Warming Arctic and associated change in DMS emission.

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Abstract

The Arctic sea ice extent is shrinking due to global warming. The reduction in sea ice thickness as well as cover has led to enhanced solar insolation at the sea surface which promotes increased net primary production (NPP). Being linked to NPP, Dimethyl Sulphide emission is also increasing. But the changes are not evenly distributed. Some regions are changing more than the others. In this study we have tried to understand the linkage between the warming Arctic and DMS emissions in the different regions. We see that Barent, Greenland and Chuchuki seas are warming more rapidly, therefore NPP and DMS production have also increased more over these regions but there is a decrease in Autumn despite positive trend in SST and sea ice retreat. Central arctic is also producing more DMS, surprisingly also during Autumn.

1. Introduction

The oceans play a significant role in global carbon budgets via photosynthesis. Approximately half of all global net annual photosynthesis occurs in the oceans, with ~10-15% of production occurring on the continental shelves alone (Müller-Karger et al. 2005). Phytoplankton are one of the major contributors to the primary production in the oceans and form the base of the entire food web. Primary productivity is strongly dependent upon light availability and the presence of nutrients, and thus vary significantly from one region to other. Over the tropical region, where amount of sunlight is fairly constant throughout the year, phytoplankton concentration doesn't vary much, while in the Arctic, it varies a lot from season to season due to high variability in the sunshine hours. Overall, the net primary production (NPP) is too low in the Arctic as compared to that in the tropics. But due to warming climate, the Arctic is changing and is warming nearly 4 times faster than the globe (Isaksen, K., et al. 2022, Rantanen et al. 2022). Sea ice has already started responding to this and shown a steady decline over the past decade. Reduction in the sea ice cover or even thinning can lead to increased amount and duration of solar insolation at the ocean surface. Hence, more solar insolation due to sea ice loss in the Arctic Ocean promotes increased growing season and production of phytoplankton. This has more implications than just having an impact on the carbon budget. Phytoplankton productivity is also closely linked to DMS production in the ocean. Enzymatic decomposition of dimethylsulfonium propionate (DMSP) is the primary source of DMS in seawater with DMSP being released from phytoplankton by a variety of mechanisms. DMS is the most abundant form in which the ocean releases gaseous sulfur. Later on, in the atmosphere, DMS is oxidized to sulfate particles that alter the amount of solar radiation reaching the Earth's surface both by directly scattering solar energy and indirectly by acting as cloud condensation nuclei (CCN), thereby affecting the cloud albedo. In this project, we aim to understand the linkage between changing sea ice cover and DMS production in the Arctic using the historical simulation of Norwegian Earth system model.

2. Data

We have used historical simulations of the second version of the fully coupled Norwegian Earth System Model (NorESM2, specifically NorESM2-LM with 2o resolution for land and atmosphere and 1o for the ocean) which is based on the second version of the Community Earth System Model (CESM2). The period that we focus on is 1950 to 2014 to understand changes with respect to climatology.

3.Methods

3.1 Import pakages

In [2]:
```
import modules as md
import xarray as xr
import cftime
import numpy as np
import s3fs
import warnings
import intake
import matplotlib.pyplot as plt
import cartopy.crs as ccrs
import cartopy.feature as cfeature
%load_ext autoreload
%autoreload 2
warnings.simplefilter('ignore')
xr.set_options(display_style='html')
%matplotlib inline
model= 'NorESM2-LM'  #name of the model, other option that can be put are  C
```

3.2 Calculation of yearly trends for the Arctic region

Here yearly trends of various parameters have been calculated. The parameters are chlorophyll mass concentration, which is a proxy for the phytoplankton productivity in the ocean, Sea surface temperature (SST), Dimethylsulphide (DMS) in sea water and sea ice areal coverage.

In [4]:
```
#.................Chlorophyll.................#
model= 'NorESM2-LM'
var='chlos'
chlos=md.regional_average(model,var)

y=chlos.to_numpy()
x=chlos.year
xx=x.to_numpy()
chlos=[xx,y]

np.savetxt('Data/timeseries/chlos.txt',np.array(chlos))

#..................SST..........................#
var='tos'
tos=md.regional_average(model,var)

y=tos.to_numpy()
x=tos.year
xx=x.to_numpy()
tos=[xx,y]

np.savetxt('Data/timeseries/tos.txt',np.array(tos))

#...................DMS..........................#
model= 'NorESM2-LM'
var='dmsos'
dmsos=md.regional_average(model,var)

y=dmsos.to_numpy()
x=dmsos.year
xx=x.to_numpy()

dmsos=[xx,y]
np.savetxt('Data/timeseries/dmsos.txt',np.array(dmsos))

#.....................Sea Ice...........................#
model= 'NorESM2-LM'
```

```
var='siconc'
siconc=md.regional_average(model,var)

y=siconc.to_numpy()
x=siconc.year
xx=x.to_numpy()

siconc=[xx,y]
np.savetxt('Data/timeseries/siconc.txt',np.array(siconc))
```

```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

100.00% [1/1 00:00<00:00]

```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

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```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

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```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

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```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

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```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

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```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

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3.3 Anomaly for different seasons

Anomalies of different parameters have been calculated for each of the seasons except winter. The reference years are 1950 to 1979. To calculate the anomaly, average of particular parameter between 1980 to 2014 at a particular location is taken and then the climatology is subtracted from it. An example of the calculation is as follows:

In [3]:
```
"Anomaly in chlorophyll mass concentration"
ds_now=md.anomaly_seasonal(model,'chlos')[0] #calculates the average for the
ds_ref=md.anomaly_seasonal(model,'chlos')[1] #calculates the climatology
anm=ds_now-ds_ref  #calculation of anomaly
```

3.4 Calculation of trends

Seasonal trends are calculated using least square fitting method available in the polyfit function of Xarray. The slopes of the linear fit are obtained for each of the grid points. An example is as follows:

