A site selection tool for large telescopes using climate data

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A site selection tool for large telescopes
using climate data

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

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Bern, 29 May 2008
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Summary

This guide describes a site-selection tool for large telescope projects. The tool is a combination of a large database of global long-term climate data and a graphical user interface application software. The climatological database is composed largely of ERA40 and NCEP-NCAR reanalyses data. The software, known as "FriOWL" and which has been specially developed during the course of this project, has the ability to interact with the database in the style of a Geographical Information System, by using a range of overlaying, resampling, reclassifying and other data-layer manipulation functions.

FriOWL-v3.1 is completely web-based, and throughout this document continual reference is made to the FriOWL-v3.1 Website†, which forms an integral part of this project. Here, the software may be started directly (username: guest; password: friowl); the only pre-requisite is that the user has at least Java-5 Runtime Environment installed on his/hers computer. All FriOWL-v3.1 documents, files and images can be found in electronic format on this website. What follows now is a brief description of each chapter of this guide.

Chapter 1 of this document gives an overview and short history of the FriOWL project. The reasons and motivations for using long-term global climate datasets are presented. How we can borrow ideas from the operation of Geographical Information Systems to help us in the site selection process are also given. Several fundamental questions relating to the worldwide search for potential astronomical sites are addressed.

Chapter 2 gives a brief overview of the FriOWL-v3.1 software and database, in the form of a quick-guide or tutorial. It is designed as a hands-on introductory chapter for first-time users. Most of the software functionality is explained and a series of worked-through examples are presented, including the creation of a weighted composite global map of candidate regions.

† http://www.iapmw.unibe.ch/research/projects/FriOWL/
Chapter 3 provides a complete description of the *FriOWL-v3.1* database, which is mostly composed of ERA-40 and NCEP/NCAR reanalyses datasets, but also includes other geophysical data such as TOMS aerosols, high resolution topography and a global seismic risk layer. Detailed assessments on the quality of each dataset and their importance to astronomical observation are given. This chapter also explores in detail the reliability of the reanalyses products.

Chapters 4 and 5 are reference documents containing technical descriptions of the software. Chapter 4 is a detailed description of all of the *FriOWL-v3.1* graphical user interface menu options and functionalities, whilst Chapter 5 explains the Java classes and program code which make up the software.

Perhaps the most important chapter of this entire document (at least for those interested in site selection and climate) is Chapter 6 (Results and Discussion). Each of the different datasets are examined in turn using global images created with *FriOWL-v3.1*. Then, a selection of global composite maps created by overlaying and resampling different data layers are presented, highlighting preferred site regions. Specific emphasis is given in this chapter to the search for a site for the European Southern Observatory's Extremely Large Telescope (E-ELT).

Chapter 7 is a reference chapter provided for adminstrators and explains how to add new databases to *FriOWL-v3.1* (without having to re-compile the original Java code). Listings of all acronyms used, software problems and bugs to date (with solutions where appropriate) and details of all computing programs and scripts are provided in Appendices A to C.

Finally, a separate series of applied studies using the *FriOWL-v3.1* software as a tool for telescope site selection will accompany this guide shortly. Ultimately, it is hoped that these validate the software as a tool not only for the E-ELT site selection, but for other telescope and climate projects as well.

Eddie Graham
21 April 2008
CHAPTER 1: INTRODUCTION

This chapter starts by giving a brief history of the FriOWL project and details the project objectives and motivations. Then we discuss the atmospheric constraints on astronomical observation, before overviewing the main astronomical viewing parameters that can be used to classify the quality of a candidate site. We finish up this chapter by looking at how we can borrow ideas from Geographical Information Systems for astronomical site selection studies.

1.1: A SHORT HISTORY OF “FRIOWL“ / PROJECT OBJECTIVES

The “FriOWL“ project started in 2002 as a joint project between the European Southern Observatory (ESO; Garching, Germany) and the University of Fribourg (Switzerland). The project goal was to help find the best site(s) in the world for the ambitious 100-metre wide OverWhelmingly Large (OWL) telescope, by using a combination of long series of global climatic information (“re-analyses“) and a Geographical Information System (GIS) as a site selection tool. Thus the original “FriOWL“ acronym was born (from a combination the names “Fribourg“ and “OWL“).

The OWL project itself came to an end in 2005, when ESO decided that the building of such a huge telescope was too risky and too costly. However, this decision was followed in late 2006 by the decision of the ESO council to develop a more modest (yet still very large) 40-metre wide European Extremely Large Telescope (E-ELT; see Figure 1.1). Around the same time, the FriOWL project base in Switzerland moved from the University of Fribourg to the nearby University of Bern. Despite the move, the FriOWL name has continued in use, and has now grown to encompass many different aspects of site selection for telescopes, as well as having other new climatological uses.

The main objective of the FriOWL project has been to gather together all of the geophysical parameters that influence site selection for large telescopes into a single database, to make this database easily accessible under one single web portal or computing interface, and for the interface itself to be able to act as a tool (or an aid) in the search for, and classification of, worldwide candidate sites or regions.
Figure 1.1: An artist’s impression of the European Extremely Large Telescope (E-ELT) which will have a main mirror diameter of 40 metres. Note the size of the telescope in comparison to the car and two people standing at the bottom-left.

1.2: Project Motivations

There are three fundamental, guiding questions which have provided motivation for the FriOWL project and to which we will return to throughout this work. They are as follows:

1) Does a better site exist elsewhere than at current astronomical observatories?
2) How stable is the long-term climate at such sites?
3) Are they likely to remain the best sites? (e.g. due to climate change)

The answers to the these questions will be mostly addressed in Chapter 6 and in separate applied studies, by analysing the long-term global climatic datasets with the FriOWL-v3.1 software.

1.3: What does FriOWL consist of?

The FriOWL tool consists of computing Graphical User Interface (GUI) application, directly accessible on the World Wide Web\(^\dagger\), and a large database of long-term global geophysical information (climatological and geomorphological data). The GUI has been designed specifically to interact with the database in a quick and user-friendly fashion, and through the use of GIS-like interrogation and manipulation functions, it is programmed to aid any

\(^\dagger\) [http://www.iapmw.unibe.ch/research/projects/FriOWL/](http://www.iapmw.unibe.ch/research/projects/FriOWL/)
site selection process (Figure 1.2). A GIS (“Geographical Information System”) is a computer software which can analyse any spatial information of a geographical nature, permitting tasks such as the overlaying, reclassifying or resampling of data layers. In addition, FriOWL also provides the capability to produce monthly or annual global anomaly maps, and time series for any meteorological variable for any point on the globe. The most recent version of FriOWL (completed in 2008) is version 3.1 and is referred to from now on as “FriOWL-v3.1”.

![Graphical User Interface (FriOWL); interacts with database via Java application](image)

DATABASE: NCEP / NCAR and ERA Reanalysis

Conversion to single column binary

DATABASE Layers
(e.g. Aerosols, Temperature, Wind)

**Figure 1.2:** Schematic diagram of the FriOWL tool. A Graphical User Interface, written in the Java computing language and operating like a GIS, connects to a large database of mostly reanalyses climate data (ERA40 and NCEP-NCAR). The reanalyses data has been previously converted into single column binary data layers.

Of particular interest in the FriOWL database are the long-term (~40 years) global climatological datasets known as re-analyses. Re-analyses are reconstructions of past weather conditions using the state-of-the-art data assimilation and numerical weather prediction models of today (more details are provided in Chapter 3).

*FriOWL-v3.1* is written in the Java computing language; the only pre-requisite for use is that the user has the Java Runtime Environment installed on their internet browser (minimum version required is 1.5 / JRE 5.0 / J2SE) – links to download these are provided on the
FriOWL-v3.1 website. The complete FriOWL-v3.1 application and database have been designed and developed by Eddie Graham, Moritz Neun and Michael Hayoz and from the Universities of Fribourg, Bern and Zürich in Switzerland over the period 2002-2008. This document replaces the previous guides for FriOWL version 2.1 (issued on 17 January 2006, version 2.0 (issued on 25 August 2005) and version 1.0 (issued on 18 October 2003).

1.4: Atmospheric Constraints on Astronomical Observation

It will help considerably at this stage, if we review the main atmospheric constraints on astronomical viewing from the earth's surface. These are listed from (i) to (ix) below, but not in any strict order of importance, because relative importance of each depends on the type of astronomical observation being undertaken. Brief explanations as to why they are important are also given.

(i) **Clear skies without any clouds**; because exposure times at large telescopes are often long (~20-30 minutes), even partial or temporary cloud cover is detrimental to astronomical observation (see definition of 'photometric night' in next section 1.5). It is also worth mentioning that anthropogenic contrails (cirrus clouds formed by aviation) are a significant cause of worry at astronomical observatories.

(ii) **A stable atmosphere with a low degree of turbulence**; this is a crucial factor in determining the degree to which a stellar image “wobbles” or apparently moves around in the night sky (see definition of 'Seeing' in next section 1.5 also), and to which advanced 'Adaptive Optics' mechanisms are needed to correct. It also controls the degree of scintillation or “twinkling” (variations in the brightness or colour of the star). Stability in the atmosphere is largely determined by the vertical temperature gradient; turbulence may also be generated by airflow (wind) over nearby terrain, or may be caused by micro-to-macroscopic changes in temperature, pressure and humidity in the atmospheric column above the telescope (especially in the layers closest to the ground), which causes changes in the refractive index of air in the column.

(iii) **Low total integrated water vapour**; because water vapour is the principal absorbing gas from visible to millimeter wavelengths of the electromagnetic
spectrum. Water vapour also increases the refractive index of the air and this causes phase distortions of electromagnetic waves. Therefore, sites with very low total column integrated water vapour (IWV) are usually most sought-after locations. Typically, these are found on high, dry mountain tops in the desert regions of the earth (e.g. Atacama desert) or in polar regions (e.g. Antarctica). As a rough guide, Sarazin (2003) quotes a value of 5 mm IWV is required for satisfactory telescope operation at visible wavelengths; at infra-red wavelengths, less than 3 mm IWV is neccessary; for the microwave region, less than 2mm IWV is a pre-requisite.

(iv) **Low relative humidity**: is needed at night-time, to minimise the risk of dew on the telescopic mirrors or lenses.

(v) **Reasonably low surface and jetstream windspeeds**: Sarazin (personal communication, 2004) states that surface windspeeds in the range 2 to 9 metres per second are preferential for successful operation of the Very Large Telescope (VLT) at Paranal (Chile). This is because windspeeds below this threshold do not sufficiently 'flush' the telescopic dome, leading to what is known as 'dome seeing'. On the other hand, very high windspeeds (~18 m/sec or more) may cause the whole telescope or dome to shake, rendering observation impossible; additional locally-produced and wake turbulence is also likely at such high windspeeds. Relatively low jetstream windspeeds (approximately ~200 hPa in height) are also important because these have been shown to be linearly related to the measured speed of turbulent structures on the stellar image (Sarazin and Tokovenin, 2002). The telescopic angle over which a stellar image is coherent is also strongly controlled by jetstream turbulence, because the angle subtended to the telescope by the turbulence becomes smaller as height increases (see definition of 'isoplanatic angle' in next section 1.5 also).

(vi) **Moderate air temperatures and low variability**: because large on-site differences in air temperature may lead to 'mirror' or 'dome' seeing (this arises when either are at different temperatures to that of the surrounding air, leading to micro-thermal convection). Also, extremely cold, extremely high or extreme variations in temperatures may cause strain on instrumentation, equipment or personnel.
(vii) **Low aerosol contamination:** aerosols originating from duststorms or biomass burning contribute to atmospheric extinction (reduction in the amount of light penetrating the atmosphere). At visible wavelengths, blue-light is attenuated more strongly than red. On-site wind-blown dust and aerosols can also be detrimental to quality of the telescopic mirrors, due to wind-blasting (Giordano and Sarazin, 1994).

(viii) **Infrequent severe weather (e.g. snowstorms, lightning):** a site on a mountain top, or in a polar region naturally brings a higher risk of snow, but it is heavy snow or ice (rhime) that brings the risk of damage to instrumentation or equipment. The risk of a lightning strike is also much greater on an exposed mountain summit than elsewhere, but the choice of a dry, desert location where convective storms are rare mitigates against this risk.

(ix) **Night-Sky Brightness:** the aurora, nightglow (due to the sodium layer in the mesosphere at around 90 km) and anthropogenic light pollution are contributors to overall night-time sky brightness.

There are, of course, many other (non-atmospheric) geophysical and geo-political factors important in site selection, such as soil and rock topologies, accessibility to infrastructure or nearby facilities, as well as many other cultural, sociological and political issues. Of these, only two will be examined further in this work; these are (a) seismicity and (b) light pollution (although many of the others could as easily be represented as a 'data layer' in FriOWL in the future, if needs arose). A detailed list of all atmospheric, geomorphological and geopolitical constraints on site selection is given by Sarazin (2006).

Most of these atmospheric constraints listed above will be examined in detail later in Chapters 3 and 6, in the context of a search for a site for E-ELT. Of all of these, perhaps cloud-free skies and low turbulence are the two most important, although both operate on very different scales. The first may appear relatively easy to satisfy (by just finding a cloud-free site using climate data), but the latter is much more difficult to measure, model or quantify.
1.5: The Astronomical Viewing Parameters
Before we review the main astroclimatological parameters and their importance in the classification of worldwide candidate sites, let us consider the situation without an atmosphere, i.e. in space. Here, where there is no atmosphere, the maximum possible resolution of a stellar image viewed through a telescope is governed by the laws of diffraction, which state that the angle subtended between the first minima on opposite sides of the Airy disk is given by:

\[
\text{Angle between first diffraction minima} = 1.22 \left( \frac{\lambda}{d} \right) \quad \text{Eqn. 1.1; radians}
\]

where \( d \) is the diameter of the telescope (m), \( \lambda \) is the wavelength of the electromagnetic radiation in question (m); the resulting angle is given in radians\(^1\). Therefore, increasing wavelength and decreasing telescope diameter reduce the maximum attainable resolution. Substituting values for the Hubble space telescope into Equation 1.1 (diameter of 2.4 metres) gives a maximum resolution of \( \approx 0.05 '' \) at 0.5 \( \mu \text{m} \) wavelength.

Bearing in mind this fundamental constraint on observation, the ultimate goal of astronomical viewing on earth is to approach this diffraction limit. Indeed, one of the main driving goals of astronomical site selection over recent years is an almost obsessional desire to find sites where the atmosphere is so stable that this limit may be approached. In practice, however, this is rarely achieved, and the best resolutions obtainable on earth are around 0.5 to 1.0 ''. 

We will now review six of the main astroclimatological viewing parameters which are commonly used by astronomers to classify current or candidate sites. We will also relate each of them to the various weather and climate conditions that give arise to their occurrence. If values for these viewing parameters are known during astronomical observation, advanced image-correction techniques within the telescope (known as « Adaptive Optics ») can be employed, by rapidly distorting the telescopic mirrors on microscopic scales in order to obtain a better image. With such mechanisms, ground-based

\(^1\) To convert from radians to arcseconds multiply by \( \frac{6.48 \times 10^5}{\pi} \). An arcsecond is one 3600\(^{th}\) of a degree, denoted by ''.
astronomy is still able to compete with space-based telescopes in image quality today.

1.5.1: The Photometric Night Fraction

A photometric night is defined as a night with six hours or more of consecutive photometric night-time, where photometric night-time is time without any clouds more than 5° above the horizon, for hours when the sun is more than 18° below the horizon (Sarazin, 1995). The photometric night fraction is the ratio of photometric nights to the total number of nights (Casals and Beniston, 2002).

By meteorological standards, a photometric night is very stringent measurement of cloudiness, because the vast majority of the sky must remain free of clouds for a considerable length of time. Even over the most cloud-free regions on earth, this is an unusual occurrence, as the occasional passage of cirrus clouds on fine days and nights is not uncommon. The relationships between photometric night fraction and various climatological datasets will be tested in later parts in this work. The mean monthly photometric night fraction (averaged over 26 years from 1983 to 2006) at ESO Paranal observatory in Chile is 75%, at La Silla observatory it is 62%; the Paranal value appears to be the highest of any site in the whole world.

1.5.2: The $C_n^2$ Parameter

According to the theories developed by Kolmogorov and Tatarski (in Sarazin, 1997a; Marks et al. 1999), for well-developed turbulence there exists a temperature structure function ($C_T^2$) which can be expressed as follows:

$$C_T^2 = \frac{\langle (T(\rho) - T(\rho + \Delta \rho))^2 \rangle}{\Delta \rho^{2/3}} \quad \text{Eqn. 1.2; } K^2 m^{2/3}$$

where $T$ is temperature (K), $\rho$ is a point in space, $\Delta \rho$ is the distance to the next point, and the $\langle .... \rangle$ brackets refer to an ensemble mean. Thus, larger values of $C_T^2$ occur when there is a greater temperature difference between the two points and for a smaller distance between the two points, and vice versa. For turbulence within the inner and outer scales of turbulent motion⁴, a corresponding optical refractive index structure

---

⁴ The «inner» and «outer» scales can be understood here as the approximate minimum and maximum eddy sizes, respectively. Thermal eddies smaller than ~a few mm in size are thought to dissipate their kinetic energy into heat due to molecular friction (viscosity); conversely, a maximum
parameter ($C_n^2$) can also be described (Sarazin, 1997a):

$$C_n^2 = (80 \times 10^{-6} \frac{P}{T^2})^2 C_T^2$$ \textbf{Eqn. 1.3; $m^{2/3}$}

where $P$ is pressure (Pa). Here, humidity fluctuations at visible wavelengths may be neglected (Sarazin, 1997a), so variations in the index of refraction are caused by changes in temperature and pressure alone. Typical values of $C_n^2$ range from $10^{-13}$ (turbulent atmosphere) to $10^{-17}$ (stable atmosphere).

The $C_n^2$ parameter can be estimated on-site by micro-thermal balloon soundings, where the microthermal temperature sensors are positioned below the balloon at a distance of $\rho$ apart. Typically, a temperature and pressure measurement are obtainable every $\sim 5$ metres in the vertical (Marks et al., 1999), allowing a vertical profile of $C_n^2$ to be calculated. The $C_n^2$ parameter may also be estimated using instrumentation such as SCIDAR (Scintillation Detection and Ranging; Coburn et al., 2003) or SLODAR (Slope Detection and Ranging; Wilson, 2003) instruments. These instruments observe binary star conjunctions; by triangulation, the height of various turbulent layers in the atmosphere may be determined.

\textbf{1.5.3: The Coherence Length (or « Fried Parameter », $r_0$)}

This is the horizontal distance or length over which the stellar image wavefront is coherent. In other words, it is the distance over which one considers the considered photons to be in phase. Typical values of $r_0$ at ESO Chilean sites are around 10 to 20 cm, but perhaps up to 40 cm in Antarctica. The Coherence Length is also known as the « Fried parameter » ($r_0$), and is expressed by Fried (1966; in Sarazin, 1997a) as follows:

$$r_0 = [0.423 k^2 \text{sec} \gamma \int_{h_o}^\infty C_n^2 (H) dH]^{-3/5}$$ \textbf{Eqn. 1.4; $m$}

where $k$ is the wavenumber (reciprocal of wavelength), $\gamma$ is the zenith angle, $H$ is height (m) and $h_o$ is observing height. This equation means that the coherence size of thermal eddies of around $\sim 30$ metres is thought to exist.
length decreases with increasing zenith angle (closer to horizon, longer path through atmosphere), increasing wavenumber \(i.e.\) decreasing wavelength) and with an increased integrated \(C_n^2\) parameter (greater sum of refractive indices of atmospheric column).

1.5.4: The Coherence Time Constant \( (t_0) \)

This is just the time over which the stellar wavefront is coherent, or the time over which one considers the considered photons to be in phase. Since time = distance ÷ speed,

\[
t_0 = \frac{r_0}{\bar{V}},
\]

where \(\bar{V}\) is the mean horizontal velocity of the wavefront corrugations (along the line of sight). It has been shown by Sarazin and Tokovinin (2002) that this velocity, \(\bar{V}\), is linearly related to mean jetstream windspeed above Chilean sites; this finding is of considerable relevance for this work (see Chapters 3 and 6 for more details).

1.5.5: The Isoplanatic Angle \( (\theta_0) \)

This is the angle over which the wavefront is coherent. As stated already, a deformed wavefront hitting a telescopic mirror can be corrected precisely (on the scale of nanometres) by advanced Adaptive Optics mechanisms of the telescope, but such corrections are only valid to within a certain angle - this angle is called the isoplanatic angle \( (\theta_0) \). Furthermore, because the angle subtended by a given horizontal length is smaller at higher levels in the atmosphere than at lower levels, turbulence at the upper levels in the troposphere reduces the isoplanatic angle to a greater degree than turbulence at lower levels.

1.5.6: 'Seeing' \( (\varepsilon) \)

Seeing is defined as the full width at half maximum (FWHM; see Figure 1.4) of the stellar disc viewed at the zenith at 0.5 µm wavelength, using a telescope without optical alterations, over a long exposure time (~20-30 minutes) and is measured in arcseconds. Essentially, it is a measure of the amount of blurring of the stellar image. This blurring is caused by changes in the refractive index within the air column through which the star shines. Much like the way « flying shadows » occur at the bottom of a swimming pool when light passing through the water is deflected by ripples at the air-water interface (Figure
1.3), so spatial differences in the refractive index of air cause changes in the optical path length of light passing through the atmosphere affecting the wavefront coherence (Denis, 2005; Applied Optics Group Website, University of Galway†).

![Figure 1.3: Photograph of a swimming pool bottom, showing the « flying shadows » phenomenon. Image source: http://optics.nuigalway.ie/people/denis/ (accessed 31 May 2007).](image)

![Figure 1.4: The full width at half maximum (FWHM) of a gaussian distribution. Image source: http://commons.wikimedia.org/wiki/Main_Page (Wikipedia Commons; accessed 3 May 2008).](image)

An expression for the FWHM of the seeing disk (ε) is given as follows (Sarazin, 1997a; Marks et al., 1999);

\[
\varepsilon = 0.976 \frac{\lambda}{r_0}
\]

\textbf{Eqn. 1.5}; radians

Therefore, Seeing depends only on the wavelength (\(\lambda\)) of the radiation in question and the Coherence Length (\(r_0\); defined in section 1.5.3). Substituting a value of \(r_0 = 10\) cm into Equation 1.5 for blue light (\(\lambda = 0.5 \times 10^{-6}\) m) gives a Seeing value of 1.06 ″; shorter

† http://optics.nuigalway.ie/people/denis/ (Date accessed: 31 May 2007)
coherence lengths give larger Seeing values and *vice versa*.

![Images of good and bad seeing](image)

Figure 1.5: Examples of (a) good seeing, and (b) bad seeing, for the same view. The stellar images are shown in negative black and white. Image source: European Southern Observatory.

Typical mean seeing values at the world's best observatories are in the range 0.5 to 1.0"; mean monthly seeing values for Paranal and La Silla observatories, averaged over 16 years from 1991 to 2006, are 0.84 " and 0.94 ", respectively. Lawrence et al. (2004) claim an outstanding median seeing of 0.27" for Dome C (Antarctica), measured during winter 2004, but these results are contested by Agabi et al. (2005), who state that their results failed to take into account a very shallow but turbulent boundary layer inversion (~30m thickness) close to the ground; here, Agabi et al. (2005) measured median seeing values of over 1.0" during winter 2005. Examples of good and bad seeing are shown in Figure 1.5.

Seeing is usually measured on-site at an astronomical observatory by a Differential Image Motion Monitor (DIMM) instrument (see Figure 1.6) at a height of 6 metres above the ground, which is a device consisting of two apertures, so as to eliminate any effect of instrument shake on the measurement technique. At a fixed wavelength and zenith angle, seeing is independent of telescope diameter, although the image quality has been shown to be slightly better with very large telescopes (M. Sarazin, ESO Astroclimatology Website†).

Figure 1.6: Photograph of a Differential Image Motion Monitor (DIMM) instrument at Concordia (Dome C) station in Antarctica, operated by the University of Nice (France). The DIMM consists of two separate apertures, so as to eliminate the effect of instrument shake on the measurement. Image source: http://www-luan.unice.fr/Concordiastro/images/dimm.jpg (accessed 2 May 2008).

Although Seeing is caused by small scale fluctuations in the refractive index of air in the atmospheric column above a telescope, there has been some success in the modelling and forecasting of Seeing and other astroclimatological parameters using high resolution limited-area meteorological models (e.g. Masciadri and Egner, 2004). Although such models are unable to resolve micro-scale thermal features in the atmosphere (typical model resolution is ~500 metres in the horizontal, ~50 metres in the vertical), the behaviour of these micro-scale fluctuations may be statistically associated with the larger meso- or synoptic-scale meteorological features, which are more easily identified in the meteorological models.

Recently, Environment Canada¹ have begun to make routine daily Seeing forecasts, as a map of the North American continent, for periods up to 48 hours ahead. They state weighted wind shears, flux momentum in the low levels and temporal changes in surface temperature are the elements used to forecast the Seeing. No forecast verifications are available to date; even Environment Canada acknowledge on the same website that these forecasts are a «first-attempt» and may be «poorly tuned» for mountain areas.

¹ http://www.weatheroffice.gc.ca/astro/seeing_e.html
1.5.7: 'Sum-up' of the Astronomical Parameters

As we have seen, all of the astronomical viewing parameters are strongly controlled by the weather and climate, but are exhibited over a huge range of scales, in a continuum from millimetres and milliseconds (e.g. $C_n^2$, Seeing, $r_0$, $\tau_0$) to decades and thousands of kilometres (cloudiness variations, jetstream effects on $\theta_0$, planetary waves). It is therefore impossible to represent such a range of scales (more than 10 orders of magnitude) within a single atmospheric or geographical model.

Therefore, it was decided that this project would focus towards the latter end of the above spectrum, through the use of global re-analyses climatic datasets, the resolution of which are typically $2.5^\circ$. Although this spatial resolution is perhaps much less than desired, the spatial extent is global and the temporal extent is up to 50 years.

1.6: How Geographical Information Systems can help us

A Geographic Information System (GIS) is any system which can store, analyse, manage or display spatial information which are geographically referenced to Earth. GIS is also a tool that allows users to edit, interrogate or manipulate data and maps (Wikipedia Online Encyclopedia, 2008†). An important aspect of any GIS is the capability to overlay maps in the form of « layers » in order to make a new, single composite layer of information (see Figure 1.7).

For example, a cartographer may need to overlay many different layers of information, such as altitude (e.g. a contour map), landuse (e.g. woods, bogs, agricultural land), water bodies (e.g. rivers, streams, lakes) and infrastructure (e.g. paths, railways, roads) in order to make the a final, single layer map. Weightings or different levels of precedence may then be given to certain layers over others e.g. the infrastructure layer must be placed on top the landuse layer, not vice versa. Reclassification of a map layer may also be neccessary (e.g. show all urban areas with a single colour only). Changing the resolution of a map (resampling) also be neccessary in the creation of raster (pixel) satellite-based maps.

Figure 1.7: Schematic diagram showing how layers of different information may be overlaid using a GIS. In this particular example, the original datasets of clouds and mountains have been previously reclassified to boolean values (i.e. 0 or 1, Yes or No) before the overlay takes place.

Likewise, the same principles of GIS may be applied in the search for candidate astronomical sites, through the analysis of layers of global climatic and geophysical information. Different reclassified global maps showing e.g. cloud-free regions, areas of low water vapour, or mountains with a low seismic risk, may be overlaid upon one another in order to create a single, new composite final layer (e.g. Figure 1.7). Different importances or weightings may then be given to each layer in order to give it precedent over others.

These basic principles of GIS have been adopted during the design of the FriOWL-v3.1 software and database, with the creation of composite layers of global climatic and non-climatic information forming an ultimate final goal. The reduction of information to the bare necessities in such cases is designed to aid the site selection decision.
CHAPTER 2: TUTORIAL / QUICK-GUIDE TO FRIOWL

This chapter gives a brief overview of the FriOWL-v3.1 software. It is meant to be short enough to allow complete reading in less than 1 hour, but at the same time give enough information for first-time guest users to successfully the operate FriOWL software. It is a “hands-on” chapter, meaning it is best to read it whilst using the software itself. For more detailed information on the FriOWL database, the graphical user interface and the Java programming language classes, please consult Chapters 3, 4 and 5, respectively. For results and discussion, please turn to Chapter 6.

To help you to familiarise yourself quickly with the capabilities of FriOWL, a series of three worked-through examples are presented. These examples are by no-means fully exhaustive exercises of the various functions of FriOWL, they just present a general introduction to the application. You are encouraged to perform your own analyses at leisure.

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Figure 2.1: The FriOWL-v3.1 main index page at http://www.iapmw.unibe.ch/research/projects/FriOWL/. Enter your username and password in the applet boxes provided and click on the ‘Login’ button to start FriOWL.
2.1 Starting FriOWL

Using your internet browser, navigate to the FriOWL-v3.1 website address (http://www.iapmw.unibe.ch/research/projects/FriOWL/) and make sure that you have at least the Java Runtime Environment version 5 installed on your computer and correctly linked to your browser. Enter your username ('guest', if you are a guest) and password ('friowl') in the box provided (see Figure 2.1; other usernames and passwords can be created easily. To request one, just fill-in the 'Contact us' form on the FriOWL webpage). FriOWL should start. If you do not see the boxes for entering your username and password, or if FriOWL does not start, you may need to upgrade your Java version.

![Figure 2.2: The FriOWL-v3.1 main application window.](image)

2.2 Explanation of the GUI

Figure 2.2 shows the FriOWL-v3.1 graphical user interface (GUI) immediately after starting the software. A database file management tree ('Files' frame) is located on the left, and resulting maps are displayed in a map window on the right ('Map Image'). Map properties are shown in 'Selected Maps' window immediately below this. On the bottom left are
located a series of dropdown menus and options ('Options' window). There is also a standard file menu tab at the top of the screen ('File', 'Edit', 'Transformations', etc.).

2.3 Displaying Maps
Click repeatedly on the folder icons in the 'Files' frame to expand or collapse the database folders on offer. Expand a folder and select an individual data file by clicking upon it to view it in the display window to the right. Clicking on a whole folder icon by itself will import all the files within that folder in one go. Alternatively, use the 'File-Load' option from the main menu to load a range of files for particular datasets and time ranges.

