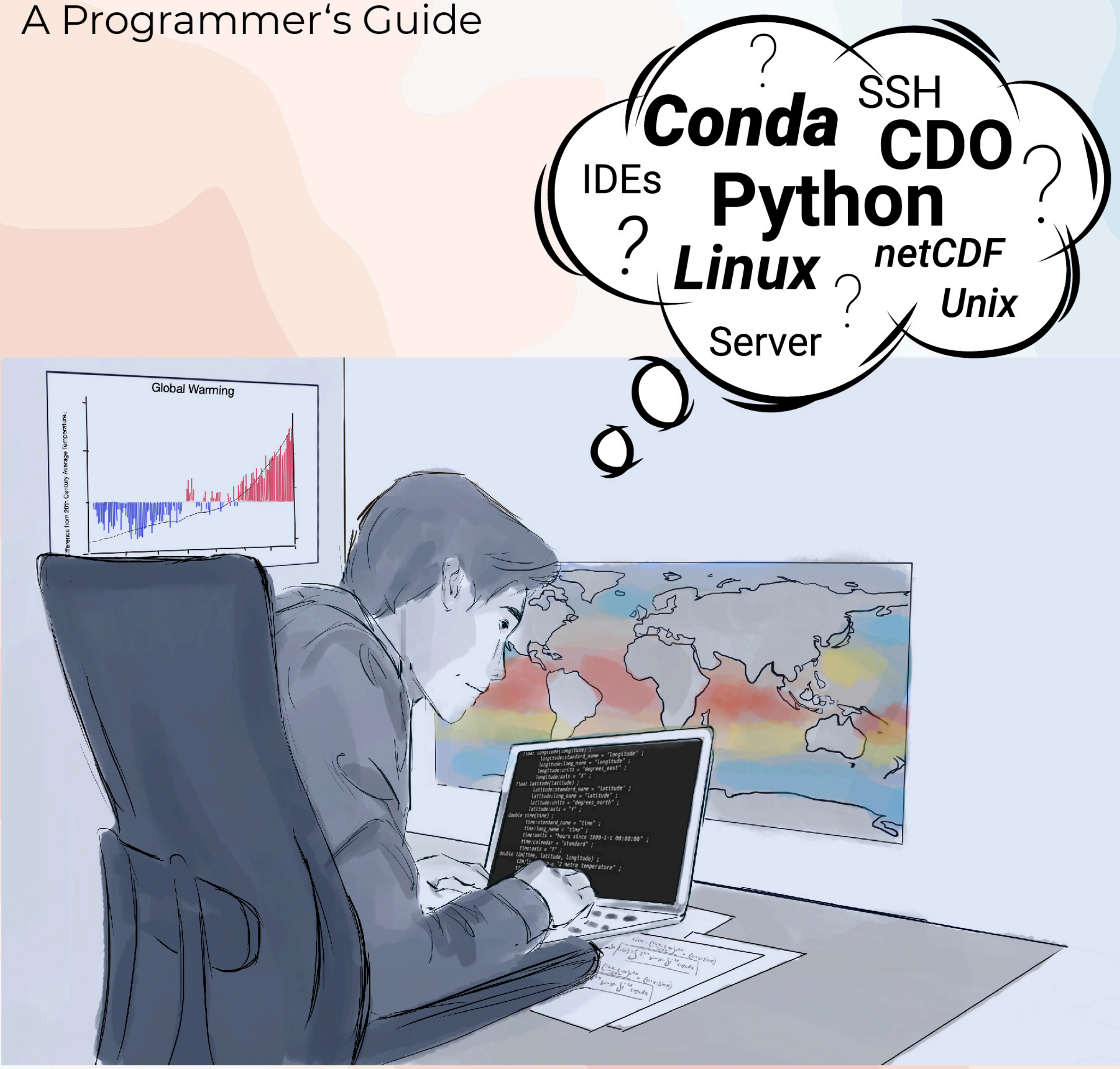
Data Analysis and Visualisation in Climate Science

A Programmer‘s Guide



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S. Engelstaedter

Data Analysis and Visualisation in Climate Science

A Programmer's Guide

Sebastian Engelstaedter

This book is available at
http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences

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This edition of the book is dedicated to the late Simon Abele - geospatial data analysis genius who helped and supported countless SoGE students and researchers over the years.

Contents

Preface

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Acknowledgements

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1. Introduction

The field of climate and environmental sciences has been constantly growing in importance over the last few decades mainly due to an increased need to understand how the climate system works and how it may change in the future as a result of man-made climate change. Similar to a craftsman who as part of his apprenticeship needs to learn what tools are available to work wood and hone his skills in how to use them, young researchers need to learn what software is available, what the software can do and how to use it.

Climate and environmental data come in a variety of formats depending on the nature of the data and the preference of the scientists or organisations who compiled or generated them. The analysis and subsequent visualisation of such data requires a good understanding of the file formats and data structures as well as the tools that can be used to manipulated them, to calculate statistics and to visualise the output.

The material presented in this book is based on about 20 years of experience working in the field of climate sciences and teaching climate data analysis and visualisation courses to students at all levels at the University of Oxford. The aim of this book is to introduce students to the technical background, set of tools and programming skills required to successfully analyse climate datasets and produce scientific output in publishable format.

1.1 Overview and Objective

In most institutions where work on climate and environmental data is being carried out the storage, analysis and visualisation of climate data is done on Unix servers. This is because Unix servers tend to have large disk arrays attached to them which provide the storage capacity needed to store large datasets (petabytes range). In addition, they allow fast read and write operations and have substantially more processing power than standard desktop or laptop machines. If storage capacity and processing power is not essential (e.g., for exploratory research) then all of the software packages discussed in this book can also be installed on local PCs or laptops as long as they are running a Linux operating system. All software packages introduced in this book are freely available for research purposes.

This book provides an introduction to different types of climate data and the main data formats in which they are being made available with a specific focus on the most commonly used formats such as comma-separated values (CSV) and Network Common Data Form (netCDF) files. The nature of gridded data will be discussed as well as ways to explore the content of netCDF files. Students will learn how to work on the Unix command line, how to use tools such as Climate Data Operators (CDO) and the Python programming language to handle climate data saved in netCDF file format, how to calculate climate statistics and how to visualise the output. Many code examples will help in the learning process. Additional tools and techniques will be discussed which will help with the data analysis and visualisation tasks including how to deal with long-running processing jobs, which code editors to use and how to set up isolated coding environments on the server.

For many of the subjects and software packages covered in this book (e.g., Unix, CDO, Python) detailed in-depth user guides, tutorials and books exist. The focus of this book is to integrate the different tools that have been shown to work well in climate computing into a single framework that allows to create a seamless work flow from understanding and analysing data through to computational data analysis and the publication of high-quality graphical output in an efficient way.

While the collection of tools and techniques presented here have been shown to work well for most climate computing tasks it should be noted that there are many roads to get from A to B and there is no doubt that scientists around the world have created data analysis environments and programming solutions that differ from what is presented here. Where appropriate references to additional tools or solutions are given.

1.2 Concept of Local and Remote Machines

It is assumed that students are familiar with working on a laptop or desktop computer running either a Microsoft Windows, macOS or Linux operating system. These computers are normally owned by the user or provided by the work place and are generally referred to as local computers or local machines.

It is also assumed that the climate data analysis and visualisation tasks will be performed on a server or server cluster running Unix/Linux. A server can be thought of as a more powerful computer with extended disk arrays attached for storage. A server may also be referred to as a remote server or remote machine because they tend to be located physically in a different place from your local machine such as in a different building or in a research centre somewhere else in the world. When multiple servers are combined to create a more powerful setup then this is refereed to as a server cluster or a computational research cluster.

In general, the local machine is used to connect to the remote server. This means that it is possible to work from anywhere in the world as long as a reasonably fast and stable internet connection is available.

1.3 Software

The software that is required on the local machine that allows to connect to the remote server differs between operating systems. The software will be introduced in Section 3.2 and will be discussed separately for each operating system. Every aspect of climate computing discussed in this book can be achieved using open source software.

The administrator rights for the installation of software on local machines will very likely lie with either the user or with IT office of the institution that provides the computer (e.g., department or research centre). In the latter case, it may be necessary to contact the IT administrator to install the required software.

With regards to software on the remote server, users will have no or only very limited control over the software installed and have to rely on the remote server system administrator. However, it is very likely that most, if not all, software is already installed on the remote server if that server is frequently used for climate data analysis.

In exceptional circumstances, where a remote server is not available or accessible and the climate data to be analysed are small enough then a local machine (PC or laptop) may be used for data analysis. While Python can be installed on any operating system (Windows, macOS or Linux) some of the other software tools such as CDO, ncdump or ncview works best on a Linux system.

2. Climate Data

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2.1 Climate Data Overview

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2.2 Data Use Licences

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2.3 Data Quality

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2.4 Accessing Climate Data

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2.5 Types of Climate Data

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2.5.1 Analyses and Reanalyses Products

In order to predict future states of the atmosphere, numerical weather prediction (NWP) models require as input spatially varying meteorological fields that describe the state of the atmosphere at the time of model initialisation. A complete and spatiotemporally consistent observational dataset without gaps is needed here. This is achieved by assimilating point observations from weather stations, buoys and ships as well as satellite retrievals into gridded observational products by means of modelling and statistical methods. The output from this process can then be used to initialise the forecast simulation. These gridded observation-based data products are called *analyses*.

