Dussin_et_al_Hypoxia_Drivers

July 31, 2019

1 Plots for Dussin et al., Biogeochemical drivers of changing hypoxia in the California Current Ecosystem., Deep Sea Research II, 2019

1.1 Import python modules and define functions

In [1]:
```
# We need to manually set the path for PROJ_LIB
# you may need to change this according to your environment
import os
# RD laptop
#os.environ['PROJ_LIB'] = '/opt/anaconda2/5.1.0/envs/pubs/share/proj/'
# binder
os.environ['PROJ_LIB'] = '/srv/conda/envs/kernel/share/proj/'
```

In [2]:
```
# all these packages are standard python modules
import netCDF4 as nc
import numpy as np
import matplotlib.pylab as plt
import matplotlib.cm as cm
import matplotlib.colors as cl
import matplotlib.ticker as ticker
from mpl_toolkits.basemap import Basemap
from scipy import ndimage as im
from scipy import spatial
import seaborn as sns
import pandas as pd
from terminaltables import AsciiTable
```

In [3]:
```
# check python version, needs to be 2.7 for basemap to work
import sys
sys.version
```

Out[3]:
```
'2.7.15 |Anaconda, Inc.| (default, Dec 14 2018, 13:10:39) \n[GCC 4.2.1 Compatible Clang
```

In [4]:
```
from Dussin_et_al_Hypoxia_Drivers_utils import *
```

1.2 Data

All data is included in the subdirectory

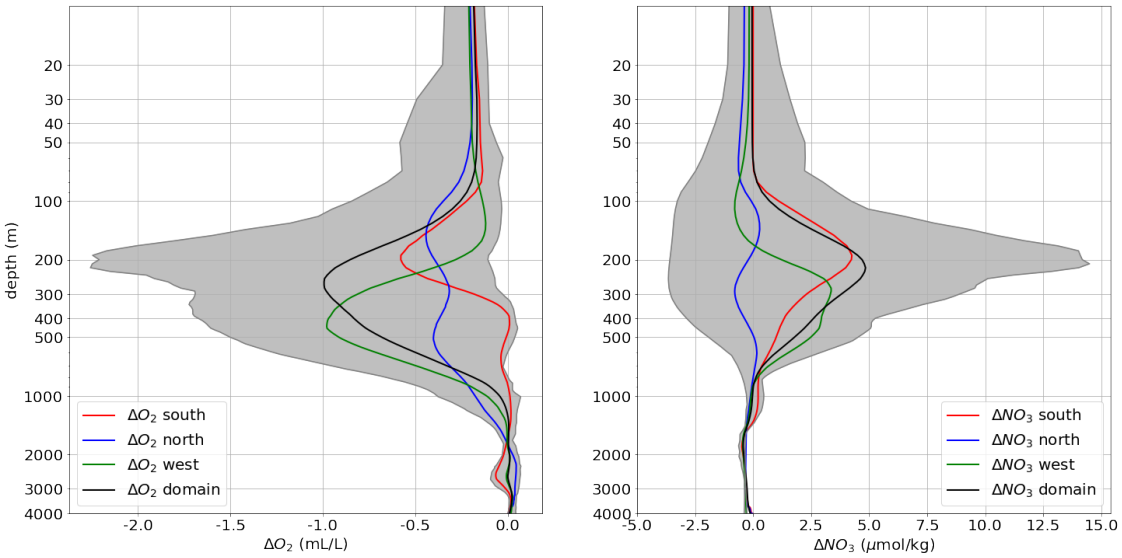
```
In [5]: datadir = './data_Dussin_Hypoxia_drivers/'

In [6]: # set to True if you want to save figures to eps files
        save_eps=False
        # set to True if you want to save figures to png files
        save_png=False
```

1.3 Figure 1: perturbation profiles from ESM2M in DO and NO3

```
In [7]: def plot_perturbation_profiles(datadir):

            file_profiles = datadir + 'delta_profiles.nc'
            unit_conv = 1035 * 22391.6 / 1000.0 # ml/L
            o2north = readnc(file_profiles, 'o2north') * unit_conv
            o2south = readnc(file_profiles, 'o2south') * unit_conv
            o2west = readnc(file_profiles, 'o2west') * unit_conv
            o2all = readnc(file_profiles, 'o2all') * unit_conv
            o2central = readnc(file_profiles, 'o2central') * unit_conv
            o2min = readnc(file_profiles, 'o2min') * unit_conv
            o2max = readnc(file_profiles, 'o2max') * unit_conv
            z= readnc(file_profiles, 'z')

            unit_conv = 1.0e+6
            no3north = readnc(file_profiles, 'no3north') * unit_conv
            no3south = readnc(file_profiles, 'no3south') * unit_conv
            no3west = readnc(file_profiles, 'no3west') * unit_conv
            no3all = readnc(file_profiles, 'no3all') * unit_conv
            no3central = readnc(file_profiles, 'no3central') * unit_conv
            no3min = readnc(file_profiles, 'no3min') * unit_conv
            no3max = readnc(file_profiles, 'no3max') * unit_conv

            fig = plt.figure(figsize=[24,12])
            plt.subplot(121)
            plt.plot(o2south, -z, 'r', o2north, -z, 'b',
                     o2west, -z, 'g', o2all, -z, 'k', linewidth=2)
            plt.plot(o2min, -z, 'grey', o2max, -z, 'grey')
            plt.fill_betweenx(-z, o2min, o2max, color='grey', alpha=0.5)
            plt.legend(('$\Delta O_{2}$ south',
                        '$\Delta O_{2}$ north',
                        '$\Delta O_{2}$ west',
                        '$\Delta O_{2}$ domain'), loc=3, fontsize=20)
            # set y axis in log and reverse
            plt.yscale('log')
            plt.ylim([10, 4000])
            plt.gca().invert_yaxis()
            plt.yticks([20,30,40,50,100,200,300,400,500,1000,2000,3000,4000],
                       [20,30,40,50,100,200,300,400,500,1000,2000,3000,4000],
                       fontsize=20)
```

```
    plt.xticks(np.arange(-2,0+0.5,0.5),
               np.arange(-2,0+0.5,0.5), fontsize=20)
    plt.ylabel('depth (m)', fontsize=20)
    plt.xlabel('$\Delta O_{2}$ (mL/L)', fontsize=20)
    plt.grid()

    plt.subplot(122)
    plt.plot(no3south, -z, 'r', no3north, -z, 'b',
             no3west, -z, 'g', no3all, -z, 'k', linewidth=2)
    plt.plot(no3min, -z, 'grey', no3max, -z, 'grey')
    plt.fill_betweenx(-z, no3min, no3max, color='grey', alpha=0.5)
    plt.legend(('$\Delta NO_{3}$ south',
                '$\Delta NO_{3}$ north',
                '$\Delta NO_{3}$ west',
                '$\Delta NO_{3}$ domain'), loc=4, fontsize=20)
    # set y axis in log and reverse
    plt.yscale('log')
    plt.ylim([10, 4000])
    plt.gca().invert_yaxis()
    plt.yticks([20,30,40,50,100,200,300,400,500,1000,2000,3000,4000],
               [20,30,40,50,100,200,300,400,500,1000,2000,3000,4000],
               fontsize=20)
    plt.xticks(np.arange(-5,15+2.5,2.5),
               np.arange(-5,15+2.5,2.5), fontsize=20)
    plt.xlabel('$\Delta NO_{3}$ ($\mu$mol/kg)', fontsize=20)
    plt.grid()

    if save_png:
        plt.savefig('figure1.png', bbox_inches='tight')
    if save_eps:
        plt.savefig('figure1.eps', bbox_inches='tight')
```