In [4]:
```
ds_ls=md.seasonal_avg_timeseries(model,'chlos') #trend calculation for chlor
```

```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

100.00% [1/1 00:00<00:00]

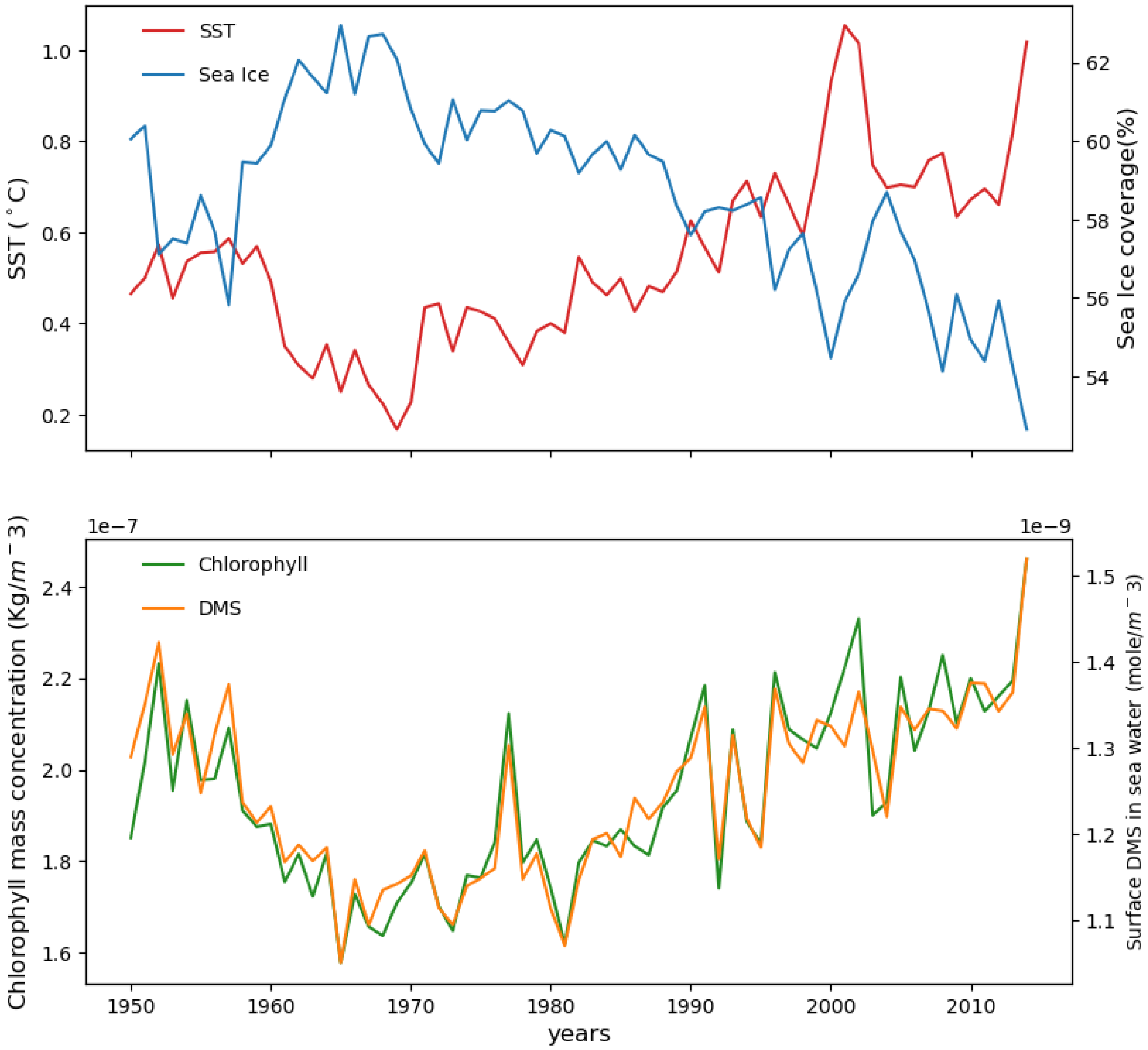
4. Results

4.1 Yearly Trends

Here, the yearly average of the whole Arctic region (above 60 degree north) have been presented. After around 1995, there is a clear increase in SST and decrease in sea ice cover. As net primary production (NPP) is closely linked to the amount of insolation, sea ice reduction has resulted in the enhanced growth of the phytoplanktons. The DMS in the ocean comes from the bacterial decomposition of DMSP released by phytoplanktons. Therefore, DMS is also depicting a rising trend. However, it is not as straightforward as it seems. DMS production can also be affected by factors like salinity and amount of nutrients in the ocean, which can vary over different parts of the arctic region. To have a clearer picture, the anomaly in chlorophyll concentration and DMS have been investigated in the next sections.

In [53]:
```
##............................plot trends for the last 'n' years..........

n=65
chlos= np.loadtxt('Data/timeseries/chlos.txt')
dmsos= np.loadtxt('Data/timeseries/dmsos.txt')
siconc= np.loadtxt('Data/timeseries/siconc.txt')
tos= np.loadtxt('Data/timeseries/tos.txt')

fig,(ax1,ax2)=plt.subplots(2,sharex=True, figsize=(9, 9))

ax1.plot(tos[0][-n:],tos[1][-n:],label='SST',color='tab:red')
ax11=ax1.twinx()
ax11.plot(siconc[0][-n:],siconc[1][-n:],label='Sea Ice',color='tab:blue')
ax1.set_ylabel('SST ($^\circ$C)',fontsize=12)
ax11.set_ylabel('Sea Ice coverage(%)',fontsize=12)



ax2.plot(chlos[0][-n:],chlos[1][-n:],label='Chlorophyll',color='forestgreen'
ax22=ax2.twinx()
ax22.plot(dmsos[0][-n:],dmsos[1][-n:],label='DMS',color='tab:orange')
ax2.set_ylabel('Chlorophyll mass concentration (Kg/$m^-3$)',fontsize=12)
ax22.set_ylabel('Surface DMS in sea water (mole/$m^-3$)')
ax2.set_xlabel('years',fontsize=12)

