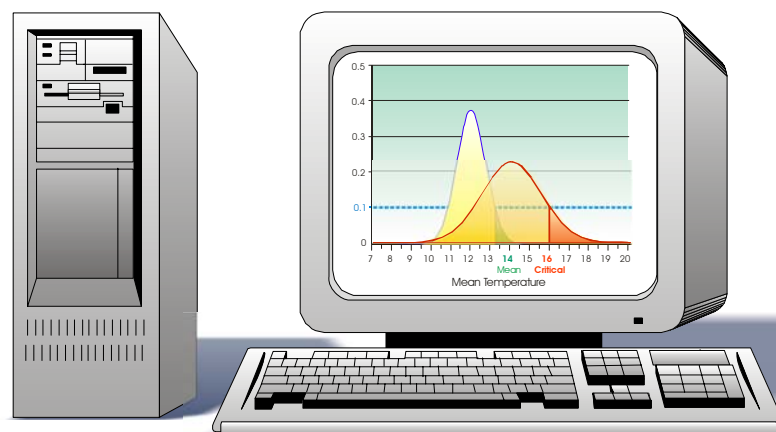




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Processing Indices of Change and Extremes from Regional Climate Change Data

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List of Acronyms

Acronym	Label
AI	Aridity Index
BIOS	Basic Input/ Output System
CC	Climate Change
CDDI	Cooling Degree Days Index
CGIAR-CIS	Consultative Group on International Agricultural Research- Consortium for Spatial Information
CLM	Climate Limited-area Modelling Community
CPU	Central Processing Unit
DDR RAM	Double Data Rate Dynamic Random Access Memory
DIMM	Dual In-line Memory Module
DMI	Danish Meteorological Institute
DOS	Disk Operating System
ECA&D	European Climate Assessment & Data
ETRS89	European Terrestrial Reference System 1989
EVDAB	European Database of Vulnerabilities to Natural Hazards
FAO	Food and Agriculture Organization of the United Nations
FAT	File Allocation Table
FSB	Front-side Bus
GDAL	Geospatial Data Abstraction Library
GIS	Geographic Information System
gsar	General Search And Replace
GUI	Graphical User Interface
HDD	Hard Disk
HDDI	Heating Degree Days Index
HWDI	Heat Wave Duration Index
IDE	Integrated Drive Electronic
IML	IDIRSI Macro Language
IT	Information Technology
LAEA	Lambert Azimuth Equal Area
JRC	European Commission Joint Research Centre
NetCDF	Network Common Data Format
NTFS	New Technology File System
OEM	On-Equipment Material
OS	Operating System
PAE	Physical Address Extension

Acronym	Label
PC	Personal Computer
PCIe	Peripheral Component Interconnect Express bus
PET	Potential Evapo-Transpiration
RAM	Random Access Memory
rpm	Rotations per minute
SATA	Serial Advanced Technology Attachment
SCSI	Small Computer System Interface
SLC	Single-Level Cell
SSD	Solid State Disk
TAR	Tape Archive
UNIX	Uniplexed Information and Computing System
VGA	Video Graphics Array
WGS84	World Geodetic System 1984

1 INTRODUCTION

In recent years advances in *Information Technology* (IT) have made the output from climate change model runs available to a wide user community through public or registered downloads using the internet. At the same time processing power and storage capacities of desktop *Personal Computers* (PCs) have increased to a level which allows storing the model output on local drives and processing the data for indicators of climate change and extremes using PC programs with reasonable processing times. An example of a PC configuration used for such processing of regional high-resolution climate change model output to produce climate change indicators is given in this document.

2 SYSTEM SPECIFICATIONS

The PC used for processing largely follows the standard construction of a file server with only few specific enhancements. When the system was purchased in 2009 the components were comparatively advanced. By today's (2012) standards the hardware is modest and the software relates to a Microsoft® Windows® 32bit environment. However, in use the system was found to be very stable and recovered from the various enhancements introduced by the user.

2.1 Hardware

The main components of the hardware are presented in Table 1. The system uses two *Central Processing Units* (CPUs) with Intel® Xeon® processors, each having 4 cores. With 2.5GHz the CPU speed is now only mid-range. Where programs do not make specific use of multiple processors or cores the CPU speed is a limiting factor to processing performance. Having 8 cores available, as in the PC used, only produces a significant increase in throughput when processes run in parallel. However, this is not the case for the standard programs used. Because many of the calculations of the indicators are disk-intensive the number of processes run on the system were kept to a minimum. An advantage of a multi-processor/multi-core system was noticeable when using file compression software. The task could be performed with a notable decrease in the time needed.

Table 1: Hardware Components

Component	Specification
Mainboard	Tyan D2568
Processor	Intel® Xeon® E5420 ¹ 2.50GHz, 4 Cores, 2x 6MB L2 cache
Total Processors	2 x Intel® Xeon® E5420
Memory Controller	Tyan 5400A Chipset Memory Controller Hub 4x 333MHz (1.33GHz) FSB, 4x 2GB DDR2 FB-DIMM 2x 333MHz (666MHz)
Total Memory	8GB DDR2 FB-DIMM
Video Adapter	NVIDIA® Quadro® ² NVS 290 16 SP 414MHz, 256MB DDR2 200MHz 64-bit, PCIe 1.00 x16
Hard disks	Seagate® ³ ST3160023AS 160GB, SATA150, 3.5", 8MB Cache Hitachi® ⁴ HUA721010KLA330 1TB, SATA300, 3.5", 7200rpm, 30MB Cache Intel® X25-E Solid State Drive, 32GB SATA II, SLC

Experimenting with different PCs and configurations showed that a major limitation to reducing processing time was file access. The *Serial Advanced Technology Attachment* (SATA) interface for 2 hard disks (HDD) of newer construction allowed faster access than the previously used *Integrated Drive Electronic* (IDE) drives. Compared to a system based on two Intel® Xeon® 2.4GHz single core CPUs with a combination of IDE and *Small Computer System Interface* (SCIS) HDDs the time of processing CC indicators could be reduced by a factor of 2.5, thus allowing some processing steps to be finished in days rather than weeks. For faster disk access a *Solid State Disk* (SSD) was installed and used to store data frequently accessed for read operations.

