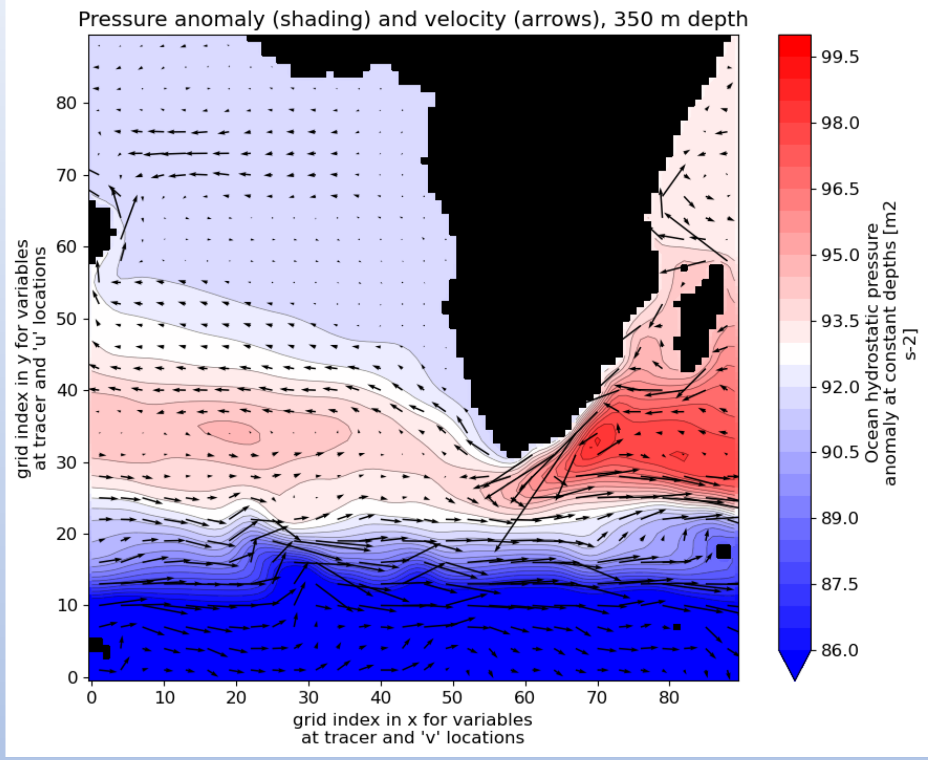
Introducing ECCO to the Next Generation of Oceanographers:

Illustrating Fundamental PO Concepts using the ECCO State Estimate



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UCLA JIFRESSE

ECCO Meeting

January 2023

Jet Propulsion Laboratory
California Institute of Technology

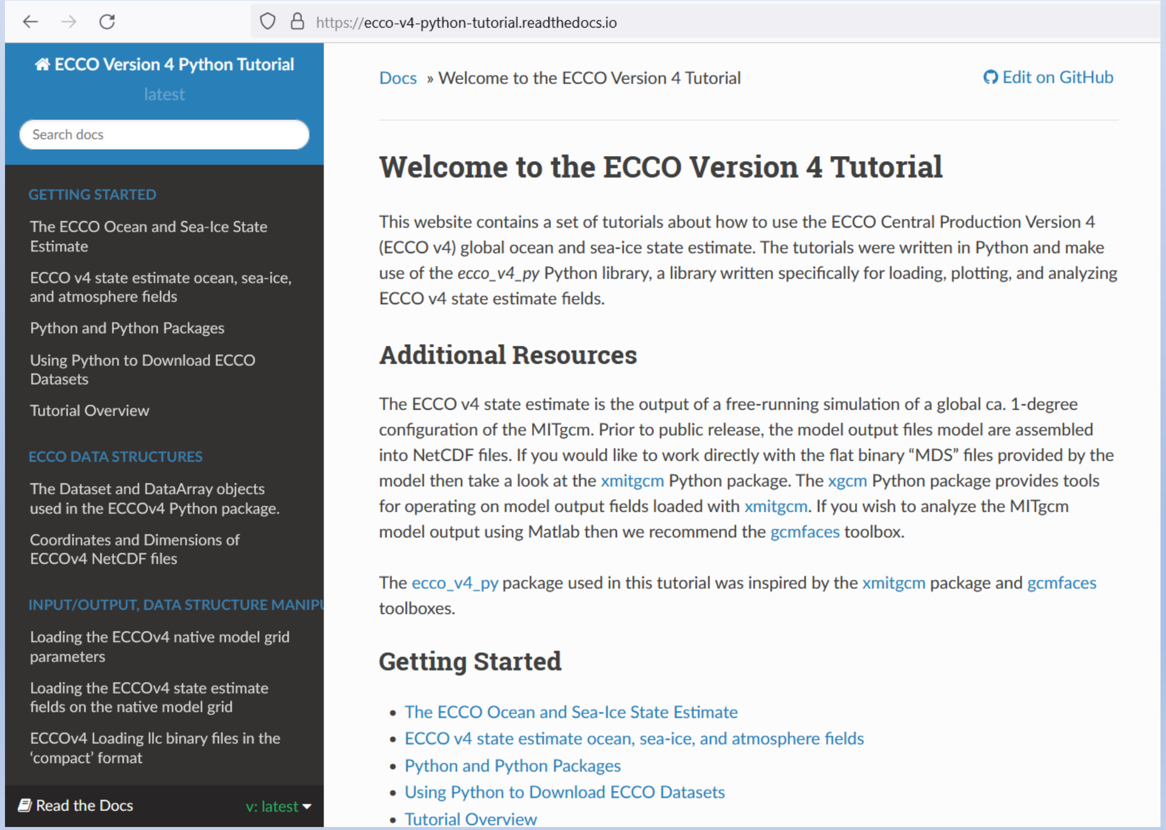
Introducing ECCO to the Next Generation of Oceanographers