Example 2.1: How to display global integrated water vapour (at the 700 hPa level) for the whole of 1971
Expand the '2.5° X 2.5° data' folder and then choose the 'ERA-40 IWV' folder. This is an integrated water vapour (IWV) dataset, as calculated from the ERA-40 re-analysis. The IWV has been calculated as partial integrations from the 800, 700, 600 and 500 hPa levels to the top of the atmosphere, in each case respectively. Expand the 'iwv700' folder. Click on '1971'. All the 12 months files for 1971 should be transferred to the 'Map Image' viewing window. You could just have easily clicked on each individual file and imported each separately.

2.4 Changing Views and Options
Go to the 'Options' window at the bottom-left of the screen. Select and choose a new option from the dropdown menu to change the color viewing palette (e.g. IDRIS256). To change the absolute ranges of the colorbar, choose 'Colorbar-Fixed' from the main menu, and enter new maximum and minimum values. To zoom in or zoom out of a map, click on the '+' or '-' buttons over a region of preference. Click the globe button to return viewing to normal. Clicking on the map itself will show the current pixel value below the colorbar legend.

At the top of the application window, choose 'View Extent' from the top menu bar. Select either 'Europe Centred' or 'Pacific Centred' to change the longitude boundaries of the map from the Greenwich meridian to 180° longitude, or vice versa. Choose the 'Outline' top menu bar option to show or hide a global map of international country borderlines.

To clear all maps from the current window, just click on the 'Clear Selected Maps' button in
the bottom left of the screen, or click on the word 'delete' in the 'Selected Maps' window.

2.5 Analysing Maps and Basic Statistical Functions

Select the Statistical Chooser (dropdown menu) in the 'Options' frame at the bottom-left of the screen (see Figure 2.3). Choose from one of the eight different mathematical and statistical functions on offer ('Mean', 'Min', 'Max', 'Root Mean Square', 'Standard Deviation', 'Standard Error', 'Anomaly', 'Sum'). Selecting any one of these will cause that function to be actioned on the all the displayed maps.

![Figure 2.3: The Statistical Chooser dropdown menu](image)

Please note, that when choosing the 'Anomaly' option, you must toggle the 'Anom' switch in the 'Selected Maps' frame from a '+' to a '-' or vice versa. The resulting displayed map (the anomaly) is equal to the average of all the “+”s minus the average of all the “-”s.

Example 2.2: How to make an anomaly map of integrated water vapour at 700 hPa ('iww700') for January 1971

Import all of the ERA-40 iww700 data for 1971 to the display window by clicking on the parent folder as before. Choose 'Anomaly' from the Statistical Chooser in the 'Options' frame. Click on the '+' toggle for January 1971 in the 'Selected Maps' frame to turn it into a '-' sign. The resulting map is the anomaly of January 1971 iww700 with respect to the rest of 1971 (please note that, just in this particular example, the map is NOT the anomaly of January 1971 with respect to all other Januaries, but the anomaly of January 1971 with respect to all the other months of that year, 1971, excluding January).
The resulting map is shown in Figure 2.4. January is during the dry season in India and the Himalaya, so there is a negative anomaly of $iwv700$ with respect to the other months of the year (yellow colours). Conversely, it is monsoon season over many parts of the tropical southern hemisphere, so anomalies are positive in these locations (blue colours).

**Figure 2.4: FriOWL-v3.1 global anomaly map of ERA-40 integrated water vapour at the 700 hPa level for January 1971 with respect to the rest of the year 1971. It is dry season in India (negative = yellow colours), but during the monsoon in Indonesia, southern Africa and South America (positive = blue colours).**

For more examples of *FriOWL*-v3.1 anomaly maps, please see Chapter 6 (“Results and Discussion”).

### 2.6 Saving Maps

Maps can be saved at any time. Click ‘File-Save’ from the top menu bar and enter an appropriate filename and text description. The file will now be saved in the folder named ‘User Files’, positioned at the bottom of the file manager menu-tree, where it can be viewed at any time just like all the other data files. Just click once on the saved file to import it into the viewing window, as before.

Saved files are also saved on the server in a variety of formats, namely ASCII, binary (single column 4-byte floating-point, with .RST extension), as images (.PNG format), and as a Google-Earth (.KMZ) files. Just choose on ‘File-Manage Files’ from the top menu bar to view or download these different file formats.
2.7 Plotting Time Series

Time series of any variable, for any single pixel, may be created. Just select “Time Series – Show Time Series” from the top menu-bar and toggle the necessary options, which are relatively straightforward to understand. Enter the latitude and longitude in the following format e.g. **52.5 N, 10.0 W**. Click on ‘Show’ to plot the time series as a line graph (Figure 2.5). You can also save and download the plotted time series as an image (.PNG) or ASCII file by selecting ‘Save’ and ‘Manage Maps’.

![Plotting Time Series](image)

*Figure 2.5: FriOWL-v3.1 plotted time series of monthly mean ERA-40 integrated water vapour from the 700 hPa level (iww700) to the top of the atmosphere for pixel point 52.5°N, 10.0°W, for all Augusts from 1958 to 2002.*

2.8 GIS Tasks and Transformation Functions

There are a number of map transformations on offer (select 'Transformations' from the top menu-bar). **Cropping** allows only a selected region of a map to be saved. **Normalising** scales the values of all displayed maps to new values of between 0 and 100. The **Reclass** function allows the user to change the values of a chosen map e.g. to eliminate areas of non-interest and focus-in on areas of interest only. **Resampling** allows the user to change the horizontal resolution of any map (increase or decrease the number of gridpoints). We will know follow an example which uses most of these functions.
Example 2.3: How to make a weighted composite global map, showing all locations which meet the following criteria:

(a) mountain peak above 2000m
(b) seismic risk (pga) less than 3.0 m / s²
(c) mean annual iwv700 is < 3mm

A *composite* map is an overlay of several different layers of information, which are then flattened into a single layer. A *weighted* map is one in which more importance is given to one layer than to another.

(a) Making the 2000m mountains layer

Open the '0.3° X 0.3° data' folder. Click on 'USGS resampled topography' file. As this is a large file (nearly 3 megabytes), please allow a short while for it to load onto the display screen. Now we will use the 'Reclass' operator to highlight mountain areas above 2000 metres only, and eliminate the rest of the data.

(i) Select 'Transformation-Reclass'

(ii) Enter the values of '2000' and '0' to make the pop-up box read as follows: *Reclass all values LESS than 2000 to 0*. Click on 'Go'

(iii) Repeat the procedure again, entering the values of '2000' and '1' to make the pop-up box read as follows: *Reclass all values GREATER than 2000 to 1*. Click on 'Go'

A reclassified map, comprising only of zeros and ones, is created (See Figure 2.6). Please save this map, as we will use it again in an instant.
Figure 2.6: A reclassified FriOWL-v3.1 map of global topography (0.3° X 0.3° reduced resolution USGS digital elevation model), where values of 1 (light green) correspond to mountains above 2000 metres. All other values are equal to 0 (dark green).

(b) Making the seismic risk layer

Open the '0.3° X 0.3° data' folder. Click on 'GSHAP seismic layer' file. As this is also a large file (nearly 3 megabytes), please allow a short while for it to load onto the display screen. Again, we will use the 'Reclass' operator to highlight only areas where the seismic risk (10% risk of exceedence in 50 years) is below 3.0 m / s² peak ground acceleration (pga), and eliminate the rest of the data.

(iv) Select 'Transformation-Reclass'

(v) Enter the values of '3.0' and '1' to make the pop-up box read as follows: 'Reclass all values LESS than 3.0 to 1'. Click on 'Go'

(vi) Repeat the procedure again, entering the values of '3.0' and '0' to make the pop-up box read as follows: 'Reclass all values GREATER than 3.0 to 0'. Click on 'Go'

Again, a reclassified map, comprising only of zeros and ones, is created (See Figure 2.7). Save this map also.
Figure 2.7: A reclassified FriOWL-v3.1 map of global seismic risk (GSHAP global seismic hazard mapping program), where values of 1 (beige) correspond to areas where the 10% chance of exceedance in 50 years seismic risk is below 3.0 m / s² peak ground acceleration. All other areas are equal to 0 (lilac), which are the most earthquake-prone regions of the world (pga risk > 3.0 m/s²).

(c) Making the iwv700 layer

Many potential astronomical sites are found on mountain tops near to the 700 hPa pressure level (about 3000 metres altitude in sub-tropical regions). We are going to make a map which highlights all areas where the mean annual integrated water vapour at this level is less than 3mm.

Open the '2.5° X 2.5° data / ERA-40 IWV / iwv700' folder. Click on all the folders 1991-2000 to import 120 data files to the display screen. Just for this example, we will assume that these 10 years of data represent the long term mean of iwv700.

Once all the maps are loaded onto the display, select 'Mean' from the statistical 'Options' chooser. The average of all 120 maps is displayed. Save this map, and then delete all 120 maps from the display. Load the saved map by clicking on it in 'User Files' folder. You should now have just one map in the display.

Again, we will use the 'Reclass' operator to highlight only areas where the mean annual iwv700 is less 3mm.

(vii)Select 'Transformation-Reclass'
(viii) Enter the values of '3.0' and '1' to make the pop-up box read as follows: 'Reclass all values LESS than 3 to 1'. Click on 'Go'.

(ix) Repeat the procedure again, entering the values of '3.0' and '0' to make the pop-up box read as follows: 'Reclass all values GREATER than 3 to 0'. Click on 'Go'. Again, a reclassified map, comprising only of zeros and ones, should have been created (See Figure 2.8). Save this map also.

![Figure 2.8: A reclassified FriOWL-v3.1 map of ERA-40 integrated water vapour at 700hPa (iwr700), where values of 1 (yellow) correspond to areas where the mean annual (1991-2000) iwr700 is below 3mm. All other areas are equal to 0 (blue), where the mean iwr700 is greater than 3mm. This map was created with FriOWL-v3.1.](image)

**Figure 2.8: A reclassified FriOWL-v3.1 map of ERA-40 integrated water vapour at 700hPa (iwr700), where values of 1 (yellow) correspond to areas where the mean annual (1991-2000) iwr700 is below 3mm. All other areas are equal to 0 (blue), where the mean iwr700 is greater than 3mm. This map was created with FriOWL-v3.1.**

(d) Overlaying all three maps to make a single 'Weighted Composite Map'

We will now overlay all three maps created in sections (a), (b) and (c) to see where the initial three criteria are met. However, before we can overlay them, all three maps must be of the same resolution (i.e. have same number of columns and rows). Presently, the first two layers (mountains > 2000m; seismic risk < 3.0 pga m/s²) contain 1200 columns X 600 rows. However, the iwr700 layer has only 145 columns X 73 rows. Therefore, we must scale-up the iwr700 layer from 145 X 73 to 1200 X 600 resolution.

(i) Delete all maps from the display window and open the reclassified iwr700 map.

(ii) Choose 'Transformation-Resample' from the main menu

(iii) Enter the following 'Change width to 1200' and 'Change height to 600'. Click on 'Go'
Please allow a few seconds for the operation to be completed (as we are creating a much larger file than the previous). Save the new map. Now all three maps have 1200 X 600 resolution.

Import all three maps again into the display window. Choose 'Sum' from the Statistical 'Options' chooser. The resulting map should look like Figure 2.9.

Figure 2.9: A single composite FriOWL-v3.1 map, created by overlaying (using the 'Sum' function) the reclassified 2000m topography, seismic risk and iwv700 maps. Values of 0 (blue) correspond to areas where the none of the original criteria are met (i.e. less than 2000m altitude, pga risk > 3.0 m/s², iwv700 > 3mm). Values of 1 (magenta) show where one of the criteria are met. Similarly, values of 2 (orange) show where two of the original criteria are met. Finally, values of 3 (yellow) correspond to all areas on the globe where mountains are > 2000m, pga risk is < 3.0 m/s² and mean iwv700 is < 3mm.

Finally, one can apply varying importances or weights to each of these layers. Simply adjust the 'Weight' field in the 'Selected Maps' frame. This value of this text box is defaulted to 1, but can be changed by the user to any numerical value. Weighting can be used to give preference to any layer over other layers, or make layers transparent.
CHAPTER 3: DESCRIPTION OF THE FRIOWL-v3.1 DATABASE

This chapter provides a complete description of the FriOWL-v3.1 database. The origin and properties of each dataset and how they were created are given in turn. This is followed by a brief discussion on the quality of each dataset and its importance for site selection of telescopes. For detailed scientific discussion regarding each dataset with guided examples, please turn to Chapter 6 (“Results and Discussion”).

3.1: INTRODUCTION

The FriOWL version 3.1 software provides direct access to a large database of climatological and geophysical data. The data can then be viewed, analysed or manipulated using a variety of display modes, statistical and transformation functions of the graphical user interface of the software (see Chapter 4). Data can then be saved or downloaded to disk.

Previous versions of FriOWL, namely version 1 (Graham, 2003; Graham et al., 2005) and versions 2.0 to 2.1 (Graham, 2005; Graham, 2006) contained a mixture of global climatological data, mostly from the ERA-15 re-analysis project (ECMWF, 1997; Gibson et al., 1999) but also from the NCEP/NCAR (Kalnay et al., 1996), NOAA Outgoing Longwave Radiation (OLR; Liebmann and Smith, 1996) and TOMS aerosols (Torres et al, 1998; Torres et al., 2002b) projects.

The ERA-15 re-analysis spans a relatively short period of fifteen years from 1979 to 1993. However, it is noted that climatic patterns and anomalies may fluctuate on longer time scales than can be resolved repeatedly within fifteen years. For example, in the Pacific Ocean region, there are a number of oscillations ranging in period from a few years, such as the Southern Oscillation (the atmospheric part of El Nino; Trenberth, 1984), to decadal scale fluctuations, such the Interdecadal Pacific Oscillation (Folland et al., 2002). Such climatic fluctuations can have an long-term effect on astronomical observations at ESO's Chilean observatories of Paranal and La Silla (Sarazin, 1997; Benistion, Casals and Sarazin, 2002).

Because of these and other issues, it was decided to include climatological data from the more recent, more accurate and longer-term ERA-40 re-analysis project (Uppala et al., 2005) in the new FriOWL-v3.1 database. ERA-40 extends over a 45-year period from September 1957 to August 2002 inclusive. Of the three re-analysis projects (ERA-15, ERA-40 and NCEP/NCAR), ERA-40 is generally regarded as being the most accurate, as the data...
assimilation and numerical model is run on a spectral T159L60 resolution. T159 means the spectral model is triangularly truncated at wave number 159 and L60 means it has 60 vertical levels, which is equivalent to about 1.125° latitude X 1.125° longitude resolution on the model’s corresponding surface Gaussian grid. This is in comparison to the more poorly resolved T106L31 resolution used for ERA-15 model and only T62L28 for the NCEP/NCAR model. ERA-40 has also performed extremely well in numerous tests of accuracy and validation studies, with only slight problems identified in the simulation of tropical precipitation and with the Brewer-Dobson stratospheric circulation (see Uppala et al, 2005 and references therein).

Other newly included climatological and geophysical datasets in FriOWL-v3.1 include total cloud cover output from the Canadian Centre for Climate Modelling and Analysis (CCCma) first Global Coupled Model (CGCM1) for past and future climates (Flato et al., 2000); a global seismic hazard risk map from the Global Seismic Hazard Assessment Program (GSHAP; Giardini et al., 1999); and two versions of the United States Geological Survey's (USGS) extremely high 30 arcsecond (~1km or 0.00833°) resolution digital elevation model (DEM; USGS, 1996).

FriOWL-v3.1 still retains previous NCEP/NCAR re-analysis (updated to 2007), NOAA OLR (also updated to 2007) and TOMS Aerosols datasets, which were included in earlier versions of FriOWL, as mentioned above. These datasets are retained for reasons of comparison as well as inclusivity. Please note that the older ERA-15 dataset has been completely replaced by ERA-40 in FriOWL-v3.1. Table 3.1 which provides a comprehensive summary of all the datasets available in FriOWL-v3.1.

---

**Table 3.1 (overleaf):** The complete FriOWL-v3.1 database, listed according to source (model or origin of dataset), meteorological or geophysical parameter, levels for which the parameter is provided, SI units of the parameter, horizontal resolution (degrees latitude / longitude), time resolution and period of availability.
<table>
<thead>
<tr>
<th>Source</th>
<th>Parameter</th>
<th>Levels</th>
<th>Units</th>
<th>Resolution (Lat / Lon)</th>
<th>Time Resolution</th>
<th>Period Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA-40</td>
<td>Air temperature</td>
<td>surface</td>
<td>K</td>
<td>2.5° X 2.5°</td>
<td>monthly means of 00, 06, 12, 18 UTC</td>
<td>9/1957 to 8/2002</td>
</tr>
<tr>
<td></td>
<td>Dewpoint</td>
<td>surface</td>
<td>K</td>
<td>2.5° X 2.5°</td>
<td>monthly means of 00, 06, 12, 18 UTC</td>
<td>9/1957 to 8/2002</td>
</tr>
<tr>
<td></td>
<td>Cloud cover</td>
<td>high medium low total</td>
<td>0 to 1</td>
<td>2.5° X 2.5°</td>
<td>monthly means of 00, 06, 12, 18 UTC</td>
<td>9/1957 to 8/2002</td>
</tr>
<tr>
<td></td>
<td>Integrated water vapour (IWW)</td>
<td>surface</td>
<td>kg/m² (mm)</td>
<td>2.5° X 2.5°</td>
<td>monthly means</td>
<td>9/1957 to 8/2002</td>
</tr>
<tr>
<td></td>
<td>Windspeed</td>
<td>surface</td>
<td>m/s</td>
<td>2.5° X 2.5°</td>
<td>monthly means</td>
<td>9/1957 to 8/2002</td>
</tr>
<tr>
<td></td>
<td>Geopotential height</td>
<td>surface</td>
<td>dam</td>
<td>2.5° X 2.5°</td>
<td>monthly means</td>
<td>9/1957 to 8/2002</td>
</tr>
<tr>
<td></td>
<td>Orography / topography</td>
<td>surface</td>
<td>m</td>
<td>2.5° X 2.5°</td>
<td>time-invariant fields</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Standard deviation of orography</td>
<td>surface</td>
<td>m</td>
<td>2.5° X 2.5°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land-sea mask</td>
<td>surface</td>
<td>0 or 1</td>
<td>2.5° X 2.5°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low vegetation</td>
<td>surface</td>
<td>0 to 1</td>
<td>2.5° X 2.5°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High vegetation</td>
<td>surface</td>
<td>0 to 1</td>
<td>2.5° X 2.5°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NCEP-NCAR</td>
<td>Air temperature</td>
<td>surface</td>
<td>°C</td>
<td>2.5° X 2.5°</td>
<td>monthly means</td>
<td>1/1948 to 8/2007</td>
</tr>
<tr>
<td></td>
<td>Geopotential height</td>
<td>surface</td>
<td>dam</td>
<td>2.5° X 2.5°</td>
<td>monthly means</td>
<td>1/1948 to 9/2007</td>
</tr>
<tr>
<td></td>
<td>Total column precipitable water (PR_WTR; same as IWW)</td>
<td>surface</td>
<td>kg/m² (mm)</td>
<td>2.5° X 2.5°</td>
<td>monthly means</td>
<td>1/1948 to 6/2007</td>
</tr>
<tr>
<td></td>
<td>Orography</td>
<td>surface</td>
<td>m</td>
<td>2.5° X 2.5°</td>
<td>time-invariant field</td>
<td></td>
</tr>
<tr>
<td>NOAA</td>
<td>Outgoing longwave radiation (OLR)</td>
<td>top of atmosphere</td>
<td>W/m²</td>
<td>2.5° X 2.5°</td>
<td>monthly means</td>
<td>6/1974 to 3/2007</td>
</tr>
<tr>
<td>CGCM1</td>
<td>Cloud cover</td>
<td>total cover</td>
<td>0 to 1</td>
<td>3.75° X 3.75°</td>
<td>monthly means</td>
<td>1/1991 to 12/2000 (simulation)</td>
</tr>
<tr>
<td></td>
<td>Cloud cover</td>
<td>total cover</td>
<td>0 to 1</td>
<td>3.75° X 3.75°</td>
<td>monthly means</td>
<td>1/2021 to 12/2030 (simulation)</td>
</tr>
<tr>
<td>TOMS</td>
<td>Aerosols</td>
<td>whole atmosphere</td>
<td>Aerosol Index (AI)</td>
<td>1.0° X 1.25°</td>
<td>monthly means</td>
<td></td>
</tr>
<tr>
<td>GSHAP</td>
<td>Peak ground acceleration (PGA) 10% chance of exceedence in 50 years</td>
<td>surface</td>
<td>m/s²</td>
<td>0.3° X 0.3°</td>
<td>time-invariant fields</td>
<td></td>
</tr>
<tr>
<td>USGS</td>
<td>Global orography / topography (reduced to 0.3°)</td>
<td>surface</td>
<td>m</td>
<td>0.3° X 0.3°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Topographic tiles</td>
<td>surface</td>
<td>m; open sea = -500</td>
<td>30° X 30''</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2: Detailed Description of the FriOWL-v3.1 Database

The complete FriOWL-v3.1 database can be interrogated by using the standard “Expand-and-Collapse” file menu of graphical user interface (see Chapter 4). All the data files are ordered chronologically within each of the parent dataset folders. At the time of writing (February 2008), there are seven different parent database folders to choose from, namely:

(a) ERA-40 (2.5° X 2.5°)
(b) NCEP-NCAR (2.5° X 2.5°)
(c) NOAA OLR (2.5° X 2.5°)
(d) CCCma (3.75° X 3.75°)
(e) TOMS aerosols (1.0° X 1.25°)
(f) GSHAP seismic (0.3° X 0.3°)
(g) USGS topography (0.3° X 0.3° and 30 arcsecond)

An eighth folder, labelled 'User Files' is also provided by the FriOWL-v3.1 graphical user interface. This is a special folder who you can save your own files for viewing, manipulating or downloading at a later time (see Chapter 4, Section 4.81 for more information).

3.3: Format of Data Files

All the FriOWL-v3.1 database files are arranged in single-column binary streams of 4-byte (32-bit) floating-point (real) number data types. There is a separate file for each timestep of each variable (e.g. every monthly mean ERA-40 dataset consists of 540 individual files from September 1957 to August 2002 inclusive). Likewise, time invariant datasets (e.g. such as topography and seismic risk) consist of just one file.

“Single column” means the columns and rows of each original data matrix have been flattened into a single column stream of data, with one data value per line (instructions on how to create such files are given in Chapter 7; listings of GrADS and Matlab programs to do this are given in Appendix B with full codes available on the FriOWL-v3.1 website).

Each data file has the file extension .RST. This gives them compatibility with the IDRISI 32 Geographical Information System (GIS) software (Eastman, 1987-2002), but any other file extension can be used for FriOWL-v3.1 database files, providing it is correctly specified in the 'files.xml' XML control file by a FriOWL administrator (see Chapter 7 for more
information on XML files).

A detailed explanation of each dataset on offer in FriOWL-3.1, explaining how each dataset was created, is given over the following pages. As of February 2008, the FriOWL-v3.1 database consists of approximately 30,000 individual data files, occupying around 4 gigabytes of space on the FriOWL server.

3.4: The ERA-40 Data

Six different meteorological variables were calculated or extracted directly from the ERA-40 product database for use in FriOWL-v3.1 (see Table 3.1). These are air temperature, dewpoint, clouds (low, medium and high and total amounts), integrated water vapour, windspeed and geopotential height. All of these are available as monthly means for the period from September 1957 to August 2002 inclusive. Monthly means of the 00, 06, 12 and 18 UTC fields are also provided for air temperature, dewpoint and cloud datasets (as these three parameters have the strongest diurnal cycles).

All ERA-40 data were provided free by ECMWF (Reading, England) and were downloaded directly from the ECMWF data server (http://data.ecmwf.int/data/ last accessed 12 February 2008) in netcdf format. A set of GrADS script programs written by the author were used to extract the data from the netcdf files and convert them into single-column 4-byte data streams for FriOWL-v3.1 (listings of all GrADS programs used in the FriOWL-v3.1 project can found in Appendix B at the end of this document, with the full code supplied on the FriOWL-v3.1 website, under “User-Guide / Programs”).

The horizontal resolution of all files retrieved from the ECMWF data server is 2.5° latitude X 2.5° longitude, which is equivalent to 10,585 global gridpoints. This is less than the stated T159 / N80 resolution of the ERA-40 model, which is equivalent to approximately 1.1° latitude/ longitude (Källberg et al., 2004; Uppala et al., 2005). This discrepancy was noted by the author during the FriOWL-v3.1 project, and after investigation, it was discovered that higher resolution data (the original 1.1° latitude / longitude grid interpolated to 0.5°) were also available from ECMWF, but only to users with registered accounts.

Because of time considerations, but mostly because an increase in resolution from 2.5° to 0.5° would represent a 25-fold increase in ERA-40 file sizes, it was decided not to introduce the 0.5° resolution into FriOWL-v3.1. Such an introduction would mean an immediate need of 20-30 gigabytes of fresh computing space, which was viewed as technically infeasible as
of December 2007. The ERA-40 data available in FriOWL-v3.1 therefore remains at 2.5° latitude / longitude resolution. A discussion on both the benefits and limitations of using 2.5° resolution for astroclimatology and site selection studies can be read in Appendix D.

### 3.4.1: ERA-40 Air Temperature

Surface air temperature (K) is provided as monthly means in the FriOWL-v3.1 database for the full period of the ERA-40 project (September 1957 to August 2002). The dataset is subdivided into means of the 00, 06, 12 and 18 UTC hours, in an effort to account for the main features of the diurnal cycle of air temperature at candidate sites. These four hours are the main reporting times at World Meteorological Organisation (WMO) synoptic stations.

Air temperature is one of the most reliable parameters in re-analyses models, as it is heavily influenced by observations and is not a product of parameterisations. In the case of ERA-40, the temperatures were derived directly from surface synoptic observations. Validation of ERA-40 surface air temperatures has been undertaken by Simmons et al. (2004), with very good overall agreement between ERA-40 and a global observational temperature dataset (CRUTEM2v). Performance is poorer prior to 1967, however, due to gaps in the availability of synoptic data. Kunz et al. (2007) also report good agreement between ERA-40 and surface air temperatures in Switzerland. A simple comparison of air temperatures between Mazo Airport (La Palma, Canary Islands) and ERA-40 re-analysis data is provided by the author in Chapter 7 (“Results, Discussion and the Best Sites”).

### 3.4.2: ERA-40 Dewpoint

Surface dewpoint temperatures (K) are also provided as monthly means in the FriOWL-v3.1 database for the full period of the ERA-40 project (September 1957 to August 2002). Like air temperatures, the dataset is sub-divided into monthly means of the 00, 06, 12 and 18 UTC hourly fields.

Subtraction of dewpoint from the relevant air temperature field yields the dewpoint depression, which is inversely related to the relative humidity (at a relative humidity of 100%, dewpoint and air temperature are equal). Provision of data for the 00, 06, 12 and 18 UTC hours will therefore help to give an idea of mean maximum and minimum dewpoint depressions for sites around the world, although it should be noted, or course, that these are unlikely to occur at the exact time of the synoptic reporting hours.

It should also be noted that both the ERA-40 air temperature and dewpoint values
described here, are surface values representative of the model at the 2.5° latitude / longitude resolution. Thus, considerable sub-gridscale variation of air temperature and dewpoint can be expected in reality, especially in areas of complex terrain or near oceans (see Section 3.4.7 which describe the ERA-40 orography and some surface characteristics). These effects should be taken into account when using the ERA-40 air temperature and dewpoint datasets. However, even in such cases, we are of the opinion that the temporal variability of data within should still be of reasonably good quality, particularly if the sub-gridscale site in question is representative of the broad synoptic-scale (2.5°) topography.

For information on the validation of ERA-40 humidity data as a tool for long term trend analyses, please see section 3.4.4 “ERA-40 Integrated water vapour”.

### 3.4.3: ERA-40 clouds

The cloud cover fraction, consisting of value of between 0 and 1, is provided as monthly means of the 00, 06, 12 and 18 UTC hours in the FriOWL-v3.1 database for the full 45-year period of the ERA-40 project. Like air temperature, data from these hours are provided because because cloud cover often exhibits a strong diurnal cycle, especially in the tropical and sub-tropical regions of the earth. Monthly means of daily values are also provided.

Following traditional meteorological classification, the cloud cover dataset is further divided into four categories: (i) high cloud (ii) medium cloud (iii) low cloud (iv) total cloud. High cloud refers to clouds above 6,000 metres above ground level and at these heights the clouds are almost always composed of ice (i.e. cirrus), even in the warmest regions of the world. Medium clouds are located between heights of 2,000 and 6,000 metres, and may contain a mixture of ice and water, depending on location and season. Low clouds refer to clouds between ground level and 2,000 metres in altitude. Total cloud cover refers to the fraction of cloud occupying a gridpoint regardless of height; it is the same that a nadir-looking satellite would see from space.

It follows, therefore, that total cloud cover is NOT the sum of the high, medium and low cloud cover categories. This is because an upper cloud layer may overlap or “shield” a lower one from view, or vice versa, and the maximum possible value of total cloud cover is equal to 1. This effect is demonstrated in Figure 3.1 at its most extreme, where three layers of co-incidentally overlapping cloud, namely 50% high cloud, 50% medium cloud and 50% low cloud yield a 50% total cloud cover, as would be seen by a nadir-looking satellite.
Figure 3.1: A schematic representation of an extreme case, where 50% high cloud, 50% medium cloud and 50% low cloud covers contribute to the same amount (50%) of total cloud cover, due to all three layers co-incidentally overlapping, as would be seen by a nadir-looking satellite.

In addition, it is noted by the author that the ERA-40 cloud cover fraction may be neither what a weather observer at a WMO meteorological station would report, nor what an astronomer might report from an observatory. This is because the observer at a meteorological station views a hemisphere of sky, compared to a (nadir-looking) satellite which maps the cloud cover as a mostly planar surface. This effect should be most pronounced when the clouds are of a large vertical extent, but limited horizontal extent and is shown graphically in Figure 3.2. This has implications for astroclimatological purposes, especially given the definition of a “photometric night” (see Chapter 1 “Introduction”).
Finally, it should be noted that cloud cover may be a product of many parameterisations and calculations within a re-analyses model, because individual clouds of almost any kind are too small to be resolved on their coarse grids. Clouds are not analysed in the ERA-40 model (Chevallier et al., 2003) and Kalnay et al. (1996) give cloud cover as a “C” rating in their diagnosis of the NCEP-NCAR re-analysis model, meaning no observations directly effect the variable and that it is solely derived from model fields. Therefore, considerable caution should be exercised when examining cloud cover values, especially in relation to long term trends. This is emphasised by the conclusions of Chevallier et al. (2003), in a validation study of ERA-40 high clouds over the oceans, that interannual variations may not be reliable before 1979 in many parts of the world.

3.4.4: ERA-40 INTEGRATED WATER VAPOUR (IWV)

Integrated water vapour (IWV), as known as total column precipitable water (PR_WTR), is the vertical integral of water vapour from the surface to the top of the atmosphere.
Physically, it can be thought of somewhat as the depth of water around your ankles if all the water vapour in the atmosphere above your head was precipitated in one instant. The units of IWV are kg m\(^{-2}\) which are also equivalent to mm. We will use mm from here onwards, as it is perhaps easier for meteorologists to understand IWV in mm, as this is the same unit used to measure rainfall at meteorological stations.

ERA-40 monthly mean integrated water vapour maps are provided in the FriOWL-v3.1 database for the full period of the ERA-40 project. In a strict sense, these are maps of partially integrated water vapour, as we have started the integration not at the ground surface, but from a selection of four different heights in the atmosphere. These heights are the 800 hPa, 700 hPa, 600 hPa and 500 hPa levels. All the integrations have then been completed to the top of the atmosphere. The benefit of using partial integrations is because we are then able to make “like-with-like” comparisons between different potential sites around the world, regardless of the actual height of the topography underneath. In subtropical regions, the four above-mentioned atmospheric levels are relatively constant in height, and therefore we can compare the IWV at different sites around the earth at approximately the same altitudes. This is not always possible for maps of integrated water vapour calculated from the ground surface upwards, due to the large variations in sub-gridscale topography of the earth's surface (FriOWL-v3.1 also provides such a dataset; see section 3.5.3: “NCEP-NCAR PR-WTR”).

IWV, calculated from different starting heights in the atmosphere, is not a parameter available per se from the ERA-40 model. It was therefore necessary to calculate it ourselves for the FriOWL-v3.1 project, using ERA-40 specific humidity data (units of kgwater/kgair). A program was therefore written by the author in the GrADS scripting language to calculate the IWV, using eleven specific humidity data levels in the atmosphere, which are shown schematically in Figure 3.3 (as stated already, listings of all programs can found in Appendix B, with the full code supplied on the FriOWL-v3.1 website). The actual procedure was as follows:

\[
\frac{1}{g} \sum_{\text{start}}^{\text{toa}} q \cdot dp
\]

Eqn 3.1 (Doty, 1995)

where \(q\) is specific humidity (kgwater/kgair); \(p\) is pressure (Pa or kgair/ms\(^2\)); \text{start} is the
starting height in question (i.e. 800, 700, 600 or 500 hPa); toa is the top of the atmosphere; g is gravity (m/s²). The units are such that division by g yields kg water/m², which is equivalent to millimetres (Doty, 1995).

![Diagram of atmospheric column](image)

**Figure 3.3:** A schematic representation of how the partial integrations were calculated. The column on the left represents an atmospheric column of water vapour from the surface to 200 hPa. Specific humidity data from ERA-40 was available for eleven different levels, these are listed to the right of the column. Arrow A represents a partial integration from the 600 hPa to the “top” of the atmosphere (which is at 225 hPa, or the mid-point between the upper-most two layers). Arrow B represents a partial integration from the 700 hPa level upwards. These values are then referred to as IWV at 600 hpa (“iWv600”) and IWV at 700 hPa (“iWv700”) respectively.

The “top-of-the-atmosphere” was set to a height of 225 hPa in all calculations; this was the midpoint between the two uppermost layers (250 hPa and 200 hPa; see Figure 3.3) of the available ERA-40 specific humidity data. Although this height is not really the top of the atmosphere, the amount of water vapour above 225 hPa should contribute only a very
small amount to the total integrations.

Validation of ERA-40 IWV has been provided by Morland et al. (2006), who compared it with an independent data set of IWV obtained from nine Global Positioning Satellites (GPS) receivers in Switzerland over the period November 2000 to August 2002. They report that ERA-40 captured water vapour variations well, with a correlation coefficient of greater than 0.9 between the two datasets where the altitude difference between the ERA-40 model surface and GPS station was less than 1000 metres.

However, Bengtsson et al. (2004) have shown that significantly lower global IWV values occur in the pre-satellite era before 1972, reduced by approximately 4%. This value was determined by undertaking a sensitivity experiment with the ERA-40 system, in which all satellite data post-1972 were excluded from the model in a special control run through to 2002, in an attempt to mimic the pre-satellite period. In conclusion, based on the humidity data alone, they argue that “in its present form the ERA40 analyses are not suitable for long-term climate trend calculations”.

Furthermore, in a validation study of the overall ERA-40 hydrological cycle, Hagemann, Arpe and Bengtsson (2005) state that “conclusions drawn for hydrological trends should be taken with great care”. Most interestingly however, is the claim by Bengtsson, Hodges and Hagemann (2004) that the ERA-40 model is almost completely able to reconstitute the large-scale hydrological cycle, even when all observational humidity have been excluded from the database. This conclusion would seem to imply that humidity observations are no longer needed in future atmospheric reanalyses.

3.4.5: ERA-40 WINDSPEEDS

ERA-40 monthly mean windspeeds (m/s) are also provided in the FriOWL-v3.1 database for the full period of the ERA-40 project at four different levels: the surface (10m), 700 hPa, 500 hPa and 200 hPa.

Surface windspeed is an important parameter in the characterisation of potential astronomical sites for large telescope projects. Firstly, surface winds should ideally be in the range 2 to 8 ms-1 (Sarazin, personal communication, 2004). Windspeeds lower than this threshold do not sufficiently “flush” the telescopic enclosure, causing what is known as “dome seeing”. Conversely, windspeeds higher than 10 ms-1 may cause the whole telescope or dome to shake, as well as causing increased local air turbulence which may
lead also to poor seeing.

In all cases, surface windspeeds refer to the velocity at 10 metres above the ground, which is the World Meteorological Organisation standard height for wind observations around the world. The actual level of the “ground” above sea level in any particular instance of the dataset refers to the topographic height of the ERA-40 model at that pixel point (see section 3.4.7. for more information on ERA-40 orography).

For cases where the ERA-40 orography does not match the sub-gridscale topography near candidate sites (i.e. the ERA-40 resolution is too coarse), windspeeds at 700 hPa and 500 hPa levels are also provided, because it is around these levels (approximately 3000-5000 metres altitude in the sub-topics) that the first generation of Extremely Large Telescopes will most likely be built. Windspeeds at these levels enable “like-with-like” comparisons to be made between different locations around the world. In other words, it is beneficial to compare the windspeeds at different sites around the earth at approximately the same altitudes, regardless of the sub-gridscale topography underneath.

Finally, mean monthly global windspeeds at the 200 hPa level are also provided in FriOWL-3.1. Although not always located at this level, these are assumed to represent the mean jetstream windspeeds above candidate astronomical observatories. Sarazin and Tokovinin (2002) have shown, for certain Chilean sites, that the 200hPa jetsteam windspeed ($V_{200hPa}$) is linearly related to the mean horizontal velocity ($V_0$) of stellar wavefront corrugations along the line of sight by means of the equation:

$$V_0 \approx 0.4 V_{200hPa} \quad \text{(Eqn. 3.2; Sarazin & Tokovinin, 2002)}$$

### 3.4.6: ERA-40 Geopotential height

Mean monthly global geopotential height, expressed in decametres (dam; 101 metres) for four different pressure levels (1000, 700, 500 and 200 hPa), are provided in FriOWL-v3.1 for the complete period of the ERA-40 project.

Geopotential height is the potential of gravity at a height above a reference surface. The reference surface is usually taken to be mean sea level or the geoid, where adjustments have been made for the variation of gravity with latitude and elevation. In meteorology, it is more useful to use geopotential height rather than geometric height, because the
variations in gravity across the surface of the earth make a surface of uniform geopotential to be the only true horizontal surface (Mcllveen, 1992, p.103). In a way, geopotential height can be thought of as a kind of “gravity-adjusted height” (Wikipedia, 2008). At a height $h$ above the reference surface, the geopotential ($\Phi$) is defined as follows:

$$\Phi = \int_0^h g(\phi, z) \, dz$$  \hspace{1cm} \text{Eqn. 3.2 (after Mcllveen, 1992; Wikipedia, 2008)}$$

where $g$ is the gravitational acceleration (m/s$^2$) at latitude $\phi$ at elevation $z$. Division by gravity at mean sea level ($g_0$) then yields the geopotential height ($Z_g$) in metres (however, please note that it is normal meteorological practice to express geopotential height in decametres = 10 metres):

$$Z_g = \frac{\Phi}{g_0}$$  \hspace{1cm} \text{Eqn 3.3 (Wikipedia, 2007)}$$

Use of the geopotential height of different pressure levels can provide valuable information. Since air density is inversely proportional to air temperature, a greater amount of cold air can be fitted into a particular column of the atmosphere than warm air; thus the geopotential height of particular pressure surface is elevated over warmer regions of earth, and lower-down over colder regions. Acting against this is the increase in density associated with an increase in air pressure; however, this effect is not as strong between the equator and poles as that due to changes in temperature; furthermore, because we are analysing geopotential height at fixed pressure levels, any density differences will be due to changes in air temperature alone.

Thus, the height of a particular pressure surface reflects the mean temperature of the column of air below that height. Furthermore, assuming frictionless flow and balance with the Coriolis force, the geostropic wind should blow parallel along the isolines of equal geopotential height and the closeness of the isolines should also be proportional to windspeed.
There are a number of benefits in using geopotential height information for astronomical site selection from different levels in the atmosphere:

1000 hPa – this level corresponds approximately to conditions within the boundary layer at, or near sea level. Thus, the geopotential height pattern at this level is similar to the sea-level pressure pattern.

700 hPa – this height corresponds roughly to the site of a large telescope project (e.g. the VLT at Paranal, or other sites near 3000 metres elevation in sub-tropical latitudes). The geopotential height pattern at 700 hPa often reflects the broad-scale global synoptic elements of the sub-tropical high pressure zones and mid-latitude low pressure belts.

500 hPa – this corresponds roughly to the upper height limit of large telescope project (e.g. ALMA, or other sites near 5000 metres elevation).

200 hPa - this corresponds roughly to the height of the jetstream winds (see Sarazin and Tokovinin, 2002).

**3.4.7: ERA-40 Time-Static Layers**

A number of time-invariant (static-in-time) single layers from the ERA-40 model are provided for FriOWL-v3.1. They are as follows:

(i) ERA-40 orography
(ii) ERA-40 standard deviation of orography
(iii) ERA-40 land-sea mask
(iv) ERA-40 low vegetation fraction
(v) ERA-40 high vegetation fraction

The orography layer of ERA-40 is provided by ECMWF as the geopotential (m2s-2; see previous section) at the surface. Dividing by gravity (a value of 9.81655 ms-2 was used) therefore yields the height in metres of the surface topography. However, it is noted that the ERA-40 model orography shows some differences from the NCEP/NCAR model orography at the same 2.5° resolution (see later section 3.5.4 of this chapter), particularly near the Antarctica and Greenland ice-caps. This may be due to local variations in the value of gravity, or different definitions of the surface, due to the large ice caps. A secondary
problem of unrealistic ripples, most notable near the coast of South America and caused by the spectral model, have resulted in variations of surface topography of several tens to hundreds of metres where no-such variations exist in reality (Uppala et al., 2005).

It immediately apparent from a first examination the ERA-40 orography layer that the 2.5° resolution of global topography is extremely coarse, and many large mountain ranges are poorly represented or missing entirely (e.g. European Alps), with the notable exceptions of Greenland and Antarctica. This is because the topography of most mountain ranges varies considerably on the sub-pixel scale (unlike the smooth ice caps of Greenland and Antarctica) and it is impossible to resolve isolated mountain peaks at the 2.5° resolution. However, despite these issues, it is still useful to retain this topographic layer in FriOWL-v3.1, because it is at the same resolution at which the other ERA-40 meteorological variables (temperature, dewpoint, clouds, IWV, wind and geopotential height) are provided, and therefore makes the user aware of the representation given to mountains. Please note other much higher resolution topographic layers (e.g. the 30 arcsecond Digital Elevation Model of the United States Geological Survey) are provided with FriOWL-v3.1 for GIS-like function tasks (see section 3.10 of this chapter).

Other time-static ERA-40 layers provided for FriOWL-v3.1 include the standard deviation of orography, high and low vegetation fraction layers, and a land-sea mask layer. It is not stated in the ERA-40 archive (Simmons et al., 2004) at which resolution the standard deviation of orography layer has been calculated (i.e. whether it is sub-gridscale), or for how much area each pixel value is representative.

### 3.5: The NCEP-NCAR reanalysis

Since 1997, the National Center for Environmental Protection (NCEP) and National Center for Atmospheric Research (NCAR) of the United States have made available a joint first-generation reanalysis known as the NCEP-NCAR re-analysis (Kalnay et al., 1996). The reanalysis was produced by using a frozen global data assimilation system and a numerical weather prediction model. However, the T62 model resolution (about 1.9° latitude / longitude) used in the NCEP/NCAR reanalysis is somewhat less than that used in the later ERA-40 reanalysis (~1.1°). In comparison studies between ERA-40, ERA-15 and NCEP-NCAR, Uppala et al. (2005) state that ERA-40 generally provides better products and is more accurate than the earlier reanalyses of ERA-15 and NCEP-NCAR, with analysis increments (the difference between the analysis background and short-term forecast) generally smaller.
in the ERA-40 products.

Unlike ERA-40 however, the NCEP-NCAR re-analysis has the advantage of spanning a longer time period (starting in January 1948), and is continuously updated to the present-day (whereas ERA-40 ends in August 2002). This means we can continuously compare the monthly mean astronomical statistics of Paranal and La Silla with NCEP-NCAR products, right-up to the current time (NCEP-NCAR datasets are updated to mid-2007 on FriOWL-v3.1).

Three different meteorological variables from the NCEP-NCAR are provided in FriOWL-v3.1, namely, geopotential height, surface air temperature and total column precipitable water.

All NCEP/NCAR products were downloaded in netcdf format from the website of the Physical Sciences Division of the Earth System Research Laboratory, NOAA, USA (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml; website address valid 25 February 2008). Similar to the way that ERA-40 files were created, the NCEP-NCAR data was extracted and converted into the standard 4-byte real number single-column binary format for FriOWL-v3.1 using a set of GrADS program written by the author (see Appendix B, or the FriOWL-v3.1 website under “User-Guide / Programs”).

3.5.1: NCEP-NCAR GEOPOTENTIAL HEIGHTS

The NCEP-NCAR mean monthly geopotential height for the 1000, 700, 500 and 200 hPa levels are provided with the FriOWL-v3.1 database, for the period from January 1948 to September 2007 inclusive. These data were not orginally requested in the FriOWL-v3.1 contract, but are provided here as means of a comparison with ERA-40 data at the same levels, and also to extend the geopotential record to 2007 (as ERA-40 stops in August 2002). As for the ERA-40 geopotential height layers, NCEP-NCAR geopotential heights are also expressed in decametres (dam; 101 metres). NCEP-NCAR geopotential height is classified as an “A” variable by Kalnay et al. (1996), meaning it is in the most reliable class, and is strongly influenced by direct observations and is not solely a product of model physics or parameterisations.

3.5.2: NCEP-NCAR AIR TEMPERATURES

NCEP-NCAR surface air temperatures (°C) are provided as monthly means in the FriOWL-v3.1 database for the period from January 1948 to August 2007 inclusive. As was the case
noted with ERA-40 air temperatures and dewpoints (Section 3.4.2), it is important to remember that the temperature values described here are surface values representative of the model at the 2.5° latitude / longitude resolution. Thus, considerable sub-gridscale variation of air temperature can be expected in reality.

Like geopotential height, NCEP-NCAR air temperatures are classified as an “A” variable by Kalnay et al. (1996), meaning it is in the most reliable class, and is strongly influenced by direct observations.

3.5.3: NCEP-NCAR total column precipitable water (PR-WTR)

As already explained in the preceeding section 3.4.4 (ERA-40 IWV), integrated water vapour (IWV), or total column precipitable water (PR_WTR) as it is referred to by NCEP-NCAR, is the integrated water content of the atmosphere. NCEP-NCAR PR_WTR (kg/m² or mm) are provided as monthly means in the FriOWL-v3.1 database for the period from January 1948 to June 2007 inclusive. PR_WTR is classified as a “B” variable by Kalnay et al. (1996), meaning it is a less reliable than the “A” class variables of air temperature or geopotential height, with the model having a very strong influence on the analysed PR_WTR value, although some observational data may still directly effect the value of the variable.

Unlike the ERA-40 IWV dataset which were calculated by partially integrating the IWV from heights of 800, 700, 600 and 500 hPa to the top of the atmosphere respectively, the NCEP-NCAR PR_WTR dataset consists of one value of precipitable water from the surface to the top of the atmosphere. Therefore, please be aware that, for pixels where sub-gridscale orography is under-represented or absent on the coarse 2.5° resolution of orography (e.g. isolated volanic island peaks surrounded by large ocean expanse), the PR_WTR values will be significantly different from reality, if the desired location elevation is significantly different from the model surface. Interpolation of the PR_WTR to the correct altitude is therefore necessary in these cases. The actual surface of NCEP-NCAR model is described in the next section (3.5.3).

3.5.4: NCEP-NCAR orography

The NCEP-NCAR model orography is provided for FriOWL-v3.1 as a time-static layer. Originally, it is provided by NCEP-NCAR as the geopotential (m2s-2) of the surface, but have been divided by gravity (9.81655 ms-2) to yield the height in metres of the surface topography. As already stated (section 3.4.7), however, it is noted that the NCEP-NCAR
model orography is occasionally different from the ERA-40 model orography, particularly near the Antarctica and Greenland ice-caps, thought to be due to to local variations in the value of gravity, or different definitions of the surface, near the large ice caps. Like ERA-40, the NCEP-NCAR orography layer also shows a secondary problem of unrealistic ripples caused by the spectral model, most evident near the South American coast, and have resulted in variations of surface topography where no-such variations exist in reality (Uppala et al., 2005). Please note other much higher resolution topographic layers (e.g. the 30 arcsecond Digital Elevation Model of the United States Geological Survey) are provided with FriOWL-v3.1 for GIS-like function tasks (see section 3.10 of this chapter).

3.6: NOAA Outgoing Longwave Radiation (OLR)

Outgoing longwave radiation is the emission to space of terrestrial (infra-red) radiation from the top of the earth's atmosphere. To maintain thermal equilibrium, the earth and atmosphere must radiate OLR at exactly the same rate as the earth-atmosphere system absorbs incoming solar radiation (Salby, 1996). Typically, the highest values of OLR are associated with the warmest areas of the earth-atmosphere, because they radiate the greatest amounts of longwave radiation to space. However, water vapour and clouds may trap a significant amount of OLR and re-radiate the energy back to the earth's surface. Thus, anomalously low values of OLR may indicate the higher than normal presence of clouds, which can be linked to convergence (at surface levels) and divergence (at the top of the troposphere). Analysis of such variations on seasonal, internannual and interdecadal timescales can reveal links with long term changes in the climate system, such as El Niño / La Niña / Southern Oscillation. Allan et al. (1999) have shown that changes in mid-troposphere humidity (400 to 700 hPa) are of most importance in explaining clear-sky OLR variations. The units of OLR are watts per square metre (Wm-2).

Data from the NOAA Outgoing Longwave Radiation (OLR) dataset is available from June 1974 until March 2007 in the FriOWL-v3.1 database (except the period from April to December 1978 for which data are missing). The data was downloaded from the same website where the NCEP-NCAR data was downloaded (see section 3.5) and the monthly data was extracted from the original netcdf file using similar GrADS programs. A description of the complete NOAA OLR dataset is provided by Liebmann and Smith (1996) and numerous studies of climatic anomalies have been undertaken using OLR data.
3.7: CCCma CGCM1 CLOUD DATA

Past and future global total cloud cover output from the first Coupled General Circulation Model (CGCM1) of the Canadian Centre for Climate Modelling and Analysis (CCCma) is provided at a resolution of 3.75° latitude by 3.75° longitude in the FriOWL-v3.1 database. The data is provided for the years 1991-2000 (in an attempt to represent “present-day” climate) and 2021-2030 (the expected period of operation of an European Extremely Large Telescope).

The original idea behind including such data in FriOWL-v3.1 was motivated by the concern that meteorological changes, caused by global warming (either directly or indirectly), might lead to adverse changes in astronomical viewing conditions at candidate sites within the 10-to-30 year timeframe of planning, building and operating an Extremely Large Telescope. Therefore, it was decided to include a small amount of output data from the CCCma model, as a preliminary trial, to see if such concerns might be justified.

The CGCM1 model is described by Flato et al. (2000). It is a “coupled” model, meaning it consists of both atmospheric and oceanic components. The atmospheric component originates from the AGCM2 spectral model which has been described by McFarlane et al. (1992). It has a T32L10 resolution (triangular truncation at wave number 32 with 10 vertical levels) which is equivalent to approximately 3.75° latitude / longitude on a surface Gaussian grid. The model has successfully reproduced historic and present-day mean climate (Boer et al, 2000a; Hengeveld, 2000) and it is generally regarded that the internal processes within the model operate realistically (Hengeveld, 2000).

Five different simulations of climate over the period 1850-2100 have been performed by the CGCM1 model (Boer at al., 2000a; Boer et al, 2000b), including one where greenhouse gases and aerosols vary according to the IS92a “business-as-usual” scenario (IPCC, 2001). It is from this climate projection that the total cloud cover variable was extracted for use and analysis in FriOWL-v3.1, as clouds have the most obvious effect on astronomical viewing conditions.

The raw data was ordered through CCCma website (http://www.cccma.ec.gc.ca/) and was provided as a zipped ASCII archive file. This was later converted into the individual monthly files of single-column 4-byte floating-point data types necessary for FriOWL-v3.1, using a FORTAN program written by the author (see Appendix B at the end of this document with a full listing on the FriOWL-v3.1 website under “User-Guide / Programs”).

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The CCCma total cloud cover data should be viewed as a preliminary experiment to determine, in a very general sense, whether any substantial changes in global cloud cover may occur within 20 to 40 years timeframe. However, it should be recognised that the simulation of clouds within any climate model is fraught with uncertainties; individual clouds are too small to be resolved within even the most finely resolved models, and they are therefore the result of many parameterisations, which may or may not have been validated with observations (Trenberth, 1992; McGuffie and Henderson-Sellers, 2005). Even the more accurate ERA-40 model has considerable problems with clouds (Chevallier et al., 2003). Therefore, it is stated here that any physical interpretation of this CCCma cloud data should be treated with extreme caution.

3.8: TOMS Aerosols
The mean monthly Aerosol Index, as calculated from data measured by the Total Ozone Mapping Spectrometer (TOMS) sensor, is provided in FriOWL-3.1 database at the resolution of 1.0 latitude x 1.25° longitude, for the period January 1980 to December 2002. The original data files have been made available by the Chemistry and Dynamics Branch of the NASA Goddard Space Flight Center (GSFC), Greenbelt, Maryland, USA.

The TOMS sensor was operational on three different satellites between 1979 and 2005, namely NIMBUS-7, ADEOS and EARTH-PROBE. No data is available for the period May 1993 to July 1996 inclusive, due to the failure of NIMBUS-7 satellite on the earlier date, and until the successful launch of EARTH-PROBE on the latter. The ADEOS record overlaps the EARTH-PROBE record from September 1996 to June 1997. Since 2005, the new Ozone Monitoring Instrument (OMI) has replaced the TOMS record for aerosol, total ozone and other atmospheric chemistry measurements. Complete user guidelines of all data products derived from the TOMS instrument on each of the NIMBUS-7, ADEOS and EARTH-PROBE satellites are available in McPeters et al. (1996), Krueger et al. (1998) and McPeters et al (1998), respectively.

The original data files were downloaded as gridded monthly mean ASCII files from the GSFC ftp internet site at ftp://toms.gsfc.nasa.gov/ (last accessed 8 February 2008). The data was then converted to single-column 4-byte (32-bit) floating-point (real) number data types, in order to make them readable by the FriOWL-v3.1 software. It was also necessary to flip and transpose the original data matrices, so that the data began at the 0° longitude (Greenwich
meridian) and 90°S latitude. This was achieved using a selection of IDL and FORTRAN programs, and IDRISI macros, written by the author and Dr. Ernest Koffi at the University of Fribourg, Switzerland. Examples of these programs can be viewed in Appendix B and on the FriOWL-v3.1 website (under “User-Guide / Programs”).

While the TOMS spectrometer was not initially designed to measure aerosols, the capability of the instrument to detect desert dust and carbonaceous aerosols, as a by-product of the TOMS ozone algorithm, has been shown by Torres et al. (1998), Torres et al (2002a) and Torres et al. (2002b). The Aerosol Index (AI) itself is a dimensionless real number and is defined as the ratio between observed and calculated radiances at 0.36 μm in the near ultraviolet (UV) range. It is a measure of how much backscattered UV light from an atmosphere containing aerosols (resulting from a combination of Mie and Rayleigh scattering and absorption) differs from that of an atmosphere consisting of pure Rayleigh scattering (Anon, 2008). Rayleigh scattering predominates in an atmosphere where the size of the scattering particles (i.e. air molecules) are much smaller than the wavelength of the incident radiation; Mie theory is applied for atmospheres which contain larger particles (i.e. aerosols) of sizes close to the wavelengths in question. Essentially, the AI is just a form of the raw data measured by the satellite sensor, where the molecular component has been removed (Torres et al., 2002b). It is defined as follows:

\[
AI = 100 \log_{10} \left( \frac{I_{\text{Meas}}}{I_{\text{Calc}}^{0.36}} \right) \tag{Eqn. 3.4 (Anon, 2008)}
\]

where \( I_{\text{Meas}}^{0.36} \) = TOMS measured radiance at 0.36 μm

\( I_{\text{Calc}}^{0.36} \) = calculated TOMS radiance for pure Rayleigh atmosphere

Thus, when the ratio between measured and calculated radiances is = 1 (pure Rayleigh atmosphere), the resulting AI = 0. Under normal conditions, the AI should be positive when the atmosphere consists of absorbing aerosols, near zero in the presence of clean skies, clouds or large (> 0.2 μm) non-absorbing aerosols and negative for small non-absorbing aerosols (Torres et al., 2002a). Table 3.1 shows typical values of the Aerosol Index for a variety of conditions found around the world; values of 0 ± 0.1 may be representative of crystal clear skies, whereas in the vicinity of the dry-lake beds of Lake Chad (central Africa)
or Lake Eyre (central Australia), which are two of the largest producers of dust in the world, the mean monthly Al over the entire period 1980-2002 is close to 2.0 (see Chapter 6 “Results and Discussion” for more information).

The Aerosol Index is available from TOMS for all latitudes between -60° S and 60° N. Please note that boundary layer pollution (e.g. automobile exhaust fumes, industrial plumes caught under a low-level inversion) are not readily seen by the aerosol index method because the small amount of underlying Rayleigh scattering (under the pollution) leads to a small signal at the satellite sensor (Herman et. al. 1997). A full inversion procedure is necessary to detect these aerosols using the measured radiances as input; retrieved parameters are optical depth and single scattering albedo (Torres, personal communication, 2004). Aerosol optical depth values have been validated against sun photometer ground observations from the Aerosol Robotic Network (AERONET), with reasonable levels of agreement to within 20-30% in most cases (Torres et al., 2002a).

<table>
<thead>
<tr>
<th>( \frac{I_{\text{Meas}<em>{0.36}}}{I</em>{\text{Calc}_{0.36}}} ) ratio</th>
<th>( \log_{10} )</th>
<th>X 100 = Aerosol Index (Al)</th>
<th>Typical conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90</td>
<td>-0.045</td>
<td>-4.5</td>
<td></td>
</tr>
<tr>
<td>0.95</td>
<td>-0.022</td>
<td>-2.2</td>
<td></td>
</tr>
<tr>
<td>0.98</td>
<td>-0.008</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td>0.99</td>
<td>-0.004</td>
<td>-0.4</td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td>0</td>
<td>0</td>
<td>Crystal clear skies for Al = 0 ± 0.1</td>
</tr>
<tr>
<td>1.01</td>
<td>0.004</td>
<td>0.4</td>
<td>Hazy skies</td>
</tr>
<tr>
<td>1.02</td>
<td>0.008</td>
<td>0.8</td>
<td>Very hazy, polluted day in a big city</td>
</tr>
<tr>
<td>1.05</td>
<td>0.021</td>
<td>2.1</td>
<td>Sandstorm or forest fires nearby</td>
</tr>
<tr>
<td>1.10</td>
<td>0.041</td>
<td>4.1</td>
<td>Difficulty seeing midday sun</td>
</tr>
</tbody>
</table>

Table 3.2: Typical values of the \( \frac{I_{\text{Meas}_{0.36}}}{I_{\text{Calc}_{0.36}}} \) ratio, \( \log_{10} \) and Al values for a variety of atmospheric conditions.

For further interest, the official TOMS Aerosols products website is as follows: http://toms.gsfc.nasa.gov/aerosols/aerosols.html (last accessed 8 February 2008).
3.9: The GSHAP Seismic Risk Layer (0.3° Resolution)

The Global Seismic Hazard Mapping Program (GSHAP) was conducted from 1992 to 1998, as part of a United Nations / International Decade of Natural Disaster Reduction. One of the project goals was to produce a global map of seismic risk. This was achieved with the production of a high resolution global map depicting the 10% chance of the peak ground acceleration (PGA) exceeding a given threshold within fifty years (see Giardini et al., 1999, for more information).

The GSHAP database was downloaded from the GSHAP website (http://www.seismo.ethz.ch/GSHAP/) as an individual 95 megabyte ASCII file at an original resolution of 0.1° latitude / longitude. This dataset was converted to the 4-byte (32-bit) single-column binary data type necessary for FriOWL-v3.1, allowing for a reduction in file size by a factor of more than four. For reasons of computer server efficiency, the resolution was further reduced (“resampled”) to 0.3° latitude / longitude, allowing for another reduction of file size by a factor of nine. This was accomplished without serious deterioration in the quality of the dataset (because many tectonic features are regionally cohesive, occupying areas of 0.3° square or greater) and, in the view of the author, it remains adequate for global site selection studies.

The GSHAP map spans all longitudes from 0° to 360°, but only latitudes from 62° S to 87° N are included. Thus, all of the main continental regions of the earth, except Antarctica, are well represented. However, large gaps of missing data also occur over the oceans (e.g. Pacific, Atlantic and Indian Oceans).

The resampling algorithm to reduce the resolution consisted of a straightforward nine-square averaging kernel (which averaged the contents of nine old cells, and put the result into one new cell). The Matlab programs written by the author for these tasks are listed in Appendix B, with full program code on the FriOWL-v3.1 website, under “User-Guide / Programs”). The complete original and resampled datasets are available on both the FriOWL† and IAP‡ servers.

† /data/imapwterra/seismic/GSHAP/raw
‡ /FriOWL/data/seismic/GSHAP/raw
3.10: The USGS Topographic Layers

(a) 0.3° Resampled

In addition to the United States Geological Survey's 30 arcsecond (0.00833°) extremely high resolution topographic tiles (described in the next section [b]), a resampled global resolution of 0.3° latitude / longitude is also provided for FriOWL-v3.1. Whilst this resolution is exactly 1,296 times (9 X 144, or 36²) coarser than that of the original 30'' dataset, it was the maximum resolution deemed possible for the inclusion of it as a global layer in FriOWL-v3.1, and for the safe operation of the software (the final file size is approximately 3 megabytes).

The resampling algorithm to reduce the resolution from 30'' to 0.3° was almost the same as that of GSHAP seismic layer resampling algorithm. However, because of the large file sizes involved, it was done in two separate stages (or “passes”). Firstly, the resolution was reduced by a factor of 144, by using a twelve-square averaging kernel (which averaged the contents of 144 old cells, and put the result into one new cell). In the second pass, the resolution was further reduced by a factor of nine, by using a three-square averaging kernel (which averaged the contents of nine old cells, and put the result into one new cell). This final resolution was deemed acceptable for file upload times to the FriOWL-v3.1 software.

The Matlab programs written by the author for the two resampling passes are listed in Appendix B, with full program code available on the FriOWL-v3.1 website, under “User-Guide / Programs”). The complete original and resampled datasets are also available on both the FriOWL* and IAP** servers.

(b) 30 Arcsecond Resolution (Equivalent to 0.0083° or ~1km)

A selection of extremely high 30 arcsecond (") resolution topographic data tiles for twelve different global regions are provided for FriOWL-v3.1. This resolution is equivalent to 0.00833°, or approximately ~1km latitude / longitude. The data is provided by the United States Geological Survey (USGS) global digital elevation (DEM) GTOPO30 model (USGS, 1996). The original global dataset was furnished on a series of four CD-ROMs, given to the author by Prof. Claude Collet of the University of Fribourg, Switzerland.

The dataset itself comprises a series of sixteen regional “large tiles” of the whole earth, each one labelled with a prefix from A to P (compressed as .gz zipped files). The original

* /FriOWL/data/usgs_dem/matlab
** /data/iapmw/terra/USGS_GLOBE/matlab

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elevation data was stored in each tile on the CD-ROMs as 2-byte (16-bit) integer single-column data type. Altitude values are given in metres above sea level, whilst open-sea areas were labelled as “-500”, allowing for land areas of between 0 and 500 metres below sea-level to be distinguished. These original data files are stored on both the FriOWL* and IAP** servers.

At this very high resolution, there are a total number of 933,120,000 global grid points. Because the display of a such a vast number of pixels is not possible with FriOWL-v3.1, it was decided to include specific “tiny tiles” of candidate regions at 1km resolution, the external boundaries of each tile being limited in such a way to keep overall file sizes to within a tolerable maximum (e.g. 2 to 3 megabytes). As of late 2007, ESO has narrowed down the list of possible sites for the E-ELT telescope to the best nineteen†. Therefore, it was decided to include “Tiny tiles” at 1km resolution for the areas surrounding each of these candidate sites in FriOWL-v3.1 database.

A full listing of the various Matlab programs written by the author to view, extract and save the USGS data into the correct single-column 4-byte binary format for FriOWL-v3.1 are listed at the end of this document in Appendix B, and full copies of the all programs are also available on the FriOWL website under “User-Guide / Programs”.

3.11: User Files

A final database folder, named “User Files”, is available on FriOWL-v3.1. This is a special interactive (dynamic) folder in which the user can save individual files for viewing, manipulation or downloading, at a later time. For more information, please turn to Chapter 4, Section 4.8.1 (“Saving, Managing and Downloading Maps”).

---

* /FriOWL/data/usgs_dem/matlab
** /data/iapmw/terra/USGS_GLOBE/matlab
† This list is available for viewing at http://www.eso.org/qen-fac/pubs/astclim/espas/SiteList.htm (site accessed 15 October 2007).
CHAPTER 4: DESCRIPTION OF THE FRIOWL GRAPHICAL USER INTERFACE (GUI)

This chapter gives a detailed “fine-comb” overview of the FriOWL-v3.1 Graphical User Interface (GUI), including detailed descriptions of all of the menu options and transformation functions. If you are new to FriOWL and you want to start operating it immediately (without getting bogged down in too much detail), you should refer to Tutorial / Quick-Guide (Chapter 2). On the other hand, if you have already successfully used FriOWL but you want to learn more about the precise details of operation, you should start reading here. This chapter assumes only a basic prior user knowledge of using graphical user interfaces. For more technical information about the Java code, please consult Chapter 5 (The Java Classes).

4.1: THE MAIN FRIOWL APPLICATION WINDOW

The main FriOWL application window consists of five sub-frames nested within the main parent window (see Figure 4.1). These sub-frames are as follows (listed in clockwise order from top left):

Files – this is the file display system menu-tree

Map Image - where the images are displayed

Colors - colorbar and legend

Selected Maps – details about each map layer displayed are shown here

Options – for zooming, color palette changes and statistical operations

There is also a menu bar at the top of the main application window, with options for saving and managing maps, editing, transformation and time series functions, and changing view preferences. We will now describe in detail each of the above-mentioned items.
4.2: The 'Files' sub-frame

Navigation and browsing of the FriOWL database using the file display system (in 'Files' sub-frame) is simple. It is a straightforward menu-tree which you click on to expand or collapse the different database folders. It operates in the same way as any other clickable file display system (Figure 4.2).

Within the menu-tree, you will see many different geophysical data folders on offer. The top-of-the-hierarchy parent folders are classified according to their global horizontal latitude and longitude resolution. They are classified this way because the different data layers come from different sources and each of them are produced at widely different horizontal resolution (you will have the ability to change a layer's resolution later using the 'Resample' function; see Section 4.10.2). For example, all the the ERA-40, NOAA OLR and NCEP/NCAR re-analyses data files are available at a resolution of 2.5° latitude / longitude. They are therefore placed in the folder labelled “2.5° x 2.5° data”.

Figure 4.1: The FriOWL-v3.1 main application window
Within each of these parent folders, you will find a set of child sub-folders, and (if appropriate), further sets of grand-children sub-folders and so on. The lowest bottom-of-the-hierarchy sub-folders contain the raw database files, which are listed chronologically according to month and year (see Figure 4.2). The exceptions to this rule are the 0.3° resolution GSHAP seismic data layer and the USGS topographic layers (0.3° and 1km) which have no child folders and should therefore be considered as time invariant layers (i.e. they are static in time).

![Figure 4.2: The 'Files' sub-frame, showing a standard “Expand and Collapse” file display system. Click on a folder to expand its contents and click on an individual file to view it in the display window. Clicking a folder icon will import the whole folder to the display window. All files are listed chronologically.](image)

Just click once on a file to view it immediately in the 'Map Image' window. For example, to view the mean 500 hPa geopotential height of January 1958 as a global map, click as follows: “2.5 X 2.5 data -\> ERA-40 Geopotential -\> geo500 -\> 1958 -\> 1958 JAN geo500” (Figure 4.1) and the corresponding map will be displayed immediately in the 'Map Image' to the right. Its attributes (file properties) are listed directly below in the 'Selected Maps' window (Figure 4.3).

Similarly, if you want to import all of year 1958 at the same time (i.e. 12 monthly files from JAN to DEC 1958 inclusive, just click on the parent folder labelled '1958'. This avoids having to click on each monthly file individually. A pop-up box will then ask you “Do you really want to add 12 monthly maps?” If you are certain you want the task to be completed,
click “Yes”. For more information on all the different datasets on offer, please consult Chapter 3 (Full description of the FriOWL-v3.1 database).

As well as all the dataset folders shown in the 'Files' window, there is also one final special folder at the bottom labelled “User Files”. This folder is interactively created (and updated) by the user upon saving and editing maps on the FriOWL server during one or more successive operations of FriOWL. These saved maps can be retrieved later for viewing, manipulation or downloading in various formats during subsequent visits to FriOWL (see Section 4.8: “Saving, Managing and Downloading maps”).

4.3: The 'Map Image' Sub-frame

When a data file is clicked in the 'Files' sub-frame, it is immediately displayed in the 'Map Image' window to the right. When more than one data layer is selected, the layers are stacked upon one another (overlaid) and the resulting image is a combination of each of the layers in the stack (Figure 4.3). How these maps are stacked and displayed relative to one another (i.e. their transparency or opacity) depends on the currently active value of the Statistical Function Chooser. (The Statistical Function Chooser is the dropdown menu in the 'Options' sub-frame, listed under 'Color and Grid Operations'; see Figure 4.4). There are eight possible options to choose from the Statistical Function Chooser ('Mean', 'Min', 'Max', 'Root Mean Square', 'Standard Deviation', 'Standard Error', 'Anomaly', 'Sum'). The default value of this chooser is set to 'Mean', which indicates that the average of all the stacked maps is displayed as the final image. Full descriptions of all these options is given in Section 4.6.3.
Figure 4.3: The 'Map Image', 'Colors' (legend) and 'Selected Maps' sub-frames. All maps listed in the 'Selected Maps' window are stacked together and the result is shown in the 'Map Image' display. How these maps are stacked and displayed relative to one another (i.e. their transparency or opacity) depends on the currently active value of the Statistical Function Chooser (see Section 4.6.3).

4.4: The 'Colors' sub-frame

The 'Colors' sub-frame houses the colorbar (legend) for the currently displayed image(s). If desired, the palette for the colorbar may be changed in the 'Options' sub-frame, using the dropdown-menu (chooser) shown directly under 'Color and Grid Operations'. Below the colorbar legend is a field called 'Selected Cell'. If you click on the map with your mouse cursor, the latitude, longitude and value of the chosen pixel is displayed in this field (Figure
### 4.5: The 'Selected Maps' Sub-frame

When a map is selected from the database for display in the 'Map Image' sub-frame, the properties or attributes of this particular file are displayed immediately below the image in the 'Selected Maps' sub-frame as a series of text fields. There are a total of ten different properties listed here, some of which are interactive (i.e. the user can change them, and therefore alter how the map is displayed, which can be useful when undertaking GIS-style tasks; see Table 4.1). They are as follows (blue text means they are interactive):

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Anom'</td>
<td>Clicking this field once will activate a boolean tick-box which toggles to a '+1' or '-1' (plus or minus) sign. The result of this field is used by the 'Anomaly' and 'Sum' functions (see section 4.6.3).</td>
</tr>
<tr>
<td>'Map Name'</td>
<td>This is the filename of the currently chosen file</td>
</tr>
<tr>
<td>'Description'</td>
<td>A simple one-line text description of the current file</td>
</tr>
<tr>
<td>'Cols X Rows'</td>
<td>The number of columns and rows in the current file</td>
</tr>
<tr>
<td>'Units'</td>
<td>The SI units of the data in the current file</td>
</tr>
<tr>
<td>'Min'</td>
<td>The minimum pixel value in the whole map</td>
</tr>
<tr>
<td>'Max'</td>
<td>The maximum pixel value in the whole map</td>
</tr>
<tr>
<td>'Weight'</td>
<td>This is defaulted to a value of 1, meaning there is no extra importance (or weighting) given to this particular map (relative to all other maps which also have a weighting of 1). Clicking this field and entering a new value (any integer or floating point value can be entered e.g. 4, -3e-05, 2.718) will give a new weighting to that map. A weighting of '0' means the map is completely transparent with respect to others. See Chapter 6 (&quot;Guided Examples&quot;) to see an example of the weighting function being used.</td>
</tr>
<tr>
<td>'Transformation'</td>
<td>This is an interactive boolean toggle box, which when ticked by the user, means all future transformation functions (such as 'Reclass', 'Resample', 'Crop', 'Normalise': see Section 4.10 for more information) will be acted upon for that map. If, however, the boolean toggle is not ticked by the user, that map will be exempt from subsequent transformations.</td>
</tr>
<tr>
<td>'Delete'</td>
<td>Deletes the selected map from the viewing window</td>
</tr>
</tbody>
</table>

*Table 4.1: Explanation of the ten text fields displayed in the 'Selected Maps' window.*
The width of all the text fields in the 'Selected Maps' sub-frame can be adjusted dynamically by simply dragging and lengthening the field borders (for situations when you cannot read all the characters within each field e.g. if there are long file names). Similarly, the field positions can be dynamically moved around the 'Selected Maps' sub-frame, by simple dragging-and-dropping movements.

4.6: The 'Options' sub-frame

The 'Options' sub-frame in located in the bottom-left of the FriOWL window (see Figure 4.4). It is within this sub-frame that the image display, as shown in the 'Map Image' sub-frame, is controlled. One can zoom in and out, change color palettes as well as undertake some basic arithmetic and statistical operations on the data layers displayed. Each of these functions are now explained in turn:

4.6.1: Zooming

The first row of buttons in the 'Options' frame allow you to zoom in or out of areas of interest within your chosen map image. Clicking on the (+) button zooms in, whilst clicking on the (-) button zooms out. Clicking on the Globe / Earth button brings the image map back to its original size.

4.6.2: The Colormap / Palette Chooser

Under the words 'Color and Grid Operations' lies the Palette or ColorMap chooser (a “chooser” is a simple dropdown menu). This allows you to toggle the palette for the colormap. All colormaps are 256-colour palettes based on the GIS software Idrisi Release 3.2.2 (Eastman, 1987-2002). There are twelve options given, namely; GREY256, BIPOL256, IDRIS256, BIMOD256, QUANT256 and NDVI256 and their inverses. The user is free to choose whichever palette they prefer.
4.6.3: The Statistical Function Chooser

Immediately below the ColorMap chooser lies the Statistical Function Chooser. This dropdown menu provides eight mathematical-statistical functions for analysing a stack or selection of maps. The definition of each of these functions is given next:

**Mean;** the arithmetic mean, for each pixel gridpoint, of all the displayed maps is displayed

**Max;** the maximum pixel value for each gridpoint, of all the displayed maps is displayed

**Min;** the minimum pixel value for each gridpoint, of all the displayed maps is displayed

**Root Mean Square (RMS);** for each pixel in turn, of all the displayed maps, the value ($X_i$) is squared, then summed over all maps, then divided by number of maps ($n$) before the square root is taken. Mathematically, it is defined as follows:
\[ RMS = \sqrt{\frac{\sum_{i=1}^{n} (X_i)^2}{n}} \]

**Standard Deviation (\(\sigma\)):** for each pixel in turn, of all the displayed maps, the anomaly is calculated (value \(X_i\) minus the mean (\(\bar{X}\)), then squared, then summed over all maps, then divided by number of maps minus one (\(n-1\)), before the square root is taken. Mathematically, it is defined as follows:

\[ \sigma = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{X})^2}{n-1}} \]

**Standard Error:** is the standard deviation (\(\sigma\)) divided by the square root of the number of maps (\(n\)). Thus, a map of standard errors will look exactly the same in pattern as a map of standard deviations; they will only differ in absolute value. Mathematically, standard error is defined as follows:

\[ St. \text{Err.} = \frac{\sigma}{\sqrt{n}} \]

**Anomaly:** this is a special function involving user-input. Firstly, the user must click on the plus (‘+’) or minus (‘-’) sign under the text field labelled 'Anom' on the extreme left of the 'Selected Maps' sub-frame (see Figure 4.3). The plus sign will change to a minus sign or vice versa. When this occurs, the values of the display map are calculated as follows;

Anomaly = (average of all “+”s) – (average of all “-”s)

**Sum:** all maps are overlaid upon one another, and the arithmetic sum

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of all chosen user-maps is displayed (maps with a '+' sign are added; maps with a '-' sign are subtracted).

A final button, labeled “Clear Selection”, enables you to clear all the maps from the “Map Image” sub-frame at one instance. This is handy if you are working with large numbers or combinations of maps and you want to refresh the application. You can also delete individual files, one at a time, by just clicking the 'delete' word of the relevant map in the far-right text field of the 'Selected-Files' frame.

4.7: The Top Menu Bar
The menu bar at the top of the FriOWL application window (see Figure 4.5 and Tables 4.2 and 4.3) controls the file management system for saving and retrieving maps, various map transformation functions, time series extraction, changing view preferences and help functions. It is a standard clickable menu and is described in detail now.

![Java Applet Window]

Figure 4.5. The top menu bar of FriOWL-v3.1. There are seven options ('File', 'Edit', 'Transformations', 'Time Series', 'View Extent', 'Outline' and 'Help'). In this example, the 'File' option has been expanded, giving four sub-options ('Save', 'Manage Maps', 'Map History' and 'Exit').

4.8: The 'File' Menu Option
This menu has four options to choose from which are listed in detail in Table 4.2 and in the following sections.
<table>
<thead>
<tr>
<th>Option</th>
<th>What it does</th>
<th>More Info</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Save'</td>
<td>&quot;Flattens&quot; (compress into a single composite layer) all currently active maps in the stack, and prompts the user to enter new properties for the saved map. The new map is saved on the server and can be retrieved at a later time.</td>
<td>Upon saving a map, the user is prompted to enter a file name and file description (a short text string describing the file) for the new map. The user may also enter appropriate units for the new map, as well as specify the minimum latitude and longitude values and map resolution. After saving a map on the server, it can be retrieved at any time again by clicking on the folder 'User Files' in the file manager, or downloaded by clicking on 'Manage Files' (see next).</td>
</tr>
<tr>
<td>'Manage Files'</td>
<td>Brings the user to his / hers personal webspace, where the saved files can be downloaded in various formats (ASCII Zipped, binary .RST raster, image .PNG, Google Earth .KMZ).</td>
<td>The user's personal webspace is found at the following partial URL (i.e. <a href="http://www.iapmw.unibe.ch/research/projects/FriOWL/">http://www.iapmw.unibe.ch/research/projects/FriOWL/</a>): fio_manage.php?owner=USER&amp;pwc=PASSWORD where USER is the user's account name and PASSWORD is his / hers password.</td>
</tr>
<tr>
<td>'Map History'</td>
<td>Displays a Java applet window showing the history of each map that has been saved by a user (from where it was created)</td>
<td>All the files from which a user map have been created are listed in respective order. This function operates a bit like a “diary” and memorises all saved events that are enacted upon a user map.</td>
</tr>
<tr>
<td>'Exit'</td>
<td>Exits the FriOWL software</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Explanation of 'File' top menu bar option

4.8.1: Saving, Managing and Downloading Maps

A map can be saved at any time (see Table 4.2). Simply choose the option 'File -> Save' from the menu and enter a filename and description (both should be relatively short alphanumeric strings). If appropriate, new units need to be entered (relevant only if you have done a map transformation or overlaid maps of different units) and new latitude and longitude resolutions and limits (relevant only if you have done a map transformation). Saving a map “flattens” all currently chosen data maps into a single layer.

To view a previously saved map, click on the folder named 'User Files' in the 'Files' window file menu tree. Here, a list of all the user's saved files is displayed, with a prefix added to
the filenames. The prefix is the **USER** account name followed by an underscore character (e.g. for the user 'guest', all user filenames begin with the prefix 'guest_'). Simply click on the saved file you require, and it will appear as a single data layer in the 'Map Image' sub-frame. If you have forgotten how you created this map, you can find out it's history click by clicking on the option 'File -> Map History'.

![FriOWL screenshot](image.png)

**Figure 4.6:** An example of the personal webpage of the username 'guest' on FriOWL-v3.1. Map files are available for download in binary, ASCII, image (.PNG) and Google Earth formats. Time Series files are available in ASCII and image (.PNG) formats.

To download a saved map to your own personal disk, simply click on the menu option marked 'File -> Manage Files'. Doing this will open a new browser window and will take you automatically to your own personal webspace on the FriOWL server where your maps

† The security features of some browsers (e.g. Microsoft Internet Explorer) may cause the "File -> Manage Files" menu option to fail to open a new browser window. This can be fixed easily by disabling the "Pop-Up Window Blocker" in the Preferences option of your browser. Please see Appendix C ("Notes and Bugs") for more information.
reside. Here, you can download, delete and manage all your previously saved files (see Figure 4.6). To save a file to disk, right-click over the appropriate link. To delete a file, just press delete.

The user's personal webspace is found at the following partial URL (this is what follows after the prefix 'http://www.iapmw.unibe.ch/research/projects/FriOWL/32):

```
asio_manage.php?owner=USER&pwd=PASSWORD
```

where USER is the user's account name and PASSWORD is his / hers password. Just right click on the highlighted link of the appropriate file extension (.RST, .RDC, .ZIP, .PNG or .KMZ) to download a file to local disk. Saved map files are automatically saved on the FriOWL server in a variety of formats, namely:

- **BINARY (.RST)**: a formatted binary raster file, consisting of a single column of real (floating-point) numbers, one value per row, 4 bytes (32 bits) per value, suitable for reading by IDRISI GIS software (see Eastman 1987-2002) or any other software or programming language (e.g. Matlab). An IDRISI raster documentation text file (.RDC) is also included for download.

- **ASCII (.ZIP)**: a text file (.txt) which has been compressed for quicker download into a .ZIP file. It contains three columns of text (see below), each column separated by a comma. The first and second columns are the latitude and longitude respectively, and the third is the data value (in floating-point format) e.g.

  -90.0,0.0,1.746085357666602E0001
  -90.0,2.5,1.746085357666602E0001
  -90.0,5.0,1.746085357666602E0001

† **Important note on the saving of large ASCII files**: At approximately 24 bytes per pixel value, a typical ASCII file occupies six times more space (or greater) than its binary file equivalent. Therefore, the saving of a data layer of high spatial resolution (e.g. greater than 1.0° lat / lon) can result in very large ASCII files being saved on the server (sometimes several to tens of megabytes in size). In an un compressed state, a file of this size may exceed standard Java virtual machine settings for applets. Therefore, any user who wants to be able to save these files to disk must change settings for the Java Plug-In in the user's System Control, by adding a VM-Option “-Xmx256m”. Currently in FriOWL-v3.1 (as of January 2008), the maximum file size saveable on the server is limited to 1200 columns X 600 rows.
-90.0,7.5,1.74608535766602E001
-90.0,10.0,1.74608535766602E001
-90.0,12.5,1.74608535766602E001
-90.0,15.0,1.74608535766602E001...

Please note that, due to their much greater usage of computing space and memory, the saving of ASCII files is limited to files pixel sizes of only 800 X 400 pixels or less.

- PNG (Portable Network Graphics): a superior form of web imagery, supported by most browsers, which is similar in quality to the more commonly known JPEG format.

- KMZ (Google Earth): a KMZ file is a zipped KML (Keyhold Markup Language) file. KML is an XML-based language for managing the display of three-dimensional geospatial data (Wikipedia, 2007a). Clicking on this file will open it in Google Earth software (if you have it installed on your computer).

**4.9: The 'Edit' Menu**
The 'Edit' menu consists of just one sub-option: a simple 'Undo' or 'Redo' function, which reverses the previous task which the user has enacted.

**4.10: The 'Transformations' Menu**
There are four different map functions available under the 'Transformations' menu (three of which are new to FriOWL-v3.1). They are listed and explained in detail in Table 4.3 and in the following sections.
<table>
<thead>
<tr>
<th>Option</th>
<th>What it does</th>
<th>More Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Reclass'</td>
<td>The <em>Reclass</em> function allows the changing (or the reclassification) of values of a map. It can be used to reduce the amount of information on offer in a map to the necessities only.</td>
<td><strong>Example:</strong> A user may want to know where all the mountains in the world higher than 3000m are located. He / she is not interested in regions below 3000m. <strong>Solution:</strong> A global map of topography can be reclassified to show all areas above 3000m to be labelled as '1'. All other regions below 3000m may be labelled as '0'.</td>
</tr>
<tr>
<td>'Resample'</td>
<td>The <em>Resample</em> function changes the X-Y resolution of a map. This allows maps of previously different resolutions to be overlaid upon one another. For overlaying maps of different data types, all maps must be of the same resolution. A map may be either scaled-up or scaled-down. See Section 4.10.2 on how the <em>Resample</em> algorithm works</td>
<td>It is important to remember that <strong>no new information</strong> is created when a map is scaled-up using <em>Resample</em>. Conversely, scaling down reduces the amount of information on offer. Therefore, the <em>Resample</em> function should be used with caution. Therefore, if two maps of different data types are to be overlaid, it is recommended to scale-up the map of lowest resolution to that of the second more highly resolved map. In this way, no information is lost.</td>
</tr>
<tr>
<td>'Crop'</td>
<td>To crop is to cut a selected area from a map and to discard the remainder.</td>
<td>Crops a map within a specified pixel range</td>
</tr>
<tr>
<td>'Normalise'</td>
<td>The 'Normalise' function scales all values within a map to between 0 and 100.</td>
<td>See Equation 4.1 for a definition of the 'Normalise' algorithm</td>
</tr>
</tbody>
</table>

Table 4.3: Explanation of the 'Transformations' menu.

Please note that a fifth transformation function ('Weight') is also provided in the 'Selected Maps' sub-frame (see Section 4.11).

**4.10.1: How to operate 'Reclass'**

The *Reclass* function allows the user to change the values of a chosen map. The objective is to focus-in on areas of interest, and eliminate those areas of non-interest. Using reclass, therefore, we can significantly reduce the amount of data on offer without reducing the information. This is a powerful tool commonly used in Geographical Information Systems. Later, we may want to combine several reclassified maps to form a single, new 'Composite' map.
To use the Reclass function in FriOWL, you must have at least one map already displayed. You must also tick the boolean check-box in the 'Selected Maps' sub-frame, for each chosen map, listed under the field heading 'Transform'. All maps that have the 'Transform' box ticked will be reclassed. To activate Reclass, select 'Transformations -> Reclass' from the menu. A standard pop-up dialog box will appear (see Figure 4.7).

![Reclass All Values ...](image)

**Figure 4.7:** The 'Reclass' Pop-up dialog box. Fill in the appropriate fields as required and press 'Go'.

Simply enter values in the given fields as appropriate, and then press 'Go'. 'Reclass' works best if you have already created a map of averages or means using the Statistical Function Chooser described in Section 4.6.3. A typical objective when using 'Reclass' may be to change all pixels of non-interest to a value of 0, whilst reclassifying all interesting pixels to value of 1. See Chapter 2 (‘Quick-Guide to FriOWL’) and Chapter 6 (‘Guided Examples’) on how to do this exactly and for other worked examples of the 'Reclass' function in operation.

### 4.10.2: How to Operate 'Resample'

Resampling changes the number of pixels in an image map. This function is new to FriOWL-v3.1. It changes or 'resamples' the X-Y resolution of a map. A resampled map may be either scaled-up or scaled-down.

Many of the different geophysical datasets on offer in FriOWL-v3.1 have widely differing resolutions. However, sometimes it is necessary to overlay a layer from one dataset upon another layer from a different dataset. For this to work properly, it is required that both layers have the same latitude-longitude extent or resolution. Resampling helps us to achieve this, and it was an important objective of the FriOWL-v3.1 project to enable maps of previously different resolutions (and data types) to be overlaid upon one another.
To operate the \textit{Resample} function, simply choose \textit{Transformation->Resample}. You may also need to toggle the \textit{Transform} checkbox in the \textit{Selected Maps} sub-frame, to indicate which maps you want to resample. You will be greeted by a standard pop-up dialog box in which you must enter some values (see Figure 4.8).

Enter new grid values for the width and height of the new layer to be created. The entered values should be pixel grid values (i.e. the number of column and rows you want the new file to have) and \textbf{NOT} the latitude or longitude values. A maximum limit of 1200 (width) X 600 (height) is imposed; you cannot resample images to values greater than these. This is a security feature which prevents users from (in)advertently making very large file sizes on the server.

![Figure 4.8: The 'Resample' Pop-up dialog box. To operate 'Resample', simply enter new values for the image pixel (raster) width and height and click 'Go'. A maximum limit of 1200 (width) X 600 (height) is imposed; you cannot resample images to values greater than these.](image)

It is important to remember that \textbf{no new information} is created when a map is \textbf{scaled-up} using \textit{Resample}; the new values are just interpolated from the old values. Conversely, scaling down \textbf{reduces} the amount of information on offer. Therefore, if two maps of different data types are planned to be overlaid upon one another, it is recommended to scale-up the map of lowest resolution to become equivalent to that of the second more highly resolved map so that no information is lost. For a guided example of the resampling function in operation, please see Chapters 2 ("Quick-Guide / Tutorial") and Chapter 6 ("Guided Examples").

The \textit{Resample} algorithm works by calculating weighted averages of the old cells and applying these to the new cells. If the new cell boundaries do not overlap the old cell boundaries, then the old cell value is assigned immediately to the new cell value. If
overlapping occurs, then the new cell value is composed of the weighted averages of all the overlapping old cells. The weight is just the fraction of overlap between the new and old cells.

For example, in a row of six data points whose values are the following:

<table>
<thead>
<tr>
<th></th>
<th>3.0</th>
<th>5.0</th>
<th>7.0</th>
<th>1.0</th>
<th>2.0</th>
<th>8.0</th>
</tr>
</thead>
</table>

When scaled-up to 8 columns, the new values become the following:

<table>
<thead>
<tr>
<th></th>
<th>3.0</th>
<th>4.33</th>
<th>5.66</th>
<th>7.0</th>
<th>1.0</th>
<th>1.66</th>
<th>4.0</th>
<th>8.0</th>
</tr>
</thead>
</table>

And when the original 8 columns are scaled-down to 4 columns:

<table>
<thead>
<tr>
<th></th>
<th>3.66</th>
<th>6.33</th>
<th>1.33</th>
<th>6.0</th>
</tr>
</thead>
</table>

de. The second value of the scaled-up values has a value of 4.33. This has been calculated as follows:  

\[ 4.33 = \frac{1}{3}(3.0) + \frac{2}{3}(5.0) \]

**4.10.3: How to operate 'Crop' and 'Normalise'**

*Cropping* allows only a selected area of a map to be saved. It is straightforward to use. Just choose 'Transformation -> Crop' from the menu and enter new grid values for the left, right, top and bottom coordinates of the area from where you want the crop / cut to occur. The entered values should be grid values (i.e. the respective pixel column and row numbers) and **NOT** the latitude / longitude values.

*Normalising* scales the values of all displayed maps to new values of between 0 and 100. Just choose 'Transformation -> Normalise' from the main menu. Click 'Yes' if you want all selected maps to be normalised. The resulting pixel values are normalised (scaled) to a value between 0 and 100. The *Normalise* algorithm works as follows, for each pixel:
\[
\text{New Pixel Value} = (\text{Old Pixel Value} - \text{min}) \times \left( \frac{100}{\text{max} - \text{min}} \right) \\
\text{Eqn. 4.1}
\]

where \( \text{max} \) and \( \text{min} \) are the maximum and minimum pixel values of the map in question.

### 4.11: How to change the 'Weight' of a Map

The current weight of every displayed map is shown in the text field labelled 'Weight' in the 'Selected Maps' window (see Figure 4.9). This is an interactive field and its value may be altered by the user. As explained in Table 4.1, changing the weight of a map changes that map's importance with respect to others (given a stack of several map layers).

<table>
<thead>
<tr>
<th>Units</th>
<th>Min</th>
<th>Max</th>
<th>Weight</th>
<th>Transf...</th>
<th>Delete</th>
</tr>
</thead>
<tbody>
<tr>
<td>decametres</td>
<td>496.48...</td>
<td>585.21...</td>
<td>2</td>
<td></td>
<td>delete</td>
</tr>
<tr>
<td>decametres</td>
<td>482.73...</td>
<td>587.63...</td>
<td>3</td>
<td></td>
<td>delete</td>
</tr>
<tr>
<td>decametres</td>
<td>488.16...</td>
<td>586.75...</td>
<td>1.5</td>
<td></td>
<td>delete</td>
</tr>
</tbody>
</table>

*Figure 4.9: The 'Weighting' function highlighted in red*

The weight of any map layer is automatically defaulted by FriOWL to to a value of 1, meaning there is no extra importance (or weight) given to that particular map, relative to all other maps which also have a weighting of 1. Clicking the 'Weight' field and entering a new value (any integer or floating point value can be entered e.g. 4, -3e-05, 2.718) will give a new weighting or importance to that map layer. A weighting of 0 means the map is completely transparent with respect to others.

Applying weights to maps can be useful once a series of maps has been already normalised or reclassified. It is also useful after a set of priorities or importances has been defined. For example, an astronomer interested in the site selection for a new telescope may decide that that, for the given values, a low value of integrated water vapour at an potential observatory is *twice as important* as a low value of the 200 hPa jetstream windspeed.
Therefore, the ratio of importance between the two variables is 2 to 1. Put simply, the *Weight* that one would apply to the integrated water vapour layer is = 2, whereas it would be only = 1 for 200hPa jetstream windspeed layer.

To activate the weighting function, simply click on the field labelled 'Weight' in the 'Selected Maps' sub-frame, for each particular map. One can toggle the value to any positive or negative real number. The map pixel values are multiplied by the value entered (Figure 4.9).

4.12: The *Time Series* Menu

Extracting, plotting and downloading time series for any global gridpoint from any dataset is possible with FriOWL-v3.1. Simply choose 'Time Series -> Show Time Series' from the top menu bar. Upon selection, a new Java applet window appears (which is separate from the main FriOWL application window). Here, you have the ability to display a temporal series of any meteorological parameter on offer in the FriOWL-v3.1 database for the whole length of its duration (see Figure 4.10) .
At the top the time series applet window (see Figure 4.10), lie the meteorological parameter chooser (e.g. 'IWV at 700hPa', 'High Cloud Cover 12UTC') and the time period chooser (e.g. 'SEP 1957' to 'AUG 2002'). Immediately below these dropdown menus, you can select which month to display (from 'JAN' to 'DEC', or all of them). Directly beside this, you must enter the latitude and longitude of the global gridpoint that you are interested in. The latitude / longitude co-ordinates must be entered in the following formats e.g.

Latitude  **53.5 N** or **80.0 S** or **10.0 N**  
Longitude:  **10.0 W** or **75.0 E** or **245.5 E**

Please note that entering the latitude or longitude in other formats such as “-10 ” or “350.0” will result in an error (you must always append a ‘N’, ‘S’, ‘E’ or ‘W’ suffix to the co-ordinate). Alternatively, just click on the latitude / longitude position that you are interested
in the main FriOWL 'Map Image' window, and your chosen latitude / longitude of the chosen point will appear in these fields automatically.

Pressing the button 'Show' will plot a line graph of the time series you have requested (please wait a few seconds to allow retrieval of data; see Figure 4.10). Pressing the button 'Save' will prompt you for a filename with which to save the requested file in your personal webspace on the server. Pressing the 'Manage' button will bring you to your personal webspace where the time series files are available for download in image (.PNG) and ASCII text (.TXT) formats. This option works exactly the same way as the 'File -> Manage Files' option in the main FriOWL application window.

The ASCII text file for time series files consists of a single line header indicating the latitude and longitude of the point in question, followed by 3 columns of text, separated by a comma. The first and second columns indicate the year and month respectively, whilst the third column contains the data value (in floating-point format).

e.g. extract from a saved ASCII time series file:

60.0 N Lat / 20.0 W Lon
1958, JUN, 5.19663572311401E-001
1959, JUN, 4.87502455711365E-001
1960, JUN, 5.81801831722260E-001
1961, JUN, 4.89387243986130E-001
1962, JUN, 5.36536931991577E-001
1963, JUN, 2.57393509149551E-001
1964, JUN, 2.86308586597443E-001
1965, JUN, 4.12709206342697E-001
1966, JUN, 4.23569202423096E-001
1967, JUN, 3.91617506742477E-001...

**4.13: The 'View Extent' Menu Option**
Toggling the 'View Extent' menu option controls the longitude at which the map is centered for display in the 'Map Image' sub-frame. There are two options available: 'Pacific Centred',

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in which the Greenwich meridian (0° longitude) forms left and right borders of map and 'Europe Centred' (where the 180° longitude meridian forms left and right borders of map). Changing between either does not alter the position of the columns in the raw data file - it is for viewing purposes only.

4.14: The 'Outline' menu option

Toggling the 'Outline' menu option enables or disables the appearance of a world map outline. The world map shows the main continental and international country borderlines. If you save a map with the world map toggled off, the world map outline will not be saved in any resulting PNG images saved on the server, and vice versa. The world map is for display purposes only.

4.15: The 'Help' menu option

An online help system is provided as a link to the most recent version of the FriOWL guide (this document) on the FriOWL website. Clicking the 'File -> About FriOWL' menu option launches a pop-up box which provides basic information about FriOWL for first-time users.
CHAPTER 5: THE JAVA CLASSES

This chapter deals solely with the Java programming aspects of FriOWL-v3.1. Because of the large number of Java classes and many thousands of lines of code contained in the FriOWL-v3.1 software, it is only possible to give brief explanations of the classes here. Full Java documentation and source code is provided on the FriOWL-v3.1 website. This chapter has been prepared by Eddie Graham, with the class documentation provided by Moritz Neun.

5.1: Introduction to Java

Java is a computer programming language developed by Sun Microsystems (USA) and was first released publicly in 1995. It soon became popular after the introduction of Java applets in webpages around 1996, and the Java language and technologies grew quickly thereafter. As of 2007, the language became an “open-source” software, meaning that the language has become freely available to anyone under the “GNU” free public software licence (see http://www.gnu.org/licenses/gpl-3.0.txt for more information; website accessed 1 March 2008).

Java was chosen for FriOWL-v3.1 because it is a platform independent language, meaning that code which is written and compiled with a Java compiler may be run on any computer thereafter, regardless of platform (e.g. Windows, Linux, Macintosh, etc..). It also has a reputation as being stable and secure, because the Java programs are client-based. Powerful web or standalone graphical applications can be built relatively easily with Java, and it is used widely in the mobile-phone industry today.

Java is a object-orientated language, meaning that the code is composed of classes or objects. Class definitions may be placed almost anywhere in a Java program. This is unlike procedural languages such as Fortran or BASIC, where the code is actioned sequentially (e.g. line 2 of the code is actioned after line 1, and so on).

Every Java class must have certain pre-defined characteristics. Each class must also descend from pre-defined hierarchy of Java classes, meaning that certain classes have precedence over others. Child classes automatically inherit the properties of their parents. Classes can also be bunched together into packages, which are an organised collection of classes.

For example, a tree could be described as a parent class. Every tree has a trunk, branches,
twigs and leaves; these are the properties defining the class “tree”. An instance of the class can then be created to define a particular tree e.g. an Oak tree or a Maple tree, but every tree will have similar attributes (trunk, twigs, leaves), regardless of tree type. Likewise, the tree may shed an acorn, which a few years later grows in another tree; this “child” class inherits exactly the same properties as its parent. The Java language hierarchy works in a similar way.

What follows next are brief descriptions and explanations of the main Java classes in FriOWL-v3.1, which are provided for documentation purposes. Due to space considerations, however, full source codes are not provided; these can be found on the FriOWL-v3.1 website.

### 5.2: Notes on Authors and Writing of Code

The code of FriOWL-v3.1 was written mostly by Moritz Neun of the University of Zürich, Switzerland, under the instruction, design and guidance of Eddie Graham. However, it followed on largely from the previous FriOWL versions 2.1 and 2.2 (2004-2006), which were designed, built and written by Moritz Neun, Michael Hayoz and Eddie Graham, then at the University of Fribourg, Switzerland (Graham et al., 2005). This was based, in turn, on on earlier version of FriOWL (version 1.0), which was written in the PHP language (Graham, 2003), also by Hayoz, Neun and Graham.

Most of actual Java code was not manually typed, but was written using integrated development environments (IDE), which are themselves graphical applications designed to aid programmers to write code very quickly (even a small Java application may contain several hundred lines of code). The IDE used by Eddie Graham for FriOWL-v2.2 was Borland Jbuilder, although the open-source Eclipse software is more widely used today. The statistical operators of the software were mostly manually coded.

### 5.3. Java Classes and Packages of FriOWL-v3.1

At the time of writing (1 March 2008), FriOWL-v3.1 contains approximately fifty Java classes in total, containing many thousands of lines of code. The classes are organised into five different packages, namely:

1. `org.eso.friowl`
2. `org.eso.friowl.actions`
3. `org.eso.friowl.operators`
(iv) org.eso.friowl.timeseries
(v) org.eso.friowl.tools

Each package refers to a particular part of the software. Many of the package and class names are self-explanatory. Each of these are now briefly described in the following sections.

5.3.1: Package “org.eso.friowl”

Package org.eso.friowl consists of 18 different classes; these control the main application window and layout of the software.

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AboutFrame</td>
<td>This is the frame showing the About-Message in FriOWL.</td>
</tr>
<tr>
<td>ColorScheme</td>
<td>A ColorScheme contains the complete color table of a RDC file.</td>
</tr>
<tr>
<td>ColorsPanel</td>
<td>The panel of the right side of the MainWindow showing the color-bar.</td>
</tr>
<tr>
<td>FilesPanel</td>
<td>The panel of the upper left side of the MainWindow showing the file-tree.</td>
</tr>
<tr>
<td>FilesPanelMonitor</td>
<td>A status bar can be used for displaying the progress of opening a file.</td>
</tr>
<tr>
<td>FriOWLApplet</td>
<td>The small Applet in the homepage where a user enters a username and password.</td>
</tr>
<tr>
<td>MainWindow</td>
<td>This is the main class of FriOWL.</td>
</tr>
<tr>
<td>MapHistoryFrame</td>
<td>Window to display the history of a map.</td>
</tr>
<tr>
<td>MapImage</td>
<td>The panel of the upper middle of the MainWindow containing the map display.</td>
</tr>
<tr>
<td>MapImagePanel</td>
<td>The scroll-panel of the upper middle of the MainWindow containing the MapImage.</td>
</tr>
<tr>
<td>MenuBar</td>
<td>The menu-bar at the top of FriOWL.</td>
</tr>
<tr>
<td>MenuSaveDialog</td>
<td>The dialog which opens when a map is being saved.</td>
</tr>
<tr>
<td>OptionsPanel</td>
<td>The panel of the lower left of the MainWindow.</td>
</tr>
<tr>
<td>RasterMap</td>
<td>Each file which is opened and added to the SelectedMapsTable is represented by a RasterMap-Object.</td>
</tr>
<tr>
<td>Resources</td>
<td>Utility class containing settings and methods to open and save files at the server.</td>
</tr>
<tr>
<td>SelectedMaps</td>
<td>Container to hold all selected maps which are then displayed by the SelectedMapsTable in the SelectedMapsPanel.</td>
</tr>
<tr>
<td>SelectedMapsPanel</td>
<td>The panel of the lower middle of the MainWindow containing the SelectedMapsTable.</td>
</tr>
<tr>
<td>StatusBar</td>
<td>Status-bar at the bottom of the MainWindow.</td>
</tr>
</tbody>
</table>

5.3.2: Package “org.eso.friowl.actions”

Package org.eso.friowl.actions consists of nine different classes, but the only action they need to control is the Undo function. This package also implements a Java interface 'lundo' (a Java interface is a similarity that various classes share, without necessarily having a class relationship e.g. both trees and humans tend to grow with time, but one would not classify them together as similar objects).
<table>
<thead>
<tr>
<th><strong>Class Name</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>UndoAdd</td>
<td>Undo adding a map.</td>
</tr>
<tr>
<td>UndoChangeWeight</td>
<td>Undo changing the weight in the SelectedMapsTable.</td>
</tr>
<tr>
<td>UndoClear</td>
<td>Undo clearing the SelectedMapsTable.</td>
</tr>
<tr>
<td>UndoCrop</td>
<td>Undo cropping the map.</td>
</tr>
<tr>
<td>UndoNormalize</td>
<td>Undo normalizing the map.</td>
</tr>
<tr>
<td>UndoReclass</td>
<td>Undo reclassing a map.</td>
</tr>
<tr>
<td>UndoRemove</td>
<td>Undo removing a map from the SelectedMapsTable.</td>
</tr>
<tr>
<td>UndoResampling</td>
<td>Undo resampling a map.</td>
</tr>
<tr>
<td>UndoZoom</td>
<td>Undo zooming.</td>
</tr>
</tbody>
</table>

**5.3.3: Package “org.eso.friowl.operators”**

Package org.eso.friowl.operators holds all the operator classes (e.g. Anomaly, Max, Min, Root Mean Square, etc..); their names are self-explanatory. This package also implements the interface GridOperator. For a full explanation and definition of each operator, please see Chapter 4 (“Description of the GUI”).

<table>
<thead>
<tr>
<th><strong>Class Name</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anomaly</td>
<td>The Anomaly Operator.</td>
</tr>
<tr>
<td>Crop</td>
<td>The Crop Transformation.</td>
</tr>
<tr>
<td>Max</td>
<td>The Maximum Operator.</td>
</tr>
<tr>
<td>Mean</td>
<td>The Mean Operator.</td>
</tr>
<tr>
<td>Min</td>
<td>The Minimum Operator.</td>
</tr>
<tr>
<td>Normalize</td>
<td>The Normalize Transformation.</td>
</tr>
<tr>
<td>Reclassification</td>
<td>The Reclassification Transformation.</td>
</tr>
<tr>
<td>Resampling</td>
<td>The Resampling Transformation.</td>
</tr>
<tr>
<td>RootMeanSquare</td>
<td>The RootMeanSquare Operator.</td>
</tr>
<tr>
<td>StandardDeviation</td>
<td>The Standard Deviation Operator.</td>
</tr>
<tr>
<td>StandardError</td>
<td>The Standard Error Operator.</td>
</tr>
<tr>
<td>Sum</td>
<td>The Sum Operator.</td>
</tr>
</tbody>
</table>
5.3.4: **Package “org.eso.friowl.timeseries”**

Package `org.eso.friowl.timeseries` holds the four classes of the FriOWL-v3.1 time series applet. This package also implements the interface 'Iseries'.

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SeriesLocal</td>
<td>Just a placeholder for allowing to select the Files in the SelectedFilesTable from the MainWindow as input for the time series.</td>
</tr>
<tr>
<td>SeriesMonthly</td>
<td>Each time series is parameterized in a SeriesMonthly object and saved in the drop-down field in the TimeSeriesFrame.</td>
</tr>
<tr>
<td>TimeSeriesFrame</td>
<td>The window containing the time series functionalities.</td>
</tr>
<tr>
<td>TimeSeriesGraphPanel</td>
<td>Panel which shows the actual time series graph.</td>
</tr>
</tbody>
</table>

5.3.5: **Package “org.eso.friowl.tools”**

There are just two classes in the package `org.eso.friowl.tools`, namely:

<table>
<thead>
<tr>
<th>Class Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ClientHttpRequest</td>
<td>Client HTTP Request class.</td>
</tr>
<tr>
<td>LifoStack</td>
<td>A small utility implementing a &quot;last in, first out stack&quot;.</td>
</tr>
</tbody>
</table>

5.4. **Final note on FriOWL-v2.2 Java classes**

The previous version of FriOWL-v2.2 held a smaller number of Java classes (approximately twenty) in a single package. Since the new FriOWL-v3.1 has superseeded FriOWL-v2.2, it is decided as being not necessary to list or detail the classes here, but full listings and source code of these classes can be found on the FriOWL-v3.1 website.
CHAPTER 6: RESULTS AND DISCUSSION

This chapter presents scientific results and discusses the use of *FriOWL-v3.1* software and database as a site-selection tool for large telescope projects. Specific emphasis is given in characterising fourteen worldwide candidate regions for the site of the European Extremely Large Telescope (E-ELT). This chapter is long and is organised as follows: Firstly, each of the main climatic and geophysical variables are examined in separate sub-sections using global images and data output created with *FriOWL-v3.1*. Results are presented in terms of the suitability of each region for the E-ELT and some recommendations are given. Later, a selection of global composite maps are presented by overlaying and resampling the results from the earlier sections. Finally, we finish-up this chapter by showing a more general example of how *FriOWL-v3.1* can be used for other types of climatological studies.

6.1: THE E-ELT CANDIDATE SITES

If the necessary funding becomes available, ESO plan to begin construction of the E-ELT within three years from now (~2010) and it is hoped to have it ready by the year 2017. The site selection decision will need to be made much sooner than this, however. Already, ESO have identified nineteen potential worldwide candidate sites for the E-ELT which are listed in Table 6.1.1. Please note that this list is by no means exhaustive, nor are the sites listed in any preferential order.

Because the pixel size (2.5° square) of the *FriOWL-v3.1* re-analysis data is very much larger (by several orders of magnitude) than each individual mountain summit listed in Table 6.1.1, direct mountain-top estimates of each climatic variable cannot be attempted in this study. Instead, tabular values are presented for a reduced set of fourteen worldwide regions, but in which all of the original nineteen E-ELT candidate sites are sited. These 14 regions are listed in Table 6.1.2, together with the re-analysis gridpoint co-ordinate which was used for that region.
<table>
<thead>
<tr>
<th>Site</th>
<th>Place / Country</th>
<th>Lat °</th>
<th>Lon °</th>
<th>Alt (m)</th>
<th>Light Pollution Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dome C</td>
<td>Antarctica</td>
<td>-75.10</td>
<td>123.40</td>
<td>3233</td>
<td>0</td>
</tr>
<tr>
<td>2 Grand Benare</td>
<td>La Reunion Island</td>
<td>-21.10</td>
<td>55.42</td>
<td>2896</td>
<td>80</td>
</tr>
<tr>
<td>3 Tolar</td>
<td>Chile</td>
<td>-21.95</td>
<td>-70.08</td>
<td>2290</td>
<td>35</td>
</tr>
<tr>
<td>4 Chajnantor</td>
<td>Chile</td>
<td>-22.98</td>
<td>-67.63</td>
<td>5100</td>
<td>2</td>
</tr>
<tr>
<td>5 Gamsberg</td>
<td>Namibia</td>
<td>-23.34</td>
<td>16.23</td>
<td>2347</td>
<td>20</td>
</tr>
<tr>
<td>6 Macon</td>
<td>Argentina</td>
<td>-24.50</td>
<td>-67.29</td>
<td>5000</td>
<td>3</td>
</tr>
<tr>
<td>7 La Chira</td>
<td>Chile</td>
<td>-24.52</td>
<td>-70.37</td>
<td>2559</td>
<td>13</td>
</tr>
<tr>
<td>8 Armazones</td>
<td>Chile</td>
<td>-24.58</td>
<td>-70.18</td>
<td>3064</td>
<td>8</td>
</tr>
<tr>
<td>9 Paranal</td>
<td>Chile</td>
<td>-24.62</td>
<td>-70.40</td>
<td>2636</td>
<td>9</td>
</tr>
<tr>
<td>10 La Silla</td>
<td>Chile</td>
<td>-29.25</td>
<td>-70.73</td>
<td>2400</td>
<td>9</td>
</tr>
<tr>
<td>12 El Teide, Izaña</td>
<td>Tenerife Island</td>
<td>28.30</td>
<td>-16.50</td>
<td>2367</td>
<td>169</td>
</tr>
<tr>
<td>13 Roque de los Muchachos</td>
<td>La Palma Island</td>
<td>28.77</td>
<td>-17.88</td>
<td>2396</td>
<td>55</td>
</tr>
<tr>
<td>14 Lekst</td>
<td>Anti-Atlas, Morocco</td>
<td>29.80</td>
<td>-9.04</td>
<td>2359</td>
<td>45</td>
</tr>
<tr>
<td>15 Yanbajing</td>
<td>Tibet</td>
<td>30.11</td>
<td>90.53</td>
<td>4500</td>
<td>16</td>
</tr>
<tr>
<td>16 San Pedro Martir</td>
<td>Baja California, Mexico</td>
<td>31.05</td>
<td>-115.49</td>
<td>2980</td>
<td>4</td>
</tr>
<tr>
<td>17 Hanle</td>
<td>Himalaya, India</td>
<td>32.78</td>
<td>78.97</td>
<td>4500</td>
<td>19</td>
</tr>
<tr>
<td>18 Maidanak</td>
<td>Uzbekistan</td>
<td>38.68</td>
<td>66.90</td>
<td>2600</td>
<td>16</td>
</tr>
<tr>
<td>19 Greenland Summit</td>
<td>Greenland</td>
<td>72.57</td>
<td>-38.28</td>
<td>3225</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.1.1: The nineteen E-ELT candidate sites identified by ESO, listed according to site name, country, latitude, longitude and altitude. Also given on the far right is a light-pollution index for each site (units of ha/km/km/dmasl), provided by ESO*.

† http://www.eso.org/gen-fac/pubs/astclim/espas/SiteList.htm (site accessed 11 April 2007)
<table>
<thead>
<tr>
<th>Region</th>
<th>Sites which region includes</th>
<th>FriOWL pixel used (lat°, lon°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dome C (Antarctica)</td>
<td>Dome C</td>
<td>(-75.0, 122.5)</td>
</tr>
<tr>
<td>2 La Réunion</td>
<td>La Réunion</td>
<td>(-20.0, 55.0)</td>
</tr>
<tr>
<td>3 Namibian coast</td>
<td>Gamsberg</td>
<td>(-22.5, 15.0)</td>
</tr>
<tr>
<td>4 Hawaii Islands</td>
<td>Mauna Kea</td>
<td>(20.0, -155.0)</td>
</tr>
<tr>
<td>5 North-Atacama</td>
<td>Tolar Chajnantor</td>
<td>(-22.5, -70.0)</td>
</tr>
<tr>
<td>6 Mid-Atacama</td>
<td>Macon Aramones, Paranal, La Chira</td>
<td>(-25.0, -70.0)</td>
</tr>
<tr>
<td>7 South-Atacama</td>
<td>La Silla</td>
<td>(-30.0, -70.0)</td>
</tr>
<tr>
<td>8 Canary Islands</td>
<td>La Palma, Tenerife</td>
<td>(27.5, -17.5)</td>
</tr>
<tr>
<td>9 Anti-Atlas, Morocco</td>
<td>Lekst</td>
<td>(30.0, -10.0)</td>
</tr>
<tr>
<td>10 Tibetan plateau</td>
<td>Yanbajing</td>
<td>(30.0, 90.0)</td>
</tr>
<tr>
<td>11 Baja California</td>
<td>San Pedro Martir</td>
<td>(30.0, -115.0)</td>
</tr>
<tr>
<td>12 Hanle (Indian Himalaya)</td>
<td>Hanle</td>
<td>(32.5, 80.0)</td>
</tr>
<tr>
<td>13 Uzbekistan (Himalaya)</td>
<td>Maidanak</td>
<td>(37.5, 67.5)</td>
</tr>
<tr>
<td>14 Greenland Summit</td>
<td>GeoSummit</td>
<td>(72.5, -37.5)</td>
</tr>
</tbody>
</table>

Table 6.1.2: The fourteen worldwide regions in which all of the original nineteen E-ELT candidate sites (Table 6.1.1) are sited. The latitude and longitude of the re-analysis gridpoint used for each region is also given.
6.2 Analysis of ERA-40 Clouds

As already stated in chapter 3, cloud cover is traditionally classified by meteorologists according to its height above the ground. Thus, high cloud cover (hcc) refers to cloud with a height of at least 6000 metres, medium or mid-level cloud cover (mcc) refers to cloud between 2,000 and 6,000 metres, whilst low cloud cover (lcc) refers to cloud below 2,000 metres. Global cloud cover amounts for each of these three levels are available in FriOWL-v3.1, for the full period of the ERA40 project (1957-2002), for each of the main WMO synoptic reporting hours (00, 06, 12 and 18 UTC), and also as daily means. Here, we analyse these different global datasets to search for (and confirm) the best astronomical sites.

It is almost an astronomical convention to assume that the extremely large telescopes of the future will all be located in high, dry desert zones of the earth. However, there are still many other outside factors at play (such as those listed in chapter 1). These influences notwithstanding, it is still very likely that the future site of the E-ELT will be on a mountain summit or plateau of greater than 2,000 metres in height, possibly even as high as 5,000 metres. One of the reasons astronomers build on such high mountain-tops is to avoid any low cloud cover (lcc) layers in the vicinity; indeed, if a site were not above low clouds, it would not be a candidate site. Therefore, we can limit our use of cloud layers in our study to just hcc and mcc, by assuming a priori that any candidate site will lie above lcc. Using only hcc and mcc clouds here may also be beneficial from the point-of-view that hcc and mcc clouds should be, in theory, easier to detect from satellites (i.e. they are higher up, less chance of shielding by other clouds).

Furthermore, we have decided to limit our analyses here to cloud data only from the post-satellite period of 1976 to 2002. This is because there are considerable uncertainties in the estimation of cloud by the ERA40 model, especially for periods during the early years of ERA40 project (Chevallier et al., 2003). These concerns were discussed earlier in section 3.4.3 (Chapter 3).

6.2.1 Diurnal variation of cloud: creation of ‘night-time-only’ maps

Cloud is an extremely dynamic quantity, changing on timescales of a few seconds to hours, but it can also vary cyclically over months, years and decades. The most obvious
rhythmic fluctuation in cloud cover occurs between day-and-night, especially in lower latitudes and during the summer-half of the year in other areas, but many other seasonal and interannual oscillations also occur in cloud cover, examples of some of which will be shown shortly. Such differences between night-and-day can be considerable, so the use of daily means to estimate night-time cloud cover should be avoided.

Unfortunately, since the ERA40 project only provides data values for each of the main WMO synoptic reporting hours (namely 00, 06, 12 and 18 UTC), together with daily means, so direct values of 'daytime' or 'night-time' cloudiness are not provided. This is because, at any single UTC time, it may be either daytime or night-time depending on one's position on the globe and the time of year. However, it is possible to make approximate or 'effective' night-time cloudiness maps, using manipulations provided with FriOWL-v3.1. The procedure to do this is now explained.

The 'effective night-time cloudiness' maps were created as follows: the mean global cloud cover (in this case, hcc and mcc) for January 00 UTC was calculated, and a map was saved. This procedure was repeated for January 06 UTC, January 12 UTC and January 18 UTC, and again for other months of the year, saving a map of mean values for each time. Then, it was assumed that the minimum value for each pixel of all four aforementioned UTC maps (00, 06, 12 and 18 UTC) for each month corresponded to a night-time value. It is judged that this assumption should be correct in most cases, since there are no widespread high and mid-level cloud forming processes that occur preferentially at night (except perhaps cirrus cloud formation due to aviation schedules, or minor changes at the top of thick frontal or thunderstorm cirrus due to radiational cooling during night). Most night-time cloud-making processes operate close to ground level (due to radiational cooling of the earth's surface), giving rise to low-level cloud features (i.e. fog, stratus), which are not relevant in this work. The result is a map of estimated night-time cloudiness.

With all of these considerations in mind, Figures 6.2.1 (a) to (d) show the global mean 'effective' night-time January, April, July and October sum of ERA40 hcc+mcc cloud amounts, as calculated for the period 1976-2002. Here, night-time means maps that have been created using the 'night-time' procedure as explained above. Meanwhile, Figure 6.2.2 shows the approximate annual means of night-time for (a) hcc and (b) mcc. Please note that values of greater than 1 are possible in these images, as the quantity shown is the
arithmetic sum of high \((hcc)\) and mid-level \((mcc)\) cloud cover amounts (the maximum possible value is \(= 2\); the minimum possible value is \(= 0\)). The choice of the four individual months in Figure 6.2.1 highlights the main differences between the seasons.

Figure 6.2.1: Mean 1976-2002 ERA40 global night-time sum of high cloud and mid-level cloud amounts for (a) January (b) April (c) July, and (d) October. For a definition of 'night-time', please see the text. The value for each pixel shown is the arithmetic sum of \(hcc+mcc\); thus the maximum possible value \(= 2\), and the lowest possible value is \(= 0\).

Figure 6.2.2: Approximate mean annual (mean of January, April, July, October) 1976-2002 ERA40 global 'night-time' cloud cover fraction for (a) high cloud \((hcc)\) (b) mid-level cloud \((mcc)\). For a definition of 'night-time', please see the text. The cloud cover fraction is the % of cloud cover divided by 100.
The main features of Figures 6.2.1 and 6.2.2 confirm the most cloud-free elevated (>2,000 metres) regions of the earth and seem to justify the non-coincident locations of the world's currently largest astronomical sites (except perhaps Hawaii). These observatories are essentially concentrated in four regional zones or 'tongues' which can be identified in Figures 6.2.1 and 6.2.2, and are namely (i) the south-east Pacific and northern Chile coastal zone (ii) Namibia and south-west Africa coast (iii) coastal California (USA and Mexico) and (iv) Canary Islands and western Morocco. Regular oscillations in the degree of cloudiness occur between the seasons (Figure 6.2.1), although the Namibian zone appears to be remarkably persistent all year round. In fact, it is a somewhat surprising result that the most cloud-free region above 2000 metres in the world lies near coastal Namibia and over the south-east Atlantic Ocean; it is actually less cloudy than the Atacama desert of northern Chile. However, frequent low cloud and stratus plague these coastal regions near the sea surface; a high mountain summit is a pre-requisite to penetrate these stable surface layers. Some increase in hcc near these regions might be expected due to the formation of orographic cirrus over nearby mountains.

Furthermore, it can be noted from Figures 6.2.1 and 6.2.2 that a fifth zone of very low hcc and mcc, stretching roughly from Egypt to Pakistan (referred to from now on as the “Arabic“ zone) is particularly evident, especially during the summer half of the year. There are many mountains above 2000 metres in this zone, but few astronomical observatories. The deficiency in large telescopic facilities suitable for research across the Arabian peninsula has already been noted by Sultan and Graham (2005).

**6.2.2 Diurnal range in cloudiness**

As a converse to the procedure outlined above for the calculation of 'night-time' maps, the maximum value of each pixel (as opposed to the minimum) may be taken in turn, yielding an map of approximative 'afternoon cloudiness'. Then, subtraction of a 'night-time' map from an 'afternoon' map yields the approximate magnitude of the diurnal range in cloudiness for any global pixel. An example of such maps are shown for high and mid-level cloud in Figures 6.2.3(a) and (b), respectively. Interestingly, these maps double as (i) an indicator of sites where the the diurnal range in cloud cover is extremely stable (low values, blue colours, e.g. northern Chile coast, Namibian coast) and (ii) where the diurnal cycle in
convection is especially strong (high values, orange colours e.g. Amazonia, central Africa). Areas where the diurnal range in cloudiness are great are most likely to have conditionally unstable atmospheres; on the other hand, areas where diurnal range in cloudiness are negligible indicate, either (a) there is a very stable atmosphere both day and night, or (b) it is very unstable both day and night. The same five areas already mentioned can also be seen to be areas of great stability.

Overall, diurnal ranges in hcc exceed those of mcc. This is to be expected, since the amount of high cloud in the atmosphere generally exceeds that of mid-level cloud (Figure 6.2.2). This is because convection and uplift are constrained at the tropopause and the horizontal spreading-out of cloud (e.g. cirrus anvils) occurs. The fact that the coastal Namibia and Chile have such low values in Figure 6.2.3 confirms that diurnal changes in cloudiness, particularly mcc, are nearly negligible here. Interestingly also from Figure 6.2.3, from a climatological point-of-view, is that the southern hemisphere generally shows a lower values in the diurnal range of hcc and mcc cloudiness than its northern counterpart; this may be because of a greater percentage of continental landmasses in the northern hemisphere, or it could be because of inaccuracies in the ERA40 model due to a lack of observations in southern hemisphere (see Chapter 1 also).

![Figure 6.2.3: Mean 1976-2002 global ERA40 diurnal range (difference between 'night-time' and 'daytime') cloud amount for (a) high cloud cover (hcc) (b) mid-level cloud cover (mcc). For definitions of 'night-time' and 'daytime', please see the text.](image)

### 6.2.3 Hovmöller plots at 30°N and 25°S

It is noted from Figures 6.2.1 and 6.2.2 that the most cloud-free mid-to-upper troposphere regions of the earth are rather conveniently located along the latitude axes of
approximately 30°N and 25°S (although some north / south oscillation occurs with the seasons). They are located along these axes because they represent the descending arms of the global Hadley cell circulations, perennial features of the sub-tropical latitudes (the northern hemisphere cloud-free zone is located slightly further away from the equator than its southern counterpart because the mean effective “thermal” equator is shifted north of 0° latitude, due to the shape and position of Africa and the other continents). Therefore, it is worthwhile investigating whether plots of cloud cover at the fixed latitudes 30°N and 25°S through time may reveal any additional information about the spatial-temporal patterns of global cloud cover. Such time-longitude plots are known as Hovmöller plots.

Figure 6.2.4: Hovmöller plot (time versus longitude) of the sum of ERA40 high and mid-level cloud cover amounts at 30° latitude north, from 1995 to 2000. The approximate locations of Egypt, the
Himalaya, California and La Palma (Canary Islands) are marked on the X-axis.

Figure 6.2.4 and 6.2.5 show Hovmöller plots of the sum of hcc+mcc for the period 1995 to 2000 for the latitudes of 30°N and 25°S, respectively. The period 1995 to 2000 was chosen because, being relatively short, it is easier to display but it also accompanies a period of both strong El Niño and La Niña oscillations. The 1995 to 2000 period also covers the most accurate years of the ERA40 reanalysis.

Figure 6.2.5: Hovmöller plot (time versus longitude) of the sum of ERA40 high and mid-level cloud cover amounts at 25° latitude south from 1995 to 2000. The approximate locations of Namibia, Australia and Chile are marked on the X-axis.

Longitudinally travelling waves through time may be identified on Hovmöller plots where
gradient features exist either sloping to the left or right. For example, in Figure 6.2.4 between 60°W and 0°W (‘La Palma’), the main cloud-free summer-time period is bordered to the west by decreasing and increasing cloud amounts during respective springs and autumns of each year. The slope of these gradients indicate that decreasing cloud amounts move westwards from the east during the spring, whilst increasing cloud amounts move in from the west (eastwards) during the autumn. A similar pattern seems to occur off coastal California. Other features apparent from Figure 6.2.4 are the very large spatio-temporal extent of low hcc+mcc across the 'Arabic' zone, and the cyclical onset/decay of the monsoon over the Himalaya each year. Overall, the patterns of 'La Palma' and 'Arabian' cloudiness seem remarkably stable through time over this period of six years, although slight increases in 'California' cloudiness during the summers of 1999 and 2000 seem to be simultaneous (i.e. teleconnected) with increased springtime cloudiness in the eastern Pacific and increased autumnal cloudiness in the sub-tropical Atlantic.

Meanwhile, Figure 6.2.5 shows the same type of Hovmöller plot, but for the fixed latitude of 25°S. The spatio-temporal patterns of northern Chile and coastal Namibian appear remarkably stable and persistent throughout the analysed period. There is a hint that increased sub-tropical South Pacific cloudiness during the winters of 1999 and 2000 impact slightly on the western boundary of the 'Chilean' zone, but do not effect the Chilean mainland. Further west, a smaller spatio-temporal extent of cloud-free skies stretches across the southern Indian Ocean towards La Réunion island, but it is not as cloud-free as the other aforementioned zones.

6.2.4: Standard deviations of cloud cover

Figure 6.2.6 (a) shows the standard deviation of the twelve monthly means (calculated over 1989-2002) of the sum of ERA40 high and mid-level cloud cover (sum of hcc+mcc). This first image gives an indication of the degree of variability of mid-to-upper tropospheric cloud for each pixel from month-to-month within any given year. The highest values are located mostly in the tropical monsoon regions and in other areas showing a large seasonality in cloudiness. Note that only a small region of northern Chile exhibits low values, with higher values to the south but especially to the north (Bolivian and Peruvian monsoons). Coastal Namibia also lies near the boundary of two zones of highly differing variability. Much lower variability occurs over the southern Oceans than in the northern hemisphere, for perhaps the same reasons as mentioned in section 6.2.2.
Figure 6.2.6: (a) Standard deviation of monthly means of the sum of ERA40 high and mid-level cloud cover (hcc+mcc), calculated using FriOWL-v3.1 over the period 1989-2002. This first image highlights inter-monthly variability; (b) Standard deviation of yearly means of hcc+mcc over the period 1989-2001. This latter image highlights areas of interannual variability. Note that India and the Himalaya exhibit high variability in (a) but low variability in (b).

Meanwhile, Figure 6.2.6 (b) shows the standard deviation of the yearly means of the sum of ERA40 hcc+mcc from 1989 to 2001. This image is different from that shown in (a) because it highlights the variability of cloud for each pixel from year-to-year, rather than from within each year. Most prominent in this image is the strong El Niño signal over the tropical south Pacific Ocean, but reasonably low values over practically the whole of the northern hemisphere. Note that India and the Himalaya exhibit high variability in (a) but low variability in (b), meaning that each year there are great variations in cloudiness between the dry and wet seasons, but that these changes occur with much the same extent every year.

6.2.5: Cloud cover animations

Three different animations of global cloud cover are provided for viewing on the FriOWL-v3.1 website†, and these help to give further insight into the spatio-temporal patterns of global cloudiness and their relevance for astronomical site selection. The first movie is an ERA-15 animation of mean monthly total cloud cover (tcc), as calculated for the period 1979-1993. Please note that, in this case, the tcc variable includes all low, mid-level and high cloud covers (hcc, mcc, lcc), although it is not their direct sum (as explained in Chapter 3). Note the remarkable singularity of northern Chile throughout the seasons. The 'Arabic' zone and Antarctica ice cap are also worthy of attention.

† http://www.iapmw.unibe.ch/research/projects/FriOWL/friowl_users_guide.php
The second animation is similar to the previous, except it is using ERA40 \textit{hcc+mcc} data only, and the maps have been calculated over the most accurate 1989-2002 period of the ERA40 reanalyses. The remarkable persistence of the mid-to-upper troposphere cloud-free zone near the Namibian coast is dominant. During the northern summer, the mid-to-upper troposphere of the Arabic zone near Sinai and the Gulf of Aqaba is the most cloud-free region in the world. Interestingly, a longitudinally travelling wave of cloud-free skies moves westwards across Australia during the latter half of the year.

The final cloud movie is an animation of twelve ERA40 mean monthly standard deviations of \textit{hcc} only, calculated over the period 1989-2001. This animation attempts to show the long-term stability of each month's high cloud cover for each pixel on the earth. Whilst there seems to be a considerable degree of random noise in most of these images, the signal near Namibia appears more stable (low values = blue colours) than its Chilean counterpart. There is an indication of two hemispheric eastward propagating (longitudinal) waves during the second half of the year; the first one begins in June over the Canary Islands travelling eastwards to the Himalaya by December; the second starts over Namibia in June and moves eastwards to Australia by October.

\textbf{6.2.6: E-ELT CANDIDATE REGIONS CLOUD COVER SUMMARY TABLE}

Finally, Table 6.2.1 presents estimated values of mean, minimum, maximum and standard deviation \textit{hcc+mcc} for the fourteen E-ELT candidate regions, as calculated using \textit{FriOWL-v3.1} ERA40 data. The maximum, minimum and standard deviation values are given here in an attempt to compare the seasonality of the different regions. Direct estimations of cloud cover for each of the original nineteen previously identified E-ELT sites (given in Table 6.1.1) is not attempted here, since the pixel size of the re-analysis product (2.5° square) is several orders of magnitude larger than each individual mountain peak. Instead, the presented values should be treated more as 'regional' estimates of the cloud cover near these sites. Furthermore, as stated before in Chapter 3, because of the ERA40 model's incapability to effectively estimate true cloudiness, all cloud data should be treated with caution and this table should serve only as a moderately reliable guide.
<table>
<thead>
<tr>
<th>Region</th>
<th>FriOWL pixel used (lat, lon)</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dome C (Antarctica)</td>
<td>(-75.0, 122.5)</td>
<td>0.36</td>
<td>0.52</td>
<td>0.24</td>
<td>0.10</td>
</tr>
<tr>
<td>2 La Réunion</td>
<td>(-20.0, 55.0)</td>
<td>0.35</td>
<td>0.57</td>
<td>0.19</td>
<td>0.13</td>
</tr>
<tr>
<td>3 Namibian escarpment</td>
<td>(-22.5, 15.0)</td>
<td>0.13</td>
<td>0.28</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td>4 Hawaii islands</td>
<td>(20.0, -155.0)</td>
<td>0.34</td>
<td>0.45</td>
<td>0.28</td>
<td>0.04</td>
</tr>
<tr>
<td>5 North-Atacama</td>
<td>(-22.5, -70.0)</td>
<td>0.08</td>
<td>0.15</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>6 Mid-Atacama</td>
<td>(-25.0, -70.0)</td>
<td>0.07</td>
<td>0.10</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>7 South-Atacama</td>
<td>(-30.0, -70.0)</td>
<td>0.20</td>
<td>0.30</td>
<td>0.14</td>
<td>0.06</td>
</tr>
<tr>
<td>8 Canary Islands</td>
<td>(27.5, -17.5)</td>
<td>0.15</td>
<td>0.30</td>
<td>0.01</td>
<td>0.09</td>
</tr>
<tr>
<td>9 Anti-Atlas, Morocco</td>
<td>(30.0, -10.0)</td>
<td>0.17</td>
<td>0.32</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>10 Tibetan plateau</td>
<td>(30.0, 90.0)</td>
<td>0.70</td>
<td>1.21</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>11 Baja California</td>
<td>(30.0, -115.0)</td>
<td>0.16</td>
<td>0.32</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td>12 Hanle (Indian Himalaya)</td>
<td>(32.5, 80.0)</td>
<td>0.29</td>
<td>0.46</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>13 Uzbekistan (Himalaya)</td>
<td>(37.5, 67.5)</td>
<td>0.36</td>
<td>0.61</td>
<td>0.09</td>
<td>0.21</td>
</tr>
<tr>
<td>14 Greenland Summit</td>
<td>(72.5, -37.5)</td>
<td>0.58</td>
<td>0.69</td>
<td>0.47</td>
<td>0.07</td>
</tr>
<tr>
<td>* Sinai peninsula</td>
<td>(30.0, 32.5)</td>
<td>0.12</td>
<td>0.23</td>
<td>0.00</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 6.2.1: Summary table of high and mid-level cloud cover (hcc+mcc) for the 14 E-ELT candidate regions, plus an additional Sinai peninsula location (not originally listed as an E-ELT candidate site). The values presented are regional estimates based on the value of the 2.5° square pixel co-ordinate location indicated in the 3rd column from left. The mean annual hcc+mcc value, the maximum of the 12 monthly hcc+mcc means, the minimum of the 12 monthly hcc+mcc means, and the standard deviation of the 12 monthly hcc+mcc means, are given in the adjoining columns to the right. All values are calculated using FriOWL-v3.1 ERA40 data over the period 1989-2002.

Despite these limitations, valuable conclusions can still be drawn from Table 6.1.1. The remarkably low values in all four columns of the Table for northern Chile (especially mid- and northern Atacama) confirm its destination as the site for many of the world's largest and most expensive telescope projects to date. These values are borne out by the official photometric night percentages for ESO's Paranal and La Silla observatories (data available from ESO's Astroclimatology Website†), which reach 75% at Paranal (24.4°S, 70.2°W) and 62% at La Silla (29.2°S, 70.4°W) over the 23-year period 1983 to 2006. Using these data, we can estimate that 5% increase in the (sum of) hcc+mcc leads to an approximate 10% decrease in photometric night fraction; these statistics will be examined further in a separate study on the astroclimatology of Paranal and La Silla (see FriOWL-v3.1 Website‡).

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† http://www.eso.org/gen-fac/pubs/astclim/paranal/clouds/
‡ http://www.iapmw.unibe.ch/research/projects/FriOWL/friowl_users_guide.php
The earlier Figures 6.1.1 and 6.12 showed that coastal Namibia has the least amount of mid-to-upper tropospheric cloud anywhere on the earth. However, the given values for this region in Table 6.1.1, although still astonishingly low, are somewhat higher than the north and mid-Atacama Chilean sites and are more equivalent to those of Canary Islands, Morocco and Baja California. This is because the pixel chosen to represent the Namibian escarpment (Gamsberg, 22.5°S, 15°E) lies slightly inland and off-centre from the main cloud-free area (the absolute lowest $hcc+mcc$ value of 0.03 occurs over the sea at 22.5°S, 7.5°E), and the mean cloud cover fraction increases rapidly with increasing distance inland from the sea in Namibia. Also, the very low values for the Gamsberg area are not borne out by the mean photometric night statistics of Straub (1994) and Neckel (1982), published in Sarazin (1994), from which a mean annual photometric night fraction of only 53.5% can be calculated, based on limited data from 1970 to 1975.

The values for La Réunion island, Hawaii and the Himalayan sites are fairly good, but are essentially upper second-class, because larger seasonal oscillations in cloud cover occur at these locations. The high mean and maximum values for the Tibetan plateau are caused by a bias of extremely high cloud amounts there during the summer monsoon season, but all of the Himalayan sites are reasonably cloud-free during the winter half-year. In the absence of ground truth information for Tibet, it is difficult to quantify the accuracy of the ERA40 model in this highly mountainous region.

The values for Antarctica (Dome C) and Greenland Summit are rather unimpressive, especially in the case of Greenland. Indeed, orographic cirrus can often be seen streaming off the Greenland ice cap almost daily on satellite pictures; these are usually optically thin, allowing the summit to remain rather a sunny place during summer (Scorer, 1988), but would probably be detrimental for astronomical observation. As for Antarctica, the reliability of the ERA40 model's parameterisations of ice-clouds in this intensely cold, data-sparse continent is unknown. Incidentally, the author has noted that ERA40 seems to produce more cloud over Antartica than its less accurate predecessor, ERA15.

Penultimately, a special row of data has been added to bottom of Table 6.1.1, which includes data for the pixel (30.0°N, 32.5°E), located over the mountainous region of the Sinai peninsula of Egypt and nearby Arabian Hejaz mountains above the Gulf of Aqaba (Eilat in Israel) where many mountain peaks reach over 2,000 metres in altitude (2.629
metres at Mount St. Catherine, highest mountain in Egypt). Overall cloud statistics for this pixel compare favourably with those of Namibia and the northern Atacama. Indeed, this 'Arabic' pixel is the only location on earth to report effectively zero cloud during the summer months. This area deserves further investigation by ESO.

It is also recommended that ESO commence investigations, albeit preliminary, into the isolated coastal peak of Brandbergmassif (Königstein), about 250 km north-west of Gamsberg, which reaches a height of 2606 metres (the highest point in Namibia). This region deserves close monitoring as it lies closer to the sea than Gamsberg and slightly nearer the centre of cloud-free skies. However, it may have a stronger and more powerful monsoon during the wet season than Gamsberg and a greater frequency of (detrimental) easterly winds because of its more northerly location. Unfortunately, the island of St. Helena (15.9°S, 5.7°W), which lies directly under the area of lowest \( hcc + mcc \) (mean value = 0.07), reaches only to 818 metres at its highest point, and is likely to be plagued by fog and low clouds; if it had higher mountains, it would be a prime candidate site.

Finally, FriOWL-v3.1 has the capability to make monthly mean anomaly cloud maps, which can be very informative, showing teleconnection links between regional and continental-scale positive and negative anomalous features. Examples of such maps will be shown in the accompanying applied study of FriOWL-v3.1 “The Paranal-La Silla Astroclimatology Report“.
6.3: **Integrated Water Vapour (IWV) Analyses**

In this section, we make analyses of integrated water vapour (IWV) for E-ELT site study purposes, using data mostly from the levels of 500 hPa (iwv500) and 700 hPa (iwv700). These particular levels are chosen, because they correspond to the approximate upper and lower altitude limits of candidate E-ELT sites. Only data from the post-satellite period of the ERA40 re-analysis (1976-2001) are used in this study, due to inhomogeneity concerns in the global specific humidity dataset, as expressed earlier in Section 3.4.4.

6.3.1: **Mean Global IWV and Variability**

![Figure 6.3.1: FriOWL-v3.1 maps of (a) mean annual (1976-2001) ERA40 IWV at 700 hPa; (b) mean annual (1976-2001) ERA40 IWV at 500 hPa. Please note different scales for both images.](image)

Figures 6.3.1 (a) and (b) show the mean annual ERA40 IWV at the 700 and 500 hPa levels, respectively. Whilst IWV amounts (kg/m² or mm) are obviously much greater at the 700 hPa level (left), the distributional pattern of global IWV remains much the same at both levels. Of particular note are the four reasonably symmetric 'tongues' of relatively low water vapour, stretching equator and westwards, located on the eastern flanks of the zones of four main sub-tropical high pressure circulations (namely Aleutian high, Azores high, south-east Pacific high and south-east Atlantic high); the location of these 'tongues' has already been noted in the previous section on clouds (6.2). Also of great prominence are the extremely low mean IWV values over Antarctica, which contribute to a very low infra-red background sky radiation there, by far the lowest on earth (Chamberlain, 2000).

Animations of global ERA40 monthly mean iwv700 and iwv500 values, and NCEP/NCAR total column precipitable water are provided on the FriOWL-v3.1 Website† (click on ‘User Guides / Documentation -> Animations’). These show the regular north-south movement of

global IWV with the seasons; Antarctica and northern Chile are remarkable exceptions to a generally marked seasonal cycle. Of particular interest in the iwv500 movie is the area around Egypt and the Sinai Peninsula, which actually becomes slightly drier during the northern summer, despite the movement north of the monsoon into southern Arabia at this time (presumably due to a stronger Hadley cell circulation).

![Image](image1.png)

**Figure 6.3.2**: FriOWL-v3.1 maps of (a) standard deviation of mean monthly ERA40 iwv700 (1976-2001) and (b) standard deviation of mean monthly ERA40 iwv500 (1976-2001).

Figures 6.3.2 (a) and (b) show the standard deviations of mean monthly iwv700 and iwv500, respectively (i.e. the monthly means for each of the twelve months were calculated using 1976-2001 period, then the standard deviation of these twelve months was taken). These maps show the areas of greatest and lowest IWV variability throughout the year. Again, one of the most distinct features of these maps are the same four symmetric 'tongues' of very low variability, located on the eastern flanks of the equatorward moving air of the four main sub-tropical high pressure systems (i.e. the descending arms of each Hadley Cell circulation, as said before). Also of prominence again is an area of low variability centred near Egypt and the Sinai peninsula, particularly at 500 hPa. Likewise, exceptionally low IWV values all-year-round on Antarctica contribute to almost negligible variability there.

Meanwhile, Figure 6.3.3 (a) shows a reclassified FriOWL-v3.1 map, highlighting only areas where the mean annual iwv700 is less than a threshold of 4 mm. Again, note the overwhelming prominence of the four 'tongues' of low IWV, again stretching equatorwards and westwards. It is of no co-incidence that these tongues are located over regions of cool, upwelling equatorward-moving sea currents on the western sides of the main continents, and that many of the world's current largest astronomical observatories are located in areas near these 'tongues'. It is of interest, however, that the tongue on the eastern side of
the Aleutian high, although crossing the mountains of California, does not stretch
completely over either Hawaii (Mauna Kea observatory) or Baja California (San Pedro Martir
observatory). Likewise, the tongue over the south-east Atlantic does not quite stretch over
Namibia (Gamsberg site). However, all of the Chilean sites lie within their respective
'tongue', as do the Canary Island observatories of La Palma and Tenerife (although not
Morocco). Particularly interesting, however, and evident from Figure 6.3.3 (a) is the
separate tongue over Egypt, the Sinai Peninsula, Jordan and north-western Arabia (the
'Arabic' zone) where several mountain ranges reach over 2000 metres in height (2,637 m
at Mt. St. Catherine).

Figure 6.3.3: FriOWL-v3.1 maps showing (a) only locations where mean annual IWV at 700 hPa is
less than 4 mm (yellow) and greater than 4 mm (blue); (b) only areas of the globe where mean
annual (1991-2000) ERA40 vertical velocities exceed 2.5 cm/sec (descent); these are indicated by
green / yellow/ red colours; purple colors indicate areas where mean annual vertical velocities are
less than 2.5 cm/sec or negative (ascent).

Figure 6.3.3 (b) is a FriOWL-v3.1 reclassified map of the mean annual (1991-2000 in this
case) ERA40 vertical velocity, but showing only areas of the globe where it exceeds a value
of 2.5 cm/sec (a positive value means the air is sinking, and vice versa). Notice the
remarkable similarity between images (a) and (b), although both maps are showing entirely
different meteorological variables. As well as the usual four 'tongues', large areas of
descending air can be seen near Egypt and the Sinai (again), as well as to the west of
Australia (but no mountains). Of meteorological interest in Figure 6.3.3(b) are the extreme
positive values (red colours) near the edges of the Greenland and Antarctica ice caps – due
to large scale katabatic wind drainage. Less apparent, but also evident, are zones of
descent to the lee of the Rocky and Appalachian mountains in North America and also to
the lee of the Patagonian highlands in South America. Gently descending air usually means


dry air means stable air; that is why there is such good correlation between images (a) and (b) in this case.

Finally, maps of monthly IWV anomalies are easily created with FriOWL-v3.1 (an example was shown in Figure 2.4). Such maps may yield valuable information on regional or even continental wide variability of IWV over inter-monthly and interannual timescales, as monthly and annual IWV anomalies are strongly controlled by the prevailing synoptic pattern (particularly at higher levels in the atmosphere). Some further examples will be shown in a separate applied study entitled “The Paranal and La Silla Astroclimate Report”.

### 6.3.2: Estimated Mean Annual IWV for E-ELT candidate sites

<table>
<thead>
<tr>
<th>Site (Region)</th>
<th>Alt. of site (m)</th>
<th>Est. site pressure (hPa)</th>
<th>Pressure level used (hPa)</th>
<th>Est. mean IWV (mm)</th>
<th>Est. std. dev. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dome C (Antarctica)</td>
<td>3233</td>
<td>651</td>
<td>650</td>
<td>0.4</td>
<td>0.23</td>
</tr>
<tr>
<td>2 La Réunion Island</td>
<td>2896</td>
<td>719</td>
<td>720</td>
<td>6.4</td>
<td>3.46</td>
</tr>
<tr>
<td>3 Namibia (Gamsberg)</td>
<td>2347</td>
<td>760</td>
<td>760</td>
<td>7.3</td>
<td>3.45</td>
</tr>
<tr>
<td>4 Mauna Kea (Hawaii)</td>
<td>4580</td>
<td>593</td>
<td>590</td>
<td>2.0</td>
<td>0.34</td>
</tr>
<tr>
<td>5 Tolar (North-Atacama)</td>
<td>2290</td>
<td>763</td>
<td>760</td>
<td>4.4</td>
<td>1.87</td>
</tr>
<tr>
<td>6 Chajnantor (North-Atacama)</td>
<td>5100</td>
<td>555</td>
<td>550</td>
<td>1.2</td>
<td>0.43</td>
</tr>
<tr>
<td>7 Macon (Mid-Atacama)</td>
<td>5000</td>
<td>561</td>
<td>560</td>
<td>1.1</td>
<td>0.22</td>
</tr>
<tr>
<td>8 Armazones (Mid-Atacama)</td>
<td>3064</td>
<td>705</td>
<td>710</td>
<td>2.9</td>
<td>0.72</td>
</tr>
<tr>
<td>9 Paranal (Mid-Atacama)</td>
<td>2636</td>
<td>737</td>
<td>740</td>
<td>3.4</td>
<td>0.89</td>
</tr>
<tr>
<td>10 La Chira (Mid-Atacama)</td>
<td>2559</td>
<td>743</td>
<td>740</td>
<td>3.4</td>
<td>0.89</td>
</tr>
<tr>
<td>11 La Silla (South-Atacama)</td>
<td>2400</td>
<td>753</td>
<td>750</td>
<td>4.8</td>
<td>0.83</td>
</tr>
<tr>
<td>12 La Palma Island</td>
<td>2396</td>
<td>757</td>
<td>760</td>
<td>4.7</td>
<td>1.69</td>
</tr>
<tr>
<td>13 Tenerife Island</td>
<td>2367</td>
<td>759</td>
<td>760</td>
<td>4.7</td>
<td>1.69</td>
</tr>
<tr>
<td>14 Lekst (Anti-Atlas, Morocco)</td>
<td>2359</td>
<td>759</td>
<td>760</td>
<td>5.6</td>
<td>1.94</td>
</tr>
<tr>
<td>15 Yanbajing (Tibetan plateau)</td>
<td>4500</td>
<td>594</td>
<td>590</td>
<td>6.4</td>
<td>5.06</td>
</tr>
<tr>
<td>16 San Pedro Martir (Baja California)</td>
<td>2980</td>
<td>711</td>
<td>710</td>
<td>4.7</td>
<td>2.75</td>
</tr>
<tr>
<td>17 Hanle (Indian Himalaya)</td>
<td>4500</td>
<td>595</td>
<td>590</td>
<td>6.1</td>
<td>4.63</td>
</tr>
<tr>
<td>18 Maidanak (Uzbekistan Himalaya)</td>
<td>2600</td>
<td>738</td>
<td>740</td>
<td>6.1</td>
<td>2.31</td>
</tr>
<tr>
<td>19 Greenland Summit</td>
<td>3225</td>
<td>669</td>
<td>670</td>
<td>1.5</td>
<td>0.94</td>
</tr>
<tr>
<td>*Sinai (Mt. St. Catherine)</td>
<td>2637</td>
<td>736</td>
<td>740</td>
<td>3.6</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Table 6.3.1: Estimated mean annual ERA40 IWV (2nd column from right, in bold) and standard deviation of mean monthly IWV (far-right column, italics) for the nearest FriOWL-v3.1 pixel of all nineteen E-ELT candidate sites (plus an additional proposed Sinai Peninsula location at 30°N, 32.5°E). For the latitude / longitude co-ordinates of each pixel, see Table 6.1.2. All values have been calculated over the period 1976-2002. See text for more information on how the IWV values were
estimated.

Meanwhile, Table 6.3.1 attempts to summarise the IWV for all nineteen candidate E-ELT regions by providing estimates of the mean annual IWV and standard deviation of mean monthly IWV. Please note that, although values for each individual site are given here per se, great caution should be applied before treating them as such. Instead, they should be considered rather as estimates for the broad region surrounding each site, because the pixel size (2.5° square) from which the IWV value is calculated is several orders of magnitude larger than each individual mountain peak. Therefore, the given IWV values may not be representative of single site location, particularly where there are strong sub-gridscale local or orographic effects. The two exceptions to this rule are the ice cap locations of Greenland and Antarctica; here the surface topography is very gentle and smooth, even at spatial scales of much larger than 2.5° square.

The IWV values in Table 6.3.1 were calculated as follows: Firstly, estimation of the mean IWV for each individual summit required prior knowledge of the mean summit air pressure. This was calculated for each of the candidate E-ELT sites by interpolating between the values of mean annual geopotential height of the 500 and 700 hPa levels (these data are available in the FriOWL-v3.1 database). The resulting estimated mean annual air pressures are shown in the 4th column from left in Table 6.3.1. Then, using this mean summit pressure value (rounded to the nearest 10 hPa; 5th column in Table 6.3.1), the IWV was estimated by linearly interpolating between the IWV values at the 500, 600, 700 or 800 hPa levels. The results, expressed as an annual mean and standard deviation of mean monthly IWV, are presented in far-right-most two columns of Table 6.3.1. Please note that although standard deviation values are given, it is quite common for IWV distributions to be skewed towards higher values.

It is difficult to estimate the magnitude of error in these given estimates without precise observations of mean summit air pressure for each site. Such observations are available for only a limited number of sites; the given values in Table 6.3.1 for Paranal, La Silla and San Pedro Martir show agreement to within ± 0-30 hPa of observed mean annual air pressures of 743, 773 and 746 hPa, respectively (ESO ambient conditions database†; Michel, 2003). For La Silla, an error of ± 20 hPa results in an IWV error of approximately ± 0.4 mm. Other

† http://archive.eso.org/asm/ambient-server
sources of errors, such as poor representation of surface effects in the ERA40 model (due to sub-gridscale topography within each 2.5° square) are potentially large.

Nevertheless, the results shown in Table 6.3.1 broadly confirm the general knowledge that the IWV depends on latitude and altitude, with the lowest values found at the highest or most poleward regions. An exception to this are the Himalayan sites of Ynbajing (Tibet) and Hanle (India) which, due to the very high elevation of the area and a strongly marked summer monsoon, mean and standard deviation IWV values are greater than would be expected for these altitudes (although the accuracy of the ERA40 model in this highly mountainous region has not been validated here). Overall, the results are in reasonably good agreement with the published results of mean annual IWV for Paranal (2.9 mm; ESO Astroclimatology Website†), La Silla (6.3 mm; ESO Astroclimatology Website), Chajnantor (0.68 mm; Sarazin et al., 2006) and Gamsberg (6.1 mm; Sarazin, 1994). Of particular note from Table 6.3.1 are the extremely low values (~1 mm) and low variability at the ~5000 metre sites in Chile; they even show more stability than the correspondingly harsher environment of Greenland summit at just 3200 metres. The values for a potential site on the summit of Mt. St. Catherine (Sinai, Egypt) are very impressive; they are almost comparable with those of the mid-Atacama. Also of note are the relatively high values for the Namibian escarpment (Gamsberg), more twice the amount measured at Paranal. This has already been noted by Sarazin (1994). So, although coastal Namibia has the most cloud-free mid-to-upper troposphere in the world (see section 6.2 on clouds), it does not have the lowest IWV, far from it. The slightly greater amounts of cloud in Chile are probably due to a higher incidence of jetstream cirrus clouds, where saturated vapour pressures are extremely low anyway, and contribute little to the overall IWV.

6.3.3: Estimated IWV at fixed 700 hPa altitude for E-ELT Candidate Regions

Finally, it is worthwhile to compare the IWV for different worldwide sites at a fixed altitude at 700 hPa. Such a comparison imposes a “level playing field” between different candidate regions around the world, and gives a rough answer to the question “What is the IWV for each site, assuming they are at the same height?” . Estimated mean annual, maximum and minimum of monthly means, and standard deviation of monthly means of IWV at 700 hPa are presented in Table 6.1.2. Please note that values for the 500 hPa level are given instead of 700 hPa for the two high altitude Himalayan regions of Tibet and Hanle (this is because

† http://www.eso.org/gen-fac/pubs/astclim/paranal/h2o/
the 700 hPa level lies below the surface at these locations).

The results show that, with the exception of the very low Antarctica and Greenland values, that the traditional mid-Atacama sites of around 3000 metres in altitude have the lowest 700 hPa IWV anywhere in the world. However, if one could reach to 700 hPa on the Sinai Peninsula, similar values to those estimated for northern Chile could be attained (the highest mountain on the Sinai, Mt. St. Catherine, is around \(-740\) hPa). One needs to ascend to perhaps 3500-4000 metres to obtain similar IWV values at the other mid-latitude sites (e.g. San Pedro Martir), and possibly as high as 5700 metres (the mean geopotential height of the 500 hPa level) in the Himalaya for similar mean annual values.

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Dome C (Antarctica)</td>
<td>0.6</td>
<td>1.1</td>
<td>0.3</td>
<td>0.31</td>
</tr>
<tr>
<td>2 La Réunion</td>
<td>5.7</td>
<td>10.2</td>
<td>2.1</td>
<td>3.15</td>
</tr>
<tr>
<td>3 Namibian coast</td>
<td>5.1</td>
<td>9.3</td>
<td>1.8</td>
<td>2.55</td>
</tr>
<tr>
<td>4 Hawaii Islands</td>
<td>4.1</td>
<td>5.2</td>
<td>3.2</td>
<td>0.69</td>
</tr>
<tr>
<td>5 North-Atacama</td>
<td>3.2</td>
<td>5.4</td>
<td>2.0</td>
<td>1.30</td>
</tr>
<tr>
<td>6 Mid-Atacama</td>
<td>2.7</td>
<td>3.9</td>
<td>2.1</td>
<td>0.67</td>
</tr>
<tr>
<td>7 South-Atacama</td>
<td>3.5</td>
<td>4.5</td>
<td>2.9</td>
<td>0.53</td>
</tr>
<tr>
<td>8 Canary Islands</td>
<td>3.5</td>
<td>5.8</td>
<td>2.2</td>
<td>0.78</td>
</tr>
<tr>
<td>9 Anti-Atlas, Morocco</td>
<td>4.1</td>
<td>7.0</td>
<td>2.7</td>
<td>1.47</td>
</tr>
<tr>
<td>10 Tibetan plateau* (500 hPa)</td>
<td>3.4</td>
<td>7.6</td>
<td>0.7</td>
<td>2.65</td>
</tr>
<tr>
<td>11 Baja California</td>
<td>4.4</td>
<td>9.6</td>
<td>2.5</td>
<td>2.59</td>
</tr>
<tr>
<td>12 Hanle (Himalaya)* (500 hpa)</td>
<td>2.9</td>
<td>7.2</td>
<td>0.9</td>
<td>2.14</td>
</tr>
<tr>
<td>13 Uzbekistan (Himalaya)</td>
<td>4.7</td>
<td>7.5</td>
<td>2.7</td>
<td>1.66</td>
</tr>
<tr>
<td>14 Greenland Summit</td>
<td>1.7</td>
<td>3.8</td>
<td>0.7</td>
<td>1.11</td>
</tr>
<tr>
<td>Sinai Peninsula (30°N, 32.5°E)</td>
<td>2.8</td>
<td>4.2</td>
<td>2.1</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table 6.3.1: Estimated mean annual, maximum and minimum mean monthly values, and standard deviation of monthly means of ERA40 IWV at 700 hPa (iww700) for each of the 14 E-ELT candidate regions. The object of this table is to show the IWV at a fixed altitude of 700 hPa for all of the different locations around the world. IWV values at 500hPa are shown for Tibet and Hanle locations, (because 700 hPa is below the surface here).

Please note again, that the results of these analyses should be treated with caution. For example, the North-Atacama region shows slightly higher values than the mid-Atacama (especially in absolute monthly mean maximum and standard deviation); as far as the
author is aware these are not reflected in reality (personal communication with M. Sarazin; 2005), and may be the consequence of the very large (sub-gridscale) IWV gradient between the Chilean and Bolivian side of the Andes, which the ERA40 model “smoothes” in its 2.5° re-analysis.

Finally, values of the 10th, 50th and 90th percentiles of IWV could be calculated for each site using ERA40 00, 06, 12 and 18 UTC daily values. Unfortunately, FriOWL-v3.1 does not contain IWV data at such temporal resolution; but this could be accomplished at a later time if required. In addition, a better way to show IWV variability might through the plotting of maps of the percentage variation of IWV, rather than using standard deviation (e.g. where IWV values are low, standard deviations will always be low too; plotting percentage variation of IWV would eliminate this constraint). Also, a table of heights of the 3, 2 and 1 mm global IWV “surfaces” for the different sites could be prepared.
6.4: **Analysis of TOMS Aerosols**

6.4.1: **Annual means of TOMS aerosols**

Figure 6.5.1 shows the mean annual global TOMS aerosol index (AI; multiplied by a factor of 10), as calculated using *FriOWL-v3.1*. This figure has been created by averaging the AI monthly means provided by NASA over the period 1980 to 2002. Of immediate note is the predominance of Africa in the global production of aerosols. These aerosols originate from a mixture of Saharan duststorms and seasonal biomass burning in Central Africa and the Sahel. Under powerful convection currents, they can remain buoyant in the atmosphere for many days to weeks, travelling across the Atlantic to the Americas under the prevailing easterly trade winds, where they are known to deteriorate air quality and even add to fertilisation of the soil in the Amazonian rain forest (Koren *et al.*, 2006). Furthermore, Evan *et al.* (2006) have recently made a robust link between amount of dust outflow from Africa and the number of Caribbean hurricanes in the same year.

![Map of aerosol index](image)

*Figure 6.5.1: Mean annual TOMS aerosol index (multiplied by a factor of 10), as calculated for the period 1980-2002. Note the predominance of high values over Central and Northern Africa, which are spread westwards over the Atlantic by the prevailing easterly winds.*
As Figure 6.5.1 is a map of annual means, it hides the seasonal variation of global aerosols, which are significant. For reasons of efficiency and space, however, we do not show individual monthly mean aerosol maps here, but these can be viewed as an animation on the FriOWL-v3.1 Website† (click on 'User's Guide / Documentation -> Animations -> Aerosols'). The monthly mean animation shows the seasonal north-south movement of aerosol production across the continents, as well aerosols due to the seasonal forest fires and burning of vegetation in Indonesia, South America and many other locations. Of particular note are a number of aerosol “hotspots” (some of which can be seen in Figure 6.5.1 also), which locate a few but prolific sources of aerosols. These hotspots are namely:

(i) The region near (dry) Lake Chad and the Bodele depression in central Africa (ii) The dry salt-lake bed of Lake Eyre (central Australia) (iii) The Rub' Al Khali desert (Arabian peninsula) and (iv) The Taklimakan desert in north-western China, among others. These locations agree more or less with the results of Washington et al. (2003) in a study of duststorm source areas, using a mixture of TOMS data and surface observations.

Figure 6.5.2: Maximum mean monthly value of the TOMS aerosol index (X 10) of all months over the period 1980-2002. In addition to the features shown in Figure 6.5.1, this map also shows regions of occasional aerosol contamination.

† http://www.iapmw.unibe.ch/research/projects/FriOWL/
Figure 6.5.2 shows the *maximum* mean monthly value of the TOMS aerosol index (X 10) of all months over the period 1980-2002 (*i.e.* the maximum value of each pixel during all months of data from January 1980 to December 2002). The reason for showing the maximum pixel values in this instance is to highlight regions which occasionally suffer from elevated aerosol indices, but are hidden from conspicuousness in the map of annual means (Figure 6.5.1). Of particular note in this map are the higher values over the Pacific and Southern Oceans (presumably seaspray) and (also presumed) forest fire signals over northern Asia and North America. Of relevance for astronomical site selection are the higher values over the mountainous south-western United States and Mexico, very high values over northern Africa, Arabia and the Middle East, as well as many western parts of the Himalaya, some contamination over the eastern Andes, but complete absence of any signal near the Chilean coast.

### 6.4.2: Implications of TOMS AI Results for Astronomical Site Selection

Whilst astronomers have traditionally chosen high, dry and warm desert locations as sites for telescopes, such locations also bring the risk of desert dust and sandstorms, which are detrimental to astronomical viewing and instrumentation. Giordano and Sarazin (1994), in a special experiment using test mirrors in Paranal (Chile), demonstrated rapid degradation in the quality of astronomical mirrors within two weeks due to the effect of wind-blasting of dust and aerosols onto the mirror surface, despite Paranal having a very low mean aerosol value (lower than those of industrial cleanrooms). Meanwhile, Siher *et al.* (2004) have made a link between TOMS aerosols and atmospheric extinction (penetration of light) at La Palma (Canary Islands) and Oukaimeden (Morocco). This is not surprising, as Morocco and La Palma are located just north of the largest global plume of aerosols stretching westwards from the Saharan desert (Figures 6.5.1 and 6.5.2, and Table 6.5.1).

Meanwhile, Table 6.5.1 gives the mean annual TOMS aerosol index (X 10) for the nineteen candidate E-ELT sites, as extracted from the *FriOWL-v3.1* pixel closest to each location. The results show that the the mean aerosol index is particularly high at Lekst, Morocco (4.03) and at the two Canary Islands sites (Tenerife 2.20 and La Palma 1.81). San Pedro Martir (Baja California, Mexico) also has a relatively high value (2.03). Volcanic fog (vog) and aerosols from vents on Kilauea\† may be contributing to the slightly high value for Hawaii.

At most other sites, the amounts are negligible, and the relatively high value for the ALMA site of Chajnantor (0.94) seems to be just a result of its more easterly location allowing contamination of pixel values from locations on the Argentine side of the Andes where aerosol indices are much higher. All other Chilean sites have a mean aerosol index value of 0.0. No values are available for the ice cap locations of Greenland Summit and Dome C, Antarctica, as the TOMS algorithm does not stretch to these latitudes; however, values could be expected to be effectively zero here.

<table>
<thead>
<tr>
<th>Site</th>
<th>Aerosol Index (X 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dome C (Antarctica)</td>
<td>n/a</td>
</tr>
<tr>
<td>La Réunion Island</td>
<td>0.062</td>
</tr>
<tr>
<td>Tolar (Chile)</td>
<td>0.000</td>
</tr>
<tr>
<td>Chajnantor (ALMA)</td>
<td>0.938</td>
</tr>
<tr>
<td>Gamsberg (Namibia)</td>
<td>0.102</td>
</tr>
<tr>
<td>Macon (Argentina)</td>
<td>0.071</td>
</tr>
<tr>
<td>La Chira (Chile)</td>
<td>0.000</td>
</tr>
<tr>
<td>Armazones (Chile)</td>
<td>0.000</td>
</tr>
<tr>
<td>Paranal (Chile)</td>
<td>0.000</td>
</tr>
<tr>
<td>La Silla (Chile)</td>
<td>0.000</td>
</tr>
<tr>
<td>Mauna Kea (Hawaii)</td>
<td>0.542</td>
</tr>
<tr>
<td>El Teide, Izaña (Tenerife)</td>
<td>2.196</td>
</tr>
<tr>
<td>La Palma Island</td>
<td>1.813</td>
</tr>
<tr>
<td>Lekst (Morocco)</td>
<td>4.026</td>
</tr>
<tr>
<td>Yanbajing (Tibet)</td>
<td>0.000</td>
</tr>
<tr>
<td>San Pedro Martir (Mexico)</td>
<td>2.026</td>
</tr>
<tr>
<td>Hanle (India)</td>
<td>0.129</td>
</tr>
<tr>
<td>Maidenak (Uzbekistan)</td>
<td>0.187</td>
</tr>
<tr>
<td>Greenland Summit</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 6.5.1: Values of mean annual (1980-2002) TOMS aerosol index X 10, for the nineteen E-ELT candidate sites, as calculated using FriOWL-v3.1. Note the relatively high values for Lekst (Morocco), Izana (Tenerife) and La Palma. No values are available for the Greenland and Antarctic sites.

The high values at the Canary Islands and Morocco are not perennial; they are concentrated mainly during the summer months from June to September (as was seen in the mean monthly animation). This is due to the movement north of the easterly trade wind belt during the summer season. Even at this time, the islands remain on the north-western
fringe of the main aerosol plume, with the result that La Palma (most north-westerly island) experiences a slightly lower mean aerosol index than Tenerife (see Table 6.5.1). An analysis of daily TOMS aerosol indices would reveal the percentage of summer days subject to high aerosol amounts. It is unlikely that the plume is a sustained and static feature of the summer climate; it is more probable that it comes in periodic swaths accompanying each new outflow of air from the African interior. Similarly, the relatively high Al values at San Pedro Martir observatory (Baja California, Mexico) are concentrated during the months from May to August.

Siher et al. (2004) noted that there appears to be some correlation between the La Palma / Moroccan TOMS Al and a time series of the North Atlantic Oscillation (NAO; see section 6.12). However, since the Canary Islands are located quite a distance away from the centre of action of the NAO, a better result might be obtained by using an index representing the frequency of summertime easterly wind outbreaks from the Sahara towards the Canary Islands. This in turn might be related to the advance of the Inter-Tropical Convergence Zone (ITCZ), which reaches its most northerly extent at the same time. Such a task could be accomplished using ERA-15 maps of wind directional frequency available with (earlier) version FriOWL-v2.2†.

Finally, trend analyses of time series of TOMS aerosols have not been investigated in this study. Such a study may not yield meaningful results, due to a lack of ground-truth data for validation or homogeneity tests. The author notes that the Mt. Pinatubo eruption of June 1991 does not seem to be captured visually in the images of the TOMS Al dataset - this is confirmed also by Siher et al. (2004). Unrealistically low global values of Al also seem to occur during years 2001 and 2002.

† http://archive.eso.org/friowl/
6.5: Analyses of Dewpoint (Relative Humidity)

The dewpoint depression is the difference in degrees Celsius (Kelvin) between the air temperature and the dewpoint temperature. It is inversely related to the relative humidity (which is the ratio of actual water vapour pressure to the vapour pressure if the air was saturated at the same air temperature). Thus, at low relative humidities, dewpoint depressions are large and vice versa.

![Dewpoint Depression Maps](image)

(a) January  
(b) April  
(c) July  
(d) October

Figure 6.8.1: Minimum ERA40 (1957-2002) surface dewpoint depression (air temperature minus dewpoint) of the monthly means of four main synoptic reporting hours (00, 06, 12, 18 UTC), for (a) January, (b) April, (c) July, and (d) October. These maps highlight the dry deserts of the world where night-time / dawn relative humidities remain low.

Figure 6.8.1 attempts to show all regions in the world where the dewpoint depression is large, even at night-time (i.e. night-time relative humidities are low) for (a) January, (b) April, (c) July, and (d) October. This map was created as follows; using ERA40 surface air temperature and dewpoint data, the dewpoint depression for each of the four main synoptic reporting hours (00, 06, 12, 18 UTC) for each month was calculated. Then, the minimum value of each of these four values was taken, and assumed to be attributable to night-time or close to dawn. This assumption is easily made because surface relative
humidity should always be greater during the night or close to dawn than during the daytime. Even if this is not the case, it is still important to know the most extreme values for telescope operation, regardless of the time of occurrence. Finally, because these calculations were made using only the 00, 06, 12, 18 UTC values, the results probably over-estimate the minimum dewpoint depression by a few degrees.

While always bearing in mind the coarse scale of the reanalyses, especially in the under-representativeness of mountain regions, Figures 6.8.1 (a) to (d) essentially confirms the locations of all of the warm, dry deserts of the world (yellow / red / non-green colours), which are also the locations for most of the world's current largest astronomical observatories. These deserts have already been identified several times in this work. They are, namely; south-west United States and Mexico, the Atacama (Chile), the Sahara-Arabia zone, the Kalahari (Namibia), the northern-western Himalaya and Australia. However, it is worth noting that the latter four desert zones here-mentioned are considerably less exploited in terms of astronomical facilities than the first two, despite the first two occupying considerably less dry-area extent (i.e. yellow / red colours) in Figure 6.8.1 than the latter four. Prominent exceptions to all of these cases are the island peaks of Hawaii and the Canary Islands, however (such isolated peaks cannot be resolved on this coarse ERA40 surface analysis). Furthermore, this method of 'dry-desert' detection also fails in the case of Antarctica and Greenland, because the very low saturation vapour pressures accompanying the extremely low air temperatures in these regions yield smaller dewpoint depressions.
6.6: Analysis of CCCma CGCM1 clouds

In Chapter 3 (database description) we stated that climate output from general circulation models for the future might be useful in the determination of climate change at potential astronomical sites. For this purpose, it was decided to include total cloud cover data from the CGCM1 model of the Canadian Centre for Climate Modelling and Analysis (CCCma) in the FriOWL-v3.1 database, for the years of 1991-2000 (“present climate“) and the future years of 2021-2030 (expected period of operation of E-ELT). At the same time, however, it was stringently noted that such data needs to be treated with utmost caution, as modelled clouds are often the products of many parameterisation schemes, and the cloud output of the model in control runs may not have been validated by observations.

6.6.1: What can (not) CCCma clouds tell us?

It is important to understand exactly what the CCCma model data can and cannot show us. Because it is a climate model, and not a reanalysis, the meteorological data which it produces for a specific time may not be real i.e. without being forced by regular weather observations, sea ice extents or sea surface temperatures, it cannot simulate the actual weather at any moment in time, but it can provide an estimate of the mean climate of that time (if climatic means of the above observations are included).

![Figure 6.10.1: (a) Anomaly of global ERA40 total cloud cover fraction for the year 1998, compared to the decade 1991-2000. (b) Same image, but using CCCma CGCM1 total cloud cover data.](image)

An example of such limitations are shown visually in Figure 6.10.1(a) and (b). The image on the left (a) is a map of the global anomaly of total cloud cover for the year 1998, compared to the whole decade of 1991-2000, as seen by the ERA40 reanalysis model (“reality“). The year 1998 was characterised by one of the strongest El Niño events of the 20th century,
with significant changes in regional precipitation, circulation patterns and cloud cover, most
evident in tropical Pacific regions. These are captured well by the ERA40 map in (a) which
shows a typical El Niño dipole signature across the equatorial Pacific Ocean. The same
procedure, but using CCCma CGCM1 total cloud cover data is re-enacted in Figure (b), on
the right. Here, there are no real coherent or anomalous patterns of cloud cover during
1998. This happens because the CGCM1 model simulates the mean climate, not the
weather; without direct forcing by, for example, daily or monthly sea surface temperature
variations, it does have the capability to resolve oscillations such as El-Niño on monthly
timescales.

6.6.2: Changes in cloud cover by 2021-2030

![Figure 6.10.2](image)

**Figure 6.10.2:** (a) Mean CCCma CGCM1 global total cloud cover fraction for the decade 1991-2000
(b) Mean CCCma CGCM1 global total cloud cover fraction for the decade 2021-2030 (c) Difference
between the two images (a) and (b); (d) Mean ERA40 global total cloud cover fraction for 1991-2000.
The colour legend is the same in all images, except (c) where it is the same as in Figure 6.10.1.

Taking all these considerations into account, Figures 6.10.2 (a) and (b) show the mean
global total cloud cover from the CCCma CGCM1 model for the decades of 1991-2000 and
2021-2030, respectively. The difference between these two images is shown in Figure
6.10.2 (c). Also shown is the ERA40 mean total cloud cover for 1991-2000 in (d). Whilst the
CGCM1 model simulates mean global cloud cover fairly well when compared to ERA40 (compare [a] and [d]), there are no coherent differences evident whatsoever between the two CGCM1 maps in (a) and (b); subtraction of one map from the other just gives a map of apparent random noise (c). Thus, no meaningful conclusions can be drawn about likely global changes in cloud cover and their implication for astronomical site selection of the E-ELT. Given the limitations of simulating cloud cover, even in the most highly resolved and accurate atmospheric models, this disappointing result should not be taken with any great surprise.

6.6.3: Recommendations on using future model data

Because of the problems of parameterisation of clouds in climate models and the lack of validation of cloud estimates with observations, it is recommended that any future work conducted using model output for the future should concentrate on validated meteorological fields (e.g. temperature). The use of more highly resolved regional climate models with many ensemble members, is also encouraged.
CHAPTER 7: HOW TO ADD NEW DATABASES TO FriOWL-v3.1

This short chapter describes the capability of adding new datasets to FriOWL-v3.1 at any time. The capability of being able to add new data layers or datasets, of practically any resolution, is new to FriOWL-v3.1. This can be done at any time, without having the disadvantage of having to edit or re-compile the Java source code. It is achieved by the editing of a simple XML text file, which controls the description of and path to each data set of the FriOWL database. This XML file is re-loaded to the server every time the FriOWL software is started, which allows instant access to any new data sets.

7.1 WHAT IS AN XML FILE?

![XML File Example](image)

Figure 7.1: Part of the ‘files.xml’ XML file. It is a standard text file consisting of user-defined tags, which control the details of all datasets available to the FriOWL-v3.1 server.

An XML (Extensible Markup Language) file is a standard ASCII text file consisting of HTML-style tags, and therefore it may be opened or saved in any text editor (see Figure 7.1). Unlike HTML however, the tags are not pre-defined, and may be created uniquely for any
particular use. In the case of FriOWL, authorised users may move, add, delete or edit the various tags or their properties within the XML file in order to specify or change the details of any data sets available to the server. A number of rules must be observed when editing or changing the XML file, however.

7.2 How to Edit 'files.xml'

The name of the XML which controls the database is called 'files.xml' (Figure 7.1) and it resides on the data/ folder of the FriOWL-v3.1 website. If you want to add a new database to FriOWL, you must first have write permissions to edit this file (these are normally available only to a FriOWL administrator). Even if you are an experienced programmer, it would be wise to always keep a backup of the most recent copy of 'files.xml', as this file contains important information which allows the FriOWL software to operate. A full printed copy of 'files.xml' is listed in Appendix A.

Editing of the file is straightforward and uncomplicated. The file consists of series of text tags, the order and hierarchy of which control the visual layout of the database as it appears in the FriOWL file manager menu-tree. The tags' properties control the paths to the data sets and various display and description parameters.

At the time of writing (January 2008), there are three tags used in the XML 'files.xml' file, namely;

<folder></folder>

<month></month>

<file></file>

Each <folder> tag corresponds to the names of the folders within which the particular datasets are located. <folder> tags may be nested within each other.

The <monthly> tags are used to list all data files of a complete mean monthly time series data set. This eliminates the necessity of having to type the name of each data file individually in the XML file e.g. only one instance of referral is necessary to list the complete ERA-40 18 UTC high cloud cover data set, which contains 540 individual monthly data files from September 1957 to August 2002 inclusive.

Finally, the <file> tags specifies time-invariant data sets e.g. the USGS Antarctica topographic tile, which is static in time and therefore consists of just one file.
As in HTML, each tag must be completed (i.e. have a starting tag <>, followed by a end tag </>) and all tags must be nested correctly (overlapping of tags is not permitted). For example:

```html
<folder name="FriOWL database">
   can write stuff here
</folder>

any stuff here is illegal
```

A number of obligatory attributes (or properties) must also be provided with each tag. These are fully explained in the following pages and in Tables 7.1 to 7.3. All properties should be written as text strings and should be enclosed in double quotations (" "). Examples are given afterwards on how to use each tag.

### 7.3 The `<folder>` Tag

The `<folder>` tag is used to create an individual database folder for classification purposes. There is just one (obligatory) property value that must be included; the name of the folder ("name", see Table 7.1). Nesting and sub-nesting of folder tags within each other creates child and grandchild folders, and so on.

<table>
<thead>
<tr>
<th>Tag</th>
<th>Property</th>
<th>Ob.?</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>&lt;folder&gt;</code></td>
<td>name</td>
<td>Yes</td>
<td>name of the folder to appear in the FriOWL menu tree e.g. <code>&lt;folder name=&quot;ERA-40 Clouds&quot;&gt;</code></td>
</tr>
</tbody>
</table>

Table 7.1: Explanation of the `<folder>` tag; “Ob.” means obligatory

### Example 7.1: Nesting parent, child and grand-child folders

Like HTML, you must nest each tag within a parent tag. Overlapping of tags is not permitted.

```html
<folder name="ERA-40 IWV">
   <folder name="IWV at 500 hPa">
      1st child folder: might include a <monthly> tag here, etc..
   </folder>
</folder>
```

(PARENT FOLDER)

(PARENT FOLDER)

(PARENT FOLDER)
7.4 The <monthly> tag

The <monthly> tag is used to list complete sets of individual time-varying data files, and only one instance of the <monthly> tag is needed to refer to a complete dataset. There are a total of 16 properties (14 of which are obligatory) that may be included. See Table 7.2 for full explanations.

<table>
<thead>
<tr>
<th>Tag</th>
<th>Property</th>
<th>Obligatory</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;monthly&gt;</td>
<td>name</td>
<td>Yes</td>
<td>name of the folder to appear in the FriOWL menu tree e.g. &lt;monthly name=&quot;hcc&quot; ... (followed by other properties)</td>
</tr>
<tr>
<td></td>
<td>url</td>
<td>Yes</td>
<td>full path to the individual data files e.g. url=&quot;<a href="http://www.iapmw.unibe.ch/research/projects/FriOWL/data/era40_clouds/18UTC/hcc/era40_18UTC_hcc_%25m_%25y.RST">http://www.iapmw.unibe.ch/research/projects/FriOWL/data/era40_clouds/18UTC/hcc/era40_18UTC_hcc_%m_%y.RST</a>&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>where %m refers to a 3-character month of the form of one of the following: JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>where %y refers to a 4-digit year e.g. 1957, 1975, 2003. See also Section 7.9 (naming of database files)</td>
</tr>
<tr>
<td></td>
<td>ymin</td>
<td>Yes</td>
<td>the first year of the dataset e.g. &quot;1957&quot;</td>
</tr>
<tr>
<td></td>
<td>ymax</td>
<td>Yes</td>
<td>the last year of the dataset e.g. &quot;2002&quot;</td>
</tr>
<tr>
<td></td>
<td>yminmonth</td>
<td>Yes</td>
<td>the month of the first year in which the dataset begins e.g. &quot;9&quot; (for September 1957)</td>
</tr>
<tr>
<td>Property</td>
<td>Optional</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>----------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>ymaxmonth</td>
<td>Yes</td>
<td>the month of the last year in which the dataset ends e.g. &quot;8&quot; (for August 2002)</td>
<td></td>
</tr>
<tr>
<td>description</td>
<td>Yes</td>
<td>short text string to describe dataset, used for display in 'Selected Files' sub-frame e.g. &quot;High cloud cover 06UTC&quot;</td>
<td></td>
</tr>
<tr>
<td>unit</td>
<td>Yes</td>
<td>The SI unit of the dataset e.g. &quot;kg per m² (mm)&quot; for IWV</td>
<td></td>
</tr>
<tr>
<td>width</td>
<td>Yes</td>
<td>the number of columns in the data set e.g. &quot;145&quot;</td>
<td></td>
</tr>
<tr>
<td>height</td>
<td>Yes</td>
<td>the rows of rows in the data set e.g. &quot;73&quot;</td>
<td></td>
</tr>
<tr>
<td>lonres</td>
<td>Yes</td>
<td>the longitude resolution e.g. &quot;2.5&quot; (for 2.5°)</td>
<td></td>
</tr>
<tr>
<td>latres</td>
<td>Yes</td>
<td>the latitude resolution e.g. &quot;2.5&quot; (for 2.5°)</td>
<td></td>
</tr>
<tr>
<td>lonmin</td>
<td>Yes</td>
<td>the minimum longitude e.g. &quot;0.0&quot; (for Greenwich meridian)</td>
<td></td>
</tr>
<tr>
<td>latmin</td>
<td>Yes</td>
<td>the minimum latitude e.g. &quot;-90.0&quot; (for South Pole)</td>
<td></td>
</tr>
<tr>
<td>startrow</td>
<td>No</td>
<td>a value of &quot;up&quot; means that the row order starts at bottom left</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>a value of &quot;down&quot; means that the rows start at top left (reversed)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>See Section 7.7 for more information</td>
<td></td>
</tr>
<tr>
<td>outlinemap</td>
<td>Yes</td>
<td>a value of &quot;145&quot; means that the outline map of international borderlines used for display is defaulted to the style used for maps of width=&quot;145&quot;</td>
<td></td>
</tr>
<tr>
<td>nullvalue</td>
<td>No</td>
<td>an integer or floating-point number which indicates &quot;missing&quot; data values; these data will be ignored by the FriOWL display</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: Explanation of the <monthly> tag and its properties; “Ob.” means obligatory

Example 7.2: Use of a one monthly tag to include 540 individual data files

```
<monthly name="iwv500"
url="http://www.iapmw.unibe.ch/research/projects/FriOWL/data/era40_iwv/iwv500/era40_iwv500_% m_%y.RST" ymin="1957" ymax="2002" yminmonth="9" ymaxmonth="8" description="IWV at 500hPa" unit="kg per m² (mm)" width="145" height="73" lonres="2.5" latres="2.5" lonmin="0.0" latmin="-90.0" startrow="down" outlinemap="145"/>
```
7.5 The <file> tag

The <file> tag is used for specifying individual files which are static in time (e.g. topography and seismic data layers). There are a total of 11 properties that must be included, most of which are identical to those used in the <monthly> tag. See Table 7.3 for full explanations.

<table>
<thead>
<tr>
<th>Tag</th>
<th>Properties</th>
<th>Obligatory ?</th>
<th>Explanation</th>
</tr>
</thead>
</table>
| <file> | name       | Yes          | name of the folder to appear in the FriOWL menu tree  
|        |            |              | e.g. <file name="USGS Tile: Antarctica-Dome C" ... (followed by other properties) |
| url    | Yes        | full path to the individual data file e.g. url="http://www.iapmw.unibe.ch/research/projects/FriOWL/data/usgs_dem/tiny_tiles/USGS_TINY_TILE_ANTARCTICA.RST" |
| description | Yes       | short text string to describe dataset, used for display in 'Selected Files' sub-frame e.g. "USGS 1km DEM topography" |
| unit   | Yes        | The SI unit of the dataset e.g. "metres ASL" |
| width  | Yes        | the number of columns in the data set e.g. "600" |
| height | Yes        | the rows of rows in the data set e.g. "400" |
| lonres | Yes        | the longitude resolution e.g. "0.008333" (degrees) |
| latres | Yes        | the latitude resolution e.g. "0.008333" (degrees) |
| lonmin | Yes        | the minimum longitude e.g. "0.0" (for Greenwich meridian) |
| latmin | Yes        | the minimum latitude e.g. ":-90.0" (for South Pole) |
| outlinemap | Yes      | a value of "145" means that the outline map of international borderlines used for display is defaulted to the style used for maps of width="145" |
| nullvalue | No         | an integer or floating-point number which indicates "missing" data values; these data will be ignored by the FriOWL display |

Table 7.3: Explanation of <file> tag and its properties.

Example 7.3: Use of <file> tag to include a static topographic layer

<file name="USGS Tile: Antarctica-Dome C"  
url="http://www.iapmw.unibe.ch/research/projects/FriOWL/data/usgs_dem/tiny_tiles/USGS_TINY_TILE_ANTARCTICA.RST"  
description="USGS 1km DEM topography"  
unit="metres ASL"  
width="600"  
height="400"  
lonres="0.008333"  
latres="0.008333"  
lonmin="121.675"  
latmin="-76.6667"  
outlinemap="145"/>
7.6 Other Tags
FriOWL-v3.1 is mostly composed of re-analysis data sets of mean monthly temporal resolution. However, in the future, further tags could be created for new datasets spanning different temporal resolutions (e.g. <daily>, <hourly>, <weekly>), as the FriOWL-v3.1 design is not restricted to use monthly data alone. Re-writing and re-compilation of the Java code would be necessary for this, however.

7.7 Format of FriOWL-v3.1 Data Files
So far, we have explained the form of the XML file which describes the data files. We must now explain how any new data files should created, formatted and named for correct reading and display in FriOWL-v3.1.

All FriOWL data files are composed of single column binary 4-byte (32-bit) floating-point (real) numbers. “Single column” means the columns and rows of your data (the original data matrix) must be flattened into a single column stream of data, with one data value per line. Therefore, if you are planning to make a new data set for FriOWL, your data must be saved in this format in individual regular files. There must be one data file per time step of your variable (supplying all your data in one large file is not permitted). Please note that the number of lines in your data file must equal the total number of rows multiplied by total number of columns of your original data matrix (because the data has to be in a single column).

You should flatten the original data matrix from the bottom-left corner first, working upwards through each row, one at a time. If you flatten your matrix starting from the top-left corner (Windows softwares may do this by default e.g. IDRISI), you must specify that the row order is reversed, by including the “startrow” property value as “down” within the <monthly> or <file> tag (see also Table 7.2):

**e.g. startrow=”down”**

Examples of programs used to create single column 4-byte (32-bit) floating-point binary files for FriOWL-v3.1, using GrADS, Fortran and Matlab computing languages and softwares are given in Appendix B.
7.8 Missing Values

Missing data values should be specified by a fixed integer or floating-point number, such as '999.9', '-999.9' or '32766'. This number should then be specified in the "nullvalue" property value within the <monthly> or <file> tag.

e.g. nullvalue="999.9"

The TOMS aerosols data set already has a missing data value set to 999.9 and the NOAA OLR dataset has a missing value set to 32766 (see Chapter 3: “The FriOWL-v3.1 Database” for more information).

7.9 Naming of new data files

New data files must be named in the same way as described in Tables 7.1 and 7.2. Individual files which are static in time (time invariant) may be named in any way, and their full path and file name must be specified in the associated <file> tag (see Table 7.3 and Example 7.4).

Multiple files of a monthly time series of maps (e.g. 540 files of ERA-40 mean monthly integrated water vapour at 500 hPa, from September 1957 to August 2002 inclusive) must all be named the same, except for suffixes which indicate the time that they refer to. The suffixes should be of exactly the same form as listed under the url property of the <monthly> tag in Table 7.2 (which are repeated in Table 7.4 and Example 7.4 below for the sake of brevity).

<table>
<thead>
<tr>
<th>year</th>
<th>4-digit year e.g.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>month</th>
<th>3-character month e.g.</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN, FEB, MAR, APR, MAY, JUN, JUL, AUG, SEP, OCT, NOV, DEC</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.4: The suffixes that needed to be added to a filename, for new data sets consisting of multiple monthly files.

As stated in Section 7.6, FriOWL-v3.1 is not restricted to data sets of mean monthly data; the data varying over different time periods could be included in the future, with the
introduction of new XML tags. However, it may be already possible to simulate datasets comprising of other temporal resolutions in FriOWL-v3.1, using an elaborate combination of <monthly> and <file> tags.

**Example 7.4: How to name database files**

A single file should be named as follows:

**e.g. GSHPUB_GLOBE_RESAMPLED.RST** -> corresponds to a single time-invariant static global seismic layer. Such a file can be named in any way, so long as the name is correctly listed in the name property of the <file> tag within the XML file. Again, the file extension in this case is .RST, but any other extension may be used, providing it is specified in the “url” property of the <monthly> or <file> tags in the XML “files.xml” file, and the data file is composed of 4-byte single column binary data (see Section 7.7).

Multiple files should be named as follows:

**e.g. era40_iwv500 APR 1958.RST** or **era40_iwv500 JAN 1963.RST** -> corresponds to two different files of mean monthly integrated water vapour (IWV) from the ERA-40 dataset for April 1958 and January 1963 respectively. The file names should be the same, except for the month and year suffixes, which should be written in the format as specified in Table 7.4. In these cases, the file extension is .RST, meaning they are compatible with the IDRISI 32 software (Eastman, 1987-2002), but any other extension may be used, providing it is specified in the “url” property of the <monthly> or <file> tags in the XML “files.xml” file, and the data file is composed of 4-byte single column binary data. Any of the following are valid names:

*era40_iwv500 JAN 1958.RST*
*era40_iwv500 FEB 1958.RST*
*era40_iwv500 MAR 1958.RST*
*era40_iwv500 APR 1958.RST*
*era40_iwv500 MAY 1958.RST*
*era40_iwv500 JUN 1958.RST*
**Conclusions and Recommendations**

We began this document in Chapter 1 with a short history of the FriOWL project since its inception at the University of Fribourg in 2002. The main constraints imposed by the atmosphere on astronomical viewing were discussed and special note was made to the huge range of scales over which these operate. The idea of using Geographical Information Systems as a tool to analyse long-term global re-analysis climatic datasets in relation to astronomical site selection was introduced. FriOWL-v3.1 became this tool.

In Chapter 2, a tutorial with examples was provided for first-time users to familiarise themselves with the FriOWL-v3.1 software. In Chapter 3, we explored in detail the origins and reliability of the various datasets, particularly the ERA-40 re-analysis. This was followed later in Chapter 4 by a detailed explanation of all the technical features of the FriOWL-v3.1 software tool. A full listing of the Java classes and packages was provided in Chapter 5. In Chapter 6, the FriOWL-v3.1 software was used extensively and results were presented with a special focus on site selection for the European Extremely Large Telescope; these results are summarised below. Chapter 7 provided future administrators with a technical description on how to update the FriOWL database with new datasets, if required.

Based largely on the results presented in Chapter 6, and according to the re-analysis data, we can conclude the following:

(i) Five global areas were persistently identified as having superior astronomical viewing qualities; these regions are Coastal Namibia, Northern Chile, the Canary Islands and Morocco, Baja California and an 'Arabic' zone centred near Egypt and the Sinai peninsula. The first four areas are generally well-known to the astronomical community; the fifth has been considerably less exploited. We therefore recommend that the European Southern Observatory investigate the possibility of conducting surveys of potential sites near the Sinai peninsula / north-west Arabia, where several mountain ranges reach above 2,000 metres in height.

(ii) Coastal Namibia is the region with the lowest amount of mid-to-upper level clouds in the world. This region also exhibits low variability. Northern Chile ranks as the next least-cloudy region. However, the mountains of the Namibian escarpment do not
reach as high as the Andes, and the climate rapidly becomes more cloudy and moist as one moves inland from the Namibian coast. The Brandbergmassif in north-western Namibia was identified as a possible candidate site (although it is understood to have religious significance; M. Sarazin, personal communication, 2008).

(iii) The mid- to north-Atacama region of Chile has the lowest amount of integrated water vapour at the 700 hPa level (~3000 metres altitude) anywhere in the world, excluding Antarctica. Namibia is two to three times moister at the same level. One must ascend to 3,500 to 4,000 metres at the other E-ELT sites to achieve a similar mean annual IWV, and up to 5,500 metres in the Himalaya.

(iv) During the summer months, the Sinai peninsula of Egypt is the least cloudy region in the world, with IWV values almost matching that of the Chilean Atacama, although no mountains reach up to the 700 hPa / 3000 metre level here.

(v) The Canary Islands and Morocco show considerably higher values of aerosol contamination than the other E-ELT candidate sites. Further work is needed to determine the actual number of aerosol days and their relationship to easterly wind outbreaks from the Saharan desert.

(vi) Further studies are needed to test whether ERA-40 cloud data are valid for the frigid, data-sparse continent of Antarctica.

(vii) It is recommended that any following work conducted using model output for the future should concentrate on validated meteorological fields. The use of high resolution regional climate models with many ensemble members is also encouraged.

Finally, readers are reminded that the FriOWL-v3.1 software is completely web-based and are therefore encouraged to refer to the project Website†. A series of smaller, accessory documents entitled «Applications of FriOWL», will accompany this document in due course.

† http://www.iapmw.unibe.ch/research/projects/FriOWL/
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**APPENDIX A: ACRONYMS USED**

The following lists all the various acronyms used throughout 'The FriOWL Guide' and associated documentation.

This list last updated: 15 April 2008 by Eddie Graham

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI</td>
<td>Aerosol Index</td>
</tr>
<tr>
<td>ALMA</td>
<td>Atacama Large Millimeter Array</td>
</tr>
<tr>
<td>ASL</td>
<td>Above Sea Level</td>
</tr>
<tr>
<td>CCCma</td>
<td>Canadian Centre for Climate Modelling and Analysis (Victoria, Canada)</td>
</tr>
<tr>
<td>CGCM1</td>
<td>Canadian General Circulation Model number 1</td>
</tr>
<tr>
<td>DIMM</td>
<td>Differential Image Motion Monitor</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium Range Weather Forecasting (Reading, England)</td>
</tr>
<tr>
<td>E-ELT</td>
<td>European Extremely Large Telescope (ESO)</td>
</tr>
<tr>
<td>ENSO</td>
<td>El Niño / Southern Oscillation</td>
</tr>
<tr>
<td>ERA-15</td>
<td>ECMWF 15-year (1979-1993) Reanalysis</td>
</tr>
<tr>
<td>ERA-40</td>
<td>ECMWF 45-year (1957-2002) Reanalysis</td>
</tr>
<tr>
<td>ESO</td>
<td>European Southern Observatory (Garching, Germany)</td>
</tr>
<tr>
<td>FriOWL</td>
<td>University of Fribourg (Switzerland) project for OWL telescope site selection</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half-Maximum</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical Information System</td>
</tr>
<tr>
<td>GrADS</td>
<td>The Grid Analysis and Display System (software)</td>
</tr>
<tr>
<td>GSHAP</td>
<td>Global Seismic Hazard Assessment Program</td>
</tr>
<tr>
<td>GSHPUB</td>
<td>Global Seismic Hazard Assessment Program's published data set</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>IAP</td>
<td>Institute of Applied Physics (University of Bern, Switzerland)</td>
</tr>
<tr>
<td>IPO</td>
<td>Interdecadal Pacific Oscillation</td>
</tr>
<tr>
<td>ITCZ</td>
<td>Inter-tropical Convergence Zone</td>
</tr>
<tr>
<td>IWV</td>
<td>Integrated Water Vapour</td>
</tr>
<tr>
<td>MW</td>
<td>Microwave Group</td>
</tr>
<tr>
<td>NCAR</td>
<td>National Center for Atmospheric Research (USA)</td>
</tr>
<tr>
<td>NCEP</td>
<td>National Centers for Environmental Prediction (USA)</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>OLR</td>
<td>Outgoing longwave radiation</td>
</tr>
<tr>
<td>OWL</td>
<td>Over-Whelmingly Large Telescope (ESO)</td>
</tr>
<tr>
<td>PDO</td>
<td>Pacific Decadal Oscillation</td>
</tr>
<tr>
<td>PGA</td>
<td>Peak Gravitional Acceleration</td>
</tr>
<tr>
<td>PR_WTR</td>
<td>Precipitable Water Vapour (same as IWV)</td>
</tr>
<tr>
<td>SO</td>
<td>Southern Oscillation (atmospheric component of El Nino)</td>
</tr>
<tr>
<td>TOMS</td>
<td>Total Ozone Mapping Spectrometer</td>
</tr>
<tr>
<td>UNIBE</td>
<td>University of Bern, Switzerland</td>
</tr>
<tr>
<td>UNIFR</td>
<td>University of Fribourg, Switzerland</td>
</tr>
<tr>
<td>URL</td>
<td>Uniform Resource Locator</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>UTC</td>
<td>Universal Time Co-ordinate</td>
</tr>
<tr>
<td>VLT</td>
<td>Very Large Telescope (ESO, Paranal, Chile)</td>
</tr>
<tr>
<td>WMO</td>
<td>World Meteorological Organisation</td>
</tr>
</tbody>
</table>
**APPENDIX B: BUGS AND PROBLEMS TO DATE**

Whilst every effort has been made to fully test and eliminate all possible causes of bugs with the FriOWL-v3.1 software, it is still possible that occasional problems will arise from time to time. Below you will a list of all bugs and problems to date, given in reverse chronological order, together with the appropriate solution, if found.

This page last updated: 15 April 2008

<table>
<thead>
<tr>
<th>Date of bug</th>
<th>Description of problem</th>
</tr>
</thead>
</table>
| 14 April 2008        | **Cropping problem**  
After cropping a map, there is an error on the resulting .PNG image saved to the server. Although the data is successfully cropped, the overlayed global map of country outlines does not crop, giving the visual impression that the crop has not worked. This error does not effect the FriOWL-v3.1 display of maps, only the saved .PNG file on the server.  
**Solution:** Forthcoming                                                                                                                                 |
| April 2008           | The 'Load' function is missing an option 'ALL' where all months of the year (January, February,... December) cannot be selected in one go.  
**Solution:** to be investigated                                                                                                                                                                      |
| April 2008           | Saving a map when using the Time Series 'Selected Files' option does not work.  
**Solution:** Forthcoming                                                                                                                                                                           |
| April 2008           | *Time Series:* It is not possible to make a fixed Y-axis.  
**Solution:** to be investigated                                                                                                                                                                      |
| 28 February 2008     | *Time Series:* One cannot subtract one time series from another (e.g. 06 dewpoint from 06 air temps, and plot the difference).  
**Solution:** to be investigated                                                                                                                                                                      |
| 1 February 2008      | **Important note on the saving of large ASCII files**  
At approximately 24 bytes per pixel value, a typical ASCII file occupies six times more space than its binary equivalent. Therefore, the request to save
a data layer of high spatial resolution can result in very large ASCII files being saved on the server. In an uncompressed state, files of this size may exceed standard Java virtual machine settings for applets, and cause the program or server to hang or even crash.

**Solution:** ASCII files are now only saved for files of 800 X 400 pixel size or less. Files larger than this cannot be saved in ASCII (but can still be saved in other binary formats). The saving of all ASCII files is optional (you must tick the toggle box at the bottom of the 'File-Save' menu option to enact it).

Alternatively, any user who wants to be able to save large ASCII files to disk must change settings for the Java Plug-In in the user's System Control, by adding a VM-Option “-Xm256m”.

### 15 October 2007

**Error in latitudes for USGS 1km topographic tiles**

The United States Geological Survey's 1km (0.00833° lat / lon) digital elevation model topographic tiles, as listed in the FriOWL database under “USGS 1km DEM topography” had a latitude display problem. Latitudes north of the equator were wrongly expressed as being south of the equator and vice versa.

**Solution:** Problem solved in January 2008. The error was fixed by reversing the sign of the latitude in the 'files.xml' file.

### 2007

**Pop-Up Window Blocker Error**

The security features of some browsers (e.g. Microsoft Internet Explorer) may cause the 'File -> Manage maps' menu option to fail to open a new browser window. The same error may prevent FriOWL from starting for the first time in Microsoft Internet Explorer. A message usually appears at the top of your browser window saying a pop-up window has been blocked.

**Solution:** This can be fixed easily by disabling the “Pop-Up Window Blocker” in the 'Preferences' option of your browser. Or just click on the appropriate button or link to de-activate the pop-up blocker.

### 2007

**'Save' and 'Manage Maps' options do not work**

It is possible that the “Save” and “Manage Maps” options (as well as others) may not work if an old version of the Java Runtime Environment is installed on your computer. To resolve this problem, you must upgrade your Java
<table>
<thead>
<tr>
<th>Runtime Environment to at least version 2.0 (this version is available for download on the FriOWL website)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution:</strong> Upgrade your Java version by downloading the appropriate software from <a href="http://java.com/en/download/manual.jsp">http://java.com/en/download/manual.jsp</a> (or see the link 'JRE 6 download' on the FriOWL-v3.1 website for more information).</td>
</tr>
</tbody>
</table>
APPENDIX C: PROGRAMS AND SCRIPTS

For reasons of space and efficiency, it is not possible to list all of the computing programs and scripts used during the FriOWL-v3.1 project here in print. However, in order to allow access for potential future users to view, update or edit them, all of the individual programs are available for examination and download via the FriOWL-v3.1 website†. The README text file, found at the same web address and re-printed in the following section, details exactly where all programs reside and explains their file extension.

README file to help navigate the FriOWL-v3.1 'appendices' folder
http://www.iapmw.unibe.ch/research/projects/FriOWL/docs/appendices/

This file written by Eddy Graham, IAF, Uni Bern, CH
Last updated: 15 April 2008

This file explains the format of the various computer programs and scripts used in the FriOWL-v3.1 project. All scripts and programs are contained within six different folders, namely:

/ERA40 programs
/USGS_programs
/GSHAP programs
/NCEP-NCAR-NOAA programs
/TOMS aerosols programs
/CCCma programs

There is also an additional folder labelled 'Javadoc' (Java class documentation) and an example of the XML file 'files.xml'.

Within each of the above folders, you will find all of the respective programs and scripts which created the FriOWL-v3.1 database. All files are in ASCII. Most programs are commented. Files ending with following extensions are explained as follows:

† http://www.iapmw.unibe.ch/research/projects/FriOWL/docs/appendices/ or just go to the FriOWL-v3.1 website, and click 'User's Guide / Documentation -> Listings of programs'
.gs  ->  GrADs script
.m   ->  Matlab
.for ->  Fortran (Windows)
.pro ->  IDL
.iml ->  Idrisi macro script

For further information, please contact a FriOWL administrator using the 'Contact us' form on the FriOWL-v3.1 website, or email: eddie.graham(at)iap.unibe.ch
**OFFICIAL CITATIONS**

The ECMWF ERA-15 and ERA-40 reanalysis data used in this study have been provided by ECMWF, Shinfield Park, Reading, England and have been obtained from the ECMWF data server at http://data.ecmwf.int/data/

The NOAA OLR and NCEP-NCAR reanalysis data have been provided by the NOAA-CIRES Climate Diagnostics Center and NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, available at http://www.cdc.noaa.gov

The CCCma CGCM1 data used in this work have been provided by the Canadian Centre for Climate Modelling and Analysis, Environment Canada, Victoria, British Columbia, Canada, available at http://www.cccma.bc.ec.gc.ca

The TOMS Aerosol Index data has been provided by the Chemistry and Dynamics Branch of the NASA Goddard Space Flight Center in Greenbelt, Maryland, USA, available at ftp://toms.gsfc.nasa.gov/ and http://toms.gsfc.nasa.gov/

The global seismic data set is provided by the Global Seismic Assessment Hazard Program, available at http://www.seismo.ethz.ch/GSHAP/

The USGS digital elevation model data was provided by the Earth Resources Observation and Science (EROS) group of the United States Geological Survey (USGS), Sioux Falls, South Dakota, USA, available at http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html

Java is a registered trademark of Sun Microsystems Incorporated.
ACKNOWLEDGEMENTS

This work has been completed between 2002 and 2008 at the Universities of Fribourg and Bern, Switzerland, under contracts with the European Southern Observatory, Garching, Germany.

There are many people who deserve my thanks and gratitude. Specifically, I would like to offer sincere thanks to Dr. Marc Sarazin of the European Southern Observatory, Prof. Dr. Martin Beniston of the University of Geneva, Prof. Dr. Niklaus Kämpfer and Prof. Dr. Christian Mätzler of the Institute of Applied Physics, University of Bern. It would not have been possible for me to continue this work through to the end without their support, faith and confidence, especially at the difficult times. I would also like to sincerely thank all my work colleagues in Fribourg and Bern over the past six years.

On a personal note, I would like to thank my wife, June Christine, for her support throughout the time of this project, as well as our two children, Ailsa (5) and Daniel (2), who have brought much fun over the past years in Bern and made our lives infinitely more exciting and interesting than they would be otherwise. As a parting note, Ailsa has drawn a special “astronomy” picture, which is included on the following page.

Sincerely

Eddie Graham

5 May 2008

Bern, Switzerland
CURRICULUM VITAE OF E. GRAHAM

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EDUCATIONAL QUALIFICATIONS

M.Sc. in Applied and Agricultural Meteorology, University of Reading, England (October 1994 to December 1995).
I studied Applied and Agricultural Meteorology, including courses on Atmospheric Physics, Remote Sensing, Weather Systems and Concepts, Statistical Climatology, Micrometeorology and Energy and the Environment (among others). I completed my Master's dissertation at Wageningen University in the Netherlands (funded by ERASMUS).

B.A. (Mod) in Natural Sciences, Trinity College Dublin, Ireland (September 1989 to July 1993).
I studied Geology, Geography, Maths and Physics for my first two years. Later, I specialised in Earth Sciences attaining a II-1 grade in my final exams. I went on frequent field trips around Ireland and Europe and was an active member of many student societies. My undergraduate dissertation was published as a paper in Irish Geography (1993).

EMPLOYMENT

• PhD Assistant, University of Bern, Switzerland (October 2006 to May 2008)
After a eight-month pause period, I resumed by doctoral studies at the University of Bern. My PhD title is “A site selection tool for large telescopes using climate data”. I have enjoyed my time in Bern and have given two weather and climate seminars during my time here.

• Meteorologist, Institute of Applied Physics, University of Bern (February 2006 to September 2006)
I was employed as a research meteorologist for 7 months (as a maternity leave replacement), funded by NCCR Climate. I attended the European Geosciences Reunion in Vienna (April 2006) and I won a prize at the 7th Swiss Pro-Clim Global Change Day (2006) for my poster “Water vapour dynamics over Switzerland during severe precipitation in August 2005”.

• PhD / Graduate Assistant, University of Fribourg, Switzerland (May 2002 to January 2006)
I was employed at the Institute of Geography, University of Fribourg as a PhD student funded by the European Southern Observatory. My research area was "Site Selection for Large Telescopes Climate Data". I attended several conferences (Scotland, Hungary,
France) and gave some seminars and presentations, as well as writing scientific papers (Meteorological Applications, Weather).

**Environment Canada, Toronto, Canada (April 2000 to April 2002)**
I occupied several tasks whilst working within the Climate Research Branch of the Canadian Government: Firstly, I designed two new climate-ice websites (www.crys.ca and www.socc.ca). Later, I worked on the homogenisation of a Canadian air pressure database with Dr. Victoria Slonosky; our results were later published in the *International Journal of Climatology*.

**Yellow Pages, Reading, England (January to June 1999)**
I was employed as a team-leader for a group of five in the internet department of Yellow Pages (temporary contract). We created $600,000 worth of internet advertisements over a six month period.

My duties included analysis of numerical model output and the writing weather forecasts for television, newspapers, radio and the internet. On an earlier occasion in 1994, I worked from my home for a small Irish weather company. I gave occasional radio interviews plus one live "chat-show".

**WeatherNet Ltd, Bournemouth, England (September 1996 to September 1997)**
I worked as a meteorologist and climatologist for a small weather insurance company, checking weather related insurance claims. My duties also included weather forecasting and the issuing of severe weather warnings. I did some live and pre-recorded radio interviews. I also took part in an automatic weather station installation in a remote part of Wales.

**Talking Pages, Reading, England (December 1995 to May 1996)**
I worked as part of a customer service "helpline" team, answering telephone calls from clients and helping to resolve their difficulties.

**ERA-Maptec, Dublin, Ireland (August 1993 to July 1994)**
I was a Geographical Information Systems (GIS) Officer, interpreting very high resolution satellite imagery (LANDSAT, SPOT) to detect farmer fraud under a European Union scheme. I digitised Ordnance Survey maps using GIS software.

**Tour Guide (summers 1991 and 1999)**

**INTERESTS / ACHIEVEMENTS**
- **Societies**: Elected Fellow of Royal Meteorological Society; past-Committee Member of Irish Meteorological Society; past Member of Canadian Meteorological and
Oceanographic Society, Geographical Society of Ireland and American Meteorological Society.

- **Hobbies:** I maintain a weather station and weather diary, and I take daily readings. I also make time-lapse cloud photography.
- **Other Hobbies:** Cycling, environmental issues.
- **Languages:** English, French, spoken-German, school Irish.
- **Speaking:** I have been guest-speaker for the Irish Meteorological Society on two occasions (1993 and 1998). In early 1998, I also gave a talk at the Department of Meteorology, University of Reading. I have acted as chairman at Irish Meteorological Society meetings on two occasions. In more recent years (2002-2006), I have given occasional seminars at the University of Fribourg and University of Bern. I have presented the weather on the radio on numerous occasions (see above).