A gridded observational dataset without gaps has considerable value for the study of climate. However, due to model updates and continuous improvements in the assimilation process, analysis products can develop inconsistencies through time. For this reason initiatives have been set up to regenerate observational input fields over extended periods (usually decades) using a 'frozen' (fixed) version of the assimilation and model code. These products are called *reanalyses*. Reanalysis products also contain model-generated fields that are not based on observations. Because reanalyses are internally consistent over time they are often used to study climate processes and variability from the recent past. Some of the latest reanalysis products and their properties are listed in Table 2.5.1.1.

Table 2.5.1.1: Some of the reanalyses commonly used in climate science and modelling.

Institution	Name	Period	Resolution	Reference
ECMWF	ERA-40	1957 - 2002	1.125 x 1.125 x 60	Uppala et al., 2005[1]
ECMWF	ERA-Interim	1979 - 2018	0.75 x 0.75 x 60	Dee et al., 2011[2]
ECMWF	ERA-5	1950 - present	0.28125 x 0.28125 x 137	Hersbach et al., 2020[3]
ECMWF	ERA-20CM	1900 - 2010	0.75 x 0.75 x 137	Hersbach et al., 2015[4]
NCEP/DOE	Reanalysis 2	1979 - present	2.5 x 2.5 x 28	Kanamitsu et al., 2002[5]

[1]https://doi.org/10.1256/qj.04.176
[2]https://doi.org/10.1002/qj.828
[3]https://doi.org/10.1002/qj.3803
[4]https://doi.org/10.1002/qj.2528
[5]https://doi.org/10.1175/BAMS-83-11-1631

Table 2.5.1.1: Some of the reanalyses commonly used in climate science and modelling.

Institution	Name	Period	Resolution	Reference
NCEP	CFSR	1979 - present	0.5 x 0.5	Saha et al., 2010[6]
NASA	MERRA	1979 - 2016	0.667 x 0.5 x 42	Rienecker et al., 2011[7]
NASA	MERRA-2	1980 - present	0.625 x 0.5 x 42	Gelaro et al., 2017[8]
JMA	JRA-55	1958 - present	? x ? x 60	Kobayashi et al., 2015[9]

2.5.2 Climate and NWP Model Output

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2.5.3 Point observations

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2.6 Data File Formats

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2.6.1 Plain Text and ASCII

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[6]https://doi.org/10.1175/2010BAMS3001.1
[7]https://doi.org/10.1175/JCLI-D-11-00015.1
[8]https://doi.org/10.1175/JCLI-D-16-0758.1
[9]https://doi.org/10.2151/jmsj.2015-001

2.6.2 Binary

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2.6.3 GRIB

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2.6.4 netCDF

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2.6.5 PP

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3. Unix

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3.1 Introduction to Unix

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3.1.1 Linux Distributions

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3.1.2 Desktop versus Server

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3.1.3 High Performance Computing on a Server

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3.2 Accessing a Remote Server

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3.2.1 Remote Server Login Details

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3.2.2 Virtual Private Network (VPN)

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3.2.3 X Window System (X11 forwarding)

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3.2.3.1 X Window System on Windows OS

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3.2.3.2 X Window System on macOS

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3.2.3.3 X Window System on Linux

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3.2.4 Connecting to a Remote Server

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3.2.4.1 Connecting to a Remote Server from Windows OS

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3.2.4.2 Connecting to a Remote Server from macOS

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3.2.4.3 Connecting to a Remote Server from Linux OS

For users working on a Linux OS such as *Ubuntu* or *Mint* the communication between the local machine and remote server is relatively straightforward. Access the remote server from a Linux machine by following the steps outlined below.

1. Open a command line interface (CLI) by starting the program *Terminal*. It should be available in all Linux distributions by default.
2. Use the command below to connect to the remote server. `ssh` starts a Secure Shell connection. `-Y` enables *X11 forwarding*.

```
ssh -Y jsmith@linux.ouce.ox.ac.uk
```

3. `username` is the username of user's Unix server account. `servername` is the name of the Unix server.
4. The user will be prompted to enter a password.

Upon first login to a remote server the following prompt may appear.

```
The authenticity of host 'servername (163.1.38.97)' can't
be established. RSA key fingerprint is
4d:fa:ab:36:c0:c4:5f:c2:e6:a6:0f:2a:d4:48:af:24. Are you
sure you want to continue connecting (yes/no)?
```

Confirm this by typing `yes`. This message will not appear on subsequent logins.

3.3 First Steps on the Unix server

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3.3.1 The Terminal Window

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3.3.2 The Shell

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3.3.3 Linux Directory Structure and Home Directory

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3.3.4 Quota

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3.3.5 File Transfer to and from the Server

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3.3.5.1 File Transfer between Windows OS and Remote Server

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3.3.5.2 File Transfer on the Command Line for macOS and Linux

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3.3.6 Mapping the Linux Home Directory as a Remote Network Drive

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3.3.6.1 Mapping Home Directory on Windows

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3.3.6.2 Mapping Home Directory on macOS

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3.3.6.3 Mounting Home Directory on Linux

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3.4 Some More Unix Server Basics

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3.4.1 Unix Command Syntax}

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3.4.2 Manual Pages

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3.4.3 Editing Text Files

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3.4.4 Full versus Relative Paths

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3.4.5 Special Characters

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3.5 Working with Files and Directories

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3.5.1 Creating Text Files and Directories

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3.5.2 Listing Files and Directories

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3.5.3 Moving Around in the Directory Tree

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3.5.4 Copying, Moving, Renaming and Deleting Files and Directories

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3.6 Advanced Unix Commands

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3.6.1 Examining Text Files

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3.6.2 File and Directory Properties

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3.6.3 File Permissions

Understanding the permission part of the file properties (first line in Table 3.6.2.1) can be challenging at first. However, it is important to understand file permissions as they control who can read, edit and execute the file.

File permission are divided into four sections and contain a total of ten characters Figure 3.6.3.1. The first section (yellow) is a single character that shows the file type.

The letter `d` indicates a *directory*, a hyphen (`-`) indicates a *file* and the letter `l` indicates a link.

The following three sections contain sets of three characters showing the permissions for the *user* (blue), *group* (green) and *others* (orange) (Figure 3.6.3.1). The *user* is also sometime referred to as the *owner*.

The order of the three characters in each section shows the permissions for *read* (`r`, first character), *write* (`w`, second character) and *execute* (`x`, third character). If the letter `r`, `w` or `x` is set then read, write and execute permission have been granted. If, instead of a letter, a hyphen (`-`) is shown then the specific permission has not been granted.

The example shown in Figure 3.6.3.1 (`-rwxr-xr-x`) is a very commonly used set of permissions that allows the user to read, write and execute the file and members of the group and others (everyone else on the system) to only read and execute the file. This means that no one apart from the user can modify the file but everyone else can read, copy and execute it.

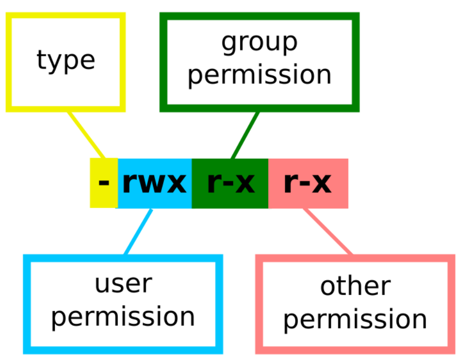

Figure 3.6.3.1: Unix file permissions.

In some cases a plus symbol (`+`) is shown as an eleventh character indicating that extended file permissions have been set using *Access Control Lists* (not covered in this book).

3.6.4 Changing File Permissions and Ownership

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3.6.5 Changing the Unix Account Password

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3.6.6 Redirecting Command Output

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3.6.7 Finding Files

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3.6.8 File Compression and Archives

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3.6.9 Download Files from the Command Line

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3.7 Long-running Jobs

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3.7.1 GNU Screen (recommended)

4. Multi-dimensional Gridded Datasets

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4.1 The Earth's Coordinate System and Realms

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4.2 The Model Grid

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4.3 Grid Indexing and Geographical Referencing of Data Points

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4.4 The Time Dimension

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4.5 Horizontal Resolutions and Grid Types

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4.5.1 Spectral Resolution

The atmospheric part of most global climate models consists of a spectral model that uses spherical harmonics to calculate model variables instead of calculating them for grid points. Spectral models are computationally more efficient than grid point models. The model resolution is usually expressed in the form T<spectral_resolution>L<number_of_levels> whereby T is the spectral resolution of the model and L is the number of vertical levels. The vertical levels part is, however, often omitted. The spectral resolution of some reanalysis models is listed in Table 4.5.1.1.

Table 4.5.1.1: Spectral resolution of some reanalysis models.

Parameter	Spectral Resolution	Resolution [km]	Grid Resolution [°]
ERA-40	T159L60	125	1.125 x 1.125
ERA-Interim	T255L60	80	0.75 x 0.75
ERA5	T639L137	30	0.28125 x 0.28125
NCEP CFSR	T382L64	38	0.25 x 0.25, 0.5 x 0.5
NCEP-DOE R2	T62L28		2.5 x 2.5
MERRAv2		50	0.5 x 0.625
JRA-55	TL319L60	55	1.25 x 1.25

4.5.2 Full and Reduced Gaussian Grid

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4.5.3 Regular latitude-longitude Grid

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4.6 Vertical Level Types

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4.6.1 Pressure, Potential Temperature and Potential Vorticity Levels

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4.6.2 Sigma (Model) Levels

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4.6.3 Sigma-Hybrid Levels

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5. The netCDF File Format

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5.1 Introduction to the netCDF File Format

The netCDF file format (Section 2.6.4) has become the most commonly used data file format for saving gridded climate data in recent years. The first step in climate data analysis after obtaining access to data files is to get a good understanding of the contents of the file. It is essential to understand how the data stored within netCDF files are organised and what the data represent as this is the basis for any subsequent data operations. The most important questions to ask of a data file are as follows:

- What temporal and spatial dimensions are associated with the data fields?
- What is the spatial resolution and what spatial domain is covered?
- What is the temporal resolution and what time period is covered?
- Which data variables are saved in the file?
- What units are the data variables saved in?