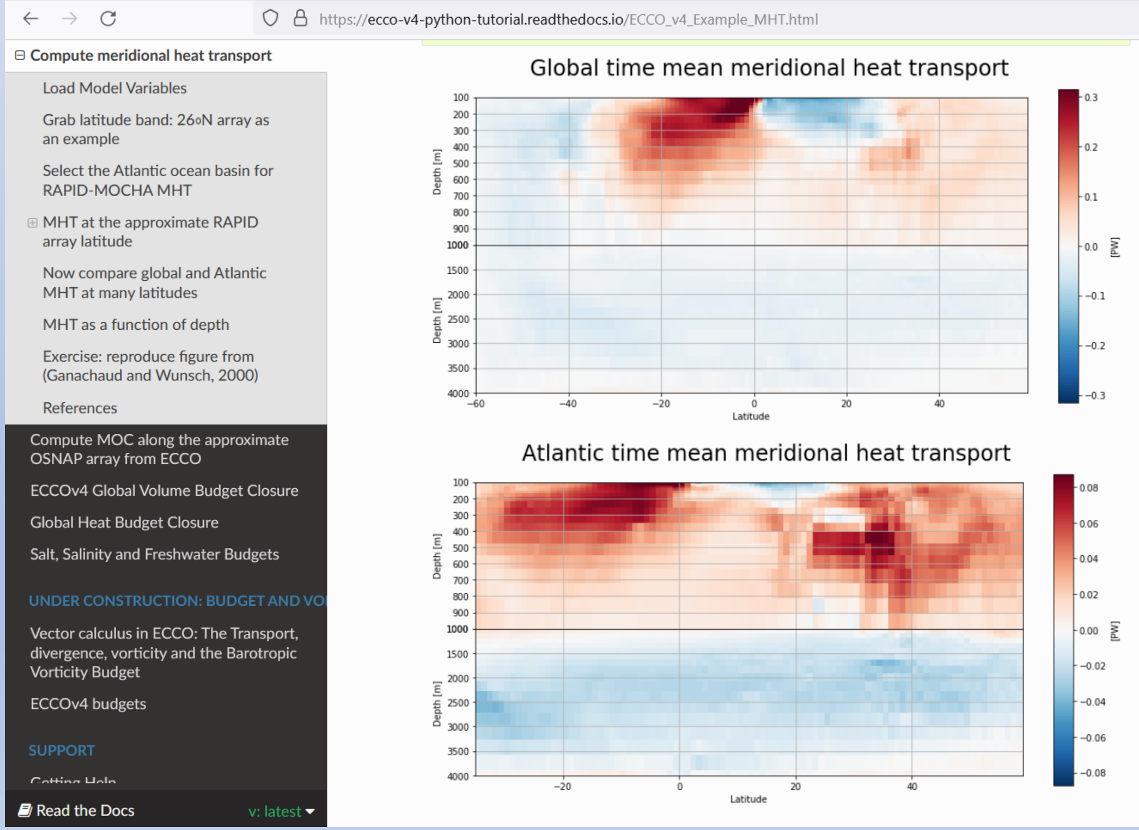
Outline

- ECCO Python Tutorials
- Updating ECCO access in the transition to NASA Earthdata Cloud
- Intro to PO Tutorials
  - The motivation and "vision"
  - Walkthrough of a tutorial
  - Planned Tutorials

ECCO Python Tutorials

- Tutorials website (by Ian Fenty et al.) to provide oceanographers with demos and code for ECCO analysis
- Comprised mostly of Jupyter notebooks that can be downloaded or git cloned to user's machine
- https://ecco-v4-python-tutorial.readthedocs.io





MHT tutorial credit: Timothy Smith

ECCO Python Tutorials

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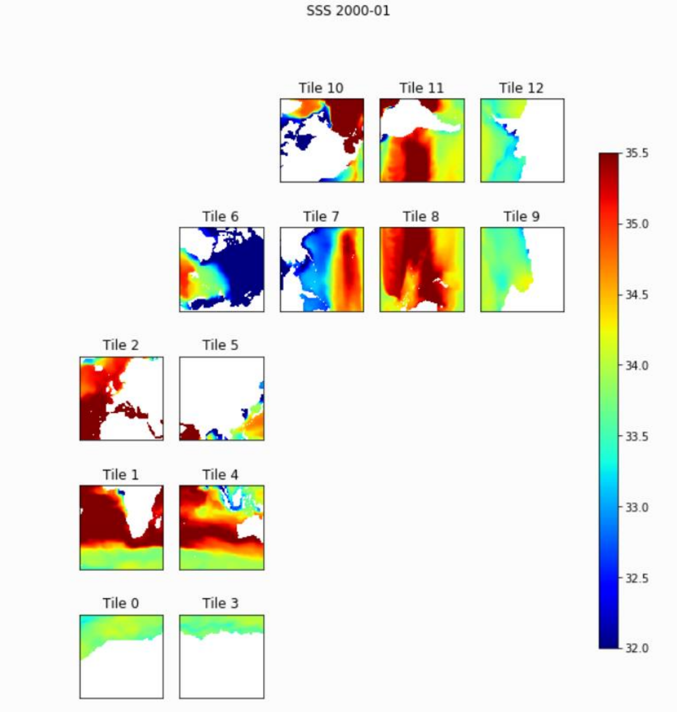
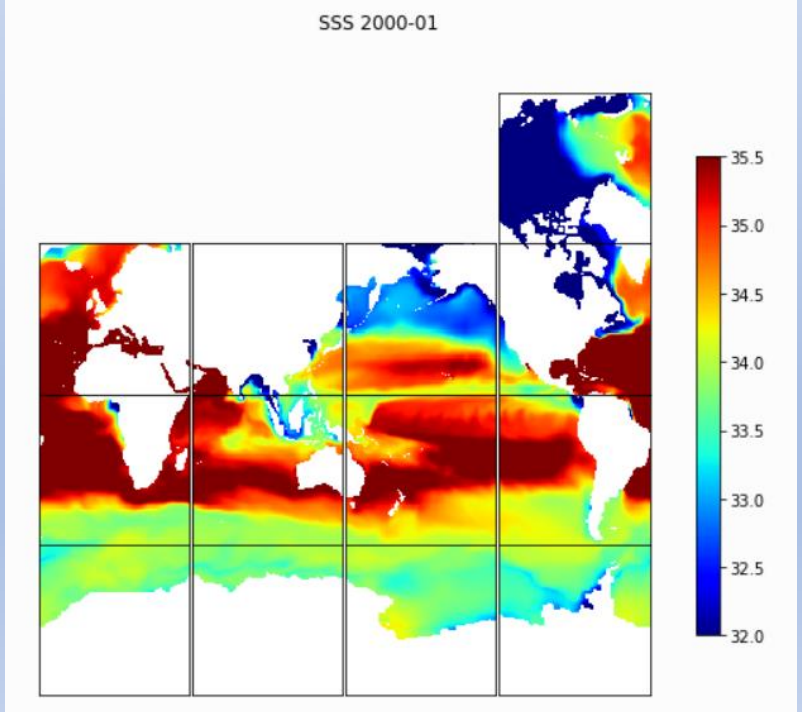
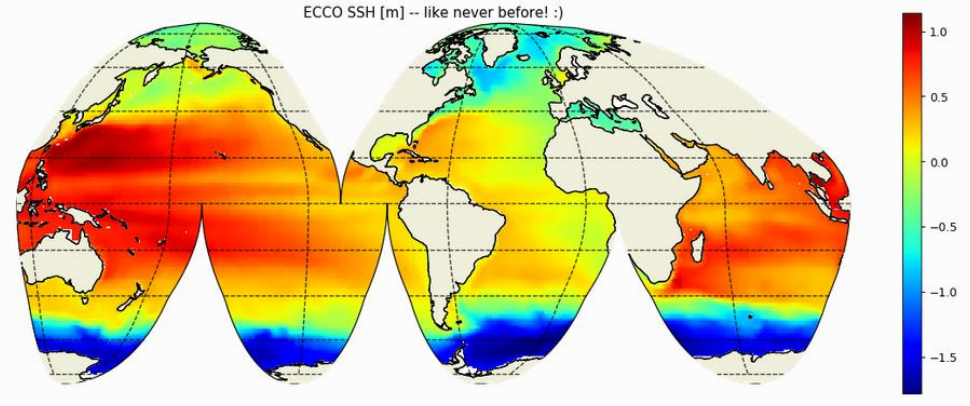
- Comprised mostly of Jupyter notebooks that can be downloaded or git cloned to user's machine
- https://ecco-v4-python-tutorial.readthedocs.io
- Also associated with the *ecco_v4_py* Python package, with support for analyzing and plotting ECCO output in a number of formats