In [8]:
```
plot_perturbation_profiles(datadir)
```

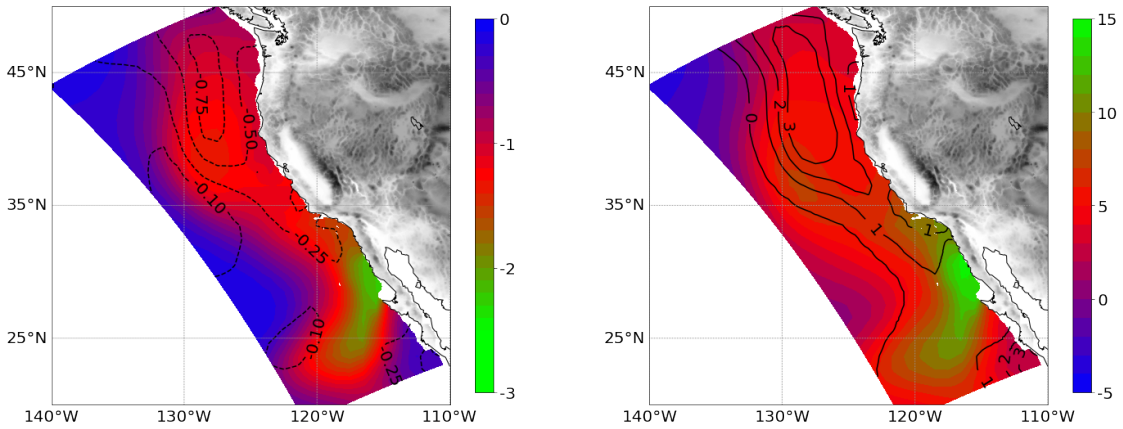


1.4 Figure 2: pertubations maps from ESM2M of DO and NO3

```
In [9]: def make_perturbation_maps(datadir):
            ''' make plot for no3/o2 perturbations'''
            file_slices_200m = datadir + 'deltas_200meters.nc'

            lon = readnc(file_slices_200m, 'lon')
            lat = readnc(file_slices_200m, 'lat')
            delta_o2_200  = readnc(file_slices_200m, 'diff_o2_200')
            delta_no3_200 = readnc(file_slices_200m, 'diff_no3_200')
            delta_o2_100  = readnc(file_slices_200m, 'diff_o2_100')
            delta_no3_100 = readnc(file_slices_200m, 'diff_no3_100')

            delta_O2_200 = delta_o2_200 * 1035 * 22391.6 / 1000.0 # ml/L
            delta_NO3_200 = delta_no3_200 * 1e+6 # umol/kg

            delta_O2_100 = delta_o2_100 * 1035 * 22391.6 / 1000.0 # ml/L
            delta_NO3_100 = delta_no3_100 * 1e+6 # umol/kg

            contours_no3 = np.arange(-5, 15.+1, 1)
            contours_o2 = np.arange(-3, 0.1, 0.1)

            norm_no3 = cl.Normalize(vmin=-5, vmax=15)
            norm_o2 = cl.Normalize(vmin=-2.5, vmax=0)

            ticks_no3 = np.arange(-5,15+5,5)
            ticks_o2 = np.arange(-3,1,1)
```

```
    pal_no3 = cm.brg
    pal_o2 = cm.brg_r

    cbarfmt = '%1f'

    # start figure
    fig = plt.figure(figsize=[24.,12.])
    # NO3
    ax  = fig.add_subplot(122)
    m = setup_map_small(datadir, hide_grid=False)
    C = m.contourf(lon, lat, delta_NO3_200, contours_no3,
                   cmap=pal_no3, norm=norm_no3)
    cbar = plt.colorbar(C, format=cbarfmt, shrink=0.7,
                        ticks=ticks_no3)
    cbar.ax.set_yticklabels(ticks_no3, fontsize=20)

    conts = m.contour(lon, lat, delta_NO3_100, [0,1,2,3],
                      colors='k')
    plt.clabel(conts, inline=1, fontsize=20, fmt='%2i')

    # O2
    ax  = fig.add_subplot(121)
    m = setup_map_small(datadir, hide_grid=False)
    C = m.contourf(lon, lat, delta_O2_200, contours_o2,
                   cmap=pal_o2, norm=norm_o2)
    cbar = plt.colorbar(C, format=cbarfmt, shrink=0.7,
                        ticks=ticks_o2)
    cbar.ax.set_yticklabels(ticks_o2, fontsize=20)

    conts = m.contour(lon, lat, delta_O2_100,
                      [-0.75,-0.5,-0.25,-0.1],
                      colors='k')
    plt.clabel(conts, inline=1, fontsize=20, fmt='%.2f')

    if save_png:
        plt.savefig('figure2.png', bbox_inches='tight')
    if save_eps:
        plt.savefig('figure2.eps', bbox_inches='tight')
```

```
In [10]: make_perturbation_maps(datadir)
```



1.5 Figure 3: SST and [Chl] in REF, ESM2M vs NOAA OISST and SeaWIFS

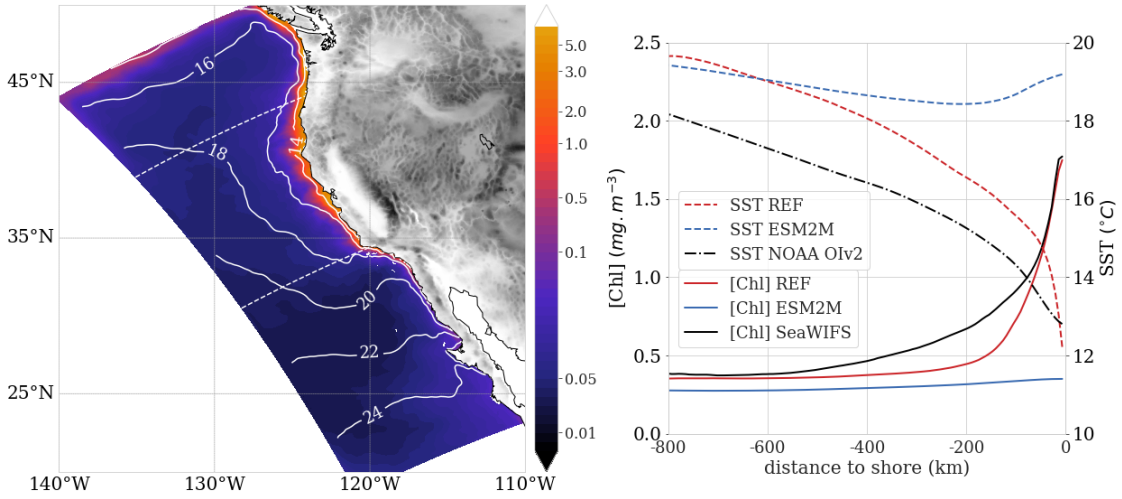
```
In [11]: def make_plot_cross_shore_chl_sst(datadir):
             ''' make validation plot on SST/Chl '''

             # Files needed
             gridfile = 'CCS1_grid.nc'
             file_sst_2d_REF = 'sst_CCS1-RD.NVOcobalt31S_1996-2006-JJA_season.nc'
             file_chl_2d_REF = 'surf_chl_CCS1-RD.NVOcobalt31S_1996-2006-JJA_season.nc'

             file_sst_prof_REF = 'sst_alongshore_mean_CCS1-RD.NVOcobalt31S_JJA_1996-2006.nc'
             file_sst_prof_ESM2M = 'sst_alongshore_mean_ESM2M_JJA_1996-2006.nc'
             file_sst_prof_OISST = 'sst_alongshore_mean_NOAA_OIv2_JJA_1996-2006.nc'

             file_chl_prof_REF = 'surf_chl_alongshore_mean_CCS1-RD.NVOcobalt31S_JJA_1996-2006.n
             file_chl_prof_ESM2M = 'surf_chl_alongshore_mean_ESM2M_JJA_1996-2006.nc'
             file_chl_prof_seawifs = 'surf_chl_alongshore_mean_Seawifs_JJA_1996-2006.nc'

             # Read data
             lon = readnc(datadir + gridfile, 'lon')
             lat = readnc(datadir + gridfile, 'lat')

             map_sst = readnc(datadir + file_sst_2d_REF, 'temp')
             map_chl_surf = readnc(datadir + file_chl_2d_REF, 'chl')
             #--- units change: [ug/kg] * [kg/m3] / [ug/mg] = [mg/m3]
             map_chl_surf = map_chl_surf * 1035 / 1000.

             cross_shore_dist = readnc(datadir + file_sst_prof_REF,
                                       'cross_shore_dist')
             sst_ref = readnc(datadir + file_sst_prof_REF, 'sst')
             sst_esm2m = readnc(datadir + file_sst_prof_ESM2M, 'sst')
             sst_obs = readnc(datadir + file_sst_prof_OISST, 'sst')
```

```
surf_chl_ref = readnc(datadir + file_chl_prof_REF, 'surf_chl')
surf_chl_esm2m = readnc(datadir + file_chl_prof_ESM2M, 'surf_chl')
surf_chl_obs = readnc(datadir + file_chl_prof_seawifs, 'surf_chl')

# figure options
sns.set_style("whitegrid", {
"font.family": "serif",
"font.serif": ["Times", "Palatino", "serif"],
'fontsize':'large'
})
my_colors = define_colors()

# begin figure
fig = plt.figure(figsize=[20.,10.])
ax0 = plt.subplot2grid((10, 20), (0, 0),
                       colspan=10, rowspan=10)
m = setup_map_small(datadir)
contours = np.arange(-1.4, 1, 0.05)
cticks = [0.01, 0.05, 0.1, 0.5, 1., 2., 3., 5., 7.]
ticks = np.log10(cticks)
norm= cl.Normalize(vmin=-1.4, vmax=2)
m.contourf(lon, lat, np.log10(map_chl_surf),
           contours, cmap=cm.CMRmap,
           norm=norm, extend='both')
cbar0 = m.colorbar(ticks=ticks)
cbar0.ax.set_yticklabels(cticks, fontsize=16)
conts = m.contour(lon[:,10:], lat[:,10:],
                  map_sst[:,10:], [14., 16.,18.,20.,22.,24.],
                  colors='w')
manual_locations = [(360-124, 41), (360-130, 45),
                    (360-130, 40), (360-120, 31),
                    (360-120, 28), (360-120, 24)]
plt.clabel(conts, inline=1, fontsize=18, fmt='%2i',
           manual=manual_locations)

# central CCS
m.plot(lon[220,:135],lat[220,:135],'w--')
m.plot(lon[380,:155],lat[380,:155],'w--')

ax1 = plt.subplot2grid((10, 20), (1, 12), colspan=8, rowspan=8)
ax1.plot(-cross_shore_dist, surf_chl_ref,
         color=my_colors['my_red'], linewidth=2, label='[Chl] REF')
ax1.plot(-cross_shore_dist, surf_chl_esm2m,
         color=my_colors['my_blue'], linewidth=2, label='[Chl] ESM2M')
ax1.plot(-cross_shore_dist, surf_chl_obs,
         color='k', linewidth=2, label='[Chl] SeaWIFS')
ax1.set_ylabel('[Chl] $(mg.m^{-3})$', color='k', fontsize=20)
```

```
    for tl in ax1.get_yticklabels():
        tl.set_color('k')

    plt.xlim([-800,0])
    plt.ylim([0,2.5])
    plt.yticks(np.arange(0,2.5+0.5,0.5),
               np.arange(0,2.5+0.5,0.5), fontsize=20)
    plt.legend(loc=(0.025,0.22,), fontsize=18, frameon=True)

    ax2 = ax1.twinx()
    ax2.plot(-cross_shore_dist, sst_ref, color=my_colors['my_red'],
             linestyle='--', linewidth=2, label='SST REF')
    ax2.plot(-cross_shore_dist, sst_esm2m, color=my_colors['my_blue'],
             linestyle='--', linewidth=2, label='SST ESM2M')
    ax2.plot(-cross_shore_dist, sst_obs, color='k', linestyle='-.',
             linewidth=2, label='SST NOAA OIv2')
    ax2.set_ylabel('SST $(^{\circ} C)$', color='k', fontsize=20)
    for tl in ax2.get_yticklabels():
        tl.set_color('k')

    ax1.set_xticklabels(np.arange(-800,200,200),
                        fontdict={'fontsize':18})
    ax1.set_xlabel('distance to shore (km)', fontsize=20)
    plt.legend(loc=(0.025,0.42,),fontsize=18,frameon=True)
    plt.ylim([10,20])
    plt.yticks(np.arange(10,20+2,2), np.arange(10,20+2,2), fontsize=20)
    plt.xticks(np.arange(-800,0+200,200),
               np.arange(-800,0+200,200), fontsize=20)
    plt.grid()

    if save_png:
        plt.savefig('figure3.png',bbox_inches='tight')
    if save_eps:
        plt.savefig('figure3.eps',bbox_inches='tight')
```