ax1.legend(loc=(0.05,0.9),frameon=False)
ax11.legend(loc=(0.05,0.8),frameon=False)
ax2.legend(loc=(0.05,0.9),frameon=False)
ax22.legend(loc=(0.05,0.8),frameon=False)
```

Out[53]: <matplotlib.legend.Legend at 0x7fb3245142b0>



4.2 Anomalies in different seasons

4.2.1. SST and Sea Ice

In [8]:
```
##...........................SST.........................##
dsst_now=md.anomaly_seasonal(model,'tos')[0]
dsst_ref=md.anomaly_seasonal(model,'tos')[1]
```

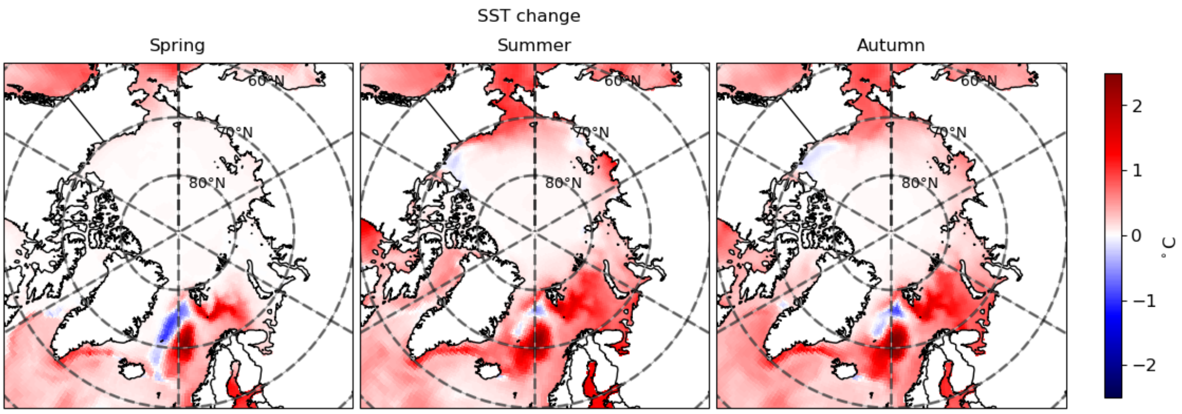
In [9]:
```
##....................Sea Ice coverage....................##
ds_ice_now=md.anomaly_seasonal(model,'siconc')[0]
ds_ice_ref=md.anomaly_seasonal(model,'siconc')[1]
```

In [10]:
```
##....................Anomaly calculation....................##
anm_sst=dsst_now-dsst_ref #SST
anm_ice=ds_ice_now-ds_ice_ref #Sea Ice
```

In [20]:
```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']
seasons=['MAM','JJA','SON']

for i in range (len(axs.flat)):
    cs=anm_sst.tos.sel(season=seasons[i]).plot(ax=axs.flat[i],x='longitude',
```

```
                                 ,transform=ccrs.PlateCarree(), cmap='seismi
    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False

# Adjust the location of the subplots on the page to make room for the color
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs, shrink=0.4, location='right',pad=0.03)
cbar.ax.tick_params(labelsize=12)

cbar.set_label('$^\circ$C',horizontalalignment='right',fontsize=12)
fig.suptitle('SST change',y=0.71,x=0.48)
#plt.savefig('plots/anomaly/SST.png',dpi=500)
```

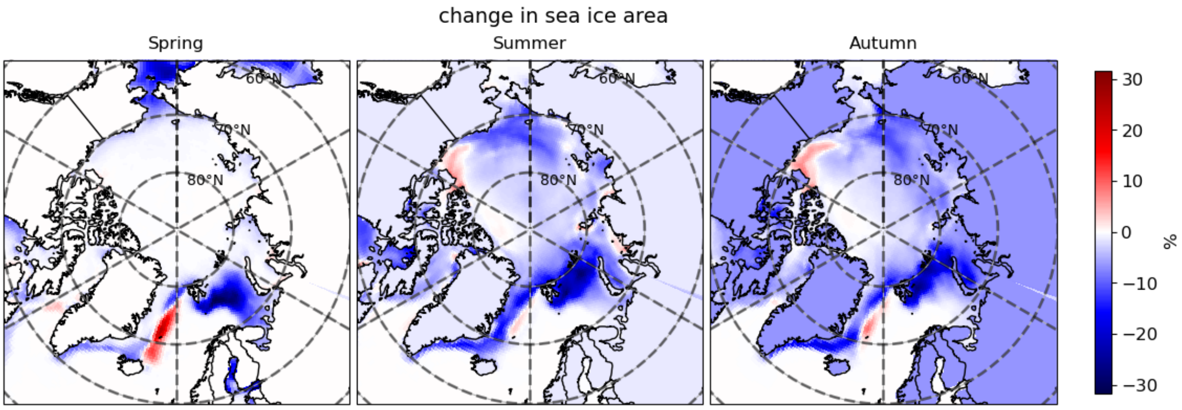
Out[20]: Text(0.48, 0.71, 'SST change')



In the Arctic region, there is significant increase in SST (summer and autumn) over the Greenland sea and the Barent sea while among the two, the later has warmed more. There is a cooling spot emerging between the Greenland sea and the rapidly warming Norwegian sea.

In [13]:
```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']
seasons=['MAM','JJA','SON']

for i in range (len(axs.flat)):
    cs=anm_ice.siconc.sel(season=seasons[i]).plot(ax=axs.flat[i],x='longitud
                                 ,transform=ccrs.PlateCarree(), cmap='seismi
    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    #axs.flat[i].stock_img()
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False

# Adjust the location of the subplots on the page to make room for the color
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs, shrink=0.4, location='right',pad=0.03)
cbar.ax.tick_params(labelsize=12)

cbar.set_label('%',horizontalalignment='right',fontsize=12)
fig.suptitle('change in sea ice area',y=0.71,fontsize=14)
#plt.savefig('plots/anomaly/sea_ice.png',dpi=500)
```

Out[13]: Text(0.5, 0.71, 'change in sea ice area')



The warming sea has influenced sea ice significantly over the Barent sea region which has now lost 10-20% of the sea ice. There is a rise in the sea ice cover over the cooling spot between the Norwegin sea and the Greenland sea, which is more pronounced in the spring. Greenland sea has lost more ice during the summer and Autumn while almost no change in the spring. The effect of global warming has reached upto the central arctic too, but bigger differnces in sea ice and SST are observed mostly in the lower latitude.

4.2.2. chlorophyll and DMS

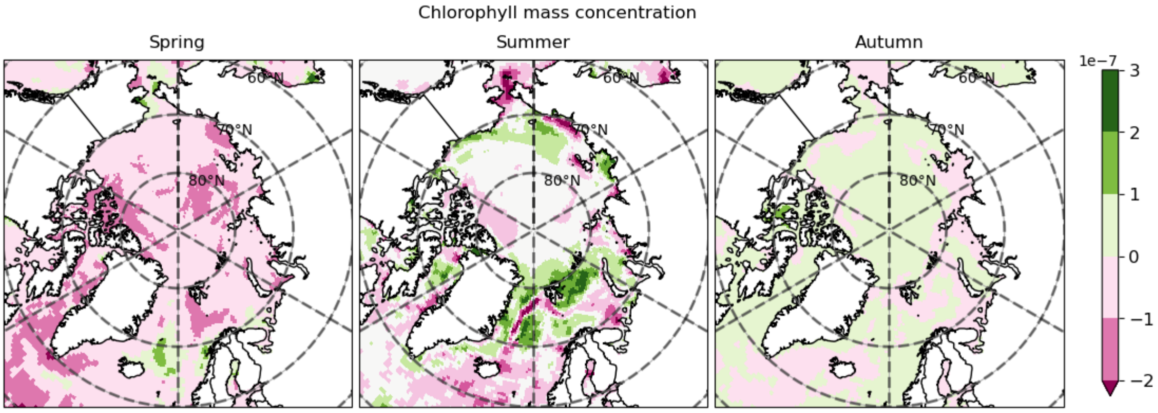
In [14]:
```
##............................Chlorophyll..........................##
ds_chlos_now=md.anomaly_seasonal(model,'chlos')[0]
ds_chlos_ref=md.anomaly_seasonal(model,'chlos')[1]
anm_chlos=ds_chlos_now-ds_chlos_ref  #anomaly chlorophyll
```

In [16]:
```
##............................DMS..........................##
ds_DMS_now=md.anomaly_seasonal(model,'dmsos')[0]
ds_DMS_ref=md.anomaly_seasonal(model,'dmsos')[1]
anm_DMS=ds_DMS_now-ds_DMS_ref #anomaly DMS
```

In [33]:
```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']
seasons=['MAM','JJA','SON']

