Southern_Ocean_Oxygen_Trends

May 10, 2017

A notebook displaying analysis and results from Southern Ocean observed trends in dissolved oxygen. All data was downloaded from https://cchdo.ucsd.edu on April 10, 12 and May 1, 2017.

In [1]:
```
from IPython.display import HTML

HTML('''<script>
code_show=true;
function code_toggle() {
 if (code_show){
 $('div.input').hide();
 } else {
 $('div.input').show();
 }
 code_show = !code_show
}
$( document ).ready(code_toggle);
</script>
<form action="javascript:code_toggle()"><input type="submit" value="Click here to toggle on/off
```

Out[1]:
```
<IPython.core.display.HTML at 0x104946090>
```

In [2]:
```
# Load Packages and Such
import numpy as np
import pandas as pd
import sys
import gsw
import iris.quickplot as qplt
import matplotlib.pyplot as plt
from scipy.interpolate import griddata
sys.path.append('/RESEARCH/paper_ocean_heat_carbon/code/python')
import colormaps as cmaps
import numpy.ma as ma

sys.path.append('/RESEARCH/chapter3/functions')
from o2sat import o2sat


%matplotlib inline
```

In [7]:
```
## Define Functions used in Analysis
def load_data(fname, path, header_no, variables, new_names, lon_lims):
    # Load Data
    data = pd.read_csv(path+fname, header = header_no, na_values='-999.000')
```

```python
    # Isolate Desired Variables
    var = data[variables].copy()

    # Rename variables if desired
    var.columns = new_names

    # Drop data that is flagged
    var = var[var.oxygen_flag!=5]
    var = var[var.oxygen_flag!=9]

    # Drop row with units
    var = var.drop(data.index[[0]])


    var = var[var.longitude<=lon_lims[0]]
    var = var[var.longitude>=lon_lims[1]]

    return var

def retrieve_old_grid(frame):
    depi = frame.press.values
    lati = frame.latitude.values
    old_grid = (lati.flatten(), depi.flatten())

    return old_grid

def regrid(frame, old_grid, new_grid):
    o2_grid   = griddata(old_grid, frame.oxygen.values.flatten(), new_grid,
                      method='linear')

    aou_grid   = griddata(old_grid, frame.aou.values.flatten(), new_grid,
                      method='linear')

    sigma_grid   = griddata(old_grid, frame.sigma.values.flatten(), new_grid,
                      method='linear')
    return o2_grid, aou_grid, sigma_grid
```

0.1 Aim:

Examine if the observed change in oxygen over the observational period is consistent with the ventilation changes documented by Waugh et al., 2013.

Use the GFDL ESM2Mc to establish the relationship between ideal age and oxygen in the Southern Ocean. Using the age changes found in Waugh et al., 2013, determine if the observed change in oxygen is consistent with the changes in circulation. Expectation that in SAMW where the age decreases, oxygen concentration will increase. In AABW where age increases, oxygen concentration will decrease.

Figure generated in ipython notebook: Southern Ocean Age-Oxygen Relationship

0.2 Methods:

Calculated the change of both dissolved oxygen and apparent oxygen utilization (AOU) for each repeat hydrography transect in the Southern Ocean. Following figure shows the percent change per decade for both oxygen and AOU for two watermasses: Subantarctic Mode Water (SAMW) and Antarctic bottom Water (AABW). SAMW is defined as the water between latitudes 20S and 50S which lies between isopycnal surfaces 26.6 and 27.0. AABW is defined at the water South of 50S that lies between isopycnal surfaces 27.2 and

27.7.

Apparent Oxygen Utilization is defined as the following:

$$AOU = O_2^{sat} - O_2$$

where O_2 is the measured dissolved oxygen and O_2^{sat} is the calculated oxygen saturation. The oxygen saturation is calculated from the measured salinity and potential temperature following the emperical formulation described in Weiss, 1970.

0.3 Results:

- Found **negative trend** in SAMW oxygen (~3% per decade), except on track P16 which was slightly positive.
- Found **positive trend** in SAMW AOU (~10% per decade).
- Very little change in AABW oxygen or AOU.

This is the opposite response than suggested given the above relationship between age and oxygen and the documented changes in SAMW age.

In [3]:
```
## Create a dictionary of raw data information:
data_dict = {'P16_1991': {'fname': '5_p16s_hy1.csv', 'path': '/RESEARCH/chapter3/data/GO_SHIP/P
             'P16_1992': {'fname': '8_p16a_hy1.csv', 'path': '/RESEARCH/chapter3/data/GO_SHIP/P
             'P16_2005': {'fname': '6_33RR20050106_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/P16/33RR200501/', 'head_no':
             'P16_2015': {'fname': '6_320620140320_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/P16/320620140320/', 'head_no
             'P18_1994': {'fname': '0_31DSCG94_1_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/P18/31DSCG94_1/', 'head_no':
             'P18_2007': {'fname': '6_33RO20071215_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/P18/33RO20071215/', 'head_no
             'P18_2016': {'fname': '33RO20161119.exc.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/P18/33RO20161119/', 'head_no
             'A16_1989': {'fname': '1_a16s_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/A16/318MSAVE5/', 'head_no':1
             'A16_2005': {'fname': '0_a16s_2005a_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/A16/33RO200501/', 'head_no':
             'A16_2014': {'fname': '3_33RO20131223_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/A16/33RO20131223/', 'head_no
             'I08_1994': {'fname': '7_i08s_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/I08/316N145_5/', 'head_no':1
             'I08_2005': {'fname': '6_33RR20070204_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/I08/33RR20070204/', 'head_no
             'I08_2016': {'fname': '4_33RR20160208_hy1.csv',
                          'path': '/RESEARCH/chapter3/data/GO_SHIP/I08/33RR20160208/', 'head_no
             }
```

