XSLICE: An Efficient Visualization and Diagnosis Tool for 4-Dimensional Climate Dynamics

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Early Online Release: This preliminary version has been accepted for publication in *Journal of Atmospheric and Oceanic Technology*, may be fully cited, and has been assigned DOI 10.1175/JTECH-D-24-0113.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

ABSTRACT: This paper introduces a convenient and fast computer visualization tool for climate data defined on 4-dimensional (4D) spatiotemporal coordinates: longitude, latitude, elevation or depth, and time. The tool is named XSLICE, which stands for Cross-Sectional Layers with Interactive Cropping and Exportation. The name also means an anatomy by cross-sectional slices for a 4D climate field. The sliced field is thus visualized on a plane of two variables, such as xy-plane for a horizontal cross-section, xz-plane for a zonal vertical cross-section, and yt-plane for a latitude-based Hovmöller diagram. As a demonstration, we applied XSLICE to the monthly data from the Global Ocean Data Assimilation System (GODAS). The GODAS dataset is a NOAA real-time ocean analysis and reanalysis consisting of 40 depth layers on a $\frac{1}{3}^{\circ} \times 1^{\circ}$ latitude-longitude spatial grid ranging from 74.5°S - 64.5°N for latitude and $0^{\circ} - 359^{\circ}$ for longitude with temporal coverage from January 1980 to present. The GODAS variables include potential temperature, salinity, u-current, v-current, and others. We show that XSLICE can conveniently and quickly display various kinds of climate dynamics patterns, such as El Niño and equatorial upwelling, sliced in different planes at proper locations and displayed with customizable coloring and cropping. As such, XSLICE can serve as an exploratory research tool to gain insight on process dynamics before pursuing further quantitative analysis of observed data or model outputs. XSLICE's easiness to use make it attractive as an educational and public outreach tool to inspire and engage in climate science or in a broader range of science and engineering fields.

Significance Statement: We present a fast and convenient tool to visualize 4-dimensional space-time climate data. The tool is named XSLICE (Cross-Sectional Layers with Interactive Cropping and Exportation) and can visualize the gridded spacetime data of ocean or atmosphere with six different space-space or space-time cross-sections. The easy and efficient use of XSLICE allows to quickly visualize and diagnose climate dynamic patterns or significant anomalies, which can guide further quantitative analysis. XSLICE does not require computer programming training and can be used in classrooms to engage and inspire students in climate science. XSLICE is portable and can be applied to 3- or 4-dimensional gridded data in any other spacetime fields of science and engineering.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

1. Introduction

Visualization of spacetime climate data is needed by both researchers and the general public. How can a researcher, without much computer coding knowledge, quickly and conveniently interrogate the outputs of a climate model to gain insight in climate dynamics, or even possibly discover some unknown climate patterns for further investigations? Can instructors in a classroom visualize the water temperature structure or zonal flow pattern in the 3-dimensional (3D) ocean or atmosphere based on the gridded climate data when teaching students? Is it possible to have an easy-to-use computer tool so university students can visually explore El Niño and La Niña patterns while reading climate dynamics books or doing their climate homework?

With these questions in mind, we have developed a climate data visualization tool named XSLICE, or Xslice, an acronym for Cross-Sectional Layers with Interactive Cropping and Exportation. XSLICE is a computer visualization tool that quickly visualizes 4-dimensional (4D) gridded spacetime climate data. It allows users to scroll through different horizontal latitude-longitude layers and vertical latitude-altitude or longitude-altitude cross-sections. XSLICE allows users to quickly and visually dissect any given 4D (x, y, z, t) gridded climate data, from observations or model output, by fixing any two coordinate variables. Here, x indicates longitude, y latitude, z depth or elevation or pressure level, and t time.

For example, we can visualize the vertical structure of an El Niño defined on the depth and longitude coordinates, i.e., the vertical $xz-$ cross-section by fixing coordinate variables y and t. This helps diagnose the 3D structure of the El Niño Southern Oscillation (ENSO) dynamics. Thus, XSLICE enables scientists to make cross-sectional visualizations of data defined on a 4-dimensional spacetime domain (described by x, y, z, and t coordinates) faster and more easily. Although visualizations have been used for decades in climate science for cross-sectional maps, such as the xt-Hovmöller diagrams to show the evolution of an El Niño event along the equator, XSLICE enables one to do this faster and easier by "slicing and dicing" of 4-dimesional fields in six different planes spanned by the xz, yz, xy, xt, yt, and zt-axes.

The purpose of this paper is to document XSLICE for quickly graphing 4-dimensional datasets. Our explanation helps users not only understand the basic algorithm design of XSLICE, but also provides users with a tutorial through examples. Our examples demonstrate the use of XSLICE through its application to the Global Ocean Data Assimilation System (GODAS) data (GODAS

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

2024). GODAS is an ocean reanalysis consisting of 40 depth layers on a $\frac{1}{3}^\circ \times 1^\circ$ latitude-longitude spatial grid ranging from 74.5°S - 64.5°N and 0° - 359° with temporal coverage from January 1980 to present. We will demonstrate how to use XSLICE to visualize potential temperature, salinity, the zonal u-current, and the meridional v-current.

XSLICE has a user-friendly control dashboard, which has various control buttons for longitude, latitude, altitude (for atmosphere) or depth (for ocean), time, and climate variables. A user can slide a button to adjust a control variable, say y. The user can also zoom into the 2D cross-section by moving the proper buttons on the XSLICE control dashboard. Thus, the user can slide the control button to scan an oceanic domain or atmospheric domain or both to search for the key climate dynamic patterns or phenomena, such as ENSO, equatorial upwelling, Hadley cells, and Walker circulation. If a user likes a picture on the XSLICE interface and wishes to examine it further, then they can download the picture via many popular picture formats like png, jpg, and pdf.

Like a CT scan of a human body, our XSLICE scans the ocean or atmosphere through cross-sections. It greatly simplifies diagnostic explorations of climate model data. It also helps more efficient detection of interesting climate patterns. For example, our coordinates are controlled by sliding control buttons, e.g., sliding latitude y while fixing time t in the depth-longitude $(z-x)$ scan of ENSO. XSLICE thus demonstrates variations of ENSO's vertical structure.

Sometimes, a dramatic change in the $x-z$ scan with a fixed time may appear while a user moves the control button with a small increment of y coordinates. This may detect the boundary of some climate dynamic pattern, such as the equatorial upwelling's depth (z)-longitude (x) pattern while moving the latitude(y) control button.

Several climate visualization tools are available and each has its own unique features (see Table 1). For example, the following four tools (i.e., Nullschool, VentuSky, 4DVD, and Argovis) can be easily used in school classrooms and museums for educational purposes, in addition to research applications. Nullschool (2024) has an appealing interface showing the current and recent weather conditions. VentuSky (2024) is an easy-to-use tool to view the global hourly weather conditions from 1979 to the present. 4DVD (2024) is a 4-dimensional visual delivery system for big climate data and allows both visualization of maps and time series and data download, as demonstrated by examples in Shen et al. (2020). Argovis (2024) visualizes the ocean Argo buoy data and also allows

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

data download, as described by Tucker et al. (2020). On the other hand, there are some other tools

TABLE 1. Summary of the Key Features for Climate Visualization Tools

Tool Name	Author / Reference	Main Features
NullSchool	Nullschool (2024)	Shows current/recent weather, wind/wave animation, mode/projection changes
VentuSky	VentuSky (2024)	Global hourly weather, advanced parameters (feels-like temp, wind gusts, etc.), forecasting animations
4DVD	Pierret and Shen (2017)	Visualizes big climate data, produces maps/time series, 3D background settings, data download, statistical computing
Argovis	Tucker et al. (2020)	Visualizes ocean Argo data, basic filters, time range selection, data download
WRIT	NOAA (2024); Smith et al. (2014)	Reanalysis plots (maps, anomalies, cross-sections), time-series and correlation analyses, trajectories, distribution/Hovmöller analyses
Giovanni	Acker and Leptoukh (2007)	Various map plots (time-averaged, recurring), comparisons (correlation, scatter), time series, vertical cross-sections, units conversion
Panoply	Panoply (2024)	Display users' data, data computing, wind vector plots, time series plots, difference maps

that are more appropriate for research applications, but less for the general public. Two examples are listed here: WRIT (2024) visualizations are NOAA Web-Based Reanalyses Intercomparison Tools (see Smith et al. (2014)); Giovanni (2024) is an NASA interface between data and science designed for NASA data.

In addition, some creative visualizations have appeared in journal papers and books, e.g., Crawford et al. (2018) displayed a series of longitude-depth cross-sections, created by a MatLab code, to show the 3D empirical orthogonal functions (EOFs) for the California coastal current. The popular atmospheric science book by Wallace and Hobbs (2006) also includes some creative visualizations. The books of Shen and North (2023) and Shen and Somerville (2019) have included many R and Python codes for climate data visualization. Also, there are many professional data visualization software packages available based on various kinds of software tools, such as Geographic Information System (GIS), MatLab, and Tableau.

Our XSLICE enriches the existing visualization tools and provides some convenient functionalities, such as many kinds of depth cross-sections. NASA's Panoply (2024) can graph many cross sections too, but has a much more complex interface that does not directly allow quick switching between multiple datasets. NASA's Worldview (2024) does have a simpler interface but lacks the complexity to fine-tune the plotting parameters of the climate variables, as discussed in Carn (2021). Another NASA climate data visualization in 3D, named DV3D, attempts to have a friendly interface compatible with R, MATLAB, ParaView, and others Maxwell (2012). DV3D is a tool

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

in the Ultra-scale Visualization Climate Data Analysis Tools (UV-CDAT) consortium for gridded Earth systems datasets (Williams et al. 2013). A new development of this interpretable form of data visualization is interactive visualization of 3D data cubes with Jupyter notebooks (Söchting et al. 2025). The Royal Netherlands Meteorological Institute (KNMI) developed a tool called Climate Explorer that shows maps and time series for both paleoclimate and modern data (KNMI 2025). Since 2012, Climate Change Institute at the University of Maine has been developing a tool called Climate Reanalyzer which now has the capability to display climate data and their interpretation at different timescales, such as current weather, forecast maps, and climate model outputs (Climate Change Institute 2025). The Copernicus Climate change service also provides a suite of data and visualization services for customized indicators of climate impacts in energy, agriculture, insurance, health and others (Buontempo et al. 2022).