Running a benchmark on the drives the random access time for the HDDs is 9.4ms, compared to 0.72ms for the SSD⁵. The average transfer rate of the HDDs is 69.2 Mb sec⁻¹, while the transfer rate of the SSD as used in the system gives 235.4 Mb sec⁻¹. The difference in data access and transfer was very noticeable in practical use, but the SSD also showed times when it was not responding, particularly after deleting large amounts of files. However, this was not obvious when performing disk operations from the command line and could therefore be caused by the Explorer program.

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⁵ Using Benchmarks from Sandra 2012 by SiSoft (<http://www.sisoftware.net/>)

2.2 Software

The software used to operate the PC and run programs is summarized in Table 2.

Table 2: Software Components

Component	Specification
BIOS	Phoenix (OEM) 1.03.2568 08/06/2008
Operating System	Microsoft® Windows XP® ⁶ Professional 32bit Service Pack 3
Programs	IDRISI Andes, Taiga ⁷ FWTools ⁸ V. 2.4.7 Windows 32bit with GDAL ⁹ Notepad2 ¹⁰ gsar ¹¹ V. 1.21 Gavotte RAMdisk ¹² 7-ZIP ¹³

The *Geographic Information System* (GIS) Idrisi from *Clark Labs* was used because several routines to process climate change indicators were developed over the years using this software, which could be adapted to process indicators from data provided by various other sources. Another advantage of using the GIS is that the output can be directly used to be integrated the indicators with other GIS data layers.

In order to improve the management of the large number of files generated by climate change model runs the data are frequently stored in *Network Common Data Format* (NetCDF)¹⁴. To extract the parameter fields from the NetCDF format files of the climate change model output the utility FWTools was used. This software allows access to the *Geospatial Data Abstraction Library* (GDAL)¹⁵ library through scripts run in a command window. With the Taiga release the Idrisi GIS could manage NetCDF files through an interface to the GDAL library. However, the processing chain was already developed to make use of alternative methods to run with older versions of the program and the feature was not used.

⁶ Windows is a registered trademark of Microsoft Corporation in the United States and other countries.

⁷ © 2012 Clark Labs, Clark University 950 Main Street, Worcester MA 01610-1477 USA

⁸ FWTools is a set of Open Source GIS binaries for Windows (win32) and Linux (x86 32bit) systems produced by Frank Warmerdam. Available from: <http://fwtools.maptools.org/>

⁹ Homepage: <http://www.gdal.org/>

¹⁰ Homepage: <http://www.flos-freeware.ch/>

¹¹ Homepage: <http://home.online.no/~tjaberg/>

¹² Ramdisk Tools:

<http://archive.msdn.microsoft.com/ramdisktools/Wiki/View.aspx?title=Home&version=3>

¹³ Homepage: <http://www.7-zip.org/>

¹⁴ Homepage: <http://www.unidata.ucar.edu/software/netcdf/>

¹⁵ Homepage: <http://www.gdal.org/>

Where settings in the files had to be modified, for example to convert *Uniplexed Information and Computing System* (UNIX) to DOS conventions for line endings, the tool *General Search And Replace* (gsar) from Tormod Tjaberg and Hans Peter Verne (available from Tormod's page, see Table 2) was used.

Most processing was automated by scripts run from the command line or using the scripting language of IDRISI (*IDRISI Macro Language* (IML)). The conversion of the compressed files, extracting a field from NetCDF format files and processing the data under Idrisi can all be achieved with scripts. The files were generated and managed using the text editor *Notepad2* from Florian Balmer, available at *flo's freeware* (see Table 2).

The NetCDF files are often compressed using the TAR (derived from *tape archive*) file format¹⁶ when coming from a UNIX environment or other compression formats used on PCs. To manage compressed files the program 7-Zip was used (see Table 2 for source). 7-Zip is open source software and manages a wide range of file archive formats. It has the advantage of allowing batch processing of archives by scripts from a command line.

To use part of the available *Random Access Memory* (RAM) as a disk of more than 64Mb several free and commercial products are available. In this case the driver from Gavotte¹⁷ was used. It may not be the fastest option¹⁸ but is free for use, easy to install and gave no trouble over years of use. It was configured to generate a RAM disk of 5Gb to store temporary processing data.

2.3 System Configuration

The objective of adjusting the system configuration was to increase the performance for data throughput. Initially, video performance was not considered an issue because most processing is run as scripts using the command window. Scripts and batch files were also used to manage the data files because the Windows Explorer was found to introduce massive delays to file operations. Specific measures taken to improve data processing times are presented in the following sections.

2.3.1 System Settings

Several modifications to the standard system settings were investigated:

- The performance settings of the operating system were set to "Adjust for best performance" (under System Properties – Advanced – Performance Settings).

¹⁶ TAR is also the name of a programme to manage files with the format of the same name.

¹⁷ There are numerous references to the tool on the WEB, but the responsible author could not be identified with certainty. Gavotte is cited as having developed the GUI, but is also quoted as the developer of the driver based on the ramdisk.sys driver from Microsoft®. Other sources give Iyh728 as the author of the GUI (<http://alternativeto.net/software/gavotte-rramdisk/about>).

¹⁸ For a comparison of RAM disk speeds see: <http://fiehnlab.ucdavis.edu/staff/kind/Collector/Benchmark/RamDisk/ramdisk-benchmarks.pdf>

- Automatic defragmentation was disabled to avoid defragmenting the SSD and interference with processing. Other HDDs were defragmented manually.
- The Windows Indexing Service was disabled on all drives (drive property).
- The temporary environment variable was set to a directory on the RAM disk (under System Properties – Advanced – Environment Variables).

The paging file was left on the primary disk. It could have been moved to the RAM disk, but concerns about the system stability and the need of more than 4Gb for the RAM disk to hold the data were arguments against the move. The issue is discussed controversially on various forums (see e.g. <http://www.megaleecher.net/RAMDisk>). On the system used creating an additional paging file on the RAM-drive was found to have no effect on processing times and was not used for routine operations.