In [12]:
```
make_plot_cross_shore_chl_sst(datadir)
```

```
/opt/anaconda2/5.1.0/envs/pubs/lib/python2.7/site-packages/ipykernel_launcher.py:53: RuntimeWa
```

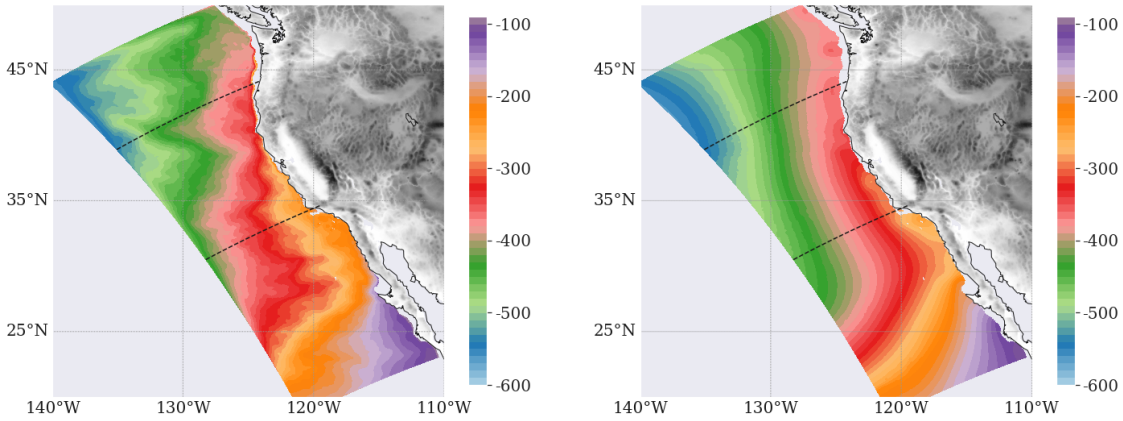


1.6 Figure 4: Comparison of hypoxic boundary in REF and WOA13

```
In [13]: def make_plot_hypoxic_bdry_map(datadir):
             ''' make validation plot on hypoxic boundary '''
             # get colormap from file
             rt_colormaps = rt_getcolormaps()
             pal = rt_colormaps['pastel1']
             # colorbar options
             cbarfmt = "%01g"
             norm = cl.Normalize(vmin=-600, vmax=0)
             contours=np.arange(-600.,-90.+10.,10.)
             ticks=np.arange(-600,-100+100,100)
             # layout options
             sns.set(font_scale=1.4)
             sns.set_style("darkgrid", {
             "font.family": "serif",
             "font.serif": ["Times", "Palatino", "serif"],
             'grid.linestyle': '-'
             })

             # read data
             file_REF = 'CCS1-RD.NVOcobalt31S_hypoxic_bdry_annual_1996-2006.nc'
             file_WOA = 'WOA13_hypoxic_bdry_annual_clim.nc'
             lon = readnc(datadir + file_REF, 'lon')
             lat = readnc(datadir + file_REF, 'lat')
             hyp_bd_REF = readnc(datadir + file_REF, 'hypoxic_boundary')
             hyp_bd_WOA = readnc(datadir + file_WOA, 'hypoxic_boundary')
             # mask special values
             hyp_bd_REF = np.ma.masked_values(hyp_bd_REF,-9999.)
             hyp_bd_WOA = np.ma.masked_values(hyp_bd_WOA,-9999.)
```

```
    # start figure
    fig = plt.figure(figsize=[24.,12.])
    # model
    ax  = fig.add_subplot(121)
    m = setup_map_small(datadir, hide_grid=False)
    C = m.contourf(lon, lat, hyp_bd_REF, contours, cmap=pal, norm=norm)
    cbar = plt.colorbar(C, format=cbarfmt, shrink=0.7, ticks=ticks)
    cbar.ax.set_yticklabels(ticks, fontsize=20)
    # add central CCS band
    m.plot(lon[220,:135],lat[220,:135],'k--')
    m.plot(lon[380,:155],lat[380,:155],'k--')

    # WOA
    ax  = fig.add_subplot(122)
    m = setup_map_small(datadir, hide_grid=False)
    C = m.contourf(lon, lat, hyp_bd_WOA, contours, cmap=pal, norm=norm)
    cbar = plt.colorbar(C, format=cbarfmt, shrink=0.7, ticks=ticks)
    cbar.ax.set_yticklabels(ticks, fontsize=20)
    # add central CCS bands
    m.plot(lon[220,:135],lat[220,:135],'k--')
    m.plot(lon[380,:155],lat[380,:155],'k--')

    if save_png:
        plt.savefig('figure4.png',bbox_inches='tight')
    if save_eps:
        plt.savefig('figure4.eps',bbox_inches='tight')
```

