Freezing Occurrence in Mangrove Distribution Regions Under Climate Scenarios.

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Abstract

Global warming associated with climate change is linked with altered distribution and abundance of species and ecosystems worldwide. However, the ecological impacts of the occurrence and changes in the frequency of extreme events have not been as well documented, especially for coastal and marine environments (Cavanaugh et al., 2014). Under global warming, mangrove forests will undergo significant alteration in their distribution patterns. Several studies also show that one of the main drivers of this projected shift and alterations are attributed to changes surface temperature (Friess et al., 2022). Understanding the potential impacts of this driver is essential for predicting changes in long term global mangrove ecosystem status.

Here we assess freezing occurrence in global mangrove areas under different climate change and future scenarios (“moderate emissions": SSP2-4.5) and SRM scenario (ARISE SAI; Richter et al., 2022) using the NSF supported Community Earth System Model v.2 (CESM2 Danabasoglu et al., 2020) in python environment.

Key Points

Shared Socioeconomic Pathways (SSP2-4.5), Solar Radiation Modification (SRM), Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection (ARISE-SAI).

Introduction

Mangrove ecosystems are critical to biodiversity and provide vital ecosystem services, including serving as nursing grounds for fishes, coastal protection and carbon sequestration. In a recent study, it was estimated that the tree and sediment of mangrove forests along the world's coastlines hold ~ 3 billion metric tons of carbon - more than tropical forests (Friess et al., 2022). Understanding the changes in mangroves extent has become increasingly significant due to this carbon storage and sequestration capacity. Mangrove distribution is largely restricted to tropical and subtropical regions due to their sensitivity to freezing temperatures. With rising global temperatures driven by climate change, there is increasing potential for mangroves to expand their range. Studies, such as those by Gouvêa et al., (2022) and Cavanaugh et al., 2014, suggest that the expansion of mangroves correspond to the frequency of cold events in these regions, with certain temperature thresholds serving as ecological limits for mangrove survival and growth. This project aims to investigate the occurrence of these freezing events in mangrove regions under two climate scenarios (SSP2-4.5 and ARISE-SAI).

The Shared Socioeconomic Pathways (SSPs) are a set of standardized global scenarios used in climate science to investigate how socioeconomic factors, such as population growth, economic development, and technological advancements, interact with climate change (Meinshausen et al., 2020). They provide a framework for analyzing the potential impacts of climate policies and the future evolution of greenhouse gas (GHG) emissions (Welch, 2024). Each SSP is combined with different levels of radiative forcing—measuring the additional energy trapped in the Earth's atmosphere by GHGs, expressed in watts per square meter (W/m²) (Meinshausen et al., 2020). SSP2-4.5 represents a "middle-of-the-road" scenario within the SSPs framework. It assumes moderate challenges to both climate mitigation and adaptation, with policies and societal behaviors striking a balance between high and low levels of ambition. In this scenario, GHG emissions are expected to stabilize by mid-century and then decline, leading to a radiative forcing of 4.5 W/m² by 2100 (Welch, 2024).

Stratospheric Aerosol Injection (SAI) is the most widely studied and well-understood solar geoengineering approach proposed so far (National Academies of Sciences, Engineering, and Medicine, 2021). It involves adding small liquid or solid particles to the stratosphere to reflect sunlight and reduce global warming (Zarnetske et al., 2021). Unlike the turbulent troposphere, the stratosphere is relatively stable, allowing these particles to remain in the atmosphere for a year or longer before they gradually settle into the troposphere and are eventually removed by natural processes like sedimentation and precipitation. Aerosols in the stratosphere tend to spread evenly around the globe in longitude and move toward the poles in latitude during their time in the atmosphere and as a result, the cooling effects of SAI would naturally have a global reach, influencing temperatures worldwide (National Academies of Sciences, Engineering, and Medicine, 2021). Solar climate intervention through SAI is a proposed strategy to mitigate rising global temperatures and help prevent the most severe impacts of climate change (Richter et al., 2022). The Assessing Responses and Impacts of Solar climate intervention on the Earth system with Stratospheric Aerosol Injection (ARISE-SAI) project uses advanced simulations to explore this concept. These simulations are conducted with the Community Earth System Model, version 2, paired with the Whole Atmosphere Community Climate Model, version 6 (CESM2(WACCM6)) (Richter et al., 2022). The goal is to model a realistic scenario for deploying stratospheric aerosol injection and provide a foundation for understanding how such interventions might influence the Earth's climate system. The first ARISE-SAI simulations, ARISE-SAI-1.5 presented here, aim to keep the global mean temperature at ∼1.5 °C above pre-industrial levels (Richter et al., 2022). Examining the impact of SSP2-4.5 and ARISE-SAI on mangrove distribution through temperature dynamics is crucial for accurately projecting future mangrove ecosystems and understanding potential shifts in their range and viability.