2.3.2 RAM Disk

An important element of improving the system performance was to use part of the RAM as a disk. The 32bit OS can only address 4Gb and use about 3Gb directly with the rest lying dormant. With 8Gb of RAM installed 5Gb can be used as a disk to provide fast access to data and reduce the wear and tear of the HDD components. To make use of the RAM above 4 Gb the *Physical Address Extension* (PAE) was enabled. Using memory above 4Gb as a RAM disk also limits the number of freely available utilities.

2.3.3 Use of SSD

The addition of a SSD introduced further changes to the system configuration. Some changes put forward for SSDs relate to configurations with the SSD being the primary drive and holding the OS. This is not the case here, which is why several optimization options, such as turning off Windows write cache buffer flushing (in any case not recommended for Intel SSDs) or the Windows prefetcher, were not adopted. Other improvements recommended for SSD were not applied to maintain computability of the system with legacy software, e.g. the 8.3 filename creation was enabled, or because they are not applicable to the OS used.

The SSD partition alignment offset was verified using the following commands:

```
Diskpart ↵  
List disk ↵  
Select disk n ↵  
List partition
```

For n in the command "Select disk" use the number of the SSD given in the list of drives. The partition offset was found to be 32kb. This value was considered suitable to assure that the start of a logical sector is aligned to the beginning of a physical page of the SSD. The issue of aligning SSDs, in particular under Microsoft Windows XP®, is covered by a large number of WEB-sites, see e.g.

- <http://www.sevenforums.com/tutorials/113967-ssd-alignment.html>
- <http://thesdreview.com/ssd-guides/optimization-guides/the-ssd-optimization-guide-2/>
- http://www.tweaktown.com/articles/3116/tweaktown_s_solid_state_drive_optimization_guide/index1.html

With developments advancing rapidly in the field of SSDs these sites may no longer exist or are modified by the time this report is published.

Utilities to optimize SSDs are available from the producers of the drives, but also from independent sources. It should be noted that most recommendations relate to a SSD being used as a primary partition and to hold the OS. With the limited number of write operations for SSDs before wearing out SSDs may not be the first choice for intensive file operations, but can be used for providing fast access to files for further processing.

2.4 Data Processing

Processing the CC data is divided into two main steps:

1. Data Preparation
2. Indicator Processing

In the preparatory step data are first converted from the TAR.GZ archive to the NetCDF format. Daily data for individual parameters in IDRISI raster format are then extracted from files using GDAL. These tasks are performed by processing batch files from the command line under the FWTools shell.

The thus extracted IDRISI raster files need further processing before they can be used. The files are generally inverted for rows and, depending on the source, the file dimensions need to be re-set. This is done using macros within IDRISI. The raster files are then archived for future use.

The second step concerns the processing of indicators using IML scripts run under the IDRISI GUI. The IMLs are configured and assembled from a pool of scripts according to specific situations, such as data paths settings, preparing ancillary files or using IMLs depending on days in a month, by command line scripts from batch files. This procedure is used because the IMLs allow only one level of passing on parameters to a sub-routine, while batch files can pass on parameters over several levels of CALL commands.

2.4.1 Processing Considerations

The distribution of files to the RAM disk, SSD and hard disk was governed by the number of read and write operations to and from files. As a general rule the processing was arranged as follows:

- all temporary and frequently modified files were stored in the RAM disk;
- intermediate files which were frequently accessed for read operations were stored on the SSD;
- permanent storage of files and back-up operations were assigned to HDDs.

The Idrisi GIS was installed on the SSD, which reduced the available free space on the drive to 28Gb (29.7Gb were available after formatting drive). Depending on the size of the climate change data the available free space is not enough to store more than 1 or 2 parameters for all 30-year periods included in the processing. The periods processed were generally 1961 to 1990 and 2011 to 2099 (total of 119 years, data for 2100 not widely available). For a daily parameter with 30-day months this amounts to 42,840 days. As a rough guide the available free space on the SSD should allow storing all files of a single parameter up to a size of 680kb. When using Idrisi raster files the data file is accompanied by a document file. Although the file is usually < 1kb in size the cluster size of the SSD (4kb) increases the space needed for the files on the disk.

Thus, the SSD storage can only hold two parameters for all periods of the data from the *Climate Limited-area Modelling Community* (CLM), which are 273kb per parameter with values in real format. For data with the spatial resolution of the regional run of the *Danish Meteorological Institute* (DMI) data (512kb) only a single parameter could be stored on the SSD. Hence, it was not possible to use the SSD for storing both the source and the output data without swapping files in and out. The SSD was thus only used to hold the main output from processing data.

To reduce wear and tear of the storage media the RAM-disk was configured to hold most of the data of the temporary processing steps. One such processing is extracting the NetCDF data from TAR.GZ archives and then saving data in IDRISI format. The largest archives used were those of the CLM, which amount to 120Mb for the GZ and 180Mb for the TAR archive, which contain the data of all parameters for one month. The RAM-disk can thus hold data for one year of TAR archives for further processing.

Using IDRISI to process the data for indicators requires extracting a parameter from the compressed NetCDF container a separate file for each parameter and date. For daily data this amounts to 85,680 disk files (1 data + 1 meta-data file) for a run with 30-day months and 119 years of data. Improving processing performance is therefore largely a question of optimizing file management.

2.4.2 Performance Tests

Given the faster access time and transfer rates of the SSD using the storage media should make a significant difference. The file transfer times of copying 7,300 files (971Mb) were:

HDD to HDD:	30 sec
HDD to SSD:	12 sec
HDD to RAM-drive:	9 sec (NTFS) 30 sec. (XCOPY FAT32) 52 sec (first copy from HDD)

All HDDs and the SSD were formatted to the *New Technology File System* (NTFS) and without indexing. The RAM-disk was formatted to either NTFS or the FAT32 (*File Allocation Table*) file system. The allocation size for the cluster was left as default. The size of the cluster size may influence the performance, but this was not further investigated.