In [14]: `make_plot_hypoxic_bdry_map(datadir)`



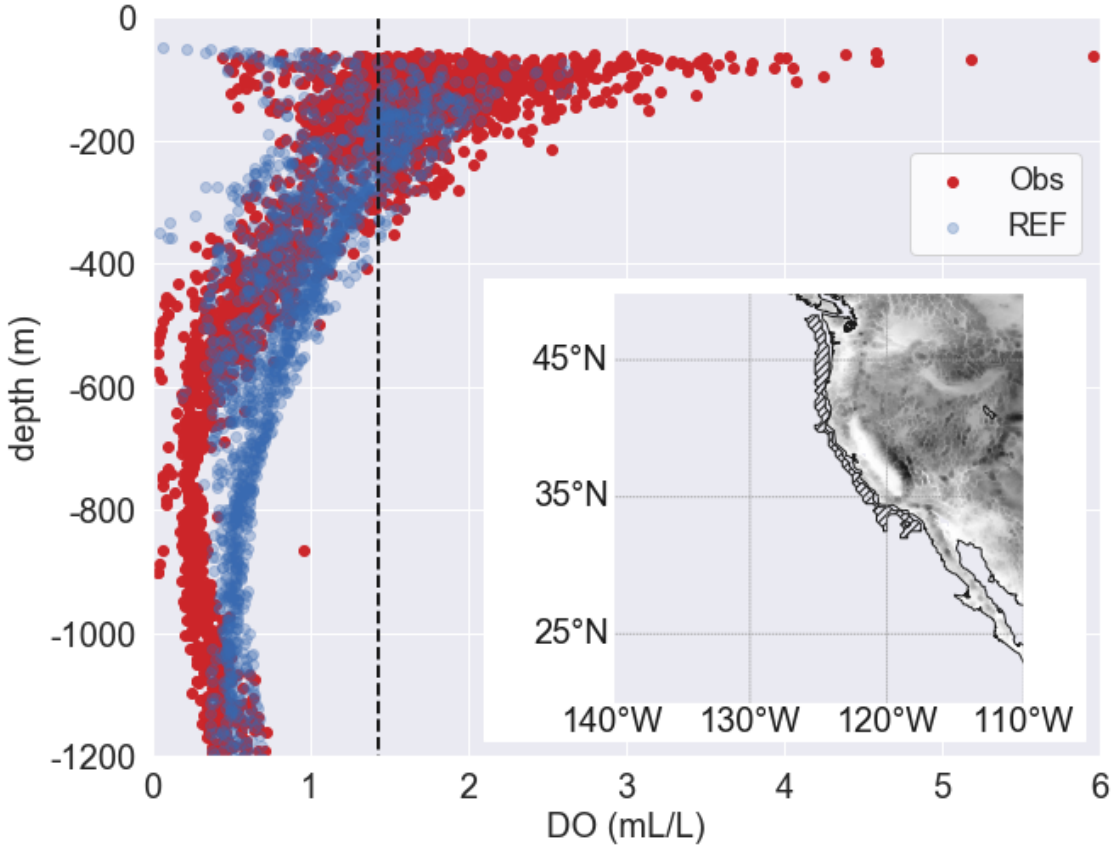
1.7 Figure 5: Validation of bottom DO

```
In [15]: def make_plot_DO_vs_NOAA(datadir):
             ''' make plot of DO vs NOAA data '''
             datadir_csv = datadir + '/csv/'
             # read the reference run data from easy_coloc csv files
             data_runref = pd.DataFrame(columns=['lon', 'lat', 'depth', 'O2', 'month'])
             data_obs    = pd.DataFrame(columns=['lon', 'lat', 'depth', 'O2', 'month'])

             # read the model 1996-2006 avg
             for month in ['june', 'july', 'aug']:
                 tmp = pd.read_csv(datadir_csv + 'roms_run31S_onto_o2noaa_' + \
                                   month + '_1996-2006.txt',
                                   header=None, names=['lon','lat','depth','O2'])
                 tmp['month'] = month
                 data_runref = pd.concat([data_runref,tmp], ignore_index=True)

             # read the DO data from observation
             for month in ['june','july','aug']:
                 tmp = pd.read_csv(datadir_csv + 'oxygen_o2noaa_' + month + '.txt',
                                   header=None, names=['lon', 'lat', 'depth', 'O2'])
                 tmp['month'] = month
                 data_obs = pd.concat([data_obs,tmp], ignore_index=True)

             # mask and set depth from bottom to top
             spval=1.0e+15
             dataplt_runref = np.ma.masked_values(data_runref['O2'].values, spval)
             dataplt_obs    = np.ma.masked_values(data_obs['O2'].values, spval)

             depth_runref = -1*np.ma.masked_values(data_runref['depth'].values, spval)
             depth_obs    = -1*np.ma.masked_values(data_obs['depth'].values, spval)

             depths=np.arange(0, 1200+5, 5)

             sns.set_style('darkgrid', {'legend.frameon':True})
             my_colors = define_colors()

             plt.figure(figsize=[10.,8.])

             # obs
             plt.scatter(dataplt_obs, depth_obs, c=my_colors['my_red'],
                         alpha=0.99, marker='o',
                         label='Obs', edgecolors=None)
             # model
             plt.scatter(dataplt_runref, depth_runref, c=my_colors['my_blue'],
                         alpha=0.3, marker='o',
                         label='REF', edgecolors=None)
             # hypoxia threshold
```

```
plt.plot(1.43*np.ones(depths.shape), -depths,'k--', linewidth=2)
ax = plt.gca()

legend = plt.legend(loc=[0.8,0.68], fontsize=18)
frame = legend.get_frame()
frame.set_facecolor('white')

plt.title('')
plt.xlim([0.,6.])
plt.ylim([-1200,0])
plt.xticks(np.arange(0,6+1), np.arange(0,6+1), fontsize=20)
plt.yticks(np.arange(-1200,200,200),
           np.arange(-1200,200,200), fontsize=20)

plt.xlabel('DO (mL/L)',fontsize=20)
plt.ylabel('depth (m)',fontsize=20)

# add white patch for map insert
fp = ax.add_patch(plt.Polygon([[2.1,-1175],[5.9,-1175],
                               [5.9,-425],[2.1,-425] ], closed=True,
                              fill=True,color='white'))

# insert map
ax_insert = plt.axes([0.46, 0.18, 0.42, 0.42])

m = setup_map_small(datadir, plt_topo=True,
                    hide_grid=False)

lon = readnc(datadir + 'CCS1_grid.nc','lon')
lat = readnc(datadir + 'CCS1_grid.nc','lat')

#add patch for obs location
obs_lon = data_obs['lon'].values + 360
obs_lat = data_obs['lat'].values
isobs = np.ones(obs_lon.shape)

lon_patch = np.arange(220, 250, 0.25)
lat_patch = np.arange(20, 50, 0.25)
H, xedges, yedges = np.histogram2d(obs_lat, obs_lon,
                                   bins=[lat_patch, lon_patch])

mask_obs = np.zeros(H.shape)
mask_obs[np.where(H > 0)] = 1
lon_patchplt, lat_patchplt = np.meshgrid(lon_patch[:-1],
                                         lat_patch[:-1])

fig_temp = plt.figure()
m =setup_map_small(datadir)
```

```
        cont = m.contour(lon_patchplt, lat_patchplt,
                         mask_obs,[0.99,1.01])
        plt.close(fig_temp)

        for cont_tmp in cont.allsegs[0]:
            fp = ax_insert.add_patch(plt.Polygon(cont_tmp, closed=True,
                                                 fill=False, hatch='/////',
                                                 color='k', linewidth=1))
        if save_png:
            plt.savefig('figure5.png', bbox_inches='tight')
        if save_eps:
            plt.savefig('figure5.eps', bbox_inches='tight')
```