Research Questions

1. How different are the climate scenarios (SSP2-4.5 and ARISE-SAI) from each other in terms of freezing regions?
2. Do freezing events occur in mangrove areas, tropical or sub-tropical regions, and will they have any impacts on mangrove shifts?

Methods

This study employs a systematic approach to occurrence of temperature extremes in global mangrove regions, focusing on critical ecological threshold, climate data preparation, geospatial integration, and visualization.

The first step involved defining critical temperature thresholds necessary for mangrove survival and growth. A thorough review of existing literature on mangrove ecology was conducted to identify temperature-related limit that dictate mangrove viability. This thresholds served as a benchmark to assess the potential presence or absence of mangroves under varying climate-scenarios, offering a foundational basis for subsequent analyses.

To analyze historical and future temperature patterns, data from the CESM2 model was utilized, focusing on regions subject to extreme cold events. Historical temperature data was sourced from CESM2 historical simulations, while future temperature projections were based on the moderate emissions scenario (SSP2-4.5) and Solar Radiation Management (SRM) scenarios using ARISE-SAI model outputs. The data processing workflow involved several key steps. Temperature datasets were loaded and preprocessed using Python libraries such as `xarray`, `numpy`, and `matplotlib`. Surface temperature data for specific time periods were extracted, and minimum daily temperatures were calculated for each grid cell.

A grid-based mask is developed to identify coastal grid cells where mangroves are likely to occur. This mask is initialized with zeros on the CESM2 grid and iteratively refined by marking cells as coastal if they represent ocean adjacent to land. This step ensures the accurate delineation of coastal areas, enhancing the precision of the spatial analysis. This coastal mask was then applied to ensure precise mapping of land-ocean boundaries, facilitating targeted analysis of coastal regions.

The coastal mask was applied to historical and future temperature datasets to isolate regions where temperatures drop below the critical thresholds. This analysis enables the identification of areas potentially vulnerable to cold-induced mangrove loss.

To understand the implications of different climate scenarios, this study compares the moderate emissions scenario (SSP2-4.5) and SRM scenarios on mangrove distribution. For each scenario, the mean minimum temperature was computed across coastal regions using the masked datasets. This comparison provides insights into the potential shifts in mangrove habitats under varying climatic conditions.

Mangrove polygon shapefiles from the Global Mangrove Watch version 3 (GMW v.3) (Bunting et al., 2022) dataset were used for this purpose. The polygons were overlaid on temperature projections, enabling geospatial visualization of the spatial occurrence cold events in mangrove areas. Comparative maps are generated for historical and future scenarios.

To account for variability in model outputs, data from four ensemble members (EM1, EM2, EM3, and EM4) were processed for each scenario. The mean of these ensemble members were calculated to provide an aggregated projection for each scenario. Surface temperature data for specified time periods were extracted for each ensemble member and the mean ensemble, ensuring a robust and comprehensive analysis.

The findings are communicated through detailed visualizations. Global temperature maps were generated, overlaid with mangrove polygons to highlight the spatial mangrove rgions susceptible to freezing occurrence. Time-series plots were developed to illustrate trends in minimum daily temperatures across scenarios, providing a temporal perspective on climate variability.

Results

This study's analysis explored freezing temperature occurrences under two climate scenarios—SSP2-4.5 and ARISE-SAI. The results showed notable differences between the two scenarios in terms of the spatial and temporal distribution of freezing temperatures in mangrove regions. Using CESM2 model data, ensemble member outputs, and geospatial overlays with mangrove polygons, critical insights into the impacts of freezing events on mangrove viability were derived.