Writing to the SSD instead of a HDD shortens the time needed by a factor of 2.5. The shortest transfer times for writing new files were achieved when writing to the RAM drive formatted to NTFS (9 sec.). Faster times (7 sec.) were achieved when using XCOPY to read from the SSD and over-write existing files on the RAM-disk formatted to NTFS. Formatting the RAM-disk to the FAT32 file system notably lengthened the process of copying files (30 sec.). However, when writing a first copy under FAT32 or indexing the files on the RAM-drive transfer times increased up to 52 sec., in cases even more. Faster random read times of the SSD than the RAM-disk for the same combination of components and driver were found by other users (e.g. http://www.neowin.net/forum/topic/612086-xp-pagefile-on-a-ram-disk/page_st_90).

The transfer time for copying files can only be used as an approximate indicator for system performance. Much depends on the preparatory tasks performed by the OS and the method used to copy files, e.g. if writing new files or over-writing exiting files. Writing new files was only tested with previous copies deleted from the drive and the recycle bin. Copying files under the command line (XCOPY) instead of the Explorer program give more repeatable results, but not necessarily faster transfers for copying files. In general, the first time the files are copied the management overhead to prepare the files can lengthen the time needed by a factor of 3 compared to repeated copying from the same source. This was found for both, using the Explorer program and the command line.

The situation is very different when deleting files where the command line interpreter gives much faster results than the GUI application. Notable is a difference in CPU utilization between writing to the RAM disk or a HDD/SSD. Writing to the RAM disk uses 90% CPU, to the SSD 45% and to a HDD <20% of the CPU time. Notable is also that the performance of copying files deteriorates towards the end of copying.

The performance of the set-up for processing data under practical conditions was tested for two repeatedly used processes:

- a) extracting data from the compressed NetCDF files to Idrisi raster format (from command line);
- b) converting extracted raster files to format conventions (Idrisi GUI).

The tests were performed on 10 years of daily CLM data. The results are given in Table 3.

Table 3: Extracting Idrisi Raster Files from Compressed NetCDF for 10 Years Daily Data

Read from	Temporary storage on	Write to	Time		
			create files & window minimized	overwrite files & window minimized	overwrite files & window maximized
<i>Media</i>	<i>Media</i>	<i>Media</i>	<i>Minutes</i>	<i>minutes</i>	<i>minutes</i>
Data extraction (command line)					
HDDa	HDDb	HDDb	14	18	18
HDDa	RAM	SSD	12	15	15
Data conversion (GUI)					
HDDa	HDDb	HDDb	14	15	29 / 48*
HDDa	RAM	SSD	14	15	30 / 43*

a, b: different physical HDDs

* repeated execution of processing, overwriting existing files

The tests were performed without running the Windows Explorer program. According to the results the differences in the various configuration for the processing times are unexpectedly small. Significant differences in processing are caused by three conditions:

- a) Creating or overwriting files (both processing steps)
- b) Visibility of processing window (GUI processing)
- c) Repeatedly executing processing without closing application

When overwriting existing files instead of creating new files, for example when running a procedure twice without deleting the previously generated output, the processing time increases. This is contrary to the findings from copying files between disks (see above).

The second observation is the overhead in processing time required to up-date the GUI. For the graphics card the latest available driver was used (Version 6.14.12.9573 from 09.02.2012). By minimizing the Idrisi window to the task

bar the time can be reduced up to 1/2 of the time needed when the window is visible (maximized or reduced in size). Reducing the display resolution or the colour depth did not noticeably affect processing time unless the monitor is set to *Video Graphics Array* (VGA) definition. In VGA mode no difference in processing time between the windows status was found.

The effect of reducing processing time is only noticeable for GUI processing. For running processes in the command window no difference in processing time was found when minimizing the command window or sending the output to the NUL device. Updating the screen makes use of the CPU, or at least the progress displayed in the window make use of it, which is also visible in the performance tab of the Task Manager.

When executing repeatedly the same script under Idrisi without closing the application processing time may increase notably. Based on the Task Manager information it seems that the program does not release the used memory when running the IML. A difference in processing time is also possible in case the log file is not restarted and the previously used log file increases in size to append the new run.

Other changes to the processing environment did not much affect the performance. Evaluated were:

- Moving programs from HDD to RAM drive;
- Second paging file on RAM drive;
- Set environment variable temporary directory to RAM drive;
- Disable 8.3 filenames;
- Disable date stamping;
- Enable write caching on HDD/SSD;
- Running processes through a remote desktop.

When extracting the compressed files only one of the eight cores is used. The task manager indicates a peak load of 100% for this task. For all other tasks the processor cores are used to about 15%. Memory usage is generally < 300Mb, although it increases for multiple runs of the IML when the application is not restarted (see above).

2.4.3 Configuration for Processing Indicators

The configuration used to process the CC indicators is presented in Figure 1.

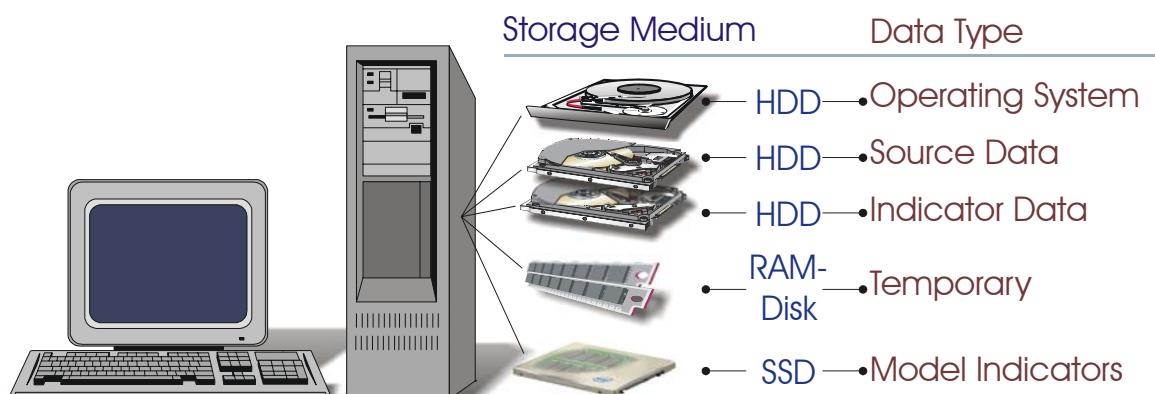


Figure 1: Configuration for Climate Change Indicator Processing

The OS and the paging file were stored on a HDD of its own. The programs to run the procedures were stored on the SSD. During processing the CC source data were read from a HDD, any temporary files were stored on the RAM disk and the output for an indicator of a data set was then written to the SSD. The individual indicators when then moved from the SSD to the second HDD for collecting all indicators.

The steps and times for processing a mean temperature indicator for the CLM consortial data are given in Table 4.

Table 4: Processing Steps and Times for CLM Temperature Mean-Type Indicator (1961-90 and 2011-99)

PROCESSING STEP	TIME <i>minute</i>	COMMENT <i>Source - Temporary - Output</i>
1. Data Preparation		
Extract TAR from GZ	84	HDDa (197GB) - none - HDDb (240GB)
Extract NetCDF from TAR	12	HDDb - none - HDDa (12GB)
Extract RST from NetCDF	77	HDDa - none - HDDa (12GB)
Transpose RST	171	HDDa - RAM Disk - SSD (12 GB)
2. Indicator Processing		
Mean-Type Indicator	45	SSD - RAM Disk - RAM Disk (380MB)
Standardized output	2	RAM Disk - RAM Disk - HDD

The total time needed to process a climate change indicator using changes in the mean over 30-year periods is 391 minutes. Most of the processing time is spent for generating files in the IDRISI format (244 minutes for CLM consortial data). Not included in the time is the transfer of the raster files to HDD storage and re-setting the processing environment. With some housework on the computer the time allows to process one indicator within a working day.

When estimating the total time needed to process the CC indicators it should be noted that extracting the data from the archives and processing the file format for use in the GIS has to be done but once for a parameter. These files are stored in compressed format on a HDD for further use. Extracting all files for all periods for a parameter to the SSD takes approx. 5 minutes. Computing a mean-type indicator is one of the faster operations. Other indicators generally take more processing time, in particular computing percentiles and the Heat Wave Duration Index, but can generally be processed within a day by setting the scripts to run also outside working hours.

3 CLIMATE CHANGE INDICATORS

A comprehensive list of indicators for climate change is given by the *European Climate Assessment & Data* (ECA&D) project¹⁹. The project provides the definition and mathematic formulation of the indicators in "Indices of Extremes" under the Indices directory (<http://eca.knmi.nl/indicesextremes/indicesdictionary.php>). The indicators listed on the page are not all related to extremes, but include indicators of more general changes in climate conditions, such as changes in the mean daily temperature.

The indicators used to process the climate change model output date back to a listing published in 2006. Since then some indicators have been added to the list or were modified. This is the case for the *Heat Wave Duration Index* (HWDI), which is no longer listed, but still computed.

All indicators are computed for 30-year periods. The base period covers 1961 to 1990. The start of the period is set to the start of a decade. i.e. 01. January, XXX1. Starting a decade at XXX0 would simplify coding the computations, but is not would not follow the definition of decades. The scenario periods cover 2011-2040, 2041-2070 and 2071-2099. The final year used varies between 2098 to 2100, depending on the model output. The number of years in the final period may be of little consequence for indicators based on value means, but have to be considered when an index concerns the number of events for the whole period. In this case the index of the final period is scaled to 30 years.

The indicators calculated from the regional CC data can be grouped following several criteria, such as change or extremes, temperature and precipitation, etc. Fir the indicators of climate change and extremes calculated most relate to changes in the climate and few to extreme events. The parameters assessed are mainly based on temperature (minimum, maximum, mean, dew point) and only a small set of indicators are computed for precipitation and relative humidity. As regards processing data for indices the statistical type of the data is of greater importance.

The indicators of climate change and extremes derived from the model runs are grouped according to the type of processing performed and listed in Table 5.

¹⁹ Homepage: <http://eca.knmi.nl/>

Table 5: Indicators of Climate Change

INDICATOR	INTERVAL (30 YEARS)		
	Annual	Season	Month
Mean value			
Mean Daily temperature	x	x	x
Maximum daily temperature	x	x	x
Minimum daily temperature	x	x	x
Daily diurnal temperature range	x	x	x
Total precipitation	x	x	x
Precipitation intensity on wet days	x	x	x
Longest period of consecutive dry days	x		
Maximum amount of precipitation in 5 consecutive days		x	
Relative Humidity	x		x
Aridity Index	x		
Standard Deviation			
STD of daily mean temperature			X
Percentiles			
95 th percentile of monthly mean of maximum daily temperature			J, J, A
99 th percentile of monthly mean of maximum daily temperature			J, J, A
99 th percentile of precipitation during wet day		x	
Conditional			
No. of days with Tmax>25C (Summer days)		Summer	J, J, A
No. of days with Tmax>35C			
No. of Days with Tmin>20C (Tropical nights)		Summer	J, J, A
No. of Days with Tmin>25C		Summer	J, J, A
Total annual number of wet days	x	x	x
Heating Degree Days			
Cooling Degree Days	x		D, J, F
HUMIDEX		Summer	
HUMIDEX > 25		Summer	
HUMIDEX > 35		Summer	
Heat Wave		Summer	J, J, A

J, J, A: June, July and August
D, J, F: December, January, February

Most indicators relate to changes in a mean value of a parameter, such as the mean daily temperature. Other indicators relate to number of days, such as the summer days or tropical nights. Computationally, these indicators are also mean values, but derived from averaging whole numbers.

Conditional indicators use a threshold for defining a yes/no conditions and are often more complex than other indicators. In this context not considered composite indicators are those for which the regional CC models provide data

as output. In cases where the mean of the diurnal temperature range is not provided by the source data it may be computed from the maximum and minimum temperature. Also the relative humidity can be computed from suitable temperature data. However, in the classification of indices they are listed as mean values, because they are also available as direct output.

3.1 Mean Values

Indices belonging to this group provide the averaged value of a parameter recorded on a ratio range. The mean values are found either by averaging from daily data or using averaged values from periods.

3.1.1 Means from Daily Data

For indicators specifying mean values the first aggregation of the data is computing the monthly means for each year of a 30-year period. The monthly means for a given year are computed as:

$$\bar{I}_m^j = \frac{1}{n} \times \sum_{i=1}^{d_m} t$$

where

- j year
- m month of year
- d_m number of days in month of year
- t parameter

The next step is the computation of the annual means for a parameter as:

$$\bar{I}^j = \frac{1}{d_a} \times \sum_{i=1}^{d_a} t$$

where

- j year
- d_a number of days in year
- t parameter

The number of days in a year can be either 360 (30-day months) or 365 (calendar day months). Where calendar day months are in the model output used leap years are ignored in the computation. This approach was taken because the IML used to process the data has very limited options for conditional treatment of data and the number of days in a month has to be pre-determined in the script. Using leap years in the computations was found to be a source of errors in the computations without adding relevant

information. The annual means are calculated from the daily values rather than the monthly means because the output of some models uses calendar days. However, seasonal means are computed from the monthly means. This treatment of seasonal data seems justified because seasonal means are compared as changes rather than absolute values.

From the monthly, seasonal and annual means for each year in a period the corresponding period means are calculated as

$$\bar{I}^p = \frac{1}{a} \times \sum_{j=1}^a \bar{I}^j$$

where

- a number of years in period
- j year in period
- p 30-year period

When calculating means for precipitation the indicator defines a period over daily precipitation is first summed up. For example, the mean annual precipitation for a period is the mean of the sum of the daily precipitation over the number of years of the period. Monthly mean precipitations for a period are computed correspondingly.

3.1.2 Aridity Index

An exception to the procedure of the defining the indicator as the mean derived from averaging daily values is the *Aridity Index* (AI). The AI is defined as the ratio between the mean annual precipitation and the mean annual *potential evapo-transpiration* (PET) (UNEP, 1997). The annual mean values of precipitation and PET are the annual values calculated over a period of 30 years. Hence, the AI is not computed from averaging individual annual mean AI values over a period, as the other indices of this group.

While precipitation data are available from the model output PET has to be calculated. For the AI the equation for the standard evapo-transpiration (ET_o) from Hargreaves (1985) is used:

$$ET_o = 0.0023 \times (T2_M + 17.8) \times (T2_{MAX} - T2_{MIN})^{0.5} \times R_a$$

where

- $T2_M$ mean monthly temperature at 2m [C]
- $T2_{MAX}$ mean monthly maximum temperature at 2m [C]
- $T2_{MIN}$ mean monthly minimum temperature at 2m [C]
- R_a monthly extra-terrestrial radiation [$mm \ day^{-1}$]

This equation is equivalent to the one used by the *Consultative Group on International Agricultural Research- Consortium for Spatial Information* (CGIAR-CIS)²⁰. One may note that in the FAO Penman-Monteith equation²¹, radiation expressed in $MJ m^{-2} day^{-1}$ is converted to equivalent evaporation in $mm day^{-1}$ by using a conversion factor equal to the inverse of the latent heat of vaporization:

$$ET_o [mm day^{-1}] \approx 0.408 \times R_a [MJ m^{-2} day^{-1}]$$

The extraterrestrial solar radiation R_a is computed as (FAO, 1998; FAO, 2009):

$$R_a = \frac{24 \times 60}{\pi} \times G_{sc} \times c_e (\omega_s \times \sin(\varphi) \times \sin(\delta) + \cos(\varphi) \times \cos(\delta) \times \sin(\omega_s))$$

where

- R_a extraterrestrial radiation [$MJ m^{-2} day^{-1}$]
- G_{sc} solar constant = $0.0820 MJ m^{-2} day^{-1}$
- d_r inverse relative distance Earth-Sun
- ω_s sunset hour angle [rad]
- φ latitude [rad]
- δ solar declination [rad]

with the inverse relative distance Earth-Sun d_r as

$$d_r = 1 + 0.033 \times \cos\left(\frac{2\pi}{365} \times J\right)$$

where

J Julian day of year

the solar declination angle δ as

$$\delta = 0.409 \times \sin\left(\frac{2\pi}{365} \times J - 1.39\right)$$

and the sunset hour angle ω_s as

$$\cos(\omega_s) = -\tan(\varphi) \times \tan(\delta)$$

ET_o and mean annual precipitation are first computed as monthly means for a 30-year period as:

$$AI_m^p = \frac{ET_o}{TAP_m^p}$$

where

²⁰ http://csi.cgiar.org/aridity/Global_Aridity_PET_Methodolgy.asp
²¹ <http://www.fao.org/docrep/X0490E/x0490e07.htm#radiation>

p	period
m	month of year
ET_o	reference evapo-transpiration
TAP	total annual precipitation

Seasonal and annual AIs are determined from the corresponding means for the period, not by averaging the means of the monthly AIs.

3.2 Standard Deviation Indicators

The standard deviation computed only for the mean daily temperature parameter. It is computed after the parameter mean value has been processed as

$$\sigma_m^p = \sqrt{\frac{1}{a \times n} \sum_{j=1}^a \sum_{i=1}^{d_m} (t - \bar{I}_m^p)^2}$$

where

a	number of years in period
d_m	number of days in month
j	year in period
m	month
p	30-year period

The mean parameter value is the mean monthly value for the 30-year period.

3.3 Percentiles Indicators

The 95th and 99th percentiles are computed from the relative frequency distribution of a parameter across the whole period. The percentiles are the mean of a portion of values taken from an ordered list of all values in the period. For example, the 95th monthly percentile of T_{max} is the mean of the upper 45 values of that month. Thus, this indicator does not assume a distribution of the data and is not based on the standard deviation.

3.4 Conditional Indicators

Where an indicator is the number of days of a defined event taking place it is linked to one or more binary conditions.

3.4.1 Summer Days, Tropical Nights, Wet Days

The indicator value for conditional indices is found by evaluating the condition and by incrementing a counter when the condition is met. In the processing the number of days (sum) is first established for each month in a year by evaluating the condition:

$$\bar{I}_m^j = \sum_{i=1}^{d_a} c, \quad c = \begin{cases} 1, & t > x \\ 0, & \text{otherwise} \end{cases}$$

where

j	year
m	month of year
d_a	number of days in month of year
t	parameter
x	threshold value

Next, the monthly mean number of days for a period is computed as:

$$\bar{I}_m^p = \frac{1}{a} \times \sum_{j=1}^a \bar{I}_m^j$$

where

a	number of years in period
j	year in period
m	month of year
p	30-year period

The seasonal number of days are then found by the sum of the monthly mean number of days:

$$\bar{I}_s^p = \sum_{k=1}^y \bar{I}_m^p$$

where

k	month in season
s	season

Although indicators based on the number of days or events are mean values when describing a period they depend on the number of days used to evaluate the condition. Therefore, the number of days in a year (360 or 365) may result in a difference in the indicator. For example, the summer season (June, July and August) may have 60 or 62 days. As a consequence, an indicator such as the number of summer days, will have on average 3.3% more summer days for data with calendar days than for data with 30-day months. The processing performed did not standardize on a number of days for these indicators.

3.4.2 Heating Degree Days

Actual *Heating Degree Days Index* (HDDI) express the severity of the cold in a specific time period taking into consideration outdoor and room temperature. To establish a common and comparable basis, Eurostat (2006) defined the following method for the calculation of heating degree days:

$$HDDI = \begin{cases} 18 - T_m \times d, & T_m \leq 15 \\ 0, & otherwise \end{cases}$$

where

d number of days
 T_m mean outdoor temperature [*Celsius*]

and the mean outdoor temperature T_m is defined as

$$T_m = \frac{T_{\min} + T_{\max}}{2}$$

Since the calculations use daily values $d = 1$. Despite the indicator name the values are not number of days, but the temperature sum of the days for which the condition is met.

Analogous to other conditional indicators, the next step is to calculate the monthly mean degrees of heating degree days for a period:

$$\overline{HDDI}_m^p = \frac{1}{a} \times \sum_{j=1}^a \sum_{i=1}^{d_m} HDDI$$

where

a number of years in period
 d_m days in month
 j year in period
 m month of year
 p 30-year period

Seasonal means for a period are then found by summing up the monthly means for the corresponding period.

3.4.3 Cooling Degree Days

Methods of defining indices for *Cooling Degree Days* (CDDI) are more varied than for HDDIs. For the conditional thresholds of the CDDI no generally applicable equation or a reference equation from EUROSTAT exists. Using a similar reasoning as for the HDDI a CDDI can be formulated using a suitable threshold for a comfort temperature and a buffer range. The threshold temperature for the CDDI varies, e.g. a threshold of 24°C and 3°C range is

used in Australia²², a threshold of 18°C (65°F) and 3°C range is used in North America²³.

In the computation of indicators the CDDI was defined as:

$$CDDI = \begin{cases} T_m - 18 \times d, & T_m \geq 21 \\ 0, & \text{otherwise} \end{cases}$$

In the absence of a specific threshold for Europe the routine implemented sets the threshold as a parameter and can be easily adjusted should other thresholds be investigated. The computations follow those of the HDDI.

3.4.4 HUMIDEX

The HUMIDEX (Masterson & Richardson, 1975) intends to describe the perceived temperature of an the average person²⁴. The index is defined as:

$$HUMIDEX = T2_M + 0.5555 \times \left(6.11 \times 10^{5417.7530 \times \left(\frac{1}{273.16} - \frac{1}{T2_D} \right)} - 10 \right)$$

where

$T2_M$ mean air temperature at 2m [Celsius]
 $T2_D$ dew point temperature at 2m [Kelvin]

In the definition the mean air temperature is in degree Celsius while the dew point temperature is in degree Kelvin. To further complicate the computation the HUMIDEX is computed only for dew point temperature $T2_D$ above zero (0°C) and a mean air temperature $T2_M$ of 20°C or above.

The HUMIDEX is processed only for summer months June, July and August and the summer season.

3.4.5 Heat Wave Duration Index

The *Heat Wave Duration Index* (HWDI) (Frich, 2002) was listed in the ECA&D dictionary of indices of extremes²⁵ at least until 2006, but was removed from the list at a later stage (before 2010). The HWDI expresses the frequency of a heat wave event occurring relative to a base period. The condition for a potential *Heat Wave Day* (HWD) is met when the daily maximum temperature exceeds the mean temperature of a 5-day window calculated over the base period by 5°C. The condition for counting a day in the succession of days for a heat wave event is defined as:

²² http://www.bom.gov.au/jsp/ncc/climate_averages/degree-days/index.jsp#how

²³ http://www.weather2000.com/dd_glossary.html

²⁴ http://www.ccohs.ca/oshanswers/phys_agents/humidex.html

²⁵ <http://eca.knmi.nl/indicesextremes/indicesdictionary.php>

$$HWD = \begin{cases} 1, & T2_{MAX_i}^{ps} > \frac{1}{5} \times \sum_{i=d-2}^{d+2} \overline{T2_{M_i}}^{pb} + 5 \\ 0, & otherwise \end{cases}$$

where

HWD	Heat Wave Day
$T2_{MAX_i}^{ps}$	maximum temperature for day i in scenario period [<i>Celsius</i>]
$\overline{T2_{M_i}}^{pb}$	mean of daily mean temperature for day i throughout base period [<i>Celsius</i>]
d	day of year
p^s	scenario period
p^b	base period

A heat wave of length n occurs when the condition for a HWD is met for at least 6 successive days:

$$HW_n = \begin{cases} 1, & \sum_{i=1}^n HWD \geq 6 \\ 0, & otherwise \end{cases}$$

The HWDI is only calculated for the length of the summer season. Because it is defined as an accumulation of days the sum of the events for each summer month is less than the total number of events for the summer season.

Given the limited dimensions for information to be displayed when comparing the scenario to the control period a graphic representation of the HWDI for spatial layers has to concentrate either on the aspect of magnitude or of frequency.

The mean number of heat waves of a given length for the summer season over a period is then given by:

$$\overline{HWDI}_n = \frac{1}{a} \times \sum_{j=1}^a \sum_{i=1}^{d_s} HW_n$$

where

a	number of years in period
d_s	days in summer season
j	year in period
m	month of year
p	30-year period

In the computations heat waves ranging from 6 to 20 days are calculated. For a more general number of heat waves, such as the number of heat waves of 6 days or longer, the mean values for each length needs to be summed up.

3.5 Standardized Output

The output data of regional climate change models from different sources, but also data from the same source but different configurations for model runs, often have very divergent spatial properties. All indices are processed to raster data using a common projection and grid spacing. The output data properties are summarized in Table 6.

Table 6: Standard Processing Output Specifications

ITEM		SPECIFICATION
Projection		European Terrestrial Reference System 1989 (ETRS89) Lambert Azimuth Equal Area (ETRS-LAEA)
Grid spacing		10000 m
Coverage	min. X	800000.0000
	max. X	7500000.0000
	min. Y	700000.0000
	max. Y	6500000.0000
Background value		-9000
Temperature		Degree Celsius
Precipitation		mm

The background value is set for all areas without data. Depending on the data used this may include large water bodies and oceans. The data are projected using the latitude/longitude field as source and a 3rd order polynomial mapping function (cubic convolution) with a nearest neighbour resampling type.

4 CLIMATE CHANGE DATA PROCESSED

Indicators for climate change were computed from several model outputs:

- Special high-resolution run by the *Danish Meteorological Institute* (DMI) under the PRUDENCE project²⁶
IPCC A2 climate scenario, approx. 12km grid, daily data for periods 1961 - 1990 and 2071 - 2100 used. Data have been provided through the PRUDENCE data archive, funded by the EU through contract EVK2-CT2001-00132.
- Consortial Simulation²⁷ of *Climate Limited-area Modelling Community* (CLM)
IPCC A1B climate scenario (0.165 degree grid, daily data for periods 1961 - 1990 and 2011 - 2100 used).
- Output from 12 ENSEMBLES²⁸ runs with bias-correction for temperature and precipitation
IPCC A1B scenario, mainly 25km grid, daily data for periods 1961 - 1990 and 2011 - 2099 used; one IPCC E1 scenario run processed with 50km grid.

Runs processed from the bias-corrected set are:

C4I_RCA_HadCM	METO_HC_HadRM3Q0
CNRM_ALADIN_ARPEGE	MPI_REMO_ECHAM5
DMI_HIRHAM5_ARPEGE	SMHI_RCA_BCM
DMI_HIRHAM5_BCM	SMHI_RCA_ECHAM5
DMI_HIRHAM5_ECHAM5	SMHI_RCA_HADCM3Q3
ETHZ_CLM_HadCM3Q0	
KNMI_RACMO2_ECHAM5	MPI_REMO_E1_ECHAM5 (E1 scenario)

Not all indices could be computed for all data sets. For example, the indices related to humidity could only be computed where corresponding data (humidity or mean and dew point temperature) were available.

²⁶ Homepage: <http://prudence.dmi.dk/>

²⁷ Homepage: <http://www.clm-community.eu/index.php?menuid=29&reporeid=37>

²⁸ Homepage: <http://www.ensembles-eu.org/>

5 SUMMARY

Indicators of climate change and extremes derived from the daily output of high-resolution regional CC models for Europe could be processed using a desktop server with largely standard components. Configuring the system for the processing task proved to be more complex than anticipated, with some components not producing the expected results. From the multitude of suggestions given on the internet for configuring the system to improve the processing performance many were found to have little or no effect on the system used. The benchmarks derived from data transfer rates, access times or copying files for the various storage devices (HDD, SSD and RAM-disk) were found to be only limited use for assessing overall system performance. More consequential than any system tweaks were the setting of the video when running processes under the GUI. Using a RAM disk was less an enhancement in performance than hoped for, but is still recommended to reduce the wear and tear of a HDD.

The output files from the various climate change models were processed using batch files executed from the command line. CC indicators of change and extremes were derived from running macro scripts under the GUI of IDRISI. The indicators were standardized to a common map projection, grid size and spatial extent. Indicators from different CC models or runs can therefore be directly used in spatial overlay functions, or integrated with other spatial data. However, when comparing or integrating the indicators the characteristics of the source data should be considered.

Indices of climate change and extremes resulting from the processing described in this report were used in a number of projects. Examples are

- European Climate Adaptation Platform (CLIMATE-ADAPT)
(<http://climate-adapt.eea.europa.eu/>)
- European Database of Vulnerabilities to Natural Hazards (EVDAB)
(<http://moland.jrc.ec.europa.eu/evdab/HTML/home.html>)
- FP7 RESPONSES Project
(http://www.responsesproject.eu/part_jrc.html)
- HDDI and CDDI in support to DG ENV.

Temperature indicators are further used in the evaluation of changes in soil organic carbon under climate change scenarios.

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Abstract

Advances in computer hardware have made it possible to calculate indicators of climate change and extremes derived from the daily output of high-resolution regional CC models for Europe could be processed using a desktop server using standard components. Using a combination of conventional hard disks, solid state and RAM disk improved the system performance but configuring the server for the processing task proved to be quite complex.

Indicators of climate change and extremes from regional models coming from the PRUDENCE project of the Danish Meteorological Institute, the consortial simulation of the Climate Limited-area Modelling Community and 12 runs of bias-corrected data from the ENSEMBLES project were processed. The resulting indicators were standardized to a common map projection, grid size and spatial extent to be directly available for further analysis or integration with other spatial data. The indicators were used in the data available from the European Climate Adaptation Platform (CLIMATE-ADAPT), the European Database of Vulnerabilities to Natural Hazards (EVDAB), the JRC activities within the FP7 RESPONSES project and support the evaluation of changes in soil organic carbon under climate scenarios.

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