In [16]: `make_plot_DO_vs_NOAA(datadir)`



1.8 Figure 6: NPP in REF and perturbations

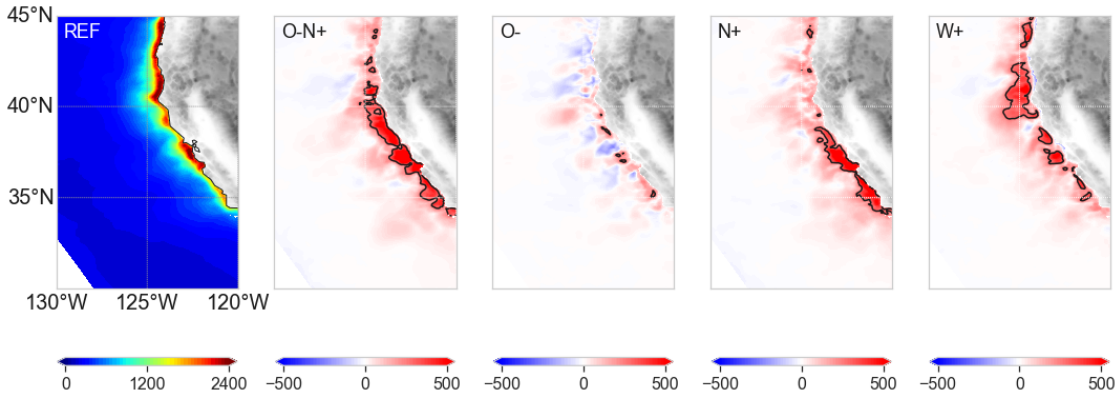
In [17]: `def plot_npp_map(datadir):`

```
        # data for map plot
```

```
lon = readnc(datadir + 'CCS1_grid.nc','lon')
lat = readnc(datadir + 'CCS1_grid.nc','lat')

R31S = readnc(datadir + 'npp100_CCS1-RD.NVOcobalt31S_JJA_1996-2006.nc','npp_100')
R32R = readnc(datadir + 'npp100_CCS1-RD.FCcobalt32R_JJA_1996-2006.nc','npp_100')
R33O = readnc(datadir + 'npp100_CCS1-RD.FCcobalt33O_JJA_1996-2006.nc','npp_100')
R34N = readnc(datadir + 'npp100_CCS1-RD.FCcobalt34N_JJA_1996-2006.nc','npp_100')
R35W = readnc(datadir + 'npp100_CCS1-RD.FCcobalt35W_JJA_1996-2006.nc','npp_100')

R31S = convert2ma(R31S)
R32R = convert2ma(R32R)
R33O = convert2ma(R33O)
R34N = convert2ma(R34N)
R35W = convert2ma(R35W)

norm1= cl.Normalize(vmin=0, vmax=2400)
norm2= cl.Normalize(vmin=-500, vmax=500)

contours1=np.arange(0, 2400+50, 50)
contours2=np.arange(-500, 500+10, 10)
diffticks=[-500,0,500]

cmap1=cm.jet
cmap2=cm.bwr

sns.set_style('whitegrid')

plt.figure(figsize=[18,8])
plt.subplot(151)
map1 = setup_map_verysmall(datadir)
map1.contourf(lon, lat, R31S, contours1, norm=norm1,
              cmap=cmap1, extend='both')
cb = plt.colorbar(orientation='horizontal', shrink=0.99,
                  ticks=[0,1200,2400])
cb.ax.tick_params(labelsize=16)
plt.annotate('REF', xy=(0.04, 0.92), xycoords='axes fraction',
             fontsize=18, color='w')

plt.subplot(152)
map2 = setup_map_verysmall(datadir, hide_grid=True)
map2.contourf(lon, lat, R32R-R31S, contours2, norm=norm2,
              cmap=cmap2, extend='both')
cb = plt.colorbar(orientation='horizontal', shrink=0.99,
                  ticks=diffticks)
cb.ax.tick_params(labelsize=16)
map2.contour(lon, lat, R32R-R31S, [250], colors='k')
plt.annotate('O-N+', xy=(0.04, 0.92), xycoords='axes fraction',
             fontsize=18, color='k')
```

```
    plt.subplot(153)
    map3 = setup_map_verysmall(datadir, hide_grid=True)
    map3.contourf(lon, lat, R33O-R31S, contours2, norm=norm2,
                  cmap=cmap2, extend='both')
    cb = plt.colorbar(orientation='horizontal', shrink=0.99,
                      ticks=diffticks)
    cb.ax.tick_params(labelsize=16)
    map3.contour(lon, lat, R33O-R31S, [250], colors='k')
    plt.annotate('O-', xy=(0.04, 0.92), xycoords='axes fraction',
                 fontsize=18, color='k')

    plt.subplot(154)
    map4 = setup_map_verysmall(datadir, hide_grid=True)
    map4.contourf(lon, lat, R34N-R31S, contours2, norm=norm2,
                  cmap=cmap2, extend='both')
    cb = plt.colorbar(orientation='horizontal', shrink=0.99,
                      ticks=diffticks)
    cb.ax.tick_params(labelsize=16)
    map4.contour(lon, lat, R34N-R31S, [250], colors='k')
    plt.annotate('N+', xy=(0.04, 0.92), xycoords='axes fraction',
                 fontsize=18, color='k')

    plt.subplot(155)
    map5 = setup_map_verysmall(datadir, hide_grid=True)
    map5.contourf(lon, lat, R35W-R31S, contours2, norm=norm2,
                  cmap=cmap2, extend='both')
    cb = plt.colorbar(orientation='horizontal', shrink=0.99,
                      ticks=diffticks)
    cb.ax.tick_params(labelsize=16)
    map5.contour(lon, lat, R35W-R31S, [250], colors='k')
    plt.annotate('W+', xy=(0.04, 0.92), xycoords='axes fraction',
                 fontsize=18, color='k')

    if save_png:
        plt.savefig('figure6.png', bbox_inches='tight')
    if save_eps:
        plt.savefig('figure6.eps', bbox_inches='tight')
```