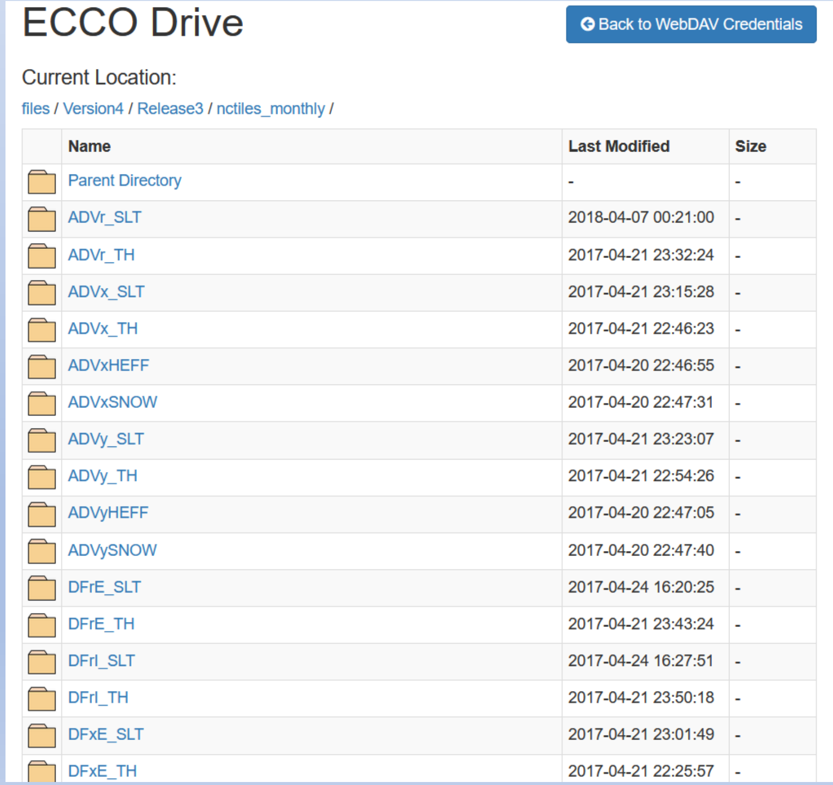


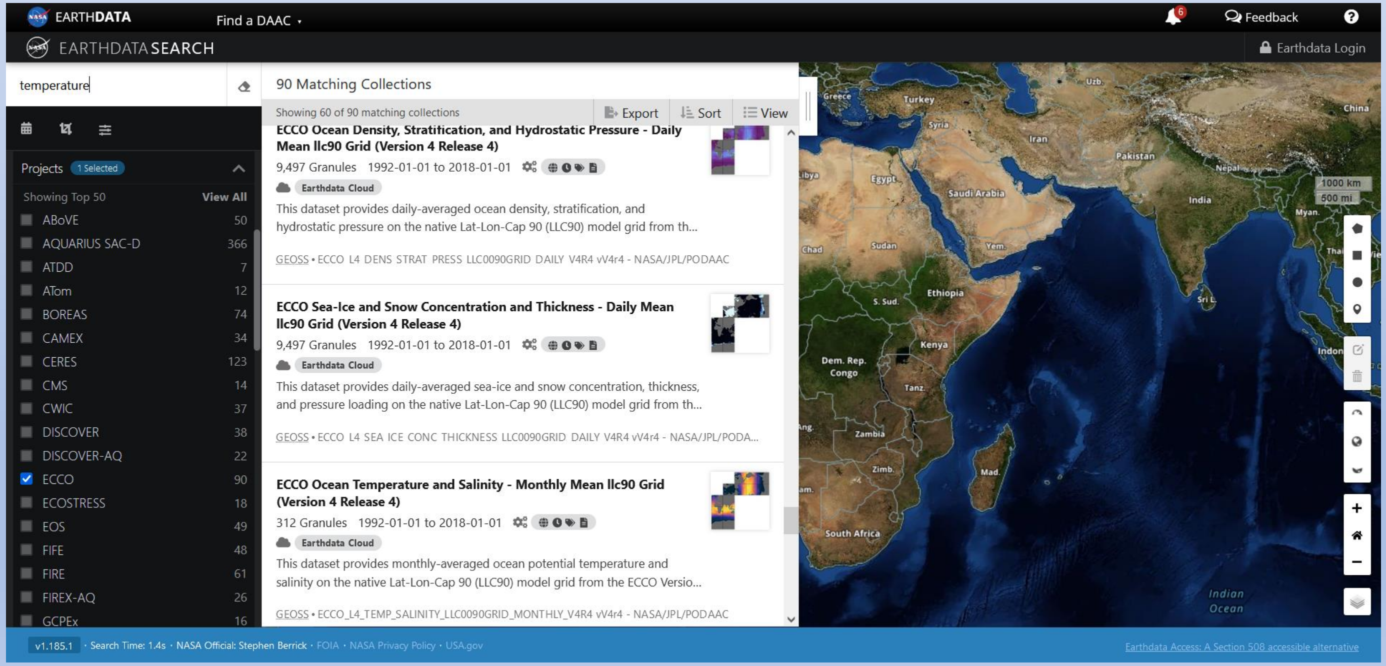


Updating Tutorials and ECCO Access

- The tutorials have been oriented around ECCOv4 release 3 output, accessed via ECCO Drive
- But we have release 4 now (with release 5 on the way), and ECCO Drive/PO.DAAC Drive are being decommissioned...