for i in range (len(axs.flat)):
    cs=anm_chlos.chlos.sel(season=seasons[i]).plot(ax=axs.flat[i],x='longitu
                                   ,transform=ccrs.PlateCarree(), cmap='PiYG',
    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    #axs.flat[i].stock_img()
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False


#ticks=np.arange(-2e-7,+3.5e-7,1e-7)
# Adjust the location of the subplots on the page to make room for the color
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs,shrink=0.4, location='right',pad=0.03)
#cbar.ax.locator_params(nbins=5)
cbar.ax.tick_params(labelsize=12)
```

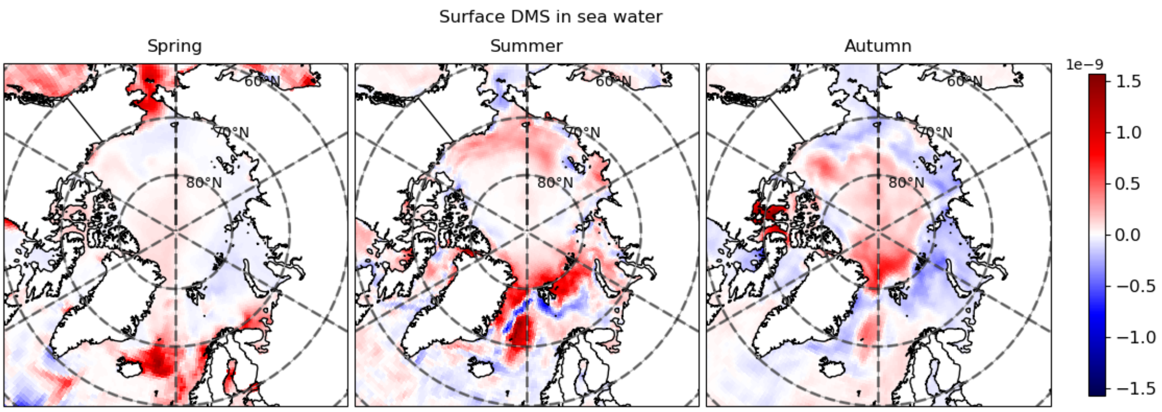
```
cbar.set_label('Kg$m^-3$',horizontalalignment='right',fontsize=12,y=0.55)
fig.suptitle('Chlorophyll mass concentration',y=0.71)

#plt.savefig('plots/anomaly/chlos.png',dpi=500)
```

Out[33]: Text(0.5, 0.71, 'Chlorophyll mass concentration')



In [34]:

```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']
seasons=['MAM','JJA','SON']

for i in range (len(axs.flat)):
    cs=anm_DMS.dmsos.sel(season=seasons[i]).plot(ax=axs.flat[i],x='longitude
                                                 ,transform=ccrs.PlateCarree(), cmap='seismi
    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    #axs.flat[i].stock_img()
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False

# Adjust the location of the subplots on the page to make room for the color
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs, shrink=0.4, location='right',pad=0.03)
cbar.ax.tick_params(labelsize=12)

cbar.set_label('mole $m^-3$',horizontalalignment='right',fontsize=12,y=0.6)
fig.suptitle('Surface DMS in sea water',y=0.71)

plt.savefig('plots/anomaly/DMS.png',dpi=500)
#levels = np.linspace(-2e-7,3e-7,6)
```



Chlorophyll and DMS have increased in the Barent, Greenlad and Chuchuki sea. Barent sea has warmed more and also more primary prodection is happening there. Despite it, DMS anomaly is almost the same as in the greenland sea. This indicate that DMS has a connection to some other factors also. Importantly, there is decrese in chlorophyll and DMS production in the regions where they have increased in the summer (except the Norwegian sea).

4.3. Trends in the Arctic in different seasons

4.3.1 Chlorophyll and DMS

In [ ]:
```
##...................Chlorophyll...................##
ds_ls=md.seasonal_avg_timeseries(model,'chlos')

ds_spring=md.slice_assign(ds_ls[1])
ds_summer=md.slice_assign(ds_ls[2])
ds_autumn=md.slice_assign(ds_ls[3])

ds_chlos=[ds_spring,ds_summer,ds_autumn]
```

```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

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In [22]:
```
##.................DMS.............................##
dms_ls=md.seasonal_avg_timeseries(model,'dmsos')

dms_spring=md.slice_assign(dms_ls[1])
dms_summer=md.slice_assign(dms_ls[2])
dms_autumn=md.slice_assign(dms_ls[3])

dms=[dms_spring,dms_summer,dms_autumn]
```