Having learned from the aforementioned tools, we design XSLICE also with Jupyter notebooks for both classroom instruction and scientific research. It offers multiple services: (i) visualizing six types of cross sections (i.e., choosing any two out of four coordinate variables: x, y, z, t), which can be highly customized through cropping; (ii) highly customizable visualization with custom text fonts, text size, color maps, dark mode, and more; and (iii) various image saving options including png, jpg, and pdf. In this way, XSLICE helps overcome the various obstacles facing people who are not proficient with computer coding but wish to visualize netCDF datasets, since XSLICE allows users to use a computer browser to scan through a dataset.

The current version of XSLICE posted on GitHub is tailored for GODAS data. However, future releases will incorporate flexible mechanisms to interpret user-provided data in several formats such as .csv and .txt. In addition, future updates will add the capability of data extraction - enabling users to export the digital data for any figure produced by XSLICE.

The sections of this paper are as follows: Section 2 explains the methodology of this visualization tool and also provides an XSLICE tutorial; Section 3 describes the main features of XSLICE through climate dynamics examples using slider buttons on the XSLICE dashboard; and Section 4 includes conclusions and discussion.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

2. Methodology

a. Generality

XSLICE uses a Python package called *ipywidgets* for the graphical user interface Podrzaj (2019). XSLICE uses the following key features of `Ipywidgets`:

(a) Range sliders, used for cropping, time selection, or location selection;

(b) Drop-down menus, used for selecting file types for saving images, color maps, Hovmöller diagrams, text fonts, and more;

(c) Select menus for selecting datasets to be visualized; and

(d) Toggle buttons for selecting which type of cross-section to graph, and for toggling the view environments, such as “dark mode.”

We have designed our XSLICE configuration to allow updates with more `Ipywidgets`, when they are necessary for certain datasets. To support the updates, XSLICE has been created to meet the following standards:

- Easy to display spatial maps for all the six cross-sections in the following coordinates combinations: lat-lon, lat-depth, lon-depth, lat-time, lon-time, depth-time;
- Easy to make high levels of customization with visually appealing colors;
- Easy to update with new datasets and features; and
- Easy to save images in a variety of file types, such as pdf, eps, png, and jpg.

The computer code for XSLICE is split across four Python files:

(i) Data download, which will automatically download data from data sources, such as NOAA and NASA, generate a new netCDF file to be used for Hovmöller diagrams, and store all the downloaded data in a separate folder;

(ii) User interface, which is primarily used for the creation and implementation of new widgets;

(iii) XSLICE collection of functions, where new functions and features are implemented; and

(iv) Output, which combines the user interface with functions to display results.

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b. Graphing

Our Hovmöller diagram visualization is made possible through concatenating the netCDF files in the time dimension through a Python package called *xarray*. This concatenating procedure takes extra storage space of a user's computer. In our GODAS example, we concatenate annual files from 1980 to 2022 in the first axis, which is time. The resulting files for potential temperature, salinity, u-current, and v-current have a total approximately 30 GB of storage space. Not all users may have this much storage space for data visualization. For this case, we have an XSLICE version without the Hovmöller function. This version uses less than 1.0 GB of disk space in the case of the GODAS data.

XSLICE generates figures using the Python software package named *matplotlib*. The package includes the tools *Basemap* for graphing latitude-longitude maps and *countourf* for all other cross-sectional figures. The cropping function of XSLICE re-plots the dataset based on the new indices determined by the sliding widgets. A drop-down menu provides strings that contain arguments of the functions for figure update.

Toggle buttons are associated with if-else statements in the Python code which determines the direction the code follows, based on which of the if-else statements is true. For example, if the toggle button for *Dark Mode* is on, then the variable *dark* is true and the following code will run:

```
import matplotlib.pyplot as plt
...
if dark:
    plt.style.use("dark_background")
```

If the toggle button is off, then the code skips over everything indented after the if-statement.

c. About the GODAS data

GODAS (2024) is an ocean reanalysis dataset that assimilates observed data into an ocean general circulation model. The GODAS monthly data have $\frac{1}{3}^{\circ} \times 1^{\circ}$ latitude-longitude resolution, 40 depth layers, with temporal coverage from January 1980 to the present. The GODAS dataset may be downloaded from the NOAA website by running

```
from data_download import download_data
```


Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

```
download_data()
```

from the XSLICE interactive Python notebook interface. This downloads all of the GODAS data from the NOAA website to a new folder on the user's computer.

For the GODAS dataset, our x, y, z, t variables are specifically explained as follows.

- Longitude x: 360 longitudes at 1-degree resolution, ranging from 0° to 359°;
- Latitude y: 418 latitudes at 1/3-degree resolution, ranging from 74.5°S to 64.5°N;
- Depth z: 40 layers of different depth thicknesses: The complete depth values of 5, 15, 25, ..., 4736 meters are given as an array and can be found from GODAS website (GODAS 2024); and
- Time t: 12 months per year. Due to the XSLICE requirement of 12 months per year, the data of the months from the most recent year are excluded from the data downloading process.

d. XSLICE tutorial

The user can download the XSLICE zip file from GitHub. The zip file contains Python (`.py`) files that are responsible for the functions and graphical user interface for XSLICE. The zip file also has an interactive Python notebook (`.ipynb`) file for a user to run XSLICE.

The data downloading cell in the Python notebook environment needs to run only once, in order to get the data to the user's local computer. This downloading process may take a few minutes or longer, depending on internet speed. The good thing is that the user will no longer need to run the downloading cell again in the future use. Accidentally running the cell again does not do any harm, but delays the execution of the remaining XSLICE tasks.

From here, the user will see the user interface shown in Fig. 1. The first tab, *Data*, contains two selection menus between datasets and how the dataset is altered locally by the user's computer.

In our GODAS example, there are four datasets to choose from:

- *pottmp*, or potential ocean water temperature;
- *salt*, displaying salinity in $\frac{g}{L}$;
- *ucur*, displaying the u-current, i.e., speed of the east-west zonal ocean water flow; and

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

- *vcur*, displaying the v-current, i.e., speed of the north-south meridional ocean water flow.

This version of XSLICE allows a user to have four choices to alter the raw data: *None, Mean Subtracted, Standardized Anomalies*, and *Detrended Anomalies*. To look at the raw data, set *Alter* to *None*. The user may also view anomalies (i.e., the temporal "mean" of the selected month, say January, in the entire data period removed from the data) by choosing the *Alter* button *Mean Subtracted*, or standardized anomalies (i.e., the anomalies divided by standard deviations) by choosing *Standardized Anomalies*, or even detrended anomalies (i.e., with linear trend removed from the mean-removed anomalies) by choosing *Detrended Anomalies*. Here the "standard deviations" also refer to the selected month, say January.

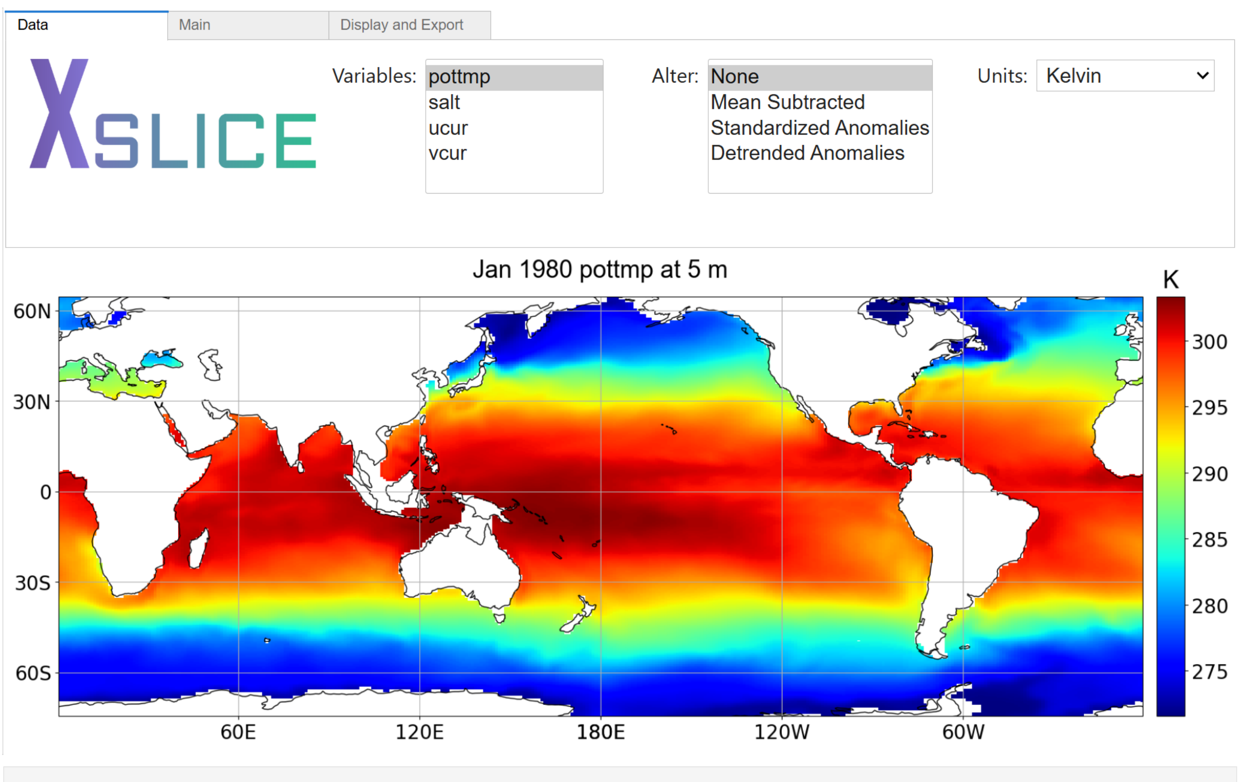

FIG. 1. The XSLICE interface when XSLICE is first loaded the Python notebook.

Figure 2 shows the *Main* button and its functions for x, y, z and t dimension values that help a user to slice a proper cross-section. To choose time, navigate to the *Main* tab. The following sliders appear: *Month, Year, Depth, Latitude*, and *Longitude*. *Month* is a single slider (i.e., with only one empty circle to move). A user can move the slider empty circle to select a month, e.g., 1

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

for January, and 12 for December. *Year* a dual slider with two empty circles that allow a user to choose the two end points of a time interval, say, 1980 - 2021. The *Depth, Latitude,* and *Longitude* sliders are also dual sliders that allow a user to adjust the corresponding intervals for the purpose of spatial crops (as we will see later in Section 3b of the paper).