...in favor of NASA Earthdata Cloud, accessed via Earthdata Search





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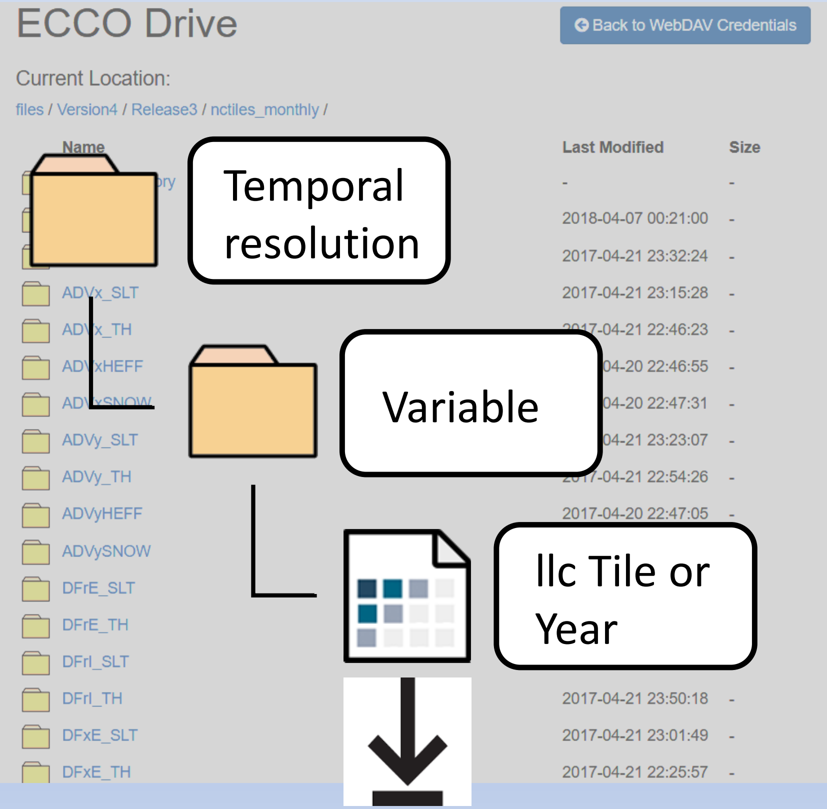

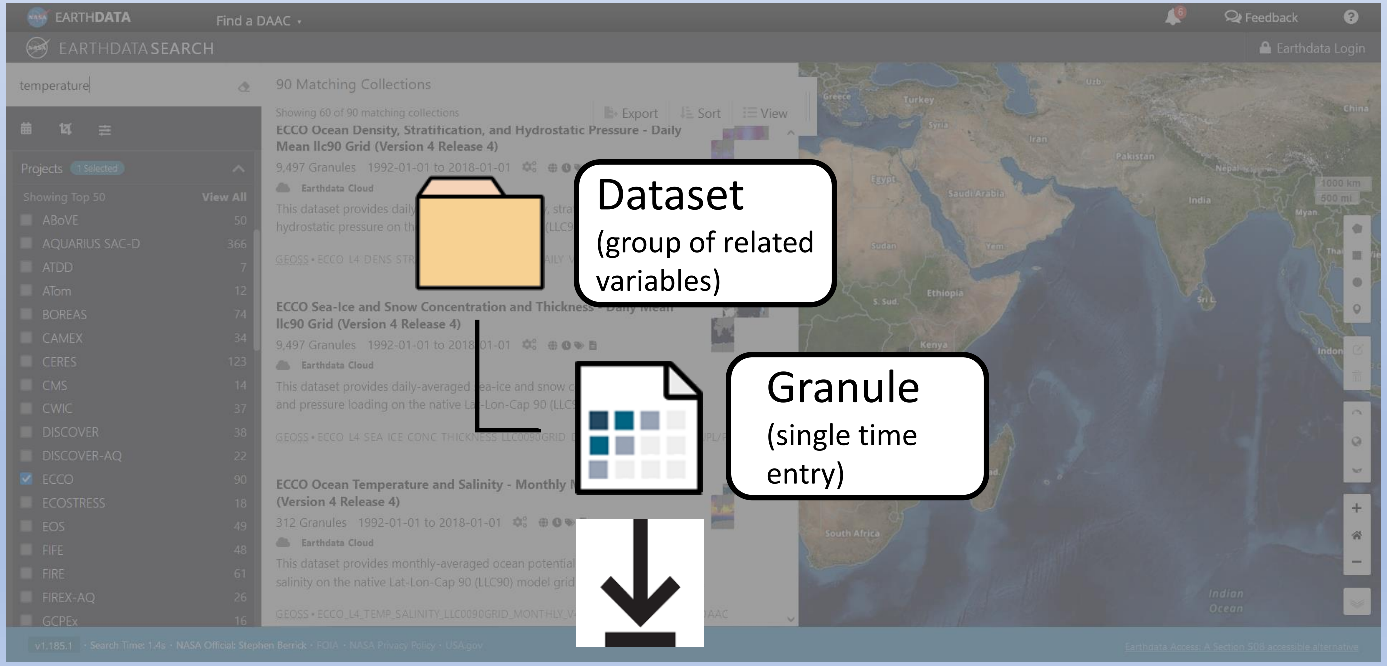

Updating Tutorials and ECCO Access

- Now the ECCO Python Tutorials include a tutorial on how to download ECCOv4 release 4 output from the cloud

https://ecco-v4-python-tutorial.readthedocs.io/Downloading_ECCO_Datasets_from_PODAAC_Python.html

GETTING STARTED

The ECCO Ocean and Sea-Ice State Estimate

ECCO v4 state estimate ocean, sea-ice, and atmosphere fields

Python and Python Packages

Using Python to Download ECCO Datasets

Note: This notebook was modified by Andrew Delman (updated 2023-01-12) from the tutorial on the ECCO-GROUP Github by Jack McNelis and Ian Fenty, Version 1.1 dated 2021-06-25.