In [18]:
```
plot_npp_map(datadir)
```



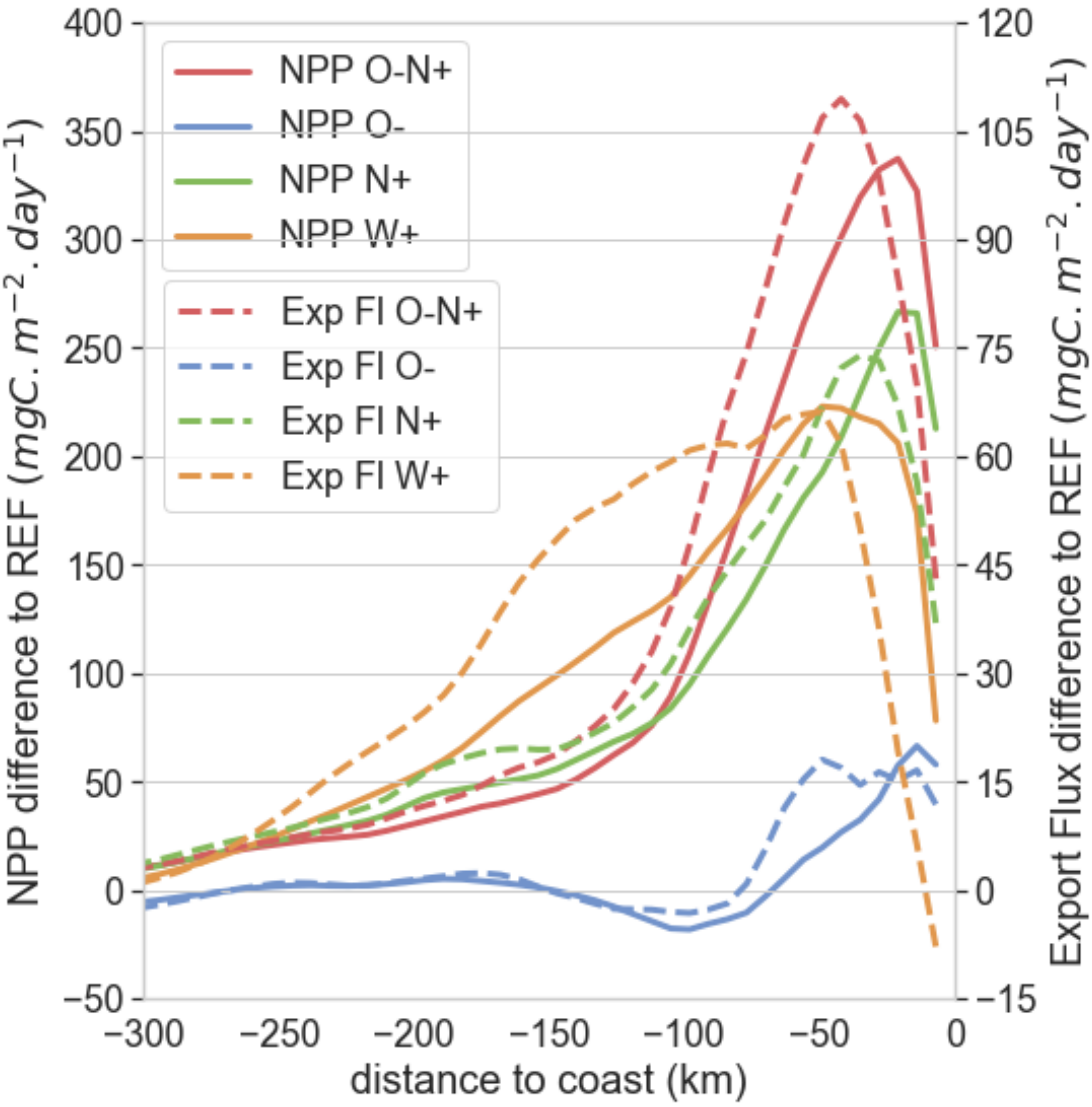
1.9 Figure 7: NPP and Export flux difference to REF

```
In [19]: def plot_sensitivity_npp_ef(datadir):
             ''' make plot of NPP/EF difference to REF cross shore profile '''

             # data
             season = 'JJA' ; period = '1996-2006'
             cnpp = 'npp100_alongshore_mean_34.5-44'
             cef = 'exportflux100m_alongshore_mean_34.5-44'
             file_npp_ref    = '{}_CCS1-RD.NVOcobalt31S_{}_{}.nc'.format(cnpp,
                                                                         season,
                                                                         period)
             file_npp_pertON = '{}_CCS1-RD.FCcobalt32R_{}_{}.nc'.format(cnpp,
                                                                         season,
                                                                         period)
             file_npp_pertO  = '{}_CCS1-RD.FCcobalt33O_{}_{}.nc'.format(cnpp,
                                                                         season,
                                                                         period)
             file_npp_pertN  = '{}_CCS1-RD.FCcobalt34N_{}_{}.nc'.format(cnpp,
                                                                         season,
                                                                         period)
             file_npp_pertW  = '{}_CCS1-RD.FCcobalt35W_{}_{}.nc'.format(cnpp,
                                                                         season,
                                                                         period)

             file_ef_ref    = '{}_CCS1-RD.NVOcobalt31S_{}_{}.nc'.format(cef,
                                                                         season,
                                                                         period)
             file_ef_pertON = '{}_CCS1-RD.FCcobalt32R_{}_{}.nc'.format(cef,
                                                                         season,
                                                                         period)
             file_ef_pertO  = '{}_CCS1-RD.FCcobalt33O_{}_{}.nc'.format(cef,
                                                                         season,
```

```
                                                                period)
file_ef_pertN  = '{}_CCS1-RD.FCcobalt34N_{}_{}.nc'.format(cef,
                                                                season,
                                                                period)
file_ef_pertW  = '{}_CCS1-RD.FCcobalt35W_{}_{}.nc'.format(cef,
                                                                season,
                                                                period)

cross_shore_dist= readnc(datadir + file_npp_ref, 'cross_shore_dist')
nppcross_ref    = readnc(datadir + file_npp_ref, 'npp100')
nppcross_pertON = readnc(datadir + file_npp_pertON, 'npp100')
nppcross_pertO  = readnc(datadir + file_npp_pertO, 'npp100')
nppcross_pertN  = readnc(datadir + file_npp_pertN, 'npp100')
nppcross_pertW  = readnc(datadir + file_npp_pertW, 'npp100')

efcross_ref    = readnc(datadir + file_ef_ref, 'exportflux100m')
efcross_pertON = readnc(datadir + file_ef_pertON, 'exportflux100m')
efcross_pertO  = readnc(datadir + file_ef_pertO, 'exportflux100m')
efcross_pertN  = readnc(datadir + file_ef_pertN, 'exportflux100m')
efcross_pertW  = readnc(datadir + file_ef_pertW, 'exportflux100m')

# convert units from mmol/m2/day to mgC/m2/day
efcross_ref    = efcross_ref    * 6.625 * 12
efcross_pertON = efcross_pertON * 6.625 * 12
efcross_pertO  = efcross_pertO  * 6.625 * 12
efcross_pertN  = efcross_pertN  * 6.625 * 12
efcross_pertW  = efcross_pertW  * 6.625 * 12

diff_nppcross_pertON = nppcross_pertON - nppcross_ref
diff_nppcross_pertO  = nppcross_pertO  - nppcross_ref
diff_nppcross_pertN  = nppcross_pertN  - nppcross_ref
diff_nppcross_pertW  = nppcross_pertW  - nppcross_ref

diff_efcross_pertON = efcross_pertON - efcross_ref
diff_efcross_pertO  = efcross_pertO  - efcross_ref
diff_efcross_pertN  = efcross_pertN  - efcross_ref
diff_efcross_pertW  = efcross_pertW  - efcross_ref

# standard colors for plots
my_colors = define_colors()
color_ref    = my_colors['my_violet']
color_pertON = my_colors['my_red_bar']
color_pertO  =  my_colors['my_blue_bar']
color_pertN  =  my_colors['my_green_bar']
color_pertW  =  my_colors['my_orange_bar']

plt.figure(figsize=[8,8])
```

```
    ax1 = plt.subplot(111)
    ax1.plot(-cross_shore_dist, diff_nppcross_pertON,
             color=color_pertON, linewidth=3, label='NPP O-N+')
    ax1.plot(-cross_shore_dist, diff_nppcross_pert0,
             color=color_pert0, linewidth=3, label='NPP O-')
    ax1.plot(-cross_shore_dist, diff_nppcross_pertN,
             color=color_pertN, linewidth=3, label='NPP N+')
    ax1.plot(-cross_shore_dist, diff_nppcross_pertW,
             color=color_pertW, linewidth=3, label='NPP W+')
    ax1.legend(loc=2,frameon=True,fontsize=18)
    plt.ylabel('NPP difference to REF $(mgC.m^{-2}.day^{-1})$',
               fontsize=20)
    plt.xlabel('distance to coast (km)', fontsize=20)
    plt.xticks(np.arange(-300,50,50), fontsize=18)
    plt.xlim([-300, 0])
    plt.ylim([-50, 400])
    plt.yticks(np.arange(-50, 400+50, 50),
               fontsize=18)
    plt.grid()
    ax2 = ax1.twinx()
    ax2.plot(-cross_shore_dist, diff_efcross_pertON,
             color=color_pertON, linewidth=3,
             label='Exp Fl O-N+', linestyle='dashed')
    ax2.plot(-cross_shore_dist, diff_efcross_pert0,
             color=color_pert0, linewidth=3,
             label='Exp Fl O-', linestyle='dashed')
    ax2.plot(-cross_shore_dist, diff_efcross_pertN,
             color=color_pertN, linewidth=3,
             label='Exp Fl N+', linestyle='dashed')
    ax2.plot(-cross_shore_dist, diff_efcross_pertW,
             color=color_pertW, linewidth=3,
             label='Exp Fl W+', linestyle='dashed')
    ax2.legend(loc=(0.025,0.50,), frameon=True, fontsize=18)
    plt.ylabel('Export Flux difference to REF $(mgC.m^{-2}.day^{-1})$',
               fontsize=20)
    plt.ylim([-15, 120])
    plt.yticks(np.arange(-15, 120+15, 15),
               fontsize=18)
    plt.xlim([-300,0])

    plt.tight_layout()

    if save_png:
        plt.savefig('figure7.png', bbox_inches='tight')
    if save_eps:
        plt.savefig('figure7.eps', bbox_inches='tight')
```

In [20]:
```
plot_sensitivity_npp_ef(datadir)
```



1.10 Figure 8: Shoaling of the hypoxic boundary

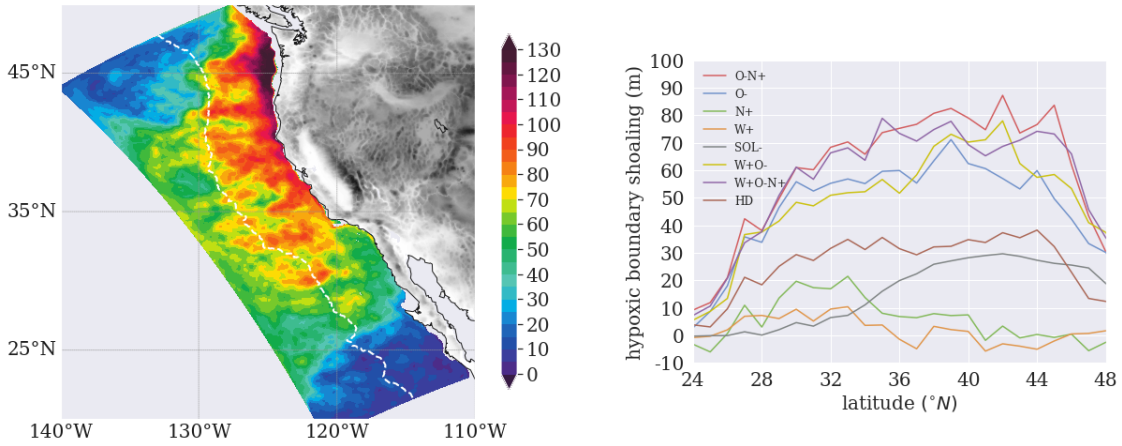
```
In [21]: def make_plot_shoaling_hypoxic_bdry_map(datadir):
             ''' shoaling of the hypoxic boundary in perturbation experiments'''
             rt_colormaps = rt_getcolormaps()
             pal = rt_colormaps['capet']
             cbarfmt = "%01g"
             norm = cl.Normalize(vmin=-10, vmax=130)
             contours=np.arange(0,130+5,5)
             ticks=np.arange(0,130+10,10)

             # data files needed
             cbin = 'binned_hypoxic_bdry_coastal500kmannual_1996-2006.nc'
```

```
cbin2 = 'binned_hypoxic_bdry_Tpert_coastal500kmannual_1996-2006.nc'
file_diff_2d_pertON       = 'compare_hypoxic_bdry_CCS1-RD.FCcobalt32R' + \
                            '-CCS1-RD.NVOcobalt31S_annual_1996-2006.nc'
file_hypbdry_bins_ref     = 'CCS1-RD.NVOcobalt31S_' + cbin
file_hypbdry_bins_pertON  = 'CCS1-RD.FCcobalt32R_' + cbin
file_hypbdry_bins_pertO   = 'CCS1-RD.FCcobalt33O_' + cbin
file_hypbdry_bins_pertN   = 'CCS1-RD.FCcobalt34N_' + cbin
file_hypbdry_bins_pertW   = 'CCS1-RD.FCcobalt35W_' + cbin
file_hypbdry_bins_pertSOL = 'CCS1-RD.NVOcobalt31S_' + cbin2
file_hypbdry_bins_pertWO  = 'CCS1-RD.FCcobalt37WO_' + cbin
file_hypbdry_bins_pertWON = 'CCS1-RD.FCcobalt38WON_' + cbin
file_hypbdry_bins_pertHD  = 'CCS1-RD.FCcobalt39HD_' + cbin

# grid
lon = readnc(datadir + 'CCS1_grid.nc', 'lon')
lat = readnc(datadir + 'CCS1_grid.nc', 'lat')
dist500km = readnc(datadir + 'dist500km.nc', 'dist500km')

# data for map
hyp_bd_diff = readnc(datadir + file_diff_2d_pertON, 'hypoxic_boundary_diff')

# data for line plot
lat_bins = readnc(datadir + file_hypbdry_bins_ref, 'lat')
hb_ref   = readnc(datadir + file_hypbdry_bins_ref, 'hypoxic_boundary')
hb_32R   = readnc(datadir + file_hypbdry_bins_pertON, 'hypoxic_boundary')
hb_33O   = readnc(datadir + file_hypbdry_bins_pertO, 'hypoxic_boundary')
hb_34N   = readnc(datadir + file_hypbdry_bins_pertN, 'hypoxic_boundary')
hb_35W   = readnc(datadir + file_hypbdry_bins_pertW, 'hypoxic_boundary')
hb_sol   = readnc(datadir + file_hypbdry_bins_pertSOL, 'hypoxic_boundary')
hb_37WO  = readnc(datadir + file_hypbdry_bins_pertWO, 'hypoxic_boundary')
hb_38WON = readnc(datadir + file_hypbdry_bins_pertWON, 'hypoxic_boundary')
hb_39HD  = readnc(datadir + file_hypbdry_bins_pertHD, 'hypoxic_boundary')

hb_ref[np.where( np.isnan(hb_ref) )] = 0.
hb_32R[np.where( np.isnan(hb_32R) )] = 0.
hb_33O[np.where( np.isnan(hb_33O) )] = 0.
hb_34N[np.where( np.isnan(hb_34N) )] = 0.
hb_35W[np.where( np.isnan(hb_35W) )] = 0.
hb_sol[np.where( np.isnan(hb_sol) )] = 0.
hb_37WO[np.where( np.isnan(hb_37WO) )] = 0.
hb_38WON[np.where( np.isnan(hb_38WON) )] = 0.
hb_39HD[np.where( np.isnan(hb_39HD) )] = 0.

hb_ref = np.ma.masked_values(hb_ref,0.)
hb_32R = np.ma.masked_values(hb_32R,0.)
hb_33O = np.ma.masked_values(hb_33O,0.)
hb_34N = np.ma.masked_values(hb_34N,0.)
hb_35W = np.ma.masked_values(hb_35W,0.)
```

```
hb_sol = np.ma.masked_values(hb_sol,0.)
hb_37WO= np.ma.masked_values(hb_37WO,0.)
hb_38WON= np.ma.masked_values(hb_38WON,0.)
hb_39HD= np.ma.masked_values(hb_39HD,0.)

# style
sns.set_style("dark", {
"font.family": "serif",
"font.serif": ["Times", "Palatino", "serif"],
'grid.linestyle': '-'
})

my_colors = define_colors()

# begin figure
fig = plt.figure(figsize=[20.,10.])
ax0 = plt.subplot2grid((10, 20), (0, 0),
                       colspan=10,rowspan=10)

# map
m = setup_map_small(datadir, hide_grid=False)
C = m.contourf(lon, lat, hyp_bd_diff, contours,
               cmap=pal, norm=norm, extend='both')
cbar = plt.colorbar(C, format=cbarfmt, shrink=0.7,
                    ticks=ticks)
cbar.ax.set_yticklabels(ticks, fontsize=20)

# use alt figure to get 500km line
figtmp = plt.figure()
m = setup_map_small(datadir, hide_grid=False)
cont500km = m.contour(lon, lat, dist500km, [0.99,1.01])
xseg = cont500km.allsegs[0][0][:,0]
yseg = cont500km.allsegs[0][0][:,1]
plt.close()

# plot 500km line
m.plot(xseg,yseg,'w--',linewidth=2)

# line plot
ax1 = plt.subplot2grid((10, 20), (2, 12),
                       colspan=8,rowspan=6)
plt.plot(lat_bins, hb_32R-hb_ref, label='O-N+',
         color=my_colors['my_red_bar'])
plt.plot(lat_bins, hb_33O-hb_ref, label='O-',
         color=my_colors['my_blue_bar'])
plt.plot(lat_bins, hb_34N-hb_ref, label='N+',
         color=my_colors['my_green_bar'])
plt.plot(lat_bins, hb_35W-hb_ref, label='W+',
```

```
            color=my_colors['my_orange_bar'])
    plt.plot(lat_bins, hb_sol-hb_ref, label='SOL-',
            color=my_colors['my_grey_bar'])
    plt.plot(lat_bins, hb_37WO-hb_ref, label='W+O-',
            color=my_colors['my_yellow_bar'])
    plt.plot(lat_bins, hb_38WON-hb_ref, label='W+O-N+',
            color=my_colors['my_violet_bar'])
    plt.plot(lat_bins, hb_39HD-hb_ref, label='HD',
            color=my_colors['my_darkred_bar'])

    plt.xlim([24.,48.])
    plt.ylim([-10.,100.])
    plt.legend(loc=2, frameon=False, fontsize=12)
    plt.xlabel('latitude $(^{\circ} N)$', fontsize=20)
    plt.ylabel('hypoxic boundary shoaling (m)',
               fontsize=20)
    plt.xticks(np.arange(24,48+4,4),
               np.arange(24,48+4,4), fontsize=20)
    plt.yticks(np.arange(-10,100+10,10),
               np.arange(-10,100+10,10), fontsize=20)

    plt.grid()

    if save_png:
        plt.savefig('figure8.png', bbox_inches='tight')
    if save_eps:
        plt.savefig('figure8.eps', bbox_inches='tight')
```