In [8]:
```
# Load Data
data = {}
for key, info in data_dict.iteritems():
    if key == 'P16_1991' or key =='P16_1992' or key =='P16_2005' or key =='P16_2015':
        YY = [-148, -156]
    elif key == 'P18_1994' or key =='P18_2007' or key=='P18_2016':
        YY = [-100, -105]
    elif key == 'A16_1989' or key =='A16_2005' or key=='A16_2014':
```

```
            YY = [-22, -37]
        elif key == 'I08_1994' or key =='I08_2005' or key=='I08_2016':
            YY = [100, 80]

        data[key] = load_data(info['fname'], info['path'], info['head_no'],
                              ['DATE', 'LATITUDE', 'LONGITUDE', 'CTDPRS', 'OXYGEN', 'OXYGEN_FLAG_W'
                              new_names=['date', 'latitude', 'longitude', 'press', 'oxygen', 'oxyge
                              lon_lims=YY)

    # Join P16 1990s data
    data.update({'P16_1990': pd.concat([data['P16_1991'], data['P16_1992']])})
    del data['P16_1991']
    del data['P16_1992']
```

In [19]:
```
### Water Mass Analysis:
samw = {}
o2_samw_mean = {}
aabw = {}
o2_aabw_mean = {}
o2_aou_samw = {}
o2_aou_aabw = {}

for key, frame in data.iteritems():
    frame['oxygen'] = frame['oxygen'].astype(dtype=float)
    frame['temp'] = frame['temp'].astype(dtype=float)
    frame['salt'] = frame['salt'].astype(dtype=float)

    # Calculate Sigma
    frame['sigma'] = gsw.sigma0(frame.salt, frame.temp)

    # Calculate AOU
    frame['o2_sat'] = o2sat(frame.salt, frame.temp)
    frame['aou'] = frame.o2_sat - frame.oxygen


    samw[key] = frame[(frame["sigma"] >= 26.6) &
                      (frame["sigma"] <= 27.0) &
                      (frame['latitude'] > -50) &
                      (frame['latitude'] <= -20)]
    o2_samw_mean[key] = samw[key]['oxygen'].mean()
    o2_aou_samw[key] = samw[key]['aou'].mean()


    aabw[key] = frame[(frame["sigma"] >= 27.2) &
                      (frame["sigma"] <= 27.7) &
                      (frame['latitude'] > -50)]

    o2_aabw_mean[key] = aabw[key]['oxygen'].mean()
    o2_aou_aabw[key] = aabw[key]['aou'].mean()
```

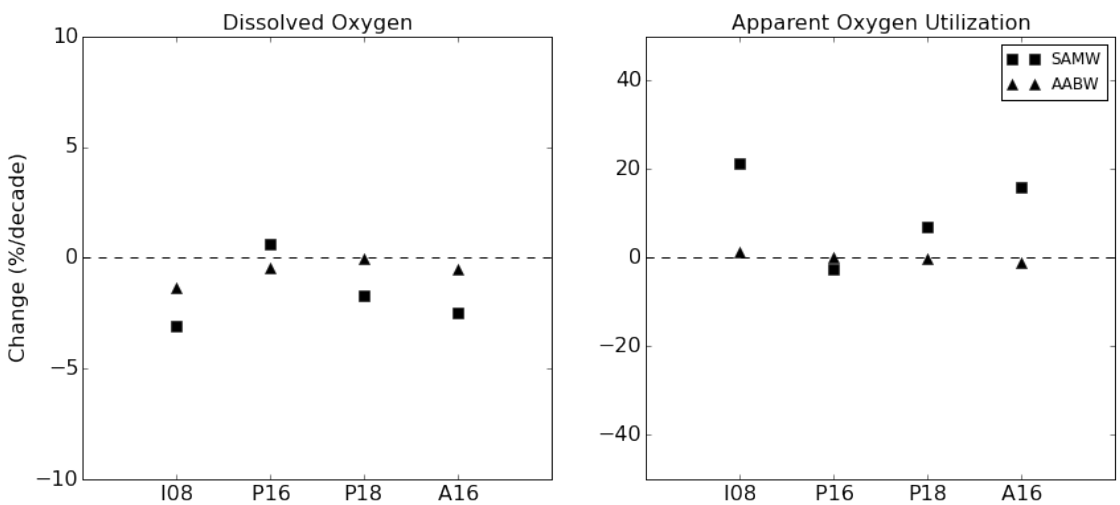
0.3.1 2010s - 1990s:

In [20]:
```
fig = plt.figure(figsize=(14,6))
data_total = [((o2_samw_mean['I08_2016'] - o2_samw_mean['I08_1994'])/o2_samw_mean['I08_1994'])
              ((o2_samw_mean['P16_2015'] - o2_samw_mean['P16_1990'])/o2_samw_mean['P16_1990'])
```

```
               ((o2_samw_mean['P18_2016'] - o2_samw_mean['P18_1994'])/o2_samw_mean['P18_1994']),
               ((o2_samw_mean['A16_2014'] - o2_samw_mean['A16_1989'])/o2_samw_mean['A16_1989']),
               ((o2_aabw_mean['I08_2016'] - o2_aabw_mean['I08_1994'])/o2_aabw_mean['I08_1994']),
               ((o2_aabw_mean['P16_2015'] - o2_aabw_mean['P16_1990'])/o2_aabw_mean['P16_1990']),
               ((o2_aabw_mean['P18_2016'] - o2_aabw_mean['P18_1994'])/o2_aabw_mean['P18_1994']),
               ((o2_aabw_mean['A16_2014'] - o2_aabw_mean['A16_1989'])/o2_aabw_mean['A16_1989']),
               ]

data_1      = [((o2_samw_mean['I08_2005'] - o2_samw_mean['I08_1994'])/o2_samw_mean['I08_1994']),
               ((o2_samw_mean['P16_2005'] - o2_samw_mean['P16_1990'])/o2_samw_mean['P16_1990']),
               ((o2_samw_mean['P18_2007'] - o2_samw_mean['P18_1994'])/o2_samw_mean['P18_1994']),
               ((o2_samw_mean['A16_2005'] - o2_samw_mean['A16_1989'])/o2_samw_mean['A16_1989']),
               ((o2_aabw_mean['I08_2005'] - o2_aabw_mean['I08_1994'])/o2_aabw_mean['I08_1994']),
               ((o2_aabw_mean['P16_2005'] - o2_aabw_mean['P16_1990'])/o2_aabw_mean['P16_1990']),
               ((o2_aabw_mean['P18_2007'] - o2_aabw_mean['P18_1994'])/o2_aabw_mean['P18_1994']),
               ((o2_aabw_mean['A16_2005'] - o2_aabw_mean['A16_1989'])/o2_aabw_mean['A16_1989']),
               ]

data_2       = [((o2_samw_mean['I08_2016'] - o2_samw_mean['I08_2005'])/o2_samw_mean['I08_2005']
               ((o2_samw_mean['P16_2015'] - o2_samw_mean['P16_2005'])/o2_samw_mean['P16_2005']),
               ((o2_samw_mean['P18_2016'] - o2_samw_mean['P18_2007'])/o2_samw_mean['P18_2007']),
               ((o2_samw_mean['A16_2014'] - o2_samw_mean['A16_2005'])/o2_samw_mean['A16_2005']),
               ((o2_aabw_mean['I08_2016'] - o2_aabw_mean['I08_2005'])/o2_aabw_mean['I08_2005']),
               ((o2_aabw_mean['P16_2015'] - o2_aabw_mean['P16_2005'])/o2_aabw_mean['P16_2005']),
               ((o2_aabw_mean['P18_2016'] - o2_aabw_mean['P18_2007'])/o2_aabw_mean['P18_2007']),
               ((o2_aabw_mean['A16_2014'] - o2_aabw_mean['A16_2005'])/o2_aabw_mean['A16_2005']),
               ]

data_aou    = [((o2_aou_samw['I08_2016'] - o2_aou_samw['I08_1994'])/o2_aou_samw['I08_1994'])/2,
               ((o2_aou_samw['P16_2015'] - o2_aou_samw['P16_1990'])/o2_aou_samw['P16_1990'])/2,
               ((o2_aou_samw['P18_2016'] - o2_aou_samw['P18_1994'])/o2_aou_samw['P18_1994'])/2,
               ((o2_aou_samw['A16_2014'] - o2_aou_samw['A16_1989'])/o2_aou_samw['A16_1989'])/2,
               ((o2_aou_aabw['I08_2016'] - o2_aou_aabw['I08_1994'])/o2_aou_aabw['I08_1994'])/2,
               ((o2_aou_aabw['P16_2015'] - o2_aou_aabw['P16_1990'])/o2_aou_aabw['P16_1990'])/2,
               ((o2_aou_aabw['P18_2016'] - o2_aou_aabw['P18_1994'])/o2_aou_aabw['P18_1994'])/2,
               ((o2_aou_aabw['A16_2014'] - o2_aou_aabw['A16_1989'])/o2_aou_aabw['A16_1989'])/2
               ]




N = 5
ind = np.arange(N)
ms=8
space = 0.15
labels = [ ' ','I08 ', 'P16 ', 'P18', 'A16 ']
fs = 16
plt.subplot(1,2,1)
plt.plot(1, data_total[0]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(2, data_total[1]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(3, data_total[2]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(4, data_total[3]*100, marker='s', color='black',markersize=ms,ls='')

plt.plot(1, data_total[4]*100, marker='^', color='black',markersize=ms,ls='')
```

```
plt.plot(2, data_total[5]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(3, data_total[6]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(4, data_total[7]*100, marker='^', color='black',markersize=ms,ls='')


plt.axhline(0, ls = '--', color = 'k')
plt.xticks(ind, labels, fontsize = fs)
plt.yticks(fontsize = 16)
plt.xlim([0, 5])
plt.ylim([-10, 10])
plt.ylabel('Change (%/decade)', fontsize = 16)
plt.title('Dissolved Oxygen', fontsize = 16)



plt.subplot(1,2,2)
plt.title('Apparent Oxygen Utilization', fontsize = 16)
plt.axhline(0, ls = '--', color = 'k')

plt.plot(1, data_aou[0]*100, marker='s', color='black',markersize=ms,ls='', label = 'SAMW')
plt.plot(2, data_aou[1]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(3, data_aou[2]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(4, data_aou[3]*100, marker='s', color='black',markersize=ms,ls='')

plt.plot(1, data_aou[4]*100, marker='^', color='black',markersize=ms,ls='', label = 'AABW')
plt.plot(2, data_aou[5]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(3, data_aou[6]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(4, data_aou[7]*100, marker='^', color='black',markersize=ms,ls='')
plt.axhline(0, ls = '--', color = 'k')
plt.xticks(ind, labels, fontsize = fs)
plt.yticks(fontsize = 16)
plt.xlim([0, 5])
plt.ylim([-50, 50])
plt.legend()
```

Out[20]: <matplotlib.legend.Legend at 0x1120c6110>

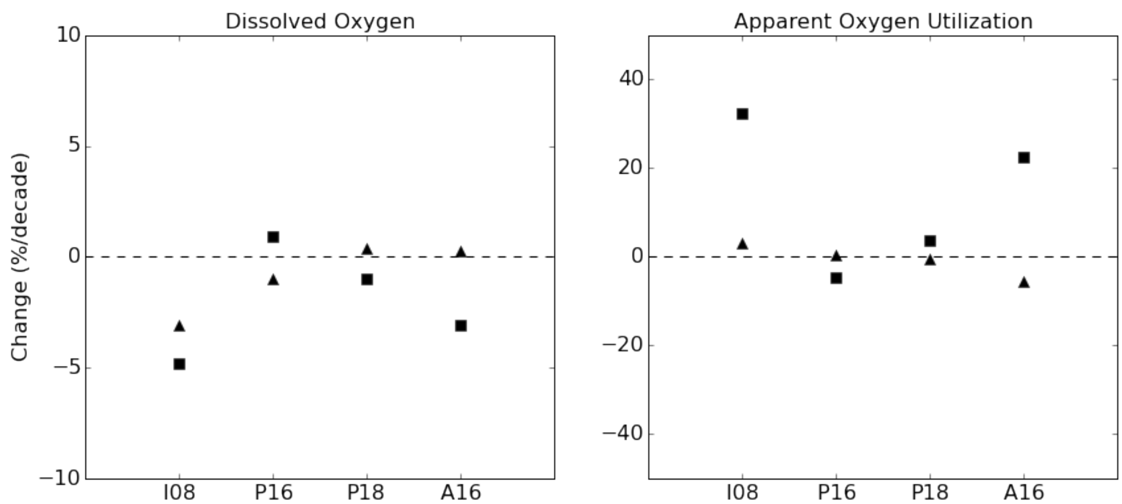


0.3.2 2000s - 1990s:

In [21]:
```
fig = plt.figure(figsize=(14,6))

data_total     = [((o2_samw_mean['I08_2005'] - o2_samw_mean['I08_1994'])/o2_samw_mean['I08_1994
                ((o2_samw_mean['P16_2005'] - o2_samw_mean['P16_1990'])/o2_samw_mean['P16_1990'])
                ((o2_samw_mean['P18_2007'] - o2_samw_mean['P18_1994'])/o2_samw_mean['P18_1994'])
                ((o2_samw_mean['A16_2005'] - o2_samw_mean['A16_1989'])/o2_samw_mean['A16_1989'])
                ((o2_aabw_mean['I08_2005'] - o2_aabw_mean['I08_1994'])/o2_aabw_mean['I08_1994'])
                ((o2_aabw_mean['P16_2005'] - o2_aabw_mean['P16_1990'])/o2_aabw_mean['P16_1990'])
                ((o2_aabw_mean['P18_2007'] - o2_aabw_mean['P18_1994'])/o2_aabw_mean['P18_1994'])
                ((o2_aabw_mean['A16_2005'] - o2_aabw_mean['A16_1989'])/o2_aabw_mean['A16_1989'])
                ]


data_aou   = [((o2_aou_samw['I08_2005'] - o2_aou_samw['I08_1994'])/o2_aou_samw['I08_1994']),
                ((o2_aou_samw['P16_2005'] - o2_aou_samw['P16_1990'])/o2_aou_samw['P16_1990']),
                ((o2_aou_samw['P18_2007'] - o2_aou_samw['P18_1994'])/o2_aou_samw['P18_1994']),
                ((o2_aou_samw['A16_2005'] - o2_aou_samw['A16_1989'])/o2_aou_samw['A16_1989']),
                ((o2_aou_aabw['I08_2005'] - o2_aou_aabw['I08_1994'])/o2_aou_aabw['I08_1994']),
                ((o2_aou_aabw['P16_2005'] - o2_aou_aabw['P16_1990'])/o2_aou_aabw['P16_1990']),
                ((o2_aou_aabw['P18_2007'] - o2_aou_aabw['P18_1994'])/o2_aou_aabw['P18_1994']),
                ((o2_aou_aabw['A16_2005'] - o2_aou_aabw['A16_1989'])/o2_aou_aabw['A16_1989'])
                ]




N = 5
ind = np.arange(N)
ms=8
space = 0.15
labels = [ ' ','I08 ', 'P16 ', 'P18', 'A16 ']
fs = 16
plt.subplot(1,2,1)
plt.plot(1, data_total[0]*100, marker='s', color='black',markersize=ms,ls='', label = 'SAMW')
plt.plot(2, data_total[1]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(3, data_total[2]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(4, data_total[3]*100, marker='s', color='black',markersize=ms,ls='')

plt.plot(1, data_total[4]*100, marker='^', color='black',markersize=ms,ls='', label = 'AABW')
plt.plot(2, data_total[5]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(3, data_total[6]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(4, data_total[7]*100, marker='^', color='black',markersize=ms,ls='')

plt.axhline(0, ls = '--', color = 'k')
plt.xticks(ind, labels, fontsize = fs)
plt.yticks(fontsize = 16)
plt.xlim([0, 5])
plt.ylim([-10, 10])
plt.ylabel('Change (%/decade)', fontsize = 16)
plt.title('Dissolved Oxygen', fontsize = 16)
```

```
plt.subplot(1,2,2)
plt.title('Apparent Oxygen Utilization', fontsize = 16)
plt.axhline(0, ls = '--', color = 'k')

plt.plot(1, data_aou[0]*100, marker='s', color='black',markersize=ms,ls='', label = 'SAMW')
plt.plot(2, data_aou[1]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(3, data_aou[2]*100, marker='s', color='black',markersize=ms,ls='')
plt.plot(4, data_aou[3]*100, marker='s', color='black',markersize=ms,ls='')

plt.plot(1, data_aou[4]*100, marker='^', color='black',markersize=ms,ls='', label = 'AABW')
plt.plot(2, data_aou[5]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(3, data_aou[6]*100, marker='^', color='black',markersize=ms,ls='')
plt.plot(4, data_aou[7]*100, marker='^', color='black',markersize=ms,ls='')
plt.axhline(0, ls = '--', color = 'k')
plt.xticks(ind, labels, fontsize = fs)
plt.yticks(fontsize = 16)
plt.xlim([0, 5])
plt.ylim([-50, 50])
```

```
Out[21]: (-50, 50)
```



0.4 Supplementary Information

Figures showing the oxygen concentration along each ship line for each year of data used as well as the change in oxygen concentration for each decade and the entire time frame.