This Jupyter notebook provides instructions and Python code for downloading a set of granules (files) for an ECCO "Dataset" hosted by PO.DAAC. The focus is on downloading datasets in the lat-

- AND an ecco_download.py module that can be imported and called from a Python shell or Jupyter notebook

```
ECCO Version 4: Fourth Release (1992-2017)  [ECCO v4r4]

These are the variables in the ECCO v4r4 output that can be downloaded as daily averages from the P(

ShortName               Variable Name     Description (units)

ECCO_L4_SSH_LLC0090GRID_DAILY_V4R4
                        SSH               Dynamic sea surface height anomaly. Suitable for comparisons wi
                        SSHIBC            The inverted barometer correction to sea surface height due to
                        SSHNOIBC          Sea surface height anomaly without the inverted barometer corre
                        ETAN              Model sea level anomaly, without corrections for global mean de

ECCO_L4_ATM_STATE_LLC0090GRID_DAILY_V4R4
                        EXFatemp          Atmosphere surface (2 m) air temperature (degK)
                        EXFaqh            Atmosphere surface (2 m) specific humidity (kg/kg)
                        EXFuwind          Wind speed at 10m in the model +x direction (m/s)
                        EXFvwind          Wind speed at 10m in the model +y direction (m/s)
                        EXFwspee          Wind speed (m/s)
                        EXFpress          Atmosphere surface pressure (N/m^2)

ECCO_L4_STRESS_LLC0090GRID_DAILY_V4R4
                        EXFtaux           Wind stress in the model +x direction (N/m^2)
                        EXFtauy           Wind stress in the model +y direction (N/m^2)
                        oceTAUX           Ocean surface stress in the model +x direction, due to wind and
                        oceTAUY           Ocean surface stress in the model +y direction, due to wind and

ECCO_L4_HEAT_FLUX_LLC0090GRID_DAILY_V4R4
                        EXFhl             Open ocean air-sea latent heat flux (W/m^2)
                        EXFhs             Open ocean air-sea sensible heat flux (W/m^2)
                        EXFlwdn           Downward longwave radiative flux (W/m^2)
```

```
[21]: from ecco_download import *

      ecco_podaac_download(ShortName="ECCO_L4_SSH_LLC0090GRID_DAILY_V4R4",\
                           StartDate="2000-01-09",EndDate="2000-01-14",download_root_dir=None,\
                           n_workers=6,force_redownload=False)

created download directory C:\Users\adelman\Downloads\ECCO_V4r4_PODAAC\ECCO_L4_SSH_LLC0090GRID_DAILY_V
{'ShortName': 'ECCO_L4_SSH_LLC0090GRID_DAILY_V4R4', 'temporal': '2000-01-09,2000-01-14'}

Total number of matching granules: 7

100%|██████████████████████████████████████████| 7/7 [00:21<

=====================================
total downloaded: 41.48 Mb
avg download speed: 1.9 Mb/s
```

Intro to PO Tutorials

Motivation

- The ECCOv4 state estimate is unique in that it **assimilates data** AND maintains **physical conservation laws**

- This makes it a valuable **teaching tool** for graduate students and others learning about physical oceanography & GFD

Vision

- ECCO tutorials to demonstrate core concepts in physical oceanography
    - Jupyter notebooks for classroom demonstrations or problem sets
- Students can enhance Python coding skills while analyzing and plotting NASA datasets
- Use open source tools that encourage transparency, accessibility, and reproducibility

Intro to PO Tutorials: An Example

- Three new PO Tutorials have been completed…more on the way!
- They have a common format…let's look at **Part 1: Geostrophic Balance**

Objectives listing tasks/skills that the user will practice in the tutorial

Part 1: Geostrophic balance

Andrew Delman, updated 2023-01-13.

Objectives

To use ECCO state estimate output to illustrate the concept of geostrophic balance; where it does and doesn't explain oceanic flows well.

By the end of the tutorial, you will be able to:

- Download ECCO fields and query their attributes using `xarray`
- Plot ECCO fields on a single tile
- Carry out spatial differencing and interpolation on the ECCO native model grid
- Compare the two sides of the geostrophic balance equations
- Compute geostrophic velocities
- Apply masks in 2-D spatial plots
- Use the `ecco_v4_py` package to plot global maps of ECCO fields
- Use a statistical measure (normalized difference) to assess the latitude and depth dependence of geostrophic balance

Introduction

The tutorials in this series use output from the ECCO version 4 release 4 (v4r4) state estimate to illustrate foundational concepts in the physics of the ocean (physical oceanography or PO for short). These tutorials are written as Jupyter notebooks; this format allows the concepts, code, and results of running the code to be viewed together in one document.
While these notebooks can be read online, it is strongly recommended to download them, and the ECCO output needed to run them, in order to allow users to interact with the data themselves. You can even tinker with the notebooks yourself to look at different regions or perform different calculations, that's part of the fun!

We'll start by visualizing one of the most basic concepts in fluid dynamics on a rotating reference frame: geostrophic balance.

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Introduction briefly discussing relevant theory as in a textbook (with references to established textbooks)

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + g\hat{\mathbf{k}} - 2\mathbf{\Omega}\times\mathbf{u} + \mathbf{F_f}$$

Of those last three terms:

1. Gravity $g\hat{\mathbf{k}}$ effectively only applies to vertical momentum, and can be neglected in the horizontal momentum equations
2. The Coriolis force $-2\mathbf{\Omega}\times\mathbf{u}$ can be approximated by its vertical component, $2\Omega\sin\theta(v\hat{\mathbf{i}} - u\hat{\mathbf{j}})$ where Ω is the rotation rate of Earth in radians and θ is latitude
3. Friction $\mathbf{F_f}$ from wind and topography is negligible in the ocean interior.

To simplify, f is defined as $f \equiv 2\Omega\sin\theta$. So using subscript notation for derivatives (u_t is the derivative of u with respect to t) the two horizontal components of momentum conservation are:

$$u_t + \mathbf{u}\cdot\nabla u = -\frac{1}{\rho}p_x + \nu\nabla^2 u + fv$$

$$v_t + \mathbf{u}\cdot\nabla v = -\frac{1}{\rho}p_y + \nu\nabla^2 v - fu$$

Geostrophic balance

The two horizontal momentum equations still have a number of terms, but in the global oceans most of the flow is explained by a balance between just two terms. In steady state (or for very slowly-varying ocean features) the time derivatives u_t, v_t are negligible, and at the large scales of major ocean currents viscosity is relatively small as well (inviscid approximation). This leaves three terms. The 2nd term on the left-hand side is usually negligible at large scales as well (we'll return to this later), so large-scale ocean flows generally follow **geostrophic balance**:

$$fv = \frac{1}{\rho}p_x$$

$$fu = -\frac{1}{\rho}p_y$$

If you've looked at weather maps that show the clockwise or counter-clockwise flow of winds around areas of high or low pressure, you've encountered