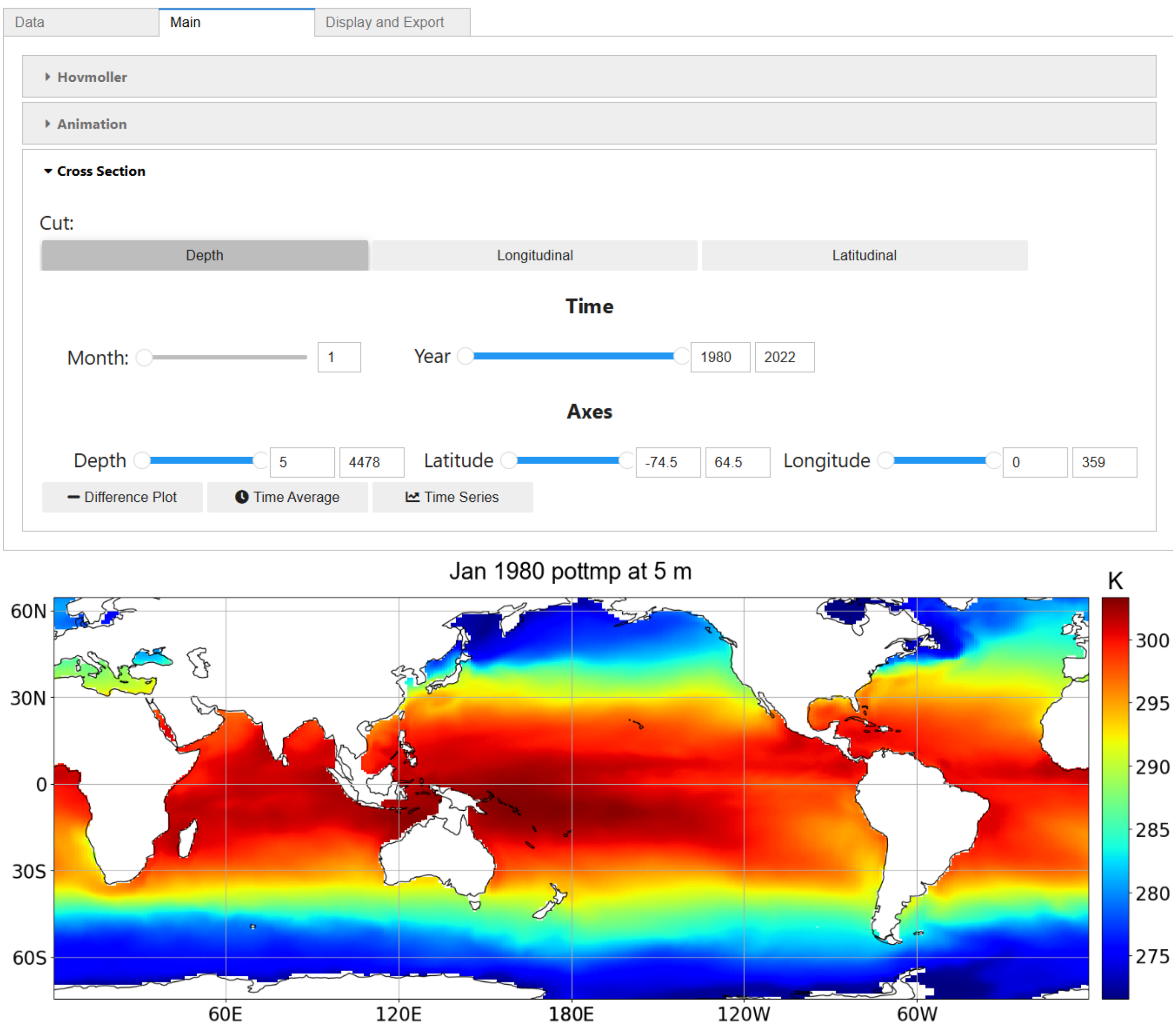

FIG. 2. XSLICE Main tab

The *Display and Export* button allows a user to choose different color scales and different file formats for saving a figure. The user may click the drop-down menus and then click the desired color scale. If he likes the cross-sectional figure, the user can save the figure as a file with specific format, such as pdf, jpg, or png.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

The two toggle buttons at the top left of the interface display are for visualizing Hovmöller diagrams, which are spacetime diagrams with a spatial dimension as the horizontal axis, and time as the vertical axis. See Persson (2017) and Shen and North (2023). The Hovmöller diagram plots from a selected month (e.g., June) from the beginning year indicated by the left empty circle button on the *Year* slider to the end year indicated by the right button. The horizontal axis of the Hovmöller diagram is determined by the spatial slice options, e.g., a slice along the equator over Pacific from 150°E to 250°E, equivalent to 110°W. The spatial domain of the longitude line slice, say a longitude interval, are further determined by the left side of the two other variables, e.g., latitudes and elevations (or depth).

XSLICE can perform zonal average, meridional average, or depth average for the other two fixed spatial dimensions to produce a time series for the average. The user can choose which average to take based on the cross-section toggle buttons: *Latitude*, *Longitude*, and *Depth*. For example, the user can select *Longitude* as the cross-section, 5 meters as the first value of the depth slider, and 0.17 as the first value of the latitude slider. By default, the average is in the longitude range of 0-360; however, this range can be adjusted, e.g. 120-220 if the interest is for the Pacific. This results in a zonally averaged time-series plot at the equator.

XSLICE can display the spatial differences between any given two dates. Clicking on *Difference Plot* button will allow a user to choose the two dates using the time slider. The spatial differences are the result of the first date minus the second date. For example, if December of 1997 and December of 1998 are chosen, then the temperature differences between a strong El Niño and a strong La Niña will show.

XSLICE can also compute a time average and display this data, Clicking on the time average button will compute and display the time average of the data across the selected years.

XSLICE has a background color selection. This version of XSLICE has two background color selections: white as default, and black.

3. Example Usage of XSLICE

Figure 3 demonstrates a horizontal slice of the oceanic potential temperature field on the xy-plane for a fixed time t being August 2017 at a fixed depth z at 175 meters. This type of figure is commonly used as the global climate map in the climate science community and the general public, and is

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

also known as the latitude-longitude filled contour plot in the data science language. This figure allows a user to visualize equatorial upwelling. The figure indicates that the water temperature in the equatorial zone is not the hottest and is even several degrees colder than the water temperature in the sub-tropical zones, particularly around 15°N or 15°S in the western Pacific. This is due to the upwelling of deeper and colder water in the equatorial zone in the depth range approximately between 150 and 400 meters. To produce this figure, the user simply clicks on *Depth* in the cross section options, then move the *Month* slider to "8" for August and moves the *Year* slider from the left to "2017." The image may be cropped by the *Latitude* and *Longitude* sliders, which are in the lower right position of the control panel, but are above the color figure. The user can move the latitude and longitude sliders to adjust the domain size of visualization. The particular image of Fig. 3 shows the entire latitude-longitude domain of GODAS at the depth of 175 meters, i.e., the latitude and longitude sliders cover their entire range. The latitude range from 0 to 417 in the *Latitude* slider means that the GODAS data have 418 zonal grid lines from 75°S to from 65°N. The value 0 in a Python code corresponds to 1 in natural number, representing the 75°S zonal grid line. Similarly, the value 417 in a Python code corresponds to the 418th zonal grid line at 65°N. The *Longitude* slider's range is from 0 to 359, corresponding to the 360 meridional grid lines, with 0 corresponding to 0.5°E, and 359 to 395.5°. The meridional grid lines are uniform with one degree resolution. The *Depth* slider ranges from 0 to 39, corresponding to 40 layers of the GODAS reanalysis model. The value 15 in Fig. 3 means 16th layer from top and corresponding to depth 155 meters, shown in the figure caption. See GODAS (2024) for the detailed definition of the netCDF data arrays and grid lines.

To see the depth structure of the equatorial upwelling, we can use XSLICE to cut a latitude-depth slice. The slice, or cross-section, can be made by adjusting the sliders with fixed longitude and time. Figure 4 shows a result for August 2017 and longitude 180.5°. To produce Fig. 4, we select the *Longitude* button as the cut. Move the *Longitude* slider to the desired cross-section position 180.5°, or index 180 for the left circle of the *Longitude* dual slider on the control dashboard. The *Depth* slider is cut towards the bottom by moving the right circle of the slider to 27, corresponding to the 28th layer from surface. This slider can be adjusted to show more or fewer depths in the vertical direction. As for the *Latitude* slider, Figure 4 shows the entire range from 0 to 417. However, if the user wants to focus on the equatorial upwelling and ignore the Arctic and Antarctic regions,