Climate Scenario Comparison

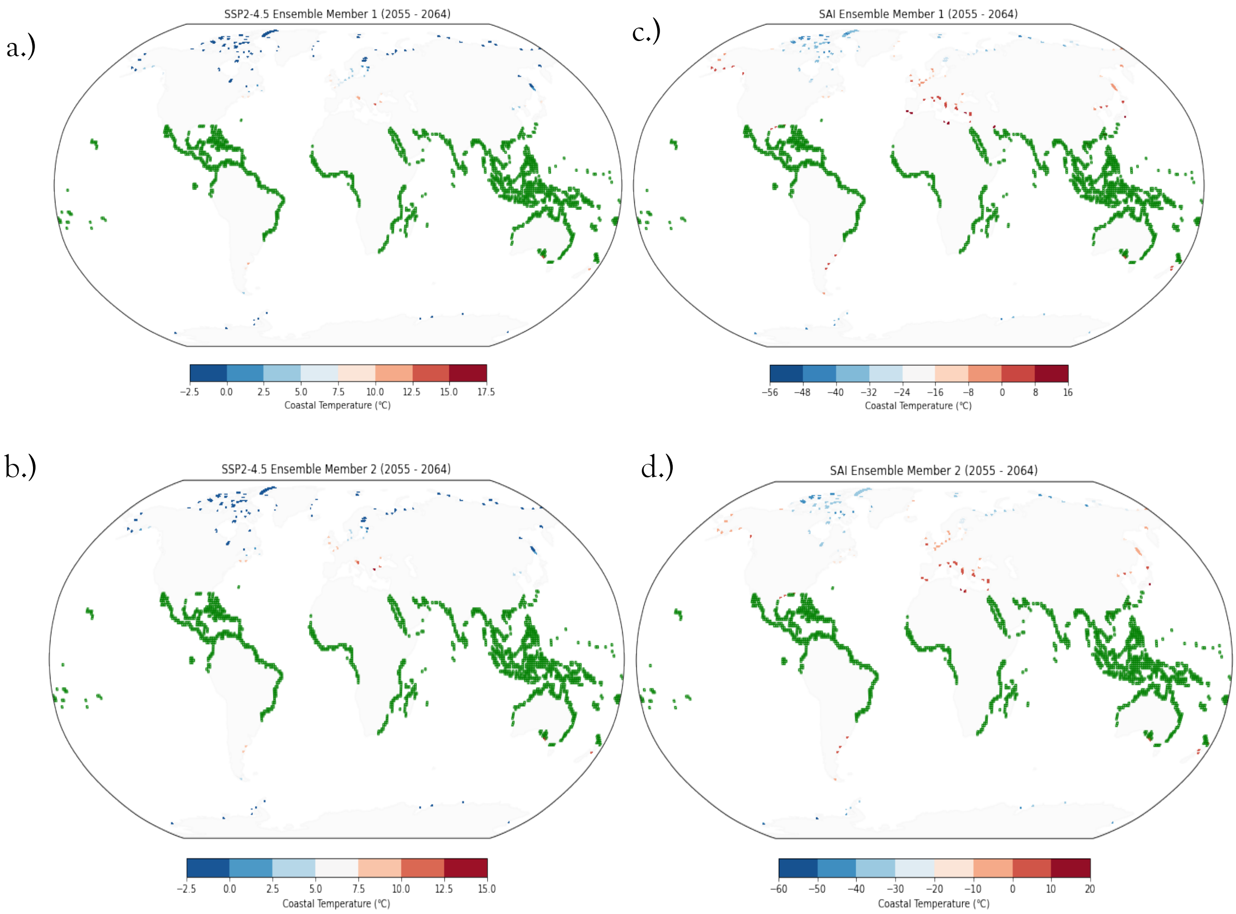

Figure 1: Freezing temperature regions under no intervention (SSP 2-4.5) a.) ensemble member 1 & b.) ensemble member 2 and intervention (SAI) c.) ensemble member 1 & d.) ensemble member 2. The green polygons represent global mangrove regions.