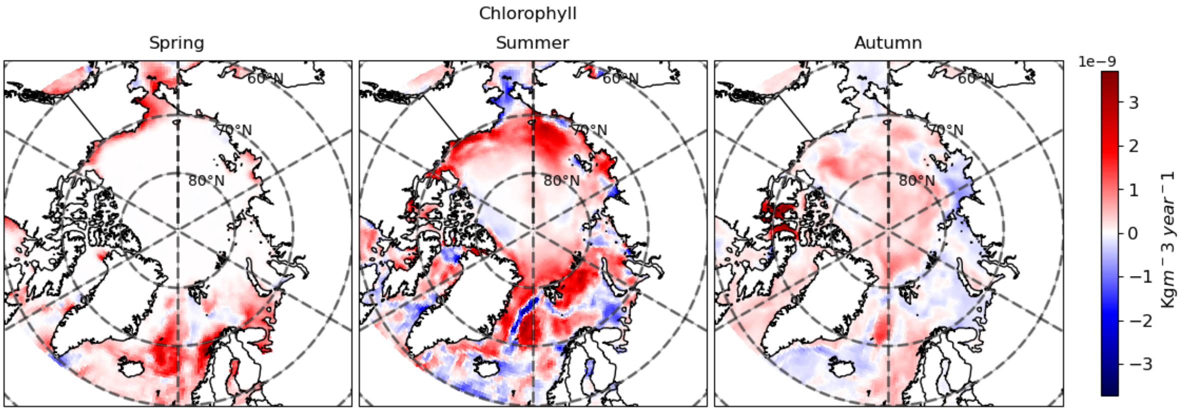
```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

100.00% [1/1 00:00<00:00]

In [121…
```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']

for i in range (len(axs.flat)):
    cs=ds[i].chlos_polyfit_coefficients[0].plot(ax=axs.flat[i],x='longitude'
                              ,transform=ccrs.PlateCarree(), cmap='seismi

    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False


# Adjust the location of the subplots on the page to make room for the color
```

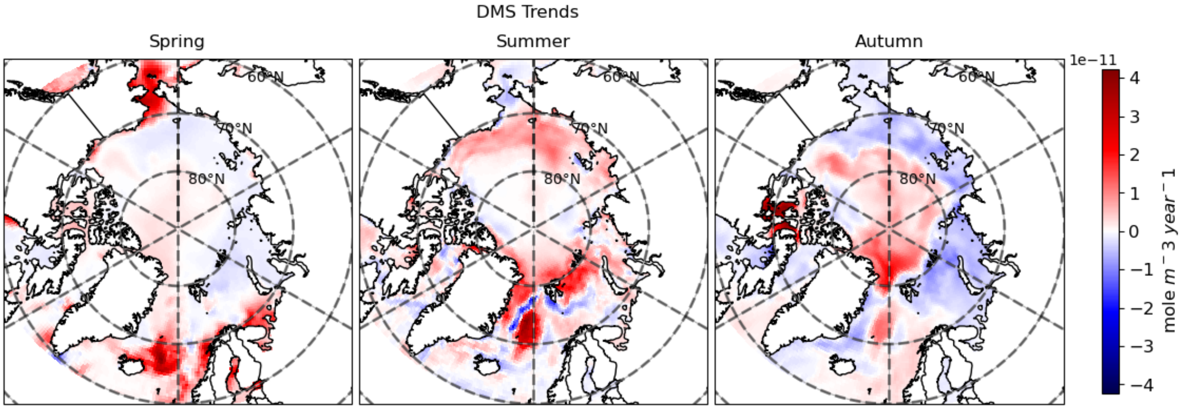
```
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs, shrink=0.4, location='right',pad=0.03)
cbar.ax.tick_params(labelsize=12)

cbar.set_label('Kg$m^-3$ $year^-1$',horizontalalignment='right',fontsize=12,
fig.suptitle('Chlorophyll',y=0.71,x=0.48)

plt.savefig('plots/Trend/SST.png',dpi=500)
```

Out[121]: Text(0.48, 0.71, 'Chlorophyll')



In [145…

```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']

for i in range (len(axs.flat)):
    cs=dms[i].dmsos_polyfit_coefficients[0].plot(ax=axs.flat[i],x='longitude
                                          ,transform=ccrs.PlateCarree(), cmap='seismi

    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False


# Adjust the location of the subplots on the page to make room for the color
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs, shrink=0.4, location='right',pad=0.03)
cbar.ax.tick_params(labelsize=12)

cbar.set_label('mole $m^-3$ $year^-1$',horizontalalignment='right',fontsize=
fig.suptitle('DMS Trends',y=0.71,x=0.48)

plt.savefig('plots/Trend/DMS.png',dpi=500)
```



4.3.2 SST and Sea ice

In [23]:
```
dsst_ls=md.seasonal_avg_timeseries(model,'tos')

dsst_spring=md.slice_assign(dsst_ls[1])
dsst_summer=md.slice_assign(dsst_ls[2])
dsst_autumn=md.slice_assign(dsst_ls[3])

dsst=[dsst_spring,dsst_summer,dsst_autumn]
```

```
--> The keys in the returned dictionary of datasets are constructed as follo
ws:
        'activity_id.institution_id.source_id.experiment_id.table_id.grid_la
bel'
```

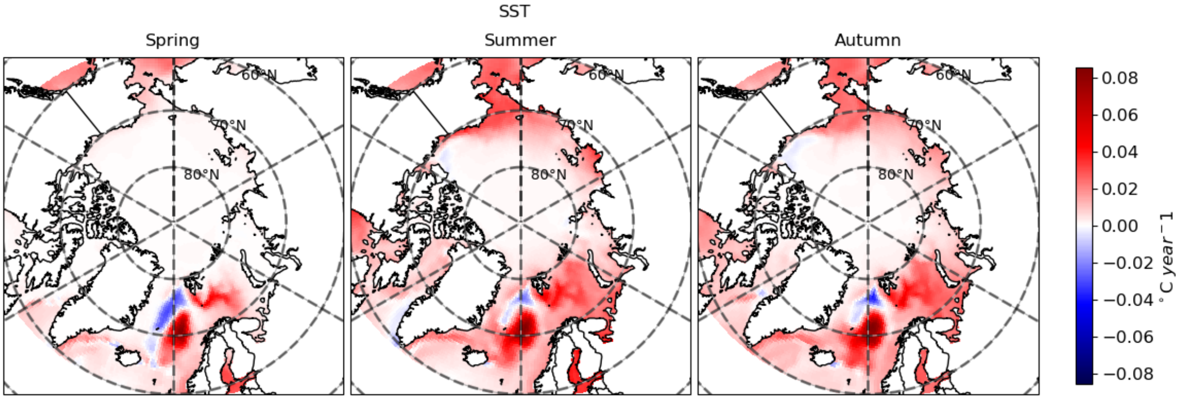
100.00% [1/1 00:00<00:00]

In [28]:
```
dice_ls=md.seasonal_avg_timeseries(model,'siconc')
dice_spring=md.slice_assign(dice_ls[1])
dice_summer=md.slice_assign(dice_ls[2])
dice_autumn=md.slice_assign(dice_ls[3])

dice=[dice_spring,dice_summer,dice_autumn]
```

In [38]:
```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']

for i in range (len(axs.flat)):
    cs=dsst[i].tos_polyfit_coefficients[0].plot(ax=axs.flat[i],x='longitude'
                                  ,transform=ccrs.PlateCarree(), cmap='seismi

