Development and Application of a Coupled Ocean-Atmosphere Model for Simulating Marine Heatwaves in the Mediterranean

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March 2025

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March 2025

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Personal Statement

Title

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Statement

This dissertation is an original work, submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy. It was validated by the Academic Committee in September 2024. Any sources or inspirations beyond my own contributions are duly acknowledged through references, notes, and other attributions.

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Acknowledgements

To those who sparked the curiosity, fueled the passion, and illuminated the path. Your unwavering moral support will echo long after the ink has dried on these pages.

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Abstract

In the face of rising global temperatures, the interplay between oceanic and atmospheric heatwaves has become a pressing concern. This study explores the complex dynamics of these coupled events, with a focus on the Eastern Mediterranean region. By leveraging high-resolution datasets and advanced modeling techniques, we investigate the feedback mechanisms driving these thermal extremes and their cascading effects on the environment. Our research aims to shed light on the intricate relationships between oceanic and atmospheric processes, ultimately contributing to a deeper understanding of the Earth's climate system.

Keywords: Ocean, SST, Marine heatwaves

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Glossary

AGL *Above Ground Level*. Vertical distance between a measurement sensor, such as a weather station, and the ground surface it is situated on. By considering this distance, the significance and relevance of the measured data can be better understood and interpreted. (*p. 14*)

AWS *Automatic Weather Station*. Specialized ground measurements systems designed to collect and transmit weather data from the ground level. These stations typically consist of a suite of sensors and instruments that measure various atmospheric and meteorological parameters, transmitted in real-time to a central server or database. (*p. 14*)

CDO *Climate Data Operators*. Software framework that provides a set of command-line operators for manipulating and processing large climate data, and supports a wide range of climate data formats, such as `netCDF` or `GRIB`. (*p. 21*)

MHW *Marine Heatwave*. Prolonged (at least 5 consecutive days) period of abnormally high sea surface temperature, in a given region of the ocean. During an event, surface waters are significantly warmer than the typical conditions for that time of year and location (90-th percentile climatology). (*p. 21*)

MSL *Above Mean Sea Level*. Reference used to express the elevation of the weather ground station above the surrounding sea level, providing a standardized reference point for comparing data from different locations. (*p. 14*)

MY-d-mean *Multi-year daily mean*. Obtained by averaging daily SST values over multiple years, yielding a single daily value for each of the 365 days of the year. This resulting daily climatology is then projected over the entire duration of the input SST data ($\approx$ 40 years). (*p. 21*)

p90 *90th percentile*. Statistical value used as a threshold, when computing multi-year daily climatology, and used to detect MHW events. (*p.* 21)

rtr *Rolling Threshold*. The p90 climatology serves as the (unfiltered) threshold. A one-sided 5-day centered rolling average is then applied to this threshold. Consequently, the *standard* threshold is transformed into the *rolling* threshold. (*p.* 21)

SST *Sea Surface Temperature*. The temperature of the ocean's surface layer, typically measured at a depth of 0-5 meters below the surface.. (*p.* 11)

WRF *Weather Research and Forecasting*. State of the art mesoscale numerical weather prediction model designed for both atmospheric research and operational forecasting applications. (*p.* 21)

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1

Introduction

Welcome to the introduction of your dissertation. The introduction to this dissertation serves as a pivotal component, setting the stage for the entire research endeavor. Its primary function is to provide a clear and concise overview of the research topic, situating it within the broader academic context and highlighting its significance. A well-crafted introduction should articulate the research problem or question, justify its relevance, and identify existing knowledge gaps. Additionally, it should outline the study's objectives, methodology, and anticipated contributions, offering a roadmap for the reader to navigate the subsequent chapters. Ultimately, the introduction aims to engage the reader, provide a framework for the research, and demonstrate its importance within the academic community

1.1 Literature Review

MHWs (Marine Heatwaves) are a growing concern for marine ecosystems worldwide. These extreme events, characterized by prolonged periods of unusually warm ocean temperatures, can have devastating impacts on marine life and ecosystems Hobday et al., 2016. In recent years, there has been an increase in the frequency and duration of MHWs, with some studies suggesting that this trend is likely to continue under global warming Frölicher et al., 2018.

The impacts of MHWs on marine ecosystems can be severe, with mass bleaching of coral reefs, shifts in species distributions, and changes to food webs Smale et al., 2019. For example, the 2016 MHW in the Mediterranean Sea caused widespread damage to marine ecosystems, including the loss of seagrass beds and the decline of fish populations Wernberg et al., 2019.

Despite the growing concern about MHWs, there is still much to be learned about these events. Recent studies have highlighted the importance of understanding the physical and biological processes that drive MHWs, as well as the impacts of these events on marine ecosystems Oliver et al., 2018.

2

Methodology

This study examines the characteristics and impacts of a specific oceanic phenomenon in a regional context, using a combination of remote sensing data and ground-based observations. The methodology involves a multi-step approach, including data collection and analysis, event identification and characterization, and statistical examination of relationships between oceanic and atmospheric variables. The study employs advanced analytical techniques to investigate patterns and trends in the data, with the goal of providing a comprehensive understanding of the phenomenon and its implications for regional climate and ecosystems.

2.1 Problem Statement

Despite the growing concern about the impacts of oceanic heatwaves on regional climate and ecosystems, there is a lack of comprehensive understanding of the characteristics and trends of these events in the region being investigated. The current gap in knowledge hinders the development of effective strategies for mitigating and adapting to the effects of oceanic heatwaves, which can have devastating consequences for marine ecosystems, fisheries, and human livelihoods. Therefore, this study aims to investigate the patterns and trends of oceanic heatwaves in the region and explore their implications for regional climate and ecosystems

2.1.1 Mathematical Formulation

Let $T(x,t)$ be the sea surface temperature (SST) at location x and time t, and let $T_{clim}(x)$ be the climatological mean SST at location x. Then, the SST anomaly $\Delta T(x,t)$ can be defined as:

$$
\begin{aligned}
\Delta T(x,t) &= T(x,t) - T_{clim}(x) && (2.1)\\
&= \left[T(x,t) - \overline{T(x)}\right] - \left[T_{clim}(x) - \overline{T(x)}\right] && (2.2)\\
&= \left[T(x,t) - \overline{T(x)}\right] - \delta T_{clim}(x) && (2.3)
\end{aligned}
$$

The SST anomaly can be used to identify oceanic heatwaves, which are defined as periods of abnormally high SST anomalies that persist for several days or weeks.

However, the current methods for detecting oceanic heatwaves are limited by their reliance on subjective thresholds and simplistic statistical models. Therefore, this study aims to develop a more robust and objective method for detecting oceanic heatwaves using advanced statistical techniques and machine learning algorithms.

2.2 Area of Interest

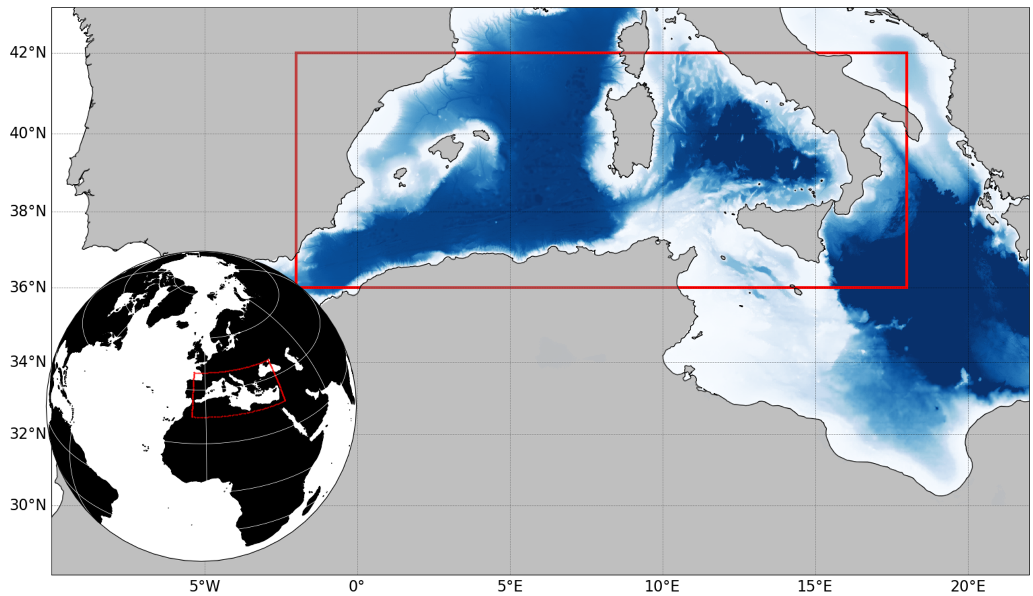

Figure 2.1: Area of Interest

3 Data

The main source of data is high-resolution SST (Sea Surface Temperature) data from Copernicus Marine. This data is obtained from satellites and provides detailed information on the temperature of the ocean.

3.1 High-Resolution Satellite-based Sea surface Temperature

The Reprocessed (REP) Mediterranean (MED) dataset provides a stable and consistent long-term SST (Sea Surface Temperature) time series over the Mediterranean Sea (and the adjacent North Atlantic box) developed for climate applications. Pisano et al., 2016. Being the data too big ($\approx$ 2GB in size), a programmatic download is necessary:

```
import copernicusmarine

copernicusmarine.subset(
      dataset_id        =   "cmems_SST_MED_SST_L4_REP_OBSERVATIONS_010_021",
      dataset_version   =   "202007",
      variables         =   ["analysed_sst", "mask"],
      minimum_longitude =   22,
      maximum_longitude =   36.2,
      minimum_latitude  =   30.5,
      maximum_latitude  =   37.5,
      start_datetime    =   "1981-08-25T00:00:00",
      end_datetime      =   "2025-02-15T00:00:00",
      force_download    =   True,
      subset_method     =   "strict"
)
```

Listing 3.1: Python submission script for programmatic download of SST data from Copernicus Marine (`copernicusmarine` API).

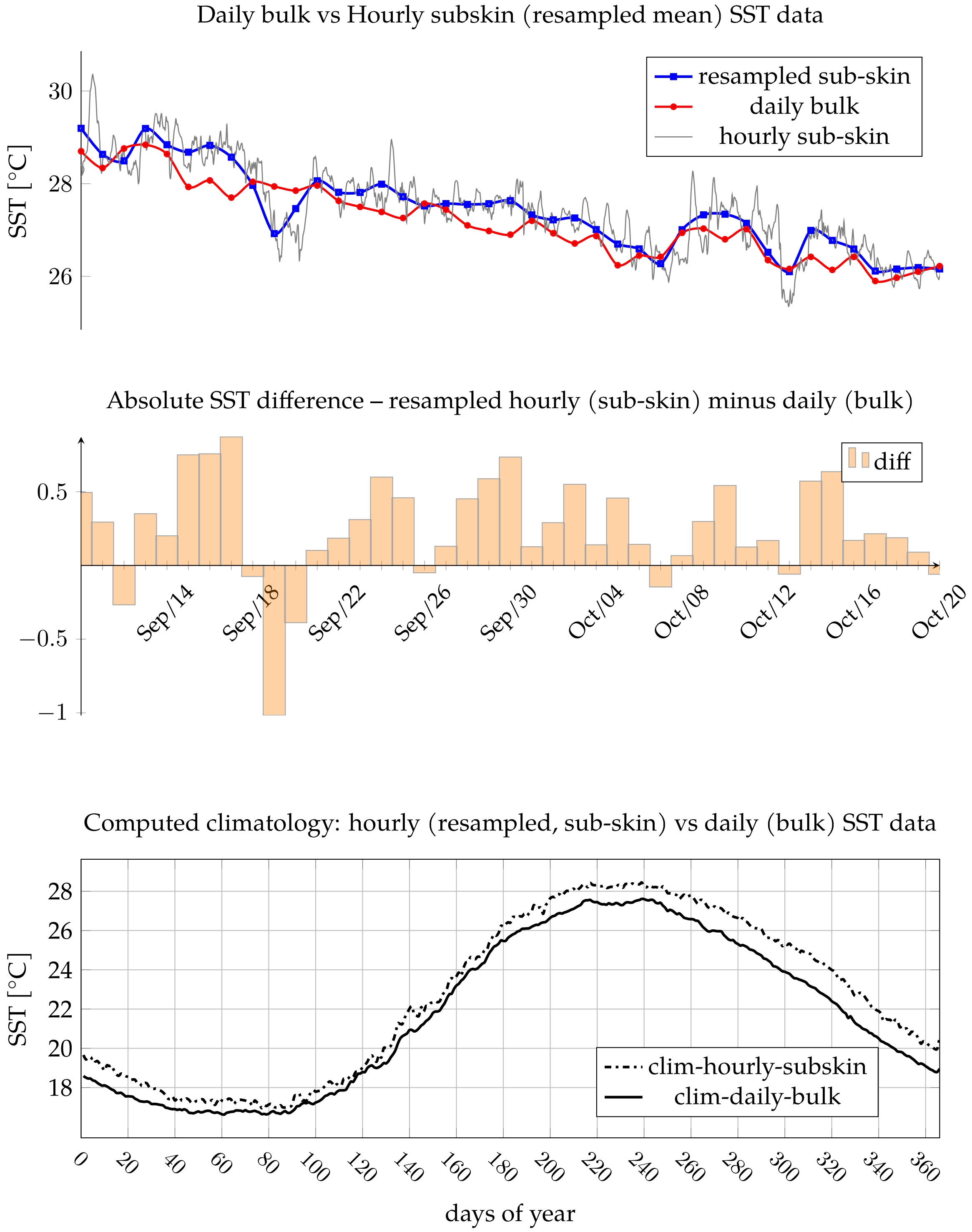

Figure 3.1: comparing SST sensed at different temporal resolutions. **Upper Panel**: Daily vs Hourly data. In addition to its original shape, hourly SST is also numerically daily averaged. **Middle Panel**: Numerical difference between computed and native daily SST. **Lower Panel**: Computed climatology (spatially averaged), for daily and hourly SST data. This latter dataset was only considered for years 2021, 2022, 2023 (full years).

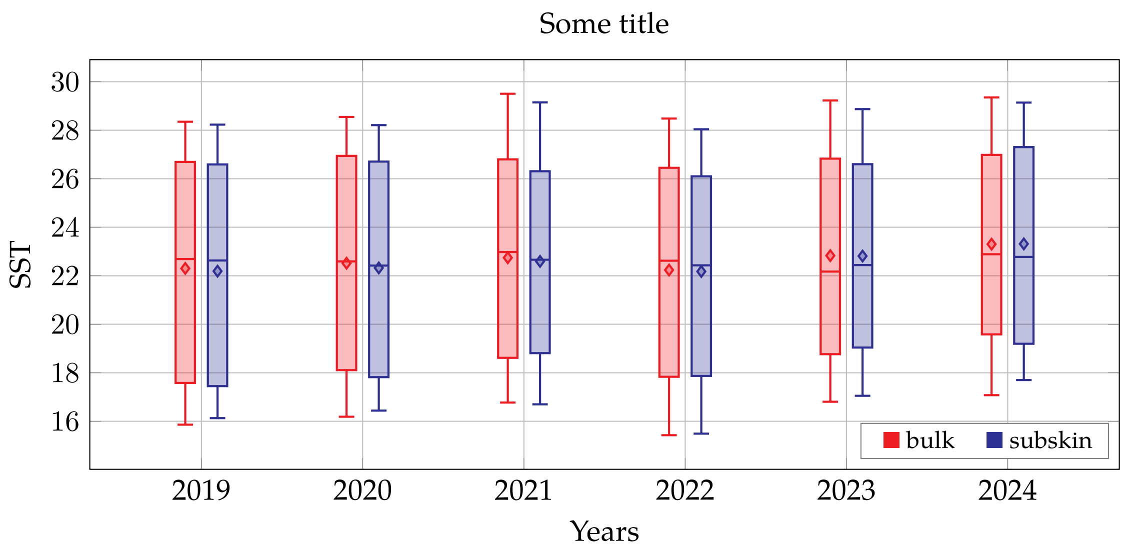

Figure 3.2: Boxplot

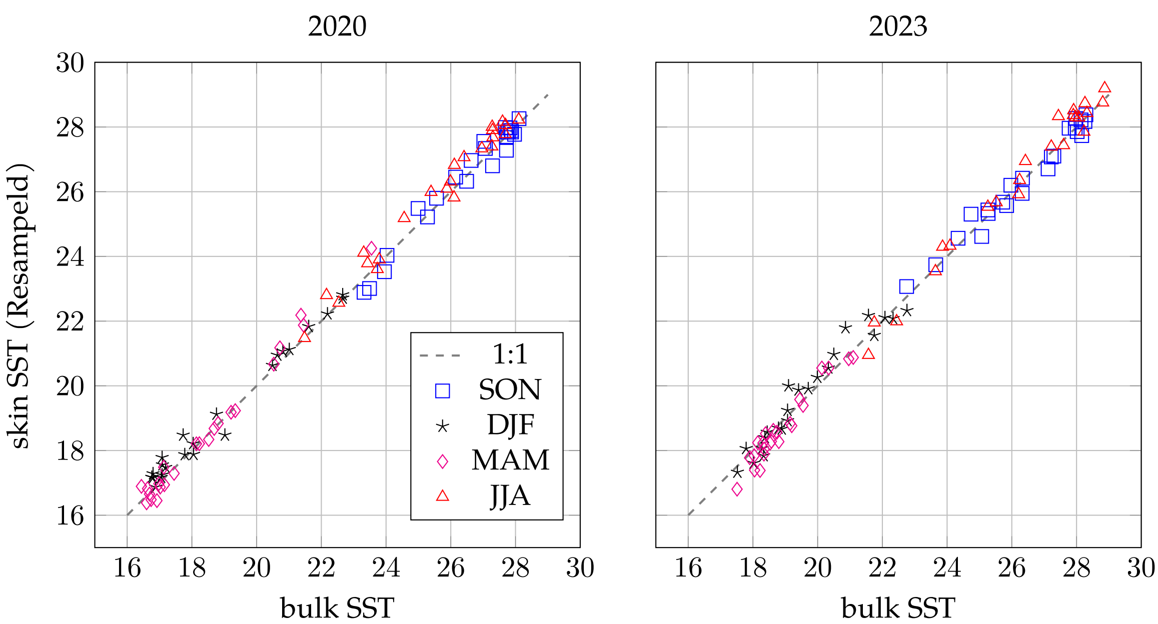

Figure 3.3: Scatterplot

3.2 Weather Ground Stations

These are all AWS (Automatic Weather Station), with a sampling rate of 5 minutes for air temperature, relative humidity, horizontal wind field, and solar radiation. The data are quality controlled. Variables are measured at different heights, however for this study we establish to settle with a significant reference value of 1.2 m AGL (Above Ground Level), for all variables. Table 3.1 presents an overview of this set-up. Weather stations are also sorted by their MSL (Above Mean Sea Level) height as that helps understanding things better.

id	Station Name	Available Sensors				Distance Shore [m]	Terrain Height [m]	Time Span 2020-01-01 ⟶ 2025-01-01
		AT	RH	Wd	SR			
1388	Cagliari	●	●	●	–	100	200	
1001	Ceuta	●	–	●	●	2000	200	
1002	Pantelleria	●	●	●	–	500	50	
–	Tarragona	–	●	●	●	50	75	
–	Valencia	–	●	●	●	10	5	

Table 3.1: Validation Ground stations in coastal areas: ID, available sensors for each station, distance to shore, terrain height (MSL), and time-span.

Each station listed in Table 3.1 was classified into one of the four categories outlined more in detail in Table 3.2:

Type	Station Features
Thin Land	Located in a sheltered area, this station is characterized by a relatively flat terrain and minimal exposure to harsh weather conditions.
Semi-Exposed	This station is situated in a partially exposed location, with some protection from surrounding terrain features, but still subject to moderate weather conditions.
Low Coastal	Located in a low-lying coastal area, this station is prone to flooding and coastal erosion, with a high risk of storm surges and saltwater intrusion.
High Coastal	This station is situated in a high-risk coastal area, with a high likelihood of extreme weather events, including storms, flooding, and coastal erosion.

Table 3.2: Ground Station Characteristics

4

Citations & Referencing

In this chapter, we provide detailed guidance on the correct procedures for citing and referencing various elements within your document Hobday et al., 2016. And for the glossary, for instance, the mechanism works as follows:

```
\newglossaryentry{MHW}
    {
        name={Marine Heatwave},
        description={A prolonged period of unusually warm ocean temperatures}
    }
```

The reason why this mechanism is not hard-coded is that it uses LaTeX's built-in commands and features to automatically generate the links and formatting. This means that:

+ no need to manually write out the glossary definitions or bibliography entries in the text.
+ no need to manually format the glossary terms or bibliography entries.
+ easy change the glossary style or citation style by modifying the LaTeX commands and settings.

Overall, this mechanism provides a flexible and efficient way to manage citations and glossary terms in our document.

5

Conclusion

And so, dear reader, it is with a sense of relief and accomplishment that we conclude this thesis, having successfully navigated the choppy waters of academic research and emerged with a newfound appreciation for the importance of marine heatwaves - and a strong desire to never again have to write the phrase 'marine heatwave' in a sentence, ever again...

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Appendices

A

Technicalities

Page layout

The next three pages illustrate how LaTeX can automatically generate and apply page layout settings, also known as the ”page frame”. These stylistic constraints and definitions enable the creation of a consistently formatted document with a professional appearance. All functional elements, including margins, headers, footers, and more, are seamlessly integrated into the page design.

Word Count

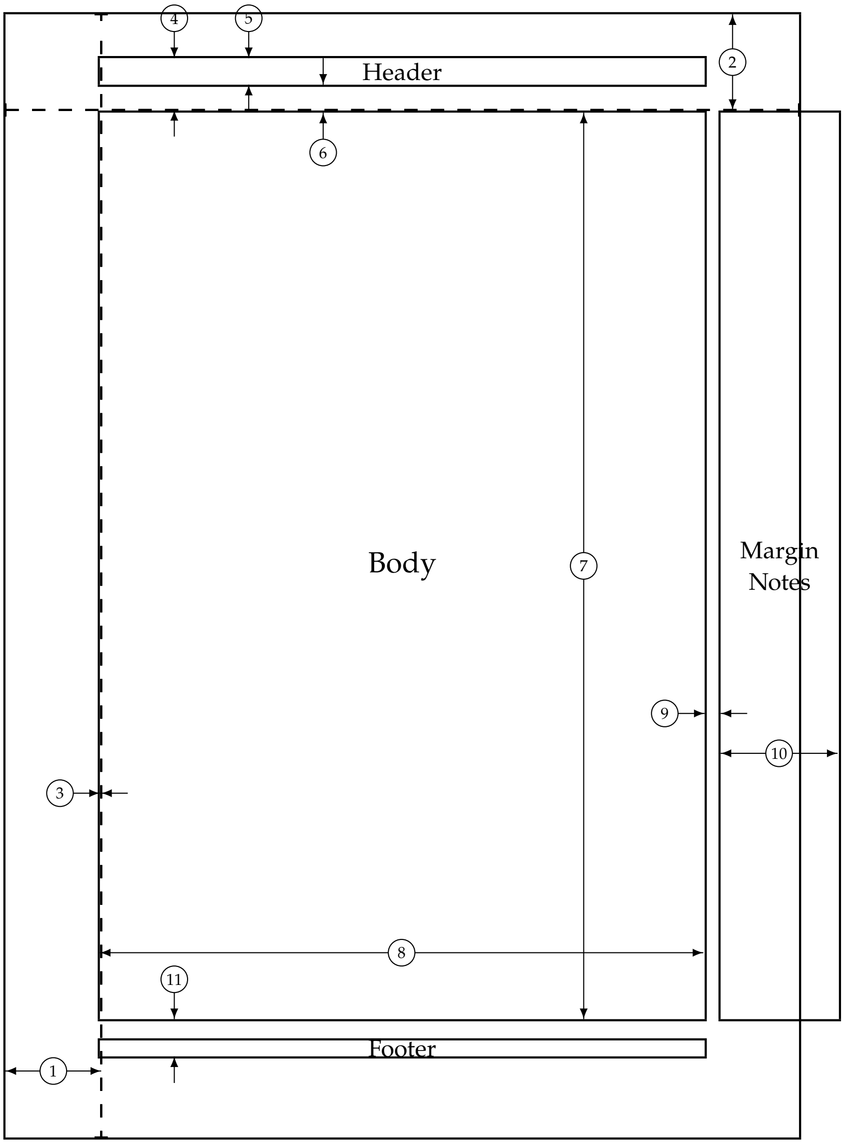
Furthermore, LaTeX also offers the capability to perform word counts, as demonstrated in the subsequent section. While the example provided is a simplified one, it is worth noting that a wide range of additional options are available, allowing for even greater customization and flexibility.

Source

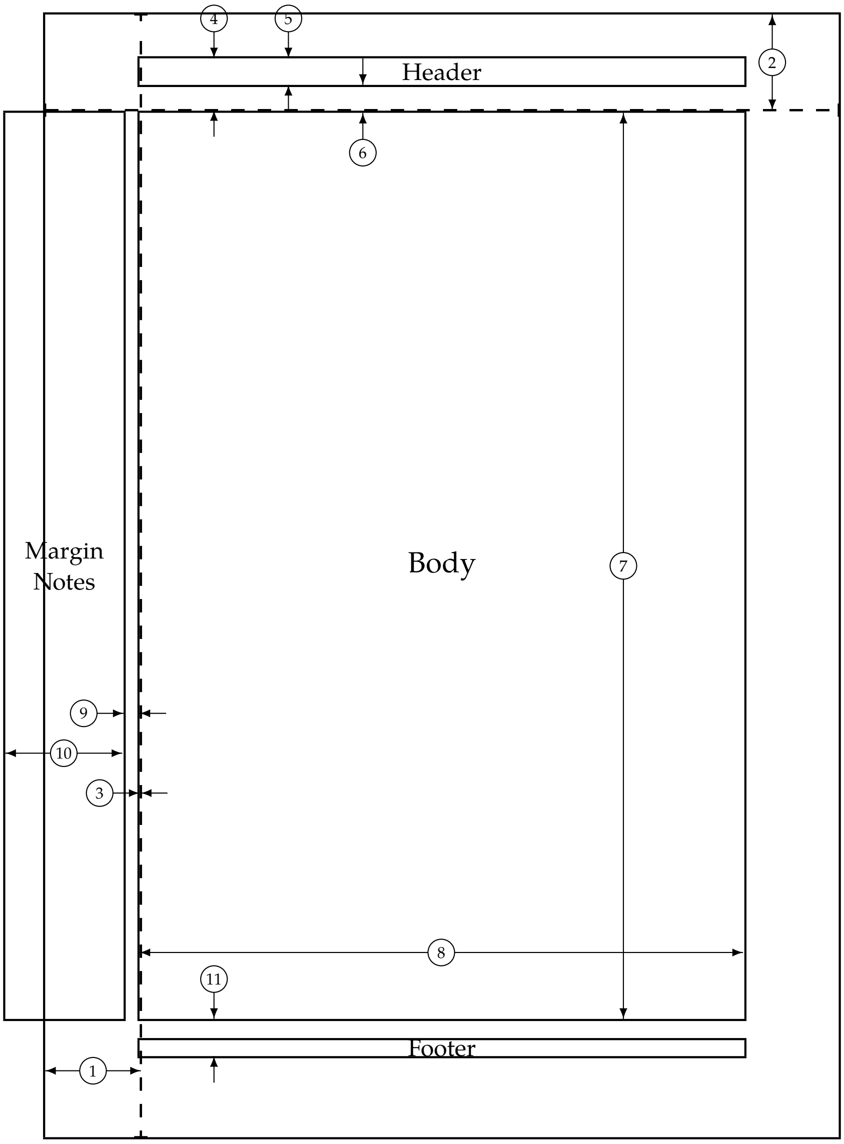
This document draws heavily from the outstanding work of José Areia, whose GitHub repository served as a primary source of inspiration.

Copyright

Page Layout (left and right pages)



1	one inch + \hoffset	2	one inch + \voffset
3	\oddsidemargin = -1pt	4	\topmargin = -39pt
5	\headheight = 20pt	6	\headsep = 21pt
7	\textheight = 682pt	8	\textwidth = 455pt
9	\marginparsep = 12pt	10	\marginparwidth = 89pt
11	\footskip = 28pt		\marginparpush = 6pt (not shown)
	\hoffset = 0pt		\voffset = 0pt
	\paperwidth = 597pt		\paperheight = 845pt



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3	\evensidemargin = -1pt	4	\topmargin = -39pt
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11	\footskip = 28pt		\marginparpush = 6pt (not shown)
	\hoffset = 0pt		\voffset = 0pt
	\paperwidth = 597pt		\paperheight = 845pt

Word Count

The word counting uses `texcount` with following flags:
`\write18{texcount -merge -nosub -sum input}`, where:

`merge`	merges included files into document (in place).
`nosub`	prevents from generating subcounts.
`sum`	produces total sum (default all words and formulae)
`input`	is the file being compiled (default: `Thesis.tex`)

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