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

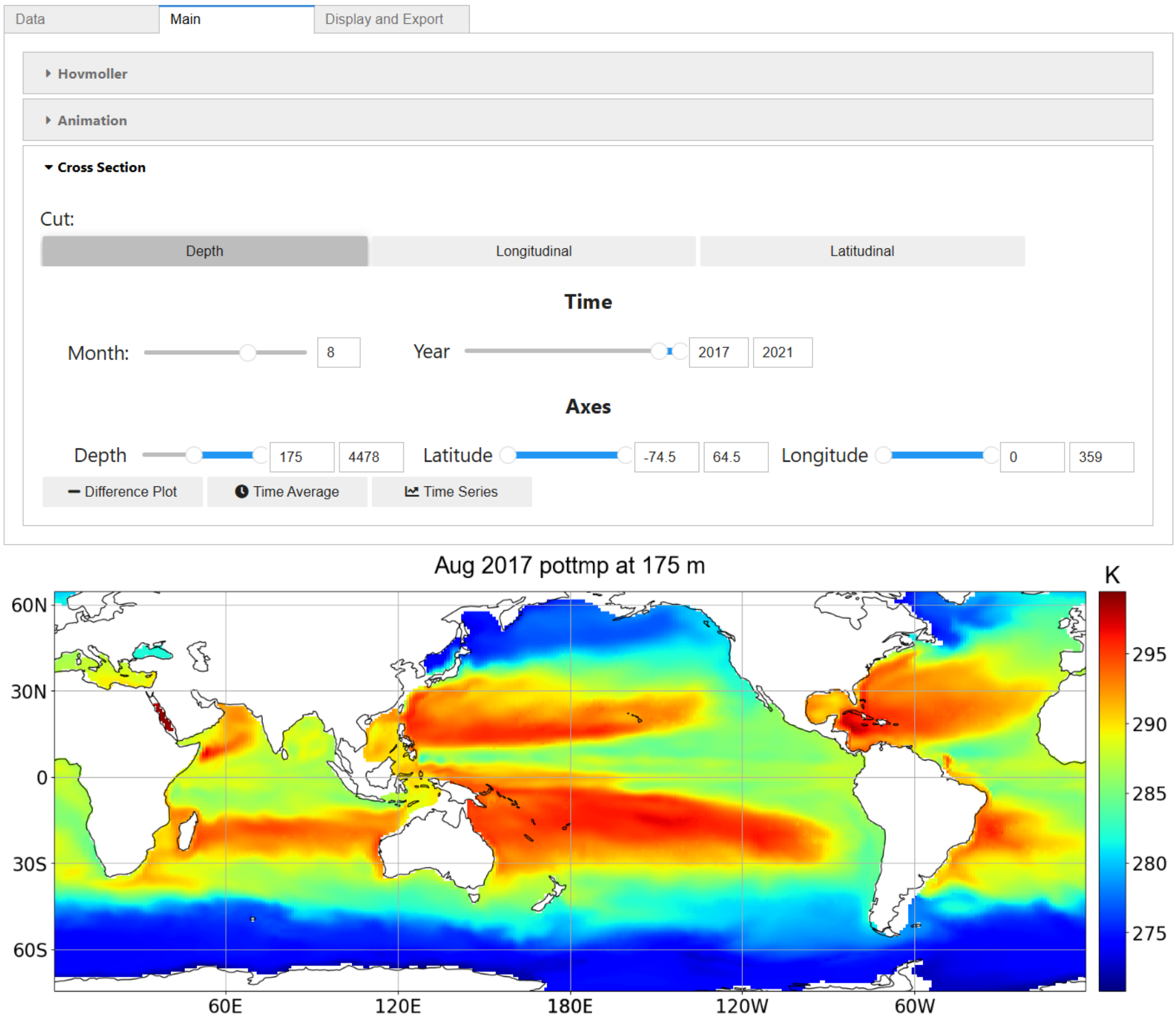

FIG. 3. A latitude-longitude map shows the equatorial upwelling on the horizontal xy-cross section of the potential temperature field for August 2017 at the depth of 175 meters. The figure was produced using XSLICE.

the *Latitude* slider can be adjusted from both ends to crop out the zonal regions. To search for the years with strong equatorial upwelling, move the left circle in the *Year* slider to visually compare years and see which years have the stronger equatorial upwelling phenomena. We choose to show August 2017 as our choice of a strong equatorial upwelling event in Fig. 4. The figure shows a clear pattern in the region below 150 meters and 20°S and 20°N: The near-equator temperatures are cooler than the off-equator regions. The warm-cool-warm temperature distribution from south to

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

north in the region is non-uniform and forms a triangular shape. The strongest equatorial upwelling signal in the event appears to be at the depth around 200 meters.

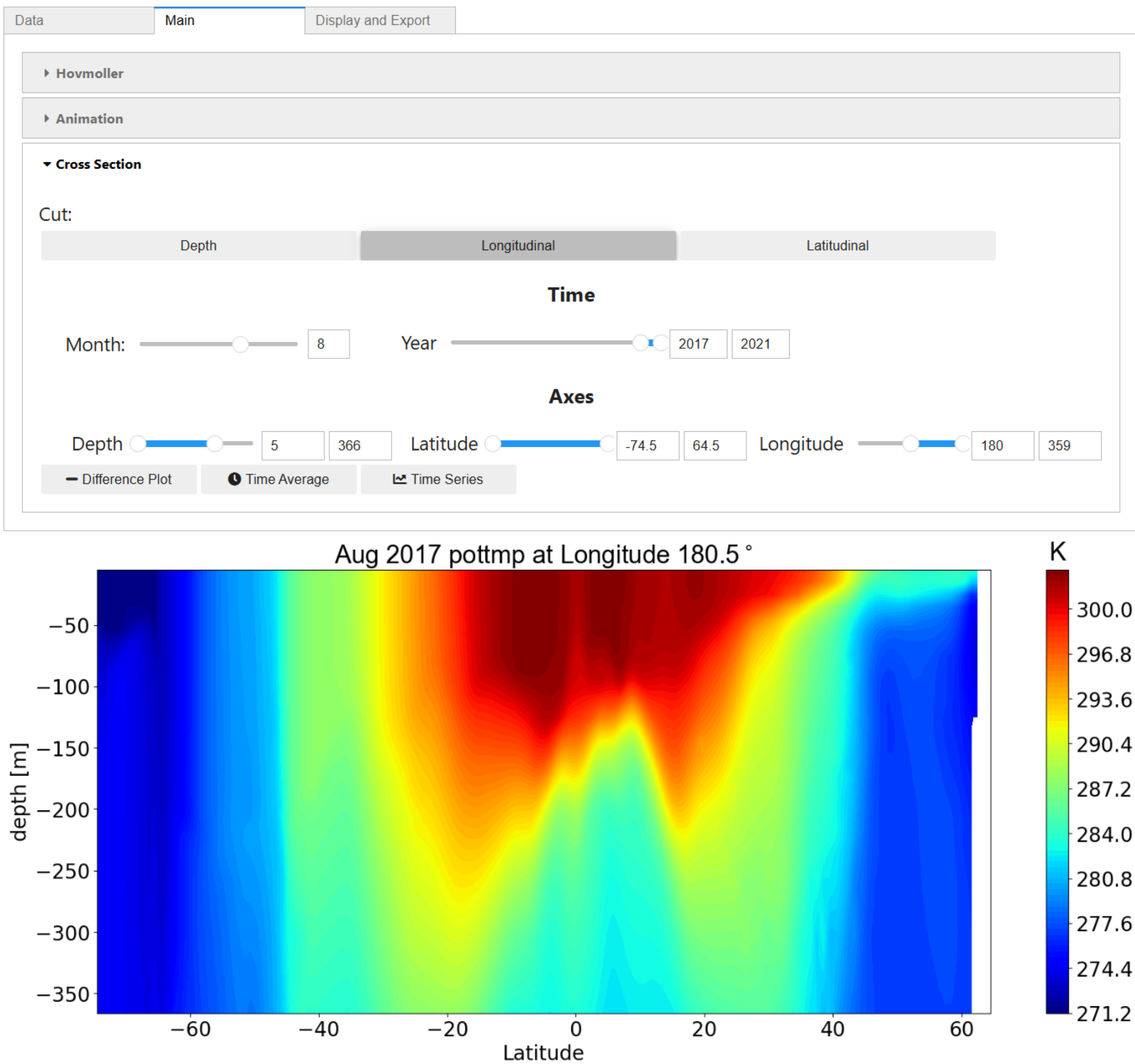

FIG. 4. A latitude-depth yz cross-section of the oceanic potential temperature field shows the equatorial upwelling of August 2017 at the fixed longitude 180.5°E across latitudes.

Cross-sections are not only in the spatial dimensions like xy, yz, and zx, but also in the spacetime dimensions like xt, yt, and zt. The spacetime maps are called Hovmöller diagrams, which is included in the *Main* drop down menu. Pressing the *Hovmoller* toggle button in the top left corner of the control panel leads to three cross-section choices: xt, yt, and zt. For example, the xt map

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

is the longitude-time Hovmöller diagram. Figure 5 shows the El Niño signals over the eastern Pacific at the equator. The strongest red lines are when the temperatures are the highest. The three strongest red lines correspond to the three strong El Niño occurred in the boreal winters 1982-1983, 1997-1998, and 2015-2016. There are other red lines, but not as prominent as these three thick lines.

This example shows a way to visualize the quasi-periodic El Niño phenomena using full values of the temperature data in the range from 293.8K to 301.9K. This is different from the traditional display of El Niño using temperature anomalies with both positive and negative values centered around zero. Our way of showing the full values of temperature is supposedly easier for the general public to understand the El Niño history and dynamics. This way is also helpful for teaching the El Niño climate phenomenon in school classrooms, since explanation of the intermediate concept of anomalies may distract school children's attention from the key point: the warming of the eastern tropic Pacific, as discussed in some education papers, e.g., Nickerson et al. (2023), Page et al. (2024), and Shen and Somerville (2020).

Figure 5 has another feature: different geometric extents of El Niño. One can see the red line extents are different. The longer ones extend all the way to the right end correspond to the eastern Pacific El Niño (EPEN) defined by Yu and Kao (2007) and Yu and Kim (2013), while the ones mainly confined to left side of the figure correspond to the central Pacific El Niño (CPEN). For example, the 1982-1983, 1997-1998, and 2015-2016 El Niños are EPEN, and the 1992-1993 El Niño is CPEN. See Mamalakis et al. (2018).

Of course, climate researchers and college students can still use anomalies and XSLICE to visually interrogate various kinds of climate dynamics for physical insight. With the assistance from XSLICE visualizations, they may perform further detailed quantitative analysis of the data and gain better understanding. However, this version of XSLICE does not have statistical hypothesis testing functions.

To reproduce Fig. 5, click on the Hovmöller accordion to toggle on the *Hovmoller* button and select *Cycle* for the seasonal cycles. Seasonal, annual, and monthly cycles are used to demonstrate different patterns. Whether a user wants to focus on a certain month, season, or year as a whole will produce graphs based on only the data selected. To change the range of years, slide both ends of the *Year* slider to fit the desired year range. The *Cut* feature now demonstrates which of the

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following spacial dimensions to view on the x axis. Then select specific values for the other two spatial dimensions: Depth and latitude. For Fig. 5, the depth is 5 meters at -1.0 degree latitude. The longitude range has been selected to only view the tropical Pacific, in order to visualize the quasi-periodic El Niño pattern which is often strongest over the region for the top ocean layers within 50 meters. See Bui et al. (2023), Lafarga et al. (2023), and Shen et al. (2017).

a. Interaction (I)

Figure 6 is a xz cross-section (i.e., the longitude-depth cross-section) near the equator with latitude fixed at 4.1672°S and time being December 1996. This figure is to show the depth pattern in a 3D La Niña, while conventional El Niño Southern Oscillation (ENSO) studies often only display the latitude-longitude maps, i.e., the xy slice at the sea surface. In contrast, our XSLICE technology allows a user to quickly visualize the 3D ENSO structure by scanning longitude-depth cross-section like Fig. 6, latitude-depth cross-section like Fig. 7, or latitude-longitude cross-section but at different depth levels like Fig. 3. Figure 6 shows a clear diagonal separation between two temperature zones in Pacific: A warm one above 294K in the western shallow region and a cool one in the eastern deep region. This December 1996 La Niña pattern displays the eastern tropical Pacific's zone of relatively cooler temperature around 290K or lower underneath the surface pushes up to the surface. This agrees with a a cooler sea surface temperature (SST) in the eastern tropical Pacific during a La Niña, often described in textbooks and research papers, e.g., Wallace and Hobbs (2006) and Li et al. (2024).