    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False


# Adjust the location of the subplots on the page to make room for the color
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs, shrink=0.4, location='right',pad=0.03)
cbar.ax.tick_params(labelsize=12)
```

```
cbar.set_label(' $^\circ$C $year^-1$',horizontalalignment='right',fontsize=1
fig.suptitle('SST',y=0.71,x=0.48)
```

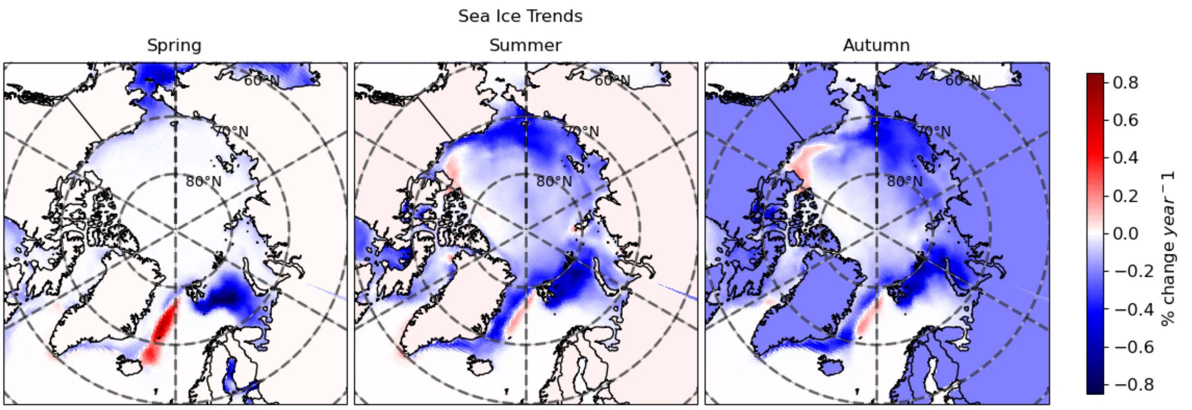
Out[38]: Text(0.48, 0.71, 'SST')



In [39]:

```
fig, axs = plt.subplots(1, 3,figsize=(14, 10),subplot_kw={'projection': ccrs

titles=['Spring','Summer','Autumn']
seasons=['MAM','JJA','SON']

for i in range (len(axs.flat)):
    cs=dice[i].siconc_polyfit_coefficients[0].plot(ax=axs.flat[i],x='longitu
                                        ,transform=ccrs.PlateCarree(), cmap='seismi

    axs.flat[i].set_extent([0, 360, 60, 90], crs=ccrs.PlateCarree())
    axs.flat[i].add_feature(cfeature.BORDERS)
    axs.flat[i].add_feature(cfeature.COASTLINE)
    axs.flat[i].gridlines()
    axs.flat[i].set_title(titles[i],pad=8,fontsize=12)
    gl = axs.flat[i].gridlines(crs=ccrs.PlateCarree(), draw_labels=True,line
    gl.xlabels_top = False
    gl.xlabels_bottom= False


# Adjust the location of the subplots on the page to make room for the color
fig.subplots_adjust(wspace=0.02,right=1)
cbar=plt.colorbar(cs, ax=axs, shrink=0.4, location='right',pad=0.03)
cbar.ax.tick_params(labelsize=12)

cbar.set_label('% change $year^-1$',horizontalalignment='right',fontsize=12,
fig.suptitle('Sea Ice Trends',y=0.71,x=0.48)
```

Out[39]: Text(0.48, 0.71, 'Sea Ice Trends')



5. Conclusion

The arctic has warmed signifcantly in the recent 30 years and it has impacted the sea ice. The rising SST has reduced the area covered by ice which allows more solar insolation to reach the ocean water. Primary production which largely depends on the amount of sunlight has also shown an increase. DMS production is also showing an increase in the Arctic. However, the changes are not evenly distributed. For example, Greenland, Barent and Chuchuki sea have warmed more than the other parts and there is significant reduction in sea ice and rise in DMS production in these regions. Most pronounced changes are happening during summer. But, surprisingly despite an increase in SST and reduction in sea ice in autumn too, there is decreasing trend in the chlorophyll and DMS production in some basins. Moreover, same changes in chlorophyll production in the Greenland sea and the Barent sea doesn't lead to a similar change in the DMS. Therefore, further analysis is required to find the relative importance and role of other parameters in DMS production. Positive trend in DMS in the central Arctic which can be due to a number of factors like undersea transport or enhanced chlorophyll production, has also be investigated further.

References

Isaksen, K., Nordli, Ø., Ivanov, B. et al. Exceptional warming over the Barents area. Sci Rep 12, 9371 (2022). https://doi.org/10.1038/s41598-022-13568-5

Muller-Karger, Frank & Varela, Ramón & Thunell, Robert & Luerssen, R. & Hu, C. & Walsh, John. (2005). The important of continental margins in the global carbon cycle. Geophysical Research Letters. 32. 10.1029/2004GL021346.

Rantanen, M., Karpechko, A.Y., Lipponen, A. et al. The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3, 168 (2022). https://doi.org/10.1038/s43247-022-00498-3

Acknowledgent

The entire courese has been a nice learning experience for me. Specially, I got a chance to refine my python coding skills and got more familiar with data analysis and plotting tools. Ada has been an amazing guide and she helped me a lot in learning the coding techniques and ways to reduce time in calculations. She was super quick in providing all types of Data required for the study. I would also like to thank Paul and Michael for giving me an opportunity to participate in the course.

Supplementry Material

In [41]:
```
import xarray as xr
import intake
import cftime
import numpy as np
import matplotlib.pyplot as plt
import cartopy.crs as ccrs
import s3fs
import glob
#%matplotlib inline