Observational data is linearly regridded to a 1° latitude × 100 dbars depth grid for following figures.

```
In [22]: # New Grid
         lat = np.arange(-72.,-16.,1)
         depth = np.arange(0,5000,100)
         XI, YI = np.meshgrid(lat,depth)
         new_grid = (XI, YI)
```

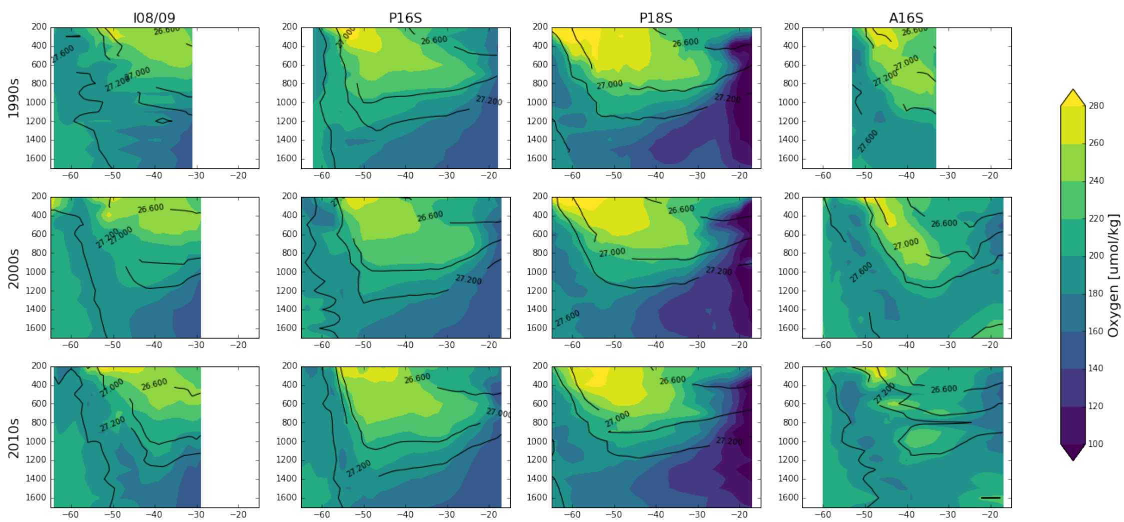
```
# Regrid:
o2_regrid = {}
sigma = {}
o2_aou = {}
for key, frame in data.iteritems():
    old_grid = retrieve_old_grid(frame)

    o2_regrid[key], o2_aou[key], sigma[key] = regrid(frame, old_grid, new_grid)
```

0.4.1 Dissolved Oxygen:

In [23]:
```
clevs = np.arange(100,300,20)

fig = plt.figure(figsize=(20,10))
ax1 = plt.subplot(3, 4, 1)
ax1.contourf(XI, YI, o2_regrid['I08_1994'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['I08_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax1.invert_yaxis()
ax1.set_title('I08/09', fontsize = 16)
ax1.set_ylabel('1990s', fontsize = 16)


ax2 = plt.subplot(3, 4, 2)
ax2.contourf(XI, YI, o2_regrid['P16_1990'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P16_1990'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax2.invert_yaxis()
ax2.set_title('P16S', fontsize = 16)

ax3 = plt.subplot(3, 4, 3)
ax3.contourf(XI, YI, o2_regrid['P18_1994'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P18_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax3.invert_yaxis()
ax3.set_title('P18S', fontsize = 16)

ax4 = plt.subplot(3, 4, 4)
ax4.contourf(XI, YI, o2_regrid['A16_1989'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['A16_1989'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax4.invert_yaxis()
ax4.set_title('A16S', fontsize = 16)
```

```
ax5 = plt.subplot(3, 4, 5)
ax5.contourf(XI, YI, o2_regrid['I08_2005'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['I08_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax5.invert_yaxis()
ax5.set_ylabel('2000s', fontsize = 16)



ax6 = plt.subplot(3, 4, 6)
ax6.contourf(XI, YI, o2_regrid['P16_2005'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax6.invert_yaxis()

ax7 = plt.subplot(3, 4, 7)
ax7.contourf(XI, YI, o2_regrid['P18_2007'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P18_2007'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax7.invert_yaxis()

ax8 = plt.subplot(3, 4, 8)
ax8.contourf(XI, YI, o2_regrid['A16_2005'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['A16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax8.invert_yaxis()

ax9 = plt.subplot(3, 4, 9)
ax9.contourf(XI, YI, o2_regrid['I08_2016'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['I08_2016'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax9.invert_yaxis()
ax9.set_ylabel('2010s', fontsize = 16)

ax10 = plt.subplot(3, 4, 10)
ax10.contourf(XI, YI, o2_regrid['P16_2015'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P16_2015'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax10.invert_yaxis()

ax11 = plt.subplot(3, 4, 11)
ax11.contourf(XI, YI, o2_regrid['P18_2016'], clevs, cmap = cmaps.viridis, extend = 'both')
```

```
CS = plt.contour(XI, YI, sigma['P18_2016'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax11.invert_yaxis()

ax12 = plt.subplot(3, 4, 12)
im = ax12.contourf(XI, YI, o2_regrid['A16_2014'], clevs, cmap = cmaps.viridis, extend = 'both'
CS = plt.contour(XI, YI, sigma['A16_2014'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax12.invert_yaxis()

cbaxes = fig.add_axes([0.94, 0.2, 0.02, 0.6])
cb = plt.colorbar(im, cax = cbaxes)
cb.set_label('Oxygen [umol/kg]', fontsize = 16)
```

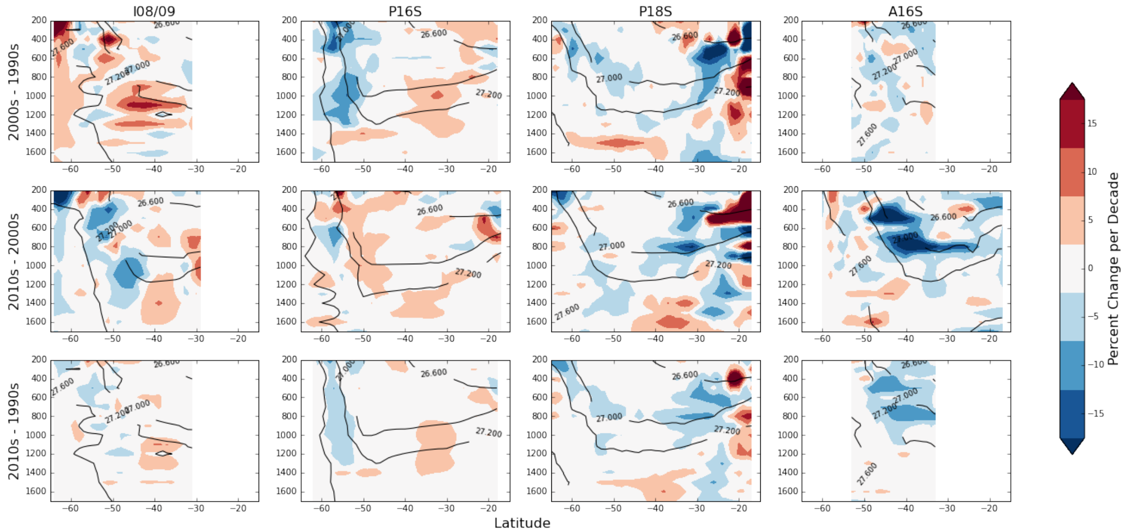


Change in Oxygen for Entire Time Frame and Each Decade (expressed as a percent change per decade)

```
In [24]: clevs = np.arange(-17.5,22.5,5)
         CMAP = 'RdBu_r'

         fig = plt.figure(figsize=(20,10))
         ax1 = plt.subplot(3, 4, 1)
         ax1.contourf(XI, YI, ((o2_regrid['I08_2005'] - o2_regrid['I08_1994'])/o2_regrid['I08_1994'])*1
         CS = plt.contour(XI, YI, sigma['I08_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
         plt.clabel(CS, fontsize=9, inline=1)
         plt.ylim([200, 1700])
         plt.xlim([-65, -15])
         ax1.invert_yaxis()
         ax1.set_title('I08/09', fontsize = 16)
         ax1.set_ylabel('2000s - 1990s', fontsize = 16)
```

```
ax2 = plt.subplot(3, 4, 2)
ax2.contourf(XI, YI, ((o2_regrid['P16_2005'] - o2_regrid['P16_1990'])/o2_regrid['P16_1990'])*10
CS = plt.contour(XI, YI, sigma['P16_1990'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax2.invert_yaxis()
ax2.set_title('P16S', fontsize = 16)

ax3 = plt.subplot(3, 4, 3)
ax3.contourf(XI, YI, ((o2_regrid['P18_2007'] - o2_regrid['P18_1994'])/o2_regrid['P18_1994'])*10
CS = plt.contour(XI, YI, sigma['P18_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax3.invert_yaxis()
ax3.set_title('P18S', fontsize = 16)

ax4 = plt.subplot(3, 4, 4)
ax4.contourf(XI, YI, ((o2_regrid['A16_2005'] - o2_regrid['A16_1989'])/o2_regrid['A16_1989'])*10
CS = plt.contour(XI, YI, sigma['A16_1989'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax4.invert_yaxis()
ax4.set_title('A16S', fontsize = 16)

ax5 = plt.subplot(3, 4, 5)
ax5.contourf(XI, YI, ((o2_regrid['I08_2016'] - o2_regrid['I08_2005'])/o2_regrid['I08_2005'])*10
CS = plt.contour(XI, YI, sigma['I08_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax5.invert_yaxis()
ax5.set_ylabel('2010s - 2000s', fontsize = 16)



ax6 = plt.subplot(3, 4, 6)
ax6.contourf(XI, YI, ((o2_regrid['P16_2015'] - o2_regrid['P16_2005'])/o2_regrid['P16_2005'])*10
CS = plt.contour(XI, YI, sigma['P16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax6.invert_yaxis()

ax7 = plt.subplot(3, 4, 7)
ax7.contourf(XI, YI, ((o2_regrid['P18_2016']-o2_regrid['P18_2007'])/o2_regrid['P18_2007'])*100
CS = plt.contour(XI, YI, sigma['P18_2007'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
```

```
ax7.invert_yaxis()

ax8 = plt.subplot(3, 4, 8)
ax8.contourf(XI, YI, ((o2_regrid['A16_2014']-o2_regrid['A16_2005'])/o2_regrid['A16_2005'])*100
CS = plt.contour(XI, YI, sigma['A16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax8.invert_yaxis()

ax9 = plt.subplot(3, 4, 9)
ax9.contourf(XI, YI, ((o2_regrid['I08_2016']-o2_regrid['I08_1994'])/o2_regrid['I08_1994'])*50,
CS = plt.contour(XI, YI, sigma['I08_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax9.invert_yaxis()
ax9.set_ylabel('2010s - 1990s', fontsize = 16)

ax10 = plt.subplot(3, 4, 10)
ax10.contourf(XI, YI, ((o2_regrid['P16_2015']-o2_regrid['P16_1990'])/o2_regrid['P16_1990'])*50
CS = plt.contour(XI, YI, sigma['P16_1990'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax10.invert_yaxis()
ax10.set_xlabel('                                                  Latitude', fontsize = 16)

ax11 = plt.subplot(3, 4, 11)
ax11.contourf(XI, YI, ((o2_regrid['P18_2016']-o2_regrid['P18_1994'])/o2_regrid['P18_1994'])*50
CS = plt.contour(XI, YI, sigma['P18_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax11.invert_yaxis()

ax12 = plt.subplot(3, 4, 12)
im=ax12.contourf(XI, YI, ((o2_regrid['A16_2014']-o2_regrid['A16_1989'])/o2_regrid['A16_1989'])
CS = plt.contour(XI, YI, sigma['A16_1989'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax12.invert_yaxis()

cbaxes = fig.add_axes([0.94, 0.2, 0.02, 0.6])
cb = plt.colorbar(im, cax = cbaxes, ticks=[ -15, -10, -5, 0, 5, 10, 15])
cb.set_label('Percent Change per Decade', fontsize = 16)
```

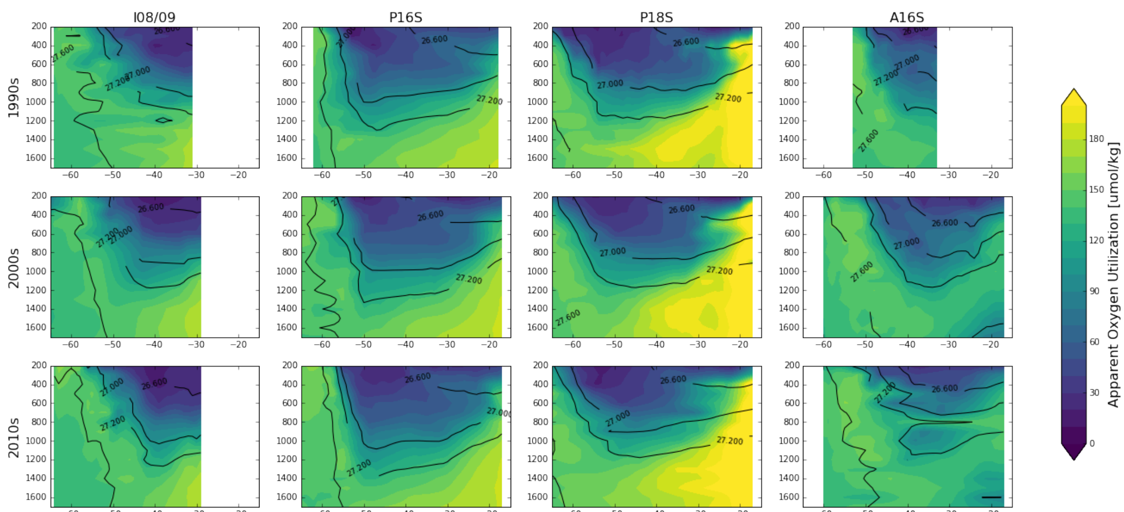


0.4.2 Apparent Oxygen Utilization:

In [27]:
```
clevs = np.arange(0,210,10)

fig = plt.figure(figsize=(20,10))
ax1 = plt.subplot(3, 4, 1)
ax1.contourf(XI, YI, o2_aou['I08_1994'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['I08_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax1.invert_yaxis()
ax1.set_title('I08/09', fontsize = 16)
ax1.set_ylabel('1990s', fontsize = 16)


ax2 = plt.subplot(3, 4, 2)
ax2.contourf(XI, YI, o2_aou['P16_1990'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P16_1990'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax2.invert_yaxis()
ax2.set_title('P16S', fontsize = 16)

ax3 = plt.subplot(3, 4, 3)
ax3.contourf(XI, YI, o2_aou['P18_1994'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P18_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax3.invert_yaxis()
ax3.set_title('P18S', fontsize = 16)
```

```
ax4 = plt.subplot(3, 4, 4)
ax4.contourf(XI, YI, o2_aou['A16_1989'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['A16_1989'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax4.invert_yaxis()
ax4.set_title('A16S', fontsize = 16)

ax5 = plt.subplot(3, 4, 5)
ax5.contourf(XI, YI, o2_aou['I08_2005'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['I08_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax5.invert_yaxis()
ax5.set_ylabel('2000s', fontsize = 16)



ax6 = plt.subplot(3, 4, 6)
ax6.contourf(XI, YI, o2_aou['P16_2005'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax6.invert_yaxis()

ax7 = plt.subplot(3, 4, 7)
ax7.contourf(XI, YI, o2_aou['P18_2007'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P18_2007'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax7.invert_yaxis()

ax8 = plt.subplot(3, 4, 8)
ax8.contourf(XI, YI, o2_aou['A16_2005'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['A16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax8.invert_yaxis()

ax9 = plt.subplot(3, 4, 9)
ax9.contourf(XI, YI, o2_aou['I08_2016'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['I08_2016'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax9.invert_yaxis()
ax9.set_ylabel('2010s', fontsize = 16)

ax10 = plt.subplot(3, 4, 10)
```

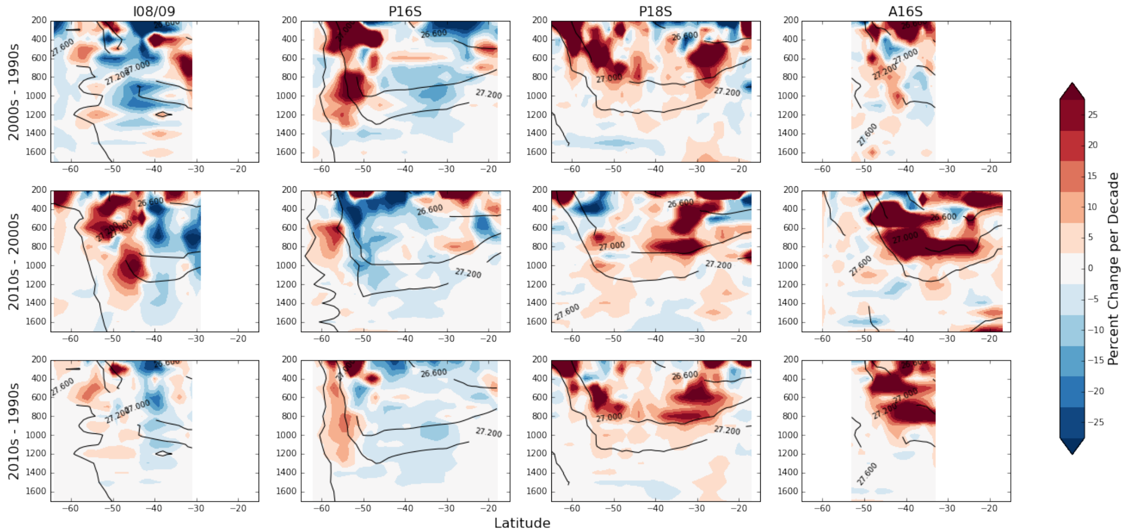
```
ax10.contourf(XI, YI, o2_aou['P16_2015'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P16_2015'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax10.invert_yaxis()

ax11 = plt.subplot(3, 4, 11)
ax11.contourf(XI, YI, o2_aou['P18_2016'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['P18_2016'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax11.invert_yaxis()

ax12 = plt.subplot(3, 4, 12)
im = ax12.contourf(XI, YI, o2_aou['A16_2014'], clevs, cmap = cmaps.viridis, extend = 'both')
CS = plt.contour(XI, YI, sigma['A16_2014'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax12.invert_yaxis()

cbaxes = fig.add_axes([0.94, 0.2, 0.02, 0.6])
cb = plt.colorbar(im, cax = cbaxes)
cb.set_label('Apparent Oxygen Utilization [umol/kg]', fontsize = 16)
```