In contrast, during an El Niño period, the eastern tropical Pacific's zone of relatively cooler temperature around 290K or lower underneath the surface sinks down, i.e., the blue region in the east retreats to the deep ocean while the relatively warmer temperature zone near the surface extends to the east. This agrees with the warm episode of the eastern or central tropical Pacific's SST in an El Niño. This warm-extension and cold-retreat can be seen by comparing Figs. 6 (for La Niña) and 7 (El Niño). This is consistent with the 3D temperature and heat context studies of Lafarga et al. (2023), Roemmich and Gilson (2011), Shen et al. (2017), and Wu et al. (2019).

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

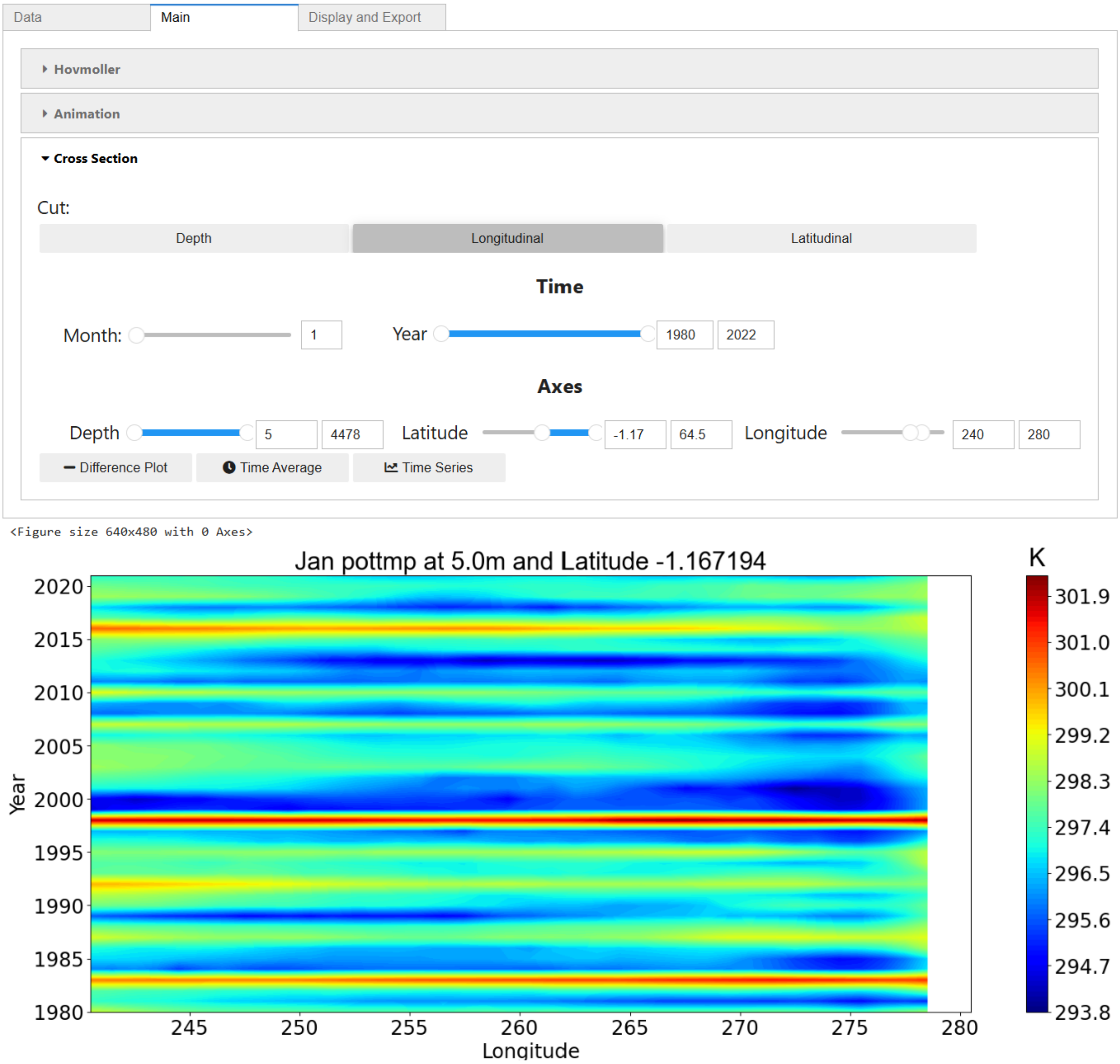

FIG. 5. A Hovmöller diagram on tropical Pacific from 1980 to 2022 shows El Niño signals indicated by red lines, depicting the warm surface-layer water temperature in the region during the El Niño time periods with specific time marked on the vertical axis. This figure helps to visualize the spacetime properties of El Niño, e.g. central Pacific El Niño for 2015/16 winter, and eastern Pacific El Niño for the 1997/98 and 1982/83 winters.

b. Cropping (C)

When moving *Year* slider a little to 1997, we observe an sudden and dramatic change in the pattern across the Pacific from December 1996 to December 1997. The December 1997 potential

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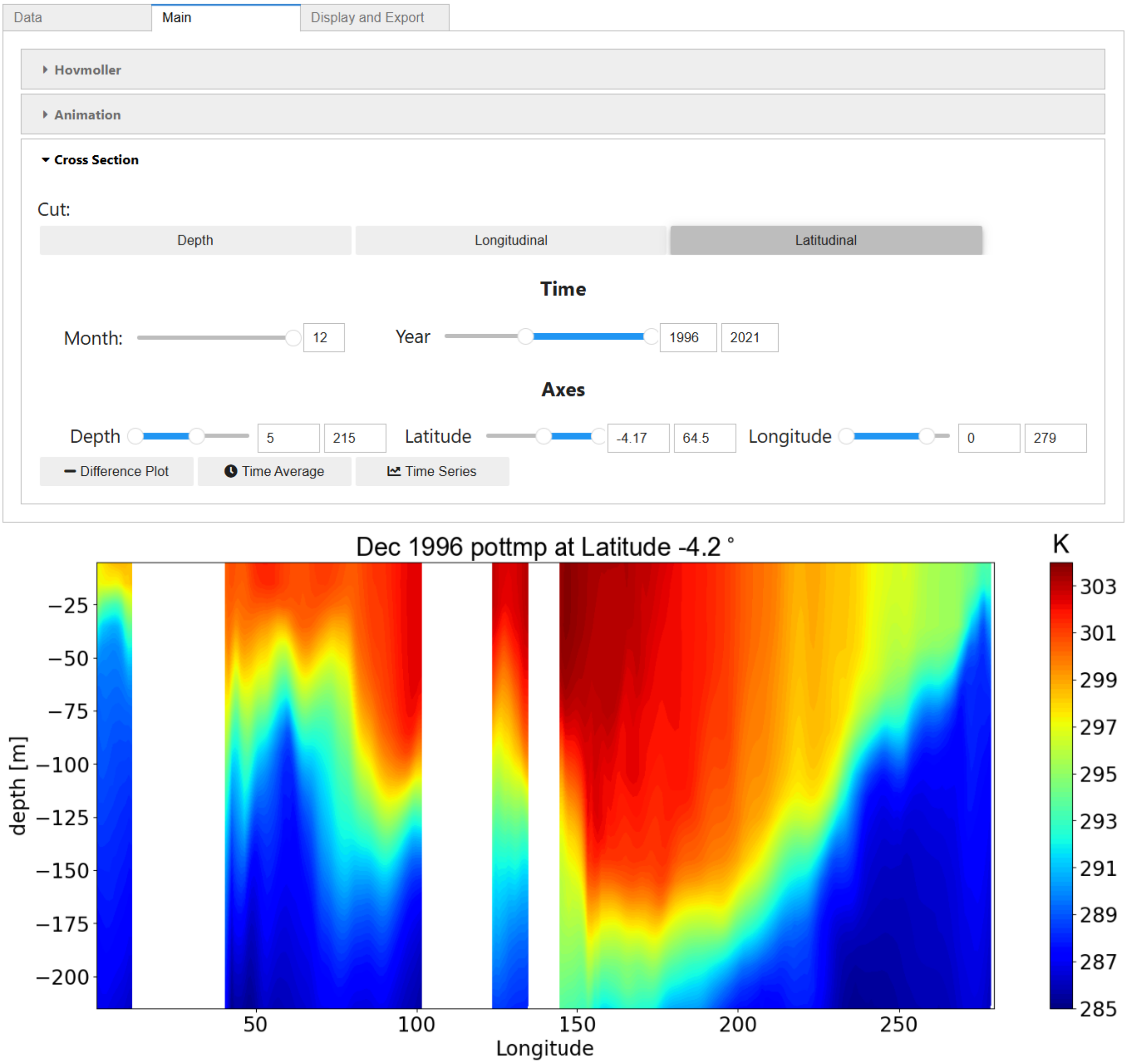

FIG. 6. Longitude-depth cross-section for the GODAS potential temperature at latitude -4°S and time being December 1996, which was a non-El Niño month.

temperature is shown in Fig. 7 as a longitude-depth cross-section. The figure displays an almost uniform warm temperature, indicated by the red color, in the top 100 meters across Pacific. This pattern is in a sharp contrast to the red pattern in Fig. 6, where the warm temperature in the tropical Pacific is located only in the western Pacific and is at a deeper layer reaching around 175 meters. The eastern tropical Pacific temperature is low. The warm and cold temperature has a