#......use 'volcello' for DMS and clos data......##

def open_file(model,var):
```

```
    s3 = s3fs.S3FileSystem(key="K1CQ7M1DMTLUFK182APD",
                           secret="3JuZAQm5I03jtpijCpHOdkAsJDNLNfZxBpM15Pi0", cl

    if model=='NorESM2-LM':
        if var == 'chlos':
            file_dir ='s3://escience2022/Ada/monthly/chlos_Omon_NorESM2-LM_h
        elif var=='dmsos':
            file_dir ='s3://escience2022/Ada/monthly/dmsos_Omon_NorESM2-LM_h
        elif var=='emidms':
            file_dir ='s3://escience2022/Ada/monthly/emidms_AERmon_NorESM2-L
        elif var == 'siconc':
            file_dir='s3://escience2022/Ada/monthly/siconc_SImon_NorESM2-LM_
        elif var == 'tos':
            file_dir='s3://escience2022/Ada/monthly/tos_Omon_NorESM2-LM_hist

    if (model=='CNRM-ESM2-1'):

        if var == 'chlos':
            file_dir ='s3://escience2022/Ada/monthly/chlos_Omon_CNRM-ESM2-1_
        elif var=='dmsos':
            file_dir ='s3://escience2022/Ada/monthly/dmsos_Omon_CNRM-ESM2-1_
        elif var=='emidms':
            file_dir ='s3://escience2022/Ada/monthly/emidms_AERmon_NorESM2-L
        elif var == 'siconc':
            file_dir='s3://escience2022/Ada/monthly/siconc_SImon_CNRM-ESM2-1
        elif var == 'tos':
            file_dir='s3://escience2022/Ada/monthly/tos_Omon_CNRM-ESM2-1_his


    if (model=='CESM2'):

        if var == 'chlos':
            file_dir ='s3://escience2022/Ada/monthly/chlos_Omon_CESM2_histor
        elif var=='dmsos':
            file_dir ='s3://escience2022/Ada/monthly/dmsos_Omon_NorESM2-LM_h
        elif var=='emidms':
            file_dir ='s3://escience2022/Ada/monthly/emidms_AERmon_NorESM2-L
        elif var == 'siconc':
            file_dir='s3://escience2022/Ada/monthly/siconc_SImon_CESM2_histo
        elif var == 'tos':
            file_dir='s3://escience2022/Ada/monthly/tos_Omon_CESM2_historica

    remote_files = s3.glob(file_dir)
    fileset = [s3.open(file) for file in remote_files]
    return fileset

def get_areacello(model,region):

    min_lat= region[0]
    max_lat= region[1]
    min_lon= region[2]
    max_lon= region[3]

    if (model=='NorESM2-LM'):
        cat_url = "https://storage.googleapis.com/cmip6/pangeo-cmip6.json"
        col = intake.open_esm_datastore(cat_url)
        cat = col.search(source_id=[model], activity_id = ['CMIP'], experime
                         table_id=['Ofx'], variable_id=['areacello'], member
        ds_dict = cat.to_dataset_dict(zarr_kwargs={'use_cftime':True})

        areacello = ds_dict[list(ds_dict.keys())[0]]
        areacello = areacello.squeeze()

        BSarea = areacello.areacello.where((areacello.latitude>=min_lat) & (
```

```
                                              & (areacello.longitude <= max_lon)  &
    if (model=='CNRM-ESM2-1'):
        cat_url = "https://storage.googleapis.com/cmip6/pangeo-cmip6.json"
        col = intake.open_esm_datastore(cat_url)
        cat = col.search(source_id=[model], activity_id = ['CMIP'], experime
                         table_id=['Ofx'], variable_id=['areacello'], member
        ds_dict = cat.to_dataset_dict(zarr_kwargs={'use_cftime':True})

        areacello = ds_dict[list(ds_dict.keys())[0]]
        areacello = areacello.squeeze()

        BSarea = areacello.areacello.where((areacello.lat>=min_lat) & (areac
                                              & (areacello.lon <= max_lon)  & (area
    if (model=='CESM2'):
        cat_url = "https://storage.googleapis.com/cmip6/pangeo-cmip6.json"
        col = intake.open_esm_datastore(cat_url)
        cat = col.search(source_id=[model], activity_id = ['CMIP'], experime
                         table_id=['Ofx'], variable_id=['areacello'], member
        ds_dict = cat.to_dataset_dict(zarr_kwargs={'use_cftime':True})

        areacello = ds_dict[list(ds_dict.keys())[0]]
        areacello = areacello.squeeze()

        BSarea = areacello.areacello.where((areacello.lat>=min_lat) & (areac
                                              & (areacello.lon <= max_lon)  & (area
    return BSarea

def get_polar_region(ds,model):  #get an xarray only for the polar region

    cat_url = "https://storage.googleapis.com/cmip6/pangeo-cmip6.json"
    col = intake.open_esm_datastore(cat_url)

    if (model=='NorESM2-LM'):
        cat = col.search(source_id=['NorESM2-LM'], activity_id = ['CMIP'], e
                     table_id=['Ofx'], variable_id=['areacello'], member_id=
    if (model=='CNRM-ESM2-1'):
        cat = col.search(source_id=[model], activity_id = ['CMIP'], experime
                         table_id=['Ofx'], variable_id=[area], member_id=['r

    if (model=='CESM2'):
        cat = col.search(source_id=[model], activity_id = ['CMIP'], experime
                         table_id=['Ofx'], variable_id=[area], member_id=['r

    ds_dict = cat.to_dataset_dict(zarr_kwargs={'use_cftime':True})
    areacello = ds_dict[list(ds_dict.keys())[0]]
    areacello = areacello.squeeze()
    areacello = areacello.where(areacello.latitude>60, drop = True)
    da=ds.sel(i=areacello.i).sel(j=areacello.j)

    return da


def regional_average(model,var):

    #calculate the regional average for each year
    min_lat=60
    max_lat=90
    min_lon=0
    max_lon=360

    region=[min_lat,max_lat,min_lon,max_lon]  #region defined

    cell_area=get_areacello(model,region)  #get cell area
```

```
    fileset=open_file(model,var)
    da = xr.open_mfdataset(fileset, combine='by_coords')

    if var!='siconc':
        ds= get_polar_region(da,model)
    else:
        ds=da

    dss=weighted_yearly_mean(ds, var)

    if (model=='NorESM2-LM'):
        BSsst = dss.where((dss.latitude>=min_lat) & (dss.latitude<=max_lat)
                      (dss.longitude <= max_lon)  & (dss.longitude >=min_lon

    if (model=='CNRM-ESM2-1'):
        BSsst = dss.where((dss.lat>=min_lat) & (dss.lat<=max_lat) &
                      (dss.lon <= max_lon)  & (dss.lon>=min_lon))

    if (model=='CESM2'):
        BSsst = dss.where((dss.lat>=min_lat) & (dss.lat<=max_lat) &
                      (dss.lon <= max_lon)  & (dss.lon >=min_lon))

    if var =='chlos':
       BSsst = (cell_area*10*BSsst).sum(dim=('i','j'))/(cell_area*10).sum(di
    if var =='dmsos':
       BSsst = (cell_area*10*BSsst).sum(dim=('i','j'))/(cell_area*10).sum(di
    else:
        BSsst = (cell_area*BSsst).sum(dim=('i','j'))/(cell_area).sum(dim=('i
    return BSsst

def weighted_yearly_mean(ds, var):
    """
    weight by days in each month
    """
    # Determine the month length
    month_length = ds.time.dt.days_in_month