The variable names and variable dimensions are especially important as these are needed to read in the data correctly into analysis software packages such as Python. In addition, it may be helpful to find out what the time unit and the reference time used is (discussed later in more detail). All the information needed to answer the above questions is stored in the netCDF file headers, sometimes also called file metadata. The netCDF file headers describe most aspects of the data the file contains, hence why this data format is referred to as *self-describing*.

5.2 netCDF File Headers

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5.2.1 Exploring netCDF File Headers with ncdump

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5.2.2 Exploring netCDF File Headers with CDO

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5.2.3 Exploring netCDF File Headers with ncview

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5.3 Packed netCDF Files

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5.4 netCDF File Format Conventions

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6. Python - Concepts and Work Environment

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6.1 Python Overview

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6.2 Python Concepts

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6.2.1 Python Modules and Packages

The concept of modular building blocks underpins Python software development. The smallest building block is a Python *module* which is just a single file that contains valid Python code (a Python module can also be written in the *C* programming language). Python files have the file extension `.py`. It is unpractical to write large Python applications in single files and therefore they tend to be split up into individual modules (files). Combining different modules to create a larger application is referred to as *packaging*. The result is a Python *package*.

100K+ Python packages have been developed over the years for all kinds of purposes. Some are well supported and being actively developed while others are not. The latter tend to not stand the test of time. For the purpose of climate computations and visualisation only a small number of well-supported Python packages is needed with each package serving a specific purpose (Table 6.2.1.1). For instance, the *NumPy* package allows computations with multi-dimensional number arrays while the *Matplotlib* package provides functionality for everything related to plotting data.

Table 6.2.1.1: Some of the Python packages commonly used in climate computing and visualisation.

Package	Purpose
Cartopy[1]	Geospatial data processing for creating maps and other geospatial data analyses.
IPython[2]	Powerful shell for interactive computing.
Iris[3]	Powerful, format-agnostic interface for working with multi-dimensional earth science data.
Matplotlib[4]	Cross-platform 2D plotting library and interactive environments.
MetPy[5]	Reading, visualizing, and performing calculations with weather data.
netCDF4[6]	Object-oriented python interface to the netCDF version 4 library.
NumPy[7]	Powerful scientific computing on N-dimensional arrays.
Pandas[8]	Data analysis and manipulation tool.
SatPy[9]	Reading, manipulating, and writing data from remote-sensing earth-observing satellite instruments.
Scikit Learn[10]	Machine learning library.

[1]https://scitools.org.uk/cartopy/docs/latest/
[2]https://ipython.org
[3]https://scitools.org.uk/iris/docs/latest
[4]https://matplotlib.org
[5]https://unidata.github.io/MetPy/latest/index.html
[6]https://anaconda.org/anaconda/netcdf4
[7]https://numpy.org/
[8]https://pandas.pydata.org
[9]https://satpy.readthedocs.io/en/stable/
[10]https://scikit-learn.org/stable

Table 6.2.1.1: Some of the Python packages commonly used in climate computing and visualisation.

Package	Purpose
SciPy[11]	Libraries for mathematics, science, and engineering.
Xarray[12]	Working with labelled multi-dimensional arrays such as data form netCDF files.

The modular Python building blocks concept can be taken one step further by combining packages to create even larger and more complex applications. This creates a semi-layered structure of lower to higher level Python packages as shown in Figure 6.2.1.1. The links between packages are further explored in the following section (Section 6.2.2).

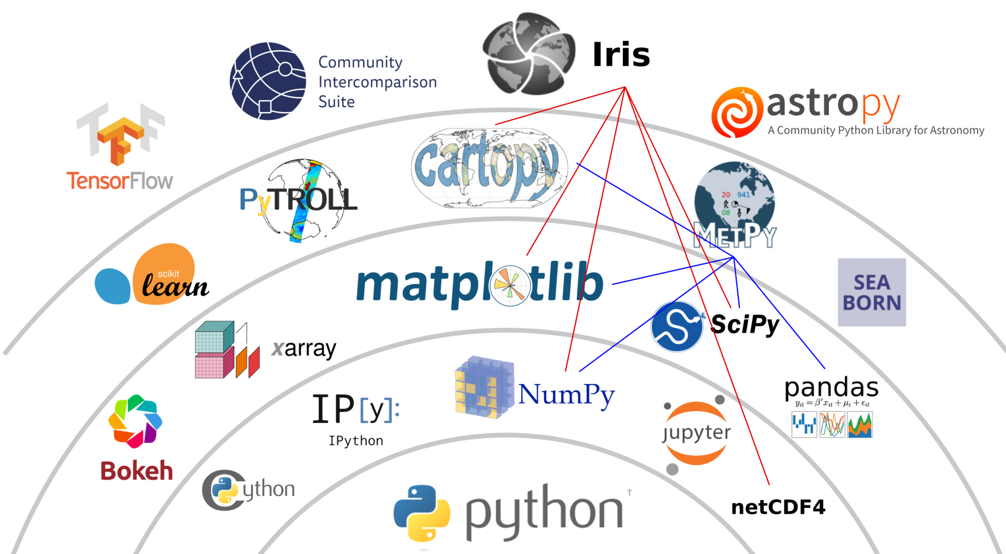

Figure 6.2.1.1: Schematic showing the semi-layered structure of Python packages from lower-level (bottom) to higher-level (top). Examples of dependencies are indicated for *Iris* (red lines) and MetPy (blue lines).

[11]https://www.scipy.org
[12]https://docs.xarray.dev/en/stable/

6.2.2 Package Dependencies

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6.2.3 Package Managers, Repositories and Channels

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6.2.4 Virtual Environments for Python

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6.2.5 Conda, Mamba or Micromamba?

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6.2.6 Micromamba

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6.2.6.1 Creating a Micromamba Environment

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6.2.6.2 Activating and Deactivating Micromamba Environments

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6.2.6.3 Installing Python Packages with Micromamba

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6.2.6.4 Listing and Deleting Micromamba Environments

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6.2.7 Conda

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6.2.7.1 Creating a Conda Environment

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6.2.7.2 Activating and Deactivating Conda Environments

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6.2.7.3 Installing Python Packages

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6.2.7.4 Listing and Deleting Conda Environments

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6.3 Python Code Development Solutions

Code written in the Python programming language is saved in plain text files (see Section 2.6.1) with file names having the extension `.py`. In principle, these files are no different from any other text file. Therefore, any software that allows to create and edit plain text files could in theory be used for Python code development. However, there are many factors to consider, and finding the most effective way to develop, edit, and execute Python code can be challenging and often depends on personal preferences, stability of the sever connection and the implementation of specific features into some of the software solutions.

In the following sub-sections some concepts and options for Python code development are discussed including Python code editors (Section 6.3.1), integrated development environments (Section 6.3.2), browser-based solutions (Section 6.3.3) and the IPython command line Section 6.3.4.

6.3.1 Python Code Editors

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6.3.2 Python IDEs

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6.3.3 Browser-based Python Code Editing

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6.3.3.1 Jupyter Notebooks

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6.3.3.2 VS Code (code-server)

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6.3.4 The IPython Command Line

IPython[13] is a enhanced Python shell that provides a kernel for Jupyter. IPython is used in Jupyter Notebooks but can also be installed in Conda or Micromamba environment. For instance, IPython can be installed in a Micrombama environment with the following command.

```
micromamba install ipython
```

The IPython command line is extremely useful for working interactively with Python. It is worth working through the official IPython tutorial[14] but there are also many IPython tutorials available on YouTube[15].

[13]https://ipython.org/
[14]https://ipython.readthedocs.io/en/stable/interactive/index.html
[15]https://www.youtube.com/results?search_query=IPython

7. Python - Programming Basics

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7.1 Basic Python Programming Building Blocks

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7.1.1 Declaring Variables

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7.1.2 Variable Types and Conversion Between them

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7.1.2.1 Numbers

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7.1.2.2 Strings

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7.1.2.3 Lists

Lists can be created using square brackets (`[]`). The elements in a list are separated by commas (`,`). The elements in a list often are but do not need to be of the same variable type. Lists containing sequences of numbers or names of models over which to loop are quite common in climate computing. List elements can be referenced using indexes. The following are some examples of indexing and manipulating lists.

```
a = [1, 2, 3, 4, 5]

print(a)            # Print whole list
print(a[0])         # Print 1st list element
print(a[2:3])       # Print 3rd to 4th list element
print(a[-1])        # Print last list element
a.append(100)       # Append value 100 at the end of the list
print(a)
a.insert(2, 50)     # Insert value 50 after the 2nd list element
print(a)
a.remove(50)        # Remove list element specified by it's value
print(a)
del a[3]            # Remove list element spedified by it's index
print(a)
```

The methods `append()` and `insert()` in the code examples above are associated with the list variable (python object) `a`. Python object *methods* and *attributes* are discussed in more detail in Section 7.1.4. The above code will generate the following output.

```
[1, 2, 3, 4, 5]
1
[3]
5
[1, 2, 3, 4, 5, 100]
[1, 2, 50, 3, 4, 5, 100]
```

Lists are *mutable* which means that they can be changed after they have been created as shown in the above examples.