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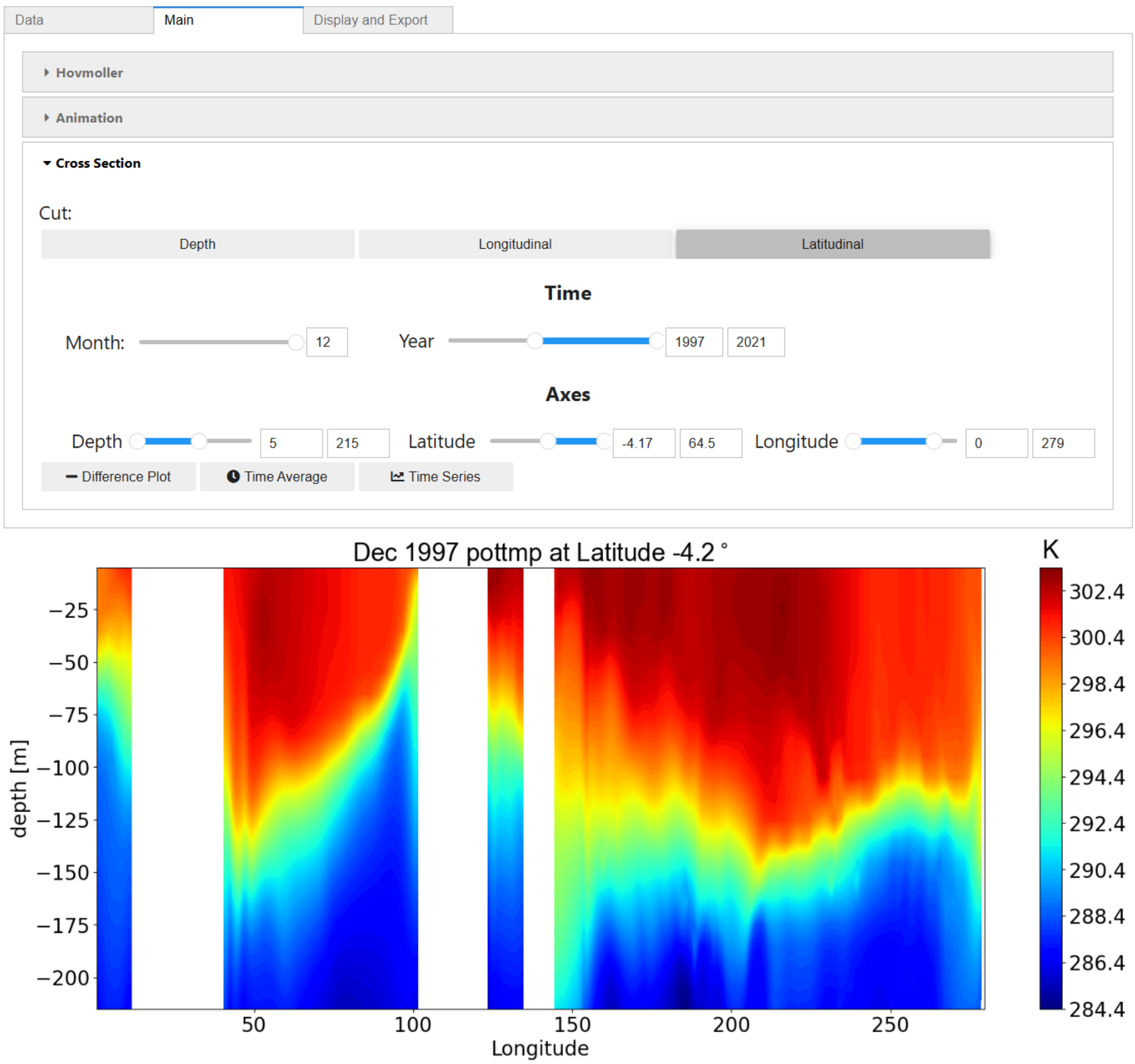

FIG. 7. Longitude-depth cross-section for the GODAS potential temperature at latitude -4°S and at time being December 1997, which was a month of strong El Niño.

clear diagonal separation line at 294K, as discussed earlier. The line's slope is approximately 1.5 meters per east-west longitudinal degree.

In Fig. 6's top two layers of 5 and 15 meters, the east and west difference as large as approximately 11K, from 293K to 304K. It is because of this large difference of water temperature on the same latitude in Pacific that makes the ENSO dynamics research important and interesting. See Li et al. (2024) and Mamalakis et al. (2018).

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

Figure 7 shows a temperature increase in the eastern tropical Pacific from surface to the depth about 120 meters. For example, at 100 meters depth and 260 longitude (i.e., 100°W), the December 1997 temperature was 299K, while that for December 1996 was approximately 288K. This 11K difference between two Decembers is approximately equal to the upper bound of the temporal variation in sea surface temperature for any given longitude near the equator. Figures 6 and 7 also clearly display the El Niño cooling underneath the surface, particularly in the depth range between 100 and 200 meters, in the western tropical Pacific. For example, at the depth of 125 meters and longitude 160°E, the December 1997 temperature was 295K in contrast to 300K in December 1998.

The large temperature variations in the tropical Pacific occur not only on the surface but also in the deep layers up to 200 meters. Studies have already shown the importance to explore 3D ENSO dynamics Lafarga et al. (2023). Detailed understanding of 3D ENSO dynamics may help explain the ENSO impact on weather, or accurately project the future precipitations Li et al. (2024), Mamalakis et al. (2018). The importance of 3D dynamics is also shown in California Coast Current Crawford et al. (2018) in the depth from surface 33 meters and in the equatorial upwelling in the depth between 150 and 400 meters. See Lafarga et al. (2023).

Of course, XSLICE can display gradual changes in various cross sections when sliding in *Depth*, *Latitude*, and/or *Longitude* dual sliders. This quick method of visually comparing adjacent data cross-sections can be used to find the maxima and minima of a certain variable, such as temperature, pressure, u-wind, or v-wind. Similar, XSLICE can easily display Walker circulations and Hadley cells when XSLICE is applied to the atmospheric reanalysis data described in Bui et al. (2023).

Various interactive widgets in XSLICE allows intuitive fine-tuning of each cross-section to find the most desirable image. The arrow keys on a computer keyboard are used for precise parameter tuning. By clicking on the end of the slider you want to move, you can quickly tap the arrow keys on your computer keyboard to shift the sliders left and right for conveniently and precisely changing the slider value. For this example, when the slider bar adjusted is *Year*, Pressing the right arrow key on your keyboard will move forward in time by one year whereas pressing the left arrow key on the keyboard will move the data back in time by one year. If you want to analyze various layers of the ocean, on a latitude-longitude cross-section, the user would simply click on the end

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of the *Depth* slider and press right arrow key to go one layer deeper into the ocean and press the left arrow key to go one layer towards the sea surface.

Cropping can also be done through the adjustment of the two control circular buttons on the dual sliders. Looking at the XSLICE dashboard, it is intuitive that a user can crop using both spatial intervals and time intervals. The spatial intervals can be determined by the dual sliders of *Depth, Latitude*, and *Longitude*, while the time interval can be determined by the dual slider of *Year*. This cropping can be done in the *Depth, Latitude*, and *Longitude* Cut tabs.

The maximum domain of a cross-section corresponds to the maximum extend of the two variables for the cross section. Figure 8 is such a map for the entire world with the full extend of latitude and longitude. This figure is a salinity map showing high salinity in the Mediterranean and Red sea, about 37 - 42 g/kg. Due to these large salinity values, the vast majority of the salinity levels on the other sea surface regions show little variation.

However, you can crop the figure and focus the image on the ocean regions just around the Americas in order to display the salinity variations better. You slide the *Latitude* and *Longitude* sliders inward until they focus on the desired region, as shown in Figure 9. This figure enables you to analyze salinity variations between 31 and 38 g/kg over the Pacific and Atlantic oceans. This cropping and fine-tuning allow you to visualize the desired data with greater precision.

This example has done cropping in both dimensions. There are extreme values around the tip of South America and near the Antarctic. These regions may be cropped out in order to better highlight the salinity patterns in the Pacific and Atlantic. The left side of the latitude slider can be moved to the 103rd index to crop out Antarctica and the tip of South America. The cropping in longitude may lead to the Pacific and Atlantic oceans when the extremes of the Mediterranean Sea, Red Sea, and Baltic Sea are cropped out. This is done by dragging each end of the longitude slider. Sliding from the left end on the horizontal axis will crop out the left side and sliding from the right end of the slider will crop out the right side of the image. Similar logic applies to the vertical axis. Cropping the axes automatically adjusts the figure size such that zooming in to a small area does not result in a graph that is too small. XSLICE automatically resizes the figure to be about the same size as the original plot for legibility.

Figure 8 shows a darker orange color in the Atlantic showing higher salinity than the Pacific, which is emphasized in Fig. 9. The blue region in the Northeast Pacific of Fig. 9 parallels the

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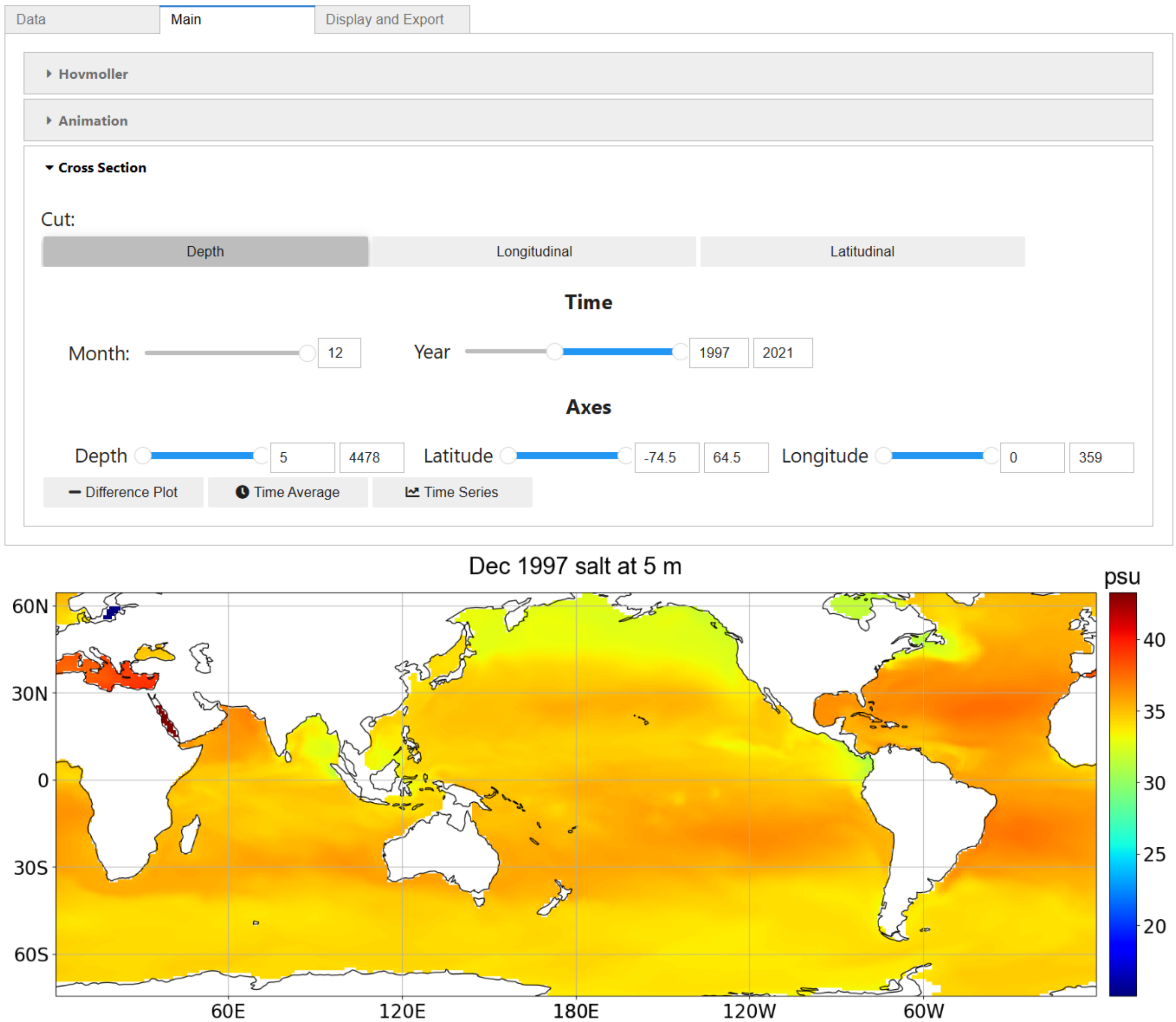