The SSP2-4.5 scenario indicated relatively warmer coastal temperatures compared to the ARISE-SAI scenario, with fewer regions falling below the critical freezing threshold for mangrove survival. However, the ARISE-SAI ensemble members highlighted significant cooling effects, with minimum daily temperatures in some coastal regions dropping to extreme levels, far exceeding the mangrove viability thresholds, specifically the coast of the gulf of mexico (Texas-Louisiana transboundary). This cooling effect is consistent with the design of ARISE-SAI, where solar radiation management through aerosol injections leads to a globally uniform temperature reduction. Notably, off the south Australian coast, both scenarios exhibit freezing events, signifying a potential shift of mangroves. The spatial maps for ensemble members of ARISE-SAI reveal that certain regions in higher latitudes, typically beyond current mangrove extents, exhibit more frequent freezing temperatures compared to the SSP2-4.5 scenario. This finding suggests that under ARISE-SAI, mangrove expansion into higher latitudes might be inhibited by extreme cold events, despite the overall cooling intended to mitigate global warming. In contrast, the SSP2-4.5 maps depict conditions that are conducive to potential mangrove range expansion, particularly in subtropical regions. Here, moderate warming reduces the likelihood of freezing events, potentially allowing mangroves to migrate into areas that were previously unsuitable due to low temperatures.

Temporal Trends

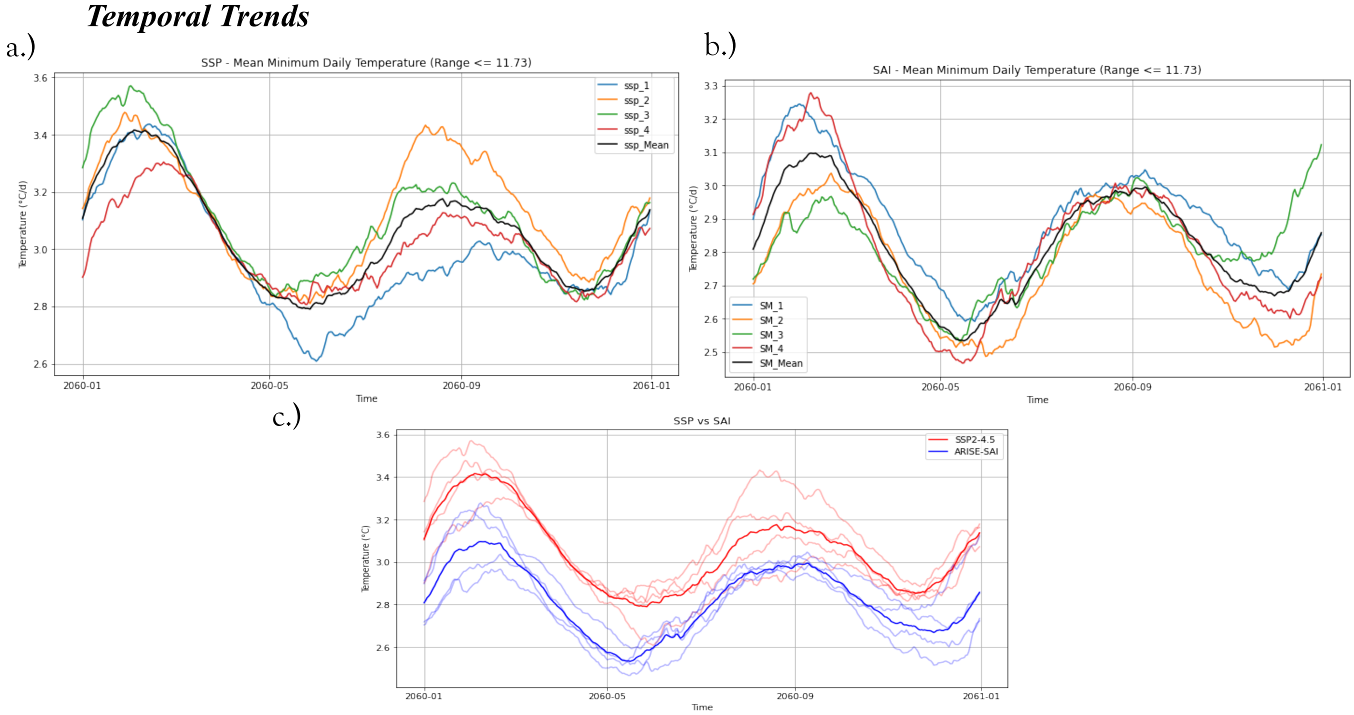

Figure 2: Comparison of minimum daily coastal temperatures between SSP2-4.5 and ARISE-SAI ensembles and ensemble mean over time.

Time-series plots of minimum daily temperatures for both scenarios show consistent cooling trends under ARISE-SAI across all ensemble members, with temperatures occasionally dropping below mangrove survival thresholds. This contrasts with SSP2-4.5, where the mean minimum temperatures remain above freezing for most regions. This divergence emphasizes the trade-offs in applying SRM—while it can mitigate global warming, it introduces the risk of extreme cooling in specific regions.

Discussion

The results of this study emphasizes the complex interplay between climate scenarios and ecosystem responses. While SSP2-4.5 provides a balanced pathway with reduced freezing occurrences in mangrove regions, ARISE-SAI introduces unintended consequences of extreme cooling that could negatively impact mangrove distribution, particularly in high-latitude.

Mangroves are highly sensitive to freezing temperatures, and the occurrence of extreme cold events under ARISE-SAI suggests potential risks to their global distribution (Cavanaugh et al., 2014). The cooling effects, while beneficial for mitigating global warming, could limit the adaptive capacity of mangroves to expand their range in response to moderate warming. However, SSP2-4.5 offers conditions that could favor mangrove growth and expansion due to the reduced frequency of freezing temperatures in subtropical and tropical regions (Cooley et al., 2023). This research highlights the importance of considering both the benefits and risks of solar climate intervention strategies, such as SAI, on ecosystems like mangroves. The findings emphasize the need for integrated assessments that account for regional and ecosystem-specific responses to climate interventions. By comparing SSP2-4.5 and ARISE-SAI, this study provides valuable insights into how different climate trajectories could shape the future of mangrove ecosystems. This study demonstrates the opposite impacts of SSP2-4.5 and ARISE-SAI on mangrove distribution through their effects on freezing events. While SSP2-4.5 presents a potential moderate and favorable pathway for mangrove survival and expansion, ARISE-SAI introduces significant risks of freezing-induced stress in certain regions. These findings could contribute to the growing body of literature assessing the ecological consequences of climate change and intervention strategies, with implications for both policy and conservation planning.

Bibliography

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R. M., Thomas, N., Tadono, T., Worthington, T. A., Spalding, M., Murray, N. J., & Rebelo, L.-M. (2022). Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0. *Remote Sensing*, *14*(15), 3657. https://doi.org/10.3390/rs14153657

Cavanaugh, K. C., Kellner, J. R., Forde, A. J., Gruner, D. S., Parker, J. D., Rodriguez, W., & Feller, I. C. (2014). Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. *Proceedings of the National Academy of Sciences*, *111*(2), 723–727. https://doi.org/10.1073/pnas.1315800111

Cooley, S., Schoeman, D., Bopp, L., Boyd, P., Donner, S., Ito, S. i, Kiessling, W., Martinetto, P., Ojea, E., Racault, M. F., Rost, B., Skern-Mauritzen, M., Ghebrehiwet, D. Y., Bell, J. D., Blanchard, J., Cheung, W. W., Bolin, J., Dupont, S., Cisneros-Montemayor, A., … Simmons, C. T. (2023). *Oceans and Coastal Ecosystems and Their Services*. Cambridge University Press. https://digital.csic.es/handle/10261/350582

Danabasoglu, G., Lamarque, J.-F., Bacmeister, J., Bailey, D. A., DuVivier, A. K., Edwards, J., Emmons, L. K., Fasullo, J., Garcia, R., Gettelman, A., Hannay, C., Holland, M. M., Large, W. G., Lauritzen, P. H., Lawrence, D. M., Lenaerts, J. T. M., Lindsay, K., Lipscomb, W. H., Mills, M. J., … Strand, W. G. (2020). The Community Earth System Model Version 2 (CESM2). *Journal of Advances in Modeling Earth Systems*, *12*(2), e2019MS001916. https://doi.org/10.1029/2019MS001916

Friess, D. A., Adame, M. F., Adams, J. B., & Lovelock, C. E. (2022). Mangrove forests under climate change in a 2°C world. *WIREs Climate Change*, *13*(4), e792. https://doi.org/10.1002/wcc.792

Gouvêa, L. P., Serrão, E. A., Cavanaugh, K., Gurgel, C. F. D., Horta, P. A., & Assis, J. (2022). Global impacts of projected climate changes on the extent and aboveground biomass of mangrove forests. *Diversity and Distributions*, *28*(11), 2349–2360. https://doi.org/10.1111/ddi.13631

Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., … Wang, R. H. J. (2020). The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geoscientific Model Development*, *13*(8), 3571–3605. https://doi.org/10.5194/gmd-13-3571-2020

National Academies of Sciences, Engineering, and Medicine. (2021). *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance* (p. 25762). National Academies Press. https://doi.org/10.17226/25762

Richter, J. H., Visioni, D., MacMartin, D. G., Bailey, D. A., Rosenbloom, N., Dobbins, B., Lee, W. R., Tye, M., & Lamarque, J.-F. (2022). Assessing Responses and Impacts of Solar climate intervention on the Earth system with stratospheric aerosol injection (ARISE-SAI): Protocol and initial results from the first simulations. *Geoscientific Model Development*, *15*(22), 8221–8243. https://doi.org/10.5194/gmd-15-8221-2022

Welch, I. (2024). *The IPCC Shared Socioeconomic Pathways (SSPs): Explained, Evaluated, Replaced?* https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4681042

Zarnetske, P. L., Gurevitch, J., Franklin, J., Groffman, P. M., Harrison, C. S., Hellmann, J. J., Hoffman, F. M., Kothari, S., Robock, A., Tilmes, S., Visioni, D., Wu, J., Xia, L., & Yang, C.-E. (2021). Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth. *Proceedings of the National Academy of Sciences*, *118*(15), e1921854118. https://doi.org/10.1073/pnas.1921854118

Appendix

List of Packages Used

```
[1]: import numpy as np
     import matplotlib.pyplot as plt
     import pandas as pd
     import geopandas as gpd
     import xarray as xr
     import cartopy
     import cartopy.util as util
     import cartopy.crs as ccrs
     import cartopy.feature as cfeature  # features such as the ocean, coastlines rivers, etc
     import cmocean
     import pop_tools
     from scipy.stats import linregress
```

Creating a Coastal Mask

```
cesm_sst_data = xr.open_mfdataset('/glade/campaign/cesm/collections/CESM2-WACCM-SSP245/b.e21.BWSSP245cmip6.f09_g17.CMIP6-SSP2-4.5-WACCM.001/ocn/proc/tseries/day_1/'+ 'b.e21.BWSSP245cmip6.f09_g17.CMIP6

SST = cesm_sst_data['SST']
SST = SST[0,:,:]

# Create a coastal mask filled with zeros
nlat=384
nlon=320
coastal_mask = np.zeros((nlat, nlon))

#Looping through each grid cell to get coastal cells

for i in range(1, nlat-1):
    for j in range(1, nlon-1):
        if not np.isnan(SST[i, j]): #I need ti first ensure that the current cell is in the ocean then I can get the neighbouring cells which are land (nan)
            if (np.isnan(SST[i+1, j]) or np.isnan(SST[i-1, j]) or
               np.isnan(SST[i, j+1]) or np.isnan(SST[i, j-1])):
               coastal_mask[i, j] = 1


lat = cesm_sst_data['TLAT']
lon = cesm_sst_data['TLONG']

np.shape(coastal_mask)

p = plt.contourf(coastal_mask)
plt.colorbar(p)

import netCDF4 as nc

filePath = '/glade/u/home/kasante/Final_Mangrove_model/'
fileName = filePath + 'coastal_cells_mask.nc'
dataSet = nc.Dataset(fileName, 'w', format='NETCDF4')

nlat = dataSet.createDimension('nlat', 384)
nlon = dataSet.createDimension('nlon',320)

var_name = 'coastal_mask'
coastal_mask_file = dataSet.createVariable(var_name, np.float32, ('nlat','nlon'))
coastal_mask_file.units = ''

TLONG = dataSet.createVariable('TLONG', np.float32, ('nlat','nlon'))#SST = ds.createVariable('SST', np.float32, ('SST',))
TLONG.units = 'degrees_east'
TLAT = dataSet.createVariable('TLAT', np.float32, ('nlat','nlon'))#SST = ds.createVariable('SST', np.float32, ('SST',))
TLAT.units = 'degrees_north'
coastal_mask_file[:,:] = coastal_mask

TLONG[:,:] = lon.values
TLAT[:,:] = lat.values
print(dataSet)
```

Plot

```
[116]: fig, ax = plt.subplots(figsize=(12, 7), subplot_kw=dict(projection=ccrs.Robinson()))
       ax.add_feature(cfeature.LAND, color='lightgray', alpha=0.09, zorder=-1)
       ax.set_global()
       ax.set_title('SSP2-4.5 Ensemble Member 4 (2055 - 2064)')
       # Create the filled contour plot
       contour = plt.contourf(tlong, tlat, data, transform=ccrs.PlateCarree(), zorder=1, cmap='RdBu_r')

       # Add the mangrove polygon shapefile boundary
       mangrove_polygon_shp.boundary.plot(ax=ax, linewidth=1, color='green', transform=ccrs.PlateCarree())

       # Add a colorbar
       cbar = plt.colorbar(contour, ax=ax, orientation='horizontal', pad=0.05, fraction=0.046)
       cbar.set_label('Coastal Temperature (℃)')  # You can customize the label here
       plt.show();
```

Using Ensemble Memebers

```
[56]: SM_1 = xr.open_dataset('/glade/campaign/cesm/collections/ARISE-SAI-1.5/b.e21.BW.f09_g17.SSP245-TSMLT-GAUSS-DEFAULT.001/ocn/proc/tseries/day_1/b.e21.BW.f09_g17.SSP245-TSMLT-G
      SM_2 = xr.open_dataset('/glade/campaign/cesm/collections/ARISE-SAI-1.5/b.e21.BW.f09_g17.SSP245-TSMLT-GAUSS-DEFAULT.002/ocn/proc/tseries/day_1/b.e21.BW.f09_g17.SSP245-TSMLT-G
      SM_3 = xr.open_dataset('/glade/campaign/cesm/collections/ARISE-SAI-1.5/b.e21.BW.f09_g17.SSP245-TSMLT-GAUSS-DEFAULT.003/ocn/proc/tseries/day_1/b.e21.BW.f09_g17.SSP245-TSMLT-G
      SM_4 = xr.open_dataset('/glade/campaign/cesm/collections/ARISE-SAI-1.5/b.e21.BW.f09_g17.SSP245-TSMLT-GAUSS-DEFAULT.004/ocn/proc/tseries/day_1/b.e21.BW.f09_g17.SSP245-TSMLT-G
```

```
[57]: # Mask the datasets to include only values <= 11.73
      masked_SM_1 = SM_1.where(SM_1 <= 11.73)
      masked_SM_2 = SM_2.where(SM_2 <= 11.73)
      masked_SM_3 = SM_3.where(SM_3 <= 11.73)
      masked_SM_4 = SM_4.where(SM_4 <= 11.73)
```

```
[58]: # Calculate the mean minimum daily temperature across latitude and longitude within the range
      MMT_SM_1 = masked_SM_1.mean(dim=["nlat", "nlon"]).sel(time=slice('2060-01-01', '2060-12-31'))
      MMT_SM_2 = masked_SM_2.mean(dim=["nlat", "nlon"]).sel(time=slice('2060-01-01', '2060-12-31'))
      MMT_SM_3 = masked_SM_3.mean(dim=["nlat", "nlon"]).sel(time=slice('2060-01-01', '2060-12-31'))
      MMT_SM_4 = masked_SM_4.mean(dim=["nlat", "nlon"]).sel(time=slice('2060-01-01', '2060-12-31'))
```

```
[59]: SM_1_time = SM_1.sel(time = slice('2060-01-01', '2060-12-31'))
      SM_2_time = SM_2.sel(time = slice('2060-01-01', '2060-12-31'))
      SM_3_time = SM_3.sel(time = slice('2060-01-01', '2060-12-31'))
      SM_4_time = SM_4.sel(time = slice('2060-01-01', '2060-12-31'))
```

```
[60]:

      # Plot the data
      plt.figure(figsize=(12, 6))
      plt.plot(SM_1_time.time, MMT_SM_1, label="SM_1")
      plt.plot(SM_2_time.time, MMT_SM_2, label="SM_2")
      plt.plot(SM_3_time.time, MMT_SM_3, label="SM_3")
      plt.plot(SM_4_time.time, MMT_SM_4, label="SM_4")

      plt.title("Mean Minimum Daily Temperature Across Time (SM_1 to SM_4)")
      plt.xlabel("Time")
      plt.ylabel("Temperature (°C/d)")
      plt.legend()
      plt.grid()
      plt.show()
```

Coastal Mask