Site selection for OWL using past, present and future climate information

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ABSTRACT

Selection of an ideal site for the new generation of Overwhelmingly Large (OWL) telescopes is dependent on many climatological and meteorological parameters. Among these are cloud cover, atmospheric humidity, aerosol content, air temperature, airflow direction, strength and turbulence. Even relatively minor changes in weather patterns can have a significant effect on seeing conditions.

A composite climatological database has been designed and built for the site selection task at the Department of Geosciences, University of Fribourg, Switzerland. The database is mainly composed of ECMWF and NCEP-NCAR reanalysis data at a global resolution of between 1° and 2.5° latitude / longitude. Using a Java™ based interface, code-named "FriOWL", and programmed in the style of a Geographical Information System, all of this relevant information can be interrogated in order to find the best possible sites for the new telescope. Perhaps the most important variable in site selection is the interaction between air-flow and topography, as atmospheric turbulence greatly affects the image quality produced by the telescope.

Global climate is changing and it will continue to do throughout the 21st century. Therefore, it is important to ascertain the effect of global warming on potential sites. An ideal site in today's climate may not prove ideal within 20 to 50 years. It is therefore planned to update the database with future climate data, using output from Canadian climate models available at the University of Fribourg. High resolution modeling of the critical parameters at preferred sites under future climates is also planned.

Keywords: astronomy, telescope, OWL, site selection, climate change, global warming

1. INTRODUCTION

The European Southern Observatory (ESO) is presently undertaking concept studies on the possibility of a new Overwhelmingly Large (OWL) 100-metre diameter optical telescope[1,2]. The construction of such a telescope would constitute a major engineering challenge[3], but current estimates indicate that the cost may be met within a budget of €1 billion[1,4,5]. A decision on whether to go-ahead with OWL project is due sometime in 2005, and a search for the best possible site in the world is well underway[6,7]. This study refers to site selection task, using the past, present and future meteorological and climatological data.

Site selection for telescopes have an long history[8]. Traditionally, astronomers have looked to the driest and least cloudy sites; thus a plethora of telescopes have been located in the dry, high-altitude or desert regions of the world, such as the Canary Islands, the Rocky Mountains in North America and the Atacama desert in South America. The reasons for choosing these sites are obvious from a meteorological viewpoint; however, few sites have undergone long periods of climatic studies, particularly when considered in relation to climatic change issues[9]. This is especially important today, as the world's climate is changing, both on a global[10,11,13] and regional scale[14,15,16]. Larger, rapid and more profound changes are expected during the 21st century[11,12], although many of the direct and indirect impacts of global warming remain unknown[17]. Marked regional variation is expected, with some areas seeing pronounced warming, others seeing changes in extreme precipitation. Some coastal areas (e.g. northwest Europe) will see increases in the storm climatology[18,19] Therefore, detailed climatological analyses of past, present and future information is essential in the site selection process.

Since its inception in 1962, ESO has chosen Chile as it premier location for large telescopes. Site selection decisions have been based mainly on climatological grounds. La Silla (29°15'S, 70°44'W) was inaugurated in 1969 as the first site, and a 3.6-metre telescope was built here in 1976. Later, Cerro Paranal (24°40'S, 70°25'W) was chosen as the site for four 8.2-metre Very Large Telescopes (VLTs), because of its excellent seeing qualities; it saw first light in May 1998. More recently in November 2003, the go-ahead has been given for the Atacama Large Millimeter Array (ALMA) project, on a 5,000-metre high desert plain near San Pedro de Atacama in northern Chile. It is interesting to note that these site decisions have largely ignored the political issues of the times, with atmospheric qualities being foremost in the decision making process. Although the recent space telescopes (Hubble) can completely eliminate the effects of the atmosphere, recent advances in technology, such as in adaptive optics, allows ground based telescopes to compete with those of space-based astronomy.

The object of this work is to find the best possible site for OWL using meteorological and climatological data for the past, present and future. The best site may be one of the currently existing astronomical sites, or it may be, as of yet, an undiscovered location in another part of the world. The past data used in this study consists of “reanalysis” data, which are described in Section 2 below. Present and future climate data can be accurately simulated by using output from various climate models; these data are also described below. The use of future climate data is crucial in order to decide whether ideal sites in today’s climate will remain ideal within the next 20-50 years.

2. CLIMATE DATA

This work uses climatological datasets known as “reanalyses”. A reanalysis is the “best-guess” state of the global atmosphere at any one given time. These best-guesses are created by re-running the most accurate weather forecast model available, using the greatest amount of input information possible, for any one particular day. A best-guess or reanalysis of the state of the global atmosphere is then produced by the weather forecast model for that day. The same weather forecasting model is then re-run for each time period in the past, using all available data, as far back as possible in time; this time period is usually limited in practice to around 50 years. A typical weather forecast model contains tens of thousands of equations, all based on standard atmospheric physics, with over 50 vertical levels. The horizontal resolution is approximately 75 km and each time step is about 15 minutes. Thus, there are about 750 million values for each meteorological variable every day! The data assimilation technique includes the incorporation of thousands of hourly weather station reports (land and sea), hundreds of radiosonde (meteorological balloons) reports, hundreds of airplane reports, and huge amounts of satellite data for various levels of the atmosphere. The benefit of re-running the same weather forecast model each time is that it avoids apparent “changes” in the climate system, which can occur due to the changeover to more accurate weather forecast models, when new data assimilation techniques are introduced, or when new satellites are launched. Such changes of climate are not real and are spurious. Thus, the only source of error in a reanalysis product will be due to the temporal and spatial availability of the initial weather reports for any one particular day.

The scale of reanalysis data output is much lower, both spatially and temporally, than in their weather forecast model counterparts, although they still represent a considerable feat of scientific computing. Typical reanalyses cover 20 vertical levels, with horizontal grid spacing of about 300km. With a six-hourly time resolution, this makes around one million daily values for each parameter (considerably less than the weather forecast model), although it is important to realize that it is the weather forecast model that has produced the reanalysis output in the first place. The most recent reanalysis data sets have over 50 directly calculated meteorological variables available for the surface. An example of a typical reanalysis product is shown in figure 1. This displays the global surface air temperature for 1 January 2001 at 12 noon Universal Time (UTC). A great advantage of reanalysis products is that they provide plausible estimates of weather or climate from where there is very little surface information or weather stations, such as the southern oceans, Arctic or Antarctica. These estimates can be considered as reliable, as they are all based on the extrapolation of standard atmospheric physics equations used in the weather forecast model and the parameterization of features such as sea-ice, all with a short lead time. In recent years, the assimilation of satellite information has grown dramatically, and it continues to improve. For example, in August 2002, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) launched a new Meteosat Second Generation (MSG) satellite; its radiometer comprises 12 different spectral channels, processing a new image every 15 minutes.

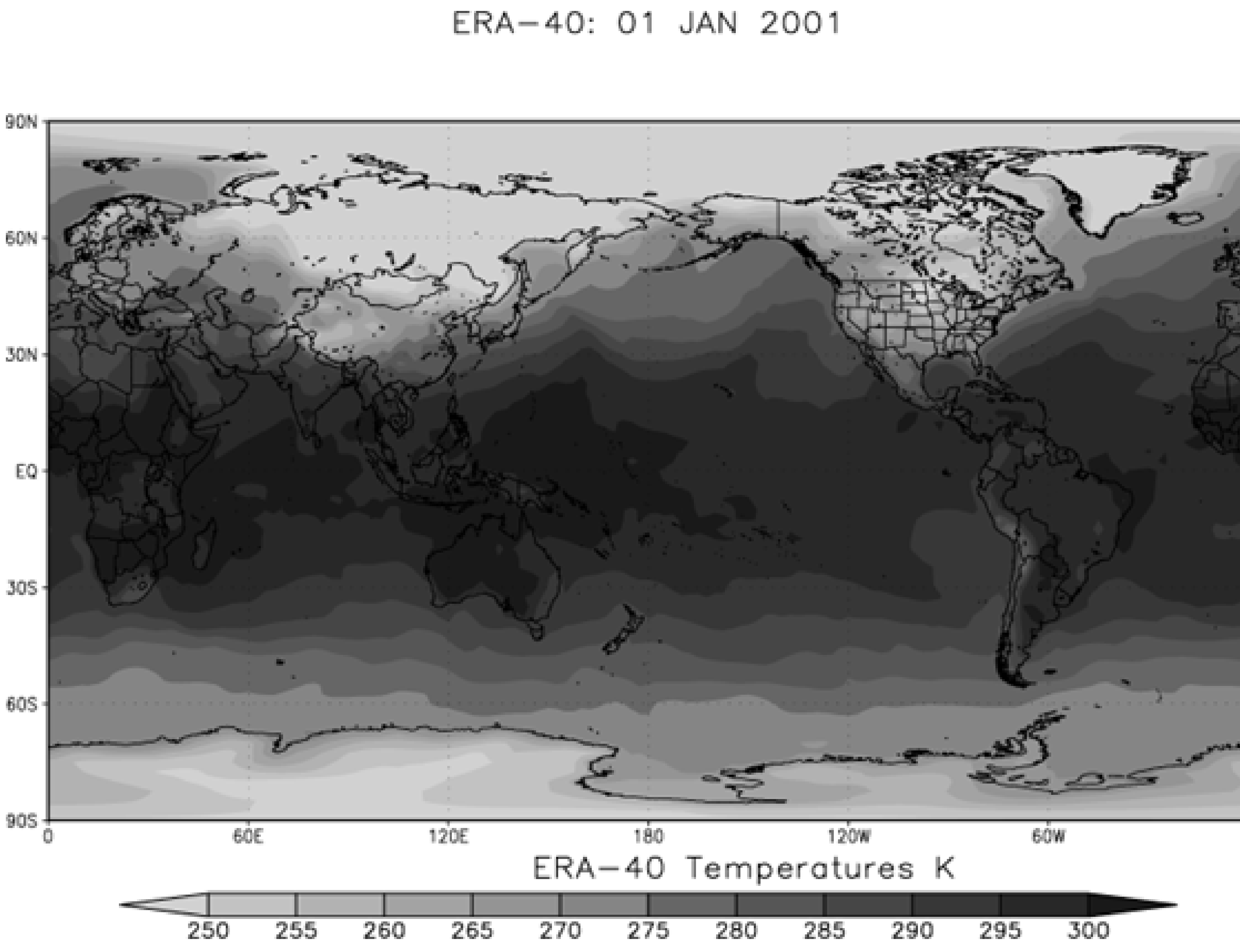

Figure 1: Surface air temperature for 1 January 2001 at 12 UTC, as determined as ERA-40 reanalysis data. The grid resolution is 2.5° latitude / 2.5° longitude.

Two of the most well-known reanalyses products used today by meteorological and climatological scientists are those originating from the European Centre for Medium Range Weather Forecasting (ECMWF) in Reading, England, and the joint product from National Centers for Environmental

Prediction (NCEP) and National Center for Atmospheric Research (NCAR) in Boulder, Colorado, USA. The reanalysis products are known as ECMWF Reanalysis[20] (ERA) and NCEP/NCAR Reanalysis[21] respectively. These reanalysis products are freely available to the scientific community for research purposes, and are available for download on the internet[i], [ii]. Our study uses data from both sets of reanalyses, in order to be as comprehensive as possible. The NCEP/NCAR reanalysis project spans the period from 1948 to the present day, although not all climatological variables are available for this period. ECMWF has produced two sets of reanalysis; ERA-15 stretches from 1979-1993, but it has just four atmospheric levels. ERA-40 is, however, much more comprehensive, covering the period 1957 to 2001 every 6 hours, with more than 25 vertical levels and nearly 60 directly calculated surface parameters[22].

There are, however, some disadvantages with reanalysis datasets. Due to the huge amount of input and output data, both temporally and spatially, as well as the considerable processing time, the creation of reanalysis datasets are slow and heavy on computer usage (it took ECMWF nearly 2 years to create the ERA-40 dataset!). Another major drawback is that they can only resolve meteorological and climatological phenomena on a broad scale; in the example shown above (figure 1) the grid resolution is 2.5° latitude by 2.5° longitude. Thus, longitudinal atmospheric waves and meso-climatic features smaller than about 250km cannot be resolved by reanalysis. Only large synoptic scale features can be distinguished, and we are missing out on potentially vital information contained within the smaller features, which are often of most interest to astronomers. Nevertheless, reanalysis data sets today present the most accurate possible consensus of the global atmosphere at any one time.

The following climatological reanalysis output variables have been used so far in this study; air temperature, precipitable water vapour, total cloud cover, outgoing longwave radiation, u and v wind speed and direction values for the surface, 850hPa and 200hPa levels. These are the direct output variables produced by the reanalysis centres. Secondary calculated meteorological variables are not yet included, such as a severe weather index (snowfall, lightning, etc; we hope to develop these later). Note that outgoing longwave radiation (OLR) is included as an indirect way of measuring cirrus cloud frequency. The ERA products used are based on the 15-year (ERA-15) project from 1979 to 1993; it is hoped to include data from the ERA-40 project at a later time, as well as pressure data for the detection of fronts. Aerosol data is also included at a resolution of 1.8° latitude / longitude, as measured by the Total Ozone Mapping Spectrometer (TOMS) and Earth Probe satellites; these data are also freely available from the Goddard Space Flight Centre (GSFC)[iii], part of the National Aeronautics and Space Administration (NASA) in the USA.

Future climate information output, based on standard projections of climate change, taken from Canadian climate models, are also being incorporated into the site selection database. This is crucial in order to decide whether ideal sites in today's climate will remain ideal in the future. The practice of using Global Circulation Models (GCMs) for the prediction of global climate in the future is well established[10]; however, the regional application of the results of GCMs has been hampered by their coarse grid scale, and the extrapolation of large scale features onto regional or local scale phenomena is problematic at best. For example, the approximate resolution of the gridded output of the third generation Atmospheric General Circulation Model (AGCM3), currently being developed at the Canadian Centre for Climate Modelling and Analysis (CCCma) in Victoria, British Columbia, Canada, is 400 km by 400 km. This scale is so large that features such as the Great Lakes in North America, or the Alps in Europe, are poorly resolved or even completely missing (see figure 2).

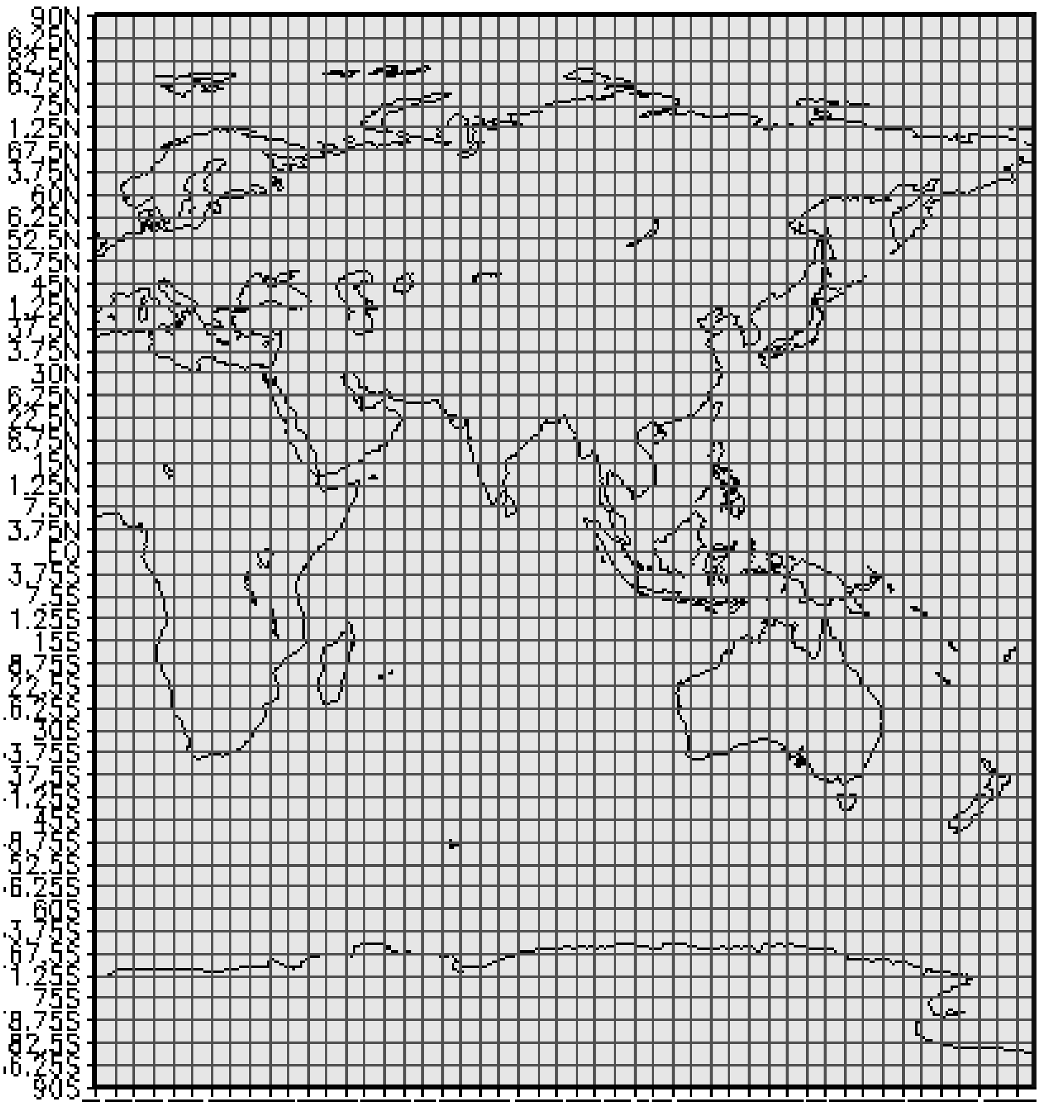

Figure 2: The global resolution of the AGCM3 model of the Canadian Centre for Climate Modelling and Analysis (CCCma), shown for the region 0°E to 180°E, 90°N to 90°S. Note that there are 32 vertical layers.

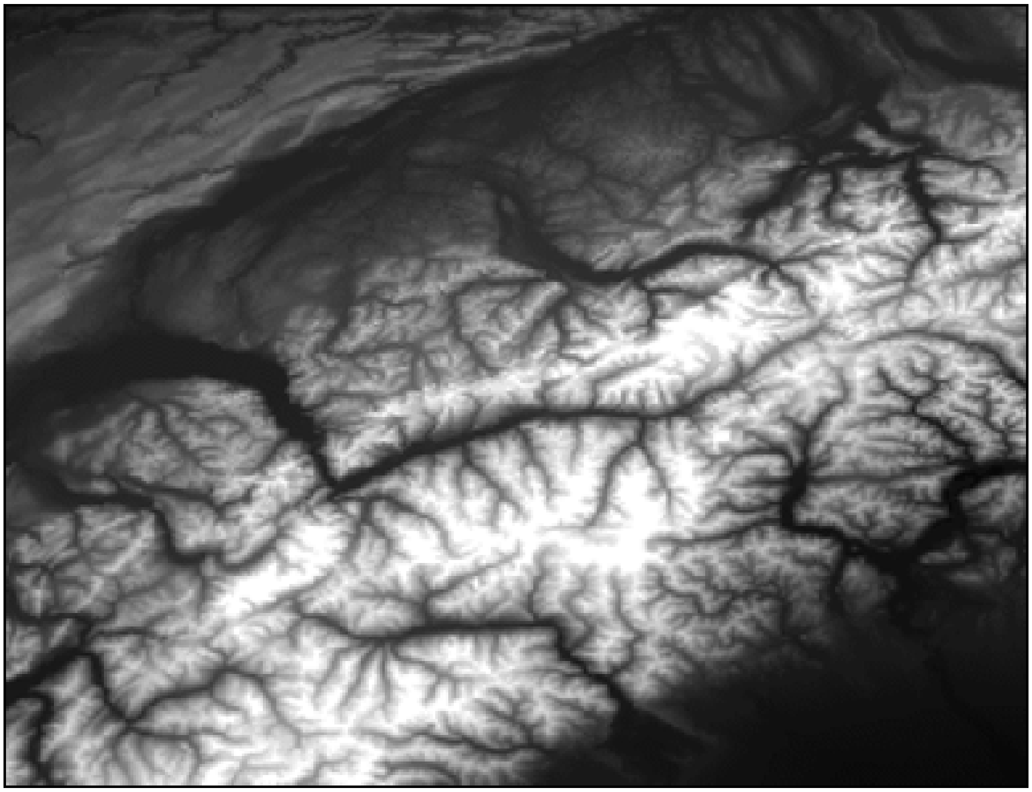

Figure 3: 1 km by 1km digital elevation model of Switzerland (data from the United States Geological Survey). This degree of resolution has been successfully used for regional climate studies in Switzerland[22].

However, all is not lost. For studies of a regional nature, the practice of “downscaling” is applied using Regional Scale Models (RCMs) and the results of such practice has been met with considerable success[,23,24,25]. Due to processing time restrictions, these models are not run on a global scale, but instead at a regional scale; a grid dimension of 1 km by 1km has been successfully used in some instances (see figure 3), with the output from the GCM being used as initial conditions for the running of the RCM. Therefore, we can still produce reasonably acceptable future climatic data at the regional scale. It is hoped to use the Canadian Regional Climate Model (CRCM) at high resolution, here at the University of Fribourg, in order to obtain high resolution images of the critical parameters at potential OWL sites under future climates. The CRCM model was initially developed by scientists at the University of Quebec at Montreal (UQAM), Canada[25].

3. A SITE SELECTION TOOL – “FRIOWL”

A user-friendly computer interface has been designed by the scientists at the University of Fribourg, Switzerland, to assist in the site selection process for OWL. The interface is known as “*FriOWL*”, a name conceived from the titles “University of *Fri*bourg”, and *OWL*. It is worth noting, in passing, that the name “OWL” stands for the eponymous bird's keen eye vision, but also as an acronym for "OverWhelmingly Large", or "Observatory at World Level"[iv]. As we are looking for the best possible site for OWL, we are also looking for the best possible "nest" for OWL.

The FriOWL interface has been created with the Java™ computing language, programmed in a Geographical Information System (GIS) fashion, so as to aid the site selection process. A GIS allows the complete analysis and interrogation of geographical data, permitting the overlaying of layers of information, the addition of weighting factors to these layers, and composition of new layers based on the original raw data. The Java computing language has demonstrated its ability to meet these needs. Java also has strong cross-platform compatibility and powerful graphical abilities. The final product is an easy-to-use graphical user interface (GUI) for non-technical users.

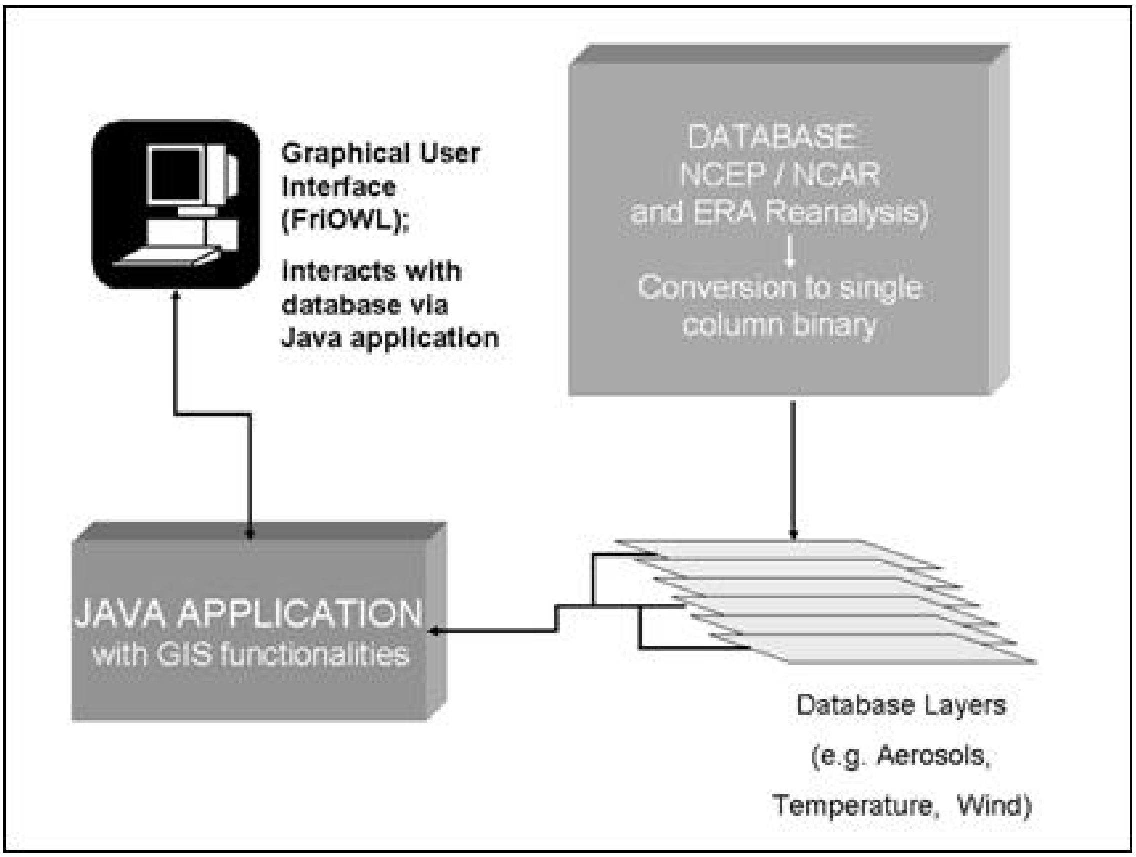

Figure 4: The conceptual design of the FriOWL interface and database.

FriOWL is available for access on the internet[v] and also on a CD-Rom. The CD-Rom is available for Windows, Macintosh, and Sun-Solaris platform users. The internet version is password protected and requires the installation of Java 2™ runtime environment on the user's computer. FriOWL continues to undergo refinements and improvements all the time, according to the needs specified by the funding agency (ESO), and the current version (as of June 2004) is expected to be improved into a multi-functional version 2.0 within several months. A schematic diagram of the design of the FriOWL interface and how it interacts with the database is shown in figure 4. Figure 5 shows an example of what the user interface looks like in a visual manner when started from the FriOWL website.

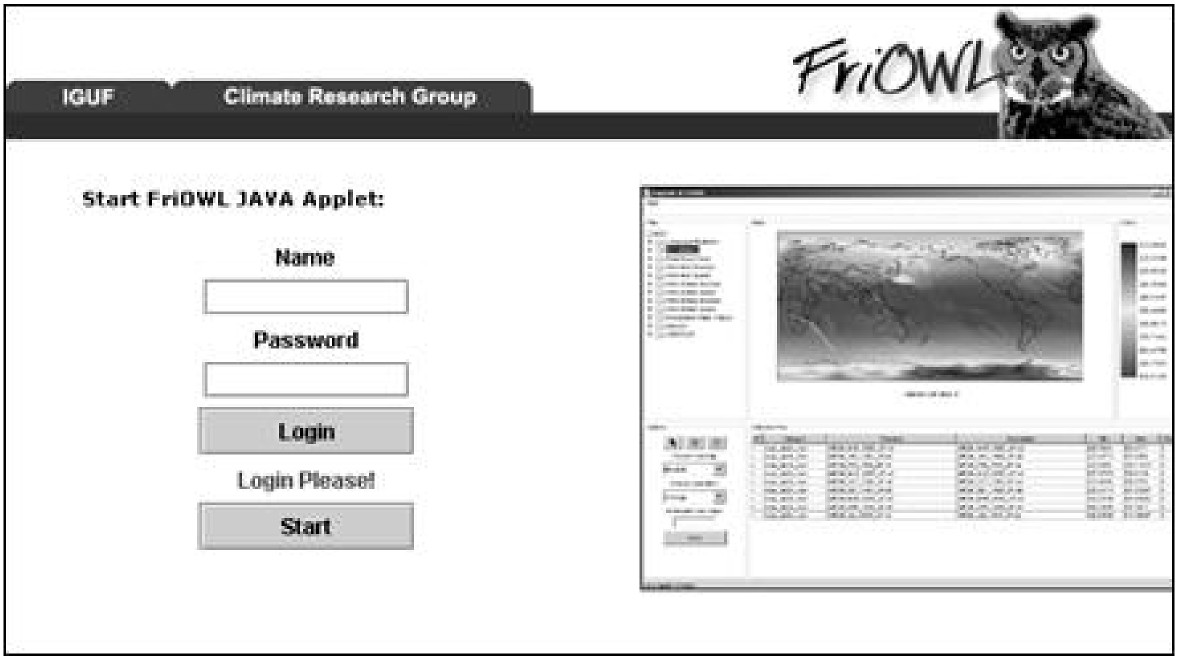

Figure 5: The FriOWL user interface before startup from the FriOWL website.

The FriOWL interface is a simple Java application, consisting of a standard graphical user interface, with several sub-frames embedded within one main user window. These frames can be interrogated easily and simply by clicking the mouse-cursor in the appropriate place. The user can display an image by simply clicking on the relevant file in the menu-tree.

At present, there are four mathematical operations than can be undertaken on the user maps displayed. These involve calculating the average, maximum, minimum and anomaly of all user maps displayed. Zooming into areas of interest, the use of different palettes and colormaps can all be enacted (the colormaps are based on the GIS software IDRISI Release 3.2[26]). The user can also save any resulting map as a single new "composite" map, deposit it on the server, and re-access it at a later time if so desired.

Thus, FriOWL allows manipulation of the meteorological and climatological database in order to refine the search for the best possible site for OWL. This refinement will continue to improve as FriOWL undergoes further development and improvements, especially with added GIS functionality. The object of FriOWL, is, for example, to narrow down locations in world where mean cloud cover is less than 10%, where jetstream winds are predominately light, where total column precipitable water content is less than 3mm, and where these regions show little change under future climates.

4. DISCUSSION AND CONCLUSIONS

Are the current sites in Chile the best in the world? Do alternative, as of yet undiscovered sites exist somewhere else? Before trying to answer these questions, we must reconsider again the limits of our climatological information. It is possible that better sites do exist, but they may not be resolved using the grid scale employed by climatological reanalysis model output used in this study (see figure 2). It is quite probable, for example, that there are many other mountain summits in Chile that boast even better qualities than the present VLT configuration at Paranal, but these mountain summits have simply not been discovered yet, nor are they located where it would be logistically practical to install a large astronomical observatory. We are considerably limited by the broad grid scale of the reanalysis output, and it will be many years hence before higher resolution products are available. Downscaling methods, employed in RCMs do go some way towards providing a present and future synopsis of the mesoscale climate, but astronomers are often interested in local variations or microclimates, which are often limited to the scale of a mountainside or less. This is something that only long periods of local observation can provide, using network of weather stations and profile masts.

However, we can still use the reanalysis output for a classification of sites on the synoptic scale; that is, the same areas which experience the influence of large scale weather systems. Figures 6, 7 and 8 show examples from the output from the reanalysis products of ERA-15, NCEP/NCAR, as well as the TOMS / Earth Probe aerosol data. In detail, figure 6 (below) shows the total mean annual cloud cover for the globe, as determined by the ERA-15 reanalysis data for the period 1979 to 1993 inclusive. Note that there are only a few regions in the world where mean annual total cloudiness has a frequency of less than 0.1 (10%); these regions are the Atacama and Sahara-Arabian deserts, the Namibian coast and parts of Australia.

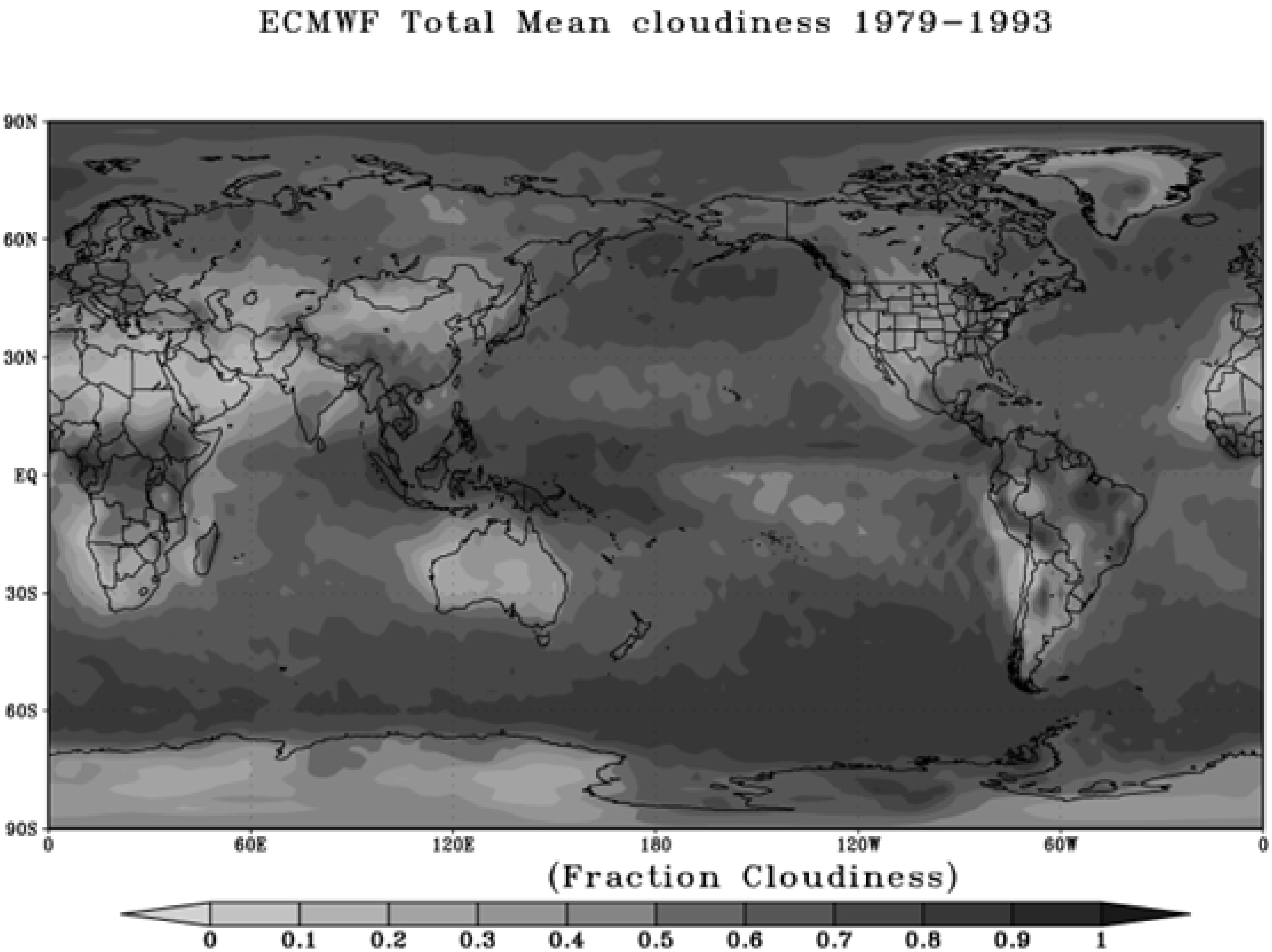

Figure 6: Mean annual total cover (in tenths) from 1979 to 1993, as calculated from ERA-15 (ECMWF) reanalysis data.

The total column precipitable water is also of great importance to astronomers. Low precipitable water contents (PR_WTR) of 1mm or less constitute optimal photometric conditions, whereas higher values are a lot less desirable. Figure 7 (below) shows the long term mean annual PR_WTR for the globe, as calculated from the NCEP / NCAR reanalysis data for the period 1948 to 2001. Again, note that there are only a few regions in the world (excluding isolated mountain tops) where PR_WTR is consistently lower than 5mm; these are the Atacama Desert, the Himalayan region and Antarctica.

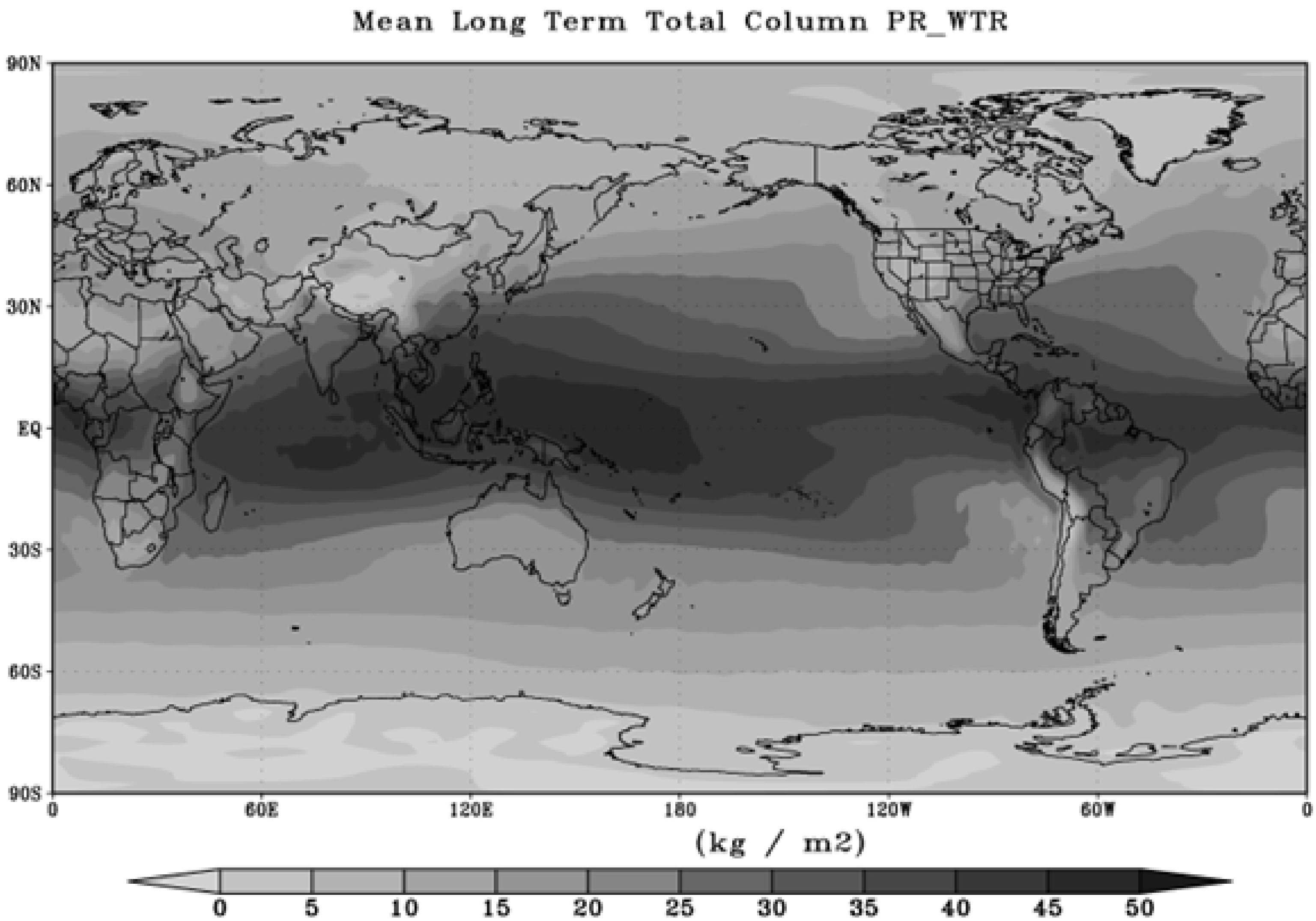

Figure 7: Mean annual long term precipitable water vapour (kg/m^2, or mm) from 1948 to 2001, as calculated from NCEP / NCAR reanalysis data.

Figure 8 shows the mean tropospheric aerosol index for the period 1980 to 2002 (with some gaps), as calculated by the TOMS Nimbus-7 and NASA Earth Probe satellites. When the TOMS Nimbus 7 satellite was launched in 1978, it was initially designed to measure ozone values in the stratosphere[27]. However, it was soon realized that, that ultra-violet light absorbing tropospheric aerosols could be distinguished also, and this lead to new algorithms being developed to calculate the Aerosol Index. The Nimbus 7 satellite failed in 1993, but it was replaced by NASA's Earth Probe satellite in 1996, which continues to operate today.

Looking more closely at figure 8, we can see large regions of high tropospheric aerosol content over Africa, with a plume westwards over the mid-Atlantic. These aerosols are related to the annual anthropogenic burning of vegetation over central Africa during the dry seasons, and mineral dust from the deserts of northern Africa and the Arabian Peninsula. Due to powerful convection, these aerosols reach high altitudes before being blown westwards across the Atlantic by the easterly trade winds. Note smaller sources of aerosols over India, China and Australia. There is also a small maximum over the South China Sea, related to seasonal typhoons in this area (which cause significant amounts of sea spray to enter the atmosphere).

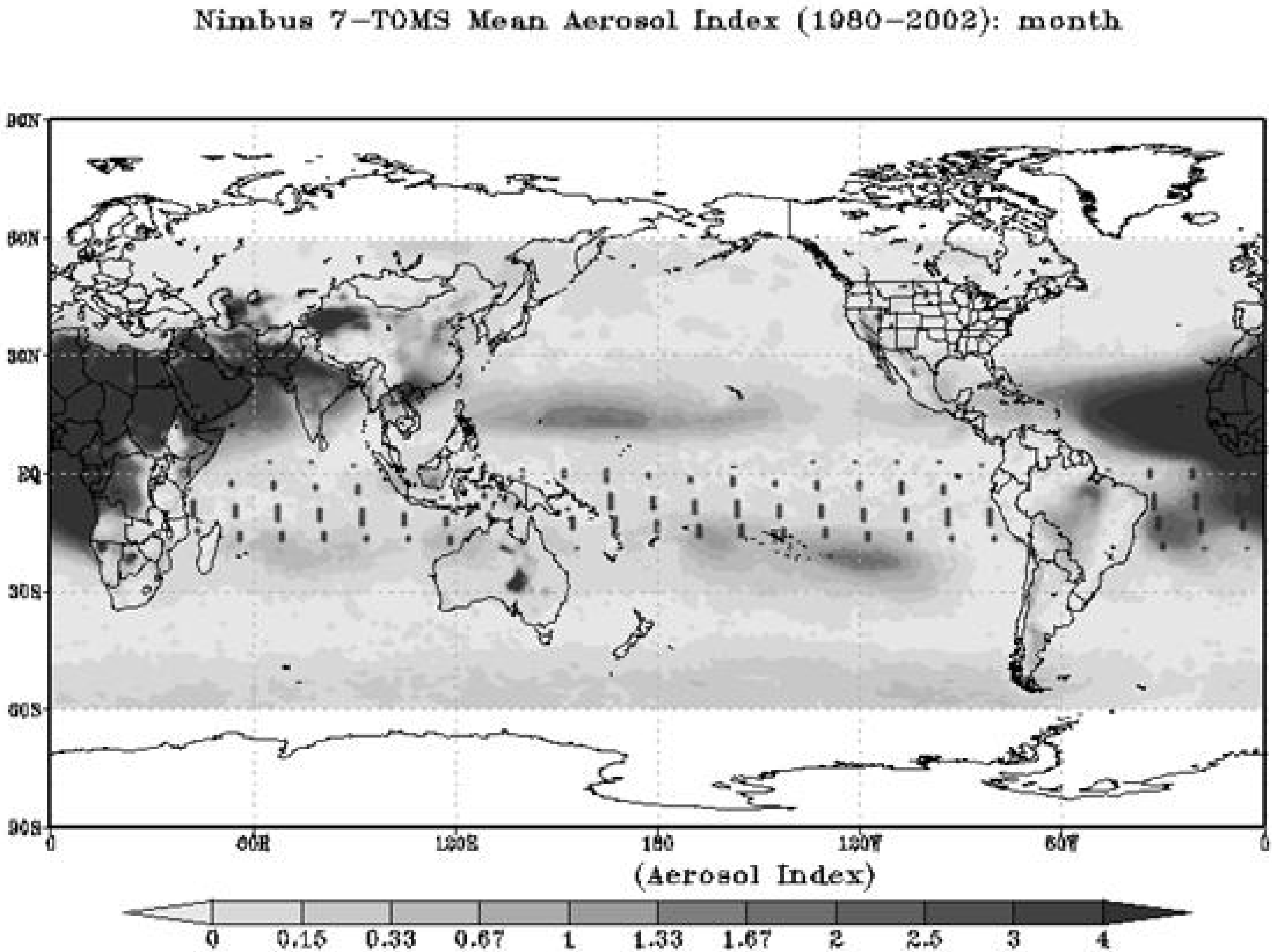

Figure 8; Total mean aerosol index for the globe from 1980 to 2002 (except for period from 1993 to 1996), as calculated by the TOMS and Earth Probe satellites.

This study represents a new approach by the astronomical community, as it is the first time that astronomers have used comprehensive climatological reanalysis data in their search for a new telescope site. So far, reanalysis data has proven that it can find ideal sites across the globe, albeit on a large scale. The use of GIS technologies enables us to overlay the different data layers, and find ideal sites that might otherwise go un-noticed. The application of future climate data, especially those from regional climate models, presents an exciting new opportunity in the search for a “nest for OWL”.

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ECMWF ERA-15 and ERA-40 data used in this study have been provided by ECMWF and have been obtained from ECMWF and the ECMWF data server at http://data.ecmwf.int/data/. NCEP Reanalysis data is provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/. Java is a registered trademark of Sun Microsystems Incorporated.

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[i] http://data.ecmwf.int/data/

[ii] http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml

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