    # Calculate the weights
    wgts = month_length.groupby("time.year") / month_length.groupby("time.ye

    # Make sure the weights in each year add up to 1
    np.testing.assert_allclose(wgts.groupby("time.year").sum(xr.ALL_DIMS), 1

    # Subset our dataset for our variable
    obs = ds[var]

    # Setup our masking for nan values
    cond = obs.isnull()
    ones = xr.where(cond, 0, 1.0)

    # Calculate the numerator
    obs_sum = (obs * wgts).groupby("time.year").sum(dim="time")

    # Calculate the denominator
    ones_out = (ones*wgts).groupby("time.year").sum(dim="time")

    # Return the weighted average
    return obs_sum / ones_out


def weighted_seasonal_mean(ds,var):  #to calculate mean of a particular seas

    """
    weight by days in each month
```

```
    """
    # Determine the month length
    month_length = ds.time.dt.days_in_month

    # Calculate the weights
    wgts = month_length.groupby("time.season") / month_length.groupby("time.

    # Make sure the weights in each year add up to 1
    np.testing.assert_allclose(wgts.groupby("time.season").sum(xr.ALL_DIMS),

    # Subset our dataset for our variable
    obs = ds[var]

    # Setup our masking for nan values
    cond = obs.isnull()
    ones = xr.where(cond, 0, 1.0)

    # Calculate the numerator
    obs_sum = (obs * wgts).groupby("time.season").sum(dim="time")

    # Calculate the denominator
    ones_out = (ones*wgts).groupby("time.season").sum(dim="time")

    # Return the weighted average
    return (obs_sum/ ones_out).to_dataset(name = var)

def seasonal_avg_timeseries(model,var):   #if I want to plot trends of a par
    """Calculates timeseries over seasonal averages from timeseries of month
    The weighted average considers that each month has a different number of
    Using 'QS-DEC' frequency will split the data into consecutive three-mont
    anchored at December 1st.
    I.e. the first value will contain only the avg value over January and Fe
    and the last value only the December monthly averaged value

    Parameters
    ----------
    ds : xarray.DataArray i.e.  ds[var]

    Returns
    -------
    ds_out: xarray.DataSet with 4 timeseries (one for each season DJF, MAM,
            note that if you want to include the output in an other dataset,
            you should use xr.merge(), e.g.
            dr = xr.merge([dr, seasonal_avg_timeseries(dr[var], var)])
    """

    fileset=open_file(model,var)
    da = xr.open_mfdataset(fileset, combine='by_coords')
    if var!= 'siconc':
        ds=get_polar_region(da,model)
    else:
        ds=da

    month_length = ds.time.dt.days_in_month
    sesavg = (ds * month_length).resample(time="QS-DEC").sum() / month_lengt

    djf=sesavg.isel(time=slice(0,None,4))
    mam=sesavg.isel(time=slice(1,None,4))
    jja=sesavg.isel(time=slice(2,None,4))
    son=sesavg.isel(time=slice(3,None,4))

    return [djf,mam,jja,son]

def slice_assign(ds_ls):
```

```
    "get the dataset for the last 65 years and add latitude and longitude tc

    ds=ds_ls.sel(time=slice("1950-01-01", "2014-10-31"))
    dss=ds.assign_coords(time=np.arange(1950,1950+len(ds.time.values)))
    da=dss.polyfit('time',deg=1)

    da1=da.assign_coords(latitude=ds.latitude)
    da2=da1.assign_coords(longitude=ds.longitude)
    return da2

def anomaly_seasonal(model,var):

    fileset = open_file(model,var)

    ds = xr.open_mfdataset(fileset, combine='by_coords')

    now=ds.sel(time=slice("1980-01-01", "2014-10-31"))

    ref_year=ds.sel(time=slice("1950-01-01", "1979-10-31"))

    weighted_now= weighted_seasonal_mean(now,var)
    weighted_ref= weighted_seasonal_mean(ref_year,var)

    return [weighted_now,weighted_ref]


def anomaly (var):

    ## Put the variable name as stored in the NorESM data. This function wil
    #anaomaly is calculated as follows:
         #climatology is calculated usng data from 1950 to 1979
         #Present day trend is calculated for data from 1980 to 2014
    fileset=open_file(var)
    da = xr.open_mfdataset(fileset, combine='by_coords')

    if var!='siconc':
        ds= get_polar_region(da)
    else:
        ds=da

    weight= weighted_temporal_mean(ds,var)

    aa=weight#.groupby("time.year").sum(dim='time')

    now1=aa.isel(year = slice(30,None))  #remove first 30 years
    now=now1.mean('year')

    clim1= aa.isel(year = slice(None,30))  #remove last 30 years
    clim=clim1.mean('year')

    fractional_anm=(now-clim)/clim
    anm= (now-clim)

    anomaly=[anm,fractional_anm]
    return anomaly

def check_data(n,var):
    s3 = s3fs.S3FileSystem(key="K1CQ7M1DMTLUFK182APD",
                       secret="3JuZAQm5I03jtpijCpHOdkAsJDNLNfZxBpM15Pi0", cl


    if var == 'chlos':
        file_dir ='s3://escience2022/Ada/monthly/chlos_Omon_NorESM2-LM_histc
    if var=='dmsos':
```

```
        file_dir ='s3://escience2022/Ada/monthly/dmsos_Omon_NorESM2-LM_histo
    if var=='emidms':
        file_dir ='s3://escience2022/Ada/monthly/emidms_AERmon_NorESM2-LM_hi
    if var == 'siconc':
        file_dir='s3://escience2022/Ada/monthly/siconc_SImon_NorESM2-LM_hist
    if var == 'tos':
        file_dir='s3://escience2022/Ada/monthly/tos_Omon_NorESM2-LM_historic

    remote_files = s3.glob(file_dir)
    fileset = [s3.open(file) for file in remote_files[n:]]
    da = xr.open_mfdataset(fileset, combine='by_coords')

    return da
```

In [ ]: