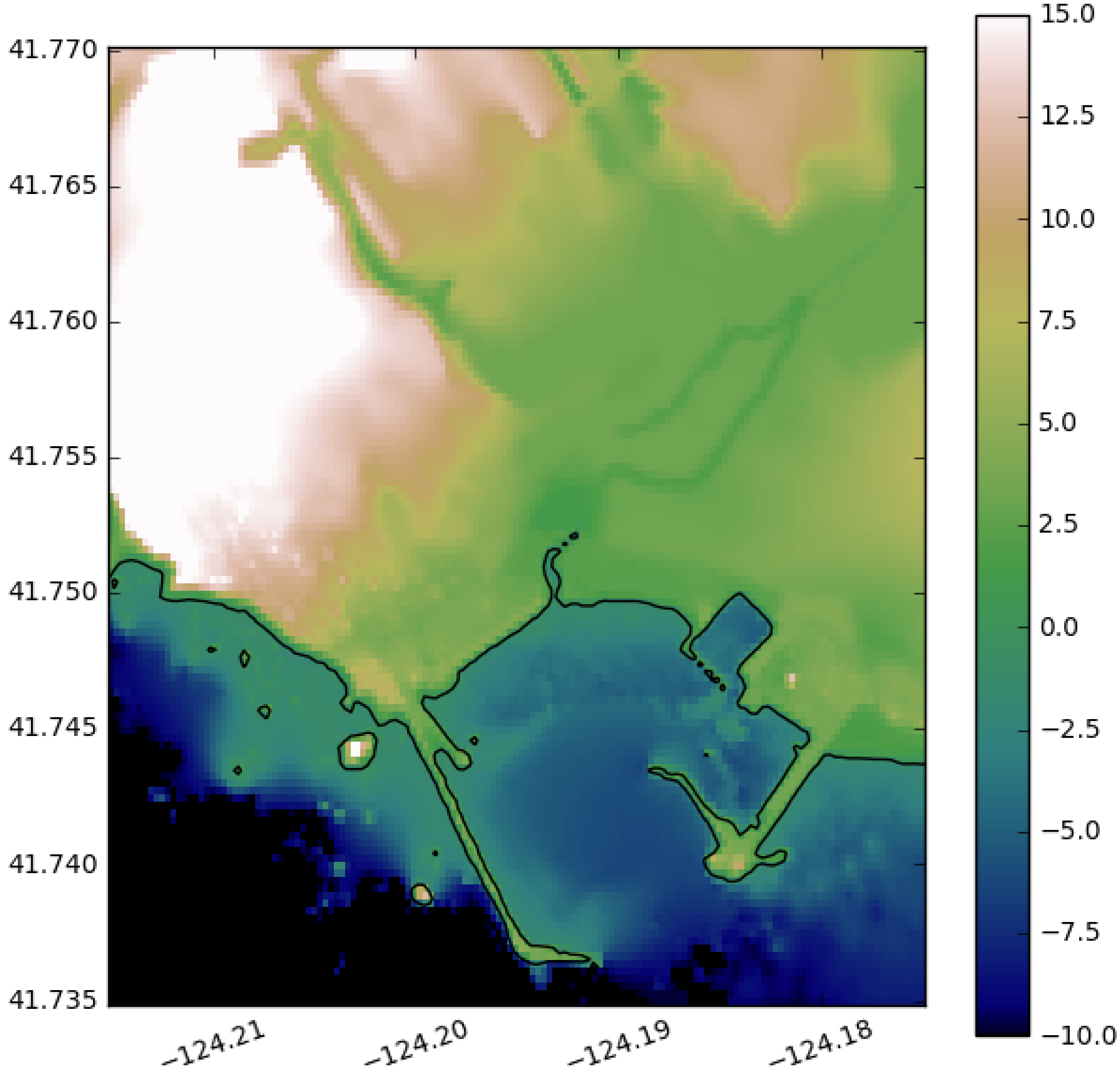
A colormap must be specified. Several are available in the matplotlib.cm module (http://matplotlib.org/api/cm_api.html#module-matplotlib.cm). For an illustration of these see matplotlib colormaps reference (http://matplotlib.org/examples/color/colormaps_reference.html).

To define your own color map, see for example custom cmap examples (http://matplotlib.org/examples/pylab_examples/custom_cmap.html).

Here we just show one example, plotting the topography using the colormap `cm.gist_earth`.

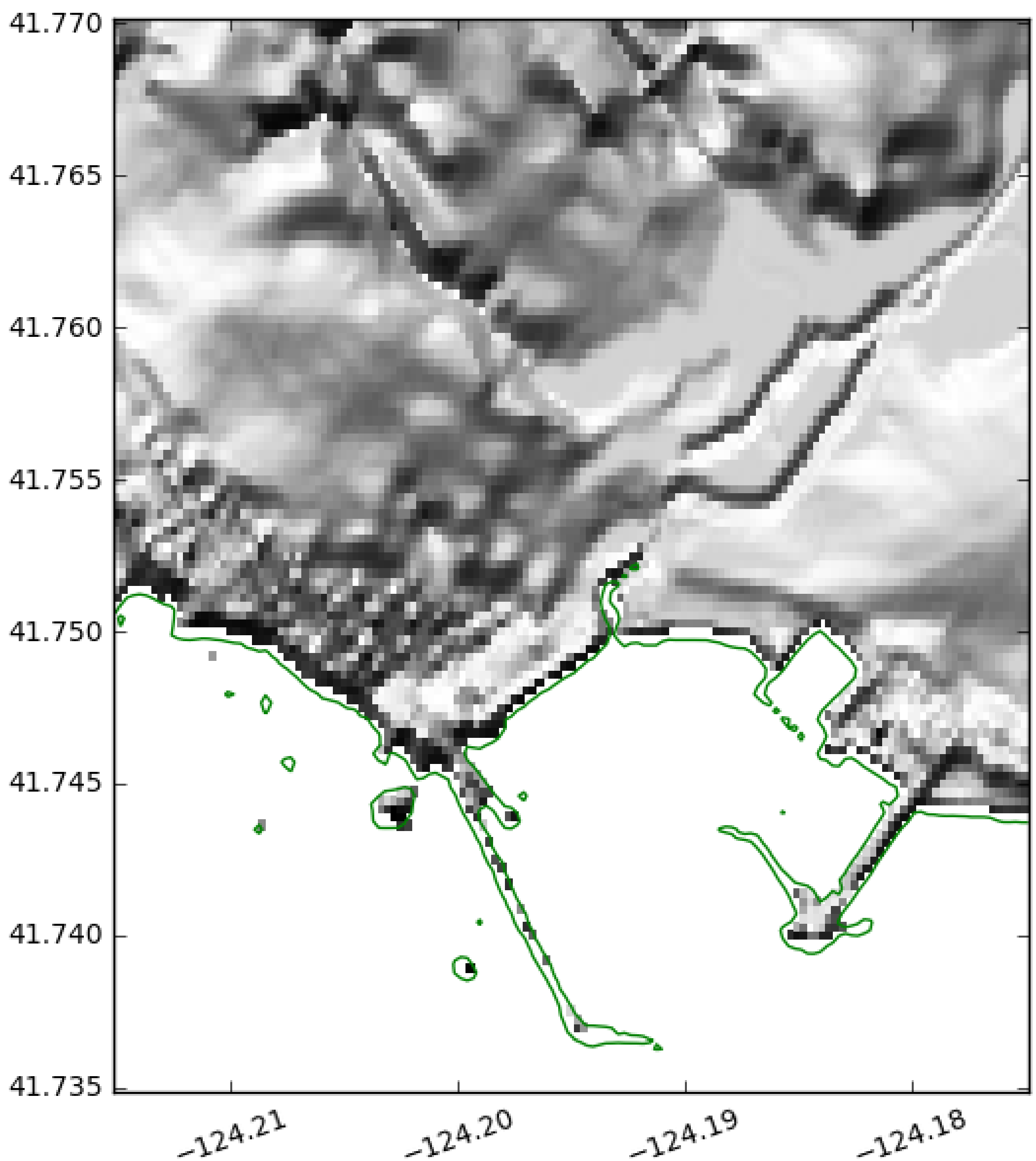
In [17]:

```
from matplotlib import cm

fig = plt.figure(figsize=(7,7))
ax = plt.axes()

plt.pcolor(X,Y,topo,cmap=cm.gist_earth)
plt.clim(-10,15)
plt.colorbar()

# add shoreline as a contour:
plt.contour(X,Y,topo,[0.],colors='k')

ax.set_aspect(1./np.cos(41.7*np.pi/180.))
ax.ticklabel_format(format='plain',useOffset=False)
plt.xticks(rotation=20);
```



You can do fancier things too, such as apply a light source to show hill shading. See also a more complete example (http://matplotlib.org/examples/specialty_plots/topographic_hillshading.html)

In [18]:
```
from matplotlib.colors import LightSource

ls = LightSource(azdeg=200, altdeg=45)

fig = plt.figure(figsize=(7,7))
ax = plt.axes()

plt.pcolor(X,Y,ls.hillshade(ma.masked_where(topo<-1,topo), vert_exag=3), cmap='gr

# add shoreline as a contour:
plt.contour(X,Y,topo,[0.],colors='g')

ax.set_aspect(1./np.cos(41.7*np.pi/180.))
ax.ticklabel_format(format='plain',useOffset=False)
plt.xticks(rotation=20);
```

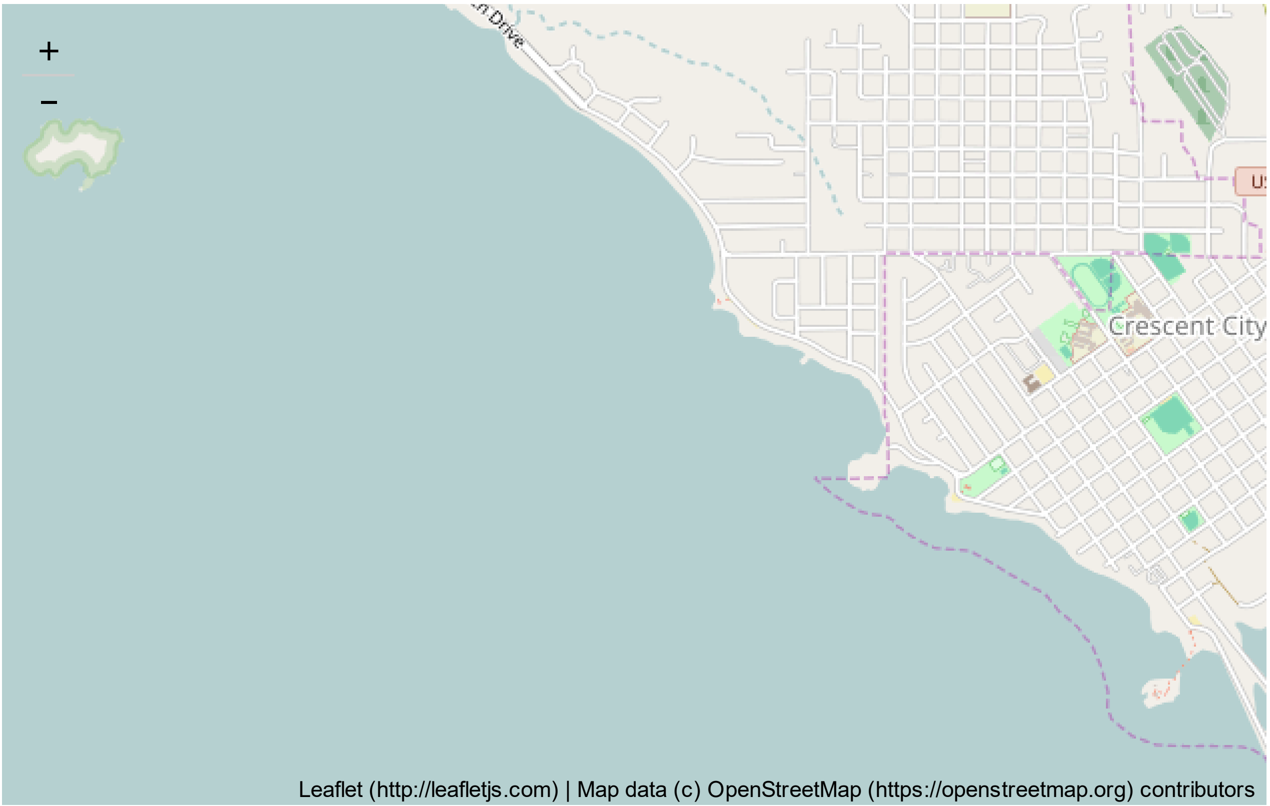


Interactive map

The ipyleaflet (https://github.com/ellisonbg/ipyleaflet) package allows creating interactive maps in the notebook. You can zoom in below to explore Crescent City.

Is it possible to plot our data on this map??

In [19]:
```
from ipyleaflet import Map

CCmap = Map(center=[41.745, -124.19], zoom=14)
CCmap
```



In [ ]: