CLIMEX

VERSION 3

User's Guide

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Table of Contents

1 Introduction 7

1.1 WHAT IS CLIMEX ? 7

1.2 MINIMUM REQUIREMENTS TO RUN CLIMEX 8

1.3 INSTALLING AND RUNNING CLIMEX 8

1.4 CHANGES FROM VERSION 1 9

1.5 MAJOR CHANGES FROM VERSION 2 10

2 An Overview of CLIMEX Functions 11

2.1 THE *CLIMEX MODEL* 12

2.1.1 Compare Locations 12

2.1.2 Compare Years 16

2.2 CLIMATE MATCHING 17

2.2.1 Match Climates 17

2.2.2 Match Climates (Regional) 19

3 The conceptual basis of the *CLIMEX Model* 20

3.1 SPECIES DISTRIBUTION AND ABUNDANCE 20

3.2 THE CLIMEX INDICES 22

3.3 GROWTH RELATED INDICES 23

3.3.1 Growth Index (GI_A *and* GI_W) *........ 23*

3.3.2 Temperature Index (TI) 24

3.3.3 Moisture Index (MI) 27

3.3.4 Radiation Index (RI) 29

3.3.5 Substrate Index (SVI) 30

3.3.6 Diapause Index (DI) 31

3.3.7 Light Index (LI) 33

3.3.8 Biotic Index (BI) 34

3.4 STRESS INDICES 34

3.4.1 Cold Stress (CS) 36

3.4.2 Heat Stress (HS) 38

3.4.3 Dry Stress (DS) 39

3.4.4 Wet Stress (WS) 40

3.5 INTERACTION STRESS INDICES 40

3.6 CONSTRAINTS TO PERSISTENCE 42

3.6.1 Length of growing season (PDD) *42*
3.6.2 Obligate Diapause or Vernalisation *42*
3.7 ECOCLIMATIC INDEX (EI) 43
3.8 PARAMETER FITTING VIA INFERENCE FROM DISTRIBUTION 44
3.8.1 General Parameter Fitting Example *51*
3.8.2 Diapause Parameter Fitting Examples *60*
3.9 PARAMETER FITTING USING THE GENETIC ALGORITHM 63
4 Climate Matching and the Climate Match Indices 71
4.1 MATCHING CLIMATES USING REGION-FITTING 73
4.1.1 Preparing the Location Set *73*
4.1.2 Setting the Region Match Options *75*
4.1.3 Running and displaying the results *76*
5 Tasks 77
5.1 LOADING A CLIMEX APPLICATION 77
5.2 SPECIES PARAMETER FILE OPERATIONS 78
5.3 OPERATIONS ON SPECIES PARAMETERS 79
5.4 USING CLIMATE CHANGE SCENARIOS 82
5.5 USING IRRIGATION SCENARIOS 84
5.6 SPECIFYING LOCATION SELECTIONS 84
5.7 ADDING NEW LOCATIONS TO THE DATABASE 86
5.8 USING THE GRID-BASED CLIMATE DATA 86
5.9 CREATING AND MODIFYING MAP BACKGROUNDS 86
5.10 EXTRACTING RUN INFORMATION FOR USE IN A SPREADSHEET OR GIS 90
5.11 CONVERTING SPECIES FILES FROM VERSION 1 TO VERSION 2 91
6 The Meteorological Data Manager facility (MetManager) 94
- CREATE/EDIT/DELETE LOCATION SELECTIONS 96
- CREATE A NEW DATA-FILE 98
- OPEN AN EXISTING DATA-FILE 99
- IMPORT METEOROLOGICAL DATA 99
- EDIT LOCATION AND METEOROLOGICAL DATA 101
- DELETE LOCATIONS 102
- MAINTAIN THE DATABASE 102

7 Bibliography 103
8 Appendix I. Parameter Mnemonic Reference. 116

9 Appendix 2. The LOC/MET file format. 122

10 Appendix 3. The Species File format...125

IMPORTANT - PLEASE READ THIS

If you are a typical software user you will not read much of this guide.

If nothing else please read this page before you start.

1. Detailed installation instructions are included in Chapter 2. Please read them before you begin installation.

2. If you have an older version of CLIMEX, please read the following page as it outlines the changes that have been made since the Patch [January 2001] for Version 1.1.

3. ***This User's Guide contains the theory behind CLIMEX and an overview of the major functions and uses of CLIMEX. Instructions on how to use functions within CLIMEX can also be found in the CLIMEX and DYMEX Help files. The Help file is accessed from within the program and from context sensitive Help Buttons within specific functions. If you have not used CLIMEX before, we*** *strongly* ***recommend you read this guide from cover to cover before you try any serious predictions with the model. Understanding the theory is essential to the efficient use of the program. Previous CLIMEX users will also benefit from reading this guide as it contains expanded explanation of the theory behind CLIMEX and re-interpretations of functions within CLIMEX.***

4. Specific instructions on operation of each feature of the software are included in the Tutorials that accompany the software on the CD-ROM. More detailed instructions on the software is contained in the DYMEX User Guide.

5. We welcome any suggestions on how to improve CLIMEX. If you have any comments or ideas, please contact:

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1 Introduction

CLIMEX Version 3 is an upgraded and enhanced version of the CLIMEX 2.0 program. In the same way as its predecessor, it has been built using the DYMEX generic and modular population modelling software (http://www.ento.csiro.au/dymex/dymexfr.html). The major changes to the software are outlined in Section 1.5. Operational changes from Version 2 have been kept to a minimum, and parameter files are compatible (though a few new parameters are added to the model). For users of Version 1.1, Section 1.4 outlines the major differences between that Version and Version 2.

Some conventions used throughout this guide are as follows:

❗ *The exclamation symbols throughout the manual represent important notes.*

💡 *The light bulb represents examples and ideas that can be used when constructing a model.*

1.1 What is CLIMEX ?

The CLIMEX software contains two quite different climate-matching tools. There is the CLIMEX model (referred to as ‘CLIMEX’ or as the ‘CLIMEX model’), and the CLIMEX ‘Match Climates’ function. The latter is a tool for comparing the meteorological data of different places without reference to any particular species and we will return to it later. The CLIMEX simulation model was first described by Sutherst and Maywald (1985) and a number of enhancements and further caveats and insights into using the model have been described in a series of publications listed at the end of this Guide, particularly (Sutherst et al 1995, Sutherst 1998). The model is based on the assumption that if you know where a species lives you can infer what climatic conditions it can tolerate. In other words, CLIMEX attempts to mimic the mechanisms that limit species’ geographical distributions and determine their seasonal phenology and to a lesser extent their relative abundance. CLIMEX enables the user to estimate the *potential* geographical distribution and seasonal abundance of a species in relation to climate. It does not try to match the patterns of climate and species’ distribution in the same way that a statistical fitting would seek to achieve. More on this later.

CLIMEX is applied to a species by selecting values for a set of parameters that describe its response to temperature, moisture and light. In this guide the term ‘population’ is used as the target entity, representing an average population of an animal or plant species or biotype for example. An Annual Growth Index (GI_A) describes the potential for growth of a population during the favourable season. Four stress indices (Cold, Hot, Wet and Dry), and in some cases their interactions, describe the extent to which the population is reduced during the unfavourable season. The Growth and Stress Indices are combined into an

Ecoclimatic Index (EI), to give an overall measure of favourableness of the location or year for permanent occupation by the target species. Two limiting conditions, ie the length of the growing season and obligate diapause, act as overall constraints to the EI value where relevant. Results are presented as tables, graphs, or maps.

A species' climatic requirements are inferred from its known geographical distribution (either in its native range or in another region where it has been established for a long time), relative abundance and seasonal phenology. Some laboratory data, such as developmental threshold temperatures, can be used to fit or fine tune CLIMEX parameter values. Initial estimates of parameter values are fine-tuned by comparing the indices with the known presence or absence, seasonal phenology and, preferably, relative abundance of the species in each location.

Once the parameter values have been estimated and where possible validated against independent data, CLIMEX can be used to make predictions for other, independent locations. Independent data means that there is no connection between the data and those data used for fitting the model, hence it is not appropriate to sub-sample a geographical distribution and then use the remaining data to test the model.

1.2 Minimum Requirements to Run CLIMEX

The minimum requirements to run CLIMEX V2 are:

- Pentium 400 MHz or better.
- Windows NT 4, Windows 2000 or XP
- 256 megabytes of RAM.
- 400 megabytes of disk space.

1.3 Installing and Running CLIMEX

- **To install CLIMEX on your machine**

1. Place the CD into the drive.
2. The installation setup program should start automatically. If for some reason it does not, select **Start|Settings|Control Panel** from the Taskbar Menu. Click on the **Add New Programs** button at the left, and then the CD or Floppy button in the next dialog. Windows will search for executable files and should find **setup.exe**, if not, select the **setup.exe** file by using the browse option.
3. Now click on the **Finish** button and the CLIMEX install program will start.

If Version 2 of the DYMEX program has been installed previously, the CLIMEX components can be added by copying the CLIMEX model files (in directory \Dymex2\Dymex\Models) to the Models directory on the user's hard disk.

➢ To load a CLIMEX application

See Section 5.1 of this document for instructions on loading a CLIMEX application.

1.4 Changes from Version 1

CLIMEX has been considerably enhanced from Version 1.1. For users familiar with Version 1.1, the following list details the major differences. *Those changes that may cause models to behave differently when moved to Version 2 are shown in italics.*

The various CLIMEX applications are now DYMEX models. This has meant a radical change to the user interface and operation of the program which will require some relearning by users of CLIMEX V1.1. However, it has also allowed CLIMEX to use the very flexible display facilities provided by DYMEX. In particular, map capabilities are now much more powerful, with zoom and pan support. In addition, maps are constructed from standard shape files, many of which are available from various internet sites. A new MapManager allows map region files to be defined visually. Many map projections have been provided. Map printing has been enhanced and a Print Preview function provided.

The same flexibility is also now available for Tables and Charts, which can be configured in a multitude of ways, and the configurations can be saved and re-used in subsequent runs. Results can be saved as Microsoft Access® database tables. Charts and maps can be exported in raster (Windows bitmap, bmp or jpg) or vector (Windows enhanced metafile, emf) form.

The new MetManager program is a Microsoft Access application and overcomes the data importing problems that users commonly had with the previous version. It is easy to create multiple databases of meteorological data and Location Selections from them. Data can still be imported with the .loc/.met format, as well as from .bmt files or Access files. A 0.5° world grid of meteorological data is included for those tasks where the standard database is not sufficient. Acknowledgement should be given to the Climatic Research Unit (CRU), Norwich (http://www.cru.uea.ac.uk/cru/data/hrg.htm) when the data are used. A reformatted 0.1° grid is available for non-commercial applications by courtesy of the CRU Norwich (http://www.cru.uea.ac.uk/cru/data/hrg.htm) and users are required to agree to comply with CRU restrictions when they download the database from the CSIRO/Hearne website.

Soil Moisture and Average Temperature have been added as variables that can be included in the Match Index for Match Climates.

Species Parameters are now stored in a separate file for each species (with the extension .cxp). The comments related to a species are stored in its parameter file. A conversion utility (*cxdxconvert.exe*) is provided to convert species and comment files from the Version 1 format to Version 2.

The degree-day dependent Cold Stress uses degree-days based on a new threshold parameter (DVCS) rather than DV0. Note, however, that the default value of DVCS is the same as DV0. The new flexibility allows the users to use thresholds other than DV0.

A third component has been added to the Cold Stress. This component acts in the same way as the component based on minimum temperature, but uses average temperature instead of the minimum. It is useful when comparing responses to climates with different diurnal ranges of temperature.

The Interaction Stresses now include the time since the stress began as part of the calculation (as is done for all other Stress Indices). When such parameter files are converted using the conversion utility, the new parameter file will contain an indicator that directs CLIMEX to use the old Interaction Stress method. These species should preferably be refitted to use the new method.

The differences in the Ecoclimatic Index (EI) can be plotted on a map after two sequential runs using the same locations. Thus users can quickly appreciate the changes that would result from, for example, the application of a Climate Change Scenario or a change in a parameter value.

1.5 Major Changes from Version 2

Two species can now be fitted with interactions between them (either competition or synergy) specified via parameters. The Biotic Index that describes this interaction is described in Section 3.3.8.

Radiation (as ***Radiation Index***, section 3.3.4) is available as an additional component to the Growth Index.

Two non-specific components (definable by the user) can be added to the Growth Index. These are the ***Physical Substrate Index*** and the ***Biotic Substrate Index*** (Section 3.3.5). The variables determining these indices can either be specified as a single value for all locations or they can be location specific and read from the MetManager.

Automatic fitting of the parameter values that determine the Stress indices is available via a genetic algorithm based fitting routine (Section 3.9).

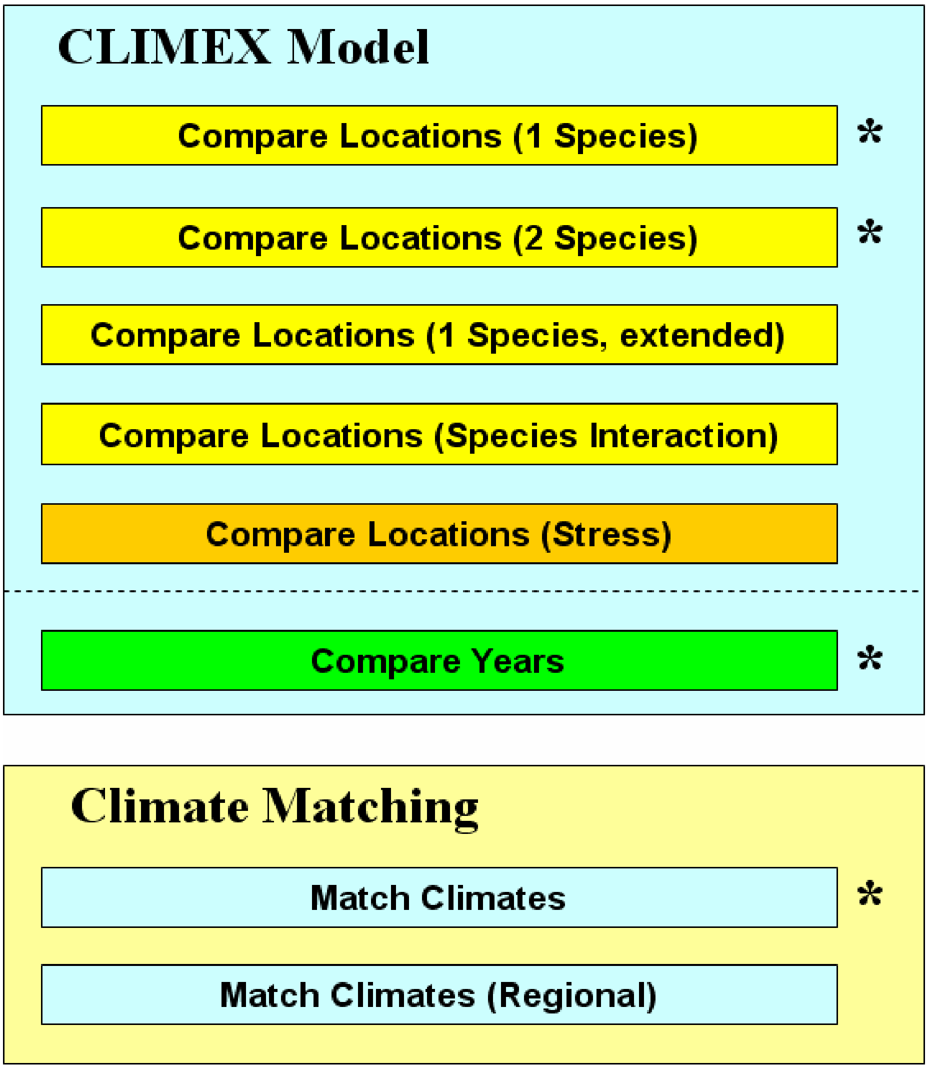
“Regional matching” (i.e, the use of a set of locations for the ‘Home’ location in the **Match Climates** function) is available (see Section 2.2.2).

The MetManager application has been extended to allow the importation of up to 5 user-defined location constants as well as up to 5 user-defined variables.

2 An Overview of CLIMEX Functions

The CLIMEX software package contains eight ‘applications’ that are optimised for different tasks. Each of the applications is in fact a separate “DYMEX model”. The term ‘application’ is used in order to avoid confusion between these and the **CLIMEX model** in this manual. The applications can be grouped into two types. Six of them are species-based and are built using the “CLIMEX Model” (described in detail in Section 3) while two others carry out simple climate-matching tasks (Fig. 2-1). Each of these applications is described later in this Section. The “CLIMEX Model” functions are further grouped into those that carry out the “Compare Locations” task and one that does the “Compare Years” task. The applications marked with an asterisk were already in CLIMEX V2 and will be suitable for the majority of tasks. The other applications add new functionality as described in the corresponding section below.

Fig. 2-1. The ‘applications’ included in the CLIMEX package, grouped into their functional types. The applications marked with an asterisk were included in Version 2.


CLIMEX Model
Compare Locations (1 Species)
*
Compare Locations (2 Species)
*
Compare Locations (1 Species, extended)
Compare Locations (Species Interaction)
Compare Locations (Stress)
Compare Years
*
Climate Matching
Match Climates
*
Match Climates (Regional)

2.1 The *CLIMEX Model*

The CLIMEX model describes the response of a species or other taxonomic unit to climate. It operates in two modes: *Compare Locations* and *Compare Years.* In the former, the response of a species to the long-term average climates of different locations is compared, while in the latter the response to climates in different years at the same place is compared. This means that there are two different types of meteorological data involved in CLIMEX. Section 3 provides a thorough conceptual treatment of the CLIMEX model and should be read before using CLIMEX.

2.1.1 Compare Locations

The Compare Locations function enables the user to predict the *potential* geographical distribution of a species or a pair of species in relation to climate only, based on its climatic preferences. This function uses a meteorological database consisting of monthly long-term average climatic variables for any number of locations. A set of parameters describes the species' response to the average climate of any given location, with the implicit assumptions that (i) the species is able to survive the annual variation in climate that is associated with that location, and (ii) that the annual variation at all locations is equal (to comply with the statistical requirement that comparison of means assumes equal variances). This latter assumption is not true and needs to be considered when comparing results from regions with different annual variation such as occurs when comparing areas with continental climates, like the southern USA or southern China, with other areas that do not experience occasional very extreme seasons, like much of Africa for example. Currently, there is no global database available to allow CLIMEX to take account of the differences in variation between regions.

The model parameters are divided into three groups: one group defines seasonal population growth, one defines stresses that limit the geographical distribution, and the third describes constraints that may exclude species from some areas. An iterative process of comparing the known and predicted distributions for the same region is used to derive values for the parameters. Once the parameter values have been defined, they can be used to predict the potential distribution of the species in other independent locations.

The Compare Locations function is primarily used for describing the potential distribution of a species as determined by climate. Being able to describe and map the potential distribution of species enables policy makers at both national and international levels to make rational decisions about managing pests or distributing natural enemies. For example, if the Compare Locations function indicates that areas are climatically unsuitable for a potential biocontrol agent, there is little point in introducing such a species. From a pest risk analysis perspective, a Compare Locations run may indicate that an area is highly suitable for an exotic pest species and so could cause costly losses of production or damage to the natural environment.

Once the species' parameters have been defined adequately, the Compare Locations function also enables the user to examine the relative seasonal potential for growth of the species in any given location. Having a relative measure of the species' likely performance in a given location has implications for the local management of pest species.

Since defining a species' parameter file involves estimating the stresses that limit its distribution, the Compare Locations function contributes towards understanding the biology of a species for which the user may have little biological information. The process of fitting the parameter values may help a user to identify areas where further research on some aspect of the biology (eg cold tolerance, or adaptations to heat stress) might prove useful.

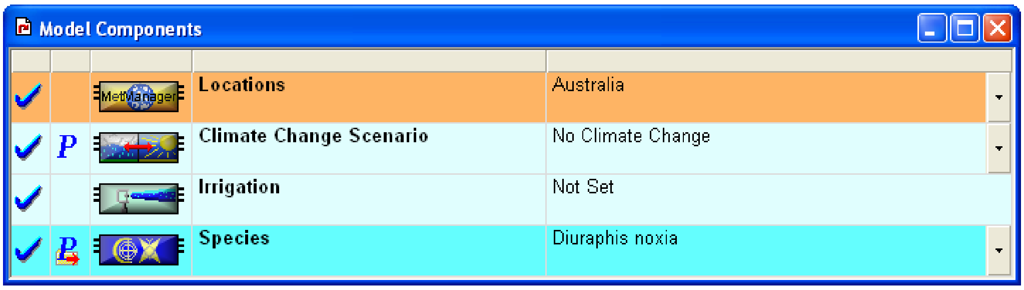
The Compare Locations function is also useful in selecting field sites for a research project. Ecological research often demands that field sites represent the range of conditions experienced by the species, from marginal to optimal. A Compare Locations run will help an ecologist readily identify the most representative field sites. Furthermore, it is usually the marginal sites that are the most interesting to the researcher. This function of CLIMEX enables the identification of sites that are marginal for different reasons (eg because they are too hot, to dry, to cold, or too wet), and thus helps the researcher to select sites that will yield interesting results.

By running CLIMEX with average data from different years, some indication of the relative changes in the geographical range can be obtained. However, note that averaging smoothes data and so such results cannot be compared directly with those from simulations using long-term average data (see below).

2.1.1.1 Compare Locations (1 species)

This application applies the CLIMEX model to a single species. It is normally the most frequently used of the CLIMEX applications and its main window is illustrated in Fig. 2-2.

Fig. 2-2 The Compare Locations (1-species) application.



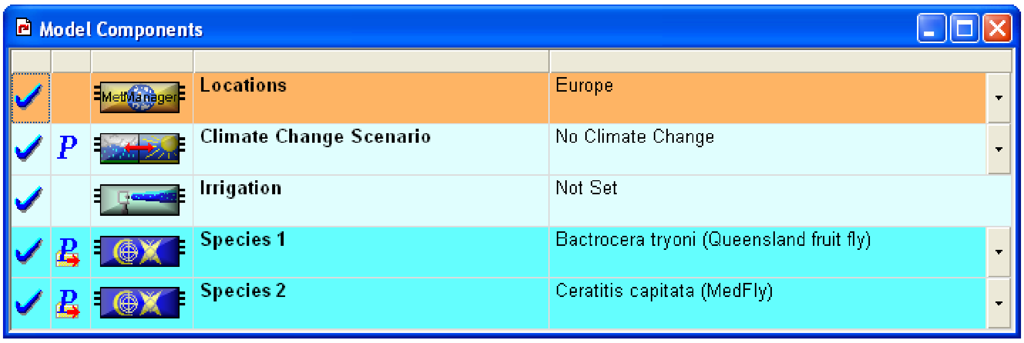
✓	Locations	Australia
✓	Climate Change Scenario	No Climate Change
✓	Irrigation	Not Set
✓	Species	Diuraphis noxia

The set of locations for which the simulation is to be run is specified in the top (***Locations***) panel (see Section 5.6 for details on how to do this). Optionally, a climate change scenario (Section 5.4) and/or irrigation regime (Section 5.5) can be set from the corresponding panels. The species is selected in the ***Species*** panel (Section 5.2).

2.1.1.2 Compare Locations (2 species)

The 'Compare Locations (2 species)' just adds a second species to the facilities offered by the 'Compare Locations (1 species)' application (Fig. 2-3). The two species are completely independent; there is no interaction between them. A common reason for using this application is to plot both the species of interest and its host on the same map for convenient comparison.

Fig. 2-3. The Compare Locations (2-species) application.



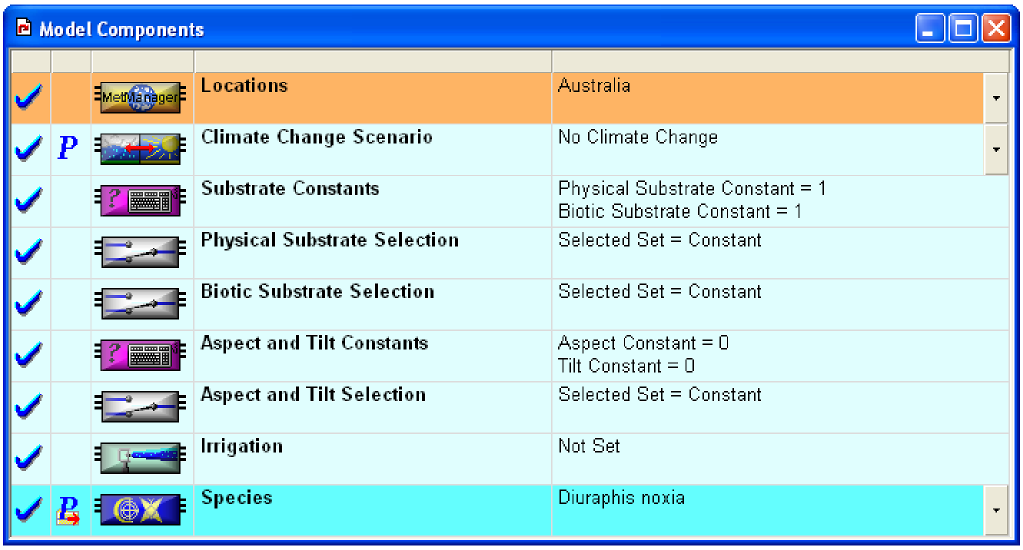
✓		MetManager	Locations	Europe
✓	P		Climate Change Scenario	No Climate Change
✓			Irrigation	Not Set
✓	P		Species 1	Bactrocera tryoni (Queensland fruit fly)
✓	P		Species 2	Ceratitis capitata (MedFly)

The setup for this application is the same as that for the 1-species application (Section 2.1.1.1), with only the addition of the second species that needs to be selected.

2.1.1.3 Compare Locations (1 species, extended)

This application models a single species, but adds several components to the Growth Index (GI). These are a Physical Substrate Index and a Biotic Substrate Index (discussed in Section 3.3.5) and a Radiation Index (Section 3.3.4). The radiation value that is used to calculate the Radiation Index can be modified by slope properties (aspect and tilt), whose values can be constant or read from the data file for each location.

Fig. 2-4. The Compare Locations (1-species, extended) application.



✓		MetManager	Locations	Australia
✓	P		Climate Change Scenario	No Climate Change
✓			Substrate Constants	Physical Substrate Constant = 1 Biotic Substrate Constant = 1
✓			Physical Substrate Selection	Selected Set = Constant
✓			Biotic Substrate Selection	Selected Set = Constant
✓			Aspect and Tilt Constants	Aspect Constant = 0 Tilt Constant = 0
✓			Aspect and Tilt Selection	Selected Set = Constant
✓			Irrigation	Not Set
✓	P		Species	Diuraphis noxia

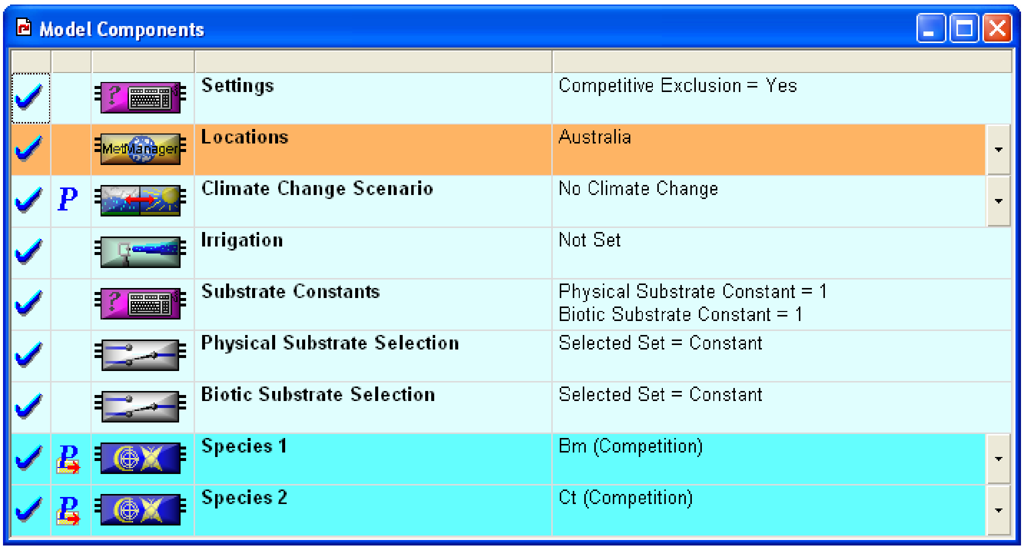
The Component Window for this application is shown in Fig. 2-4. Each of the "substrate" variables can be either the same value for all locations or be different for each location. This is specified in the ***Physical Substrate Selection*** and ***Biotic Substrate Selection*** panels, respectively. If "Constant" is selected for either substrate variable, the value that is used is that set in the ***Substrate Constants*** panel. If one of these substrate variables is set to be "Location-specific", its value must be available from the MetManager data file specified in the *Location Selection* that is being used (as set in the ***Locations*** panel).

The radiation value for calculating the Radiation Index (RI) is affected by the settings for the aspect and tilt of the slope onto which the radiation is incident. Aspect and tilt can be either constant (i.e., have a common value for all locations) or set separately for each location. If selected to be constant, the values set in the ***Aspect and Tilt Constants*** panel. If these variables are set to be "Location-specific", their values must be available from the MetManager data file specified in the *Location Selection* that is being used (as set in the ***Locations*** panel).

2.1.1.4 Compare Locations (Species Interaction)

The 'Compare Locations (Species Interaction)' application (Fig. 2-5) models two species simultaneously, but in contrast to the 'Compare Locations (2 species)' application, competition or synergy between the species can be included explicitly.

Fig. 2-5. The Compare Locations (Species Interaction) application.



✓	Settings	Competitive Exclusion = Yes
✓	Locations	Australia
✓	Climate Change Scenario	No Climate Change
✓	Irrigation	Not Set
✓	Substrate Constants	Physical Substrate Constant = 1 Biotic Substrate Constant = 1
✓	Physical Substrate Selection	Selected Set = Constant
✓	Biotic Substrate Selection	Selected Set = Constant
✓	Species 1	Bm (Competition)
✓	Species 2	Ct (Competition)

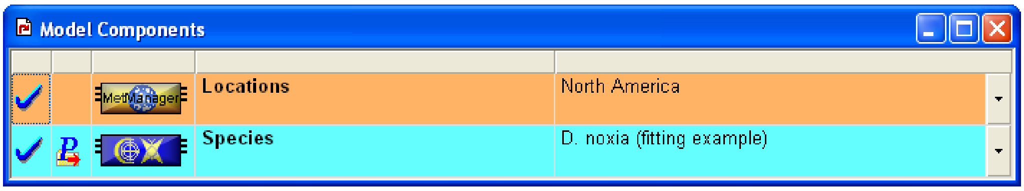
Note that this application allows use of Physical and Biotic Substrate Indices, as well as the Radiation Index (if required). The effect of competition or synergy is modelled via a *Biotic Index* that affects the value of the Growth Index, and its calculation is detailed in Section 3.3.8. In some cases of competitive interactions, the species that "wins" will exclude the other species completely. This can be modelled by selecting "Competitive Exclusion" in the

Settings panel. The substrate variables can be set to be the same for all locations, or they can vary between locations, as described for the 'Compare Locations (1-species, extended)' application (Section 2.1.1.3).

2.1.1.5 Compare Locations (Stress)

This special application is used only for the automatic parameter fitting using the built-in genetic algorithm (see Section 3.9). It is a simplified CLIMEX model that does not include any *Growth Index* components or the ability to set climate change scenarios or apply irrigation (Fig. 2-6).

Fig. 2-6. The Compare Locations (Stress) application.



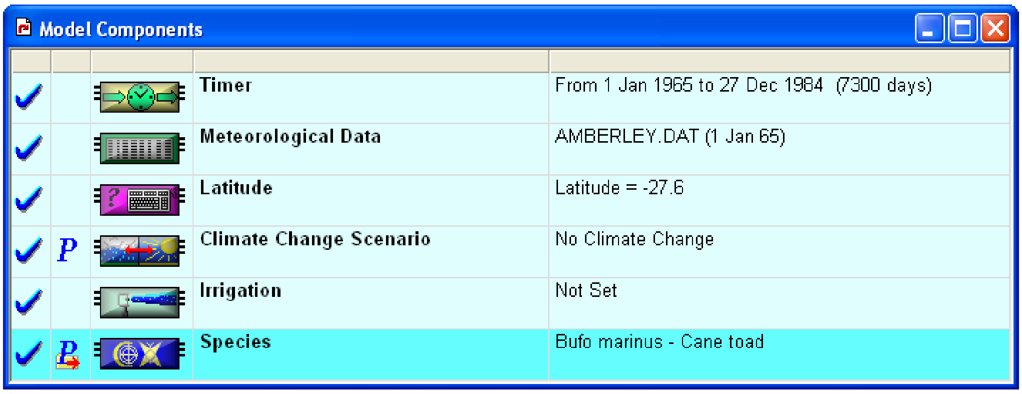
✓			Locations	North America
✓	P		Species	D. noxia (fitting example)

2.1.2 Compare Years

The Compare Years application uses a database consisting of consecutive years of monthly data from the same location, rather than long-term average data from many different places as in the Compare Locations function. Compare Years lets the user examine the effect of climatic variation on the potential population growth and survival of a species over consecutive years. The user can enter weekly or monthly climatic data for any number of years and CLIMEX will display the species' response for each year.

Another use for the Compare Years facility is to compare the times in different years when the climate of representative locations on a migration path become suitable for the establishment of migrant insects. This enables the user to differentiate between climate and arrival times as factors that limit the appearance of migrants in different years.

Fig. 2-7 The Compare Years application.



✓			Timer	From 1 Jan 1965 to 27 Dec 1984 (7300 days)
✓			Meteorological Data	AMBERLEY.DAT (1 Jan 65)
✓			Latitude	Latitude = -27.6
✓	P		Climate Change Scenario	No Climate Change
✓			Irrigation	Not Set
✓	P		Species	Bufo marinus - Cane toad

It is important to note that daily data averaged over weeks or even months will still have greater variability than the long-term average data with which the original parameter values were (usually) estimated by inference from the geographical distribution. In order to minimise the incompatibility between the different data sets it is desirable first to average daily data to monthly and allow CLIMEX to interpolate it back to weekly averages. Secondly, it is inevitable that even monthly data for a particular year will generate more extreme values than occur in long-term average data, so the results from Compare Years and Compare Locations *should not be compared*. The values of each index in the Compare Years output can be compared with each other as they are relative measures of growth or stress. Often, stress values at locations within the normal species' distribution will exceed 100 for short periods or years but this should not be interpreted as precluding the existence of the species. The value of 100 is estimated from smoothed, long-term average meteorological data and long-term average geographical distributions and so represents an average value.

2.2 Climate Matching

Climate matching consists of selecting a location and then looking for locations elsewhere that have a climate that is similar. This is a much less 'intelligent' function that the CLIMEX model. It simply enables the user to compare the meteorological data from different places, with no reference to the preferences of a given species. It answers questions such as: Are the extreme minimum and maximum temperatures similar? Do the two locations have similar amounts of rainfall and similar seasonal rainfall patterns?

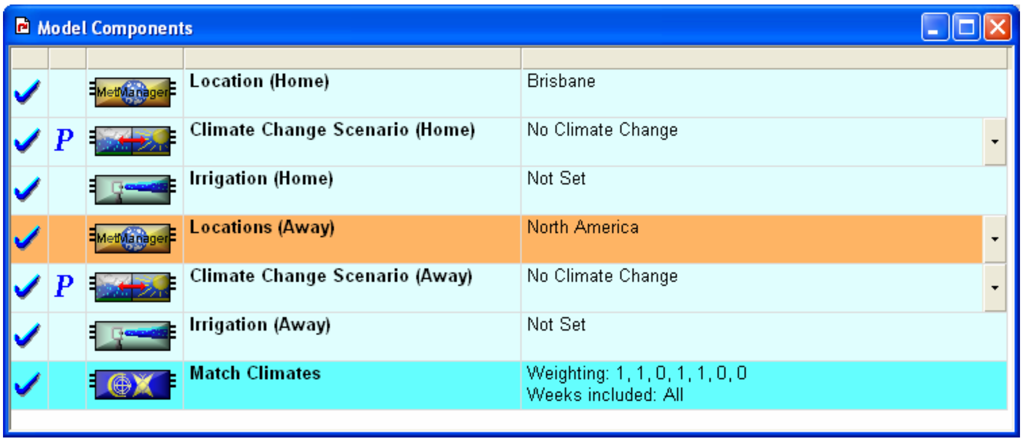
A comparison of climates in different locations does however have implications for species. If the user knows that a given species occurs in given locations in Mexico, and is looking to import that species to Australia as a biocontrol agent, a Match Climates analysis can show whether the climate of the destination is similar to that of the area of collection of the species. If the analysis indicates that there is only a small area in Australia that has a similar climate to the Mexican locations that support populations of the species, there are high risks of failure of establishment by the species in Australia.

Another use of the Match Climates function is to provide a rough assessment of the risk of a pest establishing in a new location (country, continent), with implications for quarantine and pest risk analysis. The Match Climates analysis can be conducted with no knowledge of the species, except that it does occur in certain locations. Thus, if there are no biological data or distribution map of the species, the Match Climates analysis nonetheless enables the user to qualitatively assess the risk.

2.2.1 Match Climates

The Match Climates application (Fig. 2-8) allows the user to select a location (the "Home" location) and find locations within a specified *Location Selection* (the "Away" locations) whose climate is similar to that of the "Home" location. The measure that is used to describe the similarity between a pair of locations is the ***Composite Match Index***. Its formulation is described in Section 4.

Fig. 2-8 The Match Climates application.

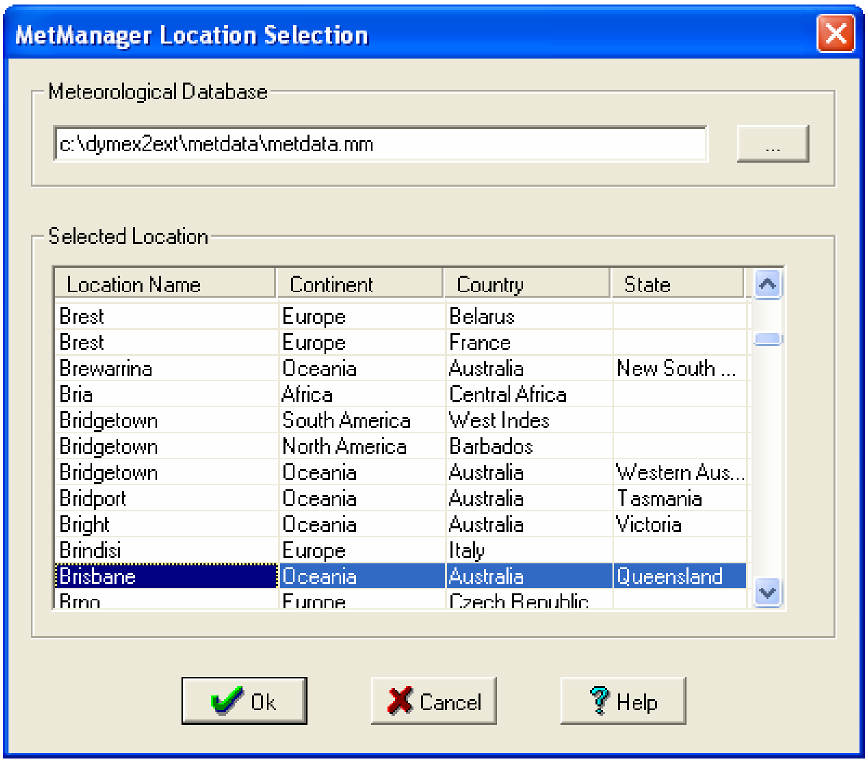


Model Components

✓		MetManager	Location (Home)	Brisbane
✓	P		Climate Change Scenario (Home)	No Climate Change
✓			Irrigation (Home)	Not Set
✓		MetManager	Locations (Away)	North America
✓	P		Climate Change Scenario (Away)	No Climate Change
✓			Irrigation (Away)	Not Set
✓			Match Climates	Weighting: 1, 1, 0, 1, 1, 0, 0 Weeks included: All

The “Home” location is specified by clicking on the Location (Home) icon and selecting “Initialize (Single Location)” from the resulting menu. This opens the **MetManager Location Selection** dialog (Fig. 2-9), showing all the locations in the currently loaded Meteorological Database. The desired “Home” location can be selected from this list.

Fig. 2-9 The MetManager Location Selection dialog, showing *Brisbane* selected as the ‘Home’ location.



MetManager Location Selection

Meteorological Database

c:\dymex2ext\metdata\metdata.mm

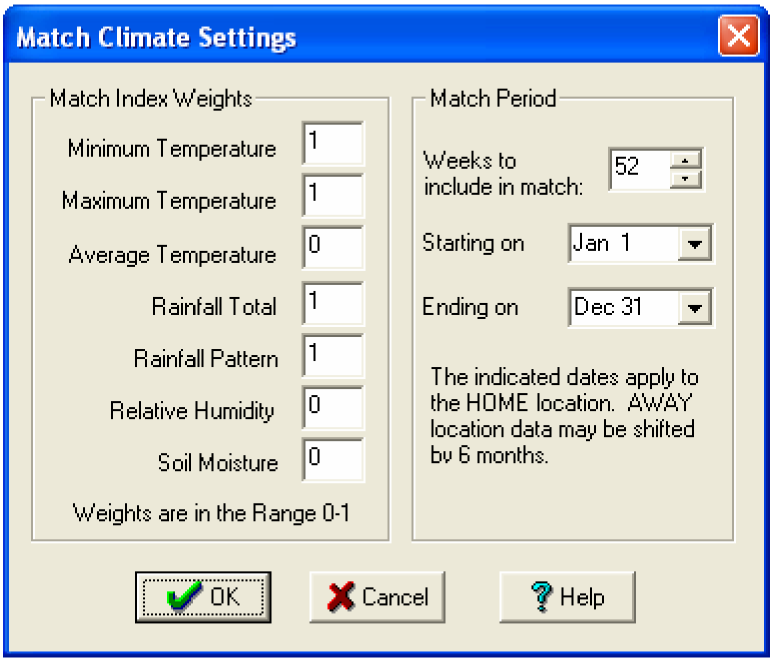
Selected Location

Location Name	Continent	Country	State
Brest	Europe	Belarus	
Brest	Europe	France	
Brewarrina	Oceania	Australia	New South ...
Bria	Africa	Central Africa	
Bridgetown	South America	West Indes	
Bridgetown	North America	Barbados	
Bridgetown	Oceania	Australia	Western Aus...
Bridport	Oceania	Australia	Tasmania
Bright	Oceania	Australia	Victoria
Brindisi	Europe	Italy	
Brisbane	Oceania	Australia	Queensland
Brno	Europe	Czech Republic	

The “Away” *Location Selection* for which the application is to be run is specified in the ***Locations (Away)*** panel (see Section 5.6 for details on how to do this). Optionally, a climate change scenario (Section 5.4) and/or irrigation regime (Section 5.5) can be set for either the “Home” or “Away” locations from the corresponding panels.

The Match Climates panel allows some match properties to be set via the **Match Climates Setting** dialog (Fig. 2-10). In particular, users can set different weights for the components of the ***Composite Match Index*** (see Section 4) and the period for which the comparison is made.

Fig. 2-10 The Match Climate Settings dialog.



Match Climate Settings

Match Index Weights

Minimum Temperature: 1
Maximum Temperature: 1
Average Temperature: 0
Rainfall Total: 1
Rainfall Pattern: 1
Relative Humidity: 0
Soil Moisture: 0

Weights are in the Range 0-1

Match Period

Weeks to include in match: 52
Starting on: Jan 1
Ending on: Dec 31

The indicated dates apply to the HOME location. AWAY location data may be shifted by 6 months.

2.2.2 Match Climates (Regional)

The “Match Climates (Regional) application is exactly the same as the Match Climates application, with the exception that a Location Selection (i.e., a set of locations) rather than a single location is specified as the “Home” location. The application’s appearance in the **Model Components** window is exactly the same as that of the Match Climates application (Fig. 2-8), and match options, climate change scenarios and irrigation can be set in the same way. Section 4.1 gives a detailed description of the use of this application.

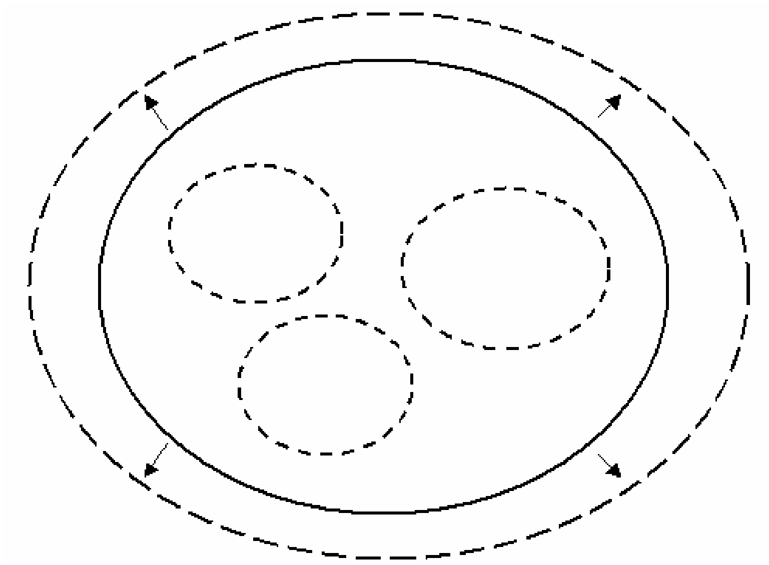
3 The conceptual basis of the *CLIMEX Model*

CLIMEX is a simplified dynamic model that enables the user to simulate the climate-related processes that determine the relative abundance, seasonal variation in numbers and geographical distributions of species. It is therefore designed to infer the mechanisms affecting population processes, rather than simply to describe the pattern of the field observations based on matching patterns of meteorological data, as most statistical models do.

3.1 Species Distribution and Abundance

It has long been recognised that the ultimate limits of the distribution of most poikilothermic animals (those that have a body temperature that fluctuates with the temperature of the environment) are determined by climate (Andrewartha and Birch, 1954; Krebs, 1978). Of course, climate is not the only factor limiting species geographical distributions (Fig. 3-1). Both physical and biotic habitat components (eg. soil type, host availability, competitors or predators, and more recently humans) are often important. However, climate is the only factor for which global data are readily available to provide an initial estimate of the potential range of the species when under the influence of other habitat components, otherwise described as the 'realised niche'. All of these modifiers must be considered when making assessments of CLIMEX predictions and a **Report Template** is provided below to prompt users to address each of those issues when fitting CLIMEX parameter values. Detailed studies will be needed to define the roles of the non-climatic factors.

Fig. 3-1 The potential range of a species in relation to climate as estimated from the observed geographical distribution (——) using CLIMEX. This equates to the 'realized' or 'ecological' niche of a species. The effect of removal of physical constraints and biotic interactions is to expand the range (— —) to fill the 'fundamental' or 'physiological' niche. Within these zones, the availability of suitable habitats (– –) will further restrict the range.



Template for CLIMEX Species Analysis

- Name:
- Biology:
- Distribution:
  - CABI CPC Ref: etc
- Comments and literature review related to fitting CLIMEX parameters
- Distribution records used to estimate CLIMEX parameter values
- Evidence for non-climatic limits to distribution
  - Physical barriers
  - Hosts
  - Vectors
  - Other species (competition, predation)
  - Artificial environments (eg irrigation or glasshouses)
- Stress indices
  - Hot
  - Cold
  - Dry
  - Wet
- Climatic Constraints
  - Obligate diapause
  - Length of growing season
- Growth
  - Temperature
  - Moisture
- Results
  - Goodness of Fit
  - Independent Validation
  - Source Risks
    - Geographical
    - Seasonal
  - Destination Risks
    - Geographical
    - Seasonal
- Discussion
- References
- Species Parameters Table

In the absence of evidence to the contrary, CLIMEX works on the assumption that the distribution of a species is determined by climate in the context of a background of biotic resistance. i.e., it uses the ecological (realised niche) rather than the physiological (fundamental niche) limits of a species to infer its responses to climate. CLIMEX assumes that similar intensities of biotic resistance (not the same species) will occur in new environments. This is a gross assumption, but specific information is rarely obtainable before a species introduction, unless a specific species interaction has occurred elsewhere. Thus CLIMEX constitutes a pragmatic tool that needs to be handled accordingly to provide guidance without any pretence of unattainable precision. As the realised range will almost always be less than the range set by physiological limits, the results are conservative in terms of conservation but may underestimate the areas at risk from invasive species.

CLIMEX also assumes that most animal and plant populations experience one season that is favourable for population growth, and one that is unfavourable and may prevent the species' persistence at a given location. In areas with bimodal rainfall for example the limiting season is less evident and CLIMEX results will need to be examined in more detail to interpret the situation.

Note that if physiological data are available for a species, the CLIMEX parameters can be estimated to describe the fundamental or physiological niche of the species. Such data are rarely available or sufficient to describe a species response to all possible climatic conditions.

CLIMEX contains a meteorological database of ~ 3000 selected locations worldwide as well as interpolated climatic grids provided by the global change community through the CRU in Norwich UK for non-commercial use (Appendix 1). CLIMEX interfaces the climatic preferences of a species with the database. To estimate the climatic suitability of locations for a species, CLIMEX applies the species response functions, which are defined in the species parameter file, to the meteorological database to calculate several indices of climatic suitability. The theory behind the CLIMEX indices is provided in this guide so that the user can gain a sound understanding of the mechanics and reasoning of CLIMEX calculations. Understanding these indices is essential to the use and interpretation of CLIMEX.

A principal aim of the model is to provide a single number (the Ecoclimatic Index, EI) to describe how favourable the climate of a location is for a particular species. This figure can be broken down into component parts for a more detailed examination of the species' response to climate at any given location (Sutherst and Maywald, 1985). In acknowledgement of the semi-quantitative nature of the results, given the type of observations on which the relationships were derived, CLIMEX presents the results on maps in the form of circles or shading that are proportional to the value of the index, rather the presenting actual numbers.

3.2 The CLIMEX Indices

CLIMEX uses several indices and two constraints to estimate the potential growth and survival of a population at a given location. These indices are grouped into growth-related indices and stress-related indices. All of the indices are calculated weekly, and the weekly values are then either used to calculate a derived index (eg Growth) or combined into an annual value of the index. The subscripts '$_W$' and '$_A$' are used to distinguish the weekly from the annual values where the distinction is necessary.

Stress Indices relate to factors limiting the geographical distribution. The component indices are:

Cold Stress (CS)
Heat Stress (HS)
Dry Stress (DS)
Wet Stress (WS)
Stress Interactions (Cold/Wet, Cold/Dry, Hot/Wet, Hot/Dry)

CLIMEX combines the growth and stress indices into an Ecoclimatic Index, which describes the climatic suitability of a location for a species as a single number between 1 and 100.

The philosophy in CLIMEX is that ‘population growth’ occurs within the range of climatic parameters defined by the Growth Indices (eg TI, MI). Stress, leading to negative population growth, is assumed to accumulate outside the range of values suitable for growth and is described by the Stress Indices.

The value of EI is reduced to zero if either of two constraints is not met. These are firstly, a minimum amount of thermal accumulation during the growing season (PDD) and secondly, suitable conditions that enable species with obligate diapause/dormancy or vernalisation (DI) to complete diapause or reproductive development.

3.3 Growth Related Indices

3.3.1 Growth Index (GI_A and GI_W)

CLIMEX uses a weekly thermo-hydrological Growth Index (TGI_W) (enhanced by radiation, light and/or a user-defined ‘substrate’ if desired) scaled from 0 – 1 to describe conditions that favour growth of a population. The target organism can be any biological entity such as a species, variety or biotype, but not an aggregate entity such as a community because the components of the latter will each have a unique response. For brevity, the terms ‘species’ and ‘population growth’ are used throughout this document to represent these concepts.

The Weekly (Thermo-hydrological) Growth Index,

$$TGI_W = TI_W \times MI_W \times RI_W \times SV_W \times LI_W \times DI_W$$

where TI_W, MI_W, RI_W, SV_w, LI_W and DI_W are the weekly Temperature, Moisture, Radiation, Substrate, Light and Diapause Indices respectively. Any or all of these indices can be included depending on the requirements of a particular analysis. $MI_{W,}$ TI_W, RI_W and LI_W model the organism’s weekly response to moisture, temperature, radiation and light, while DI_W takes into account the effects of periods of dormancy in plants, or diapause in insects, on the ability of an organism to grow or propagate. SI_W models the weekly response to a specified substrate (such as soil type).

The most comprehensive Weekly Growth Index also includes a component, the Biotic Index BI_W, which reflects the effect on population growth of interacting species

The (Full) Weekly Growth Index, $GI_W = TGI_W \times BI_W$

BI_w reflects the presence of the second species, either lowering or increasing the potential growth rate of the species under consideration. BI_W is always equal to 1 (and thus has no effect on the Growth Index) when a single species is being modelled. The indices are explained in more detail in the following sections. The GI_W values are averaged to give an Annual Growth Index (GI_A) scaled between 0 - 100.

The Annual Growth Index, $GI_A = 100 \sum_{i=1}^{52} GI_{W_i} / 52$

The GI_W describes the weekly suitability of the climate for the growth of, for example, an individual plant or a population of insects (e.g. development, reproduction, survival). GI_W is used to infer the period of seasonal growth of the species without reference to life cycle stages or generations, although the latter can be computed if the thermal requirements of the species are known in terms of degree-days per generation. It therefore effectively averages the response of different stages, although differences in responses of specific lifestages (eg susceptibility to high moisture values) may be captured if the stage occurs at a discrete time of the year. The annual GI_A describes the overall potential for growth, and gives an indication of the potential size or relative abundance of a species across its range as determined by climate alone.

When applied to a population and averaged over one generation, the GI_W is analogous to a weekly-scaled '*finite rate of increase*' that combines fecundity and mortality rates (Andrewartha and Birch, 1954), as explained by Sutherst, Maywald and Skarratt (1995). Both measures suffer from a failure to incorporate the effects of temperature on development rates of multivoltine species (which have more than one generation per year). This deficiency becomes evident when attempting to integrate the values over periods much longer than one generation. Then, multiplicative effects become apparent, and the relationship between the annual total population and GI_A (or finite rate of increase) is not linear for a variety of reasons such as cumulative growth and negative feedback (density dependent) effects. Users can accommodate these effects manually by extracting the weekly values and analysing them further outside CLIMEX.

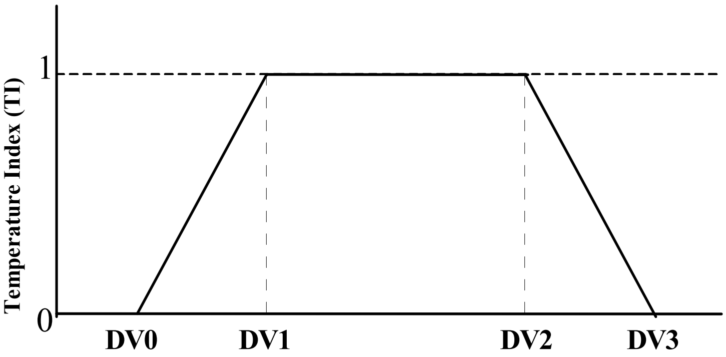
3.3.2 Temperature Index (TI)

The weekly Temperature Index (TI_W) describes the response of the species to the daily temperature cycle. It varies between 0 and 1. Population growth is maximised when $TI_W = 1$, and is zero when $TI_W = 0$.

Four parameters define the range of suitability for temperature, which are used to calculate TI_W. The four parameters used to define the range of temperatures suitable for population growth (see Fig. 3-2) are:

DV0 = the lower temperature threshold
DV1= the lower optimum temperature
DV2= the upper optimum temperature
DV3=the upper temperature threshold

Fig. 3-2 The Temperature Index as a function of population growth. TIW = 1 when the range of weekly temperatures is between the parameters DV1 and DV2, and TIW = 0 when the temperature is below DV0 or above DV3.



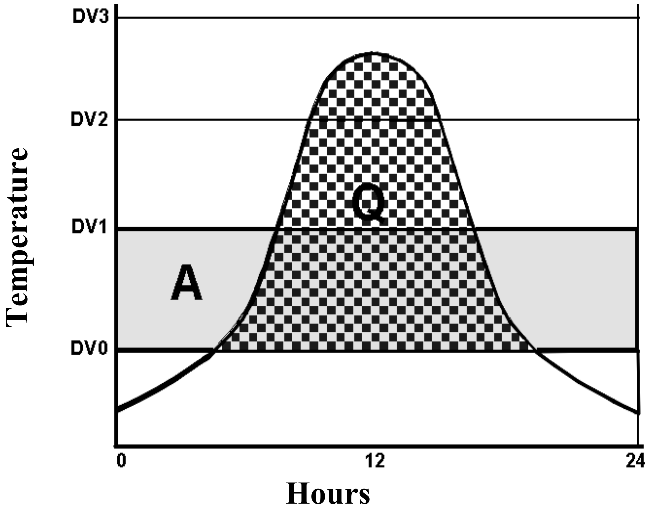
A fifth parameter, PDD, denotes the number of degree-days above DV0 (the lower temperature threshold for population growth) required to complete an entire generation. It is used to calculate the potential number of generations per year and also acts as a limiting condition when a minimum of one generation has to be completed for the species to exist in a given location. If the number of degree-days set for PDD is not reached, the species is unable to complete a generation. In this case, the EI is set to 0 and the species is deemed not to be able to persist at that location.

CLIMEX uses the degree-day concept when calculating the Temperature Index (TI) and the number of generations per year (from PDD). The value of the temperature parameters DV0 - DV3 for a species describe the temperature range in which it can live. In a 24-hour period, the total degree-days for population growth is equivalent to Q, the shaded area in Fig. 3-3, ie the area under the temperature curve above DV0 but below DV3. To calculate this area, CLIMEX uses the algorithm published by Baskerville and Emin (1969).

Annual degree-day totals above DV0 are used to calculate the number of generations per year if a value greater than zero has been entered for PDD in the parameter file. For example, if a species requires 660 degree-days above DV0 but below DV3 to complete its life cycle (PDD=660) and this total number at a particular location is 4300, the species can complete 4300/660 = 6.5 generations in a year.

The weekly Temperature Index (TI_W) is calculated from two components. The first of these (I_q) describes the effect of temperature on population growth rates at optimal temperatures and below, while the second (I_h) describes the reduction in population growth rate of a species at high temperatures. The value of I_q is calculated from the average daily maximum and minimum temperatures.

Fig. 3-3 The Temperature Index in relation to the daily temperature cycle. Q = shaded area under curve between DV0 and DV3, and A = shaded area between DV0 and DV1.



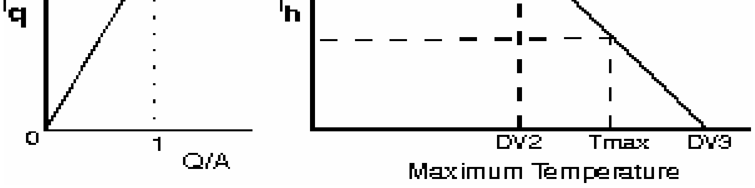
The Weekly Temperature Index, TI_W, = $I_q \times I_h$
if $Q \le A$, then $I_q = Q/A$ (fig. 3, left)
if $Q > A$, then $I_q = 1$ (fig. 3, left)

where A is the accumulated degree-days above DV0 assuming a constant temperature of DV1 (see Fig. 3-4).

The second temperature component, I_h, is defined as
if $T_{max} < DV2$, then $I_h = 1$,
if $T_{max} < DV3$ and $> DV2$, then $I_h = 1 - (T_{max} - DV2) / (DV3 - DV2)$,
if $T_{max} \ge DV3$, then $I_h = 0$,

Note that I_h reduces with increasing maximum temperature above DV2 (Fig. 3-4, right).

Fig. 3-4 The Temperature Index as a function of mean, maximum and minimum daily temperatures.



The Annual Temperature Index, $TI_A = 100 \sum_{i=1}^{52} TI_{W_i} / 52$ is quoted when querying results on Maps.

3.3.3 Moisture Index (MI)

The Moisture Index is based on the assumption that soil moisture is the dominant factor determining the moisture content of vegetation and hence the microclimatic conditions. The weekly soil moisture balance is calculated with a hydrological model from the stored soil moisture from the previous week and the current week's rainfall and evapotranspiration (moisture loss from plants and soil surface).

SM = 0 indicates no soil moisture; SM = 0.5 indicates soil moisture content is 50% of capacity; SM = 1 indicates that the soil moisture content is 100% of capacity; SM > 1 indicates a water content greater than the soil holding capacity of (S_{max}) ie run-off.

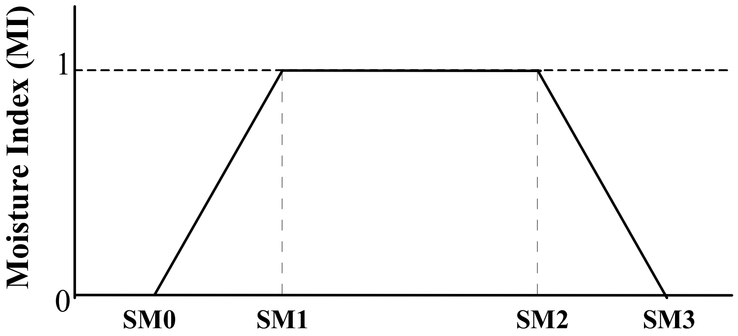
The user can adjust two parameters to affect soil moisture calculations in CLIMEX. The first of these is soil moisture storage capacity. The default capacity is set to 100mm (which represents a nominal global average value), but in reality this will vary with soil types. The 100mm moisture storage value represents a soil profile with a depth of approximately 500mm and a moderate water holding capacity. Sandy soils may only hold 50mm while clays can hold 150mm within reach of the rooting zone of typical crop plants. The second parameter is the evapotranspiration coefficient, which is the amount of moisture lost from a vegetated soil relative to rates of loss from a standard evaporation pan. The default value is 0.8 (Fitzpatrick and Nix, 1969), which is typical for mature pasture/crop areas. The value will reduce with a lower leaf area. Both parameters can be adjusted for individual species, to reflect rooting depth or morphology.

$$\textbf{Soil Moisture (SM)} = \frac{S_{i-1} + P_i - E_i}{S_{\max}}$$

Where, S_{i-1} = the estimated available water from prior week,
P_i = the rainfall from the current week,
E_i = the evapotranspiration from the current week, and
S_{max} (100 by default) = the assumed maximum available soil water storage (Fitzpatrick and Nix, 1969).

The Moisture Index (MI) describes the response of the species to the soil moisture values (Fig. 3-5). The parameters SM0, SM1, SM2 and SM3 have the same form as the temperature parameters, except that moisture is assumed to be constant over the 24-hour period.

Fig. 3-5 The Moisture Index as a function of available soil moisture.



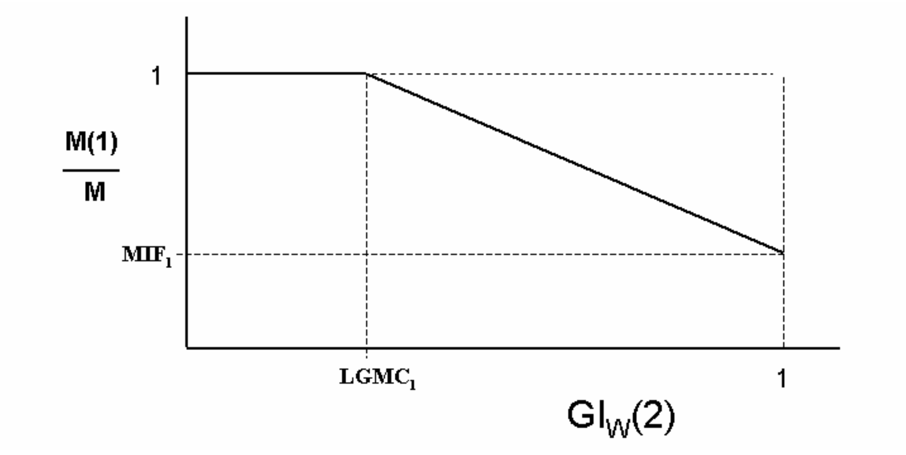
The four parameters used in calculating Soil Moisture to determine population growth include:

SM0 = lower soil moisture threshold
SM1 = lower optimal soil moisture
SM2 = upper optimal soil moisture
SM3 = upper soil moisture threshold

The Moisture Index ranges between 0 and 1. When MI = 1, population growth is maximised. This occurs when the range of soil moisture is between SM1 and SM2. At MI = 0, population growth is zero, and this occurs when the soil moisture is below SM0 or above SM3.

When two interacting species share the same root space, such as a set of competing plants, the presence of the competitor can reduce the available moisture for the first species. This is modelled by a reducing the moisture available to each species as a function of the Growth Index of the competing species in the same week (Fig. 3-6). Note that CLIMEX does not currently use an accumulated GI, which would be more appropriate for describing the size and hence water demand of a competitor.

Fig. 3-6 The Moisture Index as reduced by the presence of a competing species.



Two parameters are used to specify the interaction. Figure 3.6 illustrates the relationship with the two species designated as Species 1 and Species 2,. As the Growth Index of Species 2, $GI_W(2)$, increases above the parameter

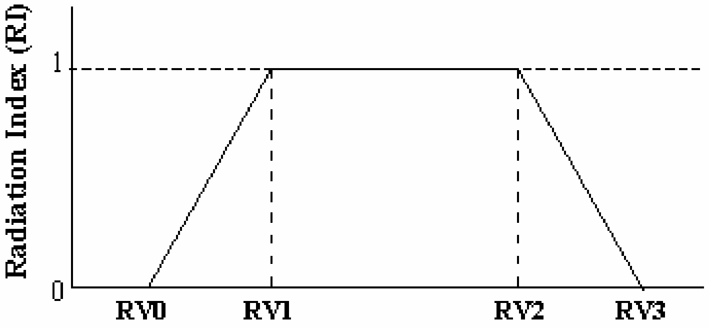
$LGMC_1$, the available moisture for Species 1, M(1), is reduced from the amount (M) predicted by the Soil Moisture Model. The second parameter (**MIF_1**) specifies the maximum reduction in available moisture when Species 2 is achieving its maximum growth rate. *The subscript ($_1$) indicates that these are parameters of species 1.* Note that setting **$LGMC_1$** to 1 specifies that Species 2 does not affect the available moisture for Species 1. A second set of equivalent parameters (**$LGMC_2$** and **MIF_2**) specifies the effect of Species 1 on the available moisture for Species 2.

3.3.4 Radiation Index (RI)

The Radiation Index is useful for defining the growth index for plants, as the amount of available radiation is an important determinant of their potential growth. Clear sky global radiation reaching the surface of the globe at any point is calculated from orbital parameters. The actual radiation on a horizontal surface (in MJ per sq. metre per day) at any point is then calculated in one of two ways. If sunshine hours are available in the meteorological data, this is used; otherwise a calculation is made using the temperature range at a location.

The Radiation Index (RI) describes the response of the species to the solar radiation values (Fig. 3-7). The parameters RV0, RV1, RV2 and RV3 have the same form as the moisture parameters.

Fig. 3-7 The Radiation Index as a function of terrestrial radiation.



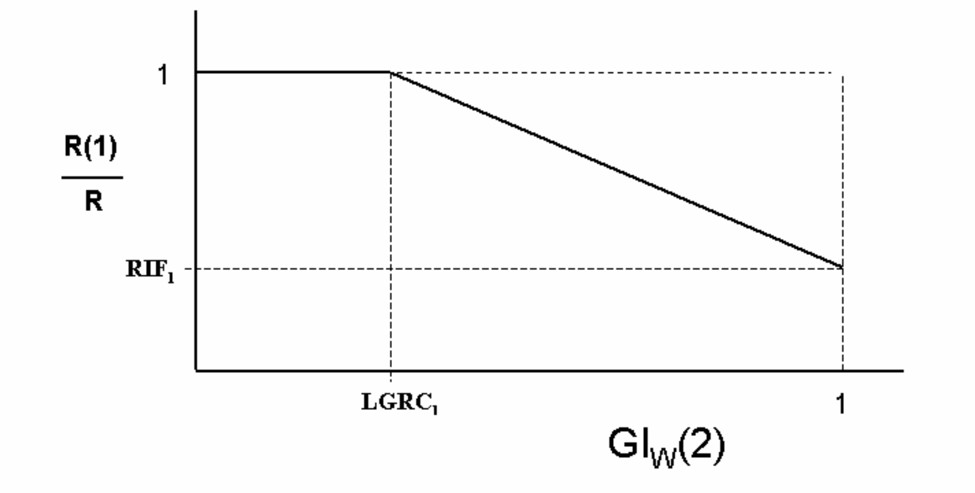
The four parameters used in calculating radiation to determine population growth are:

RV0 = lower radiation threshold
RV1 = lower optimal radiation
RV2 = upper optimal radiation
RV3 = upper radiation threshold

The value of the Radiation Index ranges between 0 and 1. When RI = 1, population growth is maximised. This occurs when the range of radiation is between RV1 and RV2. At RI = 0, population growth is zero, and this occurs when the radiation is below RV0 or above RV3.

When two interacting species are growing close to each other, one may shade the other and reduce the radiation available to it. This is modelled by a reducing the radiation available to each species as a function of the Growth Index of the competing species (Fig. 3-6). Note that CLIMEX does not currently use an accumulated GI, which would be more appropriate for describing the size and hence extend of shading by a competitor.

Fig. 3-8 The Radiation Index as reduced by the presence of a competing species.



Two parameters are used to specify the interaction. Fig. 3-8 illustrates the relationship where the two species are designated as Species 1 and Species 2,.. As the Growth Index of Species 2, $GI_W(2)$, increases above the parameter **$LGRC_1$**, the available radiation for Species 1, R(1), is reduced from the amount (R) predicted by the Radiation sub-model. The second parameter (**RIF_1**) specifies the maximum reduction in available radiation when Species 2 is achieving its maximum growth rate. *The subscript ($_1$) indicates that these are parameters of species 1.* Note that setting **$LGRC_1$** equal to 1 specifies that Species 2 does not affect the available radiation for Species 1. A second set of equivalent parameters (**$LGRC_2$** and **RIF_2**) specifies the effect of Species 1 on the radiation available to Species 2.

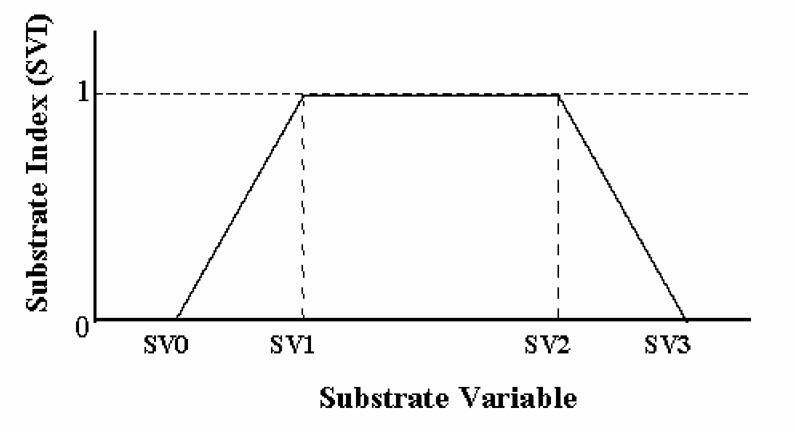
3.3.5 Substrate Index (SVI)

The Substrate Index assumes that there is a non-climatic variable (the substrate) that can affect population growth. Examples of substrates are soil type or salinity, topography, or host availability or suitability for a parasitic organism.

SVI = 0 indicates that the substrate is completely limiting (i.e., no population growth is possible during that week), while SVI = 1 indicates a substrate that is completely non-limiting to population growth for that week.

The Substrate Index (SVI) describes the response of the species to the substrate variable (Fig. 3-9). The parameters SV0, SV1, SV2 and SV3 have the same form as the temperature parameters, except that the substrate variable is assumed to be constant over the 24-hour period.

Fig. 3-9 The Substrate Index as a function of the substrate variable.



The four parameters used in calculating Soil Moisture to determine population growth include:

SV0 = lower substrate variable threshold
SV1 = lower optimal substrate variable value
SV2 = upper optimal substrate variable value
SV3 = upper substrate variable threshold

The Substrate Index ranges between 0 and 1. Population growth is maximised when SVI = 1, which occurs when the range of the substrate variable is between SV1 and SV2. Zero population growth occurs when the value of the substrate variable is below SV0 or above SV3, or when SVI = 0.

Note that CLIMEX allows two separate substrate variables to be used. These are referred to as the *Physical* and *Biotic* Substrates, and result in a *Physical Substrate Index* (SVPI) and a *Biotic Substrate Index* (SVBI). The parameter mnemonics for the former are SVP0, SVP1, SVP2 and SVP3, while those for the latter are SVB0, SVB1, SVB2 and SVB3. The names do not preclude the user from using the substrate for any other type of user-defined substrate, such as a second biotic substrate rather than a physical substrate

3.3.6 Diapause Index (DI)

Diapause (or dormancy) is an adaptation that enables a species to withstand prolonged periods of unfavourable climatic conditions. A species must be exposed to specified conditions in order to trigger diapause and also needs a set period of exposure in order to complete diapause, just as a certain number of degree-days of temperature are needed to complete normal development. In the plant kingdom, the analogous process to diapause is referred to as ‘vernalisation’, and is needed to stimulate flowering.

CLIMEX reduces the Weekly Growth Index (GI_W) to zero during the period of diapause development and it sets the annual GI_A to zero if the obligate diapause conditions are not satisfied. This has the effect of setting EI=0 and the species is excluded from that location. While a species is not experiencing diapause, the weekly Diapause Index (DI_W) =1. When the species is in diapause, $DI_W = 0$.

In CLIMEX, diapause can be triggered by short daylengths and low temperatures (winter diapause), or long daylengths and high temperatures (summer diapause). Five parameters are used in the diapause calculations.

1. **Diapause Induction Daylength (DPD0)** is the average weekly daylength that induces diapause. Setting DPD0 to 0 disables the diapause function.

2. **Diapause Induction Temperature (DPT0)** is the average weekly minimum temperature (for winter diapause) or maximum temperature (for summer diapause) that induces diapause.

3. **Diapause Termination Temperature (DPT1)** is the average weekly minimum temperature (for winter diapause) or maximum temperature (for summer diapause) that terminates diapause.

4. **Diapause Development Days (DPD)** is the minimum number of days required for diapause development to be complete. If the required number of days in diapause (DPD) is not achieved, the species is assumed not to have survived diapause and the Annual Growth Index (GI) (and hence the EI) becomes zero. The default value for DPD is zero, which corresponds to no diapause.

5. **Diapause Summer or Winter indicator (DPSW)** is set to zero for winter diapause, and to one for summer diapause.

The diapause function works in the following way.

For **Winter diapause (DPSW = 0)**

Diapause is switched **ON** when

- Daylength < DPD0 **and**
- Daily minimum temperature is < DPT0 **and**
- Daylength is decreasing (automatically calculated by CLIMEX)

Diapause is switched **OFF** when

- Daily minimum temperature > DPT1 **and**
- Daylength is increasing (automatically calculated by CLIMEX) **and**
- Diapause development is complete (at least DPD days have been spent in diapause).

Diapause development is complete when DPD days with a minimum temperature < DPT0 have passed since diapause was triggered. DPD should be set to zero to disable the diapause development condition.

For **Summer diapause (DPSW = 1)**

Diapause is switched **ON** when

- Daylength > DPD0 **and**
- Daily maximum temperature is > DPT0 **and**
- Daylength is increasing (automatically calculated by CLIMEX).

Diapause is switched **OFF** when

- Daily maximum temperature < DPT1 **and**
- Daylength is decreasing (automatically calculated by CLIMEX) **and**
- Diapause development is complete (at least DPD days have been spent in diapause).

Diapause development is considered to be complete when DPD days have occurred with an average maximum temperature > DPT0 since diapause started.

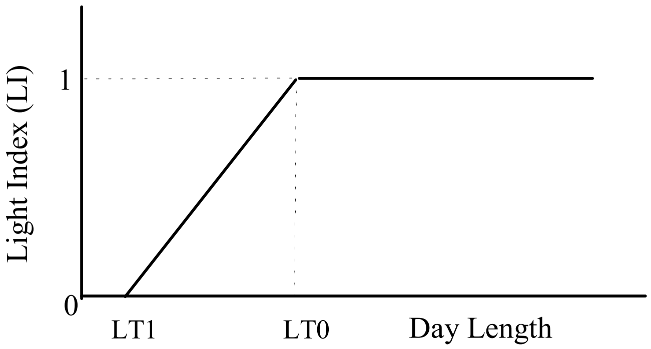
3.3.7 Light Index (LI)

The Light Index enables the growth and development of plants to be described by taking into account seasonal variation in daylength, which affects photosynthesis. The weekly LI has a value between 0 and 1. A value of 0 indicates maximum limiting conditions with inadequate hours of daylight; a value of 1 indicates no limitation to growth from light.

Two parameters determine the value of the weekly Light Index (LI). LT0 is the daylength (in hours) above which growth is at a maximum, while LT1 is the daylength below which growth is 0 (Fig. 3-10). LI is used in the calculation of the Weekly Growth Index (GI_W). The default value for the LI is one, as this has no effect on the GI_W calculations.

if D (daylength) $\geq$ LT0, then LI = 1,
if LT1 < D < LT0, then LI = 1 - (D - LT1)/(LT0-LT1),
if D $\leq$ LT1, then LI = 0.

Fig. 3-10 The Light Index function calculates the weekly LI from the day length and the value of two parameters LT0 and LT1.



3.3.8 Biotic Index (BI)

If two interacting species are being modelled simultaneously, CLIMEX allows the effects of competition or synergy between the species to be modelled using the Biotic Index (BI) . The Biotic Index is calculated weekly for each species according to the following equation:

$BI_W(1) = 1 + SIP0_1*TGI_W(2)$

$BI_W(2) = 1 + SIP0_2*TGI_W(1)$

where, $BI_W(1,2)$ are the Biotic Indices for the first (1) and second (2) species, respectively. $SIP0_1$ is a parameter that specifies the intensity and direction of the effect of species 2 on species 1. *The (1) indicates that it is a parameter of species 1.* When the parameter is 0, species 2 does not have any effect on species 1. When it is less than 0, species 2 ***reduces*** the weekly growth rate of species 1. When it is greater than 0, species 2 ***enhances*** the weekly growth rate of species 2. Note that in the latter case, BI_W has a value that is greater than 1. In that way, this index is different to the other Growth Index components. $SIP0_2$ works in the same way as $SIP0_1$, but this time giving the effect of species 1 on species 2 (*it is a parameter of species 2*).

3.4 Stress Indices

The stress indices in CLIMEX are set to limit the species' ability to survive during adverse seasonal conditions, and so determine its geographical distribution. Four of these indices represent the extremes of temperature and moisture. The philosophy used in fitting stress indices is that population growth occurs between the temperature parameters DV0 and DV3, and between the moisture parameters SM0 and SM3. Stress, leading to negative population growth, is assumed to accumulate outside these values. So for example, Dry Stress can only begin to accumulate once soil moisture drops below SM0. An annual stress value of 100 is lethal, and precludes a species from persisting in a given location.

While, we assume that there is only one period of each type of stress each year, in practice, exceptions do occur. For example, annual plants are frequently not limited by an unfavourable growth period because they are in the seed stage. Note that there are small areas of the world - in East Africa for example - where there are two seasons of favourable and unfavourable conditions each year associated with bimodal rainfall distributions. CLIMEX can describe the favourable conditions in each of the two seasons. However, as stresses are accumulated annually, care is needed in interpreting each period of stress, and the annual stress index, which is reset to zero in the favourable period between the two separate periods of stress.

There are four primary and commonly used stress indices in CLIMEX: Heat Stress, Cold Stress, Wet Stress and Dry Stress. There are also four less commonly used stress indices, which are interactions of the four primary indices: Hot-Wet Stress, Hot-Dry Stress, Cold-Wet Stress and Cold-Dry Stress.

A threshold value and an accumulation rate define all stresses. In all cases, accumulation of stress during the year is exponential: each week's stress is multiplied by the number of weeks since the stress first exceeded zero.

Each stress index in CLIMEX is associated with a stress accumulation rate. The rate parameter determines how quickly the species accumulates stress when climatic conditions exceed the stress threshold. When the accumulated weekly stress index equals 1.0, the species is unable to persist at the location. For example, the Cold Stress Temperature Threshold (TTCS) defines a temperature below which Cold Stress begins to accumulate. The rate at which this stress accumulates is determined by the Cold Stress Temperature Rate (THCS). If we were modelling a frost-susceptible plant that dies when exposed to 2°C daily for a week, stress has to accumulate to equal 1.0 or more in that week to simulate this effect. For another species that is more tolerant of cold, it may require two months before the accumulated Cold Stress is fatal. In this case a lower rate of stress accumulation would be more appropriate.

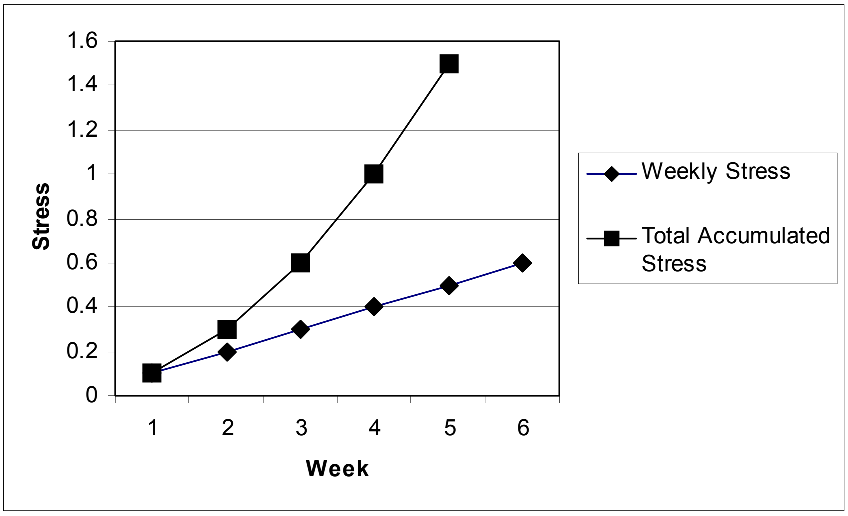
In CLIMEX, it is assumed that stress accumulates exponentially over time, to reflect the progressive increase in severity of the same amount of stress stimulus as time goes by and the population exhausts its resources. Let us assume that Cold Stress begins to accumulate below 10°C (TTCS) at a rate of 0.1 (THCS), and that the average weekly minimum temperature is consistently 9°C after week 0. The weekly Cold Stress for consecutive weeks is therefore:

Weekly Stress = Rate × (Threshold – average weekly minimum temperature) °C × week number,

OR (for Cold Stress), THCS × (TTCS - average weekly minimum temperature) × week number

Week	Weekly Stress	Total Accumulated Stress
1	0.1 × 1 × 1 = 0.1	0.1
2	0.1 × 1 × 2 = 0.2	0.3 (0.1 + 0.2)
3	0.1 × 1 × 3 = 0.3	0.6 (0.3 + 0.3)
4	0.1 × 1 × 4 = 0.4	1.0 (0.6 + 0.4)
5	0.1 × 1 × 5 = 0.5	1.5 (1.0 + 0.5)

Fig. 3-11 Comparison of weekly and accumulated stress.



The species will therefore accumulate a lethal stress of 1.0 during the 4th week (Fig. 3-11). Note that CLIMEX scales stress indices, so that an accumulated stress of 1.0 or greater becomes an annual stress index value of 100. In calculating the EI value, all Stress Index values are limited to a maximum of 100. However, to help with estimating the parameter values, the actual value of the Stress Index is shown in the tables. For example, if the Stress Index in a marginal zone is 300 it indicates that the parameters are too severe.

The yearly stress index for a variable V (eg Cold Stress) = $100 \sum_{i=1}^{52} V_i / 52$

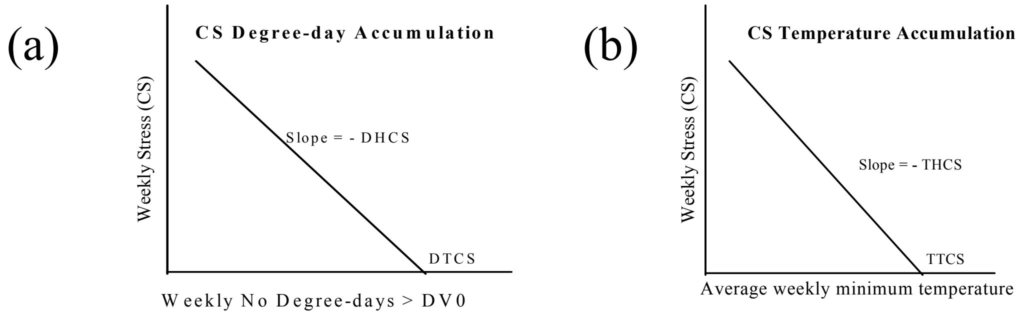
3.4.1 Cold Stress (CS)

Cold Stress can be defined in three ways. Firstly, animals may die because the daily thermal accumulation is too low to maintain metabolism. This occurs when a threshold number of degree-days above the developmental temperature threshold (DVCS) are not reached. This threshold parameter is called the Cold Stress Degree-day Threshold (DTCS) and is in units of degree-days. Cold Stress accumulates at a given rate (DHCS) if the weekly number of degree-days above DVCS (DD) does not reach the threshold value (DTCS), as in the following equation:

if DD < DTCS, then CS = (DTCS - DD) x DHCS,
if DD ≥ DTCS, then CS = 0,

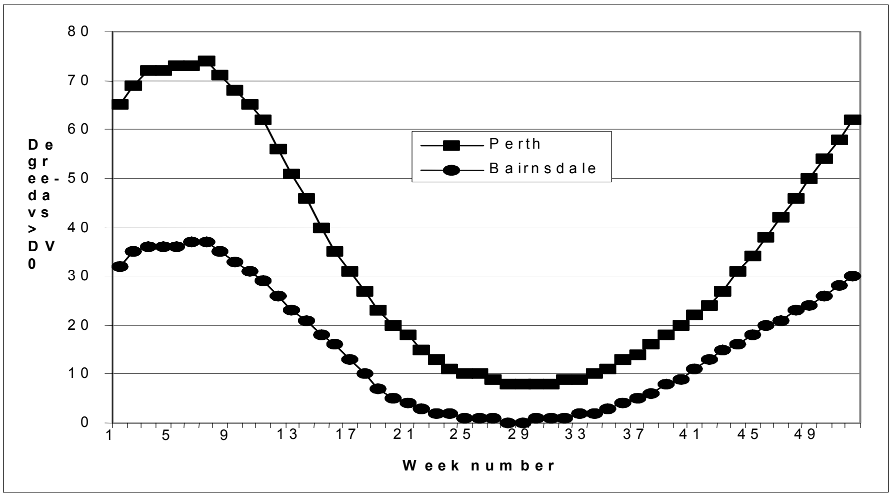
The fewer the number of degree-days experienced at a location, the more Cold Stress will accumulate. If the weekly number of degree-days exceeds the designated threshold (DTCS), a zero Cold Stress value is returned (Fig. 3-12a).

Fig. 3-12 The Cold Stress function. a) Degree-day Threshold (DTCS) below which Cold Stress accumulates at the rate DHCS; b) Temperature Threshold (TTCS) below which CS accumulates at the rate THCS.


(a)
CS Degree-day Accumulation
Weekly Stress (CS)
Slope = - DHCS
DTCS
Weekly No Degree-days > DV0
(b)
CS Temperature Accumulation
Weekly Stress (CS)
Slope = - THCS
TTCS
Average weekly minimum temperature

Refer to Fig. 3-3, Section 3.3.2, for an explanation of how degree-days are calculated. Cold stress will accumulate if area Q in Fig. 3-3, accumulated over a period of a week, is less than the threshold defined by DTCS. In practical terms, the higher the DTCS value, the more cold stress will accumulate. This is because more warmth (either longer duration or greater temperatures) will be required to prevent cold stress from accumulating. The following graph (Fig. 3-13) indicates the weekly number of degree-days above DVCS (in this case, 14°C) accumulated at two locations in Australia. With DTCS set at 30, cold stress will accumulate at both locations, and will accumulate for most of the year at Bairnsdale, probably precluding a species from occurring there. If DTCS were reduced to 10, less cold stress would accumulate at both locations. The first reason is that the total number of weeks experiencing fewer than 10 degree-days above DVCS is greatly reduced. The second reason is that the difference between the actual number of degree-days above DVCS experienced and a threshold value of 10 (as compared to 30) is also less, and so when multiplied by the rate of stress accumulation (DHCS), gives a lower cold stress value. Thus, a higher DTCS value results in a longer period of cold stress accumulation *and* a greater amount of weekly cold stress accumulation.

Fig. 3-13 Degree-days > DVCS for Perth and Bairnsdale in Australia each week.



Alternatively, a species may not survive the winter if exposed to excessively low temperatures. The Cold Stress Temperature Threshold (TTCS) represents the average weekly minimum temperature (^{o}C) below which Cold Stress accumulates. Cold Stress accumulates at a given rate (THCS) when the average weekly minimum temperature (T_{min}) drops below a given threshold value (TTCS), as in the following equation:

if $T_{min} < TTCS$, then $CS = (TTCS - T_{min}) \times THCS$,
if $T_{min} \geq TTCS$, then $CS = 0$,

If the average weekly minimum temperature is greater than the threshold TTCS, a zero CS value is returned (Fig. 3-12b). As discussed earlier, the annual cumulative Cold Stress value will also depend on the number of weeks experiencing stress.

As a third option, a species may spend the winter in locations where it is buffered from extreme minima and maxima. In such situations the Cold Stress Average Temperature Threshold (TTCSA) represents the weekly average temperature (^{o}C) below which Cold Stress accumulates. Cold Stress accumulates at a given rate (THCSA) when the weekly average temperature (T_{av}) drops below a given threshold value (TTCSA), as in the following equation:

if $T_{av} < TTCSA$, then $CS = (TTCSA - T_{av}) \times THCSA$,
if $T_{av} \geq TTCSA$, then $CS = 0$,

Again, the annual cumulative Cold Stress value will depend on the number of weeks experiencing stress.

3.4.2 Heat Stress (HS)

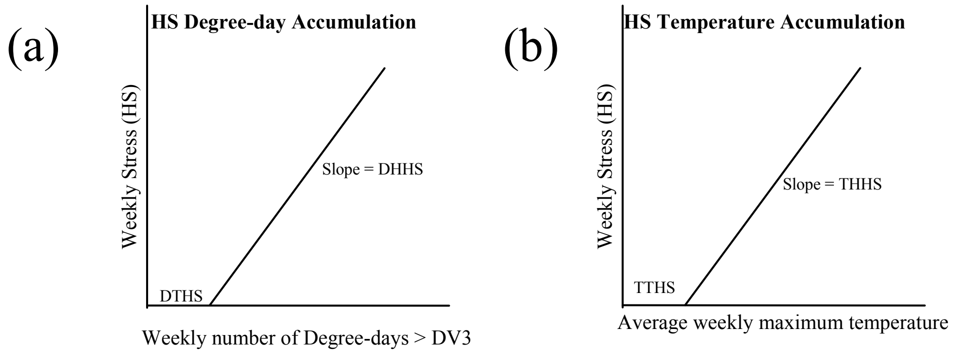
It is also possible to model Heat Stress in two ways. The degree-day model of Heat Stress accumulation assumes that species are unable to persist because the daily heat load is too high for essential physiological processes. This model distinguishes between areas that experience brief exposures to extremely high temperatures and areas that experience less extreme maximum temperatures for longer periods each week. The difference between the weekly degree-days above DV3 (DD_{DV3}) and the weekly degree-day threshold (DTHS) is multiplied by the stress accumulation rate (DHHS) to give Heat Stress.

Note: in versions of CLIMEX before Version 2, the degree-day model of Heat Stress calculated degree-days above DV0. Starting with Version 2, CLIMEX uses DV3 as the temperature threshold above which stress is accumulated. Species parameter files constructed using earlier versions of CLIMEX will need to be recalibrated to reflect this change.

if $DD_{DV3} > DTHS$, then $HS = (DD_{DV3} - DTHS) \times DHHS$,
if $DD_{DV3} \leq DTHS$, then $HS = 0$.

If the number of weekly degree-days (DD) above DV3 is less than the threshold (DTHS) value, this equation returns a negative value, which CLIMEX interprets as zero Heat Stress (Fig. 3-14a).

Fig. 3-14 The Heat Stress function. a) Degree-day Threshold (DTHS) above which stress accumulates at the rate DHHS; b) Temperature Threshold (TTHS) above which stress accumulates at the rate THHS.



The second option, the Heat Stress Temperature Threshold (TTHS) model, relates to species that fail to survive when exposed to excessively high temperatures. The threshold temperature model for Heat Stress has two parameters. TTHS is the threshold temperature (^{o}C) above which Heat Stress accumulates, and THHS is the rate at which stress accumulates. Weekly Heat Stress is calculated by the following equation:

if T_{max} > TTHS, then HS = (T_{max} - TTHS) x THHS,
if Tmax ≤ TTHS, then HS = 0.

If the average weekly maximum temperature is below the threshold (TTHS), this equation returns a zero Heat Stress (Fig. 3-14b). As discussed earlier, the annual cumulative Heat Stress value will also depend upon the number of consecutive weeks of Heat Stress. The higher the maximum temperature, the greater the Heat Stress in a given week.

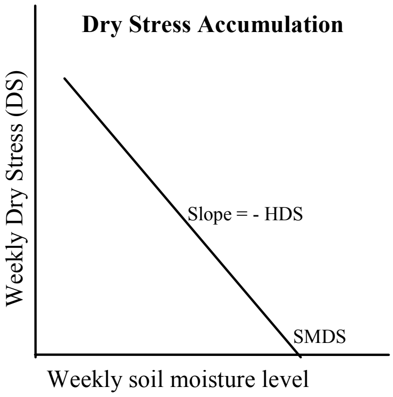
3.4.3 Dry Stress (DS)

Moisture can cause stress for a species when it is either too dry or too wet. Dry Stress accumulates when the soil moisture level falls below the Dry Stress Threshold (SMDS). The difference between SMDS and the soil moisture level (SM) is multiplied by the Dry Stress Rate (HDS) to give the resultant Dry Stress for the week. Annual Dry Stress will be a cumulative value, as described earlier, and will also depend on the number of weeks experiencing stress.

If SM < SMDS, then DS = (SMDS – SM) × HDS,
if SM ≥ SMDS, then DS = 0.

If the weekly soil moisture is greater than the Dry Stress Threshold (SMDS), the equation returns zero Dry Stress (Fig. 3-15).

Fig. 3-15 The Dry Stress Function. Threshold soil moisture (SMDS) below which stress accumulates at the rate HDS.



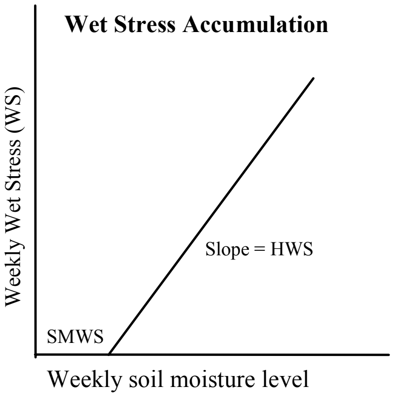
3.4.4 Wet Stress (WS)

Wet Stress accumulates if the soil moisture level exceeds the Wet Stress Threshold (SMWS). The difference between SMWS and the soil moisture level (SM) is multiplied by the Wet Stress Rate (HWS) to give the resultant Wet Stress. Annual Wet Stress will be a cumulative value as described earlier, and will also depend on the number of consecutive weeks experiencing stress.

if SM > SMWS, then WS = (SM – SMWS) × HWS,
if SM ≤ SMWS, then WS = 0.

If the weekly Soil Moisture level is less than the Wet Stress Threshold (SMWS), the equation returns zero Wet Stress (Fig. 3-16).

Fig. 3-16 The Wet Stress Function. Threshold soil moisture (SMWS) above which stress accumulates at the rate HWS.



3.5 Interaction Stress Indices

CLIMEX provides for four types of synergistic interactions between temperature and moisture. The interaction indices (CDX, CWX, HDX and

HWX) describe the combined effects of two stress factors acting simultaneously, and apply to cold-dry, cold-wet, hot-dry and hot-wet conditions, respectively. These indices are not often needed, but provide extra capability for certain situations in which the simple stress indices are inadequate. For example, Hot-Wet Stress may be needed to exclude Mediterranean species from tropical areas, or Cold-Wet stress may be needed to exclude tropical species (adapted to cool dry winters) from temperate regions that have cold wet winters.

All these indices are scaled between 0 and 1, with 0 indicating no stress interaction and 1 indicating maximum (lethal) stress.

Cold-Dry Stress (CDX)

DTCD	'Cold-Dry Degree-day Threshold'
MTCD	'Cold-Dry Moisture Threshold'
PCD	'Cold-Dry Stress Accumulation Rate'

Cold-Dry Stress is accumulated if the weekly number of degree-days above DV0 falls below DTCD and the moisture level falls below MTCD. PCD determines the rate of accumulation of stress.

Hot-Dry Stress (HDX)

DTHD	'Hot-Dry Degree-day Threshold'
MTHD	'Hot-Dry Moisture Threshold'
PHD	'Hot-Dry Stress Accumulation Rate'

Hot-Dry Stress is accumulated if the weekly maximum temperature exceeds TTHD and the moisture level falls below MTHD. PHD determines the rate of accumulation of this stress.

Cold-Wet Stress (CWX)

DTCW	'Cold-Wet Degree-day Threshold'
MTCW	'Cold-Wet Moisture Threshold'
PCW	'Cold-Wet Stress Accumulation Rate'

Cold-Wet Stress is accumulated if the weekly number of degree-days above DV0 falls below DTCW and the moisture level exceeds MTCW. PCW determines the rate of stress accumulation.

Hot-Wet Stress (HWX)

DTHW	'Hot-Wet Degree-day Threshold'
MTHW	'Hot-Wet Moisture Threshold'
PHW	'Hot-Wet Stress Accumulation Rate'

Hot-Wet Stress is accumulated if the weekly maximum temperature exceeds TTHW and the moisture level exceeds MTHW. PHW determines the rate of accumulation of stress.

3.6 Constraints to persistence

3.6.1 Length of growing season (PDD)

The severity of an unfavourable season is not the only way in which climate can limit a species' distribution. Species require different amounts of thermal accumulation during the growth season to enable them to complete a minimum amount of development and/or reproduction . At high latitudes and altitudes, the length of the growing season often limits the distribution of species with one generation per year by preventing the completion of their lifecycle. Perennials may also fail to establish populations if they do not receive enough thermal accumulation to reproduce. The PDD parameter is set to the number of degree-days of thermal accumulation above the development threshold (DV0) required by the species to reproduce or complete a generation. PDD can be estimated from field observations or laboratory data.

3.6.2 Obligate Diapause or Vernalisation

Diapause (dormancy) is an adaptation that enables a species to withstand prolonged periods of unfavourable temperature or moisture conditions. A species must be exposed to specified conditions for a set period of time in order to complete diapause, just as a certain number of degree-days of temperature are needed to complete development. In the plant kingdom, an analogous process is referred to as 'vernalisation', and is needed to switch the plant from a vegetative growth mode into a reproductive mode. In this case, a minimum period of exposure to low temperature is usually needed.

If a species has diapause development in its lifecycle, its tolerance to the relevant adverse conditions will be taken into account automatically by the CLIMEX stress functions, as these are inferred from the geographical distribution. Hence, there is no need to consider diapause when estimating the four basic CLIMEX stress functions: hot, cold, dry or wet. However, diapause does need to be considered separately when a species' distribution is limited because climatic conditions do not enable obligate diapause requirements to be met. For example, in temperate species, diapause cues involve exposure to certain low temperatures and short daylengths for a minimum period of time. Thus, if a temperate species with obligate diapause is placed in a sub-tropical or tropical environment, the required chilling conditions will not be experienced and this will prevent the species from living in these environments. In the case of annual plants that need a period of vernalisation, the plants will fail to flower and hence reproduce, which is a common phenomenon with temperate bulbs that are planted in areas where there is an insufficiently cold winter to chill the bulbs.

CLIMEX enables the user to model the constraining effects of obligate diapause or vernalisation requirements by establishing a required set of induction and termination conditions (see Section 3.3.6). Diapause can be induced by a specified combination of temperature and daylength conditions, and can be terminated by a specified temperature condition. There is also a parameter specifying the number of days below or above the diapause-inducing temperature necessary to complete diapause development. If the required number of days for diapause development is not achieved, the conditions for obligate diapause have not been met and the species will be excluded from the location. CLIMEX reduces the Weekly Growth Index (GI_W) to zero during the period of diapause development and it sets the annual GI_A to zero if the obligate diapause conditions are not satisfied. This has the effect of setting the Ecoclimatic Index to zero and excluding the species from that location. While a species is not experiencing diapause, the weekly Diapause Index (DI_W) =1. When the species is in diapause, $DI_W = 0$.

3.7 Ecoclimatic Index (EI)

The Ecoclimatic Index (EI) integrates the Annual Growth Index (GI_A), which describes the potential for population growth, with the annual stresses that limit survival during the unfavourable season and with any limiting factors, ie PDD, diapause. As few climates are 100% suitable throughout the year, the value of GI_A rarely reaches its potential, thereby limiting the maximum value of EI. The EI thus gives an overall measure of the potential of a given location to support a permanent population (Sutherst, Maywald and Skarratt 1995). The index was designed to provide simple, concise information in a form that is readily interpretable by non-scientists, such as policy makers.

The EI is scaled between 0 and 100, with an EI close to 0 indicating that the location is not favourable for the long-term survival of the species. EI values of 100 are only achievable under constant and ideal conditions comparable in incubators. An EI of more than 30 represents a very favourable climate for a species, as it means that during the (say) six months suitable for growth with a maximum GI_A of 50, the species has achieved 60% of the potential population growth. The difference is due to the daily fluctuating temperatures as well as the likely absence of continuous optimal rainfall values.

Ecoclimatic Index, EI = $TGI_A \times SI \times SX$

where GI_A, the Annual Growth Index, = $100\sum_{i=1}^{52} TGI_{W_i} / 52$

SI, the Annual Stress Index, = (1-CS/100)(1-DS/100)(1-HS/100)(1-WS/100), and
SX, the Stress Interaction Index, = (1-CDX/100)(1-CWX/100)(1-HDX/100)(1-HWX/100),
CS, DS, HS, WS are the annual cold, dry, heat and wet Stress indices respectively,
and CDX, CWX, HDX and HWX are the annual cold-dry, cold-wet, hot-dry and hot-wet Stress interaction indices.

The EI is also affected by the constraints of having sufficient degree-days to complete the lifecycle (PDD) and meeting the conditions required to complete diapause.

If CLIMEX is run with two species simultaneously, in addition to explicitly including competition via the moisture (Section 3.3.3), radiation (Section 3.3.4) and biotic (Section 3.3.8) indices (which will affect the weekly Growth Index, and hence the EI), competitive exclusion can be specified. When this is done, the Ecoclimatic Indices, EI_1 and EI_2, are compared, and the smaller of the two is set to 0, while the other is left unchanged. If they are equal, both are left unchanged. This method assumes that over a sufficient number of generations, a species that out competes another will displace the other species completely.

CLIMEX produces values for separate stages in evaluating the Ecoclimatic Index

(1) The "raw" Ecoclimatic Index (EI_A) that may include inter-species effects via the effects of moisture and radiation competition, but excludes the effects of the Biotic Index (BI) is calculated as follows:

$$\textbf{Ecoclimatic Index, } \mathbf{EI_A} = TGI_A \times SI \times SX$$

(2) An Ecoclimatic Index (EI_B) that includes the effects of the Biotic Index (EI_B) is calculated as follows:

$$\textbf{Ecoclimatic Index, } \mathbf{EI_B} = GI_A \times SI \times SX$$

(3) An Ecoclimatic Index (EI_C) that includes the effects of the competitive exclusion:

$$\mathbf{EI_C(1)} = \begin{cases} EI_B(1), & EI_B(1) >= EI_B(2) \\ 0, & EI_B(1) < EI_B(2) \end{cases}$$

$$\mathbf{EI_C(2)} = \begin{cases} EI_B(2), & EI_B(2) >= EI_B(1) \\ 0, & EI_B(2) < EI_B(1) \end{cases}$$

3.8 Parameter fitting via inference from distribution

Parameter fitting is the most skilful procedure that CLIMEX demands. An appreciation of the distinct and separate roles of the 'Stress Indices' (that limit geographical distributions) and the 'Growth Index' (that relates to seasonal population growth) is the first requirement for the successful estimation of parameter values. It is necessary to understand the nature of the stress functions, with their threshold and rate parameters and exponential accumulation rates over time, and the simple temperature and moisture functions in the Growth Index. The other requirement is to get a 'feel' for the iterative parameter fitting process by running and re-running a parameter file with different parameter values and noting the differences in indices as a result of the changes. By varying threshold values and stress accumulation rates, the user can quickly appreciate how changes in these values alter inferred species' distributions in different ways. The extent of the change in the distribution reflects the sensitivity of the species to both the particular climatic variable and the geography of the area concerned.

As with any prediction, the quality and reliability of the prediction will be determined to an extent by the quality of the supporting data. Predictions will be more reliable if they are based on accurate distribution maps, abundance and seasonal activity data, supporting experimental data and census data from specific locations. CLIMEX is popular because useful predictions (even if coarse on occasions) can be made with a minimum amount of information. However, there is a danger that a prediction is credited with greater reliability than it deserves. It should always be remembered that CLIMEX is a tool used to help in decision making: its predictions are based solely on climatic data and consideration should also be given to other factors, such as competition and habitats, etc.

Nonetheless, CLIMEX can provide valuable insights into the biology and potential geographical distribution of a species from even the most basic distribution map. Manipulating stress parameters to fit a known distribution will often alert the user to aspects of the species' climatic preferences that were previously unknown. Fitting parameters and comparing climates can lead to changes in research direction by eliminating or supporting hypotheses regarding species' distributions.

Having collated all available information on the geographical distribution of a species, it is possible to develop a general picture of its climatic preferences. One obvious starting point is to classify the species as having a tropical (wet or dry), sub-tropical (wet or dry), temperate (wet or dry), alpine, arctic, arid or other distribution. A starting set of parameter values can then be imported using the templates provided or those from another species with a similar geographical distribution. Some templates are shown Table 3-1. The templates are provided in the species list with CLIMEX to help the user begin fitting parameters. Some general guidelines for estimating parameters are given below. Essentially, it is a process of examining what is known about the species in relation to the information required for a parameter description. It is usually more effective to estimate stress parameter values first, as these will give pointers to those conditions that are not stressful and thus suitable for population growth.

Table 3-1 Parameters templates, representative of different geographical distributions, that are provided with CLIMEX.

Parameter Group	Parameter	Wet Tropical Template	Mediterranean Template	Temperate Template	Semi-arid Template	Desert Template
Temperature Index	DV0	15	10	8	10	15
	DV1	28	16	18	20	25
	DV2	33	24	24	32	40
	DV3	36	28	28	38	44

Parameter Group	Parameter	Wet Tropical Template	Mediterranean Template	Temperate Template	Semi-arid Template	Desert Template
	PDD	0	600	600	0	0
Moisture Index	SM0	0.35	0.1	0.25	0.1	0
	SM1	0.7	0.4	0.8	0.2	0.001
	SM2	1.5	0.7	1.5	0.25	0.2
	SM3	2.5	1.5	2.5	0.3	0.3
Cold Stress	TTCS	0	0	0	0	2
	THCS	0	-0.005	0	0	-0.001
	DTCS	25	15	15	15	15
	DHCS	-0.002	-0.001	-0.0001	-0.002	-0.0005
Heat Stress	TTHS	37	30	30	39	44
	THHS	0.0002	0.002	0.005	0.002	0.001
	DTHS	0	0	0	0	0
	DHHS	0	0	0	0	0
Dry Stress	SMDS	0.25	0.02	0.2	0.05	0
	HDS	-0.01	-0.05	-0.005	-0.005	0
Wet Stress	SMWS	2.5	1.6	2.5	0.4	0.3
	HWS	0.002	0.0015	0.002	0.01	0.1
Hot-Wet Stress	TTHW		23			
	MTHW		0.5			
	PHW		0.075			

After creating a new species file based upon an appropriate template, the parameter values are adjusted to better fit the species of interest. The program is run, the EI values are mapped, and the predicted distribution is compared with the information available regarding the species' known distribution. While the predicted distribution (EI) will initially vary from the known distribution, the pattern should be similar. The program is then run repeatedly in order to systematically estimate each different parameter value until a satisfactory fit is obtained in every direction away from the core of the known distribution. Depending on the detail of the data available for the species, EI values can be related to the field data.

To estimate the stress values it is helpful to map each stress index as well as the EI. This can be done using the Options button. The maps produced will show the locations where different stresses limit the species' distribution, and also the gradients from low to high stress values. The stress parameters can then be adjusted to give a gradient of sensitivity reaching 100% at the observed distributional limit. By examining the results for specific locations on the map (ie by moving the cursor over the cross or circle and clicking the left mouse button) or data in a table, the user can observe the value of each stress at each location.

The fitting of model parameters to match the known geographical distribution and seasonal population growth of a species is, in effect, generating a hypothesis on the factors that limit its geographical distribution or population. CLIMEX enables the user to test a number of different explanations for the same observations. Each of these hypotheses needs to be explored and, where possible, tested against independent data.

It takes practice to learn to fit parameters effectively. The procedure relies on the user becoming familiar with global geography and climatic patterns, the sensitivity of stress thresholds and rate value parameters, and the temperature and moisture parameters in the Growth Index. This and the following sections detail the procedures and techniques involved in deriving a set of parameters that best describe the climatic requirements for a species, given its geographical distribution. Instructions on the use of the command boxes are given in the CLIMEX Help file.

Step 1. Collate the known distribution data from the literature. This will usually be the observed geographical distribution data, seasonal population growth rate, or experimental observations on the developmental threshold temperature and moisture levels. If using the known distribution of the species, choose one continent, preferably its native distribution, to work from. Distributions in other countries or continents can be used to verify the parameters later. Check the distributional data for reliability and consistency.

Step 2. Create a new species file by copying the parameters from another species or template with a similar distribution. This is the quickest way to start building up a set of parameters and is done clicking on the right hand button of the Species panel and selecting **Add/Edit/Remove** from the menu and then choosing an appropriate species to copy by highlighting a name in the list. Enter a new name for the species and save the new file. The parameters can then be edited using the Parameter button (P).

CLIMEX provides several example species from published papers that cover a wide range of preferred climatic regions. A set of templates has also been provided for this purpose and can be used as a foundation for building a species file.

Step 3. Enter any comments regarding the data into the **Comments** field of the species parameter file by clicking on the **Model Parameters** in the **Initialisation** drop down menu, highlighting the new species and clicking the **Comments** button. Use this facility liberally so that your work will be of the maximum value to future users of your parameter file.

Step 4 Use the **Location** right hand button to choose a continent corresponding to the observed native distribution from the **Sequences**. Run CLIMEX for the new species using the **Compare Locations** option. Note the differences in the estimated predicted distribution (EI), compared with the known distribution.

Step 5. Repeatedly adjust the parameters and re-run **Compare Locations** until the estimated potential range best matches the known distribution. Once you have a "feel" for how changing the parameters changes the predicted potential range, the process of iteration will become much faster. Any laboratory or field experimental data can be used to tune or confirm the parameter values at this stage. When the best visual fit has been achieved, carefully document the justification for fitting each value for future reference.

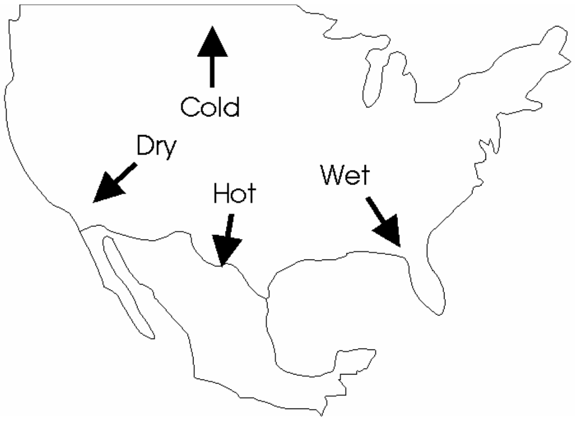
Step 6. Validate the parameter values against known distributions of the species in other continents. If the species is found in more than one country or continent, validate the parameter values by running **Compare Locations** using a new **Location Sequence** that covers an observed distribution not used to derive the original parameters. This will either confirm the parameter selection or require you to adjust some parameters until a good fit for all known locations is obtained. If further tuning is carried out, it needs to be carefully documented with appropriate justification. Such tuning may be necessary if the new **Location Sequence** includes a wider range of climate data than existed in the original set.

Step 7. Congratulate yourself for having developed a hypothesis explaining the species' distribution, while concurrently producing a tool of great practical value in further analyses of the risks posed by the species in new environments.

After selecting a starting parameter file (See **Step 2** above), make a **Sequence** from a **Location Selection** to work on or use a custom set (See 'Using MetManager' that covers defining Location Selections in Help). If using a known distribution to derive the parameters, the **Location Selection** must cover this area. If possible, choose a heterogeneous environment with the widest possible range of climates. Any continent will be suitable, but caution is needed in choosing tropical locations, as some countries have little heterogeneity. For example, Kenya in East Africa has a wide range of climatic zones, while Uganda has a limited climatic range.

Try to avoid using continents or countries with geographical boundaries that cause sudden climate changes that will make determining parameter values difficult. For example, the Himalayan Mountains to the north of India make it difficult to accurately determine the Cold Stress boundaries because the geographical changes are so dramatic that a wide range of parameter values will still give a predicted distribution limit at the base of the mountain range. Similarly, oceans often form geographical boundaries that make parameter estimation of limiting conditions difficult. If unsure of some parameters values because of geographic features, it is advisable to document the caveat and validate the parameters in an independent location whenever possible. In some cases, limits will have to remain undefined until further data is available. This is particularly so where the **Location Selection** is small, eg. Tasmania in Australia, where a species may extend beyond the island limits if there was suitable habitat instead of sea.

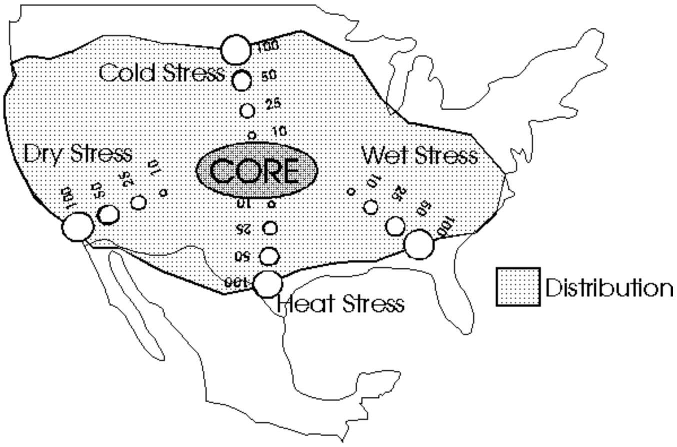
Fig. 3-17 A sketch map to reveal trends in climatic variables in North America as a guide to fitting parameter values in CLIMEX.



Using general knowledge of the climate of the continent or country, start by drawing a map of gradients of temperature and moisture using the 'Climatic-Gradients' utility. A simple example for the North America is given in Fig. 3-17. The process helps the user to visualise how gradients of stress accumulation will look.

Begin by adjusting the stress thresholds and stress accumulation rates. Using the example of the USA below (Fig. 3-18), there is a species with a distribution that is centred in central USA, spreading towards the national boundaries in each direction. The objective is to model a core distribution (locations with high EI values and little or no stress) that spreads outward to locations with progressively decreasing EI and increasing stress. At the limit of the distribution, one or more stress indices will be equal to or greater than 100, indicating that the location is not suitable for the long-term survival of the species in average years (as inferred from most distribution maps).

Fig. 3-18 Map of North America showing the hypothetical trends in each stress value in relation to distribution limits.



Pick one stress index (Cold, Hot, Wet or Dry) and identify the distribution limit defined by this stress index. In this example, Cold Stress is a likely variable that limits the northern distribution but the alternative hypothesis that the limit is determined by the availability of sufficient degree-days of development (PDD) also needs to be tested. Cold stress can be modelled either using a threshold temperature model or a degree-day model (see Section 3.4.1). Begin by using the threshold temperature model, setting TTCS to 2°C and the accumulation rate THCS to 0.001. This rate simulates a slow accumulation of stress during the winter and consequently indicates a low gradient in the total accumulated stress moving from the core to the northern distribution limit. Vary the stress threshold and/or the stress rate and re-run **Compare Locations** to try to match the northern distribution limit to that in Fig. 3-18. Then repeat the process using the degree-day based Cold Stress (DTCS) with an accumulation rate (DHCS) of 0.001 as above, with the THCS value temporarily set equal to zero to deactivate the threshold temperature model. In order to use the degree-day Cold Stress function, it is first necessary to estimate the value of DV0 (see below). Compare the results of the two models of Cold Stress and choose the threshold and rate parameters that give the best description of the distribution in Fig. 3-18.

Repeat this process for each Stress Index. Once the stress levels are set, these values can be used to set the bounds for the Growth Index parameters for Temperature and Moisture.

Temperature parameters (DV0 - DV3)

The parameters DV0 - DV3 define the temperature range that is suitable for population growth and development. Temperature stress therefore cannot accumulate in this range. The Cold Stress Temperature Threshold (TTCS) must be ≤ DV0 and the Heat Stress Temperature Threshold (TTHS) must be ≥ DV3. Once the stress thresholds have been set, the temperature parameters for growth (DV0, DV1, DV2, and DV3) can be fitted. To fine-tune the values, include any experimental results or knowledge about how the species responds to temperature. The parameter values relate to long-term average temperatures and the Temperature Index is accumulated over a daily temperature cycle. Follow these steps:

1. Relate seasonal abundance/activity or population growth rate data to temperature at a number of locations. Low temperature requirements can be inferred from the timing of first activity in spring and high temperature tolerance by quiescence or high mortality rates in summer.

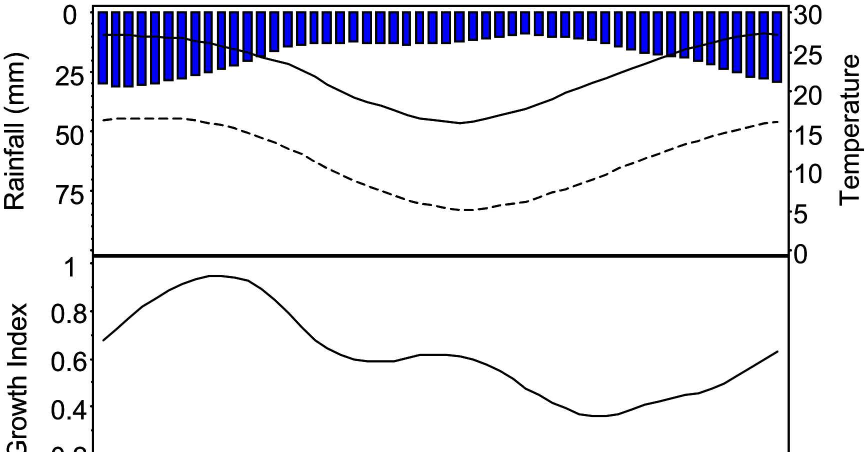
2. Check for day length effects operating to modify the GI values through the Light Index and diapause mechanisms. Diapause is taken into account by reducing the GI to zero in response to a given daylength (DLD0), or daylength in combination with temperature (DLT0). It is relaxed when the diapause termination temperature (DLT1) is reached later in the year, provided that the conditions for completion of diapause development have been satisfied.

3. Examine any experimental data relating to development rates at various temperature and moisture levels. If available, these can be extrapolated to give the four temperature indices in the absence of field data, or to confirm estimates derived from field data.

Moisture Parameters (SM0 - SM3)

The moisture range SM0 - SM3 defines soil moisture levels that are suitable for population growth and development. Moisture stress therefore cannot accumulate in this range. The Dry Stress Threshold (SMDS) must be ≤ SM0 and the Wet Stress Threshold (SMWS) must be ≥ SM3. Once the stress thresholds have been set, the moisture development parameters (SM0, SM1, SM2, and SM3) can be fitted. To fine-tune the values, include any experimental results or knowledge about how the species responds to moisture. The parameter values relate to mean soil moisture in the soil layer within rooting depths of most crops and grasses. Moisture preferences must be estimated by relating them to population growth and abundance data in the field at different locations, with different amounts of rainfall. New CLIMEX users need to become familiar with the relationship between soil moisture on one hand and both rainfall and evaporation on the other, in order to be able to estimate these parameter values (Fig. 3-19). In order to help users visualise the regimen of soil moisture at any given location, as estimated using the hydrological model in CLIMEX, we have provided '_Soil Moisture Utility' as a species file. The parameters have been set to ensure that the 'moisture index' appears as if it is directly proportional to the actual soil moisture content.

Fig. 3-19 Graph of the Moisture Index for the '_Soil Moisture Utility' (SM0=0, SM1=1, SM2=4, SM3=10) at Toowoomba, Queensland, illustrating the relationship between soil moisture and rainfall.



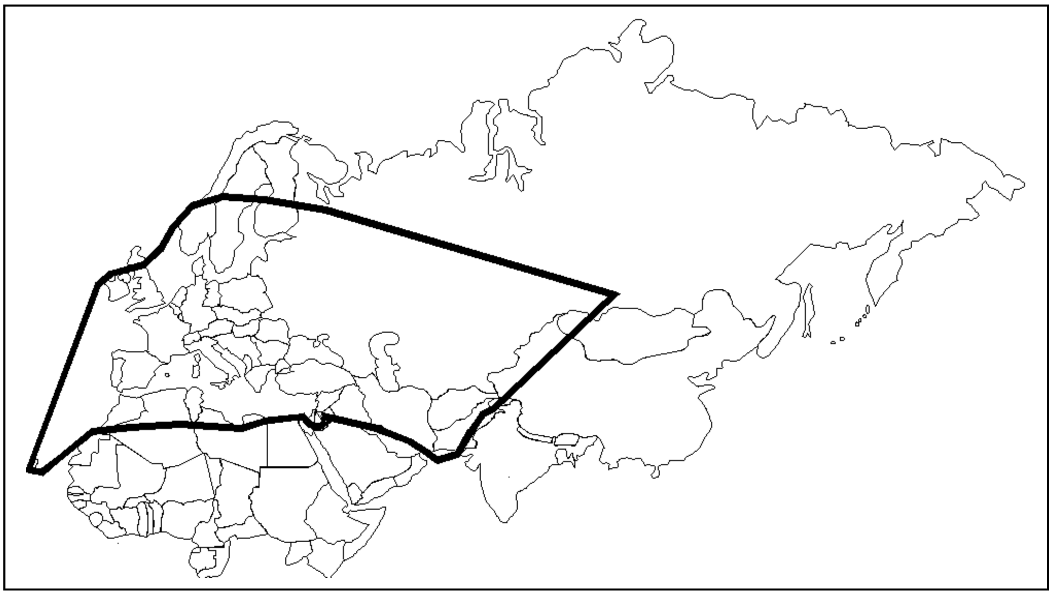
The above figure shows that soil moisture levels can be compared with the rainfall to show the seasonal changes and also the values for reference when visualising the relationship between the species requirement and soil moisture rather than the traditional relative humidity measure.

3.8.1 General Parameter Fitting Example

The best way to understand the process of parameter estimation is to work through an example.

The codling moth, [*Cydia pomonella* (L.)], is a major pest of deciduous fruit around the world. This example shows the basic principles used to predict the potential distribution of the moth from a simple distribution map, in this case its known range in Europe, North Africa and west Asia (Fig. 3-20).

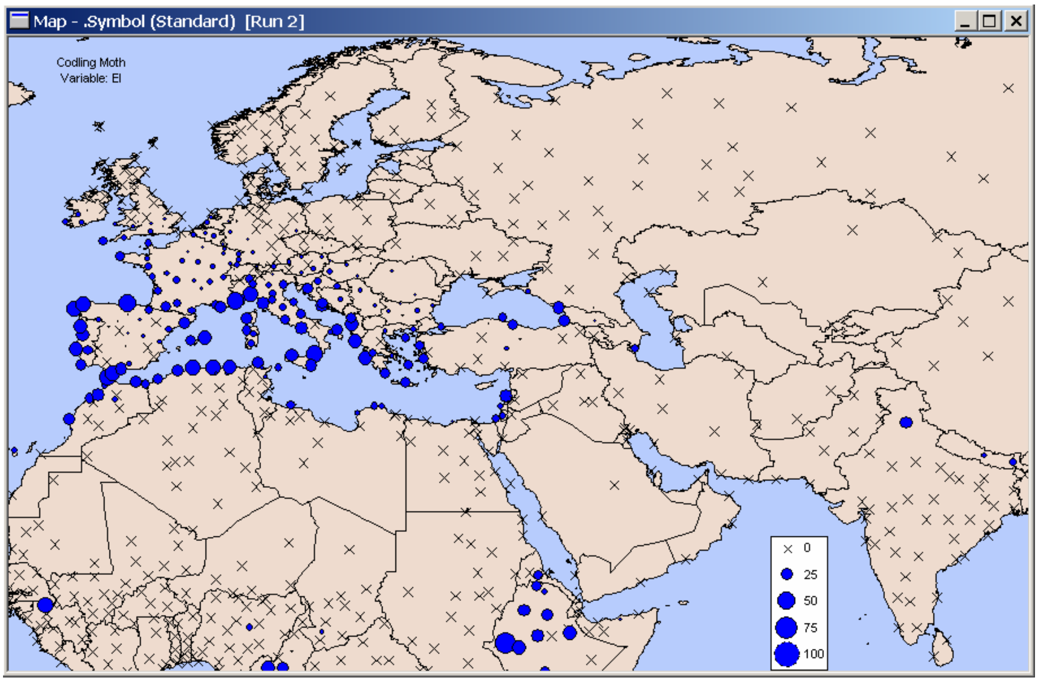
Fig. 3-20 The reported geographical distribution of the codling moth in Europe, northern Africa and western Asia. After Commonwealth Institute of Entomology, (1976).



Several conclusions can immediately be drawn from the distribution map. Firstly, the moth survives in the cold weather of northern Europe and in the warmer dry Mediterranean region, but appears not to survive in the wet tropical regions of Africa. This indicates a low developmental threshold for both temperature and moisture, and that either high temperatures or high rainfall limit the favourableness of the tropical regions. Given these observations, an initial CLIMEX prediction could be based on parameter values of a temperate species (in this case from Table 3-1 on page 45), but with DTCS set to 25 to make the exercise more instructive. A map of a CLIMEX run with these parameter values is given in Fig. 3-21.

The map in Fig. 3-21 shows a much more restricted distribution than is observed in practice. Examination of individual locations on the map shows that Heat Stress, Dry Stress and Cold Stress figure prominently. Northern Africa and western Asia are all indicated as being too hot and dry for the moth. Northern Europe and eastern European countries are too cold. As the known range of the moth includes these areas, the parameters need to be adjusted.

Fig. 3-21 The predicted distribution (EI) of the codling moth in Europe, northern Africa and Asia using the Temperate Template parameters in Table 3-1, with DTCS=25.



Cold stress makes much of Europe and Russia unsuitable. However, we know that the codling moth occurs in these areas, and that it also has an obligate winter diapause. . Thus, the first thing to do is to remove cold stress entirely, and to set the winter diapause functions. Setting diapause parameters must generally be done using data from the literature. Diapause is initiated with decreasing daylength (somewhere between 13 and 18 hours of daylight) and when summer temperatures drop below 15°C (Shel'Deshova 1967; Bajwa & Kogan 1997a; other references cited within these). A prolonged period of about 3 months below the developmental threshold is required for successful completion of diapause (Geier 1963a, b cited in Shel'Deshova 1967). Diapause is terminated when the necessary period of cooling has been completed, and temperatures begin to rise between 0°C and 10°C (Shel'Deshova 1967; Bajwa & Kogan 1997a). These findings indicate that the diapause parameters be set as follows:

These findings indicate that the diapause parameters be set as follows:

DPD0: set to 14, so that as daylength decreases below this value, diapause will be initiated when the correct temperature (DPT0) is reached. Trial and error indicated this to be the best value to enable diapause to be correctly initiated in northern latitudes while also enableing diapause to be initiated in northern Africa (at 30°N, the maximum daylength is about 14.1 hours, so a higher value will preclude diapause from being initiated).

DPT0: set to 11°C, as prolonged cooling below the developmental threshold (10-12C) is necessary (Shel'Deshova 1967). The value of 11°C is also consistent with the indication that summer temperatures below 15°C induce diapause (Bajwa & Kogan, 1997a).

DPT1: set to 6°C. This value is consistent with Shel'Deshova (1967) and other references in Bajwa & Kogan (1997a). This value of 6°C is a compromise. A higher value precludes development in northern latitudes where minimum temperatures often do not exceed 6°C whilst daylength is still increasing – ie prior to mid-June), and a lower value prevents the successful completion of diapause in northern Africa where minimum temperatures even in winter do not drop much below 6°C.

DPD: set to 90 days, as a minimum of 3 months below the developmental threshold is necessary for successful completion of diapause (Geier 1963a, b cited in Shel'Deshova 1967). A lower value (eg, 30 days) extends the distribution range of the codling moth in southern Europe, South America, Australia and Africa, but more detailed information on the occurrence of the codling moth in these specific locations would be needed to justify lowering this value. Distribution maps only indicate the broad regions where a species occurs, and tend to include rather than exclude regions.

DPSW: set to 0 for winter diapause.

The literature search for information on factors inducing and terminating diapause also indicated that the temperature parameters of the Temperate Template need adjusting. In the Temperate Template, DV0 = 8°C, DV1 = 18°C, DV2 = 24°C, DV3 = 28°C and PDD = 600 degree-days (above 8°C).

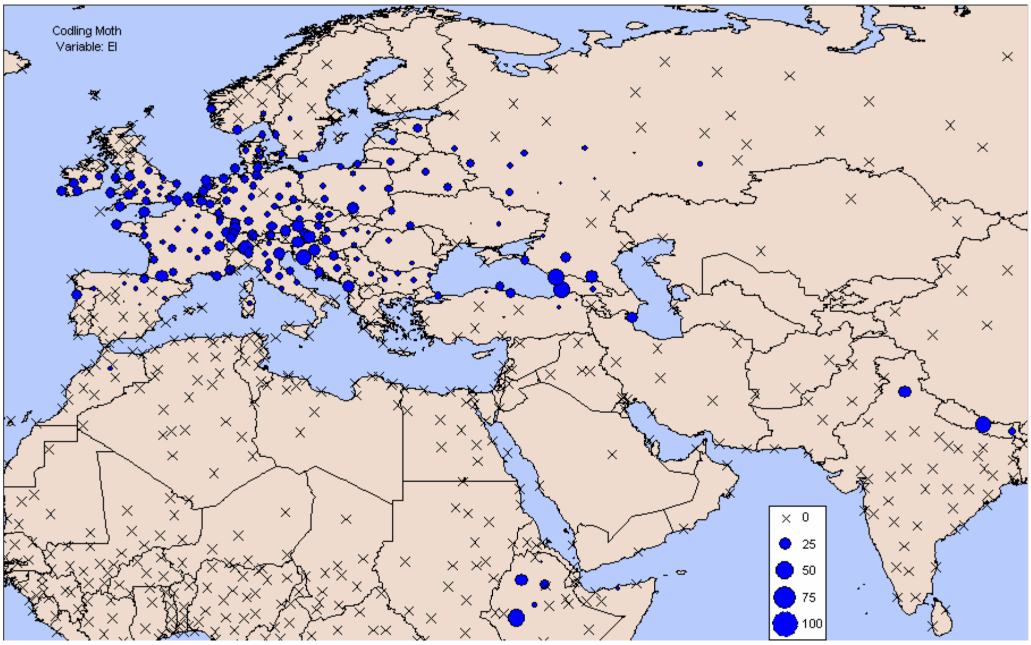
As we saw above, in fitting the diapause functions, the developmental threshold is between 10°C and 12°C, so DV0 must be adjusted. Several iterations, adjusting DV0 between each, indicated that 10°C was the most appropriate value for this parameter. The optimal temperature for codling moth seems to be between 20°C and 30°C (Shel'Deshova 1967), so DV1 is set to 20°C and DV2 is set to 30°C. DV3 must also be adjusted, and 33°C seems consistent with the literature (Shel'Deshova 1967; Pitcairn, Pickel, Falcon & Zalom 1991; and Bajwa & Kogan 1997a).

A value of 600 degree-days above 10°C (ie PDD = 600) is the widely accepted minimum heat accumulation for the completion of a generation (eg Shel'Deshova 1967). So let's begin by seeing how these changes have influenced the potential distribution. The values we have altered in our new species file, copied from the Temperate Template, are as follows:

Temperature Parameters	Diapause Parameters	Cold Stress Parameters
DV0 = 10º C	DPD0 = 14 (hrs of daylight)	TTCS = 0º C
DV1 = 20º C	DPT0 = 11º C	THCS = 0
DV2 = 30º C	DPT1 = 6º C	DTCS = 0
DV3 = 33º C	DPD = 90 days	DHCS = 0
PDD = 600	DPSW = 0 (for winter diapause)	

With all other parameter values untouched, these adjusted parameter values provide the distribution shown in Fig. 3-22.

Fig. 3-22 Prediction for the codling moth using the original Temperate Template parameters with the development temperatures and cold stress values adjusted, and the inclusion of winter diapause.

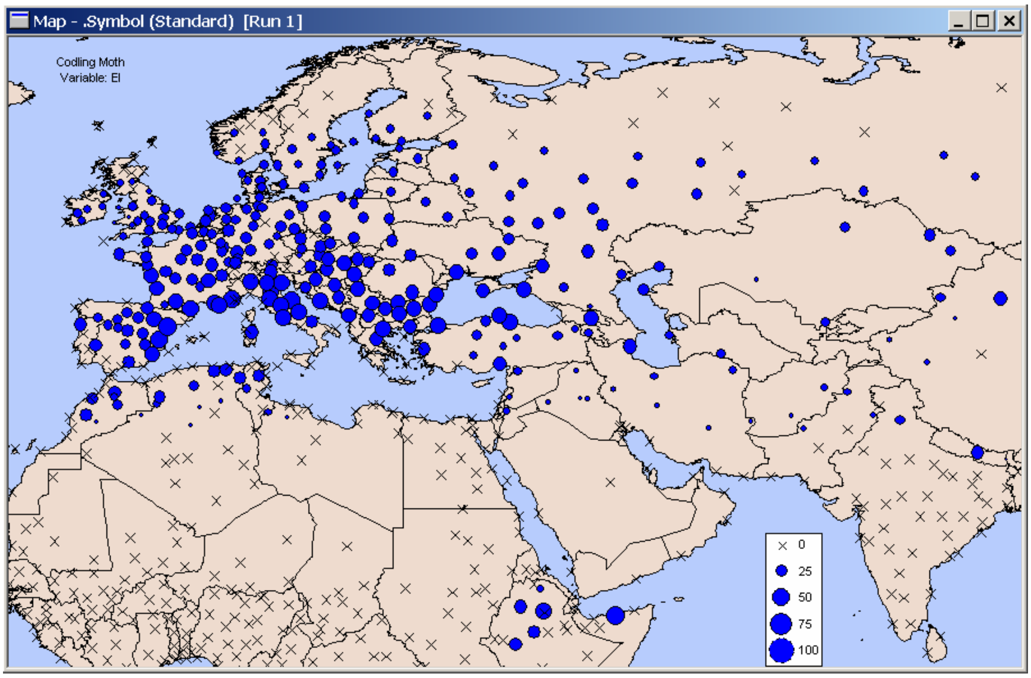


The distribution has extended further northwards, as we would have hoped by removing the cold stress parameters. Examination of locations in Scandinavia and Russia that are still unsuitable indicates that although the EI is zero, both the temperature and moisture parameters are suitable, and there is a positive GI value. Although temperature and moisture conditions are suitable for growth, and there is a positive GI value, these locations are not accumulating 600 degree-days above 10^{o}C. A generation cannot therefore be completed, and the species is excluded from the locations, with EI being set to zero. This throws into question the accuracy of the above estimate of PDD=600 degree-days > 10^{0}C.

If we reduce PDD to 450 days, we note that the potential distribution of the codling moth extends further north (Fig. 3-23), and now includes locations (eg

Kirov, Perm and Tomsk in Russia) that are known to support permanent populations (Shel'Deshova 1967).

Fig. 3-23 Potential distribution of the codling moth with PDD reduced from 600 to 450 degree-days > 10°C.

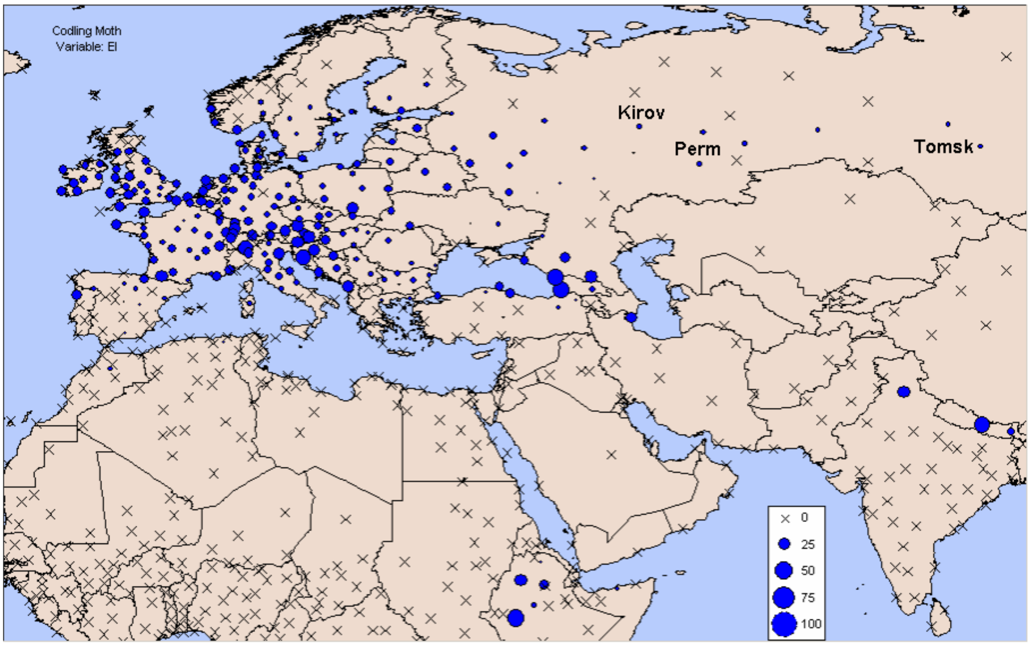


Many areas that should be within the distribution (Fig. 3-20) are still indicated as being unsuitable, either because of excessive heat or dry stress, or because the moisture index (MI) is limiting. Having adjusted all of the other temperature parameters, let’s begin by adjusting the heat stress parameters. We now have an upper temperature threshold (DV3) of 33°C, but the heat stress temperature threshold (TTHS) is still 30°C, with an accumulation rate of 0.005. As TTHS cannot be below DV3, we must increase its value to at least 33°C. Because we need to address the excessive heat stress, we also reduce the accumulation rate (THHS) from 0.005 to 0.0003.

However, in order to see a major change in the predicted distribution of codling moth, we must also alter the moisture and dry stress parameters. Adjusting these parameters is somewhat complicated. Given that the codling moth is a pest of orchard fruit, the role of irrigation in maintaining a suitable microclimate in arid zones needs to be considered. Either we can assume that 10mm (for example, this translates to ~1.5mm /day) of irrigation are applied weekly in the summer months, and use this scenario to tune the CLIMEX moisture parameters. This could be done by selecting the **Irrigation** component module, and setting the appropriate value for irrigation (1.5mm per day in summer). Alternatively, parameters can be fitted to the raw meteorological data on the assumption that the host fruit are grown in such climates. This carries the implicit assumption that irrigation must be occurring; otherwise the pome fruit could not be grown in these areas. We will try to fit the moisture and dry stress parameters to the raw meteorological data.

To reduce moisture stress, we have to alter both the moisture and the dry stress parameters. Let's begin by reducing the soil moisture parameters. The distribution map (Fig. 3-20) indicates that the codling moth occurs in dry areas, so let's reduce SM0 from 0.2 to 0.02, SM1 from 0.8 to 0.08, SM2 from 1.5 to 1 and SM3 from 2 to 1.2. Because we have reduced SM0, we must also reduce the dry stress threshold (SMDS) from 0.2 to at least 0.02 (*Note that DYMEX forces consistency in the parameter values at all times, so the order in which you make these adjustments is important*). This in itself will reduce the dry stress accumulated, and reducing the accumulation rate (HDS) from 0.005 to 0.003 will further reduce the amount of dry stress accumulated. Finally, because we have reduced SM3 from 2.0 to 1.2, we should also alter the wet stress parameters. Let us reduce the wet stress threshold (SMWS) from 2.5 to 1.2. As this should increase the amount of wet stress accumulated, let's decrease the accumulation rate (HWS) from 0.002 to 0.0005.

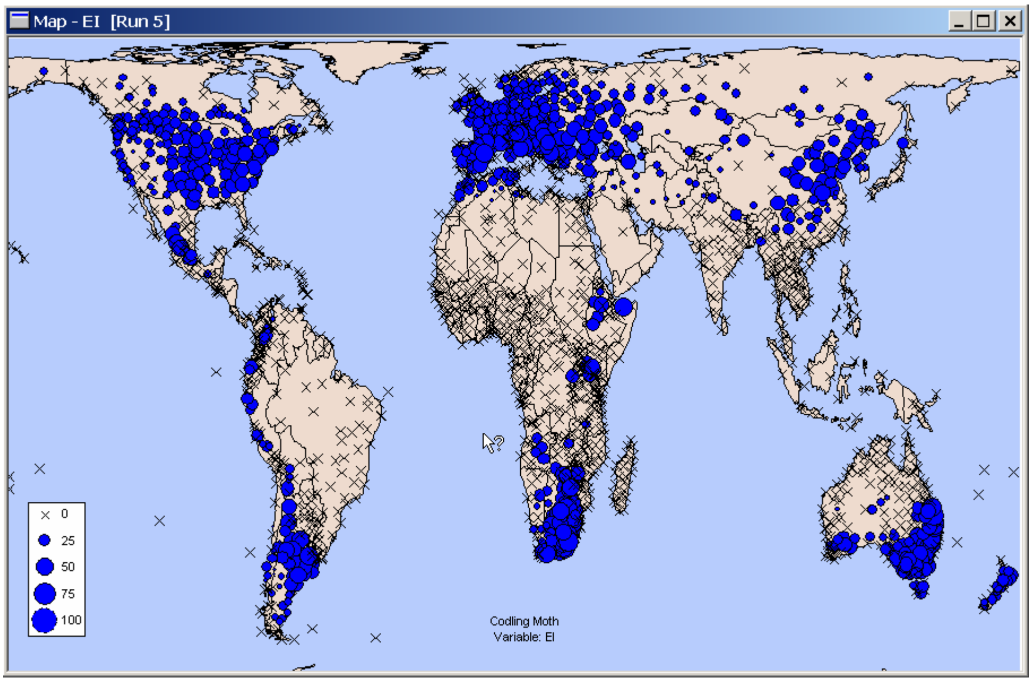
Fig. 3-24 Potential distribution of the codling moth adjusted for heat stress, moisture parameters, dry stress and wet stress.



The final prediction (Fig. 3-24) accords well with the overall distribution shown in Fig. 3-20. Some Mediterranean areas indicated as being within the distribution range in Fig. 3-20 are indicated as being unsuitable in Fig. 3-24 because obligate diapause conditions cannot be met (winters are not cold enough). Other areas in Europe and northern Russia are indicated as unsuitable in Fig. 3-24 because there are insufficient degree-days above 10^{o}C to enable a generation to be completed. To tune the model, it would be necessary to know whether or not codling moth occurs in these specific locations. It is likely that there are locations, not represented sufficiently well by the limited climate data set, that provide suitable conditions for survival.

The results of a world prediction (Fig. 3-25) can be compared to the known world distribution (Fig. 3-26). If suitability of northern Canada and Russia are thought to be too high, cold stress can be made to accumulate below temperatures of –20°C at a rate of 0.001. This would be consistent with results of various authors cited in Shel'Deshova (1967).

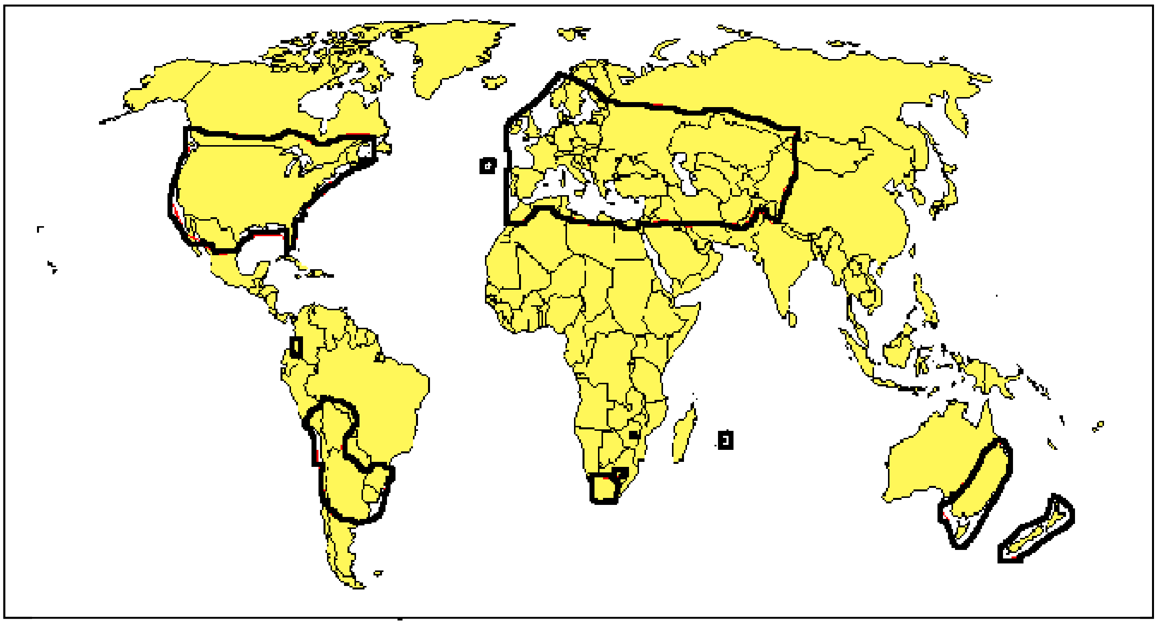
Fig. 3-25 Predicted potential world distribution of codling moth using final parameters.



There are some other discrepancies between the predicted and known distributions, but these may not be due to climate. For example, the CLIMEX model predicts that codling moth could occur in the south-western corner of Australia (Fig. 3-25), which has a Mediterranean climate that is clearly suitable for the moth (Fig. 3-20). Whilst the moth does not in fact currently occur in western Australia (Fig. 3-26), it has occurred here (Wickens 1928, cited in Shel'Deshova 1967; Jenkins 1947, 1956, cited in Shel'Deshova 1967; Barnes 1991, cited in Bajwa and Kogan 1997a). Similarly, the more restricted distribution in Africa could be due to other factors that are quite separate to the climatic factors regulating the potential distribution. CLIMEX only considers the climatic suitability of locations for a species – not the presence of suitable hosts, or other factors which may be responsible for limiting actual distributions.

This example is obviously a condensed version of the parameter fitting process, as it would take too long to describe all the iterations. Until the user becomes familiar with the program, it is suggested that only one parameter be changed at a time to keep track of the changes in distribution. The value of each of the stresses affecting the species at each location can be examined by selecting the location on the map with the mouse, viewing the results in tabular form or by mapping any of the stress indices rather than the EI using the Options button. Mapping the stresses gives a much better indication of where alterations need to be made.

Fig. 3-26 The known world distribution of codling moth. (Bajwa, W.I. and Kogan, M., 1997b).



Realistically, it will probably take a week to complete and document a CLIMEX model including literature search, parameter fitting and examination and reporting of the behaviour of the model.

References

Bajwa, W.I. & Kogan, M. (1997a). Bionomics of Codling Moth. In: Codling Moth Information Support System (Electronic database). Corvallis, OR: Integr. Plant Protect. Center. http://ippc.orst.edu/codlingmoth/bionomics

Bajwa, W.I. and M. Kogan, (1997b). Codling Moth Distribution Map. In: Codling Moth Information Support System (Electronic database). Corvallis, OR: Integr. Plant Protect. Center. http://ippc.orst.edu/codlingmoth/bionomics/cmdistri.html

Commonwealth Institute of Entomology (1976). Distribution Maps of Pests, Series A (Agricultural), Map No. 9 (revised). Commonwealth Agricultural Bureaux, London.

Ferro, D.N., Sluss, R.R. & Bogyo, T.P. (1975). Factors contributing to the biotic potential of the codling moth, *Laspeyresia pomonella* (L.), in Washington. *Environmental Entomology* **4(3)**: 385-391.

Hill, D.S. (1987). Agricultural Insect Pests of Temperate Regions and their Control. Cambridge University Press, Cambridge. p 402.

Pitcairn, M.J., Pickel, C., Falcon, L.A., & Zalom, F.G. (1991). Development and survivorship of *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) at ten constant temperatures. *Pan-Pacific Entomologist* **67(3)**: 189-194.

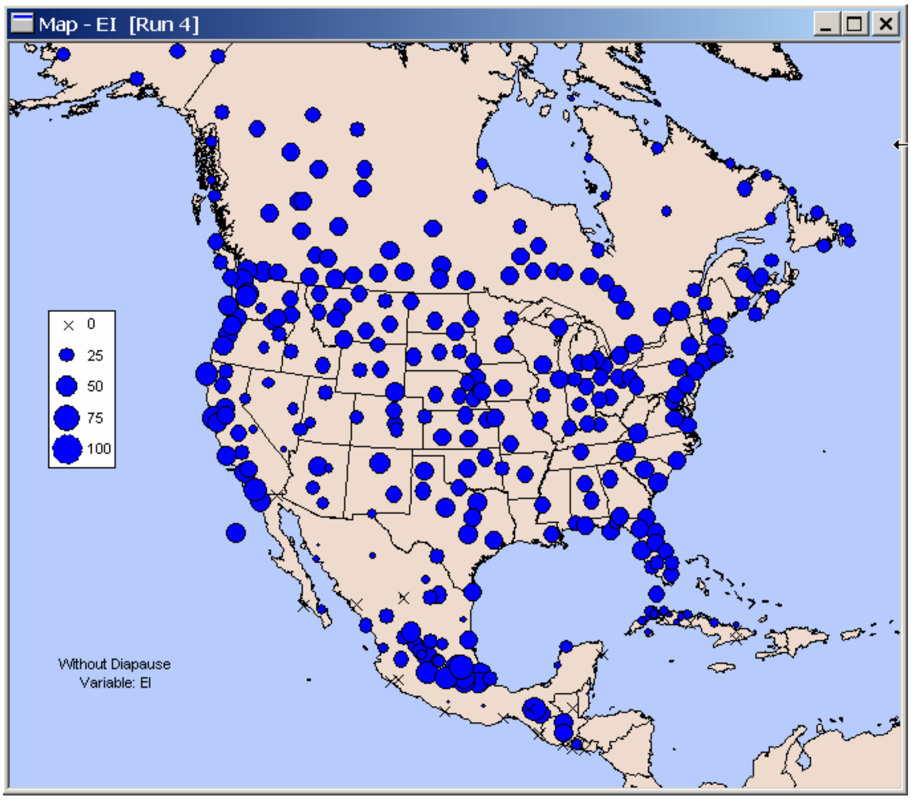
Shel'Deshova, G.G. (1967). Ecological factors determining distribution of the codling moth *Laspeyresia pomonella* L. (Lepidoptera, Tortricidae) in the northern and southern hemispheres. *Entomological Review* **46**: 349-361.

3.8.2 Diapause Parameter Fitting Examples

If a species has obligate diapause, the parameters should be set prior to estimating the stress factors. This applies especially to the “relevant” stress factors (eg Cold Stress if the species has winter diapause, and Heat Stress if the species has summer diapause). Heat and Cold Stress can still apply to species undergoing obligate diapause, but as diapause is a mechanism for avoiding unfavourable conditions, the conditions causing stress to occur during diapause are likely to be extreme. If the Heat and Cold Stress parameters are set too high, then excessive stress will accumulate during diapause development, thereby excluding the species from locations which are in fact favourable for its long term survival.

Users are referred to Section 3.3.6 and 7.1 of the User’s Guide for a description of the diapause functions and how they are implemented in CLIMEX. We start with the assumption that a requirement for diapause to complete a lifecycle is obligate in the species of interest. Thus the requirement will limit the range of habitats that the species can occupy to those that provide suitable climatic conditions for diapause development.

Fig. 3-27 Distribution of species with no diapause for North America, using parameter settings from Table 3-2.



Recall that in CLIMEX, short daylengths and low temperatures (winter diapause) or long daylengths and high temperatures (summer diapause) can trigger diapause. CLIMEX models the limiting effects of obligate diapause by establishing a set of induction and termination conditions and a number of days below/above a diapause inducing temperature to complete diapause development. CLIMEX reduces the Growth Index to zero during this period of diapause development. While a species is not in diapause the weekly Diapause Index (DI_W) = 1. $DI_W = 0$ for the time that the species is in diapause.

To assess the effect of obligate diapause on the geographical distribution of a species, let's consider a hypothetical species which has a broad distribution range and is only marginally affected by any stress factors, such that it can persist from northern Canada to Mexico (Fig. 3-27).

The parameter values used to obtain this distribution are given in Table 3-2, page 62. If we remove the marginal limiting effects of Cold Stress, and impose obligate winter diapause as a constraint (Table 3-2), we see that the species is now excluded from the warmer southern areas (Fig. 3-28).

Table 3-2 Values for parameter settings of species with and without obligate diapause.

Parameter Group	Parameter	Without Diapause	Winter Diapause	Summer Diapause
Temperature Index	DV0	2	2	2
	DV1	15	15	15
	DV2	25	25	25
	DV3	28	28	28
	PDD	0	0	0
Moisture Index	SM0	0.05	0.05	0.05
	SM1	0.1	0.1	0.1
	SM2	0.8	0.8	0.8
	SM3	2.0	2.0	2.0
Cold Stress	TTCS	0	0	0
	THCS	0	0	0
	DTCS	20	**0**	20
	DHCS	-0.000001	**0**	-0.000001
Heat Stress	TTHS	30	30	**0**
	THHS	0.0001	0.0001	**0**
	DTHS	0	0	0
	DHHS	0	0	0
Dry Stress	SMDS	0.05	0.05	0.05
	HDS	-0.001	-0.001	-0.001
Wet Stress	SMWS	2	2	2
	HWS	0.001	0.001	0.001
Diapause	DPDO	0	**10**	**10**
	DPTO	0	**10**	**30**
	DPT1	0	**0**	**30**
	DPD	0	**90**	**30**
	DPSW	0	**0**	**1**

Fig. 3-28 Distribution of a species with obligate winter diapause in North America using parameter settings from Table 3-2.

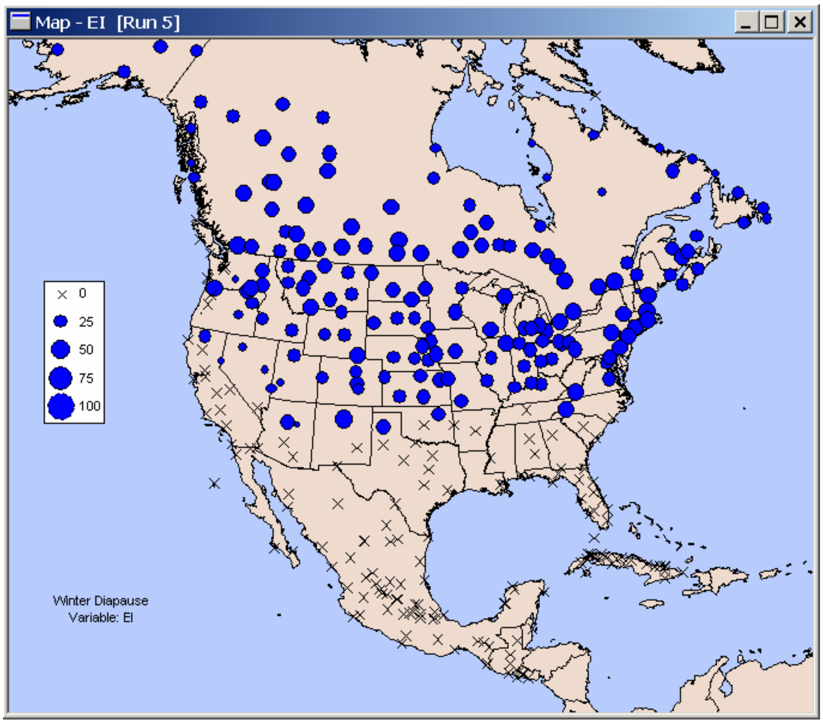
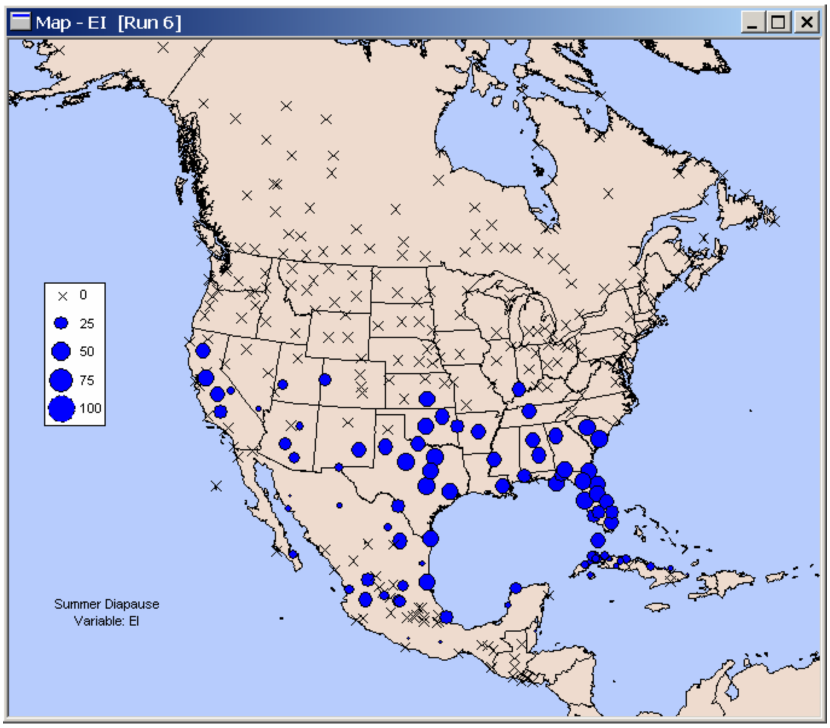

Map - EI [Run 5]
0
25
50
75
100
Winter Diapause
Variable: EI

Fig. 3-29 Distribution of a species with obligate summer diapause in north America using parameter settings from Table 3-2.


Map - EI [Run 6]
0
25
50
75
100
Summer Diapause
Variable: EI

If we impose obligate summer diapause (Table 3-2), the species is excluded from the colder northerly areas and the high altitude southern areas that do not experience the necessary heat conditions to initiate and maintain diapause (Fig. 3-29).

3.9 Parameter fitting using the Genetic Algorithm

In order to expedite the initial steps in the parameter fitting process, an automatic parameter fitting procedure, based on a "genetic algorithm" (GA), has been included in CLIMEX V3. It is used to fit the Stress parameters only. The stress parameters are fitted to presence and absence records, with constrained values of the parameters to ensure that they stay within sensible bounds. The result is a geographical distribution of the values of species performance less the effects of stress presented. These have previously been defined as the 'Core Distribution', or (1-∑Stress) (page 49). Users need to be aware that any effects of the growth indices (an 'constraints' on the limits to the geographical distribution will be in addition to these results.

In order to implement the GA procedure, the user needs to supply an observed distribution in the form of a presence, absence or unknown record for each locality in the CLIMEX meteorological database corresponding with the species geographical distribution. An initial set of species parameter values is also needed to initiate the fitting process. Such values can be derived from a species with a similar distribution or from one of the species templates supplied with CLIMEX.

The GA generates selects those parameter values that best describe the observed distribution. A general description of GAs can be found in Michalewicz, Z. (1996), *Genetic Algorithms + Data Structures = Evolution Programs*, 3rd Edition, Springer Verlag. A GA is an optimization procedure that simulates natural evolutionary processes by creating 'populations' of parameter values (each corresponding to a hypothetical 'species' in nature) and then selecting the best fitting values in each generation of the simulation. In each generation the GA introduces new variants into the populations by simulating genetic cross-overs and mutations. This allows new parameter spaces to be explored. The GA provides the best fitting parameter set after the chosen number of generations,. If the simulation is interrupted the GA stores parameter values derived up to that time.

The steps involved in the fitting procedure are described in detail below, and consist of the following:

(1) Obtain a known distribution (the *Target Distribution*) for a particular region (for example, a continent).

(2) Create a *Reference File* that reflects the distribution of the species as found in step 1. The *Reference File* is used by the GA to judge how accurately a particular set of parameter values predicts the known distribution. It contains the locations being used in the GA fitting and the status of the species (0 = absent, 1 or 100 = present, -1 = unknown) for each of the locations. If relative abundances are known, these should be indicated with a range of numbers scaled between 1 and 100.

(3) Create a new species in CLIMEX (the species to be fitted), preferably by using a template or species with a similar geographical distribution.

(4) Decide which stress parameters are to be adjusted and optionally set a range for each of the parameters to be included in the fitting. By default, the optimization routine will use the full allowed range of a parameter when searching for a best value. In order to save execution time (and to avoid "unrealistic" values of parameters being used by the fitting routine), it is strongly recommended that each parameter be given an appropriate range. Each parameter's permitted range can be set separately.

(5) Change the GA operating characteristics, if required. By default, the routine operates with a parameter set population of 100, a "crossover rate" of 0.75, a "mutation rate" of 0.1, and will run for 250 generations before stopping.

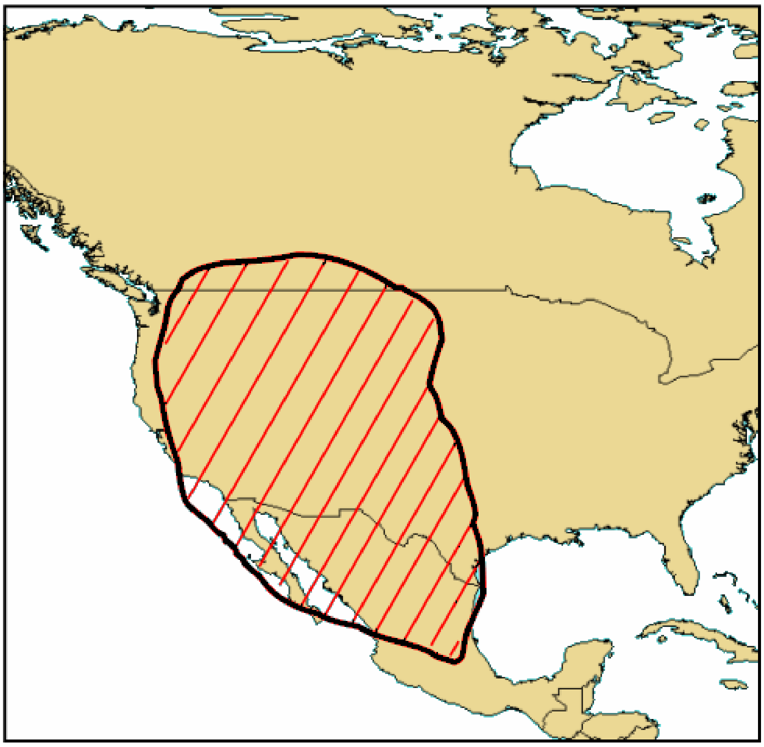
(6) Run the GA. Note that the algorithm takes a long time to run because it requires many runs of CLIMEX. It *can be interrupted at any time. If the parameters are then saved, the fitting routine can be restarted with the most recently saved parameter values.*

These steps are now described in more detail with an example that illustrates fitting the stress parameters for *Diuraphis noxia*, the Russian Wheat Aphid, in North America.

Step 1: Obtain a known geographical distribution for the target species.

A map of the aphid's known distribution is shown in Fig. 3-30, which has been adapted from Figure 2 in Hughes and Maywald (1990).

Fig. 3-30 Approximate known distribution of *Diuraphis noxia* in North America.

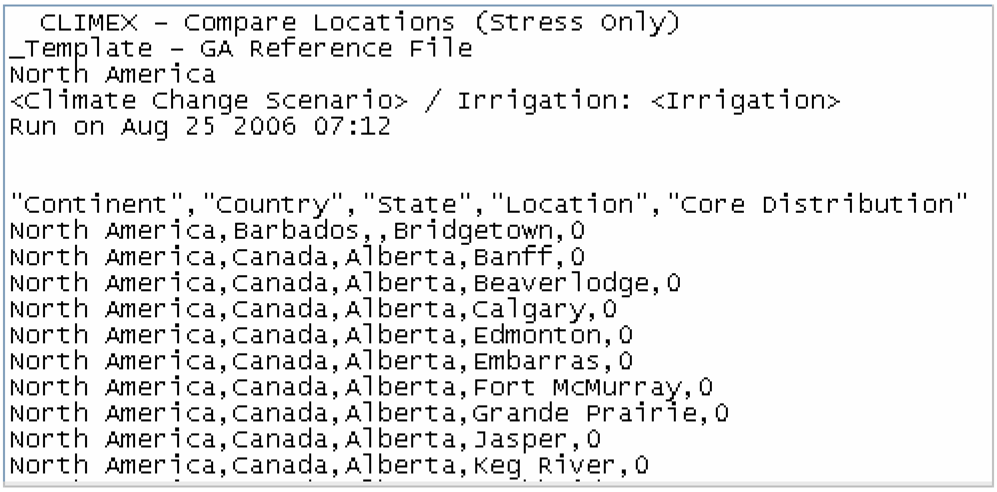


Step 2: Create a Reference File

We will use the CLIMEX station data (not the climate grid data) for fitting this species to expedite the GA calculations. We need to create a *Reference File* that describes the occurrence of the species at each of the locations listed in the *Location Selection* (ie North America) that will be used in the fitting process. The most convenient way to create the file is to run CLIMEX with the appropriate *Location Selection*, and output a *Results File* which contains a column with the item we want, the "Core Distribution".

For later editing purposes it is easiest to export a variable that has all zero values. To generate such a file, use the special "species template", "**_Template – GA_Reference File**". Run the ***Compare Locations (Stress)*** application with the desired *Location Set* and this template. Select **Results | File** from the menu and then select "**GA Reference File – Core Distribution**" from the popup menu. The resulting File Outputs dialog will be set up correctly for the required *Reference File* format. Click on the "Save" button, give the file a suitable name ("***Diuraphis noxia Reference***" for our example) and place it into the same directory as the Simulation (.dxs) file.

The first few lines of the resulting file should look as shown below (make sure that the header for the variable shows "*Core Distribution*":



```
  CLIMEX - Compare Locations (Stress Only)
_Template - GA Reference File
North America
<Climate Change Scenario> / Irrigation: <Irrigation>
Run on Aug 25 2006 07:12


"Continent","Country","State","Location","Core Distribution"
North America,Barbados,,Bridgetown,0
North America,Canada,Alberta,Banff,0
North America,Canada,Alberta,Beaverlodge,0
North America,Canada,Alberta,Calgary,0
North America,Canada,Alberta,Edmonton,0
North America,Canada,Alberta,Embarras,0
North America,Canada,Alberta,Fort McMurray,0
North America,Canada,Alberta,Grande Prairie,0
North America,Canada,Alberta,Jasper,0
North America,Canada,Alberta,Keg River,0
```

The next part of the procedure is laborious. It involves replacing the default zero value of the "Core Distribution" for each location with one of the following values:

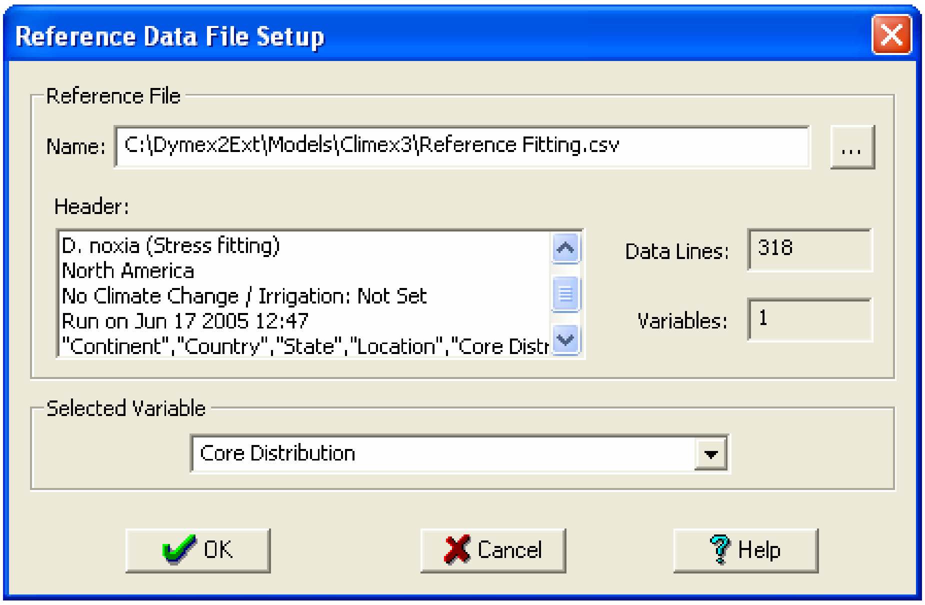
0	the species is known not to occur at that location
1	the species is known to occur at that location
-1	the status of the species at that location is unknown

Users need to be aware that the GA is sensitive to incorrect classifications of locations, so if in doubt enter a -1 rather than a potentially incorrect classification. The changes can be made using programs such as Excel, PFE, Notepad etc. but will be much faster if there is a 'global replace' feature to substitute values into blocks of lines rather than editing each line separately which may be prohibitively time consuming. Once the file has been edited, it can be checked by reloading the "***Compare Locations (Stress)***" application and selecting this file as the *Reference Data File*.

Click on the **Initialization** menu and select the **Reference Data File** sub-menu. This opens the Reference Data File Setup dialog (Fig. 3-31). Click on the small button at the top right of the dialog and in the resulting "File" dialog navigate to the reference file that you have just created. Click on "Load" to load the file into CLIMEX.

The reference file will be read during the loading operation, and if its format is correct, the file "Header" (i.e., the lines preceding the data) will be shown in the **Header** panel (Fig. 3-31). The two boxes to the right of the Header panel will be showing the number of lines containing data in the file, and the number of variables that the file contains. If the data file does not have the correct format, DYMEX will display an error message indicating that a problem has occurred. Should all be well, select the required variable ("Core Distribution") from the **Selected Variable** box by clicking on the small arrow to the right and locating it in the drop-down list.

Fig. 3-31 The Reference Data File Setup dialog, with settings for the *D. noxia* fitting.



Name: C:\Dymex2Ext\Models\Climex3\Reference Fitting.csv

Header:
D. noxia (Stress fitting)
North America
No Climate Change / Irrigation: Not Set
Run on Jun 17 2005 12:47
"Continent","Country","State","Location","Core Distr

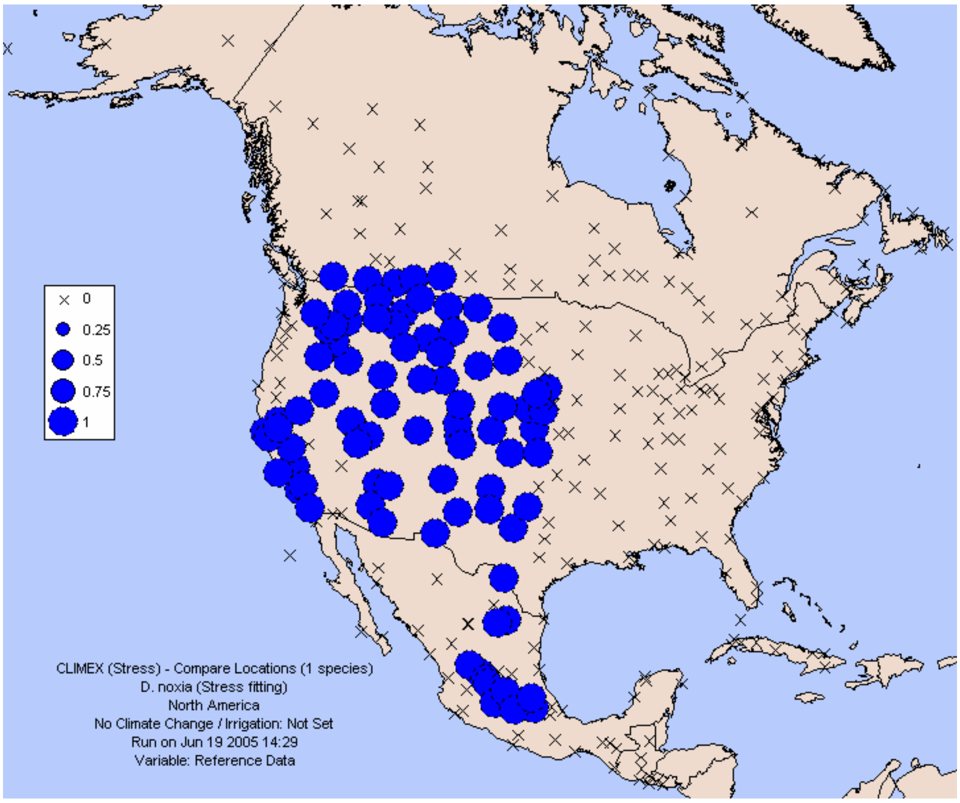
Data Lines: 318

Variables: 1

Selected Variable: Core Distribution

With the *Reference File* correctly loaded, the CLIMEX Stress application can now be run to check the data in the file. With the run completed, map the data in the file by creating a map using the output variable ***Reference Data*** (Fig. 3-32).

Fig. 3-32 A map of the data in the Reference File .


0
0.25
0.5
0.75
1
CLIMEX (Stress) - Compare Locations (1 species)
D. noxia (Stress fitting)
North America
No Climate Change / Irrigation: Not Set
Run on Jun 19 2005 14:29
Variable: Reference Data

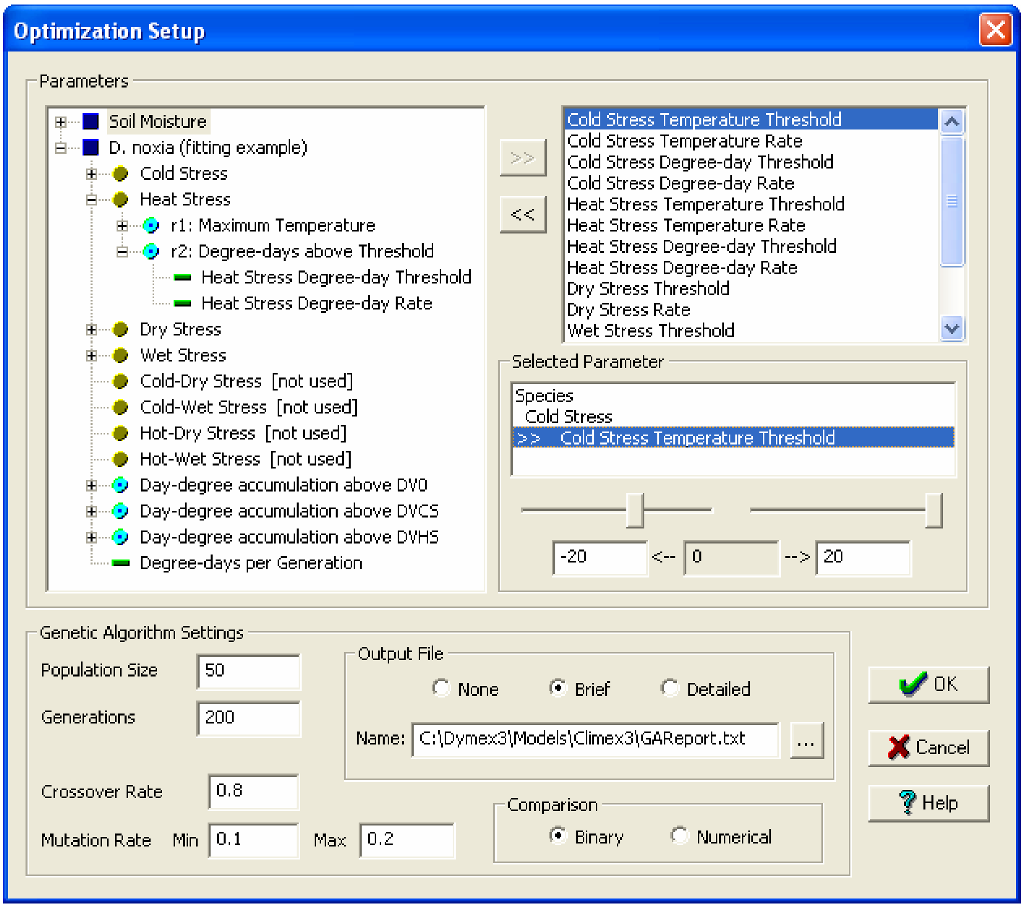
Step 3 (Create a new species):

Load CLIMEX (always use the **Stress-only** version of CLIMEX) and create a new species (see Section 5.2) that contains the initial ‘seed’ parameter values (these represent the first guess at a parameter set and will usually be one of the template “species” or a species with a similar distribution). Use the new species in the fitting procedure.

Step 4 (choose GA operational characteristics) and 5 (select Stress parameters to be optimized):

We are now ready to set up the optimization run using the “genetic algorithm”. This must be done using the “Stress Only” application of CLIMEX, ***CLIMEX – Compare Locations (Stress)***. This allows the core distribution to be fitted without the additional complications of the Growth Index or constraints caused by unsuitable daylengths or temperatures to enter obligate diapause or vernalisaion, or inadequate degree-days and thus speeds up running of the optimization. To set up the optimization run, click on the **Initialization** menu and select **Genetic Algorithm** from the drop-down menu. This opens the **Optimization Setup** dialog (Fig. 3-33).

Fig. 3-33 The Optimization Setup dialog, used for configuring the settings for the automatic fitting of parameters using the Genetic Algorithm.


Optimization Setup
Parameters
Soil Moisture
D. noxia (fitting example)
Cold Stress
Heat Stress
r1: Maximum Temperature
r2: Degree-days above Threshold
Heat Stress Degree-day Threshold
Heat Stress Degree-day Rate
Dry Stress
Wet Stress
Cold-Dry Stress [not used]
Cold-Wet Stress [not used]
Hot-Dry Stress [not used]
Hot-Wet Stress [not used]
Day-degree accumulation above DV0
Day-degree accumulation above DVCS
Day-degree accumulation above DVHS
Degree-days per Generation
>>
<<
Cold Stress Temperature Threshold
Cold Stress Temperature Rate
Cold Stress Degree-day Threshold
Cold Stress Degree-day Rate
Heat Stress Temperature Threshold
Heat Stress Temperature Rate
Heat Stress Degree-day Threshold
Heat Stress Degree-day Rate
Dry Stress Threshold
Dry Stress Rate
Wet Stress Threshold
Selected Parameter
Genetic Algorithm Settings
Output File
Comparison
OK
Cancel
Help

Selected Parameter: Species / Cold Stress / >> Cold Stress Temperature Threshold

-20 <-- 0 --> 20

Population Size: 50

Generations: 200

Crossover Rate: 0.8

Mutation Rate Min: 0.1 Max: 0.2

Output File: ○ None ● Brief ○ Detailed

Name: C:\Dymex3\Models\Climex3\GAReport.txt

Comparison: ● Binary ○ Numerical

The first step is to select the parameters to be optimized with their upper and lower limits for the target species. The parameters are listed at the left, in the Windows Explorer-style "tree" view, where various CLIMEX model components form the nodes of the tree, with the parameters forming the terminal nodes. This allows the "context" of a parameter to be determined. Nodes can be "opened" in this view by clicking on the small rectangle containing a + to the left of the node symbol. The list box at the top right of the dialogs contains the parameters that are included in the fitting. To include a parameter, select it in the **Parameters** window and click on the >> button to move it into the list box. As many parameters as required can be fitted in the optimization run. The sliders and edit boxes in the **Selected Parameter** panel allow adjustments of the range over which the highlighted parameter can be adjusted by the GA. If a panel and slider are greyed out, the corresponding limit is not adjustable. When a parameter is first included in the fitting, the adjustment range is set by default to the full range allowed by the CLIMEX model for that parameter.

The operating parameters for the genetic algorithm are set from the 'Genetic Algorithm Setting' panel at the bottom of the dialog. **Population Size** indicates the number of parameter sets being operated on at any one time, **Generations** specifies the number of generations for which to run the optimization, **Crossover Rate** is the crossover rate to be used, and **Mutation**

Rate specifies the lowest and highest mutation rates. The mutation rate declines linearly from the specified maximum value when the ratio of the standard deviation of the population's fitness to the average is above 0.1, down to the specified minimum value when the ratio is 0.

You can also select the format used to compare the data in the Reference file with the estimated values. It can be either **Binary**/categorical (representing presence or absence) or **Numerical**. In addition, there is a choice of format and destination for the **Output File** (which contains information about the fitting process). You are now ready to create your new species file and run the Genetic Algorithm.

Step 6:

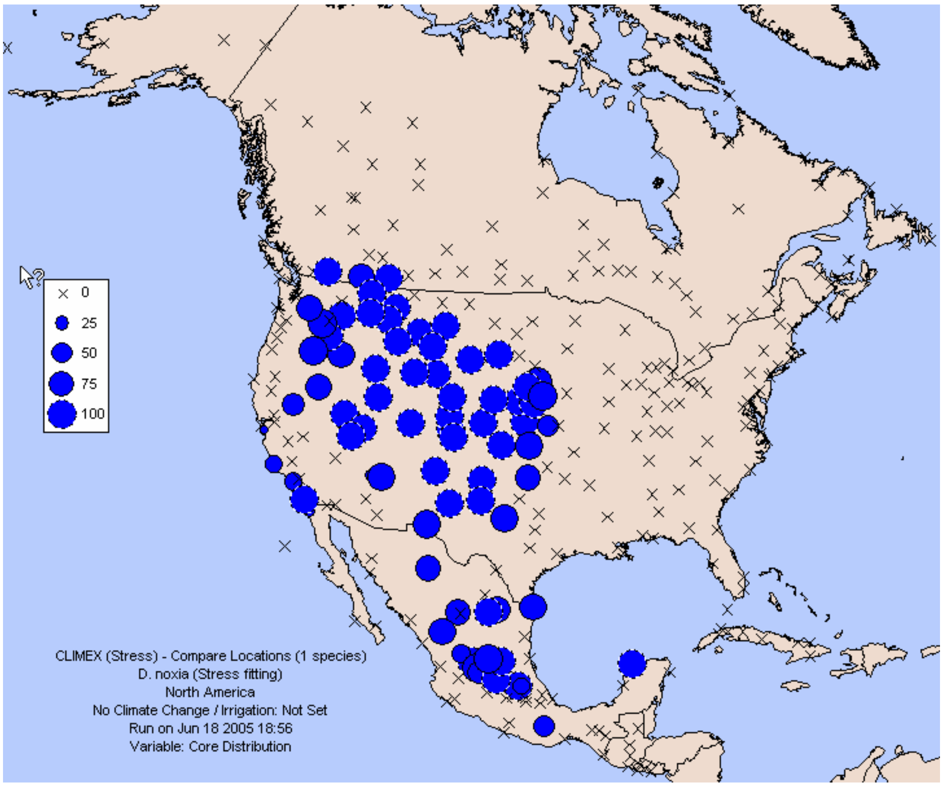
The Genetic Algorithm can now be run by selecting **Run Genetic Algorithm** from the **Execution** menu. Such a run can take a long time (many hours), but can be stopped at any time by clicking on the **Stop** button. The species will then contain the best combination of parameters found so far, and these parameters can be saved in the usual way – overwriting the starting species parameter values - from either one of the Parameter windows. The optimization run can then be restarted with these parameter values at a future time. After saving the parameter values, close the simulation and return to the simulation window and run the species as one would normally run any other species. You are then able to compare the *Core Distribution* with the *Reference Data* by mapping the two variables simultaneously. NB when mapping these values you need to de-select the **Range: Automatic** option because the values range from -1 to 1 rather than starting at zero.

A run for 200 generations, with a population of 100 and all other settings as in Fig. 3-33 produced the results shown in Fig. 3-34.

Important Note:

Several things need to be borne in mind when using the automatic fitting procedure in CLIMEX. Distributions are generally poorly defined when using sources such as museum records. The fact that a species is not recorded at a particular location can mean either that it is not there or has not been found there yet. The danger is that if all such locations are coded as 0 (absent), the genetic algorithm will produce a predicted distribution that is too conservative (i.e., it will indicate some locations as unsuitable even if they are suitable for the species). This is a problem in all such automatic fitting procedures no matter what climate model algorithm is used. Of course, such locations could be coded as -1 (species status unknown). This cannot be done for all such locations because the fitting algorithm needs some negative records to be able to fit a boundary to the distribution. Careful consideration therefore needs to be given to how locations are coded, especially around the boundaries of the known distribution. It is recommended that the genetic algorithm be used to give a "ballpark" fit of the stress parameters initially, with careful consideration being given to the data used in the fitting and following manual fitting that is used to complete the process.

Fig. 3-34 Results of a 200 generation run, showing the predicted 'Core Distribution' of *D. noxia* using the fitted parameter values.


0
25
50
75
100
CLIMEX (Stress) - Compare Locations (1 species)
D. noxia (Stress fitting)
North America
No Climate Change / Irrigation: Not Set
Run on Jun 18 2005 18:56
Variable: Core Distribution

4 Climate Matching and the Climate Match Indices

The 'Match Climates' applications compare the long-term meteorological data for each of the selected 'Away' locations with the climate of the 'Home' location. The level of similarity is given by the 'Composite Match Index, CMI', which is the product of six component indices, I_{tmax}, I_{tmin}, I_{rain}, I_{rpat}, I_{hum} and I_{sm}, indicating similarity in maximum and minimum temperature, total rainfall, rainfall pattern, relative humidity (RH) and Soil Moisture, respectively. Each of these component indices can range between 0 and 1, with a value of 1 indicating an exact match with the 'home' location. All indices can be weighted individually (using Composite Match Index Weights) to emphasise the more important variables. The default weight setting is 1.0 for each index, except the RH index that has a default weighting of zero.

Comparison of the climates of a home location can be made using a country, continent or the global database during a single run. When data from locations in different hemispheres are compared, CLIMEX automatically displaces the data from the Southern Hemisphere location by six months. The resulting Climate Match Indices can be displayed in maps, tables or as graphs. When maps are created, they show the degree of similarity as circles whose size is proportional to the difference between the value of the selected Match Index and a selected threshold (the Match Level). Only locations with an index that exceeds the Match Level are displayed in the resultant maps and tables. In the standard Simulation File, a selection of Match Levels (0.6, 0.7, 0.8 and 0.9) is available for maps of the Composite match Index, while the Match Level for the ***Standard*** table is set at 0.5.

Parts of the year can also be masked out so that only certain weeks are compared. This way, comparison of the similarities of a season or month rather than the whole year can be made. If comparison of locations in relation to the distribution of a waterweed is to be made, rainfall and humidity will not directly influence survival of the weed. In this case temperature is the driving variable and locations with a similar temperature range and pattern will need to be identified. By masking out the rainfall and humidity indices, a match on temperature alone can be made.

Index	**Weight**	**Default Value**
I_{tmin}	W_1	1
I_{tmax}	W_2	1
I_{tav}	W_3	0
I_{rain}	W_4	1
I_{rpat}	W_5	1
I_{hum}	W_6	0
I_{smst}	W_7	0

The calculations used to derive the Match Indices are given below.

Maximum and Minimum Temperature Match Indices, I_{tmax}, I_{tmin} and I_{tav}

$$I_{tmax} = \exp(-k_T T_{dmax})$$
$$I_{tmin} = \exp(-k_T T_{dmin})$$

$I_{tav} = \exp(-k_T T_{dav})$

T_{dmax}, T_{dmin} and T_{dav} are the means of the weekly absolute differences in maximum, minimum and average temperatures, respectively, between the two locations. The constant, k_T, is set to 0.1, thus giving values for the index of 0.9 for a mean weekly difference of 1^oC , and 0.6 for a mean weekly difference of 5^oC.

Total Rainfall Match Index, I_{rtot} = $\exp(-k_R R_d)$

where, $R_d = abs(R_T - R_M) / (1+a (R_T+R_M))$,
R_T = annual rainfall at Home location and
R_M = annual rainfall at Matching location.

R_d is the difference in annual rainfall between the two locations, adjusted so that a (say) 100mm difference in rainfall is more significant for locations with lower rainfall. CLIMEX uses values of 0.001 and 0.004 for the constants R_d and k_R, respectively. With these values, a difference in rainfall of 200 mm per year between two locations will result in an index of 0.64 if the average rainfall for the two locations is 400mm, and a value of 0.85 if the average rainfall is 2000mm.

Rainfall Pattern Index, I_{rpat} = $\exp (-k_P R_D)$

R_D is the mean of the absolute difference between the weekly rainfall of the 'Home' and 'Away' location, after the weekly rainfall of the 'home' location has been multiplied by R_z ($R_z = R_M/R_T$). R_M and R_T have the same meanings as in the previous section. The constant, k_P, is set to 0.005, thus giving values for the index of 0.9 for a mean weekly difference of 20 mm, and 0.6 for a mean monthly difference of 100 mm.

Humidity Index, I_{hum} = $\exp (-k_H H_d)$

H_d is the mean of the weekly absolute differences in relative humidity between the two locations. The constant, k_H, is set to 0.024 so that a difference of 10% gives an index of 0.8 and a difference of 20%, 0.6.

Soil Moisture Index, I_{sm} $=$ $\exp ((-k_{SM} S_d)$

S_d is the mean of the monthly absolute differences in estimated soil moisture between the two locations. The constant, k_{SM}, is set to 1.2 so that a mean weekly difference of 0.1 in soil moisture gives an index of about 0.9 and a mean weekly difference of 0.2 gives an index of about 0.8.

The combined **Temperature Index,** $I_t = \dfrac{I_{\min} \times W_1 + I_{\max} \times W_2 + I_{av} \times W_3}{W_1 + W_2 + W_3}$

The combined **Moisture Index,** $I_m = \dfrac{I_{rtot} \times W_4 + I_{hum} \times W_6}{W_4 + W_6}$

Rainfall Pattern Index, $I_{rp} = I_{rpat} \times W_5$

Soil Moisture Index, $I_{sm} = I_{smst} \times W_7$

The total **'Composite Match Index' (CMI),** is then calculated as

$$CMI = \left(I_t^{wt} \times I_m^{wm} \times I_{rp}^{W_5} \times I_{sm}^{W_7}\right)^{1/(wt + wm + W_5 + W_7)} \times 100$$

where ***wt*** is the maximum value of W_1, W_2 and W_3, and
wm is the maximum of W_4 and W_6.

4.1 Matching climates using Regional-fitting

The regional climate matching application (***Match Climates (Regional)***) is an extension of the ***Match Climates*** application. In effect, it takes the ***Match Climates*** application and runs it for many 'Away' Locations simultaneously. The results of all of these runs are combined by retaining the best result for each location from all of the runs.

If you have a region of interest, such as New Zealand, and you are responsible for assessing the risk of imported goods carrying live organisms that could pose a threat to New Zealand, you might like to know those regions of the world with a similar climate to anywhere in New Zealand. The region matching application allows you to select a set of locations, and to identify the best match between each of the locations in the 'Away' location selection, with all of the locations in the 'Home' region.

Another use of the region-fitting function is to refine the search area for biological control agents, to narrow the search area to zones that are climatically similar to an area into which you wish to import agents. By overlaying the native range of the target host with the regional climate match data, you can then concentrate your search efforts to the zone of overlap, confident that an agent found there is more likely to be able to persist in the introduced range should it be established there, compared with individuals or species collected form outside of that range.

Setting up a region matching run involves several steps: preparing the location set, setting options in the ***Match Climates (Regional)*** application, select the weightings, and then run the analysis.

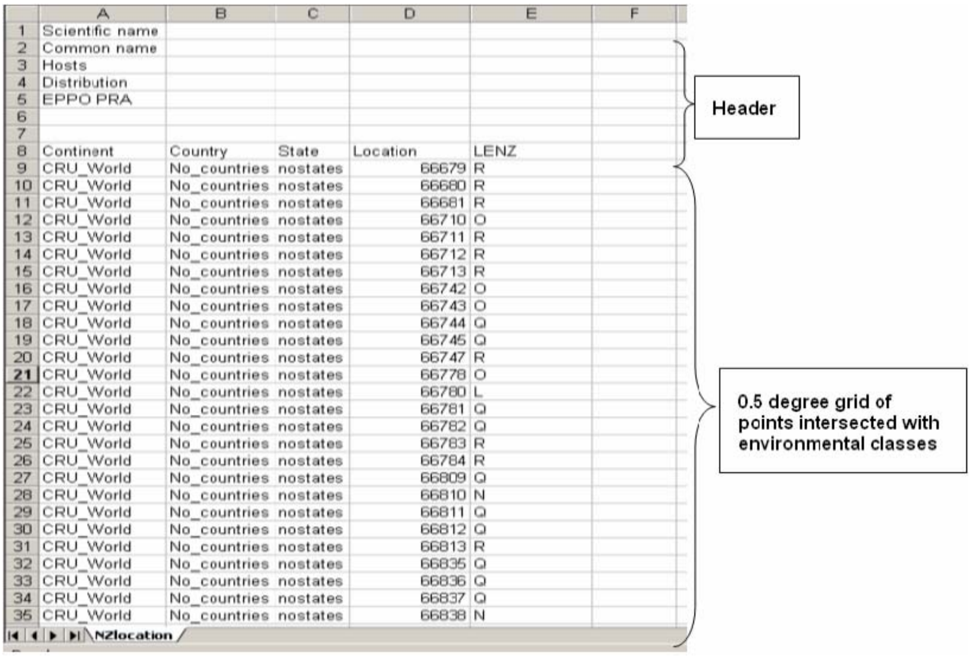
4.1.1 Preparing the Location Set

There are two means of specifying the location selection for the Home region. You can use the location selection procedure within the MetManager utility to develop a selection using a combination of filters, or you can create a comma-delimited text file. The latter option gives you the flexibility to select locations based on attributes other than those available in MetManager (continent, country, state, location name, bounding box, altitude or importance weighting). This latter option will probably be of critical importance for gridded climate datasets that do not have any of the geopolitical information associated with the location records.

To specify the location set you need to prepare a comma-separated input file containing locations from a MetManager file and a column containing a character string identifier that allows you to specify which locations to include in the run. The file must be in a specific format, with a line containing the strings “Continent”, “Country”, “State”, and “Location” in the first four columns, indicting the start of the region specification section (line 8 in the example shown in Fig. 4-1). Any lines preceding this “label” line are ignored by CLIMEX but may be included to indicate the origin of the locations or any other relevant information. The locations which can be included in the run then follow the “label” line, one location per line. The first four columns in each of these lines contain the names of the continent, country, state and location that identify the specific location. The fifth column contains the indicator that will allow you to select location subsets for inclusion in a model run. You may wish to use descriptions of the classes that are described by the classification character(s) in column five, as shown in Fig. 4-1. You may add additional information in the sixth and subsequent columns. Any such extra information will be ignored by CLIMEX for region fitting runs.

The file can be built manually using a text editor, or Excel (saving the output in comma-separated (csv) format. It can also be created by running a ***Match Climates*** or ***Compare Locations*** simulation and saving out the results in csv format with just the headers (“Continent”, “Country”, “State”, and “Location”) and a single output variable included (the file output format “EI” in Compare Locations will create such a file). You can then import this file into a text editor or Excel in order to replace the values in the 5th column with the identifying character or string.

Fig. 4-1 The first few lines of a file specifying sets of locations constituting “regions” for use in the *Match Climates (Regional)* application.



	A	B	C	D	E	F
1	Scientific name					
2	Common name					
3	Hosts					
4	Distribution					
5	EPPO PRA					
6						
7						
8	Continent	Country	State	Location	LENZ	
9	CRU_World	No_countries	nostates	66679	R	
10	CRU_World	No_countries	nostates	66680	R	
11	CRU_World	No_countries	nostates	66681	R	
12	CRU_World	No_countries	nostates	66710	O	
13	CRU_World	No_countries	nostates	66711	R	
14	CRU_World	No_countries	nostates	66712	R	
15	CRU_World	No_countries	nostates	66713	R	
16	CRU_World	No_countries	nostates	66742	O	
17	CRU_World	No_countries	nostates	66743	O	
18	CRU_World	No_countries	nostates	66744	Q	
19	CRU_World	No_countries	nostates	66745	Q	
20	CRU_World	No_countries	nostates	66747	R	
21	CRU_World	No_countries	nostates	66778	O	
22	CRU_World	No_countries	nostates	66780	L	
23	CRU_World	No_countries	nostates	66781	Q	
24	CRU_World	No_countries	nostates	66782	Q	
25	CRU_World	No_countries	nostates	66783	R	
26	CRU_World	No_countries	nostates	66784	R	
27	CRU_World	No_countries	nostates	66809	Q	
28	CRU_World	No_countries	nostates	66810	N	
29	CRU_World	No_countries	nostates	66811	Q	
30	CRU_World	No_countries	nostates	66812	Q	
31	CRU_World	No_countries	nostates	66813	R	
32	CRU_World	No_countries	nostates	66835	Q	
33	CRU_World	No_countries	nostates	66836	Q	
34	CRU_World	No_countries	nostates	66837	Q	
35	CRU_World	No_countries	nostates	66838	N	

Header

0.5 degree grid of points intersected with environmental classes

If you wish to select regions using geographic data, then you can use a Geographical Information System (GIS) to intersect the output file with a polygon or grid layer that contains geographic region information. To do this, first output a file from a ***Match Climates*** run or a ***Compare Locations*** simulation and include latitude and longitude in the output file. Save the file out as using csv format. To import the file into the GIS, you will normally need to delete the first seven lines in the location set header, leaving the column headings. Then import the file as a set of points, using the "longitude" and "latitude" columns as the X and Y coordinate source respectively. You can then intersect the resulting point file with your regional data source in order to identify the corresponding region for each metdata location. This file will then need to be output as a csv file in the above format, deleting columns as necessary.

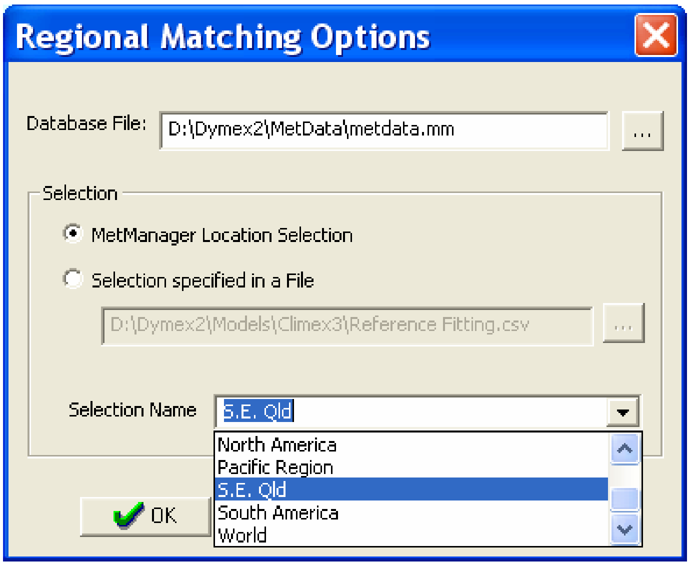
4.1.2 Setting the Region Match Options

Start the DYMEX program and open the "**CLIMEX – Match Climates (Regional)**" model using the **MC (Regional).dxs** simulation file (see Section 5.1). The application's modules (Fig. 2-8) will now be shown in the Model Components window.

From the **Initialization** menu, select the **Regional Climate Matching** menu item. In the resulting **Region Matching Options** dialog, set the appropriate database file and Home Location Selection.

If you want to use the MetManager location selection method, click on the **MetManager Location Selection** option, and then choose the appropriate Selection Name from the dropdown list. If you have prepared a text file of the locations, click on the **Selection specified in a file** option and specify the name and location of the "csv" file. If necessary, use the ... button and then navigate to the Location Selection file.

Fig. 4-2 The Regional Matching Options dialog, showing use of a *Location Selection* to specify the set of locations constituting the Home Region.



Regional Matching Options

Database File: D:\Dymex2\MetData\metdata.mm

Selection

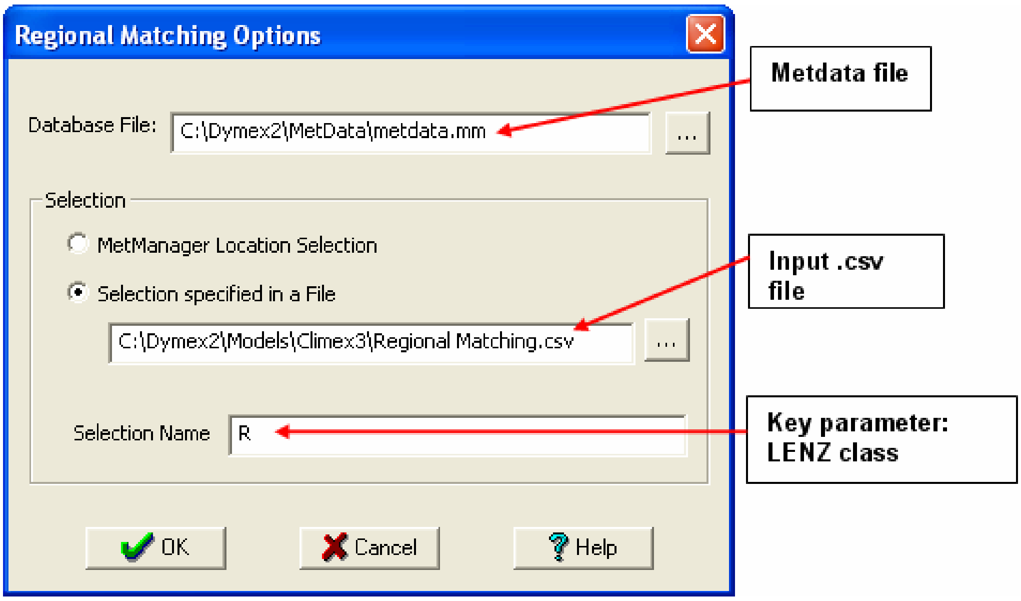
● MetManager Location Selection

○ Selection specified in a File

D:\Dymex2\Models\Climex3\Reference Fitting.csv

Selection Name: S.E. Qld

Fig. 4-3 The Regional Matching Options dialog, showing use of a *Selection Name* to specify the locations in a file constituting the Home Region.


Regional Matching Options

Database File: C:\Dymex2\MetData\metdata.mm

Selection

○ MetManager Location Selection

● Selection specified in a File

C:\Dymex2\Models\Climex3\Regional Matching.csv

Selection Name R

Metdata file

Input .csv file

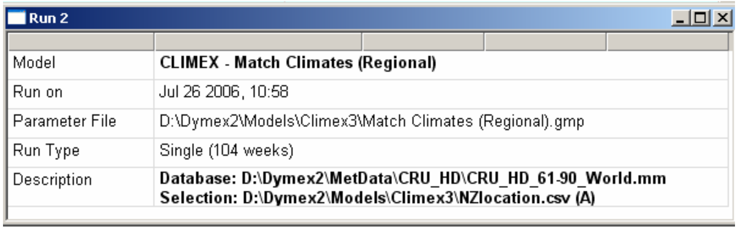
Key parameter: LENZ class

When you are satisfied with the Regional Matching Options, initialize the remaining model components, if required. Each of the remaining model components can be set in exactly the same manner as for a single location **Match Climates** run. For example, the Home and Away locations can each be modified for climate change and irrigation scenarios, and the Away location dataset can be set separately from the Home Region selection.

When you have set all of the remaining options, run the climate match analysis by selecting the **Execution | Run Regional Climate Matching** menu item, or click on the double lightning bolt symbol ⚡⚡ indicating that you want to complete a multiple location run.

4.1.3 Running and displaying the results

When the run is completed, a window giving a summary of the process parameters is displayed. Obtaining output is exactly the same as for match climates or Compare Locations runs.


Run 2

Model	**CLIMEX - Match Climates (Regional)**
Run on	Jul 26 2006, 10:58
Parameter File	D:\Dymex2\Models\Climex3\Match Climates (Regional).gmp
Run Type	Single (104 weeks)
Description	**Database: D:\Dymex2\MetData\CRU_HD\CRU_HD_61-90_World.mm** **Selection: D:\Dymex2\Models\Climex3\NZlocation.csv (A)**

If desired, results can be exported from CLIMEX as a file that can be imported into a GIS for publication quality map production.

5 Tasks

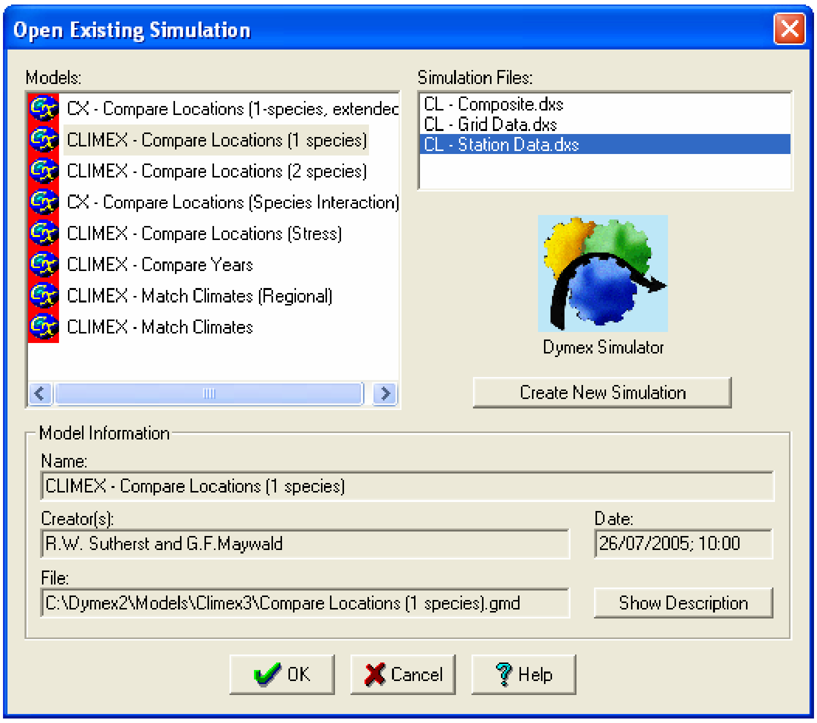
5.1 Loading a CLIMEX application

Before a CLIMEX application can be run, the ***DYMEX Simulator*** must be started, the appropriate application (equivalent to a DYMEX *Model*) selected and a suitable Simulation File loaded.

1. Go to the **Start** menu and find the **DYMEX** program group within the **Programs** group.
2. Choose ***Simulator*** to start the DYMEX Simulator.
3. Either go to the **File** menu and select **Open**, or if the button bar is displayed, left click on the **Open** button .
4. Select the application to be opened from the list labelled “Models” in the left panel (Fig. 5-1). The **Model Information** panel shows more information about the selected application.
5. If more than one Simulation File is shown in the **Simulation Files** panel at the right, select the required file by clicking on it. If only a single Simulation File is listed for the model, it can also be selected by double-clicking on the model name.

Note: If the required Simulation File has been opened recently, it can be selected from the list at the bottom of the “File” menu. Only one Simulation File (and hence one application) can be loaded into the ***Simulator*** at any one time.

Fig. 5-1. Open Existing Simulation window, showing selection of the “CL – Station Data” simulation file of the ‘Compare Locations (1 species)’ application.



Models:
- CX - Compare Locations (1-species, extendec
- CLIMEX - Compare Locations (1 species)
- CLIMEX - Compare Locations (2 species)
- CX - Compare Locations (Species Interaction)
- CLIMEX - Compare Locations (Stress)
- CLIMEX - Compare Years
- CLIMEX - Match Climates (Regional)
- CLIMEX - Match Climates

Simulation Files:
- CL - Composite.dxs
- CL - Grid Data.dxs
- CL - Station Data.dxs

Name: CLIMEX - Compare Locations (1 species)

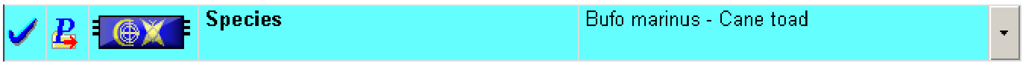
Creator(s): R.W. Sutherst and G.F.Maywald

Date: 26/07/2005; 10:00

File: C:\Dymex2\Models\Climex3\Compare Locations (1 species).gmd

5.2 Species Parameter File operations

All of the CLIMEX Model parameters for a species are stored in a CLIMEX Species Parameter File (with the extension .cxp). This file also stores any comments provided for that species. To run the CLIMEX model, a particular species must first be selected. This is done from the Species module display (see blow).



Species

Bufo marinus - Cane toad

The name of the currently selected species is shown in the panel at the right. At the far right is a button, which, when clicked, shows a drop-down menu of available species. New species may be added or unwanted species deleted with the **Add/edit/remove Species Parameter File** menu option. The same menu option can be used to indicate the directory where the Species Parameter Files are stored.

Selecting a Species

To select a species, click on the grey selector button at the far right and click the required species name in the drop-down menu. If no species names are show, it is possible that CLIMEX is not looking in the right directory. Click on the **Add/edit/remove Species Parameter File** menu option, and then navigate to the correct directory using the directory button at the top left of the **Parameter File Selection** dialog.

Creating a new Species

To create a new Species Parameter File, click on the **Add/edit/remove Species Parameter File** menu option. This opens the **Parameter File Selection** dialog. Select the template or species that you judge to be the most similar to the new species from those in the list at the left and select it by clicking on its name. Then click on the **Create/Copy** button. In the **Create CLIMEX Species dialog**, fill in the name of the new species in the corresponding edit box. Click the **Copy Comments** checkbox only if comments are to be copied from the source species. Click **OK** and the new species file will be created. To adjust the parameters of the new species, select the species as above and use the usual parameter changing procedure (see Section 5.3).

Deleting a Species

To delete a species file, click on the **Add/edit/remove Species Parameter File** menu option. This opens the **Parameter File Selection** dialog. Select the species to be deleted from those in the list at the left and select it by clicking on its name and click the **Delete** button.

Changing the name of a Species

Sometimes it may be necessary to change the name of a species after it has been created (for example, it may have been misspelled). This is done from the **Model Parameters** window (not the **Parameter Grid** window), which is opened by selecting **Model Parameters** from the **Initialization** menu. Click on the line containing the species name in the tree diagram at the left and then edit the name in the **Description** panel at the top right of the window.

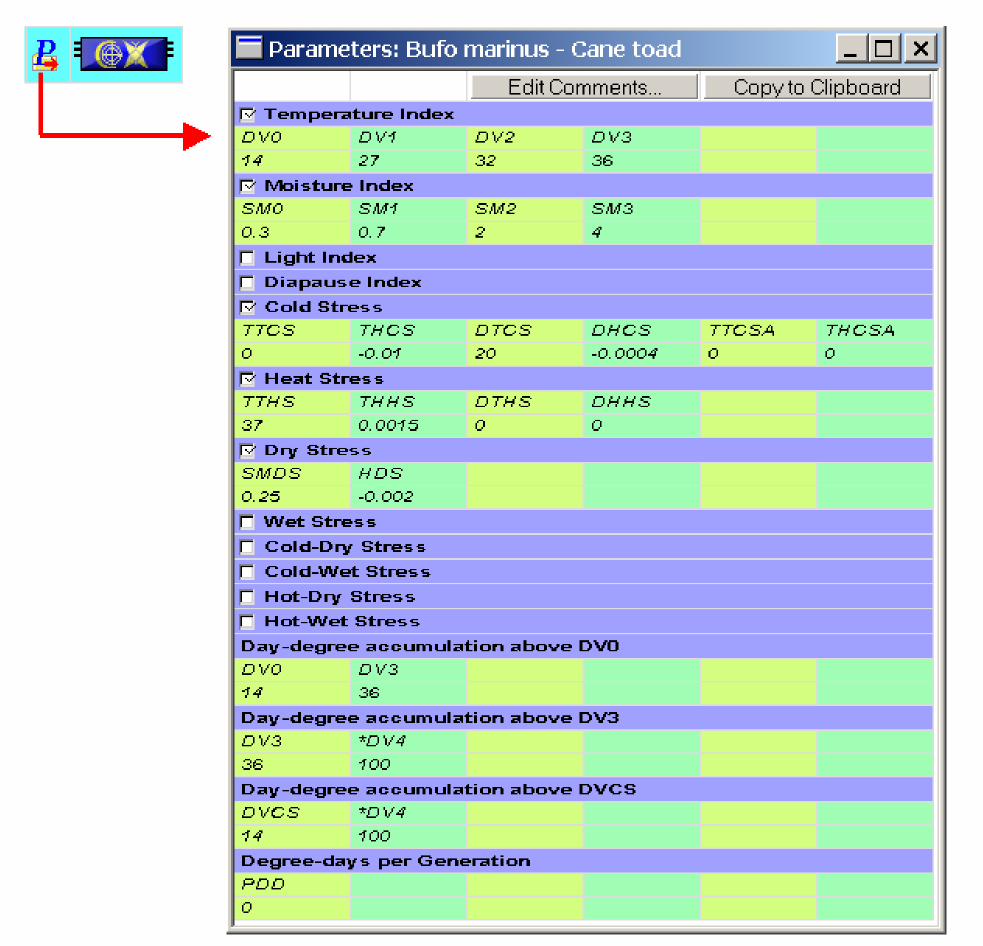
Printing the species list

Clicking on the **Print List** button within the **Parameter File Selection** dialog will print a list of all species and their corresponding Species Parameter File names.

5.3 Operations on Species Parameters

CLIMEX Species Parameter Files are text files with the extension **.cxp**, stored in the species directory (generally *..\Model\Climex\Species*). Species parameters for the currently loaded species can be viewed and modified most conveniently from the **Parameter Grid window**. Clicking on the Species module's parameter icon or picking **Show Parameters** from the popup menu that results from by clicking on the module bitmap will lead to the Parameter "Grid" window (Fig. 5-2). Note that the Parameter Grid View must be enabled by checking the "**Use Parameter Grid for non-Lifecycle modules**" option in the **Current Model** preferences (this is done with the included Simulation Files).

Fig. 5-2. Parameter Grid Window showing *Bufo marinus* parameters.



☑ Temperature Index					
DV0	DV1	DV2	DV3		
14	27	32	36		
☑ Moisture Index					
SM0	SM1	SM2	SM3		
0.3	0.7	2	4		
☐ Light Index					
☐ Diapause Index					
☑ Cold Stress					
TTCS	THCS	DTCS	DHCS	TTCSA	THCSA
0	-0.01	20	-0.0004	0	0
☑ Heat Stress					
TTHS	THHS	DTHS	DHHS		
37	0.0015	0	0		
☑ Dry Stress					
SMDS	HDS				
0.25	-0.002				
☐ Wet Stress					
☐ Cold-Dry Stress					
☐ Cold-Wet Stress					
☐ Hot-Dry Stress					
☐ Hot-Wet Stress					
Day-degree accumulation above DV0					
DV0	DV3				
14	36				
Day-degree accumulation above DV3					
DV3	*DV4				
36	100				
Day-degree accumulation above DVCS					
DVCS	*DV4				
14	100				
Degree-days per Generation					
PDD					
0					

The window shows all parameters, grouped by component indices (the blue cells, for example "Moisture Index"). The parameter names are listed in their abbreviated form. The full name of any parameter can be obtained by moving the mouse cursor over the name field and leaving it there for about a second. This will cause a small window with the full name to appear next to the cursor.

Parameter values are modified by double-clicking on the relevant parameter value field and typing the new value. Typing within a field should be terminated with either the “Enter” or “Tab” key (or clicking on another grid cell). The window is closed using the “Close” button at the top right.

To avoid clutter by “unused” parameters, groups of parameters can be specified as “unused” by un-checking the small box in front of the component index name. This will close then hide the associated parameters, and set the value of that index to its “unused” value (which will be 1 for the Growth Index components and 0 for the Stress Index components). For example, if the Wet Stress box is un-checked, the Wet Stress will always be 0, no matter what the current setting of its parameters.

If a “protected” parameter File is selected, its protected status is indicated by the word “[Protected]” after the species name in the window title, and by the fact that the component index fields are coloured grey rather than blue. These files cannot be modified using the Parameter Grid Window.

When the Parameter Grid Window is active, several File menu options become available to perform functions on the Species Parameter File. These are:

Save	Saves the modified species parameters
Revert to Saved	Retrieves the most recently saved values from the file
Print Setup	Allows changes to print settings to be made
Print	Prints the species parameters

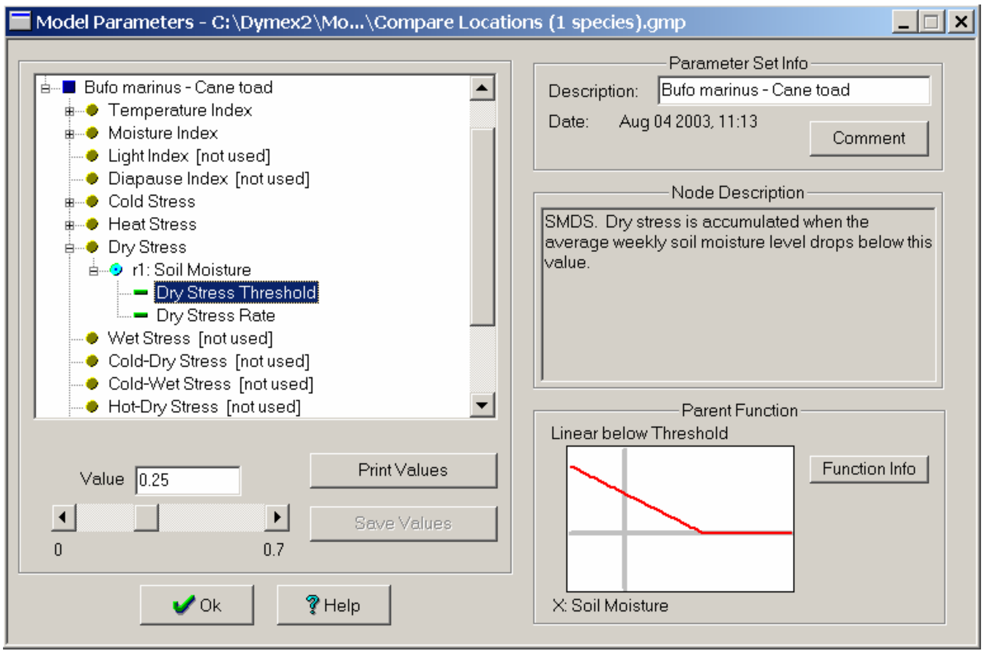
Comments can be added to the Parameter File by clicking on the **Edit Comments** button in the upper right of the Parameter Grid Window. Such comments should always be added when a species file is created, and any time modifications are made.

CLIMEX provides an alternative way of accessing and changing the species parameter values, using the **Initialization | Model Parameters** menu item from the main window. This opens the **Model Parameters** window. The Model Parameters window provides more information about each parameter than the Parameter Grid Window, while also giving more information about the context in which the parameter is used. If you made changes to parameter values using the Parameter Grid Window can save them by using the **File | Save** menu item or by saving them when closing CLIMEX. Note that saving the Simulation File does not automatically save the changed parameter settings.

The large panel at the top left shows the modules that have parameters. In the “Compare Locations” model, it will show three modules, (1) The Climate Change Scenario (labelled with the selected scenario), (2) the Soil Moisture model and (3) the Species (labelled with its name). Each module’s parameters are arranged within a “tree” of module components. To modify (say) the “Dry

Stress Threshold" parameter, click on the small rectangle (⊞) in front of the species name to show all of the component indices of the module. Then do the same with the rectangle in front of the "Dry Stress" component. This will show the component function (labelled with its driving variable, which is the *Soil Moisture* in the case of Dry Stress). Repeat with the function branch, and the two Dry Stress parameters will now be visible (Fig. 5-3). Now click on the Dry Stress Threshold node. The panel below the selection window will now show the value of the parameter, where the value can be changed either by using the slider bar or by typing a new value into the edit box. Note that the parameters description and its "context" (i.e., the function within which it is located) are shown at the right of the dialog.

Fig. 5-3 Parameter Window showing *Bufo marinus* Dry Stress Threshold.


Model Parameters - C:\Dymex2\Mo...\Compare Locations (1 species).gmp
Bufo marinus - Cane toad
Temperature Index
Moisture Index
Light Index [not used]
Diapause Index [not used]
Cold Stress
Heat Stress
Dry Stress
r1: Soil Moisture
Dry Stress Threshold
Dry Stress Rate
Wet Stress [not used]
Cold-Dry Stress [not used]
Cold-Wet Stress [not used]
Hot-Dry Stress [not used]
0
0.7
Print Values
Save Values
Ok
Help
Parameter Set Info
Comment
Node Description
Parent Function
Linear below Threshold
Function Info
X: Soil Moisture

Description: Bufo marinus - Cane toad

Date: Aug 04 2003, 11:13

SMDS. Dry stress is accumulated when the average weekly soil moisture level drops below this value.

Value 0.25

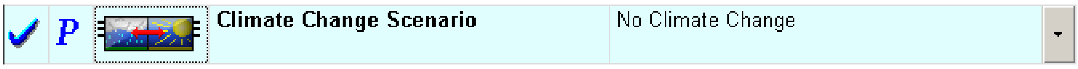
The **Print Values** button will print the parameters, while the **Save Values** buttons will become available for saving the file if either a parameter or parameter file comment is changed (either from this window or from the Parameter Grid Window). Component indices can be inactivated (i.e., set to "unused") or activated by clicking on the component in the selection panel and either checking or un-checking the box marked "**Do not use this Process"** that will appear at the lower left.

Changing the species name

Note that the name of the species can only be adjusted from within this window. Select the Species module (for example, "Bufo marinus – Cane toad" in the example in Fig. 5-3) and then type the adjusted name into the **Description** box at the top right.

5.4 Using Climate Change Scenarios

The CLIMEX software enables users to consider the potential implications of either climate change or irrigation practices on both the similarity of meteorological data of different places (Match Climates) or the potential geographical distribution and seasonal phenology and survival of species (CLIMEX model). These changes may have implications in a number of areas. As species' distributions change, some areas currently unsuitable for the species may become suitable. Alternatively, a change in the climate may force a species' range to contract or move – this has implications not only for pests but also rare and threatened species of conservation value. Changes in the climate may affect important agricultural industries if areas become unsuitable for the crops currently being grown there. By allowing the user to assess likely situations in the future, this option provides the rationale to initiate management or adaptation strategies to cope with the projected changes.


Climate Change Scenario
No Climate Change

The **Climate Change** scenario module enables users to examine the impact of different temperature and rainfall conditions. The module display (shown above) shows the name of the currently selected scenario in the right-most panel. At the far right is a button, which, when clicked, shows a drop-down menu of available scenarios. New scenarios may be added or unwanted scenarios deleted with the **Add/edit/remove** menu option. The same menu option can be used to indicate the directory where the Scenario Files (.ccs) are stored. Scenarios can apply changes to summer and winter months separately in temperate zones and a different change can be made to a user-defined equatorial zone.

Once a scenario has been selected, its parameters can be changed using the usual procedure (see Section 5.3). These parameters are listed in Table 5-1.

Table 5-1 Climate Change Scenario parameters.

Min. Temperature Change (Winter)	W_{tmin}	The change in the minimum temperature that occurs during the 'Winter' months *outside* the ***Equatorial*** zone.
Min. Temperature Latitudinal Change (Winter)	WL_{tmin}	The change in the minimum temperature for each degree of latitude away from the equator that occurs during the 'Winter' months *outside* the ***Equatorial*** zone.
Min. Temperature Change (Summer)	S_{tmin}	The change in the minimum temperature that occurs during the 'Summer' months *outside* the ***Equatorial*** zone.
Min. Temperature Latitudinal Change (Summer)	SL_{tmin}	The change in the minimum temperature for each degree of latitude away from the equator that occurs during the 'Summer' months *outside* the ***Equatorial*** zone.

Min. Temperature Change (Equatorial Zone)	E_{tmin}	The change in the minimum temperature that occurs *inside* the ***Equatorial*** zone.
Max. Temperature Change (Winter)	W_{tmax}	The change in the minimum temperature that occurs during the 'Winter' months *outside* the ***Equatorial*** zone.
Max. Temperature Latitudinal Change (Winter)	WL_{tmax}	The change in the maximum temperature for each degree of latitude away from the equator that occurs during the 'Winter' months *outside* the ***Equatorial*** zone.
Max. Temperature Change (Summer)	S_{tmax}	The change in the maximum temperature that occurs during the 'Summer' months *outside* the ***Equatorial*** zone.
Max. Temperature Latitudinal Change (Summer)	SL_{tmax}	The change in the maximum temperature for each degree of latitude away from the equator that occurs during the 'Summer' months *outside* the ***Equatorial*** zone.
Max. Temperature Change (Equatorial Zone)	E_{tmax}	The change in the maximum temperature that occurs *inside* the ***Equatorial*** zone.
Rainfall Change (Winter)	W_{rain}	The change in the rainfall (in %) that occurs during the 'Winter' months *outside* the ***Equatorial*** zone.
Rainfall Latitudinal Change (Winter)	WL_{rain}	The change in the rainfall (in % per degree latitude) for each degree of latitude away from the equator that occurs during the ‘Winter’ months *outside* the ***Equatorial*** zone.
Rainfall Change (Summer)	S_{rain}	The change in the rainfall (in %) that occurs during the 'Summer' months *outside* the ***Equatorial*** zone.
Rainfall Latitudinal Change (Summer)	SL_{rain}	The change in the rainfall (in % per degree latitude) for each degree of latitude away from the equator that occurs during the ‘Summer’ months *outside* the ***Equatorial*** zone.
Rainfall Change (Equatorial Zone)	E_{rain}	The change in the rainfall (in %) that occurs *inside* the ***Equatorial*** zone.

The ***Equatorial Zone*** (z) is a band of latitude centred on the equator and its exact extent is defined in the ***Model Preferences*** dialog. “Winter” and “Summer” seasons are defined with reference to the Equatorial Zone and the day of year. North of the Equatorial Zone, “Summer” is defined as days 92 to 274 (i.e., March 2 – September 30, inclusive), with “Winter” being the rest of the year. South of the Equatorial Zone, these are reversed.

In the following descriptions, I represents the current climate variable and O the variables after the climate change scenario is applied.

The temperature output variables are derived from the input variables and factors as follows (the "*t*" subscript can be either *"tmin"* or *"tmax", while l is the latitude, in degrees*):

in the ***Equatorial Zone***, $O_t = I_t + E_t$

elsewhere, in "Winter", $O_t = I_t + W_t + WL_t \times (abs(l) - z/2))$

elsewhere, in "Summer", $O_t = I_t + S_t + SL_t \times (abs(l) - z/2)$

The rainfall output variables are derived from the input variables as follows:

in the ***Equatorial Zone***, $O_{rain} = I_{rain} \times \left(\frac{E_{rain}}{100} \right)$

elsewhere, in "Winter",

$$O_{rain} = I_{rain} \times \left(1 + \frac{W_{rain} + WL_{rain} \times (abs(l) - z/2)}{100} \right)$$

elsewhere, in "Summer",

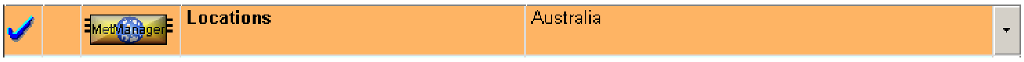
$$O_{rain} = I_{rain} \times \left(1 + \frac{S_{rain} + SL_{rain} \times (abs(l) - z/2)}{100} \right)$$

5.5 Using Irrigation Scenarios

The **Irrigation** scenario builder acts in a similar way to the **Climate Change** scenario builder with two exceptions. Firstly, it treats all regions equally and it only affects the amount of additional, simulated rainfall. There are options to apply irrigation on a monthly rather than seasonal basis and to apply 'top-up' amounts of irrigation to increase the effective rainfall to a set amount, such as 3mm per day of (rainfall + irrigation), for example. It is particularly useful when considering the suitability of climates for a species that may only be present as a result of irrigation in agricultural or urban environments. Irrigation can affect both the growth and survival of species by enabling populations to persist and grow in what would otherwise be an unfavourable dry season.

5.6 Specifying Location Selections

In normal operation, the *Compare Locations* and *Match Climates* functions are run on a set of locations (often referred to as a "Location Sequence"). For example, in the *Compare Locations* illustration below, a Location Sequence with the name of ***Australia*** is being used (The equivalent module in *Match Climates* is named **Locations (Away)**).

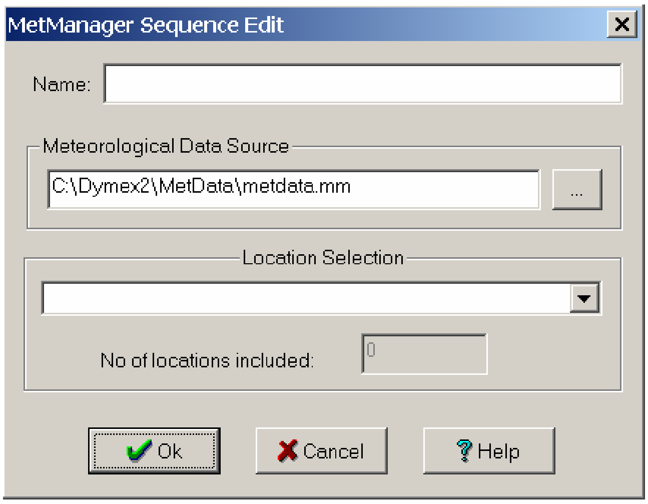


The module display (shown above) shows the name of the currently chosen Location Sequence in the right-most panel. At the far right is a button, which, when clicked, shows a drop-down menu of available sequences. New sequences can be added or unwanted ones deleted with the **Add/edit/remove** menu option.

Creating a Location Sequence

A **Location Sequence** in CLIMEX provides a link to a MetManager ***Location Selection*** (see Section 28 of the DYMEX Simulator User's Guide) that has been prepared for use by DYMEX. Hence, to create a new ***Location Sequence***, the corresponding ***Location Selection*** must first be created in the MetManager. Section □ of this Guide gives a detailed description of how to do the latter. Then, to create the new **Location Sequence**, select the **Add/edit/remove** menu option from the drop-down menu obtained by clicking on the button at the far right of the Locations module display. This opens the **Sequences (Locations)** dialog.

Fig. 5-4 The MetManager Sequence Edit dialog.


MetManager Sequence Edit

Name:

Meteorological Data Source

C:\Dymex2\MetData\metdata.mm

Location Selection

No of locations included: 0

The **Sequences (Locations)** dialog lists the existing Sequences. To add a new one, click on the **New** button, which opens the **MetManager Sequence** Edit dialog (Fig. 5-4). Here, the MetManager database (.mm file) containing the data that the Sequence will use must be specified. Click on the Browse button (...) in the **Meteorological Data Source** panel and navigate to the required file. Then click on the button (▼) in the Location **Selection** panel. A list of Location Selections defined for the chosen database will appear, from which the required one can be selected. The Name field at the top of the dialog is automatically set to the name of the Location Selection – however, it can be changed to any other name if desired. Then click **OK** to return to the Model Window, and the new Location Sequence is ready for use.

5.7 Adding new Locations to the Database

Climate data can be imported into the MetManager for use by CLIMEX from several sources.

1. Text files in .loc/.met format (the same as used by previous versions of CLIMEX), whose format is detailed in Appendix 3 of the DYMEX Simulator User's Guide.

2. CLIMEX Version 1 MetManager database (.bmt) files

3. CLIMEX Version 2 MetManager database (.mm) files

The procedure for importing from any of these sources is described in Section 28.4 of the DYMEX Simulator User's Guide.

5.8 Using the grid-based Climate data

A set of climate data derived from a global splined grid of data with a resolution of 0.5° from the Climate Research Unit (CRU) at Norwich UK (http://ipcc-ddc.cru.uea.ac.uk, New et al. 1999) has been included with the CLIMEX program. This data set can be conveniently used with the *Compare Locations* function by loading the model with the "***CL – Grid Data***" Simulation File. The "CL – Grid Data" Simulation contains Location Sequences on the grid data for every continent as well as the whole world. In addition, it defines map formats (using colour gradations to indicate index values) that are most suitable for mapping the grid data.

5.9 Creating and modifying map backgrounds

The DYMEX **Map Manager** is used to create *Region Definitions* that are then used as the base onto which the data layers of the map are drawn. The Map Manager is accessed from the File menu. Map features specified by the Map Region definition include the boundaries of the region, the included shape files that determine the geographical features visible on the map and the map projection. Before any DYMEX output variable can be mapped, the appropriate Region Definition must have been created. Region Definitions are stored in *Region Definition Files* (.mdf) in the Map Directory, as specified in the **Operating Preferences**.

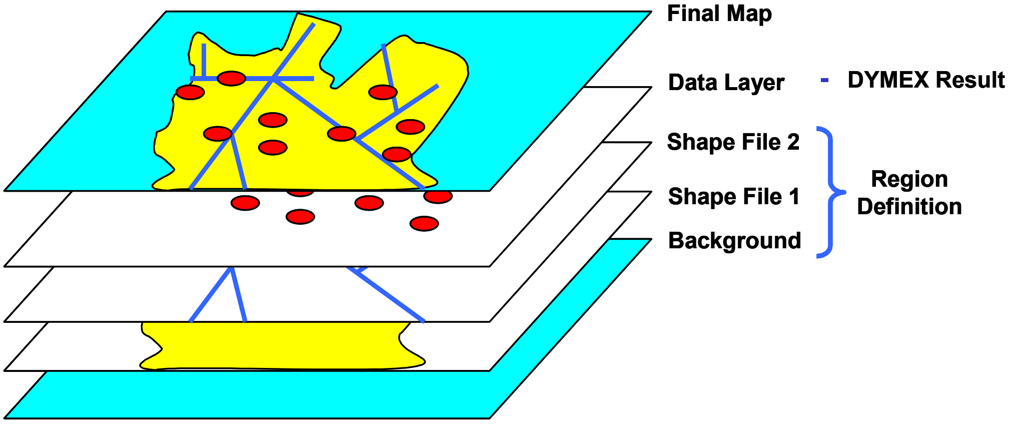
To understand how a display map in DYMEX is related to the *Region Definition*, it is necessary to understand how such a map is structured. A map consists of a number of layers, as follows:

Data Layer
Shape File n
…
Shape File 1
Background

This is illustrated in Fig. 5-5. The final map produced when selecting the "**Results|Map**" menu item after a run of DYMEX is the result of drawing all these layers (in order, from bottom to top), within the coordinate boundaries specified and with the specified map projection. Every layer except the Data layer is defined in the *Region Definition*. The Data Layer is added from the specifications provided in the *Map Format* (set in the **Map Specification** dialogs.

The Background layer is used to provide a background colour for the map. Each Shape File layer is associated with a single file containing spatial data in the ESRI® Shapefile Format (see the *ESRI Shapefile Technical Description* at www.esri.com/library/whitepapers/pdfs/shapefile.pdf. Another layer, not shown in Fig. 5-5, contains the positions of the title, legend and scale marker. This information is also stored in the *Region Definition*, though the actual contents of the title and legend are added when the map is actually drawn, again from information provided in the *Map Format*.

Fig. 5-5 The layers that constitute a map displaying a variable in DYMEX, and the map that is produced from these layers.



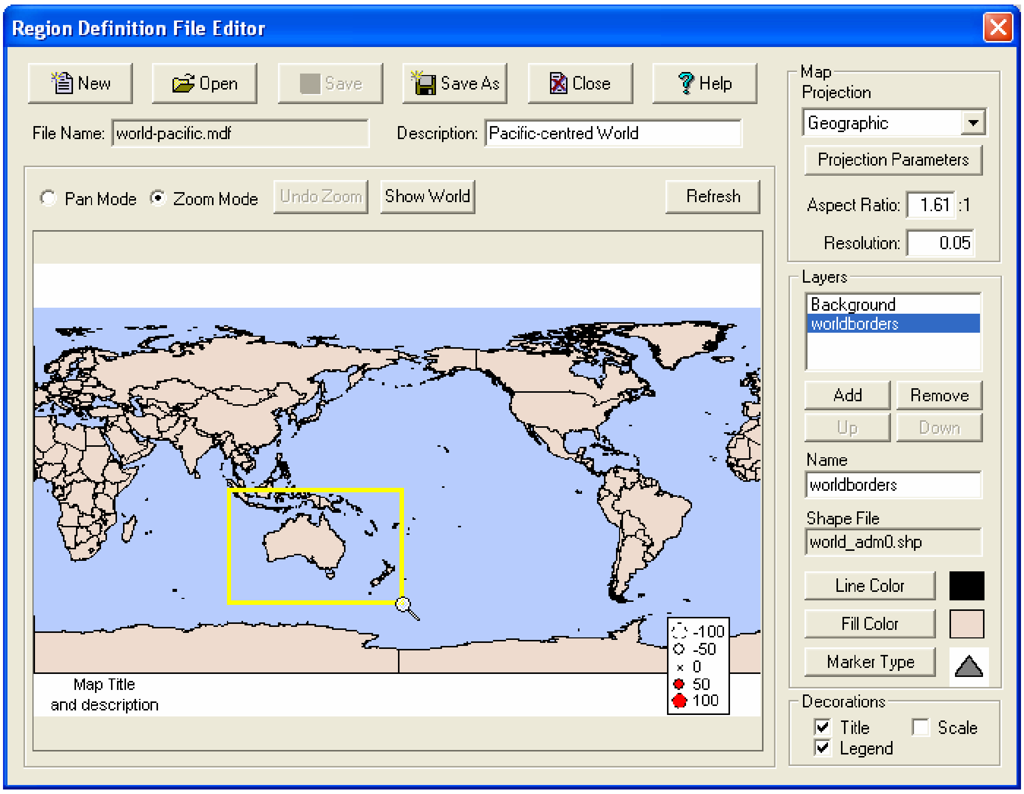
When the MapManager menu item is selected from the File menu, the **Region Definition File Editor** dialog is opened (Fig. 5-6). This is a rather complex dialog, which allows the user to create a Region Definition File by adding the required shapefiles layers to a background, specifying colours for each layer, and selecting a projection for display. The large display panel at the lower left shows the map as it will be shown (but without the data layer). The row of controls above this panel is used to pan and/or zoom the map until it is cropped to the required coordinates and to select label, title and scale marker decorations.

➢ To create a new Map Region File

1. Select the **MapManager** item from the **File** menu.
2. This will open the **Map Definition File Editor** dialog (Fig. 5-6), with only a background layer present in the **Layers** list at the right. Change the

background colours, if required, by clicking on the **Line Colour** or **Fill Colour** buttons, and then choosing the desired colours.

Fig. 5-6 The Region Definition File Editor dialog, showing a map of the world, using the *Geographic* projection with *Central Meridian* set to 180°.



Region Definition File Editor

File Name: world-pacific.mdf

Description: Pacific-centred World

○ Pan Mode ● Zoom Mode

Map Projection: Geographic

Aspect Ratio: 1.61 :1

Resolution: 0.05

Layers:
- Background
- worldborders

Name: worldborders

Shape File: world_adm0.shp

Decorations:
- ☑ Title
- ☐ Scale
- ☑ Legend

3. Add a Shapefile layer by clicking on the **Add** button, and navigating to the required shape file. Note that shape files generally have the extension ***.shp***.

Note that if shapefiles should be stored in the **Map** directory, which is specified in the **Operating Preferences** dialog.

4. To see the effect that the addition of the layer has on the appearance of the map, click on the **Refresh** button, which redraws the map with current settings applied. You can change the colours of the currently selected layer using the **Line Colour** and **Fill Colour** buttons.

5. Add more layers as required by repeating steps 3 and 4. If a layer has been added by mistake, it can be removed by selecting it and clicking on the **Remove** button. Similarly, the ordering of layers can be changed with the **Up** or **Down** buttons (however, the background layer will always be the first).

6. If a projection other than the default ***Geographic*** projection is required, click on the small arrow button to the right of the projection name and select the required projection from the drop-down list. The set the projection parameters as required using the **Set Parameters** button.

The choice of a projection and different projection parameters can make a big difference to the appearance of a map. If you are unfamiliar with projections, you may wish to consult a reference such as Maling, D.H., *Coordinate Systems and Map Projections, 2nd ed, rev.*, Woburn, MA: Butterworth-Heinemann, 1993 or Mulcahy, K., "The Map Projection Home Page." at http://everest.hunter.cuny.edu/mp/.

7. Click on the Refresh button to update the map display, then use the **Pan** and **Zoom** options to size and position the map to your exact requirements.
8. By default, the map displays a label, legend and scale marker. If any of these are not required, uncheck the corresponding box in the **Decorations** panel at the lower right of the dialog. These 'decorations" can be moved to any desired spot on the map by clicking on them and 'dragging' with the mouse button down.
9. When the map region display shows all features exactly as they are required in the final map, the map region can be given a description by typing the appropriate text into the **Description** box.
10. Click on Save to save the *Region Definition* as a file with the ***mdf*** extension.
11. Close the dialog using the **Close** button.

The map produced by the *Region Definition* is shown in the large panel that takes up most of the dialog. Most of the controls in the dialog are used to alter the Region Definition. To avoid lengthy delays after settings are changed on slower computers, the display is not updated every time a change is made to the Region Definition. The **Refresh** button is provided for this purpose.

The shape of the cursor indicates the currently set operation, either "pan" (✥) or "zoom" (🔍). When in pan mode, clicking on the map and moving the mouse with button down will move the map into the same direction as the mouse. In zoom mode, two methods can be used to zoom in onto a point or region. Left-clicking on a map point causes the map to be redrawn at an about 50% larger scale, thus showing a smaller area, positioned so that the point that was clicked stays in the same absolute position on the screen. Similarly, right-clicking on a point draws a 50% smaller version of the map, again positioned so that the clicked point does not move. Note that there are limits to the enlargement and reduction allowed for a map. An alternative way to zoom into an area is to left-click on the point that is required as the top-left corner of the zoomed area and, leaving the mouse button down, move the mouse to the desired lower-right corner of the area. A yellow rectangle outlining the zoomed area will appear as the mouse is moved on the screen (Fig. 5-6). When the mouse button is released, the area outlined by the zoom-rectangle will be drawn to occupy the full size of the map display area. Zoom operations can be reversed by clicking the **Undo Zoom** button, which takes the map back to the state it was in before the previous zoom operation. **Undo Zoom** can be invoked as often as required to reverse multiple zoom operations.

The **Show World** button changes the boundaries of the region to show the whole world (i.e., -90° to +90° latitude, -180° to +180° longitude).

Map Region Definitions can contain up to three extra features (decorations). A legend, a title and a scale marker can be specified by checking the appropriate box in the **Decorations** panel. The actual contents of both the legend and title are determined by the data plotted on the map (a "dummy" content is shown in the map panel). Each of these decorations can be "dragged" to the required position using the mouse.

The buttons along the top of the dialog allow a new *Map Region File* to be created, an existing one to be opened, or the one currently being worked on to be saved (**Save**) or saved with a different name (**Save As**). The Close button closes the Region Definition File Editor, prompting the user to save the file if it has been altered.

5.10 Extracting run information for use in a spreadsheet or GIS

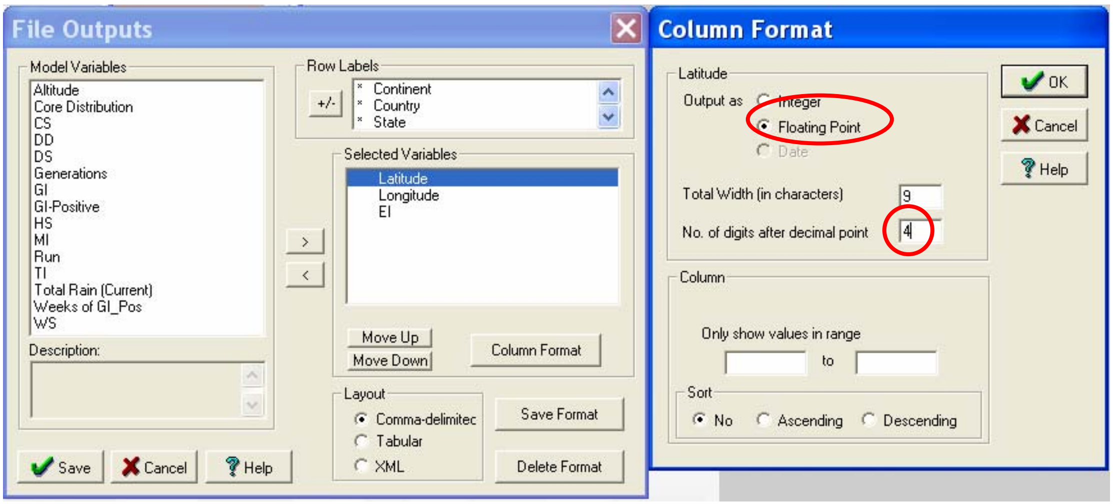
The mapping facilities within CLIMEX are intended for convenient and rapid presentation of results and may not be suitable for developing publication quality maps. In addition, the user may wish to present CLIMEX results in the same map as say a species distribution and other information that provides spatial context (e.g., roads, rivers and place names).

To extract information from a CLIMEX run, you first need to select or define a file format. With the run results window active, select **Results|File|New** to open the File Outputs dialog (Fig. 5-7). Define a new file format by selecting variables in the **Model Variables** box and clicking on the > button to transfer them into the **Selected Variables** box. Include both the Latitude and Longitude and any variables that you wish to map (e.g., EI, GI and CS). Select the Latitude variable and then click on the column format button. Set the output as floating, and the number of digits after decimal point between 2 and 4, depending upon the precision of your Meteorological locations (4 decimal points should be adequate for most applications, giving a precision of about 10 m). Click **OK**, select the Longitude variable and repeat setting the column format.

For most Geographical Information System (GIS) packages, the best layout type will be comma-delimited. When you are satisfied with the format settings, save the format using the "**Save Format**" button, navigating to a location where you will do your analysis or mapping, and give the file a new name.

The first step in using the file in a mapping situation will normally involve opening your file within a spreadsheet or text editor, and deleting the first seven lines of the file header, leaving only the column label line as the file header. After saving your file, remember to close it, otherwise some GIS packages will fail to import it. Open your GIS package and import your file as a set of points. To import the file into ArcMap 9.x, open the ArcMap application with a new or existing map, and then select Tools|Add XY Data. Click on the 📂 button to navigate to the .csv file that contains you CLIMEX point location information. ArcMAP will automatically recognise the Longitude and Latitude column labels as the X and Y coordinate columns.

Fig. 5-7 The File Outputs dialog, showing latitude, longitude and EI selected for writing to an output file.



Selected Variables: Latitude, Longitude, EI

Layout: ● Comma-delimitec ○ Tabular ○ XML

Column Format – Latitude – Output as: ○ Integer ● Floating Point ○ Date

Total Width (in characters): 9

No. of digits after decimal point: 4

Sort: ● No ○ Ascending ○ Descending

File Outputs
Model Variables
Altitude
Core Distribution
CS
DD
DS
Generations
GI
GI-Positive
HS
MI
Run
TI
Total Rain (Current)
Weeks of GI_Pos
WS
Description:
Row Labels
+/-
Continent
Country
State
>
<
Move Up
Move Down
Column Format
Save Format
Delete Format
Save
Cancel
Help
Column Format
Latitude
Column
Only show values in range
to
OK
Cancel
Help

Once imported into the GIS, there are multiple approaches that can be used to store and represent the data. As with CLIMEX, point locations can be thematically mapped using a graduated symbol size, with increasing dot radius representing increasing values of the mapped variable. Alternatively, gridded variables can be thematically mapped using either a raster or a polygon fishnet. If you are only interested in mapping one or a few variables, and you are unlikely to need to use data from the same meteorological database again, then it may be simpler to convert the points into a raster for the variable(s) of interest. If, on the other hand you want to map several variables or you could use the same meteorological database again, then it may be worth converting the point data to a raster using the location name as the raster variable. The location field can then be used to do a database join with any other files extracted from CLIMEX for the same selection. Following the database join, any of the CLIMEX variables can be mapped by selecting it as the variable of interest, classifying it and defining its symbology. Using this approach, you need only import the file once, saving considerable time in preparing maps for the second and subsequent variables. By representing the location data as polygons, the polygon shapes can be smoothly projected or clipped to geographic boundaries such as country outlines, providing an aesthetically pleasing product.

5.11 Converting species files from Version 1 to Version 2

In Version 1 of CLIMEX, parameter values for all species were stored in a single file (species.par) while species comments were stored in separate files (one per species) with the extension ‘.cmt’.

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Version 2 uses a different scheme, with each species having its own parameter file (with the extension .cxp) that stores both the parameter values and associated comments. These files are located in the 'species directory', generally '\Dymex2\Models\Climex\Species'.

To facilitate the conversion from Version 1 to Version 2, the CLIMEX release includes a program that converts the species files from Version 1 format to Version 2. The program (***cxdxconvert.exe***) is situated in the '\Program Files\Dymex2' folder, and can be started by double-clicking on it in Windows Explorer (Fig. 5-8).

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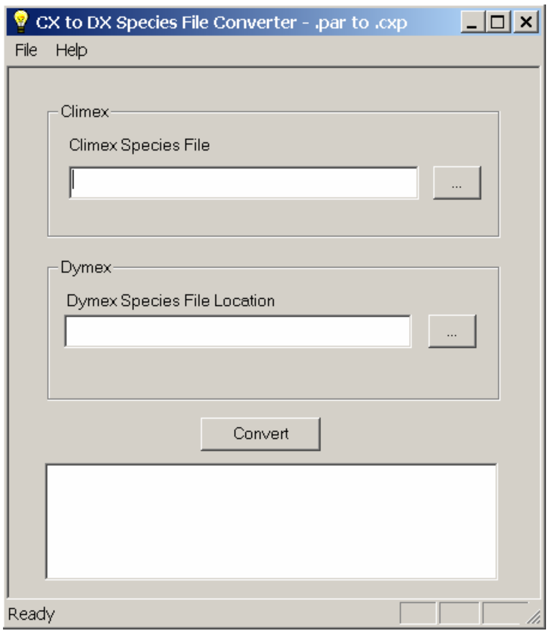
Fig. 5-8 The program that is used to convert CLIMEX species files from Version 1 to Version 2 format.


CX to DX Species File Converter - .par to .cxp
File
Help
Climex
Climex Species File
...
Dymex
Dymex Species File Location
...
Convert
Ready

Use the button at the right in the **Climex** panel to browse to the location of the Version 1 species file. Then use the equivalent button in the **Dymex** panel to locate the directory into which the converted files are to be stored. This should generally be a directory named 'Species' within the CLIMEX model directory. Then click the **Convert** button to start the conversion process.

Parameter values are kept exactly as they are in the original species file. Since Version 2 of CLIMEX is stricter about the relative values of parameters, this may cause some warnings or errors when converted files are opened in CLIMEX. For example, Version 1 of CLIMEX allowed a value of SMDS to be greater than SM0, which is not permitted in Version 2. Any such files will generate an error and will not be accepted by Version 2 of CLIMEX. In such cases, the species file will need to be opened in an editor such as Notepad and the invalid parameter changed manually (Once changed to comply, they will need to be checked to re-fit the geographical distribution). See Appendix 3 for a description of the species file format.

6 The Meteorological Data Manager facility (MetManager)

The ***MetManager*** program is a Microsoft® Access application that can be used to store and manipulate long-term average meteorological data that is then accessible to CLIMEX through the **MetManager** modules. For the rest of this section, any reference to ***MetManager*** will be to the ***MetManager*** program.

The MetManager stores its data in Access databases with the file extension ".mm". Each location's data is identified by its name, longitude and latitude. The following fields are stored for each location:

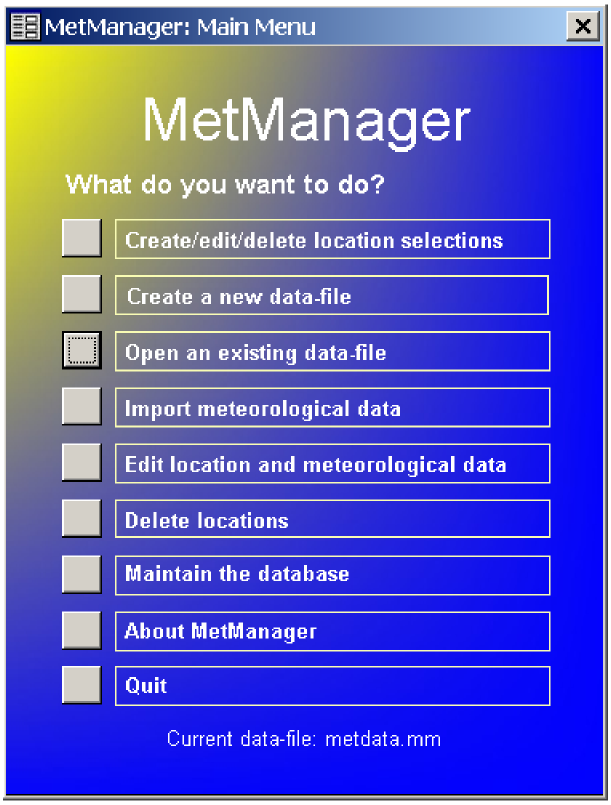
Continent	The name of the continent that the location is in.
Country	The name of the country that the location is in.
State	The name of the state that the location is in.
Location Name	The name of the location
Longitude	Longitude of the location (in degrees) (-90 to +90)
Latitude	Latitude of the location (in degrees) (-180 to +180)
Elevation	Elevation (altitude) of the location (in metres)
Importance Level	An integer (0-5) that is used to select subsets of locations
Minimum Temperature	The monthly Average Daily Minimum Temperature (12 monthly values or 52 weekly values)
Maximum Temperature	The monthly Average Daily Maximum Temperature (12 monthly values or 52 weekly values)
Rainfall	The monthly Total Rainfall (12 monthly values or 52 weekly values)
9am RH	The monthly Average Daily 9am Relative Humidity (12 monthly values or 52 weekly values)
3pm RH	The monthly Average Daily 3pm Relative Humidity (12 monthly values or 52 weekly values)

Several user-defined fields are also available for storing such variables as, for example, Evaporation.

The database can contain data for a large number of locations, and a mechanism for retrieving or accessing a subset of these locations has been provided. A ***Location Selection*** is the set of locations each of which satisfies a specified number of conditions (the ***Selection Criteria***). For example, if the Selection Criteria are that (1) the Country is *Australia* and (2) the Latitude is less than -30º, then the Location Selection will include all the Australian locations in the database whose latitude is less than 30º. Many Selection Criteria can be defined, named and stored within the database. CLIMEX uses the resulting Location Selections as sequences. Note that the term ***Location Selection*** (or ***Selection***) is commonly used for both a set of locations as well as the ***Selection Criteria*** that define that set.

The MetManager is started by clicking on the MetManager icon in the DYMEX Program Group. This displays the MetManager main menu, as shown Fig. 6-1. Note that the "menu" will be shown within a Microsoft Access window. This window has its own menu bar, which however, is not relevant to MetManager operations.

Fig. 6-1 The MetManager Main Menu.

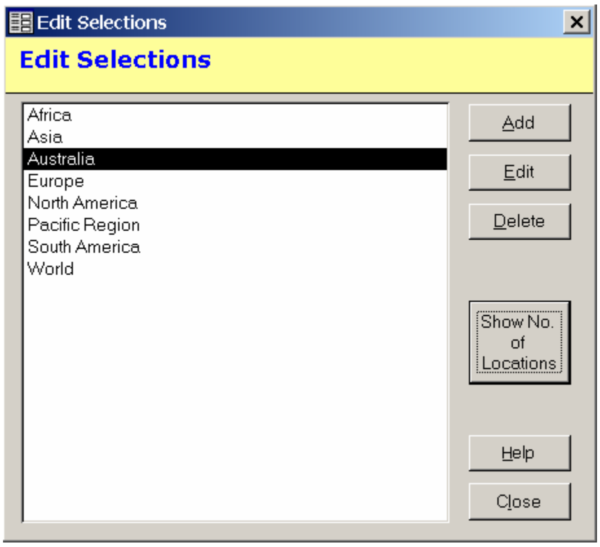

MetManager: Main Menu
MetManager
What do you want to do?
Create/edit/delete location selections
Create a new data-file
Open an existing data-file
Import meteorological data
Edit location and meteorological data
Delete locations
Maintain the database
About MetManager
Quit
Current data-file: metdata.mm

The "menu" consists of a set of buttons and their descriptions. The name of the current data-file is shown at the bottom of the menu. A data file must be specified before any other actions are possible (either by creating a new data-file, or by opening an existing one).

➢ Create/Edit/Delete Location Selections

The **Create/Edit/Delete Location Selections** option is used to create, edit or delete stored Location Selections (*Selection Criteria)*. It opens the **Edit Selections** dialog, which lists all of the currently available selections (Fig. 6-2). To add a new Selection, click on the **Add** button. To edit or delete a Selection, click on the appropriate Selection name in the list to highlight it and then click the **Edit** or **Delete** button. Note that deleting a selection only deletes the *Selection Criteria* (it does not delete any data from the database). To see the number of locations in the database that match the selection criteria, click on **Show No. of Locations**.

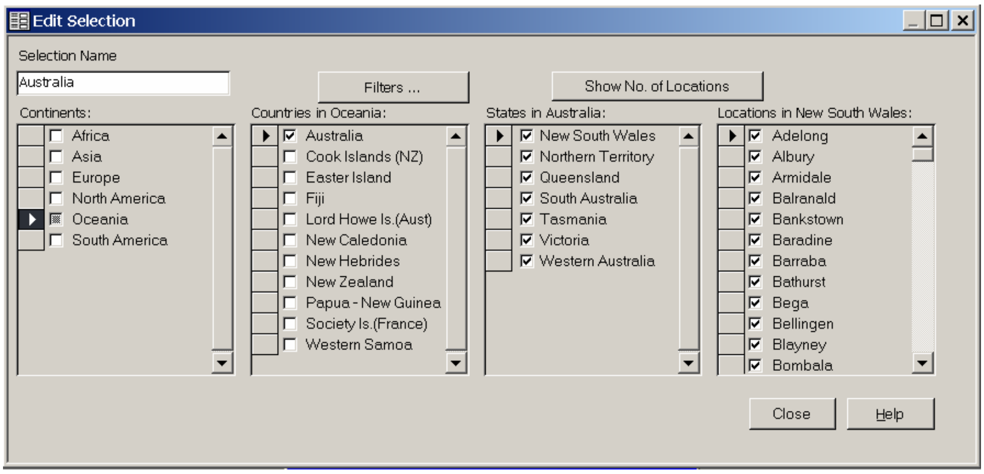
Fig. 6-2 The Edit Selections dialog.



Africa
Asia
Australia
Europe
North America
Pacific Region
South America
World

When a new selection is added, the user is first prompted for the name of the new selection. Use a unique name that clearly describes the set. The Selections dialog is then presented (the **Edit** button goes directly there), where the *Selection Criteria* are specified (Fig. 6-3).

Fig. 6-3 The Selections dialog, used for specifying the *Selection Criteria*.



Selection Name: Australia

Continents:
☐ Africa
☐ Asia
☐ Europe
☐ North America
▨ Oceania
☐ South America

Countries in Oceania:
☑ Australia
☐ Cook Islands (NZ)
☐ Easter Island
☐ Fiji
☐ Lord Howe Is.(Aust)
☐ New Caledonia
☐ New Hebrides
☐ New Zealand
☐ Papua - New Guinea
☐ Society Is.(France)
☐ Western Samoa

States in Australia:
☑ New South Wales
☑ Northern Territory
☑ Queensland
☑ South Australia
☑ Tasmania
☑ Victoria
☑ Western Australia

Locations in New South Wales:
☑ Adelong
☑ Albury
☑ Armidale
☑ Balranald
☑ Bankstown
☑ Baradine
☑ Barraba
☑ Bathurst
☑ Bega
☑ Bellingen
☑ Blayney
☑ Bombala

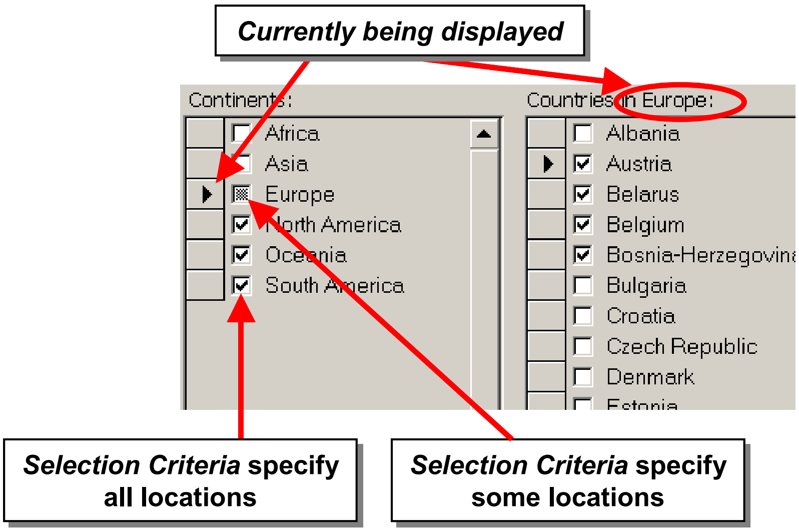
The **Selection** dialog is rather complex. It contains four lists that show *Continents*, *Countries*, *States* and *Locations*. To understand its operation correctly it needs to be understood that the dialog is actually showing two separate things within its four list panes, as follows:

1. A view into the contents of the database as a hierarchical structure organized by Continent, Country, State and Location

2. The *Selection Criteria* that use Continent, Country, State or Location names.

Considering the first of these, the **Continent** pane lists all of the continents represented within the database. Clicking on the grey, rectangular panel to the left of a continent's name will "select" that continent (indicated by an arrow symbol, ►), and show the countries belonging to that continent in the **Country** pane. Again, an arrow symbol is used to show the currently selected country, whose states are shown in the **States** panel, while the same symbol in the States panel shows the currently selected state, whose constituent locations are shown in the **Locations** pane. If a country has no states defined, selecting that country will display its locations (with an empty **State** pane).

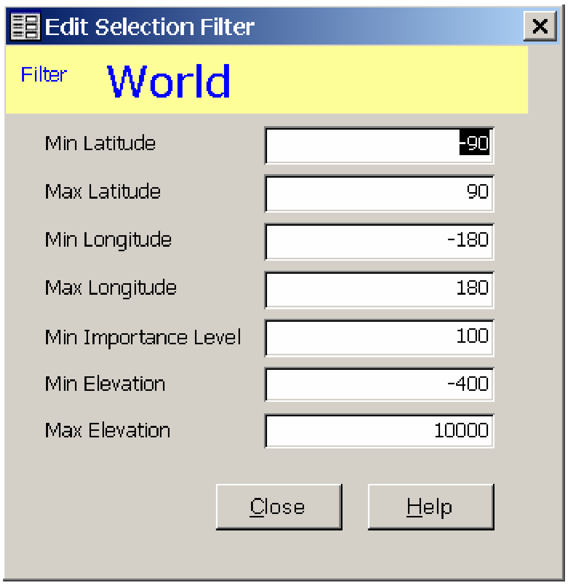
Fig. 6-4 A part of the Selections dialog, showing Europe selected for display.


Currently being displayed
Continents:
☐ Africa
☐ Asia
▨ Europe
☑ North America
☑ Oceania
☑ South America
Countries in Europe:
☐ Albania
☑ Austria
☑ Belarus
☑ Belgium
☑ Bosnia-Herzegovina
☐ Bulgaria
☐ Croatia
☐ Czech Republic
☐ Denmark
☐ Estonia
Selection Criteria specify all locations
Selection Criteria specify some locations

Whether a particular entity (continent, country, state or location) is included in the *Selection Criteria* being defined is indicated in the checkbox next to the entity's name. A tick indicates that the entity is completely included. For example, the tick next to *South America* in Fig. 6-4 indicates that the *Selection Criteria* include ALL South American locations. Note that this does not mean that the set of locations specified by the criteria (the ***Location Selection***) will include all South American locations – there may be another component of the *Selection Criteria* that (for example) specifies that locations are to have an altitude less than 2000m. The grey square within the checkbox next to *Europe* indicates that a part of Europe is included in the Selection Criteria. This can be seen by examination of the **Countries** pane, where only a few of the countries are selected.

Entities are added to the *Selection Criteria* by clicking on the checkbox so that it shows a tick. Entities are deselected by clicking until the checkbox is empty. An entity that is only partially selected can only be unselected by removing the included, lower-level entities from the *Selection Criteria*. Other items (such as latitude limits) included in the Selection Criteria can be changed by clicking on the **Filters** button (Fig. 6-3) to obtain the **Edit Selection Filter** dialog (Fig. 6-5).

Fig. 6-5 The Selection Filter dialog.



Edit Selection Filter

Filter World

Min Latitude -90

Max Latitude 90

Min Longitude -180

Max Longitude 180

Min Importance Level 100

Min Elevation -400

Max Elevation 10000

The **Edit Selection Filter** dialog specifies other criteria that a location must conform to in order to be included in the set of locations making up the ***Location Selection***. The latitude and longitude limits can be used to set a bounding rectangle within which locations must lie, while the elevation limits set an elevation band. The **Min Importance Level** can be used to limit locations to those with a specified level of “importance”.

➢ Create a new data-file

This option is used to create a new (empty) **MetManager** database file. It leads to a file dialog, from whence the user can navigate to the appropriate directory and enter the name of the file. The file should be created as a MetManager file (with extension “.mm”). When the new file has been created, it is automatically opened as the current database file within **MetManager**.

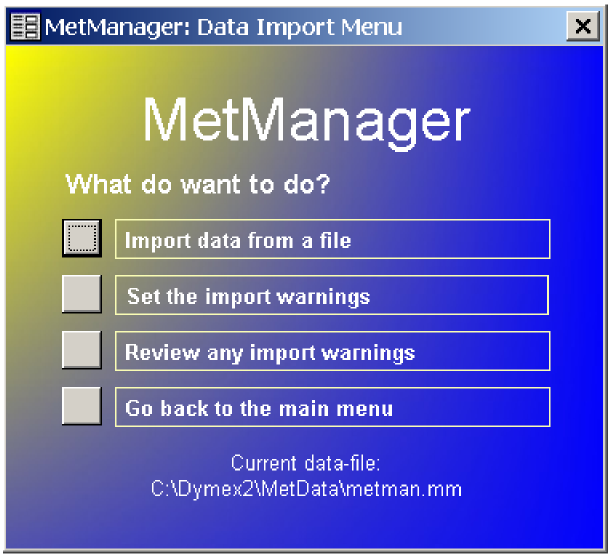
➢ Open an existing data-file

This option is used to open an existing **MetManager** database file. It leads to a file dialog, from whence the user can navigate to the appropriate directory and enter or browse for the name of the file. MetManager file should have the extension ".mm".

➢ Import meteorological data

This option is used to add meteorological data to the currently open database from another file. It leads to the Data Import Menu, which provides several choices .

Fig. 6-6 The MetManager's Data Import menu.



Current data-file:
C:\Dymex2\MetData\metman.mm

Import data from a file – this selection leads to a File Open dialog, where the file from which the data is to be imported can be selected. Three file types are supported for data input. These are (1) BMT files, with the database format from Version 1 of the MetManager program, (2) LOC/MET files (also used by Version 1 of the MetManager program as an import format) and (3) a MetManager Version 2 database file (.mm file). The LOC/MET file format is a plain text format, detailed in Appendix 3.

To import new locations, click on the Import Data button of MetManager. The MetManager will ask you if you want to replace any existing data with the corresponding imported data. If you select 'Yes' and you have locations in your new data that are already in the database (ie they have the same names for continent, country, state and location), the new data will replace the original data. If you select 'No', the original data will be protected and any such duplicate locations will not be imported.

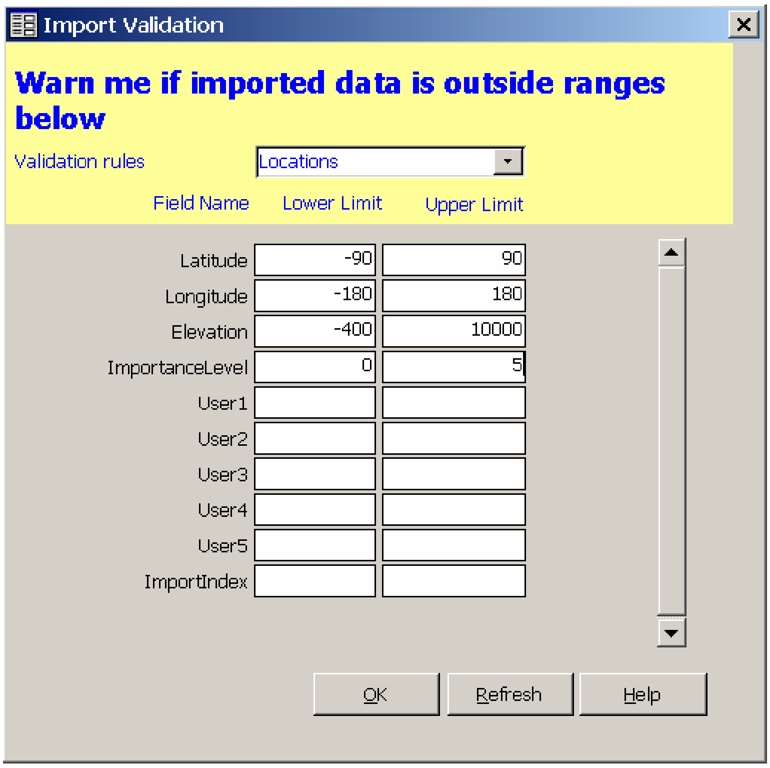
You will then be asked to select the location file (.LOC). Choose the directory where the file is located and select the file by clicking on its name and then the

'OK' button. There must also be a file containing the corresponding meteorological data (.MET file) in the same directory. The MetManager will now import the new data into the database.

The structure of your data files is very important (See Appendix 3). Example files of each (bolivia.loc and bolivia.met) are included in the ".\Dymex2\MetManager" directory. Use these files as a template for creating your files. The column setup will need to be EXACTLY the same as these example files otherwise MetManager will not import the data. Generally, an error message during the importation will identify any problems in the files. Note that if problems are found at any point during the import operation, no changes will be made to the database.

Set the import warnings – when data is imported into the database, it is checked for validity by comparing its values with a preset range. The allowed range can be set separately for each data field in the **Import Validation** dialog (Fig. 6-7).

Fig. 6-7 The MetManager Import Validation dialog.



Import Validation

Warn me if imported data is outside ranges below

Validation rules: Locations

Field Name	Lower Limit	Upper Limit
Latitude	-90	90
Longitude	-180	180
Elevation	-400	10000
ImportanceLevel	0	5
User1		
User2		
User3		
User4		
User5		
ImportIndex		

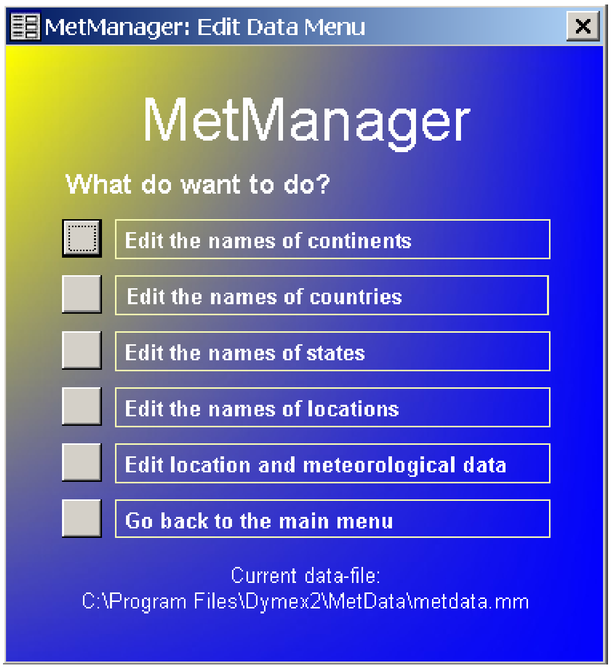
A drop-down list at the top of the dialog (labelled **"Validation Rules"**) allows selection of either "Locations or "Meteorological" data. Selecting either option shows a list of the corresponding data fields (the "Field Name" column), together with each field's current allowable limits ("Lower Limit" and "Upper Limit"). If a particular limit is blank, no error checking will be performed for the corresponding data in that direction (i.e., "Upper" or "Lower"). The scroll bar at the right can be used to change the displayed fields if there are more fields than can be displayed simultaneously in the dialog.

Review any import warnings – after data has been imported into the database, this option allows review of the warnings that were generated during the import process.

➢ Edit location and meteorological data

This option is used to edit the location and meteorological data in the currently open database. It leads to the Edit Data Menu, which provides several choices.

Fig. 6-8 The MetManager Edit Data menu.


MetManager: Edit Data Menu
MetManager
What do want to do?
Edit the names of continents
Edit the names of countries
Edit the names of states
Edit the names of locations
Edit location and meteorological data
Go back to the main menu

Current data-file:
C:\Program Files\Dymex2\MetData\metdata.mm

Edit the names of continents/countries/states – the top three buttons allow the names of the continents, countries and states in the database to be changed. Each name is shown in a separate edit field. To change a name, select the appropriate field and amend the name. Click on the "Close" button to exit the dialog. The scroll bar at the right can be used to move the list of names up or down if there are more names than can fit into the dialog at once.

Edit the names of locations – allows the names of the locations in the database to be changed. Each locations's name is shown in a separate edit field. To change a name, select the appropriate field and amend the name. Click on the "Close" button to exit the dialog. The scroll bar at the right can be used to move the list of names up or down. The "Find" button at the top of the dialog can be used to enter the first few characters in the locations's name, which helps to locate it more quickly. A "Location Details" button (...) gives access to some other location properties, which can also be changed there.

Edit meteorological data – any location’s meteorological data can be changed by selecting this menu item. The resulting “Edit Meteorological Data” dialog contains a set of selection boxes at the top, from which the desired locations Continent, Country, State and location name can be specified. When this has been done, the locations’s meteorological data is displayed in the dialog. A particular data item is changed by clicking on it and typing in its new value. The value will be recorded to the database when the cursor leaves the data field. Pressing the “Esc” button on the keyboard before the cursor leaves the data field will restore its previous value. The “Edit” button next to the “Location” name can be used to edit other location properties such as its latitude and longitude.

➢ Delete locations

This option is used to delete locations (and their associated meteorological data) from the currently open database. The locations to be deleted must be specified using a ***Location Selection***, as described in section □. All of the locations specified by the ***Location Selection*** are deleted from the database, as is the **Location Selection** itself.

➢ Maintain the database

Try to reduce the size of the database – After many deletion and editing operations, the database may be somewhat fragmented. This option will attempt to compact it so that it takes up the minimum disk space.

Set up user-defined data – Several user-defined data fields are available for provision of additional data that describes a location (such as, for example, soil characteristics). These fields could be used to supply the data that drives the Physical and Biotic Substrate indices.

7 Bibliography

Note: This list is not official and is provided as a guide for interested parties to view the range of CLIMEX applications. If you are aware of any omissions or errors please advise us.

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8 Appendix I. Parameter Mnemonic Reference.

Growth parameters

Temperature Index

DV0	Limiting low temperature. No population growth takes place at or below this average weekly temperature.
DV1	Lower optimal temperature. The lower limit of the range of ideal temperatures for population growth. Population growth rate is reduced if the average weekly minimum temperature is below this value.
DV2	Upper optimal temperature. The upper limit of the range of ideal temperatures for population growth. Population growth rate is reduced if the average weekly maximum temperature exceeds this value.
DV3	Limiting high temperature. No population growth takes place when the average weekly maximum temperature equals or exceeds this value.
PDD	Minimum degree-days above DV0 necessary to complete a generation. For univoltine species, a minimum number of degree-days must be accumulated in a year in order to complete a generation and so survive at a given location. If the value of PDD is not reached at a particular location, the EI for that location will be 0. The default value of PDD is zero.

Moisture Index

SM0	Limiting low moisture. No population growth takes place at or below this average weekly soil moisture.
SM1	Lower optimal moisture. The lower limit of the range of ideal soil moisture for population growth. Population growth rate is reduced if the average weekly soil moisture is below this value.
SM2	Upper optimal moisture. The upper limit of the range of ideal soil moisture for population growth. Population growth rate is reduced if the average weekly soil moisture is above this value.
SM3	Limiting high moisture. No population growth takes place at or above this average weekly soil moisture.

The following are used only in the Species Interaction application:

LGMC	Lower Competitor Growth Rate. The growth rate of the competing species below which it does not affect the available soil moisture. With a growth rate of the competing species above this value, less moisture is available for the current species.
MIF	Moisture Inhibitor Floor. The lowest value that the soil moisture output can reach (when the competing species has a Growth Index of 1).

Diapause Index

DPD0	Diapause Induction Day length**.** This is the average daylength that induces diapause. The default value is 0, indicating no diapause.
DPT0	Diapause Induction Temperature. This is the average weekly minimum (for winter diapause) or maximum temperature (for summer diapause) that induces diapause.
DPT1	Diapause Termination Temperature. This is the average weekly minimum (for winter diapause) or maximum (for summer diapause) temperature that terminates diapause.
DPD	Diapause Development Days. This is the minimum number of days below (winter diapause) or above (summer diapause) DPTO required for diapause development to be complete. If the required number of days in diapause (DPD) are not achieved, the species is assumed not to have survived diapause and the annual GI becomes zero. The default value for DPD is 0, which corresponds to a facultative diapause.
DPSW	Indicator for Summer or Winter Diapause. The value of this parameter determines whether the species undergoes summer or winter diapause. A value of 0 indicates winter diapause, a value of 1 indicates summer diapause.

Light Index

LT0 is the daylength (in hours) above which growth is at a maximum.

LT1 is the daylength below which growth is 0.

Radiation Index

RV0	Limiting low radiation. No population growth takes place at or below this value of average weekly radiation.
RV1	Lower optimal radiation. The lower limit of the range of ideal radiation for population growth. Population growth rate is reduced if the average weekly radiation falls below this value.
RV2	Upper optimal radiation. The upper limit of the range of ideal radiation for population growth. Population growth rate is reduced if the average weekly radiation is above this value.
RV3	Limiting high radiation. No population growth takes place at or above this value average weekly radiation.

The following are used only in the Species Interaction application:

LGRC	Lower Competitor Growth Rate. The growth rate of the competing species below which it does not affect the available radiation. With a growth rate of the competing species above this value, less radiation is available for the current species.
RIF	Radiation Inhibitor Floor. The lowest value that the radiation output can reach (when the competing species has a Growth Index of 1).

Physical Substrate Index

SVP0	Lower Physical Substrate Variable Threshold. No population growth takes place at or below this value of the average weekly physical substrate variable.
SVP1	Lower optimal Physical Substrate Variable Value. The lower limit of the range of physical substrate variable values ideal for population growth. Population growth rate is reduced if the average weekly value of the physical substrate variable falls below this value.
SVP2	Upper optimal Physical Substrate Variable Value. The upper limit of the range of physical substrate variable values ideal for population growth. Population growth rate is reduced if the average weekly value of the physical substrate variable is above this value.
SVP3	Upper Physical Substrate Variable Threshold. No population growth takes place at or above this value of the average weekly physical substrate variable.

Biotic Substrate Index

SVB0	Lower Biotic Substrate Variable Threshold. No population growth takes place at or below this value of the average weekly biotic substrate variable.
SVB1	Lower optimal Biotic Substrate Variable Value. The lower limit of the range of biotic substrate variable values ideal for population growth. Population growth rate is reduced if the average weekly value of the biotic substrate variable falls below this value.
SVB2	Upper optimal Biotic Substrate Variable Value. The upper limit of the range of biotic substrate variable values ideal for population growth. Population growth rate is reduced if the average weekly value of the biotic substrate variable is above this value.
SVB3	Upper Biotic Substrate Variable Threshold. No population growth takes place at or above this value of the average weekly biotic substrate variable.

The following is used only in the Species Interaction application:

Biotic Index

SIP0	Species Interaction Parameter. This proportion of the Growth Index of the “other” species is added to (or subtracted from, if the parameter is negative) the raw weekly Growth Index to obtain the final weekly Growth Index.

Stress Parameters

As stresses are experienced when climatic extremes outside the ranges suitable for growth occur, the threshold values must always be outside the ranges for growth (for example, TTCS < DV0, TTHS > DV3, etc).

Cold Stress

Cold stress can occur in three different ways. In the degree-day method, stress occurs because the days are not warm enough to maintain metabolism. In the lethal temperature methods, stress occurs in response to excessively low temperatures (either minima or averages). Multiple stress types may occur for the one species.

TTCS	Cold Stress Temperature Threshold. This parameter represents the average weekly minimum temperature below which Cold Stress accumulates.
THCS	Cold Stress Temperature Rate. This is the rate at which Cold Stress accumulates once temperatures drop below the threshold value of TTCS.
DVCS	Cold Stress Day-degree Temperature Threshold. The temperature threshold that is used for the cold stress day-degree calculations.
DTCS	Cold Stress Day-degree Threshold. Cold stress will begin to accumulate when this threshold number of degree-days above DVCS is not achieved.
DHCS	Cold Stress Degree-day Rate. This is the rate at which Cold Stress accumulates once the threshold number of degree-days (DTCS) above DTCS is not achieved.
TTCSA	Cold Stress Temperature Threshold (Average). This parameter represents the mean weekly average temperature below which Cold Stress accumulates.
THCSA	Cold Stress Temperature Rate (Average). This is the rate at which Cold Stress accumulates once average temperatures drop below the threshold value of TTCS.

Heat Stress

Heat stress can occur in two different ways. In the degree-day method, stress occurs because the days are too hot to allow normal metabolism. In the lethal temperature method, stress occurs because of excessively high maximum temperatures.

TTHS	Heat Stress Temperature Threshold. This parameter represents the average weekly maximum temperature above which Heat Stress accumulates.
THHS	Heat Stress Temperature Rate. This is the rate at which Heat Stress accumulates once temperatures exceed the threshold value of TTHS.
DTHS	Heat Stress Threshold. Heat stress will begin to accumulate when this threshold number of degree-days above DV3 is exceeded.
DHHS	Heat Stress Degree-day Rate. This is the rate at which Heat Stress accumulates once the threshold number of degree-days above DV3 (DTHS) is exceeded.

Dry Stress

SMDS	Dry Stress Threshold. Dry stress is accumulated when the average weekly soil moisture level drops below this value.
HDS	Dry Stress Rate. This is the rate at which Dry Stress accumulates once the soil moisture drops below the Dry Stress threshold of SMDS.

Wet Stress

SMWS	Wet Stress Threshold. Wet stress is accumulated when the average weekly soil moisture levels exceed this value.
HWS	Wet Stress Rate. This is the rate at which Wet Stress accumulates once the soil moisture exceeds the Wet Stress threshold of SMWS.

Temperature/Moisture Stress Interactions

Interactive effects occur when combinations of stress values in their own right are not lethal, but are when they occur simultaneously (eg. Cold and wet or hot and wet).

Cold-Dry Stress

DTCD	Cold-Dry Degree-day Threshold. Cold-Dry Stress will begin to accumulate when this threshold number of degree-days above DV0 is not achieved.
MTCD	Cold-Dry Moisture Threshold. This is the average weekly soil moisture level below which Cold-Dry Stress accumulates.
PCD	Cold-Dry Stress Rate. This is the rate at which Cold-Dry Stress accumulates once the threshold number of degree-days > DV0 is not reached **and** the average soil moisture level drops below the threshold value.

Cold-Wet Stress

DTCW	Cold-Wet Temperature Threshold. Cold-Wet Stress will begin to accumulate when this threshold number of degree-days above DV0 is not achieved.
MTCW	Cold-Wet Moisture Threshold. This is the average weekly soil moisture level above which Cold-Wet Stress accumulates.
PCW	Cold-Wet Stress Rate. This is the rate at which Cold-Wet Stress accumulates once the threshold number of degree-days > DV0 is not reached **and** the average soil moisture level exceeds the threshold value of MTCW.

Hot-Dry Stress

TTHD	Hot-Dry Temperature Threshold. This is the average weekly maximum temperature above which Hot-Dry Stress accumulates.
MTHD	Hot-Dry Moisture Threshold. This is the average weekly soil moisture level below which Hot-Dry Stress accumulates.
PHD	Hot-Dry Stress Rate. This is the rate at which Hot-Dry Stress accumulates once the average maximum temperature exceeds the threshold of TTHD *and* the average soil moisture level drops below the threshold value of MTHD.

Hot-Wet Stress

TTHW Hot-Wet Temperature Threshold. This is the average weekly maximum temperature above which Hot-Wet Stress accumulates.

MTHW Hot-Wet Moisture Threshold. This is the average weekly soil moisture level above which Hot-Wet Stress accumulates.

PHW Hot-Wet Stress Rate. This is the rate at which Hot-Wet Stress accumulates once the average maximum temperature *and* the average soil moisture level exceed the threshold values of TTHW and MTHW.

9 Appendix 2. The LOC/MET file format.

The two files hold the location data (.LOC files) and the meteorological data (.MET files) respectively. Each of these files can be in either a fixed-field or comma-delimited format. The MetManager automatically detects whether a file is in fixed-field or comma-delimited format.

(a) Fixed field format

An example of the *.loc file (ie bolivia.loc) is given below and could be used to add two new locations (Chulumani and Patacamaya) in Bolivia.

```
*1.00 SOUTH AMERICA
*1.01 Bolivia
#*    nostates
0     Chulumani          16.4 S   67.5 W 1580
0     Patacamaya         17.2 S   67.9 W 3789
```

The file starts with a header that includes the continent, country, and optionally, a state. Note that these items appear on separate lines of which the first two are prefixed by a * and four numeric characters followed by a space and the name of the continent or country. *1.00 denotes continent and 1.xx (where xx is any non zero integer) denotes country. The optional line for state is prefixed by # * and four spaces followed by the name of the state or ‘nostates’, where state definitions do not exist (the state line may be omitted altogether if you do not intend to use states for the entry of new locations). The name of the continent MUST be one of the continents in the CLIMEX database, or the import will fail. The name of the country and state entered should correspond to one already being used in the CLIMEX database. If an unknown name is used for a country or state, a new country or state with that name will be created and the new locations will not be added to that respective continent and/or country and/or state. Be particularly careful with spelling of these items to avoid errors.

Following the header on a new line appears the **Location Data** for each new location. This includes information about the importance level, the name of the location, its coordinates and elevation (in metres. The Location Data is of a fixed format with data in columns with each location line specified as below (for columns not referred to, insert a normal space).

1	Importance level code (0-5; blank=0)
7-25	Location name
26-29	Latitude
31	North/South indicator (N or S)
34-38	Longitude
40	East/West indicator (E or W)
41-45	Elevation (in metres)

The **Meteorological Data** file (example below) holds all the climate data for each location. For each month (1 - 12) the file holds average maximum daily temperature, average minimum daily temperature, average monthly rainfall, average daily relative humidity at 9 am, average daily relative humidity at 3 pm and the 10-character location code defined in the Location Data file above. Note in the example below that the 3pm Relative Humidity values are all zero. CLIMEX interprets these as being absent, and calculates them using the 9am value (9am RH x 0.85). The Meteorological Data file is given a **.met** file extension (ie bolivia.met).

```
  1  26.9  15.9   171  12.9    .0 CHULUMANI
  2  26.8  15.8   223  12.5    .0 CHULUMANI
  3  26.9  15.5   141  12.1    .0 CHULUMANI
  4  26.9  14.7    56  11.6    .0 CHULUMANI
  5  25.4  14.6    38  11.2    .0 CHULUMANI
  6  24.5  11.5    17  11.0    .0 CHULUMANI
  7  24.7  11.3    20  11.1    .0 CHULUMANI
  8  26.3  12.3    58  11.5    .0 CHULUMANI
  9  27.0  13.4    97  11.9    .0 CHULUMANI
 10  27.7  14.9    99  12.3    .0 CHULUMANI
 11  28.5  15.1   117  12.7    .0 CHULUMANI
 12  27.5  15.7   188  13.0    .0 CHULUMANI
  1  22.7   5.8    88  12.9    .0 PATACAMAYA
  2  21.9   6.0    69  12.5    .0 PATACAMAYA
  3  21.1   4.7    47  12.1    .0 PATACAMAYA
  4  19.3   2.1    15  11.6    .0 PATACAMAYA
  5  16.5  -1.6     8  11.2    .0 PATACAMAYA
  6  14.6  -4.8     2  11.0    .0 PATACAMAYA
  7  14.9  -4.7     1  11.1    .0 PATACAMAYA
  8  16.8  -2.6     9  11.4    .0 PATACAMAYA
  9  19.1   1.5    37  11.9    .0 PATACAMAYA
 10  22.6   3.0    18  12.4    .0 PATACAMAYA
 11  24.3   4.5    33  12.8    .0 PATACAMAYA
 12  22.6   5.7    76  13.0    .0 PATACAMAYA
```

The met file data must contain the same number of locations and be in the same order as the loc file entries. The format of the file is as follows (columns not used are spaces):

1-3	Month
5-9	Average Daily Maximum Temperature
11-15	Average Daily Minimum Temperature
17-21	Average Monthly Rainfall (mm)
23-27	Average Daily 9am Relative Humidity (%)
29-33	Average Daily 3pm Relative Humidity (%)

(b) Comma-delimited format

The Continent, Country and (optional) State lines start with a # symbol in this format. The lines that correspond to a location must contain the following items, separated by commas:

Latitude, Longitude, Elevation, Location Name, Importance level

Note the “Location Name” may not contain a comma. An example of a comma-delimited .loc file is shown below:

```
#Continent, Africa
#Country, Algeria
#State, nostates
32.8,-0.6,1072,Ain-Sefra,0
36.8,3,50,Algiers,0
```

The .MET file contains the following data items, each separated by a comma from the next item:

Month, Maximum Temperature, Minimum Temperature, Rainfall, 9am Relative Humidity, 3pm Relative Humidity

An example of a comma-delimited .MET file containing the data for two locations is shown below:

```
1,12.2,-0.6,10,79,52
2,15.6,1.1,10,76,50
3,17.2,3.9,15,68,36
4,23.3,7.8,10,58,29
5,27.2,11.1,15,59,29
6,32.8,15.6,28,46,26
7,37.8,19.4,8,39,18
8,35.6,18.9,8,46,21
9,32.2,15.6,15,51,29
10,24.4,9.4,28,68,34
11,16.1,5,28,77,46
12,12.8,1.1,18,78,48
1,15,9.4,112,75,66
2,16.1,9.4,109,72,60
3,17.2,11.1,74,71,59
4,20,12.8,41,67,57
5,22.8,15,46,72,60
6,25.6,18.3,15,72,60
7,28.3,21.1,3,73,60
8,29.4,21.7,5,70,60
9,27.2,20.6,41,74,62
10,23.3,17.2,79,72,60
11,18.9,13.3,130,73,63
12,15.6,10.6,137,72,64
```

10 Appendix 3. The Species File format.

CLIMEX species files must have the extension '.cxp' to be recognised as such. They consist of a header (everything up to, but not including, the line "Begin Values") and a values block (the rest of the file). The header block contains the species notes/comments (between the "Begin Comment" and "End Comment" lines). The "Protected" keyword, if present, prohibits the user from editing this file within CLIMEX. In the values block, parameters are hierarchically nested within their processes. Each parameter is specified in 2 lines, as follows:

```
      "Begin Parameter" "parameter name" "value"
      "End Parameter"
```

Be careful when changing any parameter value manually to ***change only the value of the parameter***. The name must never be changed – it must correspond to the name that CLIMEX uses for that parameter – or CLIMEX will not be able to find that parameter in the file. It is also important to retain the quotes around each value.

```
"DYMEX Parameter Version" "2.1"
"Begin Parameter Block" "ClimexModel"
"Begin Description"
  "Name" "_Template - Savannah"
  "Protected"
  "Date Modified" "Jan 02 2001, 12:18"
  "Begin Comment"
    Accomodates tropical savannah-type species
  "End Comment"
"End Description"
"Begin Values"
  "Begin Process" "Temperature Index"
    "Begin Parameter" "Limiting low temperature" "18"
    "End Parameter"
    "Begin Parameter" "Lower optimal temperature" "28"
    "End Parameter"
    "Begin Action" "Maximum Temperature"
      "Begin Parameter" "Upper optimal temperature" "32"
      "End Parameter"
      "Begin Parameter" "Limiting high temperature" "40"
      "End Parameter"
    "End Action"
  "End Process"
  "Begin Process" "Moisture Index"
    "Begin Action" "Soil Moisture"
      "Begin Parameter" "Limiting low moisture" "0.3"
      "End Parameter"
      "Begin Parameter" "Lower optimal moisture" "0.6"
      "End Parameter"
      "Begin Parameter" "Upper optimal moisture" "0.7"
      "End Parameter"
      "Begin Parameter" "Limiting high moisture" "0.8"
      "End Parameter"
    "End Action"
  "End Process"
  "Begin Process" "Light Index" "Unused"
    "Begin Action" "Daylength"
      "Begin Parameter" "Daylength at no growth" "0"
      "End Parameter"
      "Begin Parameter" "Daylength at maximum growth" "0.01"
      "End Parameter"
    "End Action"
  "End Process"
  "Begin Process" "Diapause Index" "Unused"
    "Begin Parameter" "Diapause Induction Daylength" "0"
    "End Parameter"
    "Begin Parameter" "Diapause Induction Temperature" "0"
    "End Parameter"
    "Begin Parameter" "Diapause Termination Temperature" "0"
  "End Parameter"
  "Begin Parameter" "Diapause Development Days" "0"
  "End Parameter"
  "Begin Parameter" "Summer/Winter Diapause Indicator" "0"
  "End Parameter"
"End Process"
"Begin Process" "Cold Stress" "Unused"
  "Begin Action" "Minimum Temperature"
    "Begin Parameter" "Cold Stress Temperature Threshold" "2"
    "End Parameter"
    "Begin Parameter" "Cold Stress Temperature Rate" "0"
    "End Parameter"
  "End Action"
  "Begin Action" "Degree-days above Threshold"
    "Begin Parameter" "Cold Stress Degree-day Threshold" "15"
    "End Parameter"
    "Begin Parameter" "Cold Stress Degree-day Rate" "0"
    "End Parameter"
  "End Action"
  "Begin Action" "Average Temperature"
    "Begin Parameter" "Cold Stress Temperature Threshold (Average)" "0"
    "End Parameter"
    "Begin Parameter" "Cold Stress Temperature Rate (Average)" "0"
    "End Parameter"
  "End Action"
"End Process"
"Begin Process" "Heat Stress"
  "Begin Action" "Maximum Temperature"
    "Begin Parameter" "Heat Stress Temperature Threshold" "36"
    "End Parameter"
    "Begin Parameter" "Heat Stress Temperature Rate" "0.0002"
    "End Parameter"
  "End Action"
  "Begin Action" "Degree-days above Threshold"
    "Begin Parameter" "Heat Stress Degree-day Threshold" "0"
    "End Parameter"
    "Begin Parameter" "Heat Stress Degree-day Rate" "0"
    "End Parameter"
  "End Action"
"End Process"
"Begin Process" "Dry Stress"
  "Begin Action" "Soil Moisture"
    "Begin Parameter" "Dry Stress Threshold" "0.2"
    "End Parameter"
    "Begin Parameter" "Dry Stress Rate" "-0.005"
    "End Parameter"
  "End Action"
"End Process"
"Begin Process" "Wet Stress"
  "Begin Action" "Soil Moisture"
    "Begin Parameter" "Wet Stress Threshold" "1.3"
    "End Parameter"
    "Begin Parameter" "Wet Stress Rate" "0.005"
    "End Parameter"
  "End Action"
"End Process"
"Begin Process" "Cold-Dry Stress" "Unused"
  "Begin Action" "Degree-days above Threshold"
    "Begin Parameter" "Cold-Dry Degree-day Threshold" "0"
    "End Parameter"
  "End Action"
  "Begin Action" "Soil Moisture"
    "Begin Parameter" "Cold-Dry Moisture Threshold" "0"
    "End Parameter"
  "End Action"
  "Begin Parameter" "Cold-Dry Stress Rate" "0"
  "End Parameter"
"End Process"
"Begin Process" "Cold-Wet Stress" "Unused"
  "Begin Action" "Degree-days above Threshold"
    "Begin Parameter" "Cold-Wet Degree-day Threshold" "0"
    "End Parameter"
  "End Action"
  "Begin Action" "Soil Moisture"
    "Begin Parameter" "Cold-Wet Moisture Threshold" "0"
    "End Parameter"
  "End Action"
```

```
      "Begin Parameter" "Cold-Wet Stress Rate" "0"
      "End Parameter"
    "End Process"
    "Begin Process" "Hot-Dry Stress" "Unused"
      "Begin Action" "Maximum Temperature"
        "Begin Parameter" "Hot-Dry Temperature Threshold" "0"
        "End Parameter"
      "End Action"
      "Begin Action" "Soil Moisture"
        "Begin Parameter" "Hot-Dry Moisture Threshold" "0"
        "End Parameter"
      "End Action"
      "Begin Parameter" "Hot-Dry Stress Rate" "0"
      "End Parameter"
    "End Process"
    "Begin Process" "Hot-Wet Stress" "Unused"
      "Begin Action" "Maximum Temperature"
        "Begin Parameter" "Hot-Wet Temperature Threshold" "0"
        "End Parameter"
      "End Action"
      "Begin Action" "Soil Moisture"
        "Begin Parameter" "Hot-Wet Moisture Threshold" "0"
        "End Parameter"
      "End Action"
      "Begin Parameter" "Hot-Wet Stress Rate" "0"
      "End Parameter"
    "End Process"
    "Begin Action" "Day-degree accumulation above DV0"
    "End Action"
    "Begin Action" "Day-degree accumulation above DV3"
      "Begin Parameter" "Dummy Parameter 1" "100"
      "End Parameter"
    "End Action"
    "Begin Action" "Day-degree accumulation above DVCS"
      "Begin Parameter" "Cold Stress DD Threshold Temperature" "18"
      "End Parameter"
    "End Action"
    "Begin Parameter" "Degree-days per Generation" "650"
    "End Parameter"
  "End Values"
  "End Parameter Block"
```

Index

abundance, 20, 44, 49

Access database, 9, 93

annual plants, 34

arid, 44

Average Temperature, 9, 37, 49, 71, 117

Away location, 17, 18, 70, 72

bimodal rainfall, 34

biological control, 12, 17

Biotic Index, 10, 23, **33**, 43, 116

Biotic Substrate, 15

Biotic Substrate Index, 10, 14, 15, 31, 101, 116

BMT files, 9, 85, 98

census data, 44

Climate Change, **81**–**83**

climate database, 22

climate matching, 17

climatic preferences, 22, 44

CLIMEX Application, 11

- Compare Locations (1 species), 13
- Compare Locations (1 species, extended), 14
- Compare Locations (2 species), 14
- Compare Locations (Species Interaction), 15
- Compare Locations (Stress), 16, 66
- Compare Years, 16
- Match Climates, 17
- Match Climates (Regional), 19

CLIMEX Model, 7, 11, 12, 20

CMI, 70, 72

Cold Stress, **36**–**37**, 49, 117

Cold-Dry Stress, 40, 118

Cold-Wet Stress, 40, 118

community, 23

Compare Locations, **12**, 13, 14

Compare Years, **16**

competition, 10, 15, 33

competitive exclusion, 43

Composite Match Index, 70

conversion utility, 10

core distribution, 45, 48, 62

crossover rate, 63, 67

cumulative stress, 35, 37, 38

data averaging, 17

data sets, 17

daylength, 32, 33, 42, 49, 52

degree-days, 25, 36, 38

density-dependence, 24

DHCS, 36, 117

DHHS, 38, 117

diapause, 23, 31–33, 41, 49, 59

- facultative, 115
- obligate, 8, 23, **41**–**42**, 52, 59
- summer, 32, 59
- winter, 32, 52, 59

diapause development, 32, 49, 60

Diapause Index, 23, **31**–**33**, 42, 115

differences, 10

distribution, 20

distribution data, 46

distribution limits, 46, 49

distribution maps, 44

DLD0, 49

DLT0, 49

DLT1, 49

dormancy, 23

DPD, 32, 33, 53, 115
DPD0, 32, 52, 115
DPSW, 32, 53, 115
DPT0, 32, 52, 115
DPT1, 32, 53, 115
Dry Stress, **39**, 56, 117
DTCD, 118
DTCS, 36, 117
DTCW, 118
DTHS, 38, 117
DV0, 10, 24, 38, 41, 49, 53, 114
DV1, 24, 49, 114
DV2, 24, 49, 114
DV3, 24, 38, 49, 114
DVCS, 10, 36, 117
DYMEX, 7, 9, 85
Ecoclimatic Index, 8, 22, 23, 25, 31, 42–**43**, 45
EI. see Ecoclimatic Index
equatorial zone, 82
Evaporation, 93
evapotranspiration, 27
extreme seasons, 12
extreme temperatures, 37, 38
extreme values, 17
extremes, 34
generation, 24, 25, 41, 54
generations, 67
Genetic Algorithm, **62–69**
geographical distribution, 12, 34, 44
geography, 46
gradients, 45
grid data, 9, 85
Growth Index, 44
  Annual, 7, **24**, 31, 42
  Weekly, **23**, 31, 33, 42, 60
growth season, 8
HDS, 39, 117
Heat Stress, **38**–**39**, 55, 117
Home location, 18, 70
Home Region, 72
host availability, 20
Hot-Dry Stress, 40, 118
Hot-Wet Stress, 40, 119
HWS, 39, 118
hypothesis, 46, 49
import data, 85, 98
Import formats, 120
Index
  Cold Stress, 10
  Ecoclimatic, 8
  Growth, 7
  Interaction Stress, 10
  Stress, 7
inference, 8, 44
installation, 8
Interaction Stress, **40**–**41**, 118
irrigation, 13, 21, 55, **83**
iteration, 47
iterative, 44
known distribution, 47, 62
laboratory data, 8, 44, 46, 47
LGMC, 28
LGRC, 30, 115
Light Index, 23, **33**, 49
limiting conditions, 12
Location Selection, 9, 47, 83, 84, 94, **95–97**
Location Sequence, 46, 47, 83, 84, 94
LT0, 33, 115

LT1, 33, 115

Map, **85**–**89**

  Legend, 89

  Projection, 9, 88

  Region Definition, **85**, 88

  Region File, 9

  Zoom, 88

Map Manager, 9, **85**–**89**

masking, 70

Match Climates, 7, **70**–**72**

  Regional, **72**–**75**

Match Index, 70, 72

  Humidity, 71

  Rainfall Pattern, 71

  Soil Moisture, 71

  Temperature, 71

  Total Rainfall, 71

Match Index Weights, 70

Match Level, 70

MetManager format, 120–22

MetManager program, 9, 84, **93**–**101**, 120

MIF, 29

Moisture Index, 23, **27**–**28**, 114

Moisture Parameters, 50

Moisture Stress, 56

MTCD, 118

MTCW, 118

MTHD, 118

MTHW, 119

multivoltine, 24

mutation rate, 63, 67

obligate diapause. see diapause, obligate

parameter, 12, 77

Parameter File

  comments, 79

parameter fitting, 8, **43**–**61**

  automatic, 10, **62**–**69**

Parameter Grid window, 78

PCD, 118

PCW, 118

PDD, 23, **25**, **41**, 42, 49, 53, 114

pest risk analysis, 12, 17

PHD, 118

phenology, 8, 44, 49

PHW, 119

Physical Substrate Index, 10, 116

population, 7

population growth, 12, 23

population growth rate, 49

population size, 67

potential distribution, 12

quarantine, 17

Radiation Index, 10, **29**–**30**, 115

rate of increase, 24

REF, 30

Reference File, 62, 64, **65**

Regional Matching. see Match Climates, Regional

RIF, 115

RV0, 29, 115

RV1, 29, 115

RV2, 29, 115

RV3, 29, 115

Scenario Files, 81

seasonal growth, 24

seasonal growth potential, 13

sensitivity, 44, 45

Sequence. see Location Sequence

Shape File, 9, 86

Simulator (DYMEX), 76

SIP0, 116

SM0, 27, 50, 114

SM1, 27, 50, 114

SM2, 27, 50, 114

SM3, 27, 50, 114

SMDS, 39, 50, 117

SMWS, 39, 50, 118

Soil Moisture, 9, 50, 70

soil moisture model, 27

soil moisture storage, 27

Soil Moisture Utility, 50

soil type, 20, 27, 44

species comments, 46

Species File, 10, 46, 77, 78

- creation, 77
- deletion, 77
- folder, 77
- printing, 77, 80
- protected, 79

species interaction, 15, 28, 30, 33, 43, 62

species name, 80

species template, 44, 45, 51

stress, 12

stress accumulation, 34, 35, 40, 44

stress boundaries, 47

stress gradient, 49

Stress Index, **34**–**36**, 43, 45, 116

Stress Indices, 22

Substrate Index, **30**–**31**

sub-tropical, 44

summer diapause. see diapause, summer

SVB0, 116

SVB1, 116

SVB2, 116

SVB3, 116

SVP0, 116

SVP1, 116

SVP2, 116

SVP3, 116

synergy, 10, 15, 33

temperate, 44, 51

Temperature Index, 23, **24**–**26**, 26, 114

- Annual, 26

Temperature parameters, 49

Template (Species Analysis), 21

THCS, 37, 117

THCSA, 37, 117

THHS, 38, 117

tropical, 44

TTCS, 37, 117

TTCSA, 37, 117

TTHD, 118

TTHS, 38, 117

TTHW, 119

validation, 47

variation, 12

vernalisation, 31

Wet Stress, **39**, 118

winter diapause. see diapause, winter