FIG. 8. Latitude-Longitude map of salinity at the top layer of 5 meters thickness in GODAS: December 1997. Mediterranean Sea and Red Sea Salinity is so high that the rest of the salinity looks almost uniform.

light yellow region in Fig. 8. Cropping of the figure also results in cropping of the colorbar. Fig. 8 salinity peaks at over 40 g/L whereas the salinity in Fig. 9 peaks around 38 g/L. The low salinity of Fig. 8 in the Baltic Sea is below 20 g/L whereas the lows of Fig. 9 is about 31 g/L. This shrinks the range of salinity values plotted from over 20 g/L to less than 10 g/L. Shrinking the range of the colorbar means that differences are much more emphasized. This is what allows the user to better visualize the salinity patterns in Pacific and Atlantic.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

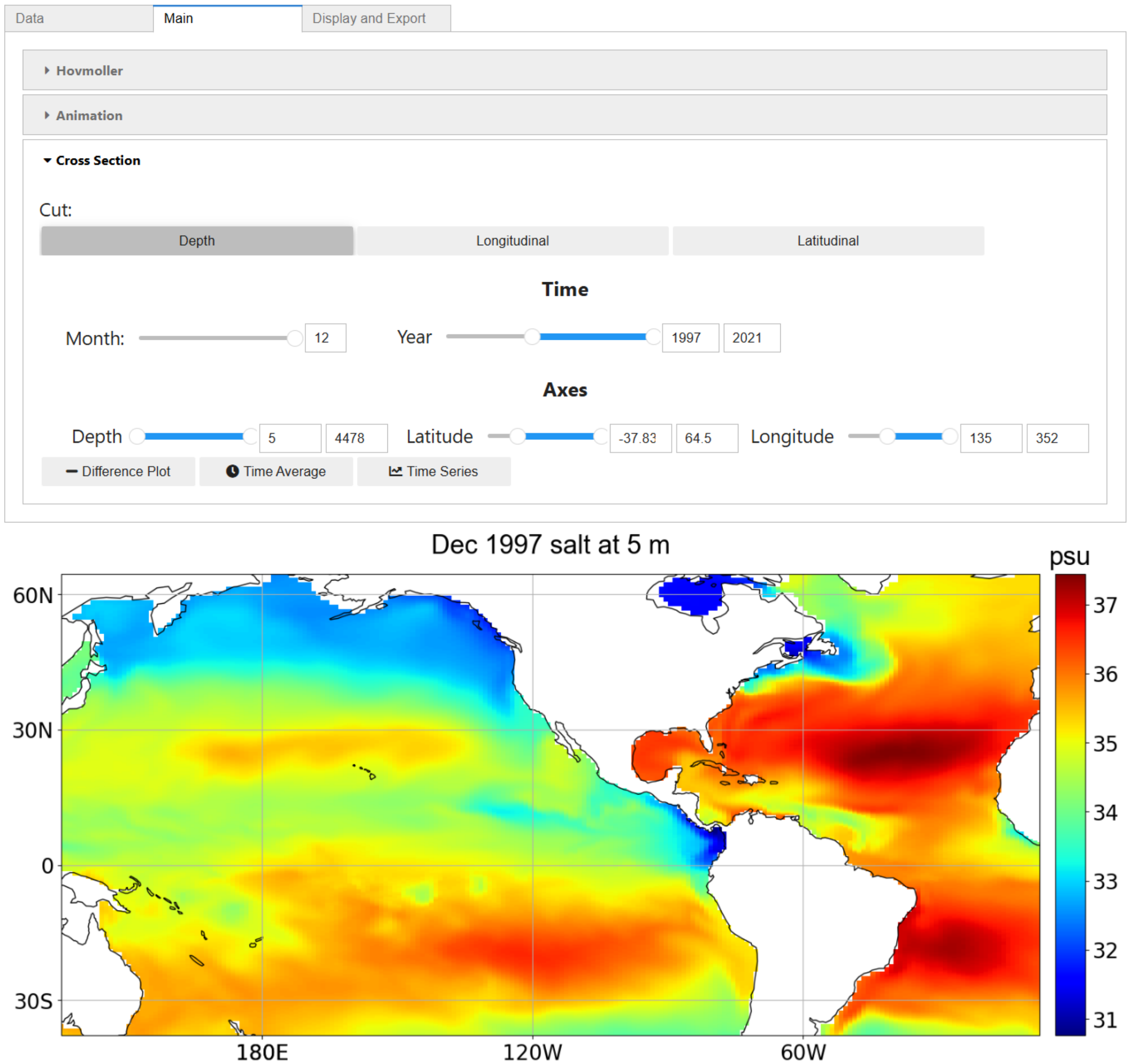

FIG. 9. A cropped Fig. 8 to show variations in salinity over the Pacific and Atlantic oceans.

c. Exporting (E)

The user can export these XSLICE cross-section images, filtered using the interactive widgets feature from Section 3a and the cropping feature from Section 3b in various supported file types. As seen in Fig. 10, XSLICE figures may be stored in the following formats: png, jpg, pdf, eps, and tiff. You may save these images into your computer and use them in papers, PowerPoint presentations, and much more, free of charge.

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You can go to the exporting images interface of XSLICE by moving from the *Main* tab to the *Display and Export* tab by clicking the text. The *Save As* dropdown is selected in order to select how the image is saved to your computer.

d. Additional Color and Display Features

In addition to the basic features to demonstrate the climate dynamics, the XSLICE users may wish to have more artistic choices or educational features. We thus have made a variety of color and display features available, such as color scales, dark mode, variable change and more, as shown in Fig. 10.

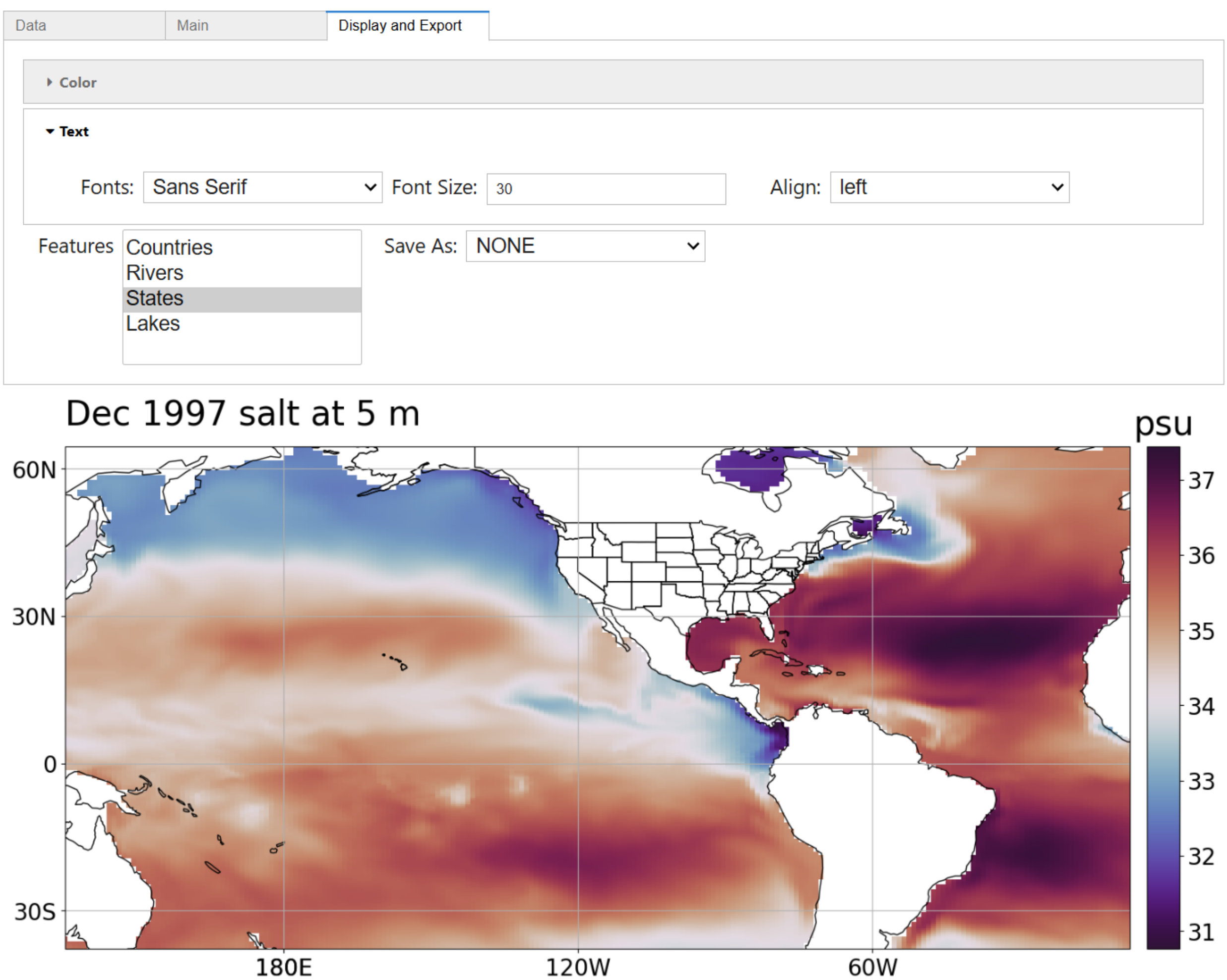

FIG. 10. Additional color and display features that can change the figure's aesthetic for export.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

The user has multiple accordions to open depending on what the user specifically would like to alter about the image. The *Color* accordion has different color scales to illustrate climate patterns for a better color scheme. Using diverging colorbars such as *twilight_shifted* is better at showing the different directions in u-current and v-current data, whereas *greys* may be better at showing salinity with darker spots being high salinity and lighter spots being low salinity. Figure 10 illustrates salinity using *twilight_shifted*. The *Color* accordion also has the option to add hashmarks to the color scale to make it colorblind-friendly and a "Dark Mode" which makes the black background with white text instead of white background with black text as default. In the *Text* accordion, you may select the font, font size, and how to align the title for the image. Figure 10 uses "Magneto" at size 30 and is left-aligned, which is shown in the figure title. Outside of both accordions, XSLICE has a "Features" multi-select option which only applies to the "Depth" cut, showing the countries, rivers, and/or states in the graph.