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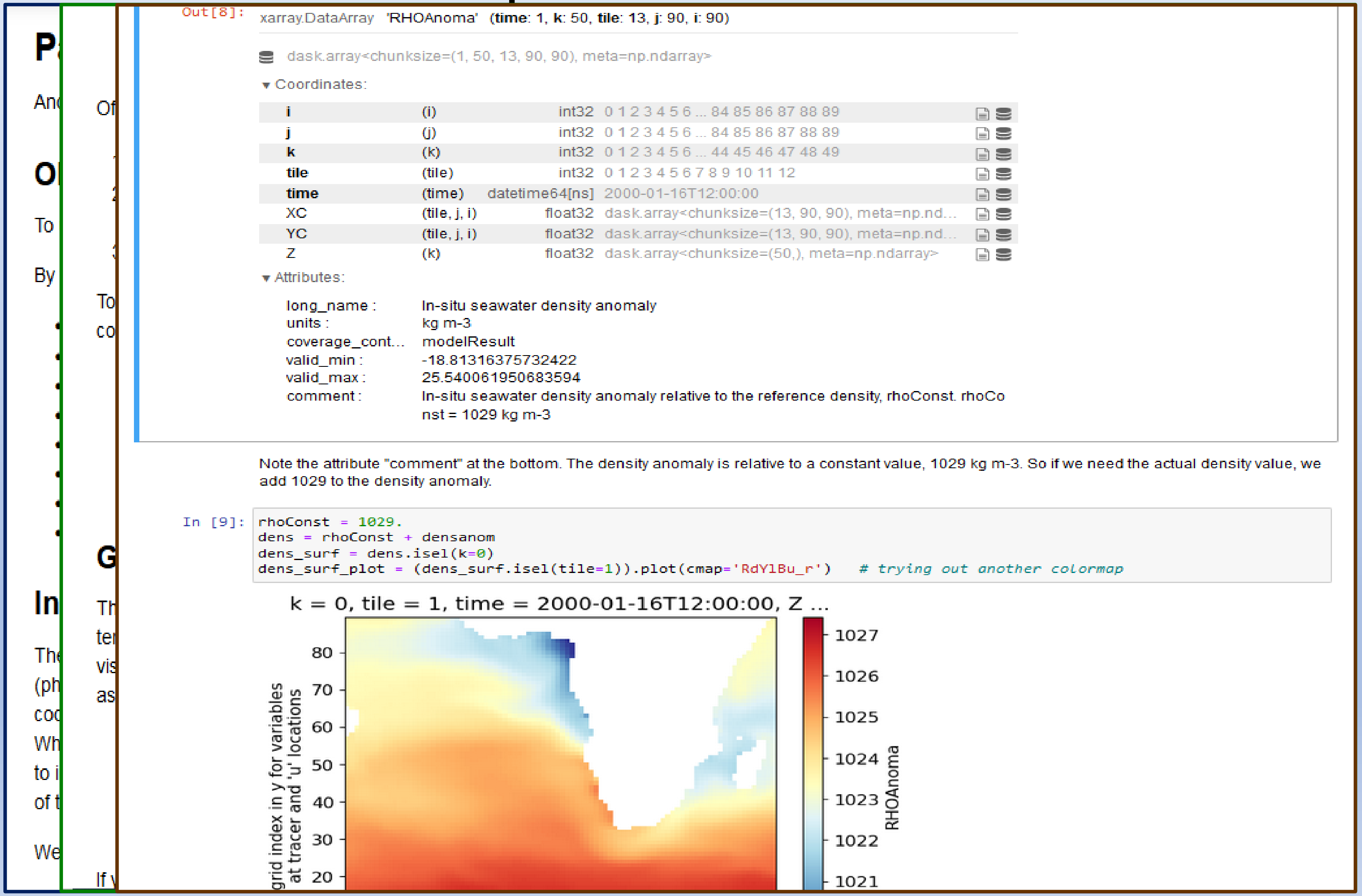
Open and view contents of ECCO file(s) needed for the calculation



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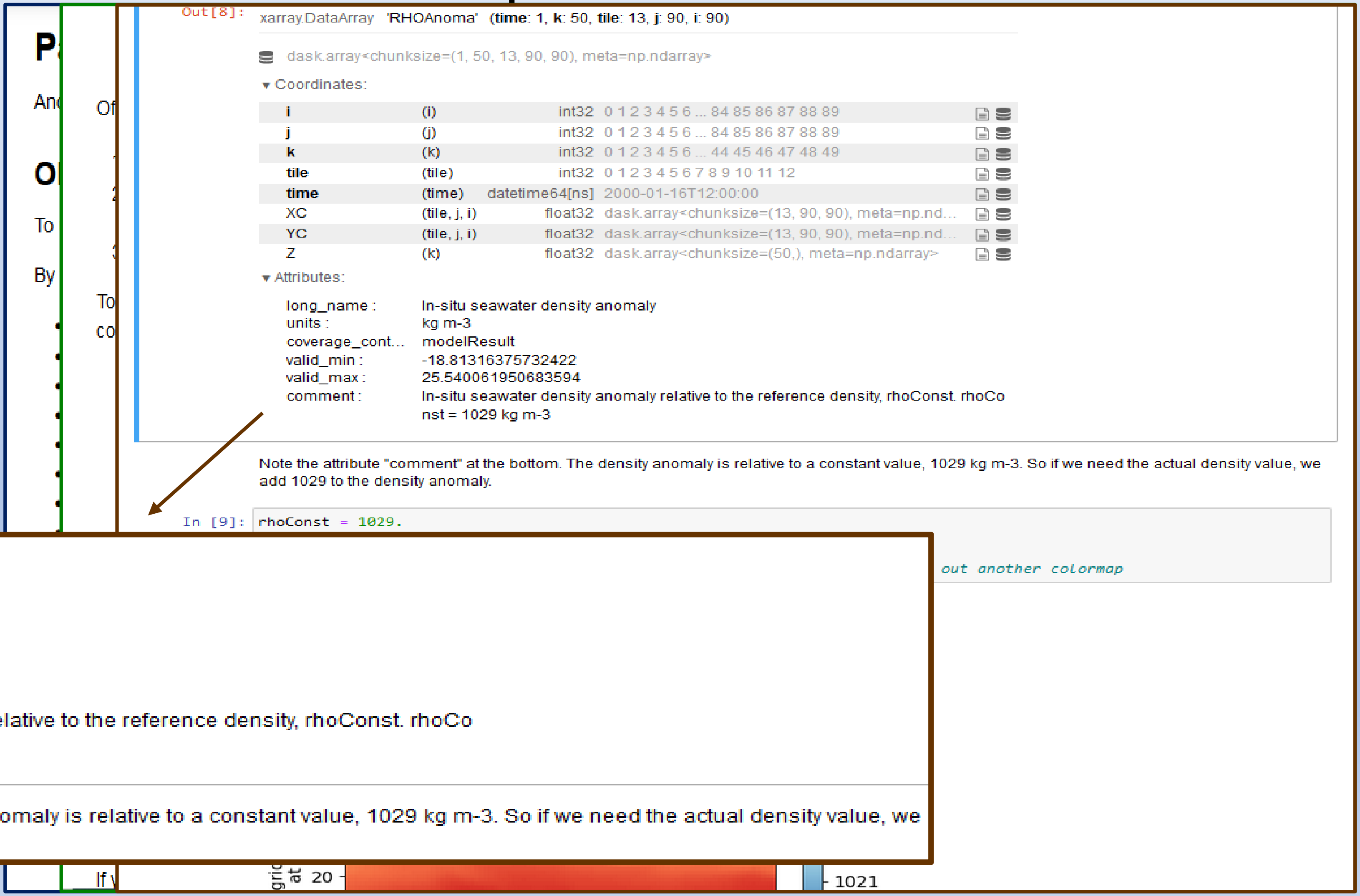