In [22]: `make_plot_shoaling_hypoxic_bdry_map(datadir)`

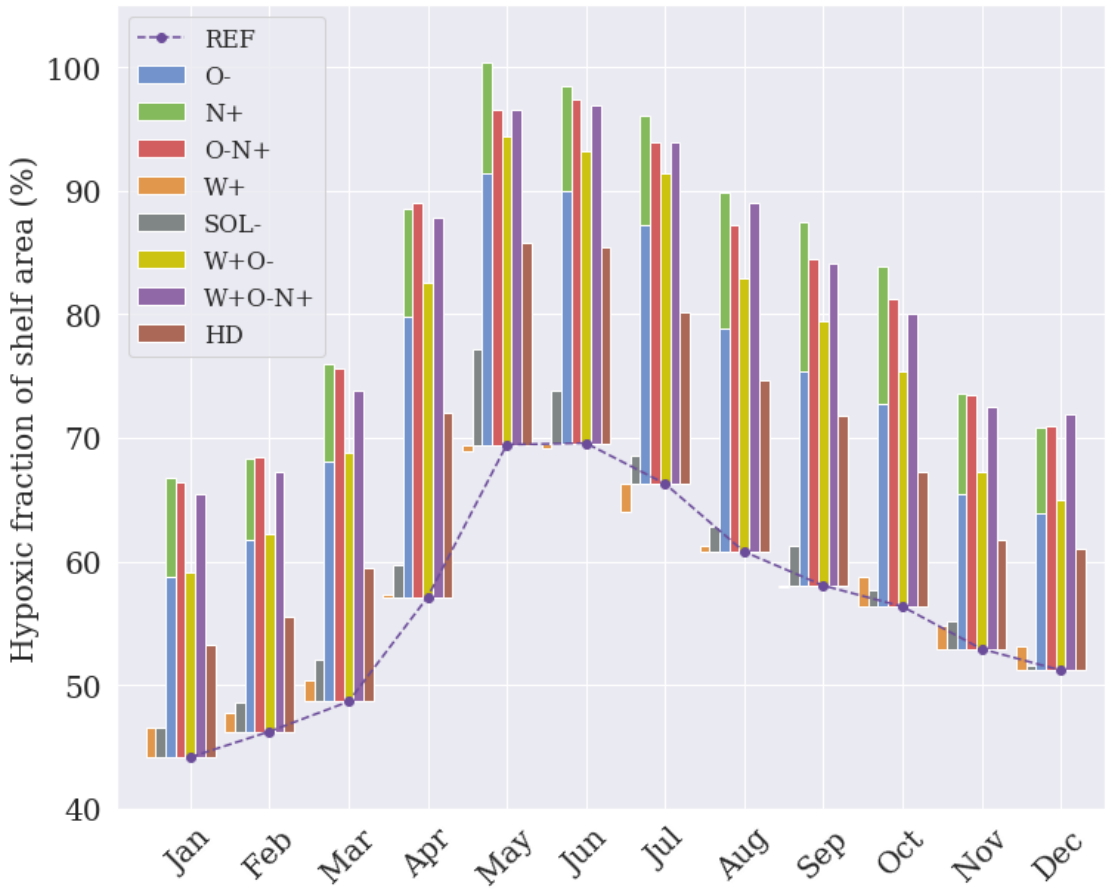


1.11 Figure 9: Hypoxia on the shelf

```
In [23]: def make_plot_hypoxic_area_pctage_shelf(datadir):
             ''' hypoxia on the shelf '''
             # data file needed
             file_hypfrac_ref     = 'hypoxic_pctage_CCS1-RD.NVOcobalt31S_1996-2006.nc'
             file_hypfrac_pertON  = 'hypoxic_pctage_CCS1-RD.FCcobalt32R_1996-2006.nc'
             file_hypfrac_pertO   = 'hypoxic_pctage_CCS1-RD.FCcobalt33O_1996-2006.nc'
             file_hypfrac_pertN   = 'hypoxic_pctage_CCS1-RD.FCcobalt34N_1996-2006.nc'
             file_hypfrac_pertW   = 'hypoxic_pctage_CCS1-RD.FCcobalt35W_1996-2006.nc'
             file_hypfrac_pertSOL = 'hypoxic_pctage_Tpert_CCS1-RD.NVOcobalt31S_1996-2006.nc'
             file_hypfrac_pertWO  = 'hypoxic_pctage_CCS1-RD.FCcobalt37WO_1996-2006.nc'
             file_hypfrac_pertWON = 'hypoxic_pctage_CCS1-RD.FCcobalt38WON_1996-2006.nc'
             file_hypfrac_pertHD = 'hypoxic_pctage_CCS1-RD.FCcobalt39HD_1996-2006.nc'

             # percentage of shelf hypoxic
             clim_o2_31S = readnc(datadir + file_hypfrac_ref,     'hypoxic_pctage_shelf')
             clim_o2_32R = readnc(datadir + file_hypfrac_pertON,  'hypoxic_pctage_shelf')
             clim_o2_33O = readnc(datadir + file_hypfrac_pertO,   'hypoxic_pctage_shelf')
             clim_o2_34N = readnc(datadir + file_hypfrac_pertN,   'hypoxic_pctage_shelf')
             clim_o2_35W = readnc(datadir + file_hypfrac_pertW,   'hypoxic_pctage_shelf')
             clim_o2_SOL = readnc(datadir + file_hypfrac_pertSOL, 'hypoxic_pctage_shelf')
             clim_o2_37WO= readnc(datadir + file_hypfrac_pertWO,  'hypoxic_pctage_shelf')
             clim_o2_38WON= readnc(datadir + file_hypfrac_pertWON,  'hypoxic_pctage_shelf')
             clim_o2_39HD= readnc(datadir + file_hypfrac_pertHD,  'hypoxic_pctage_shelf')

             time = 2 * np.arange(1,13)

             pc_tot = clim_o2_32R - clim_o2_31S
             pc_o2  = clim_o2_33O - clim_o2_31S
             pc_n   = clim_o2_34N - clim_o2_31S
             pc_w   = clim_o2_35W - clim_o2_31S
             pc_sol = clim_o2_SOL - clim_o2_31S
             pc_wo  = clim_o2_37WO- clim_o2_31S
             pc_won  = clim_o2_38WON- clim_o2_31S
             pc_hd  = clim_o2_39HD- clim_o2_31S

             fig = plt.figure(figsize=[12,10])
             bar_width=0.25
             my_yticks = np.arange(40,100+10,10)

             sns.set_style("darkgrid", {
             "font.family": "serif",
             "font.serif": ["Times", "Palatino", "serif"],
             'grid.linestyle': '-'
             })

             my_colors = define_colors()
```

```
        plt.bar(time+1.5*bar_width, pc_o2, bar_width,
                color=my_colors['my_blue_bar'],
                bottom=clim_o2_31S, label='O-')
        plt.bar(time+1.5*bar_width, pc_n, bar_width,
                color=my_colors['my_green_bar'],
                bottom=clim_o2_31S+pc_o2, label='N+')
        plt.bar(time+2.5*bar_width, pc_tot, bar_width,
                color=my_colors['my_red_bar'],
                bottom=clim_o2_31S, label='O-N+')
        plt.bar(time-0.5*bar_width, pc_w,bar_width,
                color=my_colors['my_orange_bar'],
                bottom=clim_o2_31S, label='W+')
        plt.bar(time+0.5*bar_width, pc_sol, bar_width,
                color=my_colors['my_grey_bar'],
                bottom=clim_o2_31S, label='SOL-')
        plt.bar(time+3.5*bar_width, pc_wo, bar_width,
                color=my_colors['my_yellow_bar'],
                bottom=clim_o2_31S, label='W+O-')
        plt.bar(time+4.5*bar_width, pc_won, bar_width,
                color=my_colors['my_violet_bar'],
                bottom=clim_o2_31S, label='W+O-N+')
        plt.bar(time+5.5*bar_width, pc_hd, bar_width,
                color=my_colors['my_darkred_bar'],
                bottom=clim_o2_31S, label='HD')


        plt.plot(time + 3.5*bar_width, clim_o2_31S,
                 color=my_colors['my_violet'], marker='o',
                 linestyle='--', label='REF')

        plt.legend(loc=2, frameon=True, fontsize=16)
        plt.xticks(time + 3.5*bar_width, months,
                   rotation=45, fontsize=20)
        plt.xlim([1,26])
        plt.ylabel('Hypoxic fraction of shelf area (%)',
                   fontsize=20)
        plt.ylim([40.,105.])
        plt.yticks(my_yticks, my_yticks, fontsize=20)

        if save_png:
            plt.savefig('figure9.png', bbox_inches='tight')
        if save_eps:
            plt.savefig('figure9.eps', bbox_inches='tight')
```

In [24]:
```
make_plot_hypoxic_area_pctage_shelf(datadir)
```


REF
O-
N+
O-N+
W+
SOL-
W+O-
W+O-N+
HD
Hypoxic fraction of shelf area (%)
100
90
80
70
60
50
40
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

1.12 The End