XSLICE also has functions to compute and visualize detrended anomalies, possesses many types of geographic projections, and creates mp4 animations by using the slider buttons and animation buttons shown in Figure 11. These and some other minor features are self-explanatory for an XSCLICE user and are not explained in detail here.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

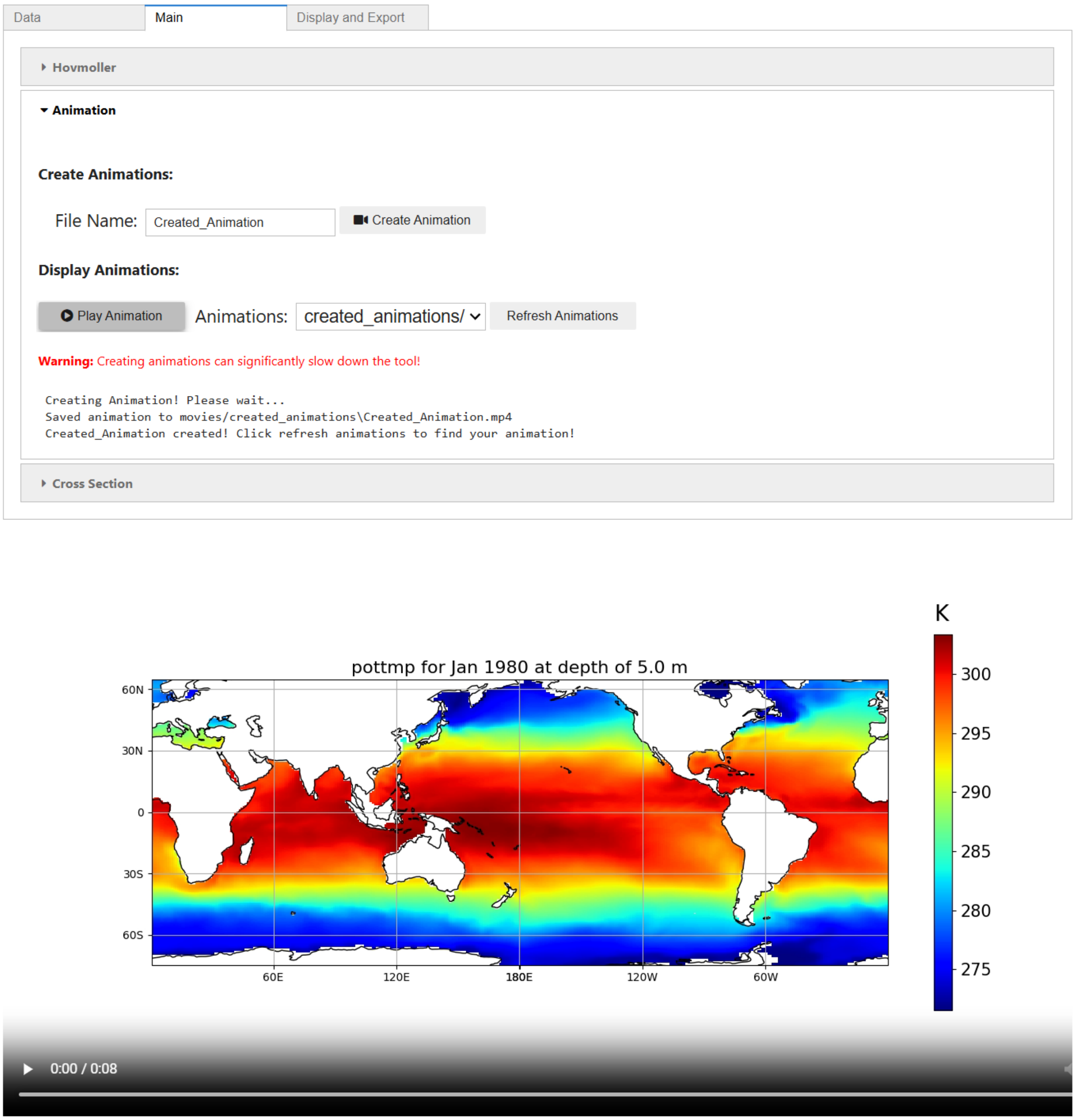

FIG. 11. Widgets for creating mp4 animations.

4. Conclusions and discussions

We have introduced the XSLICE technology for convenient and fast visualization of 4D climate data using cross-section slices. Our introduction has described our Python algorithm and included application examples using the ocean reanalysis dataset named GODAS. Through simple move

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

of the sliders, a user can quickly visualize a climate field as a cross-section in global or regional domains. Six different combinations of spacetime paired variables can be used, such as xy, yz, and xt. The desired XSLICE images in many different formats (e.g., jpg, png, and pdf) can be saved as results. XSLICE allows both climate scientists and the general public to easily scan through 4D (latitude, longitude, depth/altitude, and time) climate model data without proficient computer programming skills. This is a helpful tool for fast model diagnostics, classroom teaching, and conference presentations.

Like a CT scan for a human head, XSLICE is a CT scan for atmosphere and ocean, programmed in Python. The scan may be made as individual cross-sectional maps or an animation of the maps. We caution the user not to use the animation with a long time interval, because by default animation processes a large amount of data and slows the system. We purposefully include an animation example at the end of this paper. XSLICE animation will make motion pictures of the cross-sectional maps. The setup of animation parameters can be entered in the following way. Start with *Cross Section* tab. Followed by clicking on the *Animation* tab. Then a user is able to select animation parameters. For example, if you want to animate the potential temperature at the surface level for January from 1980 to 1990, you can select *pottmp* as the variable, set the depth slider to 5 meters, set the *Year* slider from 1980 to 1990, and then click on *Create Animation* in the *Animation* tab. An mp4 animation file is now created and saved. Click on the *Refresh Animations* button to bring up the new animation mp4 file under the *Animations* dropdown. Finally, you can play the mp4 animation file by clicking on *Play Animation* to show the motion pictures.

Although our examples in this paper are from the ocean reanalyses, XSLICE can be applied to observational and model data as long as they are gridded. For example, XSLICE can be easily applied to visualize the reconstructed 4D oceanic temperature data (Shen et al. 2017), 4D coupled atmospheric reanalysis ERA5 (2024), 3D EOFs for atmosphere (Bui et al. 2023) and for ocean (Lafarga et al. 2023). Of course, XSLICE can be used to examine many climate fields, in addition to temperature and salinity fields described in the examples of this paper. For example, XSLICE can be applied to u-velocity, v-velocity, geopotential height from NCEP/DOE (2024) Reanalysis, many variables in the Coupled Model Comparison Project 6 CMIP6 (2024) datasets, and many parameters from the high-resolution regional WRF (2024) (Weather Research and Forecasting) datasets. Of course, XSLICE can be applied to gridded data from satellite remote sensing.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology*. DOI 10.1175/JTECH-D-24-0113.1.

As a tool for slicing and dicing 4-dimensional datasets, XSLICE has the portability to be applied to any 4D data in practice, in addition to climate science. For example, XSLICE may help with quick visualization and analysis of the 4D flow cardiovascular data from the magnetic resonance imaging (MRI), which is helpful to medical doctors. See Bouaou et al. (2024) and Markl et al. (2012).

In general, XSLICE can serve as an exploratory research tool to gain insight on process dynamics before further quantitative analysis of observations or model outputs is pursued. XSLICE's easiness to use make it attractive as an educational and public outreach tool to inspire and engage in climate science or in a broader range of science and engineering fields.

Accepted for publication in *Journal of Atmospheric and Oceanic Technology.* DOI 10.1175/JTECH-D-24-0113.1.

Statements & Declarations

Acknowledgments

This work was supported in part by the US National Science Foundation (Award # IIS 2324008), the US National Oceanic and Atmospheric Administration (NOAA) (Award # NA24NESX405C0006-T1-01), and the NASA Jet Propulsion Laboratory under the Center for Academic Partnerships (CAP) Program. Thomas Bui and Danielle Lafarga received fellowship support from the NOAA Cooperative Science Center for Earth System Sciences and Remote Sensing Technologies (NOAA CESSRST) under a cooperative agreement grant (Award#: NA22SEC4810016). The detailed suggestions from anonymous reviewers have significantly improved the clarity and rigor of this paper.

Author Contributions

All authors contributed to the study's conception and graphics design. The data selection and numerical analysis were performed by Samuel S. P. Shen and Thomas Bui. The computer code was mainly developed by Thomas Bui, Maximilliano Ramirez and Danielle Lafarga. The oceanic dynamic analysis was led by Samuel Shen, Tony Y. Song, and Efi Foufoula-Georgiou. The first draft of the manuscript was written by Thomas Bui and Samuel S.P. Shen. All authors contributed to the extensive revisions of the manuscript. All authors had read and approved the final manuscript.

Data availability statement. The GODAS dataset can be downloaded from `https://www.psl.noaa.gov/data/gridded/data.godas.html` . The Python computer code for this paper is freely available and can be found on `https://github.com/MaxHinesRamirez/XSlice-Climate-Visualization-`

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