A Python object is *mutable* if it can be changed after it was created. Lists are *mutable*. In contrast, Tuples Section 7.1.2.5 are *immutable*.

7.1.2.4 Dictionaries

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7.1.2.5 Tuples

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7.1.2.6 Booleans

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7.1.2.7 Converting Between Variable Types

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7.1.3 Functions

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7.1.3.1 Built-in Functions

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7.1.3.2 User-defined Functions

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7.1.4 Methods and Attributes

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7.1.5 Controlling the Code Flow

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7.1.5.1 *for*-Loops

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7.1.5.2 Conditional Statement

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7.2 Applying Python in Climate Data Analysis

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7.2.1 Error Messages when Running Code

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7.2.2 Looping Through Input Files

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7.2.2.1 Constructing File Names Manually

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7.2.2.2 Constructing File Names Using the Python `glob` Module

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7.2.2.3 Constructing File Names Using the Unix `find` Command

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7.2.2.4 Looping over Months, Days, Hours

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7.2.3 Reading Data Files Into NumPy Variables

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7.2.3.1 Reading Data from netCDF Files

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7.2.3.2 Reading Data from Formatted ASCII Files

Sometimes climate data are made available as formatted ASCII files (see Section 2.6.1). The data values tend to be organised in rows and columns sometimes including a few lines in the beginning of the file known as file headers. If the values in each row are separated by commas then they are called *comma-separated values* (CSV files) and the standard file extension `.csv` should have been used (this is not always done). Other separators are also possible including tabs or white spaces.

The following is an example of a CSV file listing date, time, wind speed and wind direction information for every hour of the year 2011. The file includes two lines at the beginning (the file header) providing the station ID and the column headers.

```
Station ID 65340
date [YYYY/MM/DD], time [hours], wind speed [m/s], wind direction [sector]
2011/01/01, 0, 1.5, N
2011/01/01, 1, 1.8, NE
2011/01/01, 2, 2.1, N
2011/01/01, 3, 2.6, N
2011/01/01, 4, 3.7, NW
2011/01/01, 5, 5.2, W
...
2011/12/31,22, 0.2, W
2011/12/31,23, 0.5, W
2011/12/31,24, 0.3, W
```

The following Python code reads in the CSV file assuming that the data are saved in a file named `wspd_2011.csv`. The `numpy` module is imported in line 1 and given the alias `np`. Line 3 assigns the input file name to the variable `ifile`. In lines 4 to 7 the actual data values are read into the variables `d`, `t`, `wspd` and `wdir`, respectively. The `loadtxt` function from the `np` module requires some arguments (inside brackets) that tell the function how to read in the data. These arguments are the input filename (`ifile`) followed by the data type (`dtype`), the delimiter (`delimiter`), the number of rows to skip in the beginning of the file (`skiprows`) and the column to read in (`usecols`).

```
1 import numpy as np
2
3 ifile = 'long/path/to/file/wspd_2011.csv'
4 d = np.loadtxt(ifile, dtype=str, delimiter=',', skiprows=2, usecols=(0,))
5 t = np.loadtxt(ifile, dtype=int, delimiter=',', skiprows=2, usecols=(1,))
6 wspd = np.loadtxt(ifile, dtype=float, delimiter=',', skiprows=2, usecols=(2,))
7 wdir = np.loadtxt(ifile, dtype=str, delimiter=',', skiprows=2, usecols=(3,))
```

The data are now available for the remaining part of the code as NumPy arrays `d`, `t`, `wspd` and `wdir`.

7.2.3.3 Read Data from an Excel Spreadsheet

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7.2.4 Executing Unix System Commands from Within Python

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7.3 A Brief Introduction to Numpy

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7.3.1 Creating Numpy Arrays

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7.3.2 Indexing NumPy Arrays

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7.3.3 Saving and Loading NumPy Variables

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7.3.4 Some NumPy Solutions

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7.3.4.1 Round a Float Value to specified Decimal Degree

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7.4 Working with Dates and Times

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7.4.1 Creating Date Objects

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7.4.2 Converting Datetime Objects to Strings (`strftime`)

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7.4.3 Creating a NumPy Array with Datetime Objects

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7.5 Tips and Solutions

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7.5.1 Managing Paths and Filenames Using `pathlib`

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7.5.1.1 Pathlib - Basics

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7.5.1.2 Pathlib - Managing Directories

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7.5.1.3 Pathlib - Extract Parts from Directory or Filename

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7.5.1.4 Pathlib - Glob

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7.5.2 String Formatting of Numbers

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7.5.3 Zero-padding Integer Values in Filenames

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7.5.4 Calculate Height from Geopotential with MetPy

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8. Python - Data Analysis with Xarray

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8.1 What is Xarray?

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8.2 Xarray Basics

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8.2.1 Xarray Terminology

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8.2.2 Import Xarray into Python Script

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8.3 Reading in netCDF Files Using Xarray

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8.3.1 Reading in a Single netCDF File

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8.3.2 Reading in Multiple netCDF Files

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8.3.3 Reading in Very Large (memory-intensive) netCDF Files

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8.3.4 Additional Considerations for Reading in netCDF Files

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8.3.4.1 Packed netCDF Files in Xarray

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8.3.4.2 netCDF Time Handling in Xarray

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8.4 DataSets vs DataArrays

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8.5 Exploring File Content

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8.5.1 Print DataSet

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8.5.2 Print DataArray

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.5.3 Accessing DataArray Elements

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8.5.3.1 Accessing DataArray Values

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.5.3.2 Accessing DataArray Dimensions

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.5.3.3 Accessing DataArray Coordinates

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.5.3.4 Accessing DataArray Attributes

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8.5.3.5 Accessing DataArray Name

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8.6 Dates and Times in Xarray

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8.6.1 Retrieving Date/Time Information Using Datetime Accessors

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8.6.2 Passing Date/Time Information to DataArray Methods

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8.7 Selections

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8.7.1 Selecting Variables

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8.7.2 sel() vs isel()

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8.7.3 Selecting Spatial Subsets (Geographical Regions)

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8.7.3.1 Region Longitudes WITHIN Longitude Coordinates Range

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8.7.3.2 Region Longitudes OUTSIDE Longitude Coordinates Range

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8.7.4 Selecting Vertical Levels

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8.7.4.1 Selecting a Single Vertical Level

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8.7.4.2 Selecting a Range of Vertical Level

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8.7.4.3 Selecting Multiple Non-Sequential Vertical Levels

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8.7.5 Selecting Timesteps

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8.7.5.1 Selecting a Single Timestep

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8.7.5.2 Selecting all Timesteps for Single Day

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8.7.5.3 Selecting all Timesteps for a Single Month

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8.7.5.4 Selecting a Range of Timesteps

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8.7.5.5 Selecting all Timesteps for Non-Sequential Days

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8.8 Resampling - Downsampling the Time Dimension

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8.8.1 Resampling to Daily Statistics

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.8.2 Resampling to Monthly Statistics

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.8.3 Resampling to Yearly Statistics

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.8.3.1 Resampling to Yearly Statistics - Unweighted

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.8.3.2 Resampling to Yearly - Weighted Means

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.9 Aggregation - Calculating Statistics Over Dimensions

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8.9.1 Aggregation Over the Time Domain

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8.9.2 Aggregation Over the Spatial Domain

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8.9.3 Aggregation Over the Vertical Domain

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8.9.4 Aggregation Over the Zonal Domain

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8.9.5 Aggregation Over the Meridional Domain

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8.9.6 Aggregation for Hovmöller Plots

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8.10 The Split-Apply-Combine Concept

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8.10.1 Group by Hour

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8.10.2 Group by Month

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8.10.3 Group by Season

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.10.3.1 Group by Season - Unweighted

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.10.3.2 Group by Season - Weighted Means

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.11 Interpolation

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8.11.1 Simple Interpolation Example

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8.11.2 Spatial Interpolation

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.11.2.1 Spatial Interpolation to New Custom Grid

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8.11.2.2 Spatial Interpolation Fetching Grid Details from Another File

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.11.2.3 Spatial Interpolation to Single Point

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.11.3 Interpolation Between two Geographical Points

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8.12 Xarray Computations

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8.12.1 Direct Application of Arithmetic Operation

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8.12.2 NumPy Universial Functions - ufunc()

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8.12.3 Xarray Universal Functions - apply_ufunc()

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8.13 Xarray MetPy Integration

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8.14 More Xarray Methods and Attributes to Explore

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8.14.1 Some Useful Xarray Methods

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8.14.2 Some Useful Xarray Attributes

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8.15 Xarray Plotting

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8.16 Applying Xarray in Climate Computations

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8.16.1 The 1997 Indian Ocean Dipole Event

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

8.16.2 Rainfall Variability in the Sahel

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8.16.3 Winds at In Salah (Algeria)

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9. Python - Creating Plots

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.1 Matplotlib

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.1.1 Setting up a Plotting Page (Figure and Axes)

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9.1.2 Main Plotting Commands

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9.1.3 Colour Names and Colour Maps

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9.2 Line Plots

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9.2.1 Line Plot with Labels

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.2.2 Line Plot with Arrows

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.2.3 Multiple Lines Plot with Markers and Legend

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9.2.4 Multiple Lines Plot with two Scales

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9.2.5 Multiple Lines Plot with Standard Deviation

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9.3 Scatter Plots

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9.3.1 Scatter Plot with a Legend

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9.3.2 Scatter Plot with Divergent Colour Bar

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9.3.3 Scatter Plot on a Map with Colour Bar and Legend

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9.3.4 Adding Trend Line Based on Linear Regression

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9.4 Map Plots

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9.4.1 Cartopy Map Projections

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9.4.2 Cartopy Data Transformations

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.4.3 High-Resolution Map Features

For map plots on global to continental scale the default low resolution of map features such as country borders, rivers and lakes is usually fine. However, when creating map plots on country or sub-country scale a higher resolution of those features is often desirable. Cartopy has a handy *Feature*[1] class that allows to conveniently add and control map features. Those features can be added to a plot using the `ax.add_feature()` method.

Some frequently used features have been pre-defined by Cartopy at a coarse (1:110m) resolution. Those can be added to a plot quit easily after importing the Cartopy Feature class (`import cartopy.feature as cfeature`) as outlined in Table 9.4.3.1

Table 9.4.3.1: Pre-defined coarse resolution Cartopy map features.

Feature	Description
`ax.add_feature(cfeature.BORDERS)`	Country boundaries.
`ax.add_feature(cfeature.COASTLINE)`	Coastlines, including major islands.
`ax.add_feature(cfeature.LAKES)`	Natural and artificial lakes.
`ax.add_feature(cfeature.LAND)`	Land polygons, including major islands.
`ax.add_feature(cfeature.OCEAN)`	Ocean polygons.
`ax.add_feature(cfeature.RIVERS)`	Single-line drainages, including lake centrelines.

High-resolution map features can be obtained from either Natural Earth[2] or NOAA's Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG[3]) database directly via Cartopy Feature subclasses. The remainder of this section will focus on Natural Earth features.

Nature Earth features are available on three scales: 1:10,000,000, 1:50,000,000, and 1:110,000,000 which correspond to the keyword attributes `10m`, `50m` and `110m`, respectively. The features are available in the form of shapefiles (file extension `.shp`). The shapefiles do not need to be downloaded manually. The first time a high-resolution features is requested by the Cartopy Feature class it will be downloaded automatically (working internet connection is required).

[1] https://scitools.org.uk/cartopy/docs/latest/matplotlib/feature_interface.html
[2] https://www.naturalearthdata.com
[3] https://www.ngdc.noaa.gov/mgg/shorelines/gshhs.html

The `cartopy.feature.NaturalEarthFeature()` subclass requires at least three keyword arguments as input. First, the *category* can be either `cultural` or `physical`. Second, the *name* which depends on the category (e.g., `admin_0_boundary_lines_land` for the name `cultural`). Check the Natural Earth website for correct names. And, third, the *scale* which can be either `10m`, `50m` or `110m`. All other keyword control the style of the feature such as colour, linewidth or line style.

The following Code 9.4.3.1 shows how to plot high-resolution border, lake and river features at a 1:10,000,000 scale using Natural Earth data and how to control the feature styles.

Code 9.4.3.1: Plotting high-resolution country borders, lakes and rivers.

```
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.ticker as mplticker
import cartopy.crs as ccrs
import cartopy.feature as cfeature
from cartopy.mpl.gridliner import LONGITUDE_FORMATTER, LATITUDE_FORMATTER

# set up figure and map projection
fig, ax = plt.subplots(figsize=(5.5, 3.98),
                       subplot_kw={'projection':ccrs.PlateCarree()})

# get hi-res features from Natural Earth and define plotting styles
borders = cfeature.NaturalEarthFeature(category='cultural',
                                       name='admin_0_boundary_lines_land',
                                       scale='10m', facecolor='none',
                                       edgecolor='black', linestyle=':',
                                       linewidth=0.5, alpha=0.8, zorder=2)
lakes = cfeature.NaturalEarthFeature(category='physical', name='lakes',
                                     scale='10m', edgecolor='none', alpha=1.0,
                                     facecolor='navy', linewidth=0.5, zorder=1)
rivers = cfeature.NaturalEarthFeature(category='physical',
                                      name='rivers_lake_centerlines',
                                      scale='10m', facecolor='none',
                                      edgecolor='navy', linewidth=0.25,
                                      alpha=1.0, zorder=1)

# define spatial domain [lon0, lon1, lat0, lat1]
```

```
28 ax.set_extent([26, 46, -7, 6], crs=ccrs.PlateCarree())
29 
30 # add filled land and ocean; draw coastlines, country borders, lakes and rivers
31 ax.add_feature(cfeature.LAND)
32 ax.add_feature(cfeature.OCEAN)
33 ax.add_feature(borders)
34 ax.add_feature(lakes)
35 ax.add_feature(rivers)
36 ax.coastlines(linewidth=0.5)
37 
38 # add title
39 ax.set_title('High-Resolution (1:10m) Cartopy Map Features', fontsize=8)
40 
41 # format gridlines and labels
42 gl = ax.gridlines(draw_labels=True, linewidth=0.0, color='black', alpha=0.5,
43                   linestyle=':')
44 gl.top_labels = False
45 gl.xlocator = mplticker.FixedLocator(np.arange(-180, 180, 2))
46 gl.xformatter = LONGITUDE_FORMATTER
47 gl.xlabel_style = {'size':6, 'color':'black'}
48 gl.right_labels = False
49 gl.ylocator = mplticker.FixedLocator(np.arange(-90, 90, 2))
50 gl.yformatter = LATITUDE_FORMATTER
51 gl.ylabel_style = {'size':6, 'color':'black'}
52 
53 # add marker for Marsabit
54 ax.plot(37.973488, 2.339599, marker='s', color='red', markersize=0.8)
55 ax.text(37.973488+0.15, 2.339599+0.15, 'Marsabit', fontsize=4)
56 
57 # optimise layout
58 plt.tight_layout()
59 
60 # save plot to png file
61 plt.savefig('../images/8_python_cartopy_hires_300dpi.png', dpi=300)
62 
63 # close file
64 plt.close()
```

All necessary packages are imported in lines 1 to 7 including Cartopy's Feature subclass (line 5).

A figure and axis is set up in line 9 to 10 with the projections set to `PlateCarree()`.

1:10000000 resolution border data are requested from Natural Earth in lines 13 to 17 using the category `cultural`, name `admin_0_boundary_lines_land` and scale `10m` keyword arguments. The line style is set to a dotted line (`:`) with a linewidth of `0.5`. The line is semitransparent with the alpha value set to 0.8. The whole border definition is saved in the Python object *borders*.

Similarly, lakes are defined in lines 18 to 20 using the category `physical`, name `lakes` and scale `10m`.

And rivers are defined in lines 21 to 25 with the category `physical`, name `lakes` and the scale, same as for borders and lakes, `10m`.

Note the `zorder` keyword which is set to `2` for borders and `1` for lakes and rivers. This makes sure that country borders are drawn on top of lakes (see Figure 9.4.3.1).

The geographical extent of the map area is defined in line 28.

Next, map features are added to the plot by passing Cartopy Features to the `ax.add_-feature()` method. In the absence of data to be plotted, the default coarse resolution polygons for `LAND` and `OCEAN` are added here in lines 31 and 32, respectively. By default, the ocean area is coloured in a light blue and land in beige. Then, the previously defined features `borders`, `lakes` and `rivers` are added in lines 33, 34 and 35, respectively. In addition, coast lines are drawn with a *linewidth* of `0.5` in lihne 36. Note the high resolution of these features in Figure 9.4.3.1.

A title is added in line 39.

The grid lines and grid labels are configured in lines42 to 51. Setting the *linewidth* to `0.0` in line 42 means that no gridlines are being drawn. However, grid labels are plotted on the left and bottom only because *gl.top_labels* and *gl.right_labels* are set to `False` in lines 44 and 48, respectively.

A marker and label for the town of Marsabit are added in lines 54 and 55, respectively.

The plot is optimised in line 58, saved to a PNG file in line 61 and the closed in line 64.

The Code 9.4.3.1 generates the following Figure 9.4.3.1.

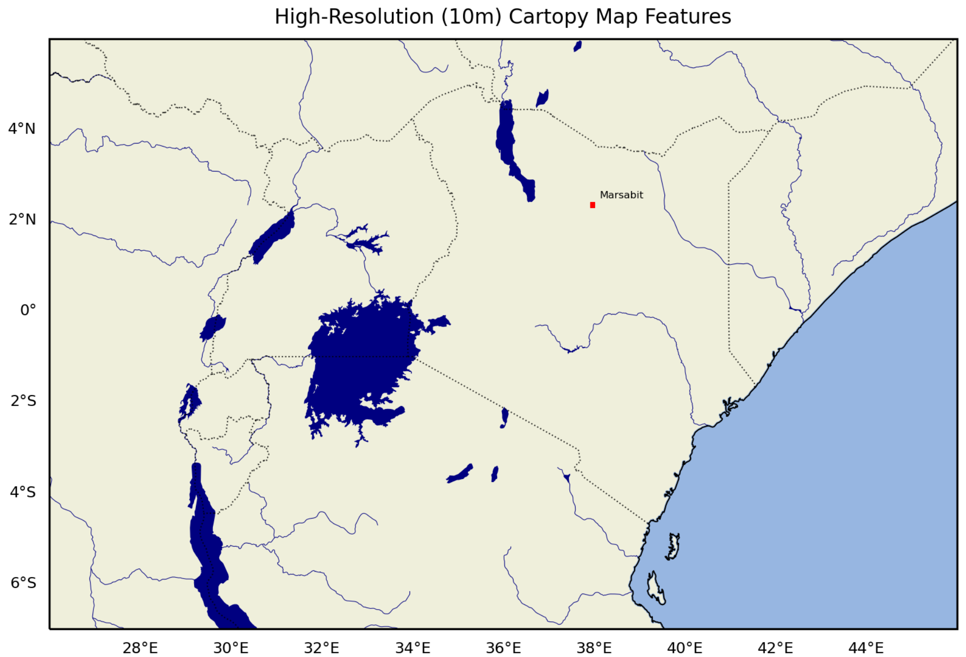

Figure 9.4.3.1: High-resolution (10m) map features such as country borders, lakes and rivers added from Natural Earth to a map of eastern Africa.

9.4.4 Simple Map of SST Anomalies

The following Code 9.4.4.1 demonstrates how to plot a map of SST anomalies over the Indian Ocean domain. HadISST v1.1 SST data were used to calculated the November 1979 anomaly compared to the 1980-2010 November mean.

Code 9.4.4.1: Plotting Indian Ocean Dipole with stock background image.

```
import xarray as xr
import numpy as np
import matplotlib.pyplot as plt
import matplotlib.ticker as mplticker
import cartopy.crs as ccrs
from cartopy.mpl.gridliner import LONGITUDE_FORMATTER, LATITUDE_FORMATTER

# reading in netCDF file
ds = xr.open_dataset('../data/HadISST_sst_Nov1997_anom.nc')
field = ds['sst'].squeeze().values
lons = ds['longitude'].values
lats = ds['latitude'].values

# set up figure and map projection
fig, ax = plt.subplots(figsize=(5.5, 4.6),
                       subplot_kw={'projection':ccrs.PlateCarree()})

# define contour levels
levels = np.linspace(-2, 2, 17)

# contour data
mymap = ax.contourf(lons, lats, field, levels, transform=ccrs.PlateCarree(),
                    cmap=plt.cm.RdBu_r, extend='both')

# add coastlines and stock image
ax.stock_img()
ax.coastlines()
ax.set_extent([29.99, 120.01, -30.01, 30.01], crs=ccrs.PlateCarree())

# format gridlines and labels
gl = ax.gridlines(draw_labels=True, linewidth=0.5, color='black', alpha=0.5,
                  linestyle=':')
gl.top_labels = False
gl.xlocator = mplticker.FixedLocator(np.arange(-180, 180, 30))
gl.xformatter = LONGITUDE_FORMATTER
gl.xlabel_style = {'size':7, 'color':'black'}
gl.right_labels = False
gl.ylocator = mplticker.FixedLocator(np.arange(-90, 90, 30))
```

```
39 gl.yformatter = LATITUDE_FORMATTER
40 gl.ylabel_style = {'size':7, 'color':'black'}
41
42 # add colorbar
43 cbar = plt.colorbar(mymap, orientation='horizontal', shrink=0.7, pad=0.07)
44 cbar.set_label('SST [C]', rotation=0, fontsize=10)
45 cbar.ax.tick_params(labelsize=5, length=0)
46
47 # add title
48 ax.set_title('HadISST SST Nov 1997 anomaly (1980-2010)', fontsize=10)
49
50 # save plot
51 plt.tight_layout()
52 plt.savefig('../images/9_python_simple_map_plot_sst_anoms_300dpi.png',
53             format='png', dpi=300)
54 plt.close()
```

All packages and functions used in the script are imported in lines 1 to 6.

The pre-calculated SST anomalies are read in from netCDF file in lines 9 using Xarray saving the field as DataSet `ds`. The variables `sst`, `longitude` and `latitude` are extracted from the DataSet ds and saved as NumPy arrays `field`, `lons` and `lats`, respectively (lines 10 to 12).

In line 15, the plot figure (`figure`) and axis (`ax`) are set up. Note that the map projection (`projection':ccrs.PlateCarree()`) is passed to the `plt.subplots()` function via the `subplot_kw` keyword.

Contour levels ranging from `-2` to `2` in steps of 0.25 are defined in line 19 using the `np.linspace()` function.

Filled contours of the SST anomalies are plotted in lines 22 to 23. As the data are on a regular lat/lon grid the data projection `ccrs.PlateCarree()` is passed to `ax.contourf()` via the `transform` keyword. The colour map red to blue reversed (`plt.cm.RdBu_r`) is used and the colour scale is extended at both ends for lower and higher values (`extend='both'`).

The map is customised by adding the standard background image (line 26) and coastlines (line 27). The plot domain is set for the Indian Ocean in line 28. Note that the coordinate reference system is set to `crs=ccrs.PlateCarree()` to make sure the values presented to the `ax.set_extent()` function are projected correctly in line with the map projection defined in line 22.

The map is further customised in lines 31 to 40. Black (`color='black'`) semi-transparent (`alpha=0.5`) dotted (`linestyle=':'`) grid lines are added in lines 34 and 35 and axis labels are switched on (`draw_labels=True`). Labels are switched off for the top and right of the map in lines 33 and 47, respectively. The plotting of major ticks and grid line positions is handled in lines 34 and 35 for meridians and in lines 38 and 39 for parallels. Label properties are set in lines 36 and 40 for x-axis and y-axis labels, respectively.

! The functions `ax.set_xlabel()` and `ax.set_ylabel()` are currently not supported in `cartopy` map projections.

A horizontal colour bar is added and customised in lines 43 to 45. Note that the handle `mymap` created in line 22 is passed to the `plt.colorbar()` function in line 43. The new handle `cbar` is then used to customise colour bar properties.

A plot title is added in line 48

The map plot layout is optimised, saved and closed in lines 51 to 54.

The Code 9.4.4.1 generates the following Figure 9.4.4.1.

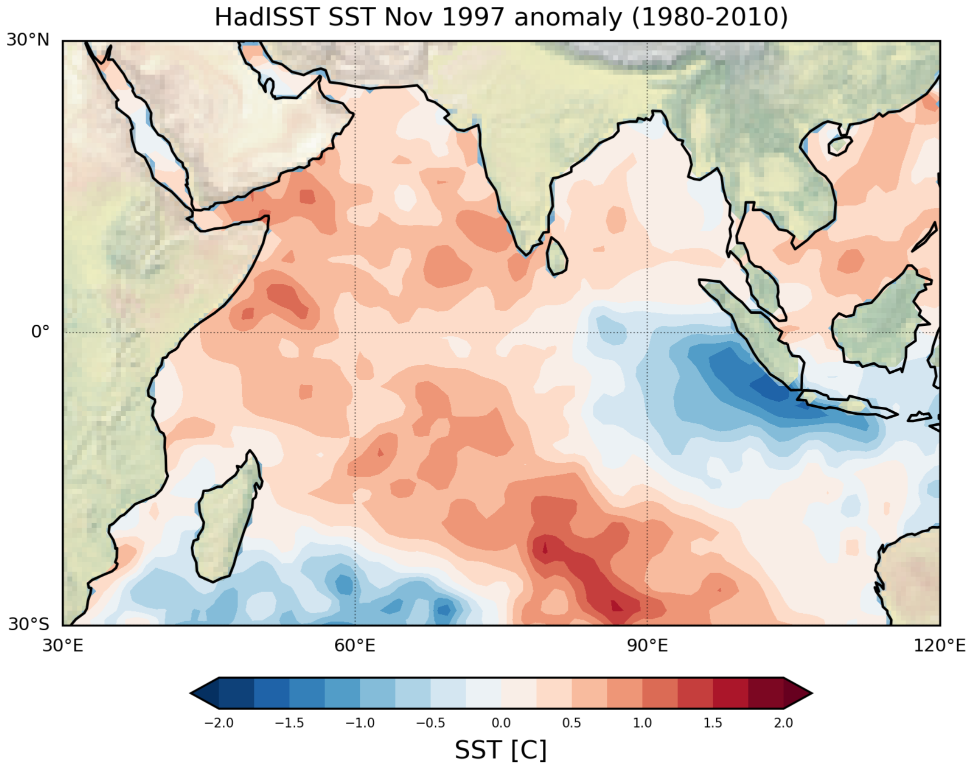

Figure 9.4.4.1: Indian Ocean Diopol (IOD) November 1997 SST anomalies (reference period 1980-2010) calculated from HadISST observed SSTs.

Figure 9.4.4.1 shows the Indian Ocean Dipole (IOD[4]) as represented with November 1997 SST anomalies. In November 1997, the IOD was in an extreme positive (negative) state with above (below) average SSTs in the western (eastern) Pacific.

9.4.5 Map with Stipples for Statistical Significance

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

[4]https://en.wikipedia.org/wiki/Indian_Ocean_Dipole

9.5 Bar Graphs

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.5.1 Anomalies Bar Graph

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9.6 Hovmöller Plots

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.6.1 Hovmöller Plot with Time as a Function of Latitude

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9.6.2 Hovmöller Plot with Time as a Function of Pressure

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9.7 Vertical Cross-Section Plots

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9.7.1 Meridional Cross-Section

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.7.2 Vertical Cross-Section Between two Points

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9.8 Skew-T Plots

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

9.8.1 Brief Introduction to Skew-T Plots

Skew-T plots are used in meteorology and climate studies to visualise the complex relationships between pressure, temperature and moisture as well as wind speed and direction within the atmospheric column at a specific location and point in time. They can be used to assess atmospheric stability. Atmospheric profiles are often obtained from radiosondes (sondes attached to weather balloons) or dropsondes (sondes attached to parachutes released from aircraft). Atmospheric profiles may also be derived from from model simulations and reanalyses.

Several online resource are available to obtain radiosonde measurements. The most popular resources are the archive of global radiosonde observations maintained by the University of Wyoming Department of Atmospheric Science[5] and the Integrated Global Radiosonde Archive Version 2 (IGRA v2[6]) maintained by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI). The Python package Siphon[7] provides an easy interface to pull

[5]http://weather.uwyo.edu/upperair/sounding.html
[6]https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00975
[7]https://unidata.github.io/siphon/latest/index.html

radiosonde data directly from these remote data services (see examples in Section 9.8.2 and Section 9.8.3) removing the need to download and store data locally.

The *Siphon* package allows to pull radiosonde data directly from remote archives. Siphon with the follwing command: `pip install siphon`.

Unidata have put together some excellent instructional video tutorials as part of their MetPy Mondays[8] series. In the playlist, the videos 11 to 14 and 144 explain how to use MetPy to develop Skew-T plots.

The complexity of a Skew-T plots can be quite daunting for a beginner. Figure 9.8.1.1 is a reminder of what the different plot features represent. Shown here is a Skew-T plot for a radiosonde released from Ndjamena (Chad) at 12 UTC on 9 July 2020. In the following subsections the use of the Python packages Siphon and MetPy for creating Skew-T plots is discussed in more detail.

[8] https://www.youtube.com/playlist?list=PLQut5OXpV-0ir4IdllSt1iEZKTwFBa7kO

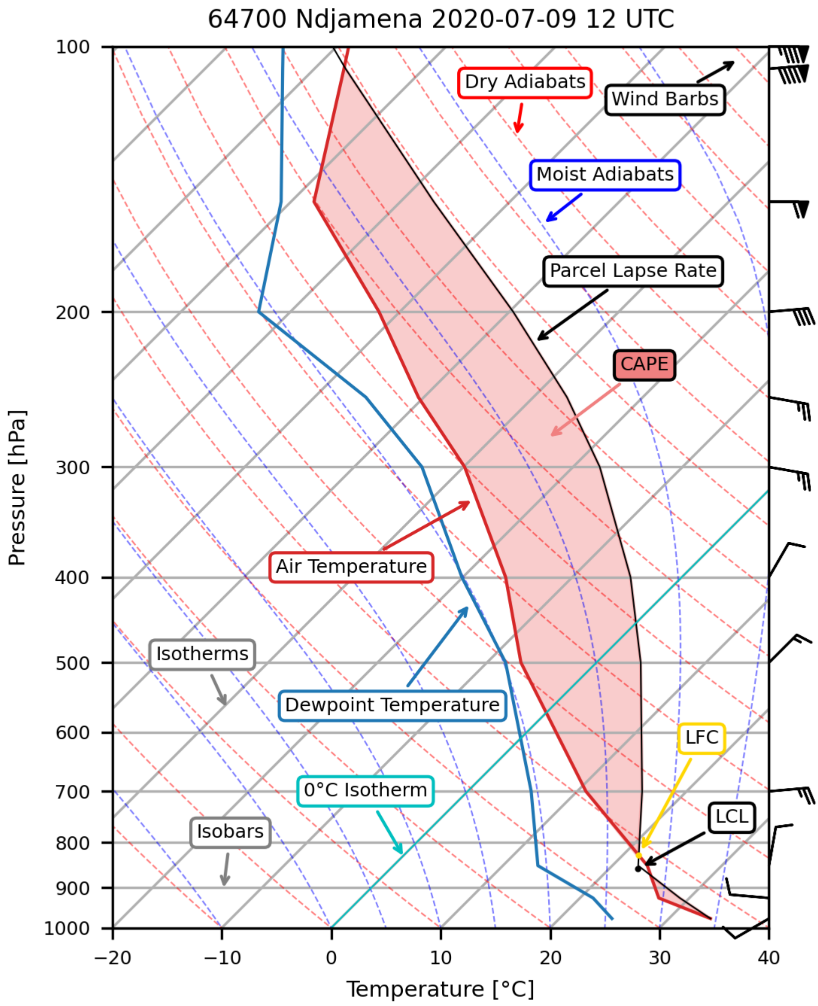

Figure 9.8.1.1: Example Skew-T plot with labels (CAPE = Convective Available Potential Energy, LFC = Level of Free Convection, LCL = Lifted Condensation Level).

For completeness, the undocumented code for [Figure 9.8.1.1] can be found in Code

9.8.1.1 below.

Code 9.8.2.1: Labelled Skew-T plot example.

```
from datetime import datetime
from siphon.simplewebservice.wyoming import WyomingUpperAir
from metpy.units import units
import matplotlib.pyplot as plt
import metpy.plots as mpplots
import metpy.calc as mpcalc
import numpy as np

# define date of interest, time and station ID
doi = datetime(2020, 7, 9, 12)
sid = '64700'
sname = 'Ndjamena'

# read data into a Pandas dataframe
df = WyomingUpperAir.request_data(doi, sid)

# extract variables from dataframe into unit-registered metpy variables
p = df['pressure'].values * units(df.units['pressure'])
t = df['temperature'].values * units(df.units['temperature'])
td = df['dewpoint'].values * units(df.units['dewpoint'])
u = df['u_wind'].values * units(df.units['u_wind'])
v = df['v_wind'].values * units(df.units['v_wind'])

# set up figure and axis adding skewt figure
fig = plt.figure(figsize=(3.98, 5.5))

# set up subplot grid
ax1 = mpplots.SkewT(fig, rotation=45)

# plot data
ax1.plot(p, t, 'tab:red', linewidth=1)
ax1.plot(p, td, 'tab:blue', linewidth=1)

# Calculate LCL height and plot as black dot. Because `p`'s first value is
# ~1000 mb and its last value is ~250 mb, the `0` index is selected for
# `p`, `T`, and `Td` to lift the parcel from the surface. If `p` was inverted,
# i.e. start from low value, 250 mb, to a high value, 1000 mb, the `-1` index
```

```
# should be selected.
lcl_pressure, lcl_temperature = mpcalc.lcl(p[0], t[0], td[0])
ax1.plot(lcl_pressure, lcl_temperature, color='black', marker='o',
         markersize=1, markerfacecolor='black')

# Calculate LFC height and plot as green dot.
lfc_pressure, lfc_temperature = mpcalc.lfc(p, t, td)
ax1.plot(lfc_pressure, lfc_temperature, color='gold', marker='o',
         markersize=1, markerfacecolor='gold', zorder=3)

# Calculate full parcel profile and add to plot as black line
prof = mpcalc.parcel_profile(p, t[0], td[0]).to('degC')
ax1.plot(p, prof, color='black', linewidth=0.5)

# Shade areas of CAPE and CIN
ax1.shade_cape(p, t, prof, color='lightcoral', alpha=0.4)
# ax1.shade_cin(p, t, prof)

# Plot slanted line at constant T (0 degree C isotherm)
ax1.ax.axvline(0, color='c', linestyle='-', linewidth=0.5)

# Add the relevant special lines
t0 = np.arange(-20, 200, 10) * units.degree_Celsius
ax1.plot_dry_adiabats(t0, color='red', linestyle='--', linewidth=0.5)
ax1.plot_moist_adiabats(linestyle='--', linewidth=0.5)

# plot wind barbs
ax1.plot_barbs(p, u, v, color='black', linewidth=0.75, length=5)

## format x-axes
ax1.ax.set_xlim(-20, 40)
ax1.ax.set_xlabel('Temperature [\u00B0C]', fontsize=7)
ax1.ax.tick_params(axis='x', which='major', labelsize=6)

# formt y-axis
ax1.ax.set_ylim(1000, 100)
ax1.ax.set_ylabel('Pressure [hPa]', fontsize=7)
ax1.ax.tick_params(axis='y', which='major', labelsize=6)

# add title
```

```
ax1.ax.set_title(f'{sid} {sname} {doi.strftime("%Y-%m-%d %H UTC")}',
                 fontsize=8)

# annotation for LCL
arrow_props = dict(color='black', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='black', lw=1)
ax1.ax.annotate('LCL', xy=(lcl_temperature, lcl_pressure), xytext=(25, 750),
                fontsize=6,verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for LFC
arrow_props = dict(color='gold', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='gold', lw=1)
ax1.ax.annotate('LFC', xy=(lfc_temperature, lfc_pressure), xytext=(15, 610),
                fontsize=6,verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for 0 degC T
arrow_props = dict(color='c', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='c', lw=1)
ax1.ax.annotate('0\u00B0C Isotherm', xy=(0.75, 840), xytext=(-15, 700),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for temperature
arrow_props = dict(color='tab:red', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='tab:red', lw=1)
ax1.ax.annotate('Air Temperature', xy=(-26, 325), xytext=(-38, 390),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for dewpoint temperature
arrow_props = dict(color='tab:blue', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='tab:blue', lw=1)
ax1.ax.annotate('Dewpoint Temperature', xy=(-17, 425), xytext=(-24.5, 560),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for isobars
arrow_props = dict(color='grey', arrowstyle='->')
```

```
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='grey', lw=1)
ax1.ax.annotate('Isobars', xy=(-13, 915), xytext=(-21, 780),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for isotherm
arrow_props = dict(color='grey', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='grey', lw=1)
ax1.ax.annotate('Isotherms', xy=(-29, 570), xytext=(-41, 490),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for wind barbs
arrow_props = dict(color='black', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='black', lw=1)
ax1.ax.annotate('Wind Barbs', xy=(-42, 103), xytext=(-50, 115),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for dry adiabats
arrow_props = dict(color='red', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='red', lw=1)
ax1.ax.annotate('Dry Adiabats', xy=(-55, 128), xytext=(-65, 110),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# annotation for moist adiabats
arrow_props = dict(color='blue', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='blue', lw=1)
ax1.ax.annotate('Moist Adiabats', xy=(-45, 160), xytext=(-50, 140),
                fontsize=6, verticalalignment='center',
                arrowprops=arrow_props, bbox=bbox_props)

# annotation for parcle lapse rate
arrow_props = dict(color='black', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='white', ec='black', lw=1)
ax1.ax.annotate('Parcel Lapse Rate', xy=(-35, 218), xytext=(-40, 180),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)
```

```
# annotation for CAPE
arrow_props = dict(color='lightcoral', arrowstyle='->')
bbox_props = dict(boxstyle='round,pad=0.3', fc='lightcoral', ec='black', lw=1)
ax1.ax.annotate('CAPE', xy=(-25, 280), xytext=(-25, 230),
                fontsize=6, verticalalignment='center', arrowprops=arrow_props,
                bbox=bbox_props)

# save plot
plt.tight_layout()
fig.savefig('../images/9_python_skewt_plot_intro_labels_300dpi.png', dpi=300)
plt.close()
```

9.8.2 Simple Skew-T Plot

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9.8.3 Multiple Skew-T Plots

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9.9 Vector and Streamline Plots

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9.9.1 Black Wind Vectors on Filled Colour Contours

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9.9.2 Coloured Wind Vectors

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9.9.3 Streamline Plot

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9.10 Looping Through Multiple Panels

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9.10.1 Multiple Line Plots (`axes.flat` method)

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9.10.2 Multiple Line Plots (`pop()` function)

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9.10.3 Multiple Map Plots (`axes.flat` method)

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10. Data Analysis with CDO

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10.1 What is CDO?

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10.2 Useful CDO Resources

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10.3 Basic Syntax of CDO Commands

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10.3.1 CDO Options

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10.3.2 CDO Operator Categories

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10.3.3 Using Multiple CDO Operators

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10.3.4 CDO Operator Parameters

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10.3.5 CDO Command Input and Output Files

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10.4 Merging Files

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10.5 Selections

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10.5.1 Selecting Variables

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10.5.2 Selecting Spatial Subsets (Geographical Regions)

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10.5.3 Selecting Vertical Levels

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10.5.4 Selecting Time Subsets

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10.6 Basic Statistics

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

10.6.1 Statistics over the Time Domain

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10.6.2 Statistics over the Spatial Domain

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10.6.3 Statistics over the Vertical Domain

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10.6.4 Statistics over the Zonal Domain

The zonal domain refers to the east-west direction of the data field (along the latitude zones). For statistical computations over the zonal domain the CDO operator `zon` combined with the statistic of interest is used (`zon<stat>`).

The following command applies the `zonmean` operator to the same input file used in Section 10.6.3 to calculate global long-term zonal mean specific humidity values. The output is saved in a file named `erai_ltm_q_zonmean.nc`.

```
cdo zonmean erai_q_ltm.nc erai_ltm_q_zonmean.nc
```

The output of the command `ncdump -h erai_ltm_q_zonmean.nc` looks like the following.

```
netcdf erai_q_ltm_zonmean {
dimensions:
        lon = 1 ;
        lat = 241 ;
        level = 37 ;
        time = UNLIMITED ; // (1 currently)
        bnds = 2 ;
variables:
        double lon(lon) ;
                lon:standard_name = "longitude" ;
                lon:long_name = "longitude" ;
                lon:units = "degrees_east" ;
                lon:axis = "X" ;
        double lat(lat) ;
                lat:standard_name = "latitude" ;
                lat:long_name = "latitude" ;
                lat:units = "degrees_north" ;
                lat:axis = "Y" ;
        double level(level) ;
                level:standard_name = "air_pressure" ;
                level:long_name = "pressure_level" ;
                level:units = "millibars" ;
                level:positive = "down" ;
                level:axis = "Z" ;
        double time(time) ;
```

```
                time:standard_name = "time" ;
                time:long_name = "time" ;
                time:bounds = "time_bnds" ;
                time:units = "hours since 1900-1-1 00:00:00" ;
                time:calendar = "standard" ;
                time:axis = "T" ;
        double time_bnds(time, bnds) ;
        double q(time, level, lat, lon) ;
                q:standard_name = "specific_humidity" ;
                q:long_name = "Specific humidity" ;
                q:units = "kg kg**-1" ;
                q:_FillValue = -32767. ;
                q:missing_value = -32767. ;
...
}
```

Note that the longitude dimension collapsed to 1 whereas the number of elements of the latitude, level and time dimensions remain unchanged. The output field represents a latitude by height cross section of the atmosphere.

The collapse of the longitude dimension longitude is demonstrated visually for a 4D data structure (as used in the example above) in Figure 10.6.4.1 and for a 3D data structure in Figure 10.6.4.2.

Statistics calculated over the zonal domain using the zon<stat> operator will result in the collapse of the longitude dimension to 1.

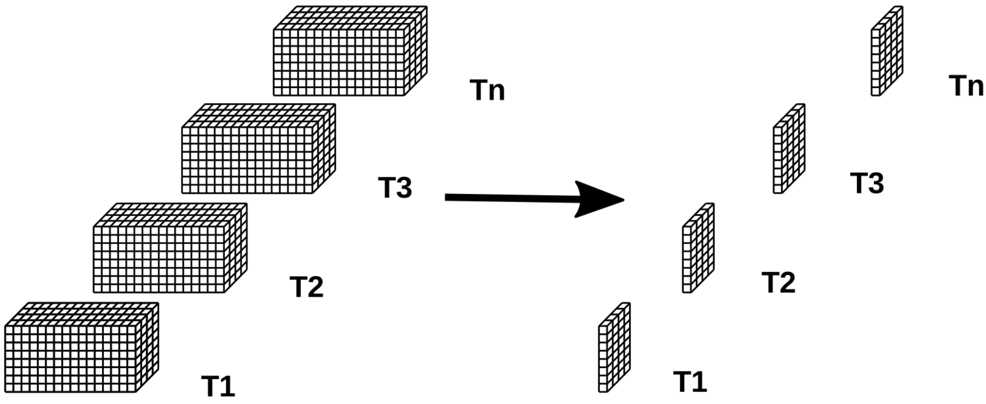

Figure 10.6.4.1: Schematic showing the collapse of the zonal dimension `longitude` when the `zon<stat>` operator is applied to a 4D (longitude, latitude, levels and time) data structure resulting in a 3D (latitude, levels and time) data structure.

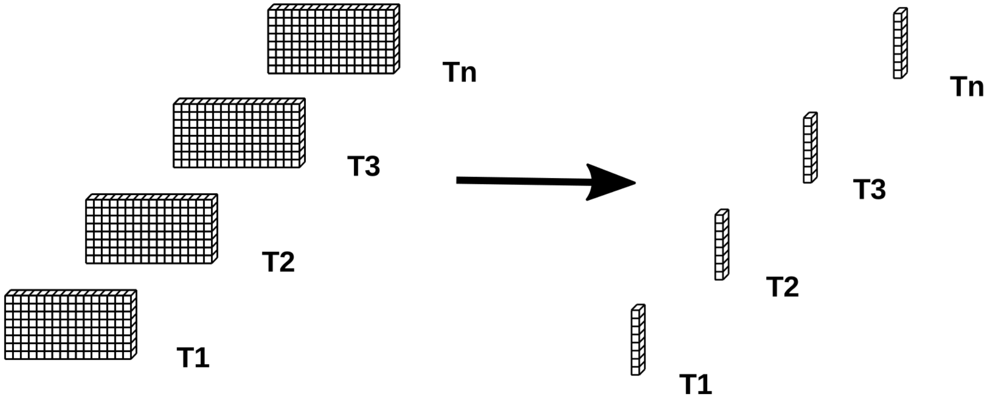

Figure 10.6.4.2: Schematic showing the collapse of the zonal dimension `longitude` when the `zon<stat>` operator is applied to a 3D (longitude, levels and time) data structure resulting in a 2D (levels and time) data structure.

10.6.5 Statistics over the Meridional Domain

This content is not available in the sample book. The book can be purchased on Leanpub at http://leanpub.com/data-analysis-and-visualisation-in-climate-sciences.

10.6.6 Statistics over Ensembles

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10.7 Interpolations

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10.7.1 Interpolation to a new horizontal grid (remapping)

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10.7.2 Interpolation in the Vertical Domain

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10.7.3 Interpolation in the Time Domain

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10.8 Basic Arithmetic

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10.8.1 Artithmetic Between Two Files

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10.8.2 Arithmetic Using a Constant Value

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10.9 Applying CDO in Climate Computations

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10.9.1 Indian Ocean Dipole Example

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10.9.2 Sahel Rainfall Variability Example

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10.9.3 Creating a Land-Sea Mask File

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10.10 Using CDO with Python

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Appendix

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List of Acronyms

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