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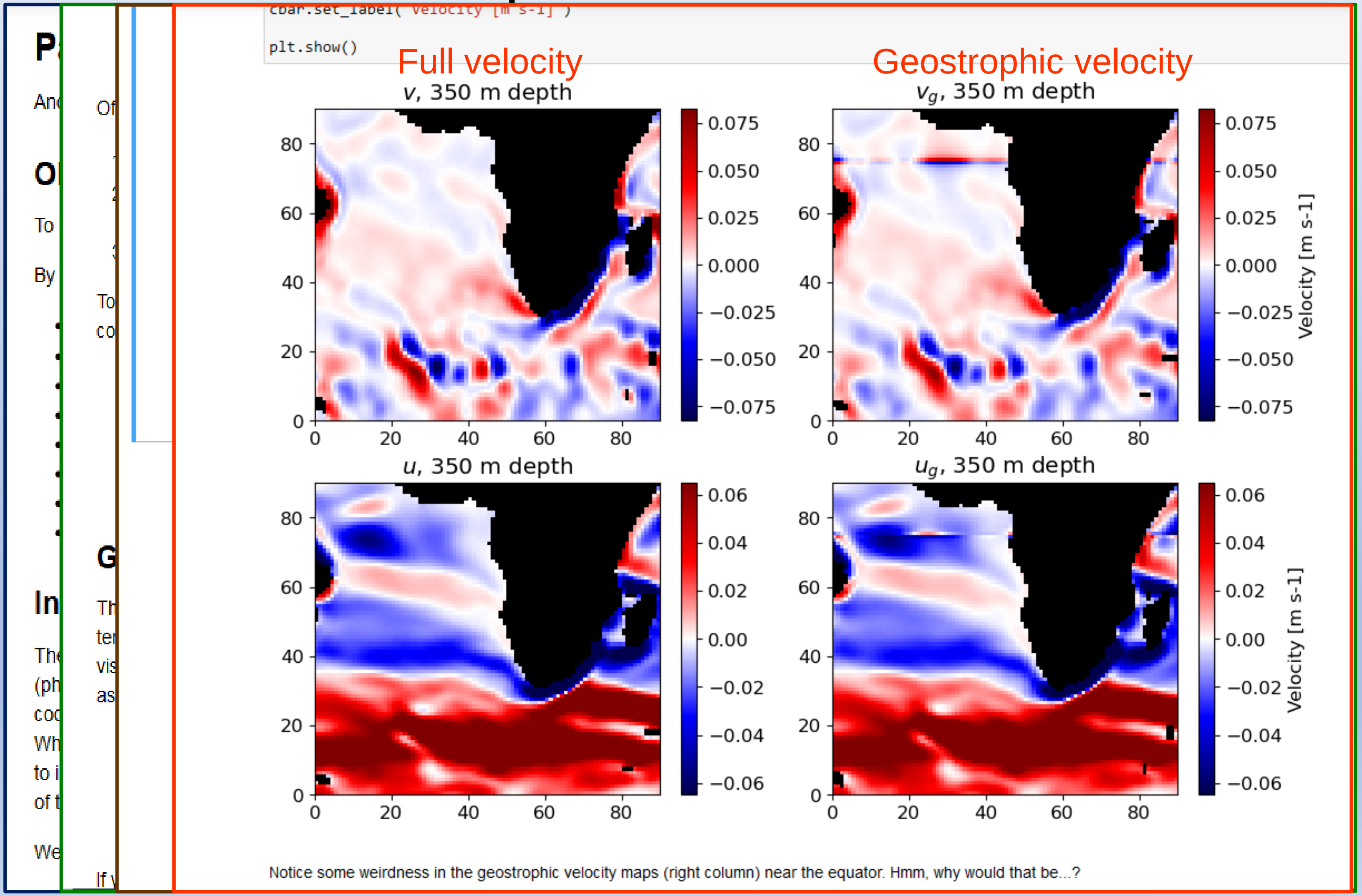

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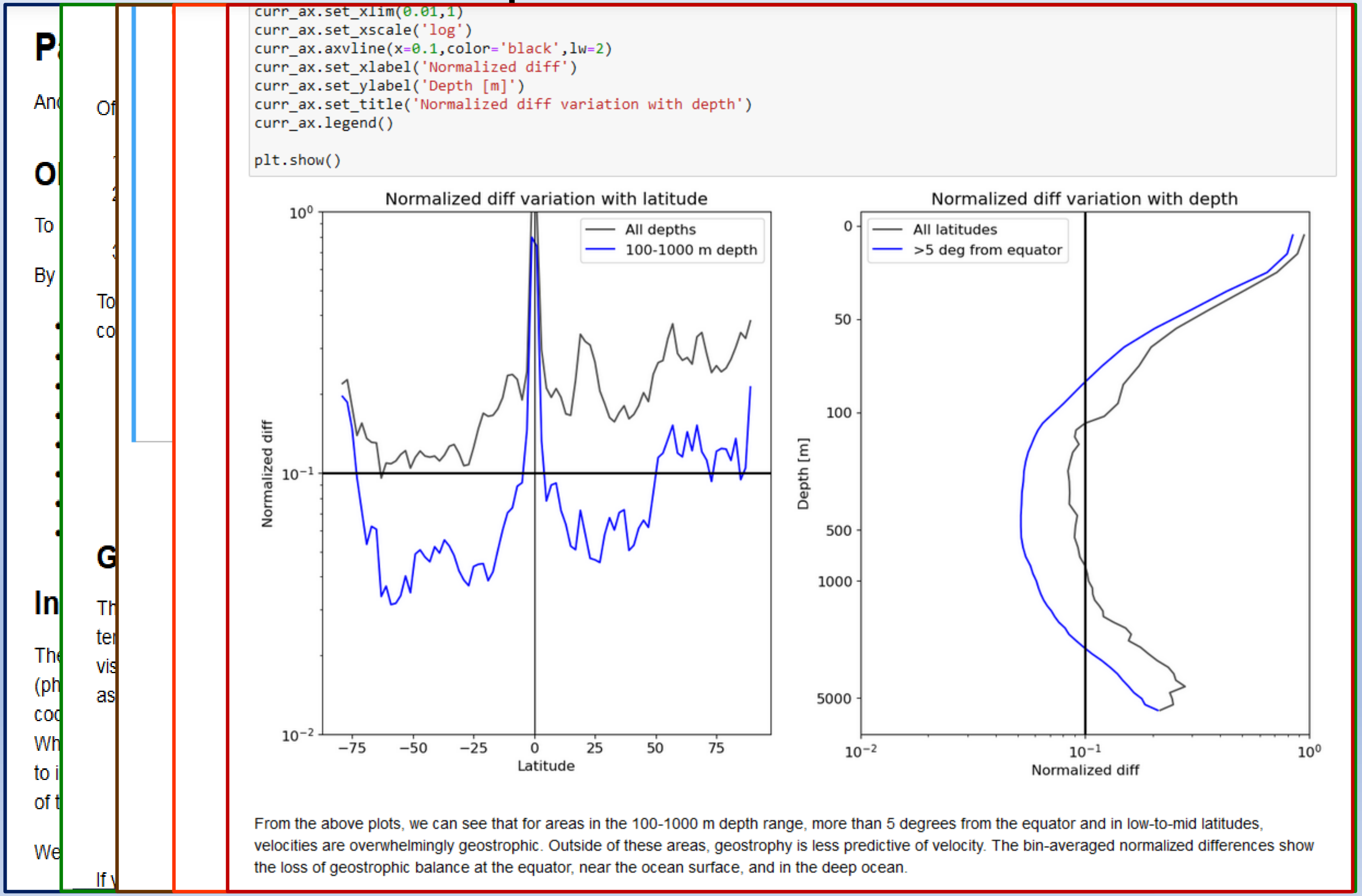
Compute the quantity or balance (in this case geostrophic balance)

Assess the concept's usefulness in application to the "real" ocean



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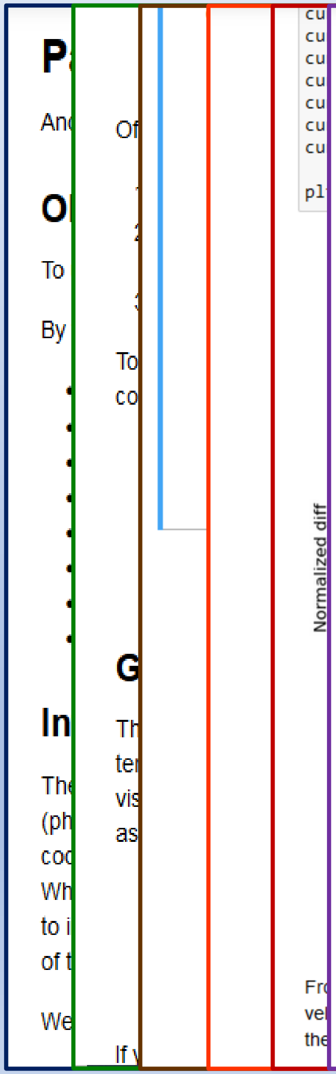
Exercises for students to do on their own



Exercises

Having made it to the end of the tutorial, you're now ready to try tweaking some of the code above to explore the ECCO data on your own. Here are a couple of suggested exercises, or you can develop your own ideas!

1. All of the mapping we just did was with monthly data for January 2000, but we also downloaded daily files for 1999-12-31 and 2000-01-01. Repeat the calculations and plots that we did, but this time with the daily files for one of those dates. How does geostrophic balance on daily timescales compare with monthly timescales? Why might they be different?
2. You probably noticed that geostrophic balance does not seem to be as good of an approximation for the flow in the Arctic as in other ocean basins. Focus on the monthly data in the Arctic tile (`tile=6`). Where is geostrophic balance the least effective, after masking out the smallest velocities? You'll probably need to change a few parameters to get informative plots in this region of lower velocities. Pick a grid cell (i,j) where there are high normalized differences (preferably one where the ocean is >500 m deep), and make a plot comparing the depth profiles of geostrophic and actual u and v. For extra credit, also plot the depth profile of the *angle* of difference between the geostrophic and actual velocity vectors.

> Tip: make a copy of this notebook before you edit it, so that you can try your own innovations while being able to easily return to the original notebook for comparison.

For future use

ecco_po_tutorials module

There are some functions used in this tutorial that it will be helpful to have access to for future tutorials (or your own analysis with ECCOv4). Hence these functions have been put into a ecco_po_tutorials module (a Python file) that will be imported in future tutorials. This module also includes a function to compute geostrophic velocities quickly, given the file containing density and pressure anomalies.

ecco_po_tutorials module

I recommend downloading it to the same directory where your tutorials are located. Some functions from this module may also be incorporated into the `ecco_v4_py` package in the future.

References

Kundu, P.K. and Cohen, I.M. (2008). ***Fluid Mechanics*** (4th ed.). Elsevier.

Vallis, G.K. (2006). ***Atmospheric and Oceanic Fluid Dynamics***. Cambridge University Press.

Intro to PO Tutorials: Planned

Geostrophic dynamics	Ageostrophic dynamics	Vorticity/QG	Property Conservation	Climate Topics
Geostrophic balance	Ekman Dynamics	Sverdrup Balance	Pot. Density/ Water Masses	MOC and Transports
Thermal Wind	Equatorial Waves	Rossby Waves	Potential Temperature	Earth Energy Imbalance
Steric Height		Vorticity Budget	Salinity, Salt, and Freshwater	Sea Level Rise
			Sea Ice	Hydrological Cycle

Completed as of Jan. 2023

In conclusion…

- The Intro to PO Tutorials are currently in development, and we are very open to ideas for concepts to cover, as well as suggestions for improvement!
  - Especially if you teach a class that could make use of them

- If you are new to Python…these tutorials will not teach you **everything** you need to know, but they are a great way to get more comfortable with computations and plotting

- Here’s the URL again: https://ecco-v4-python-tutorial.readthedocs.io
  - Can also be accessed through the ECCO Group website under Products -> Analysis Tools