In [26]:
```
clevs = np.arange(-27.5,32.5,5)
CMAP = 'RdBu_r'

fig = plt.figure(figsize=(20,10))
ax1 = plt.subplot(3, 4, 1)
ax1.contourf(XI, YI, ((o2_aou['I08_2005'] - o2_aou['I08_1994'])/o2_aou['I08_1994'])*100, clevs
CS = plt.contour(XI, YI, sigma['I08_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
```

```
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax1.invert_yaxis()
ax1.set_title('I08/09', fontsize = 16)
ax1.set_ylabel('2000s - 1990s', fontsize = 16)


ax2 = plt.subplot(3, 4, 2)
ax2.contourf(XI, YI, ((o2_aou['P16_2005'] - o2_aou['P16_1990'])/o2_aou['P16_1990'])*100, clevs
CS = plt.contour(XI, YI, sigma['P16_1990'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax2.invert_yaxis()
ax2.set_title('P16S', fontsize = 16)

ax3 = plt.subplot(3, 4, 3)
ax3.contourf(XI, YI, ((o2_aou['P18_2007'] - o2_aou['P18_1994'])/o2_aou['P18_1994'])*100, clevs
CS = plt.contour(XI, YI, sigma['P18_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax3.invert_yaxis()
ax3.set_title('P18S', fontsize = 16)

ax4 = plt.subplot(3, 4, 4)
ax4.contourf(XI, YI, ((o2_aou['A16_2005'] - o2_aou['A16_1989'])/o2_aou['A16_1989'])*100, clevs
CS = plt.contour(XI, YI, sigma['A16_1989'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax4.invert_yaxis()
ax4.set_title('A16S', fontsize = 16)

ax5 = plt.subplot(3, 4, 5)
ax5.contourf(XI, YI, ((o2_aou['I08_2016'] - o2_aou['I08_2005'])/o2_aou['I08_2005'])*100, clevs
CS = plt.contour(XI, YI, sigma['I08_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax5.invert_yaxis()
ax5.set_ylabel('2010s - 2000s', fontsize = 16)



ax6 = plt.subplot(3, 4, 6)
ax6.contourf(XI, YI, ((o2_aou['P16_2015'] - o2_aou['P16_2005'])/o2_aou['P16_2005'])*100, clevs
CS = plt.contour(XI, YI, sigma['P16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax6.invert_yaxis()
```

```
ax7 = plt.subplot(3, 4, 7)
ax7.contourf(XI, YI, ((o2_aou['P18_2016']-o2_aou['P18_2007'])/o2_aou['P18_2007'])*100, clevs, c
CS = plt.contour(XI, YI, sigma['P18_2007'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax7.invert_yaxis()

ax8 = plt.subplot(3, 4, 8)
ax8.contourf(XI, YI, ((o2_aou['A16_2014']-o2_aou['A16_2005'])/o2_aou['A16_2005'])*100, clevs, c
CS = plt.contour(XI, YI, sigma['A16_2005'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax8.invert_yaxis()

ax9 = plt.subplot(3, 4, 9)
ax9.contourf(XI, YI, ((o2_aou['I08_2016']-o2_aou['I08_1994'])/o2_aou['I08_1994'])*50, clevs, cm
CS = plt.contour(XI, YI, sigma['I08_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax9.invert_yaxis()
ax9.set_ylabel('2010s - 1990s', fontsize = 16)

ax10 = plt.subplot(3, 4, 10)
ax10.contourf(XI, YI, ((o2_aou['P16_2015']-o2_aou['P16_1990'])/o2_aou['P16_1990'])*50, clevs, c
CS = plt.contour(XI, YI, sigma['P16_1990'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax10.invert_yaxis()
ax10.set_xlabel('                                                   Latitude', fontsize = 16)

ax11 = plt.subplot(3, 4, 11)
ax11.contourf(XI, YI, ((o2_aou['P18_2016']-o2_aou['P18_1994'])/o2_aou['P18_1994'])*50, clevs, c
CS = plt.contour(XI, YI, sigma['P18_1994'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax11.invert_yaxis()

ax12 = plt.subplot(3, 4, 12)
im=ax12.contourf(XI, YI, ((o2_aou['A16_2014']-o2_aou['A16_1989'])/o2_aou['A16_1989'])*50, clevs
CS = plt.contour(XI, YI, sigma['A16_1989'], colors = 'k', levels=[26.6, 27.0, 27.2, 27.6])
plt.clabel(CS, fontsize=9, inline=1)
plt.ylim([200, 1700])
plt.xlim([-65, -15])
ax12.invert_yaxis()

cbaxes = fig.add_axes([0.94, 0.2, 0.02, 0.6])
cb = plt.colorbar(im, cax = cbaxes, ticks=[-25, -20, -15, -10, -5, 0, 5, 10, 15, 20, 25])
cb.set_label('Percent Change per Decade', fontsize = 16)
```


I08/09
P16S
P18S
A16S
2000s - 1990s
2010s - 2000s
2010s - 1990s
Latitude
Percent Change per Decade

In [ ]: