AnemoScope

Wind Energy Simulation and Mapping

Reference Guide

March 2006

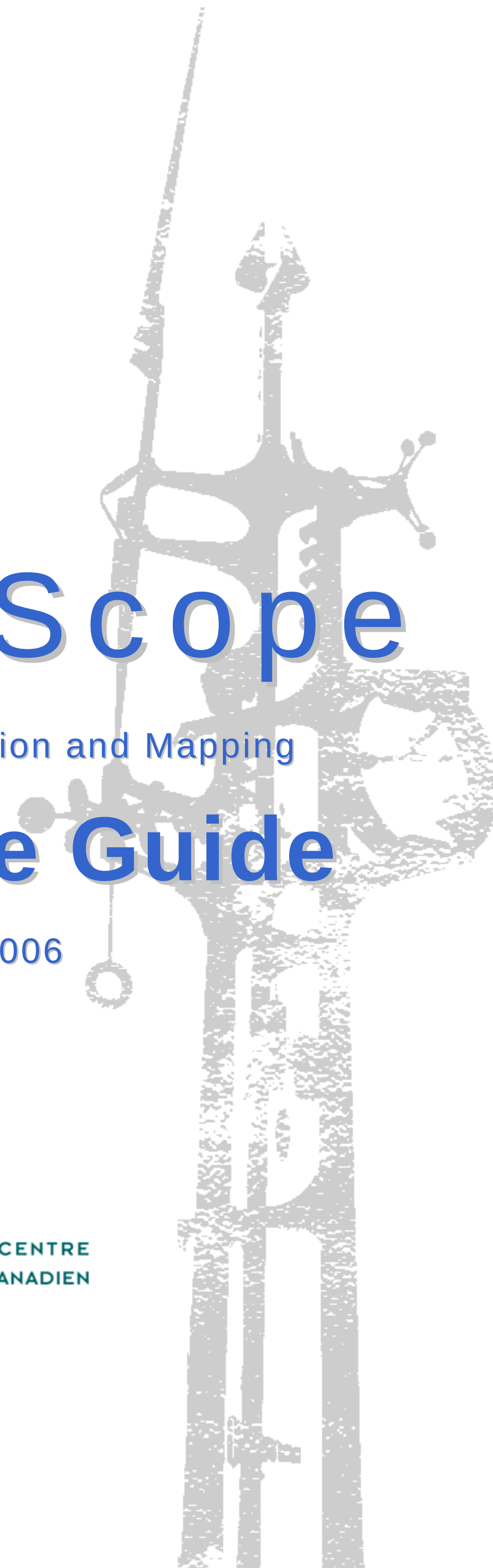

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Table of Contents

GenGeo and the Geophysical Database

What is GenGeo?

GenGeo is a tool developed at RPN and used to prepare the geophysical fields needed by the RPN Numerical Weather Prediction models.

GenGeo version 3.05.1 is integrated into AnemoScope. GenGeo is used to prepare the geophysical fields needed by both the mesoscale model and the microscale model. GenGeo extracts the relevant information from databases and projects it onto the model grid. The method used is briefly explained hereafter and the control parameters are defined.

A complete database (GENGEO_DB) is provided with the software distribution. This database is valid for use in the mesoscale modeling over Canada but is too coarse for microscale modeling. Users will therefore have to provide their own geophysical databases for the topography and the vegetation. For this reason, the required content and format for this data is also described in this section.

How Does GenGeo work?

GenGeo extracts from the geophysical databases the information needed to define the geophysical fields in the grid cells of the domain of interest. The resolution of the databases is expected to be higher than the model grid resolution. The database can be broken up into a maximum of 5 directories for each geophysical field. Each directory can contain one or several files in the standard FST format and each file can contain several records. For each field, GenGeo successively checks all the records of all the files in all the directories. If the domain is found to be intersected by a record, GenGeo extracts the information from the source grid of this record and projects it, using an aggregation method, onto the intersected portion of the destination grid. The process ends when the domain is completely covered.

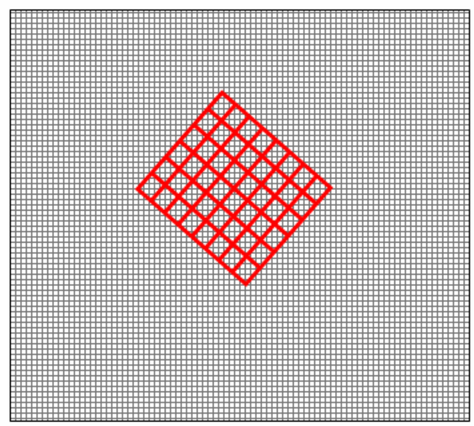
The GENGEO_DB database provided with the software distribution is actually a merger of several databases from different sources with different coverage and different resolutions. The order these databases are inspected is defined within the software, with the most accurate ones for Canada being consulted first.

If the user provides his own databases for the topography and the vegetation, it will be assumed that these databases can cover completely the domain of interest. These databases can be organized in several directories which will be inspected in alphabetical order.

GenGeo Parameters

Aggregation

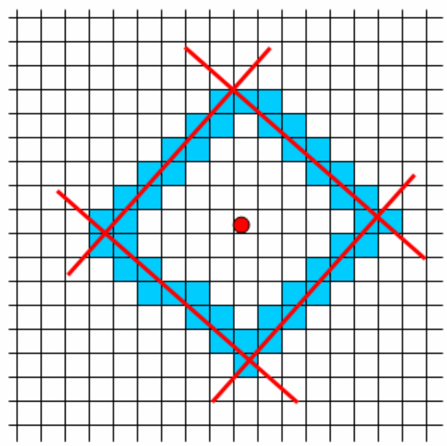
GenGeo extracts the relevant terrain information from a high-resolution, wide-coverage database and computes the terrain information in each cell of the limited area model lower resolution grid.



High resolution grid of the geophysical database (black) compared to the lower resolution grid of the model (red)

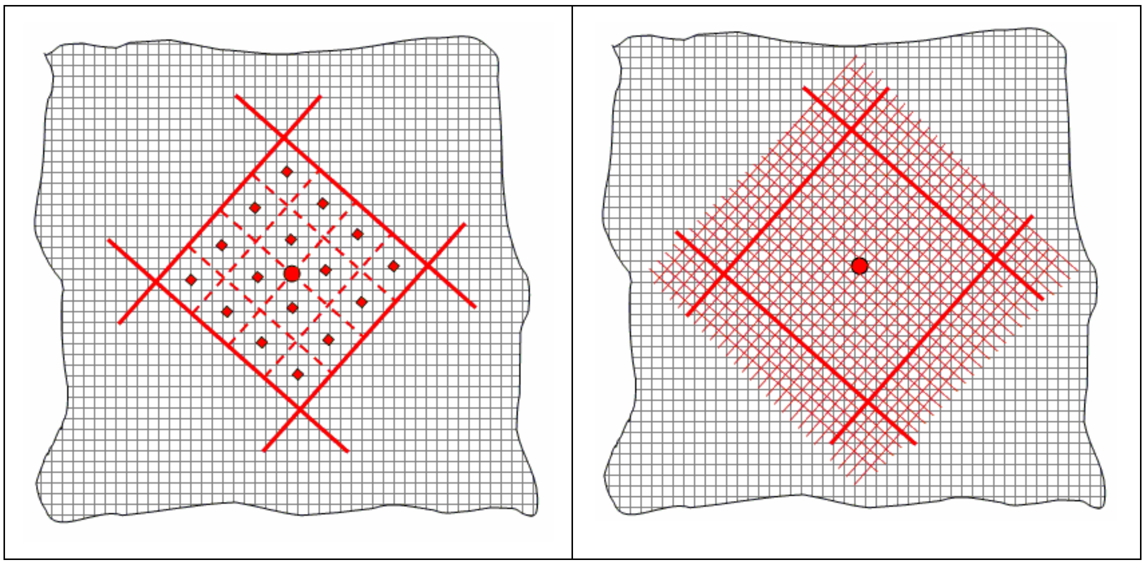
In general, one cell of the destination grid (the model grid) includes several cells of the source grid (the database grid). For the following explanations, let **ΔSRC** represent the area of the source grid cells and **ΔDST** represent the area of the destination grid cells.

The most direct method to calculate the value of a geophysical field in a cell of the destination grid would be to average the corresponding field values in the source grid cells included (completely or partially) within the destination grid cell. This method may be useful if the ratio ΔDST / ΔSRC is large (≥ 100). In other cases, the error can be significant because of the relatively large number of source grid cells being cut by the destination cell border.



The method used by GenGeo is an oversampling method consisting of splitting each cell of the destination grid into a number of smaller sub-cells whose size is similar to the source grid cell size. In each cell of the destination grid, the grid resulting from the splitting is superimposed on the source grid. The field value in each sub-cell is then obtained from the source grid using a nearest-neighbor approach. Finally, the field value in the destination grid cell results from an aggregation (an equal weight average) of all the sub-cells' values. This method performs well even if the ratio ΔDST / ΔSRC is low (~10).

In the following examples, let **OVFAC** represent the **oversampling factor**, i.e. the square root of the number of sub-cells into which each destination grid cell is divided.



Oversampling method: splitting of each cell of the destination grid in a number of smaller cells. OVFAC = 4 in the left example. The right example, with a greater value of OVFAC, is preferable because the sub-cells are of approximately the same size as the source grid cells.

By default, in order to achieve high accuracy, OVFAC is set to the square root of ΔDST / ΔSRC. In practice, OVFAC is constrained between a minimum (OVFMIN) and a maximum value (OVFMAX). These are the **Oversampling factor Min/Max** parameters.

The different **AggregType options** indicate what value of OVFAC is chosen when ΔDST / ΔSRC lies outside the bounds of the Min and Max parameters:

- AggregType = auto
  - ΔDST / ΔSRC > OVFMAX → OVFAC = OVFMAX
  - ΔDST / ΔSRC < OVFMAX → OVFAC = Max(OVFMIN, ΔDST / ΔSRC)
- AggregType = automin
  - ΔDST / ΔSRC > OVFMAX → OVFAC = OVFMIN

- ∆DST / ∆SRC < OVFMAX → OVFAC = Max(OVFMIN, ∆DST / ∆SRC)

- AggregType = oversamp
  - ∆DST / ∆SRC > OVFMAX → OVFAC = Max(OVFMAX,3)
  - ∆DST / ∆SRC < OVFMAX → OVFAC = Max(∆DST / ∆SRC,3)

The user defined OVFMIN value is not used in this last case. In this case, OVFMIN = 3 is hard-coded.

Recommended aggregation settings:

AggregType = auto, OVFMIN = 10 and OVFMAX = 20 are generally recommended.

Note: For the topography, OVFMIN cannot be greater than 10. This is a hard-coded limit.

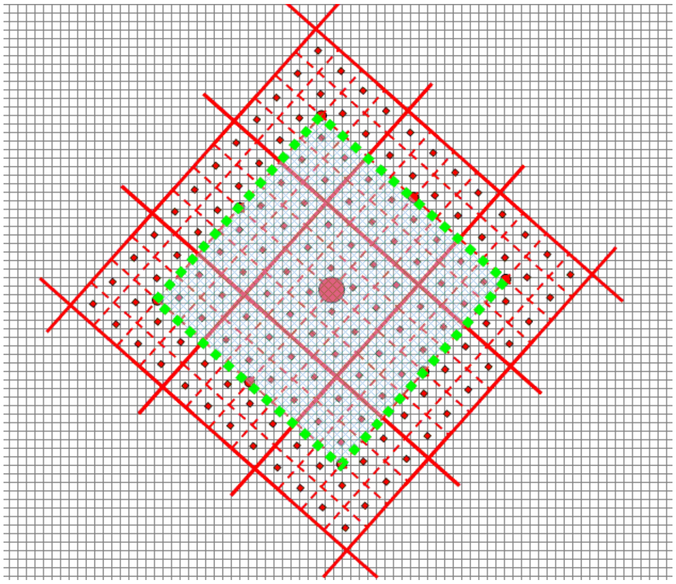
Filters

Three types of filter are available: **None**, **Aggreg** and **Mean**.

With **None**, no filter is applied. The field value in each cell of the destination grid is directly obtained from the aggregation method described above.

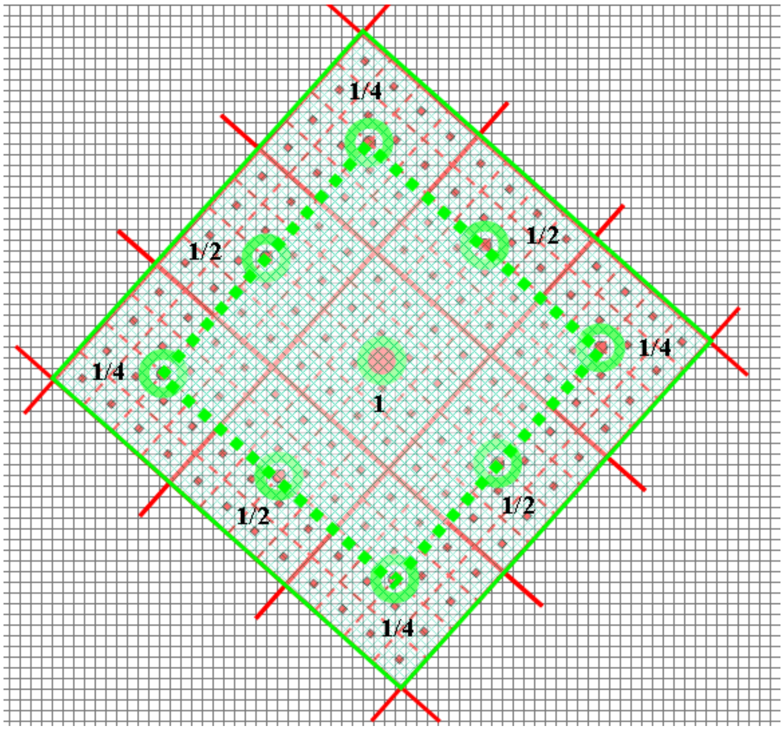
With **Aggreg** and **Mean,** a filter is applied. This means that the field value in each cell is obtained from information contained within the cell and within the neighbouring cells. The width of the filter (that is, the width of the region around the cell center that provides the information) is determined by the **NDX** parameter.

- Filter Type = Aggreg



Filter Type = Aggreg. The values in the sub-cell included in a square with sides equal to NDX × ∆DST (NDX = 2 in this example) are aggregated

- Filter Type = Mean



Filter Type = Mean. The values in the cells whose center lies within (NDX -1) from the cell center of interest are averaged using weights measuring the portion of the cell included in the central square with sides equal to NDX × ΔDST (NDX = 2 in this example).

The Aggreg and Mean types of filters are also represented in the figure below for a 1D case and 3 values of NDX. If NDX is odd, then the two filters are in fact identical. But, if NDX is even, then the Mean filter is larger than the Aggreg filter and will produce a larger diffusion of the fields. The figures below represent a cross-section of the grid, with the node at the center of the image.

NDX = 2

<table>
<tr><td>Aggreg</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Mean</td><td colspan="4"></td><td colspan="4">1/2</td><td colspan="4">1</td><td colspan="4">1/2</td><td colspan="4"></td></tr>
</table>

NDX = 3

<table>
<tr><td>Aggreg</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Mean</td><td colspan="4"></td><td colspan="4">1</td><td colspan="4">1</td><td colspan="4">1</td><td colspan="4"></td></tr>
</table>

NDX = 4

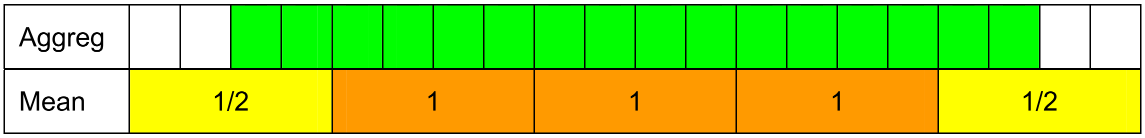


Illustration of the Aggreg and Mean filters for a 1D example with OVFAC = 4 and 3 different values of NDX.

Recommended settings:

It is recommended that you keep the default values of the parameters, which generally provide the best results: Aggreg type filter for the Topography with NDX=2, no filter applied to the Vegetation, Water/Land Mask and Soil data.

Other parameters

- **Verbose**: Level of verbosity. The higher the value, the more information is produced.

Verbose	Information
0	Quiet / no information
1	Minimum
2	Mean
3	Maximum
4	Debugging

The Geophysical Databases

The geophysical databases' content is described in this section.

Required data

GenGeo expects to find the following variables in the databases:

- Land Sea Mask

  Gives the percentage [0-100] of land per grid point. MG

- Topography [DEM]

  Mean height [m] of the ground on the grid point tile. ME

- Vegetation Index

  Main vegetation index (RPN/CMC classification) [1-26] on the grid point VG. Each grid cell is covered by one of the following classes:

Index	Description
1	Water
2	Ice
3	Inland Lake
4	Evergreen needleleaf tree
5	Evergreen broadleaf tree
6	Deciduous needleleaf tree
7	Deciduous broadleaf tree
8	Tropical broadleaf tree
9	Drought deciduous tree
10	Evergreen broadleaf shrub
11	Deciduous shrub
12	Thorn shrub
13	Short grass and forbs

Index	Description
14	Long grass
15	Arable
16	Rice
17	Sugar
18	Maize
19	Cotton
20	Irrigated crop
21	Urban
22	Tundra
23	Swamp
24	Soil
25	Mixed wood forest[1]
26	Transitional forest[2]

- Sand

  Gives the % [0-100] of Sand per grid point on 5 layers of the ground. SB

- Clay

  Gives the % [0-100] of Clay per grid point on 5 layers of the ground. AG

[1] Forest in which 26% to 75% of the canopy is coniferous. May include patches of grassland, bog, marsh or fen.

[2] From 10% to less than 50% of the area is in forest land. Scattered coniferous or broadleaved trees and broadleaved shrubs.

The GENGEO_DB Database

The GENGEO_DB database provided with the AnemoScope software distribution is made of several databases from varying sources and contains all the required geophysical fields. This database is adequate to produce the geophysical data for a mesoscale simulation (with a resolution greater than 1 km), but it is too coarse for the microscale requirements (requiring a resolution of about 100 m).

The database is in a latitude/longitude coordinate system. Its content is described below. The entries are in the same order. By default, GenGeo processes the data from the most to the least accurate sources.

Topography (ME)	
Me_usgs2002	1/60 degrees resolution (~900 m at 60˚N) – Data from the US Geological Survey agency– covers the whole earth but for efficiency the large water surfaces are removed; the data are uniform there and can be taken from a lower resolution database.
Me_us	1/6 degrees resolution (~18 km at 60˚N) – Data from the US Navy – covers the whole earth in 6 sectors.

Land/sea mask (MG)	
Mg_usgs2002	Same coverage as Me_usgs2002
Mg_us	Same coverage as Me_us

Vegetation (VG)	
Vg_usgs2002	Same coverage as Me_usgs2002
Vg_ccrn	1 degree resolution – Data from CCRN – Covers the whole earth.
Vg_sask	1/60 degrees resolution (~900 m at 60˚N)- Data from Genesis. NOT PROCESSED BY DEFAULT.

Clay (AG)	
clay_argc	1/50 degrees resolution (aggregation of 1 degree tiles, not all tiles having data refined to the 1/50 degrees resolution) – Data from Agriculture Canada - covers Canada- 198 fields AG1 to 198: AG1-38 = layer 1, AG39-78 = layer 2, AG79-118 = layer 3, AG119-158 = layer 4, AG159-198 = layer 5.
clay_usda	1/100 degrees resolution – Data from Sate Oil Geo Data – covers the USA, excepted Hawaii and Alaska.
clay_fao	1/50 degrees resolution – Data from FAO – Covers the whole earth – 75 fields AG1 to 75, 15 tiles for each layer.
clay_ccrn	Identical to Vg_ccrn. Five fields AG1 to 5 corresponding to the 5 layers but all are actually identical.

Sand (SB)	
sand_argc	Identical to clay_argc
sand_usda	Identical to clay_usda
sand_fao	Identical to clay_fao
sand_ccrn	Identical to sand_ccrn

General Database Format

- File Format: RPN STD Files (.fst)
- Grid Specification
  - Any RPN STD accepted projection [L,E,N,S...]
  - Encoded as a Z or # grid [using the ? and ^^ records for grid description1)]
- Encoding
  - The grid description records (?, ^^) should be real values encoded with datyp=1 or 5 and npak=-32
  - The field records should be Integer values encoded with datyp=4 and npak=-16
- Multi level fields (as AG, SB) should have their level specified in the ip3 record tag, not encoded (plane number from 1 on).
- Missing values: when your data do not fill the whole rectangular area covered by the grid description, points with no data should have a value of -99

(For more information on RPN STD Files (FST format) see the Document *An Introduction to RPN Standard Files*)

User's Database

Users have the option to use their own databases for the topography and for the vegetation. This is actually necessary for accurate wind modeling at the microscale level, because the GENGEO_DB is not precise enough.

As explained in the next section, the Clay and Sand data are not used in the current version of the software and there is no need for users to provide their own data for these quantities.

The user's databases for the topography and the vegetation should comply with the General Database Format and should be organized in various directories containing files in the RPN standard FST format. The easiest way of producing an FST file is to import the data into AnemoScope in any of the supported formats (such as ArcInfo Shape File, MapInfo Interchange Format, etc.) and to export them to FST format using the **Save as FST**  button .

As far as the meso- and microscale wind models integrated into AnemoScope are concerned, the vegetation only has an effect on the wind through the rugosity it introduces at the ground level. Each of the 26 classes of vegetation defined above has the associated length of rugosity specified below (as the logarithm of the rugosity is calculated, the rugosity is never set to exactly 0 but at minimum to 0.001).

The vegetation database provided by the user should comply with this classification of the vegetation, or at least with the classification by associated roughness length. In any case, vegetation types 1 and 3 are used to create a land/water mask and must be of Water or Inland Lake type.

Index	Description	Z	Index	Description	Z
1	Water	0.001	14	Long grass	0.08
2	Ice	0.001	15	Arable	0.08
3	Inland Lake	0.001	16	Rice	0.08
4	Evergreen needleleaf tree	1.5	17	Sugar	0.35
5	Evergreen broadleaf tree	3.5	18	Maize	0.25
6	Deciduous needleleaf tree	1.0	19	Cotton	0.1
7	Deciduous broadleaf tree	2.0	20	Irrigated crop	0.08
8	Tropical broadleaf tree	3.0	21	Urban	1.35
9	Drought deciduous tree	0.8	22	Tundra	0.01
10	Evergreen broadleaf shrub	0.05	23	Swamp	0.05
11	Deciduous shrub	0.15	24	Soil	0.05
12	Thorn shrub	0.15	25	Mixed wood forest	1.5
13	Short grass and forbs	0.02	26	Transitional forest	0.05

The GenGeo Outputs

The GenGeo output file contains the following fields:

Field name	Content	Method of computing
MG0	Land-Sea Mask [0-1] (unfiltered)	Extracted and aggregated data from the MG database
VF (ip1:1174 to 1199)	Vegetation fraction (26 classes - k=1,26) [0-1]	Extracted and aggregated data from the VG database
VG	Vegetation index of the main vegetation class in grid point [1-26]	Index of Max(VF[1,26])
GA	Fraction of the 2nd class of vegetation (VF index 2), i.e. the ice cover [0-1]	VF(2)
ZV	Part of the roughness Z0 due to the vegetation (weighted average of the roughness lengths due to each class of vegetation, <ZVEG>)	Roughness length computation based on VF and MG0
ZVFX	Part of the roughness Z0 due to the vegetation (exponential of the weighted average of the logarithm of the roughness lengths due to each class of vegetation, exp[<Ln(ZVEG)>])	See ZV.
MT	Topography (unfiltered) [m]	Extracted and aggregated data from the ME database
ME	Topography (filtered) [m]	Extracted, aggregated and filtered data from the ME database

LH	Launching height (variance of the subgrid scale orography H)	Small scale ME topography from the database and aggregated, unfiltered MT topography
Y7	(dH/dx)^2 mean over a tile	See LH
Y8	(dH/dy)^2 mean over a tile	See LH
Y9	(dH/dx)(dH/dy) mean over a tile	See LH
J1 (ip1:1195 to 1199)	Sand Fraction for the 5 soil layers [1-100]	Extracted and aggregated data from the SB database
J2 (ip1:1195 to 1199)	Clay Fraction for the 5 soil layers [1-100]	Extracted and aggregated data from the AG database
MG	Land-Sea Mask [0-1] (filtered/cleaned)	Extracted, aggregated and filtered data from the MG database
Z0	Roughness length [m]	Roughness length computation based on VF, MG0 and on the subgrid scale orography H
ZP	Logarithm of the roughness length [ln(m)]	See Z0.
LU	Land Use index	Index of the vegetation class of which the roughness length is the closest to ZV

GenGeo Interface With The Other Modules of AnemoScope

Input:

A regular grid has to be provided for the domain of interest.

Output:

The table above lists the GenGeo outputs and for each explains how they are computed from the data found in the geophysical database. In actuality, just a few of these outputs are used by the mesoscale (MC2) and microscale (MMC) models. The other outputs are read by MC2 but not used in the present EOLE running mode. They were kept in the present version of AnemoScope in order to preserve the capabilities of MC2 as a Numerical Weather Prediction model and allow further developments of AnemoScope towards a wind forecasting software.

In particular, the Sand and Clay data that describe the soil composition are required by the physical surface model of MC2 to evaluate the water and heat transfer properties of the surface. But this surface model is not used in the current EOLE mode of running MC2 (the surface is considered as adiabatic or isothermal and with no water flux) and the Sand and Clay data are not used.

Interface with MC2 (mesoscale model):

The following fields are used by MC2

- ME meso
- Z0 meso

Interface with WEStats (mesoscale wind statistics):

The following fields are used by WEStats

- ME meso
- Z0 meso
- LU meso
- MG meso

Interface with MMC (meso/micro scale coupler and microscale model):

The following fields are used by MMC

- ME micro
- VF micro
- MG micro
- LU micro
- LU meso
- ME meso

The GenGeo namelist file

An example of the GenGeo namelist file is shown below. Most of the parameters are editable through the GenGeo GUI and are described in the User's Guide

`!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!`	
`! GenGeo305 - namelist parameter file`	
`! Default Settings:`	
`!------------------------------------------------------------`	
`&GENGEO_CFGS`	
`gridfile = 'C:\CHC\AnemoScope\meso\grid-meso_ME.fst'`	Grid File (tape 1)
`outfile = ' C:\CHC\AnemoScope\meso\geo-meso.fst'`	Output File (Geophy)
`basedir = 'D:\MC2_data\GENGEO_DB'`	Default Database Directory
`db_topo_dir = ' C:\CHC\AnemoScope\TOPO\mytopo_db'`	Topo Dir
`db_veg_dir = ' C:\CHC\AnemoScope\VEGE\myvege_db'`	Veg Dir
`aggregtyp = 'auto'`	Aggreg Type
`ovfmin = 3`	Min Oversamp. Factor
`ovfmax = 20`	Max Oversamp. Factor
`fullscan = .False.`	Described below
`topofilt = 'aggreg'`	Topo Filter Type
`vegfilt = 'none'`	Veg Filter Type
`maskfilt = 'none'`	Mask Filter Type
`soilfilt = 'none'`	Soil Filter Type

`topofiltndx = 2.000000`	Topo Filter NDX
`vegfiltndx = 2.000000`	Veg Filter NDX
`maskfiltndx = 2.000000`	Mask Filter NDX
`soilfiltndx = 2.000000`	Soil Filter NDX
`verbose = 4`	Verbosity Level
`debug = .False.`	Debug Mode Flag
`/`	End of File

Full Scan

This parameter defines the way the records of the geophysical database that are found to intersect with the computational domain are explored. With `Full Scan=.False.` (which is the default setting), indices defining the region of the record that could possibly intersect the domain are computed and only this region is checked. With `Full Scan=.True.` (which can only be set by modifying the default GenGeo namelist file), the complete record is checked and the position of each point is tested to determine whether or not it lies within the computational domain. This option can be useful for debugging purpose when GenGeo produces bad results with patches of undefined values.

To Learn More About GenGeo

Further technical information on GenGeo can be found at

http://collaboration.cmc.ec.gc.ca/science/rpn.comm/wiki/doku.php?id=gengeo

The Climate Database

Method of Design

The climate database provided with AnemoScope was generated by classifying long-term meteorological data.

The 3D representation of atmospheric state available every six hours (for 43 years, from 1958 until 2000) at a resolution of 2.5 degrees over the globe, known as NCAR/NCEP reanalysis (Kalnay et al., 1996), was chosen as basic database. The elements of this database are categorized (Frank et al., 2001) using three parameters: the geostrophic wind[1] direction at 0 m (16 equal sectors), the geostrophic wind speed at 0 m (9 classes 2 m/s wide from 0 to 18 m/s and 5 classes 4 m/s wide from 18 to 38 m/s which gives all together 14 classes) and the sign of 0-1500 m geostrophic wind shear (positive or negative). In total, 432 categories (16x13x2+16 as no shear distinction is done for wind speeds below 2 m/s) called climate states are defined.

Each measurement of the geostrophic wind vector at 0 m is attributed to a particular climate state. For each database grid point, the classification procedure allows the determination of the climate states that occurred over the analyzed period, as well as the number of occurrences, which defines the frequency of occurrence. This information is necessary to initialize the mesoscale model and to do the post-processing.

Limitations

The climate database summarizes the climate states observed during the 1953-2000 period and does not reflect more recent climate changes. In order to study the effect of these climate changes, it would be necessary to build a new climate database including more recent measurements.

Using this climate database, the AnemoScope method allows the production of annual statistics. Four additional databases are included with AnemoScope, dividing the data into four three-month periods, and can be used to derive wind energy maps specific to particular seasons of the year.

Area Covered

The area covered by the database is shown in the picture below. The locations described by climate tables are located every 2.5 degrees:

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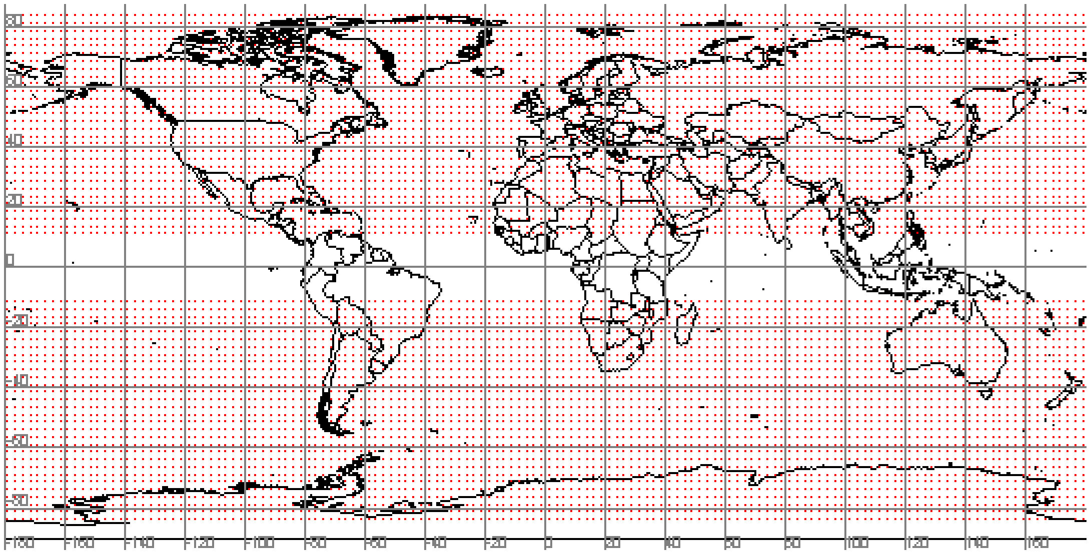
[1] The geostrophic wind is the theoretical wind which results from the equilibrium between the horizontal pressure force and the horizontal component of the Coriolis force. Only these forces are considered to be acting on the air.

- from 11.25 to 83.75 degrees latitude N, and 11.25 to 83.75 degrees S



Available climate tables in the climate database.

Database Organization:

The database is organized in 60 directories numbered 3 to 32, and 41 to 70, with each directory corresponding to one discrete zone of latitude: 1→ 83.75 S, 2→ 81.25 S … 32 → 11.25 S, and 40→ 11.25 N, 41→ 13.75 N … 70 → 83.75 N

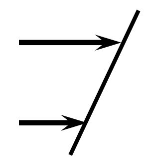
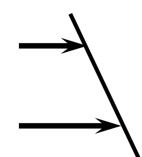
Each directory contain 144 files named ##**_table.ef** where ## is a number from 1 to 144 and corresponds to the longitude E (1 → 1.25, 2→ 3.75., … 144 → 358.75)

Content of the climate tables

The climate tables are ASCII files consisting of:

- A header containing the values of I, J, Latitude, and Longitude – where I is the directory number corresponding to the latitude and J is the table number corresponding to the longitude.
- A table listing the parameters of each climate state encountered at the climate station. The various parameters are defined in the table below. The coordinate system used to define the velocity components and the velocity direction is the one associated with the 60˚N polar plane of projection.

Column	**Definition**	**Values / Units**
Id	Names of the climate states Example: can1203237m	**can1***###S** *** : rounded value of dd.

		### : rounded value of uv×10. **S**: m if shear=(+1), p if shear=(-1)
dd	Direction of the geostrophic wind at sea level, i.e angle of the velocity vector (uu1,vv1) with the x-axis.	degrees
uv	Intensity of the geostrophic wind at sea level. Modulus of the (uu1,vv1) vector	m/s
shear	Sign of the geostrophic wind shear between 0 and 1500 m above sea level	+1 if the wind speed at 1500 m is greater than the wind speed at 0 m  -1 otherwise 
Freq	Frequency of occurrence of the climate state, i.e. number of occurrence of the climate state divided by the total number of records for the climate station.	Percentage. The sum of the Freq column over all the climate states is 100 %.
weight	Freq × uv – frequency weighted by the geostrophic wind speed at sea level.	
eweight	Freq × uv^3 – frequency weighted by the available geostrophic wind power at sea level.	
uu1	x-component of the geostrophic wind velocity at sea level	m/s
uu2	x-component of the geostrophic wind velocity at 1500m above sea level	m/s
uu3	x-component of the geostrophic wind velocity at 3000m above sea level	m/s

uu4	x-component of the geostrophic wind velocity at 5500m above sea level	m/s
vv1	y-component of the geostrophic wind velocity at sea level	m/s
vv2	y-component of the geostrophic wind velocity at 1500m above sea level	m/s
vv3	y-component of the geostrophic wind velocity at 3000m above sea level	m/s
vv4	y-component of the geostrophic wind velocity at 5500m above sea level	m/s
tt1	Temperature at sea level	Kelvin
tt2	Temperature at 1500m above sea level	Kelvin
tt3	Temperature at 3000m above sea level	Kelvin
tt4	Temperature at 5500m above sea level	Kelvin
status	Flag	*Not used*

In the table, the climate states are ordered by decreasing *eweight* value.

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MC2: The Atmospheric Model Used for the Mesoscale Wind Simulations

The MC2 software is a highly sophisticated operational Numerical Weather Prediction model. Within AnemoScope, it is used in a specific mode—the EOLE mode—adapted to the statistical-dynamical downscaling method. Both the general features of MC2 and its EOLE mode of use are described in this section.

What is MC2?

General Description

The Mesoscale Compressible Community [MC2] model is a state-of-the-art atmospheric model widely used by Environment Canada, Canadian universities, and others worldwide. It was developed for mesoscale modeling research and operational Numerical Weather Prediction [Benoît et al. 2002].

The model is an extension of the fully compressible limited area model developed by Tanguay, Robert and Laprise [Tanguay et al. 1990; Laprise et al. 1997] in the mid-1980's at the Meteorological Service of Canada, Recherche en Prévision Numérique, and Université du Québec à Montréal (UQAM). The numerical basis of the model is a sophisticated semi-Lagrangian, semi-implicit time stepping procedure, which allows for comparatively large time steps despite the presence of rapidly propagating sound waves [Tanguay et al. 1990; Benoit et al. 1997a]. The model's dynamic core is completed by a full set of physical parameterizations.

For efficiency, MC2 was designed to run on massively parallel computers using the Message Passing interface [MPI], allowing it to run on simple Linux PCs as well as supercomputers. MC2 was ported to Windows XP so that it could be integrated into AnemoScope,.

The model has been extensively tested. Its small-scale prediction capabilities were evaluated as part of the Comparison of Mesoscale Predictions and Research Experiments (COMPARE, see Gyakum et al. 1995), as well as during the Mesoscale Alpine Programme [MAP] in Europe. In addition, classical orographic flow regimes were examined with MC2 (Pinty et al. 1995), demonstrating the excellent fluid mechanics properties of the model, including its representation of momentum flux.

In the 1990's, development began on a distributed-memory parallel version of MC2. Its construction was intended not only as a proof-of-concept for the Canadian atmosphere modeling community, but also to satisfy the increasing computational demands of high-resolution studies in atmospheric turbulence and planetary boundary layer parameterization. The massively parallel implementation of MC2 has been developed at MSC/RPN based on the MSG toolkit developed for the P_SPARSLIB library of parallel iterative solvers (Thomas et al. 1997, 1998). MC2 can use a domain-decomposition as well as a multi-tasking approach (or a combination of the two), to solve a given forecast 3D grid.

The high-resolution MC2 model allows exciting new venues in the explicit numerical simulation of moist convection. It is equipped with a sophisticated microphysics package (KY scheme, Kong and Yau 1997). The need for such refined schemes, with their so-called ice-phase microphysics, was clearly demonstrated for topographically forced flow (e.g. Benoit et al. 1997b). Currently, the MC2 model is one of the very few high-resolution models available which allows—on present hardware configurations—real-time quasi-operational forecasting applications. Such real-time applications require highly efficient code (to ensure rapid integration of the governing equations), and implementation on a massively parallel supercomputer, as well as an optimized and partly dedicated hardware configuration.

MC2 Dynamic Core Features

- Fully compressible, non hydrostatic Euler equations [Tanguay et al. 1990; Benoit et al. 1997a]. MC2 can simulate, with the same code, meteorological events ranging in scale from cyclones and squall lines to tornadoes and turbulent plumes.
- Fully 3D semi-Lagrangian advection and semi-implicit time differencing formulation [with variable basic state] can use comparatively large time steps despite the presence of rapidly propagating sound waves.
- Optional Eulerian advection
- Staggered grids: C horizontal and Tokioka B vertical grid.
- Hybrid Terrain-Following Vertical coordinates [SLEVE variation of Gal-Chen, Shaer et al. 2002].
- Generalized minimal residual (GMRES) Krylov iterative solver (Thomas et al. 1998), 1D Jacobi, and 3D ADI line relaxation pre-conditioner.
- Fully distributed and optimized for speed on vector and scalar architectures.
- Limited Area Model (LAM) allows very high resolution simulation on small domains with a small number of grid points, thus allowing rapid integration.
- Open boundaries for one-way nesting implemented for semi-Lagrangian advection. MC2 is fully compliant with the Acid Test [Staniforth 1995], having the advection calculated by the driven model itself using information from outside its domain. This leads to machine precision reproducibility in one-way nesting.
- Self-Nesting Capabilities: a coarser MC2 run is used to initialize and provide lateral boundary conditions for a subsequent higher-resolution run. MC2 can cleanly achieve a very high-resolution forecast by cascading down to it.

- Davies-type lateral gravity waves absorbers.
- High order horizontal diffusion, implicit or explicit.
- Adjustable topography at startup.
- Theoretical cases [2D or 3D].
- Easy code modifications to add your own improvements or to test new schemes.
- Full CMC/RPN Physic Package [Operational and Research]:
    - Many convective schemes,
    - Several large scale condensation schemes, including 3 microphysic schemes,
    - TKE PBL,
    - Surface Scheme,
    - Solar and Infrared radiation,
    - and much more.
- Comes with ARMNLIB library, scripts and binary tools for scientific applications.
- Open Source License on LINUX platform.

The Physics Library

The RPN Physics Library consists of a set of parameterizations of the most important physical processes in the atmosphere and at the surface, and provides a unified library environment on which dynamical models can easily interface. The physical parameterizations modify the basic model variables by adding tendencies due to various physical processes. These processes are either irresolvable by the model dynamics (e.g., turbulent transfers), unresolved (e.g., deep convection, gravity wave drag), or simply missing from the basic dynamic equations (e.g., radiation, surface processes, condensation).

The unified RPN physics package has been—and is continuing to be—developed for use in the research and operational models at RPN/CMC, including the global environmental multiscale (GEM) model (Côté et al. 1998), the spectral finite-element (SEF) model (Ritchie and Beaudoin 1994), and the mesoscale compressible community (MC2) model (Benoit et al. 1997).

Much effort has been put into incorporating a detailed description of surface and boundary layer processes and realistic schemes for condensation and radiation processes. A number of aspects of the physics have been examined in various applications, such as intense orographic precipitation, summertime severe weather, polar lows, aircraft icing and explosive marine cyclogenesis (Benoit et al. 1994; Bélair et al. 1995a,b; Mailhot et al. 1996; Tremblay et al. 1996b; Huo et al. 1995). Also, model applications span a wide spectrum ranging from global-scale seasonal forecasts down to regional-scale and mesoscale systems. Therefore, for most of the physical processes, several versions of parameterization schemes are usually available for a particular process, with specific options appropriate for given temporal and spatial scales.

More recent modifications to the RPN physics package include revisions to the vertical diffusion scheme (Delage and Girard 1992; Delage 1997), revisions to the land surface processes (Mailhot et al. 1997), additions of more advanced schemes (ISBA and CLASS), improvements to the radiation package (Yu et al. 1997), and modifications to the gravity wave drag (McLandress and McFarlane 1993). New options for the condensation processes are also available: versions of so-called Kuo-symmetric, relaxed Arakawa-Schubert (Moorthi and Suarez 1992) and Kain-Fritsch (1990) cumulus parameterization schemes, and explicit cloudwater schemes with mixed phases (Tremblay et al. 1996a) and detailed microphysics (Kong and Yau 1997).

More information about the Physics Library is available at:

http://collaboration.cmc.ec.gc.ca/science/rpn.comm/wiki/doku.php?id=rpn_physic_package

MC2 in EOLE Mode

In AnemoScope, MC2 is used to obtain steady-state mesoscale wind solutions for each of the climate states described in the climate table of the selected climate station. This use corresponds to a particular setting of the model which is described in this section.

Fast Convergence

Due to the large number (~350) of mesoscale simulations that have to be performed in order to obtain significant mesoscale wind statistics, a fast convergence of the simulations is needed. The simulation time should be long enough for the atmosphere to reach a steady state, but as short as possible so as to prevent the development of a transitional weather situation. The convergence of the model towards the steady state depends mainly on the air stratification, model resolution, and the initial state at which the model starts.

The simplified physics scheme without radiation, condensation, or diurnal cycle ensures a simpler air stratification (near neutral state close to ground) and is used in order to accelerate model convergence to the final state. The initialization procedure is also crucial. It should respect the major physical equilibria and be as close as possible to the final solution.

The choice of the model resolution and domain size are constrained by the modeling capabilities and by the limits of validity of the physical hypothesis. The time step setting is also very important. The time step must minimize the number of time steps required to reach convergence while preserving the stability of the simulation. The specific procedure of mountain growth also allows a smoother initialization and therefore a better convergence.

Experiments with a 5km resolution for various 500 by 500 km^2 regions of Canada show that a six-hour physical simulation time would be enough for most climate classes to reach a steady state. In practice, a simulation time of 9 hours is recommended. With a time step of 2 minutes, a 9 hour simulation requires 270 time steps.

Simplified Physics

In the EOLE mode, MC2 is run with a simplified physics model. This choice is ideal for the sake of efficiency [simpler air stratification (near neutral state close to ground)] and convergence. Some simplifications are fully justified. For example, the atmosphere is considered to be dry (no humidity) since the condensation effect on the surface wind is relatively small.

Other simplifications introduce significant limitations. For example, the diurnal cycle and the sea/lake breeze and mountain/valley (kata- and anabatic) circulation (due to heating/cooling effects) cannot be simulated. Heat sources and sinks generally prevent equilibrium flows.

The simplifications are also justified by the fact that the method aims to produce annual statistics and that some physical effects (like radiation) have great variability over the course of a year. The use of additional physics would require additional input data and increase the complexity of the method. A kind of climatology of the geophysical fields would have to be defined and the climate state classification would have to not only account for the states of the atmosphere but also for the states of the terrain.

In spite of these limitations, the Canadian Wind Energy Atlas (http://www.windatlas.ca) was successfully produced using the same method.

Initialization

For each climate state, the mesoscale model simulation is initialized with the atmospheric wind speed and temperature profiles corresponding to the climate state. The model equations are then integrated over time from this initial state and the atmospheric fields move to an equilibrium steady-state solution. During the integration, the boundary conditions are kept constant.

The initialization is performed to preserve the equilibrium of the atmosphere:

- the geostrophic balance between the horizontal pressure force and the horizontal component of the Coriolis force, which is a valid first order approximation for the free atmosphere. The geostrophic wind results from this equilibrium and is defined by

$$Vg = -1/(\rho\ fc)\ \nabla p \wedge k.$$

- the hydrostatic approximation by which all the vertical accelerations are considered to be small and the vertical equation of motion simply relates the vertical pressure gradient to the buoyancy force

$$\delta p/\delta z = -\ \rho\ g.$$

To initialize the model, the vertical profiles of temperature and geostrophic wind from the classification (at 4 heights: 0, 1500, 3000, and 5500 m above sea level) are put at the center of the model domain. They are interpolated to the model levels (28 levels by default) using a cubic interpolation up to 5500 m. Above this height, the temperature profiles are kept constant and the wind profiles gradually set to zero.

Using the temperature profile at the center of the domain, a pressure profile is calculated by numerically integrating the hydrostatic equation. The full distribution of pressure is then determined by numerically integrating the geostrophic balance equations in the X- and Y-directions respectively, starting from the center and moving towards the edges of the domain, assuming uniformity of the geostrophic wind throughout. Finally, the temperature profiles away from the center are obtained using the hydrostatic equation again. We note that these temperature profiles must no longer be identical to the original ones obtained from the classification except at the center, since it is impossible to maintain strict hydrostatic and geostrophic balance in the large numerical model domain with uniform temperature and geostrophic wind profiles. The temperature profiles calculated this way, though slightly different (relative difference < 20%) from the original ones, offer the advantage of satisfying the geostrophic balance in the model. This is an important factor that limits the horizontal distance between model edge and center.

In the planetary boundary layer where the air flow is ageostrophic, the wind profiles are modified to account for the influence of friction originating from the surface. The wind speed is reduced by 60% and a derivation of the wind direction by 40 degrees to its left facing downstream is applied.

The three-dimensional atmospheric state is established and ready for the model integration. The model integration will modify this large scale initialization and adjust the atmospheric state to the local conditions of topography and ground friction in full dynamical concordance with the Navier-Stokes equations.

Domain Size and Grid Resolution

As explained above, the weather situation is initially simplified to a single profile of atmospheric state (temperature, wind, etc.) for the whole region. The size of the region should be large enough for a weather situation to be determined, but otherwise as small as possible, so as not to allow the development of a transitional situation during the model simulation. A domain extent ranging from 100x100 km to 800x800 km is optimal for this application.

The recommended range for the grid resolution (Delta Meso) is

$$1\text{km} < \text{Delta Meso} < 15 \text{ km}.$$

The lower bound is due to the limitation of the physical modelling. For larger grid cells, the mesoscale modeling will not be precise enough for the microscale model to exploit adequately its results.

Considering that 21 cells on the edge of the mesoscale domain are used to apply the boundary conditions and cannot be used in the analysis, it is recommended that the number of cells of the horizontal grid is not below 84 (21+42+21) in each direction. This leaves a sufficient central region over which the flow features can develop. With a 1km resolution, the minimum mesoscale domain is 84x84 km.

Time Step Restriction for Stability

The time step constraint is based on the so-called Courant-Friedrich-Levy (CFL) number defined by

$$CFL = U \text{ Delta } T / \text{ Delta } G$$

where U and Delta G are measures of the wind speed and the grid cell size, respectively. The CFL number is estimated at every grid node on the basis of the three velocity components and cell size in the three spatial directions. In order to ensure good stability, the CFL number should not exceed a value of 0.4 over the 3D domain during the simulation.

With a 5 km resolution, most of Canada can reasonably be simulated with the default parameters (step=120s, tstep = 270 for a total simulation time of 120×270 = 32400 s or 9 hours).

In principle, the time step should be adjusted according to the maximum velocity within the domain, which depends on the geostrophic wind speed (uv) specified in the climate table under consideration. In the AnemoScope process, the time step is the same for all simulations associated with the selected climate station. This means that the time step is set the same for climate conditions with a weak geostrophic wind and for climate conditions with a strong geostrophic wind. Choosing a smaller time step will ensure the stability of all of the simulations, but will be a waste of computations for most of the climate states. Choosing a larger time step will be adequate for most of the simulations but will give bad results for a few, which may affect the global statistics. The choice is not easy and results from a compromise. It may be wise to disregard the stronger geostrophic wind simulations, provided the frequency of occurrence of the corresponding climate states is very low.

For regions with steep topography, the time step must be reduced. Experiences with a 5 km resolution in the most mountainous region of Canada have shown that the following settings are appropriate to correctly control stability (in either case, the total duration is 9 hours):

- Geostrophic wind at 0m $\in$ [0,4] m/s: step = 60s, tstep = 540, Output Freq = 180
- Geostrophic wind at 0m $\in$ [4,10] m/s: step = 30s, tstep = 1080, Output Freq = 360
- Geostrophic wind at 0m $\in$ [10,18] m/s: step = 15s, tstep = 2160, Output Freq = 720
- Geostrophic wind at 0m > 18 m/s: step = 10s, tstep = 3240, Output Freq = 1080

Considering that a single time step must be selected for the whole range of geostrophic winds, a time step of 15 s may be appropriate if the highest geostrophic wind conditions have a relatively low frequency of occurrence.

Mountain Growth

In order to preserve the stability of the simulations, mountains are initially set equal to 0 m above sea level and start to grow at the first time step. The actual topography is only in place after a number of time steps (vmh_ndt) defined by the user. The recommended value for this parameter depends on the height, H, of the topography and on the time step, Delta T. This parameter should be set to produce a slow topography raising speed. In practice,

$$\text{Vtopo} = \text{H} / (\text{vmh\_ndt} \times \text{Delta\_T}) < 10 \text{ cm/s}.$$

During the mountain growth phase, the ground temperature will be adjusted to that of air in immediate contact with the ground to avoid unrealistic heat flux from the ground. When the mountains reach their steady state, the ground temperature is kept constant over time to ensure a better stability and shorter integration time.

MC2 Outputs

For each simulation, the following files are generated under the run directory. The example is given for the climate state named can1203237m; the simulation was run for Total Steps = 270 time steps with an Output Freq.=90.

can1203237m:

can1203237m_mc2dm.log	log file of the simulation
can1203237m_mc2ntr.log	log file of the preprocessing
output/	results directory
process/	input and intermediate files directory
run.py	python script that launches the simulation
status.dot	status file of the simulation.

The contents of status.dot should look as follows after a successful run:

```
_status=ABORT;_startstep=0000000000;
_endstep=0000000270;
_status-ED;
```

can1203237m/output:

This directory contains a collection of FST output files. One file is written for each of the dynamic component and the physical component of the model after each time step, starting at step=0. The step number is recorded at the end of the file name.

dm1998010100-00-00_000000p.fst	pm1998010100-00-00_000000p.fst
dm1998010100-00-00_000090p.fst	pm1998010100-00-00_000090p.fst
dm1998010100-00-00_000180p.fst	pm1998010100-00-00_000180p.fst
dm1998010100-00-00_000270p.fst	pm1998010100-00-00_000270p.fst

The dm*** files are produced by the dynamic component of the model. Each file contains the following fields:

- ME Topography
- TT Temperature
- P0 Pressure at the ground
- UU Wind velocity component along the x axis
- VV Wind velocity component along the y axis
- WZ Vertical wind velocity component

The pm*** files are produced by the physical component of the model. Each file contains the following fields:

- ME Topography
- 2B Rugosity

The dm*** and the pm*** files are not defined on the same grid. The pm*** files' grid is a subset of the dm*** grid, with 3 border cells removed around the perimeter.

can1203237m/process:

This directory contains files that are used by the MC2 model during simulations. Not all of the files are used by the model in EOLE mode, and are not needed by AnemoScope.

00-00/	Empty Directory
pilot/	
20010523.180000	dummy pilot file-- Not used
bm20010523.180000_000_000	Initial condition. Binary file
bm20010524.000000_e	East boundary conditions
bm20010524.000000_n	North boundary conditions
bm20010524.000000_s	South boundary conditions
bm20010524.000000_w	West boundary confitions
climato.fst	Dummy climatology file—not used
geophy.bin	Mesoscale geophysical data file in binary format
geophy.fst	Mesoscale geophysical data file in fst format prepared with GenGeo
helsol	Helmoltz solver data
liste_inputfiles_for_LAM	list of the pilot directory contents
model_settings.nml	namelist file of the simulation

The MC2 Namelist File

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
! MC2-EOLE namelist parameter file
! WrittenBy                 armngr2
! Application               AnemoScope
! Version                   1.0.93
! CreationDate              Thu, May 05, 2005 12:42 PM
!------------------------------------------------------------
&init_cfgs
  vraies_mtn = 2
/
&grille
  Grd_ni     = 100
  Grd_nj     = 100
  Grd_dx     = 1432.236180
  Grd_iref   = 51
  Grd_jref   = 51
  Grd_latr = 48.012030
  Grd_lonr = 275.107033
  Grd_proj_S = 'P'
  Grd_dgrw = 10.000000
/
&pil_cfgs
  Pil_runstrt_S = '20010523.180000', Pil_nesdt = 21600
  Hblen_x = 5
  gnnt = 6, grdt = 1800.0, gnnrstrt = 190, gnmtn = 1
/
&restart
  gnnls = 1
/
&pe_topo
  npex = 1, npey = 1
/
&mc2_cfgs
  hsolvpre   = 1.0e-4, precond = 'jacobi', maxite = 450, diagres =
.false.
  vmh_stime  = 0, vmh_ndt = 29
  nesmt_bgx  = 5, nesmt_bgy = 5, nesmt_ndx = 8, nesmt_ndy = 8
  gnmaphy    = 1
  gndstat    = 90, gnpstat = 90, gnstatdp = 0
  gnnls      = 1, nstepsor_d = 90, launchsor =.false.
  gndtini    = 0, grninit = 180.0
  hord_del   = 2, hord_type = 'explicit', hord_lnr = 0.0
  hord_nutop = 0.0
  hord_fuv   = 0.0, hord_fww   = 0.0, hord_fhu = 0.0
  hord_ftt   = 0.0, hord_ftr   = 0.0
  glconta    = .false., gnnohyd = 1, grepsi = 0.1, gnload = 1
  z_out      = -1
  theocase   = 'EOLE'
  htrop_star = 10000.0
  tzero_star = 273.16
/
&physics
  incore   = .true.
  radia    = 'nil', kntrad = 6
```

```
  fluvert  = 'clef', schmsol = 'FCREST'
  convec   = 'sec', stcond = 'nil'
  gwdrag   = 'nil', shlcvt = 'nil'
  pfbtyp   = 'prosplit', hrclip = -1
  runlgt   = -1
  wet      = .false., satuco = .false.
  nstepsor_p = 90
  upolist =
'DLATEN:-1',
'DLONEN:-1',
'MG:-1',
'Z0EN:90'
/
```

&series_cfg

```
  nstat    = 0
  statll   = 29.16, 32.60, 27.86, 33.44, 27.44, 33.55, 29.37, 32.52,
28.30, 33.01, 29.77, 32.70, 28.27, 33.57, 28.48, 33.95,
27.83, 34.17
  nsurf    = 10
  surface  = 'FV','FC','UE','FQ','F2','SE','IL','I0','TS','P0'
  nprof    = 9
  profil   = 'TT','UU','VV','WW','KM','EN','TU','TV','TH'
  serint   = 1
/
```

&sor_cfgs

```
  gtetikt  = 'can1135198m'
  fileout  = 'can1135198m'
  staguv   = .false.
  gnip1    = 1
  gnip3    = 0
  gnstep1  = 0, gnstep2  = 10000
  levtyp_S = 'g'
  pres_o   = 700.0, 750.0, 800.0, 850.0, 900.0, 950.0, 1000.0
  height_o = 0.0, 25.0, 50.0, 200.0, 1000.0, 5000.0, 10000.0,
15000.0, 20000.0, 25000.0
  udolist  = 'TT','P0','UU','VV','WZ'
/
```

&eole_cfgs

```
  gnk        = 28, grdt = 30, gnnt = 30, gnnls = 90
  noAB       = .true., noAB_r0 = 0.6, noAB_th0 = 45, noAB_h = 1000.0,
noAB_pow = 1
  htop       = 20000.0
  hord_zspng = 7, gnnpbl = 10
  nktop    = -1
  g_id     = -2, g_if = 1000, g_jd = -2, g_jf = 1000
  mtn_typ  = ' '
  mtn_xpos = 39, mtn_ypos = 49, mtn_heigth = 1500.0, mtn_ray = 20.0
  Hblen_x  = 5, Hblen_y = 5
  stabilite_air = 2, critstab = 0.6
  nest_rug = .false., meth_ts = 2, rotarb =.true., cycle_diurne
=.false.
  fhalo    = .true.
  uprofil1 = -14.072000, uprofil2 = -3.952000, uprofil3 = 2.967000,
uprofil4 = 9.361000
  vprofil1 = 13.914000, vprofil2 = 12.527000, vprofil3 = 10.279000,
vprofil4 = 10.251000
```

```
  tprofil1 = 280.508000, tprofil2 = 276.641000, tprofil3 =
270.273000, tprofil4 = 254.398000
  nofc  = .false.
  noms  = .true.
  flat0 = 100.000000
/
```

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To learn more about MC2

Further technical information on MC2 can be found at

http://collaboration.cmc.ec.gc.ca/science/rpn.comm/wiki/doku.php?id=mc2

The WEStats Mesoscale Statistics Module

The simulation results for each class are weighted with consideration to their frequency of occurrence to build a database of statistics. This database includes characteristics of the mean properties of simulated winds. As each mean is weighted by the frequency of the geostrophic wind classes, it represents the wind climate for the analyzed period (43 years). The statistics can be calculated for any height near the surface, where the modeling assumptions are satisfied. A logarithmic profile of surface wind is assumed to interpolate the wind speed from model vertical levels to the height where the statistics are calculated.

All variables available within the database are identified in the table below. Among them are mean values of wind speed and wind power and different frequency distributions with respect to wind speed, direction, and wind power classes. Note that the mean wind power ($0.5\rho v^3$ in Watts/m^2, with ρ the air density and v wind speed) is also called energy flux density (Frank et al., 2001).

The choice of the classes for wind speed, wind direction and wind power, necessary to generate distributions, is presented below.

By default, there are 27 wind speed classes, each of which has a 1 m/s range, except classes 0, 1, and 26. Class 0 includes wind speeds between 0 and 0.2 m/s, class 1 includes wind speeds between 0.2 and 1 m/s, classes 2 to 25 include wind speeds between n-1 and n m/s (where 'n' is the class number), and finally class 26 includes wind speeds of 25 m/s and greater. Users may change the upper limit above which all the wind speeds are considered to be in a single class.

Wind direction classes are referred to as sectors. There are 12 sectors, each 30 degrees wide, centered at 0, 30, 60… and 330 degrees. The data recorded as sector 360 contains a sum of all other sectors' values. For the variable UHR the sum is in sector 360 and class 26.

There are 8 wind power classes defined using the following thresholds: 0, 200, 300, 400, 500, 600, 800 and 1000 W/m^2. Class 1 indicates wind power between 0 and 200 W/m^2, class 2 indicates wind power between 200 and 300 W/m^2, and so on. Class 8 indicates wind power greater than 1000 W/m^2. The eight cumulative frequency classes are defined for wind power equal or greater than a threshold value.

Three variables (UR, ERN and UHR) warrant further explanation. They constitute an input for the microscale model which further downscales the wind to a higher resolution. UR is the mean wind speed distribution by sector and ERN is the frequency distribution by sector. These two variables are used by the microscale model to compute the microscale mean wind speed. UHR is the bivariate frequency distribution of mean wind by sector and class. This bivariate table is a key input for the microscale model because it allows the determination of the mean wind power from the microscale winds.

Variables calculated by the statistics module

Variable	Definition
EU (m/s)	Mean wind **speed**
EU2 (m/s)	Standard deviation of mean wind **speed**
UH (%)	**Frequency** distribution of mean wind **speed**
ER (%)	**Frequency** distribution of mean wind **direction**
ERN (%)	**Frequency** distribution of mean wind **direction**, **averaged** over the point and its eight closest neighbors on the grid
UHR (%)	Bivariate **frequency** distribution of mean wind **speed** and **direction**, **averaged** over the point and its eight closest neighbors on the grid
UR (m/s)	Mean wind **speed** distribution by **direction**, **averaged** over the point and its eight closest neighbors on the grid
UU (knots)	Mean wind along x axis
VV (knots)	Mean wind along y axis
E1 (W/m2)	Mean wind **power**
E2 (W/m2)	Standard deviation of mean wind **power**
EH (%)	**Frequency** distribution of mean wind **power**
EC (%)	Cumulative **frequency** distribution of mean wind **power**

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The Meso/Microscale Coupler and the Microscale Model

What is MMC ?

Two atmospheric flow modeling applications are incorporated into AnemoScope: MC2 for the mesoscale modeling; and MSMicro for the microscale modeling. MSMicro is able to produce high-resolution wind maps for regions of a few kilometres, approximately the size of one mesoscale grid cell. MMC is the Meso/Microscale Coupler which automates a series of microscale simulations for many small regions (tiles) located in the mesoscale domain.

For a given subset of the mesoscale domain, the coupler configures the microscale tiles to be centered at the mesoscale nodes. It then prepares and automatically launches a series of MSMicro runs, one for each tile. After the successful execution of all the microscale runs, a microscale wind solution is obtained for each tile. MMC then merges the tiles and produces a unified wind map for the whole microscale domain.

The input of the microscale model includes high-resolution terrain elevation, land use, and the bi-variate frequency distribution table UHR resulting from the mesoscale wind study, which details 12 sectors of wind direction and 26 classes of wind speed. In each tile, the model is successively applied for each mesoscale wind direction and the wind speed-up due to the local terrain features is calculated. The directional speed-up maps are then combined to produce the tile wind speed map. The frequency of occurrence and the mean mesoscale wind speed in each sector are used in this construction. The mean wind power is also computed on the basis of the UHR table and the speed-ups in each direction.

The preparation of the MSMicro runs by the Meso/Microscale coupler consists of defining the characteristics of the tiles—their position, their extent, and their grid size—and in distributing to each the information it needs. This includes the geophysical fields in the tile and the mesoscale wind features in the mesoscale cell located at the same centroid. In particular, MSMASTER.PAR, the input file for MSMicro, is automatically generated for each tile.

MSMicro, The Microscale Model

This section is largely derived from the MSMicro/3 User's Guide which is included in the documentation for AnemoScope.

MS-Micro/3 is the latest in a series of microcomputer versions of the MS3DJH/3R numerical model for computing steady-state wind flow over complex terrain. MS-Micro/3 consists of a complete set of programs developed in the 1980's that run from digitization of topographic contours and roughness boundaries through to plotting of model results. The technical aspects are not documented here as they are not exploited in AnemoScope. This section focuses on the theoretical background and on the method of computing microscale winds from the wind information at the mesoscale.

History

The original MS3DJH program was developed for accurate and efficient predictions of boundary-layer wind perturbations caused by local topography. The theory of Jackson and Hunt (1975) as simplified and extended to three dimensions by Mason and Sykes (1979) proved to be an ideal starting point for the MS3DJH series of numerical models. Before 1982, the Jackson-Hunt theory had only been applied to simple analytic terrain features. Walmsley et al. (1982) simulated the flow over real terrain in the first of the MS3DJH models and encountered reasonable success in matching predictions with field and wind-tunnel data. Since that time, the numerical model has undergone a number of changes up to the present MS3DJH/3R model (Walmsley et al., 1986) which incorporates wave-number-dependent scaling, efficient Bessel function table look-ups, and wind speed modifications due to surface roughness variations. It is this latest version of this model on which MS-Micro/3 is based. With MS3DJH/3R, a high resolution three-dimensional prediction using 256 by 256 grid points in the horizontal to define topography and aerodynamic roughness can be achieved in a fraction of the time required by finite-difference or finite-element techniques.

Brief Description of the Theory

A detailed description of the theory may be found in the references listed at the end of this document.

Briefly, the model is based on a division of an assumed neutrally-stratified flow field into inner and outer layers. The outer layer is characterized by inviscid potential flow while, in the inner layer, a balance between advective, pressure-gradient, and turbulent-viscous forces is assumed and turbulent transfers are modeled with a simple mixing length closure scheme. Scale considerations and use of a terrain-following vertical coordinate permit linearization of the equations for a range of parameters. Fourier transforms of the linearized equations result in Bessel equations in the Fourier coefficients. The transformed equations are ordinary differential equations in the vertical coordinate that can be solved analytically. An inverse transform provides the desired velocity perturbations. Neutral stratification and scale considerations, linearization and use of the Finite Fourier Transform impose limitations on the circumstances under which the model will provide valid solutions. These limitations are as follows:

- The boundary layer is assumed to be neutrally stratified. This is usually the case during high-wind situations when mechanical mixing of the air is the dominant process.
- The terrain slopes are less than about one in four. This precludes very steep or mountainous terrain where flow separation can occur.

- Steady state and invariability of background conditions are assumed. The incident wind profile is homogeneous and well-developed. Coriolis effects are assumed to be negligible.
- The prediction levels are not so high that they are above the atmospheric boundary layer nor are they so low that they are near the roughness element height. These two situations would violate the assumptions made in the scaling arguments for linearization of the equations.
- It must be possible to represent the region as an area of complex topography and aerodynamic roughness surrounded by a flat homogeneous plain. This constraint is not as stringent as it may at first appear. The terrain and roughness preprocessors for the model input can 'massage' nearly any terrain into a suitable configuration when a large enough domain is selected.

For the third and fourth limitations above, a rule of thumb is that the horizontal length scales should be between about 10 m and 10 km and the vertical solution levels should lie between about 1 m and 150 m.

The restrictions listed above need to be considered seriously when using MS-Micro/3 for deriving wind field modifications. If they are ignored, the results will be at best inaccurate and possibly entirely wrong.

Brief Description of the Method

Typically, the user will have a topographic map and a roughness (usually land-use) map of the region under study.

> **Note:** The following parameters are detailed in the MMC namelist file. This file is created by AnemoScope based on parameters selected within the program.

Next, an MMC namelist file must be created. This ASCII file contains all of the parameters required by the system to compute the wind fields as modified by the complex terrain:

- number of grid lines (x and y) used to define the topography and roughness. This must be an integer and a power of two ranging from 16 to 256. [the parameter “nu”, as defined in the MMC namelist]
- limits (north, south, east and west) of the computational domain (in meters).
- incident wind directions to be considered. Number of incident wind directions (maximum 16) for which normalized wind speed fields are to be computed

  For each incident wind direction:

  - nth direction for which normalized wind speed fields are to be computed. The direction is given in the meteorological sense - i.e., the direction from which the wind is blowing measured clockwise from the north. Response should be 000 to 359. [12 sectors]

    - mean elevation and surface roughness of the upwind terrain. [ME and Z0 information available in the output of WEStat]
    - average climatological wind speed and frequency of occurrence. [UH and ERN fields in the output of WEStat]
    - Average 10-m wind speed for this wind direction. [UR in the output of WEStat]
- the names of the topography and roughness files,
- roughness lengths corresponding to each roughness class,
- data origin shifts (if desired),
- data massaging parameters (to be explained later) and
- number and values of the vertical levels at which the modified wind field is to be computed.

The master topography grid, from which all the other (rotated) topography grids are interpolated is then created. The master grid file is 128 x 128 grid points in size.

A grid of elevations over the computational domain is then created for each specified incident wind direction. A separate grid is created for each direction because the model assumes that the incident wind blows in the direction of the positive x-axis. Therefore, the topographic and roughness grids must be rotated so that the incident wind direction is properly aligned.

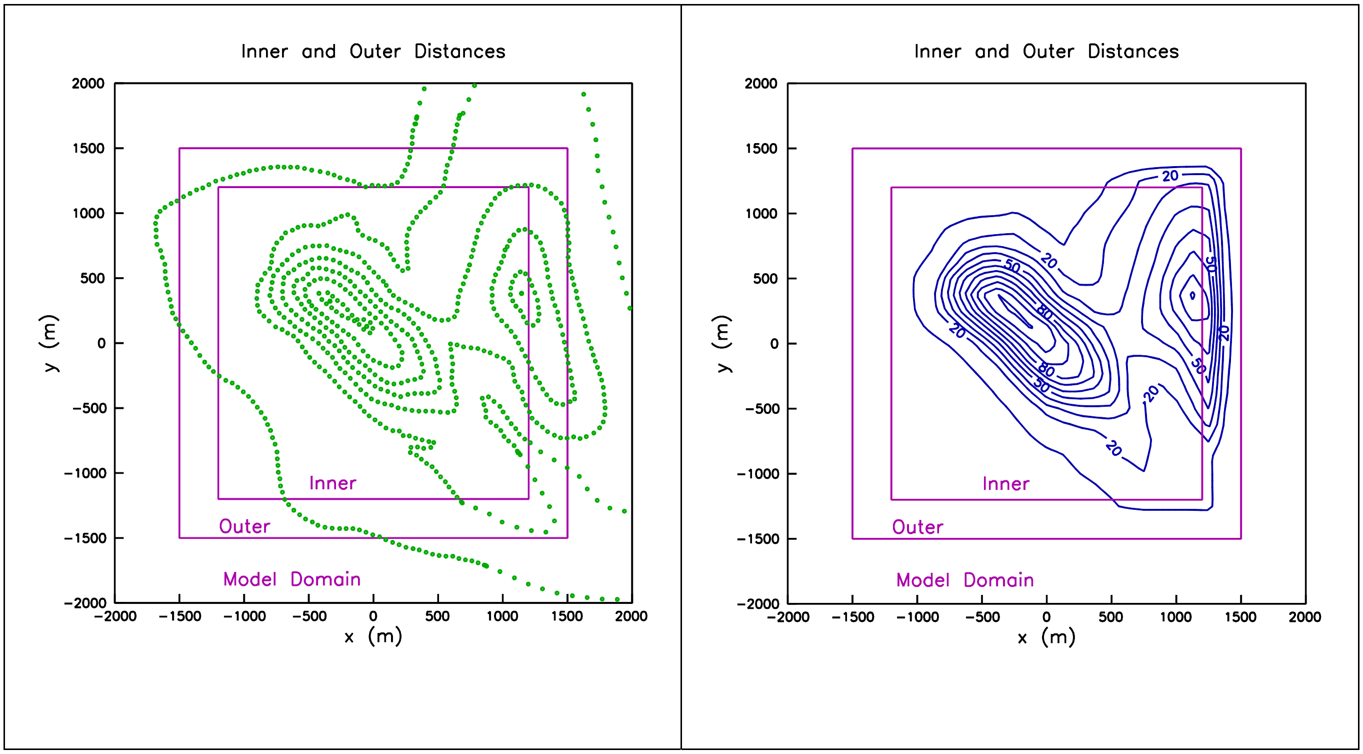
Similarly one surface roughness grid file is generated for each wind direction.

The program is then ready to perform the calculations for each specified incident wind direction and vertical level. The output consists of normalized wind speed and direction deviations for each incident wind direction. The individual normalized wind speed fields and the data on wind speed and frequency from each specified direction are finally combined to produce a direction and frequency-averaged composite wind-speed contour map for the domain.

Inner and Outer Distance Parameters

The 'inner distance' and 'outer distance' parameters are illustrated in the figure below. Topography contours are plotted in this figure. The limits of the inner and outer areas are also shown.

To avoid upstream interference by the replications implicit in the discrete Fourier transform technique, the terrain feature of interest must be surrounded by a fairly extensive flat plain. A terrain feature will usually not conform perfectly to this description. Therefore, the topography and roughness grid generation programs have facilities to 'massage' the terrain into the required form. When a topographic grid is created, it consists of three distinct areas. In the 'inner area', the topography is unchanged. In the 'outer area' is a flat plain. Finally, in the 'matching area' between the previous two, the topography is artificially transformed into a smooth transition between the 'inner area' and the 'outer area'.



An example of inner and outer distances in relation to model domain size

The choice of distances in this example is suitable if one is primarily interested in the flow over the larger central hill. If the flow over the entire two-hill complex is considered to be important, then the inner distance would have to be increased with roughly proportional increases in the outer distance and the model domain and, provided that the maximum of 256 x 256 has not yet been reached, an increase in the grid size so that the desired resolution is achieved.

The choices for the inner and outer distances are somewhat subjective and depend on the judgment of the user who must choose a combination in which the inner region containing the complex terrain under study is large enough to permit adequate resolution on the grid chosen while the outer area is sufficiently large to avoid upstream contamination. Furthermore, the matching area must be defined to provide a smooth transition between inner and outer areas and to avoid artificially-generated steep terrain. The user is referred to Salmon et al. (1981) in which it is suggested that appropriate first guesses for the inner and outer distances would be about 25% and 40% of the total domain range, respectively.

In AnemoScope, the inner and outer distances are set in the default namelist file to 30% and 40% respectively.

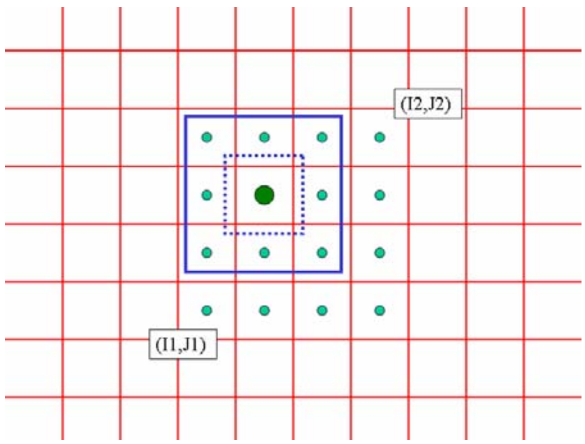
MMC Parameters

Next, we will describe the various parameters defining the microscale tiles and their arrangement in the subset of the mesoscale domain.

Several parameters can be adjusted by the user through the MMC Namelist File Editor dialog. The others are either fixed in the code or defined in the default name list file.

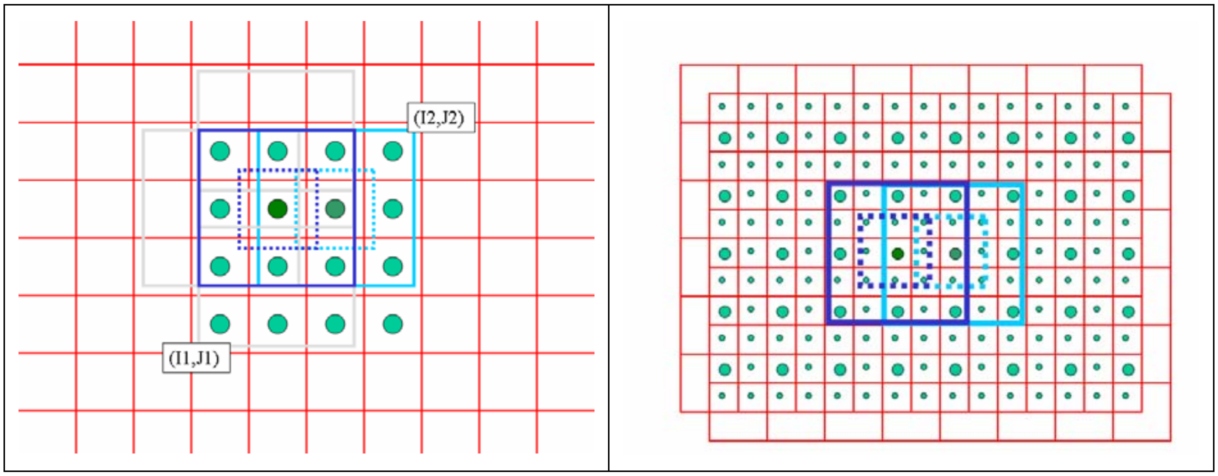
Meso DX (delta) = size of the mesoscale grid cell. This field is extracted from the mesogeophy file.

(I1,J1) and **(I2,J2)** = indices of the nodes of the mesoscale domain defining the limits of the microscale domain.



The mesoscale grid (in red) and the microscale subdomain delimited by the mesoscale cells (I1,J1) and (I2,J2). One microscale tile with its central quarter is shown around one of the mesoscale centroids.

Stride (alpha) = defines the increment between the mesoscale nodes used as centroid for the microscale tiles. **Stride=1** means that a tile is defined around each mesoscale node between (I1,J1) and (I2,J2). **Stride=2** means that every second node is a tile center.



Microscale tiles / Stride = 1 (left) vs. Stride = 2 (right).
In each case, 2 consecutive microscale tiles are shown.

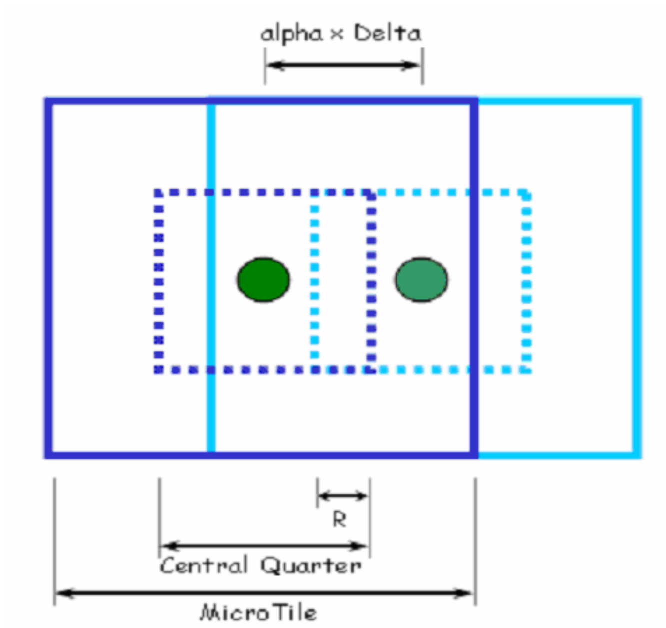
MicroTile = size of each microscale tile.

Central quarter = central part of the microscale tile of size MicroTile / 2. The mean wind speed and energy are produced for the central quarter only.

Tile Size (nu) = number of grid points in each direction of the microscale tiles.

d = microscale cell size = MicroTile / nu. This value is calculated and displayed in the dialog box.

Tile Overlap (sigma) = overlap rate between the central quarter of two successive tiles.



R = Overlap of the micro tile quarters = Central Quarter – alpha × Delta

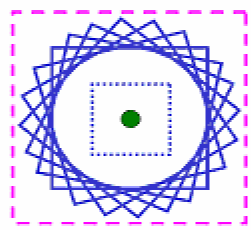
Sigma = R / Central Quarter = 1 – alpha × Delta / (0.5 × MicroTile)

= 1 – 2 × alpha × Delta / MicroTile

Therefore d = MicroTile / nu = 2 × alpha × Delta / nu / (1- Sigma)

MesoFrame = number of cells on the edge of the mesoscale domain used to establish the boundary conditions. The field values in these cells should not be used in the analysis. Therefore, the microscale domain should not overlap these cells. (MesoFrame = 21 by default)

Tr_ratio = defines the ratio of the domain used to cover the footprint of the rotated microscale tile (in pink on the picture below) with the size of the microscale tile (MicroTile)



The minimum value for tr_ratio is √2 ≅ 1.414 (sqrt(2)). Tr_ratio is set to 1.6 in the default name list file.

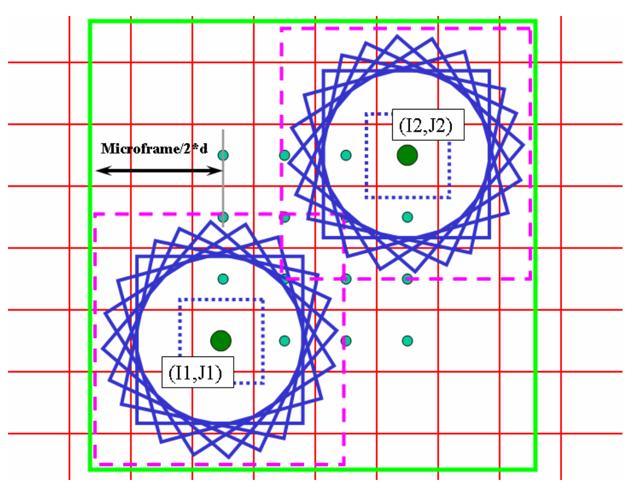
footprint_domain = tr_ratio × MicroTile

MicroFrame is defined in the figure below; on each border of the microscale domain, the distance between the first mesoscale node and the domain edge is

Microframe /2 × d

MicroFrame should be large enough for this border to cover the footprint of the rotated tile. The condition on Microframe is

MicroFrame ≥ (tr_ratio – 1) × nu



MMC Outputs

- **MS Micro Output Tiles Directory:** contains one folder for each J-row of micro scale tile. In each J-folder, the following files are created for each I index:
    - **I_mmc1.log:** log file of the mmc1 program generating the MMC Namelist
    - **I_ms3r.log:** log file of the MSMicro applied to the tile
    - **I_ms3rFlow.fst:** MSMicro flow solution in the tile
    - **I_ms3rTopo.fst:** topography and land use in the tile
    - **I_MSMASTER.PAR:** input parameters for MSMicro generated by the coupler
- **MMC_WORKING_DIR:** contains files used during the execution of MMC.
    - **MicroMerge.log*:** log file of the msplit program when called to merge all the tile solutions in one microscale domain solution
    - **MicroSplit.log*:** log file of the msplit program when called to split the geophysical file into tile geophysical file and provide the geophysical input file for each single tile computation.
    - **microGrid.std*:** basically contains the positional information for all the microscale tiles as well as the topography and land use index for the microscale domain
    - **microResults.std*:** merged solution file containing the mean wind speed EUMI and/or the mean wind power E1MI for the whole microscale domain
    - **mmc-micro.nml*:** name list of mmc: all the user defined parameters are reported into this file as well as some default parameters.
    - **mmc0.log*:** log file of the mmc0 program, the main program of the meso/microscale coupler which calls all other processes.

MMC Namelist File

`!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!`
`! MMC - namelist parameter file`
`! WrittenBy                  armngr2`
`! Application                AnemoScope`
`! Version                    1.0.104`
`! CreationDate               Mon, Jun 06, 2005 03:06 PM`
`!-----------------------------------------------------------`
	Header: general information about the namelist file.

&MMC_SETUP	
`path_meso_stats = ' C:\CHC\AnemoScope\Output\7_20_50_we.fst'` `path_micro_geophy = ' C:\CHC\AnemoScope\Output\geomicro.fst'`	

path_z0_defines = 'C:\CHC\AnemoScope\z0_define_GenGeo.txt' path_msmicro_tiles = ' C:\CHC\AnemoScope\Output\MICRODIR' merge_var = 'EUMI' run_msmicro = .True. /	
&SET_SWEEP	
delta = 5000.000000 I1 = 56 I2 = 96 J1 = 65 J2 = 105 ip1micro = 1 ip2micro = 2 ip3micro = 3 alpha = 1 nu = 128 sigma = 0.400000 tr_ratio = 1.600000 meso_frame = 5 micro_frame = 250 mmc_verbose = .True. /	
&COUPLING	
ms_proj = 'P' gen_tgrg = .True. verbose = .True. flat_z0 = .False. flat_tg = .False. reset_z0_halo = .False. keep_z0_class = .True. grid_from_topo = .True. inner_distance = 0.300000 outer_distance = 0.400000 ms_rzm = 50.000000 zref = 50.000000 first_270 = .True. varucl = .True. raducl = 3.000000 out_var = 'TG,RG,EUMI,E1MI' out_dir = '270' mmc_verbose = .True. /	

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Using EC Climatological Wind Data in AnemoScope

The distribution of AnemoScope includes a summary of all Environment Canada wind stations reporting average wind data at 15-minute intervals, for which we have computed a long term average. We call this data the wind climate file. This map shows the 499 stations included in that dataset.

The purpose of supplying this dataset is to provide users with the means to perform a rough check of the mesoscale and microscale results they've obtained with AnemoScope. Most of these stations measure wind at a height of 10 m above ground; although a detailed history of the measurement height is available for each station, we shall assume here that they are all at 10 m.

In this document, we'll show how to use this data as an *in situ* quick check for a mesoscale application of AnemoScope. The same will be done for a microscale application, but we will just show the end results.

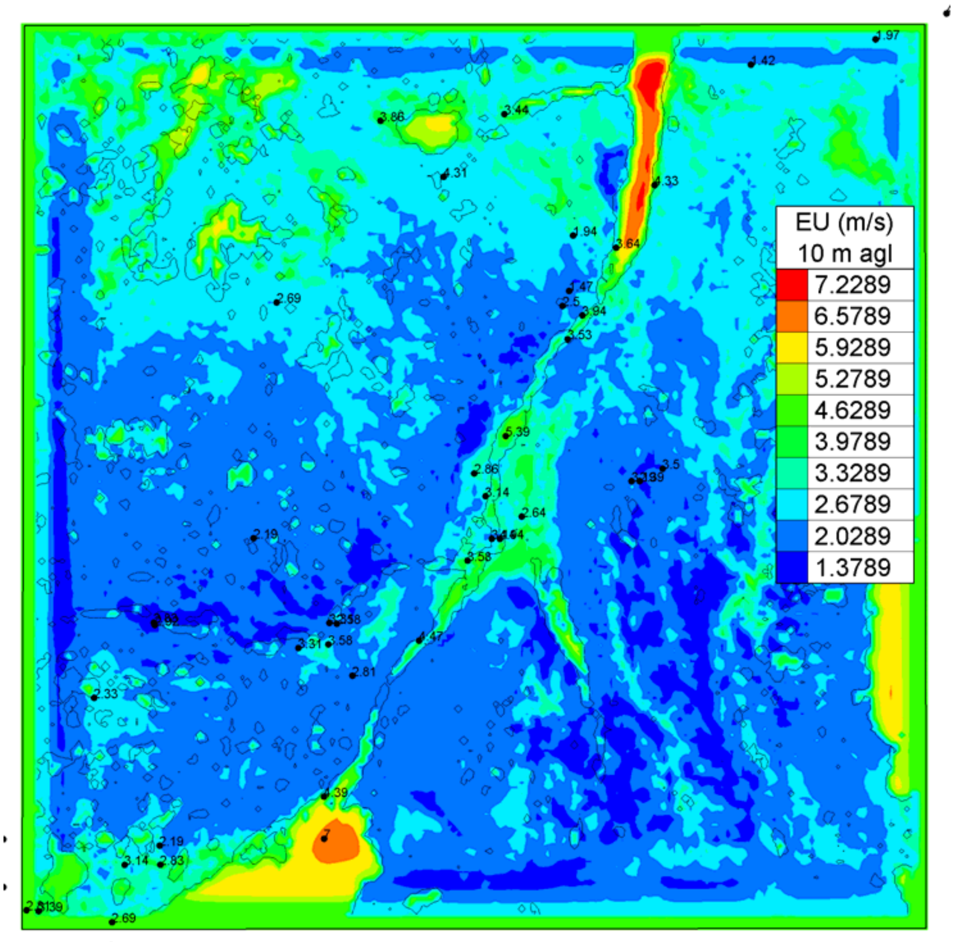
First open the wind climate file and bring up your wind statistics file. The statistics should be valid at 10 m, which will often differ from your main turbine statistics height. If that is the case, re-run WEStats with 10 m as the "Statistics Level" (mesoscale case) or re-run MMC with the "Output Elevation" set to 10 m.

Overlay your statistics file and the wind climate file. This will require you to change the coordinates of the latter to polar stereographic. The wind climate file, **ECC_ClimateStations.pt2**, is a "point file" (an EnSim core file type with the extension *.pt2), which is an ASCII file that you can view with Notepad. You can find the file in your AnemoScope installation directory.

The header indicates that there are six attributes per point: elevation, mean wind (in km/h), mean wind (in m/s), the number of observations used to produce the values, the

ID number of the station, and the name of the station. The first two numbers on each line are not attributes; they are the latitude and longitude coordinates of the station.

Ultimately, you'll want to produce a view like the following, which shows the EU (mean wind speed in m/s) field:



To do that, open the **Properties** dialog of EC_ClimateStations and go to the **Data** tab. Select the **Mean Wind** attribute and click the **Apply** button.

On the **Display** tab, check the "Show Node Labels" box, and set the Monochrome option to Black. Apply these options.

Display both data items (the EU field of the statistics file and EC_ClimateStations) in the same view, with EU on top. Be sure to set both data items to the same coordinate system. This will probably be Polar Stereographic (60, -100), but the Longitude value may vary, depending on the location of your simulation.

You can use the Live Cursor to move over the view and see how well the EU field values given by the live cursor compare with the values given next to each station.

The purpose of the remaining steps is to obtain the EU values at the stations. This will be used to produce a scatter plot, which allows a more quantitative validation of the EU grid.

a) Select a subset of wind climate stations that match the model statistics area. To do that, draw a black polygon object using the **New Closed Line** tool, as shown on the figure above. Name it “mesorectangle”.

b) Select the wind climate file as the current object. Then select **Tools→Extract Points…**.

c) AnemoScope will ask which polygon to extract the points from. Select “mesorectangle”. This will place a child object under the wind climate object.

d) Save the child object as an XYZ Point Set called “subset.xyz”. Save a duplicate file by selecting **File→Save Copy as…**. Name it “MesoRectSelect.xyz”.

e) The next step is to obtain the EU values at the points corresponding to that station subset. Open **MesoRectSelect** and make it the current object. Then select **Tools→Map Object…** from the menu bar.

   This opens a dialog showing which objects can be mapped to **MesoRectSelect**. Select the EU object. AnemoScope interpolates the EU grid to these points. **Save** the file.

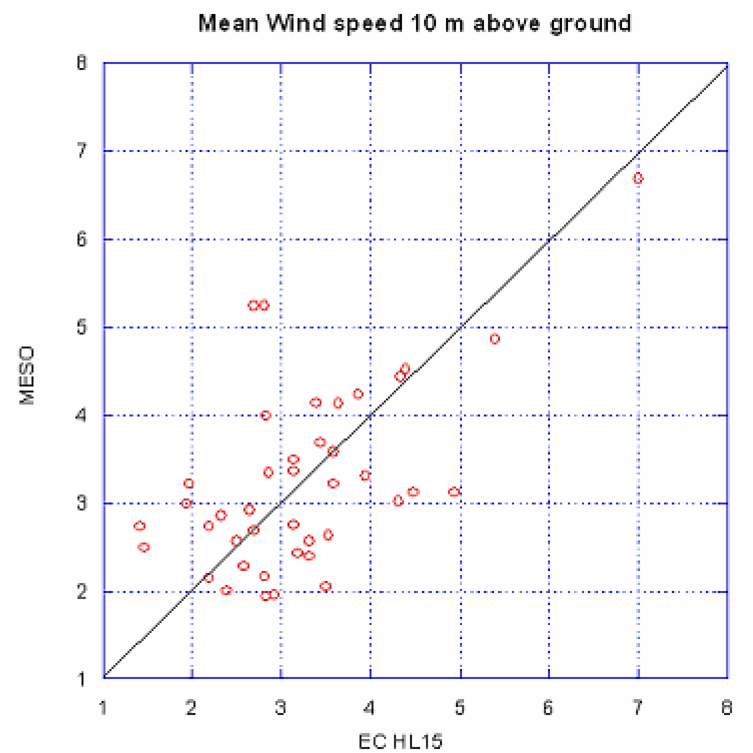
At this point, you have two ASCII files that look like the following:

```
######################################################################
:FileType xyz  ASCII  EnSim 1.0
# Canadian Hydraulics Centre/National Research Council (c) 1998-2005
# DataType                 XYZ Point Set
#
:Application              AnemoScope
:Version                  1.1.10
:WrittenBy                YourNameHere
:CreationDate             Tue, Oct 04, 2005 10:09 AM
#
#---------------------------------------------------------------------
:SourceFile   EC_ClimateStations.pt2
#
:Name  EC_ClimateStations(Subset)
:Title EC_ClimateStations(Subset)
#
:Projection PolarStereographic
:CentreLatitude 60
:CentreLongitude -100
:Ellipsoid Sphere
#
:EndHeader
2527906.155301 -3882242.033432           1.97
2409740.762025 -3906276.193167           1.42
1787011.284121 -4506579.842386           2.33
1980757.975327 -4459324.232648           3.31
1843542.375776 -4435370.480538           2.83
2095136.562352 -4452391.832534           4.47
…
```

```
######################################################################
:FileType xyz  ASCII  EnSim 1.0
# Canadian Hydraulics Centre/National Research Council (c) 1998-2005
# DataType                 XYZ Point Set
#
:Application              AnemoScope
:Version                  1.1.10
:WrittenBy                YourNameHere
:CreationDate             Tue, Oct 04, 2005 10:11 AM
#
#---------------------------------------------------------------------
:SourceFile   EC_ClimateStations.pt2
#
:Name  EC_ClimateStations(Subset)
:Title EC_ClimateStations(Subset)
#
:Projection PolarStereographic
:CentreLatitude 60
:CentreLongitude -100
:Ellipsoid Sphere
#
:EndHeader
2527906.155301 -3882242.033432 3.21947064856288
2409740.762025 -3906276.193167 2.72675752988257
1787011.284121 -4506579.842386 2.84934127679419
1980757.975327 -4459324.232648 2.55498143851742
1843542.375776 -4435370.480538 1.93803397283205
2095136.562352 -4452391.832534 3.11312093940965
…
```

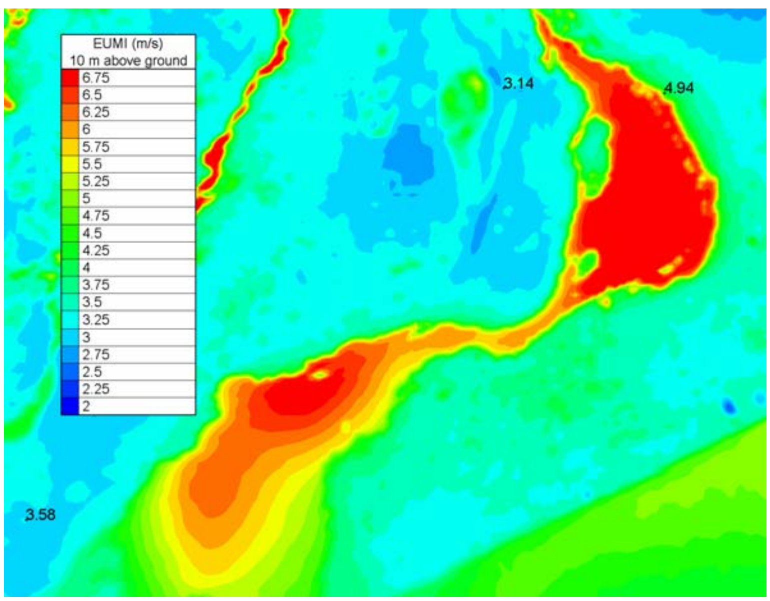
The third column contains the values for the mean wind speed, in m/s.

Import the two files into a data plotting program and you should come up with a graph that resembles the following. This graph shows a reasonably good fit.



Finally, we'll give a brief sample application for the microscale simulation.

If things go well, we can expect to get an improved match between model predictions and climatological records. The example shown below is taken from the region used for the Tutorial, Montreal Island. The MMC run has been adjusted to produce output at a height of 10 m and an improved Land Use dataset has been used, with a grid resolution better than 100 m. The overlay shows the three stations from the wind climate file with the EUMI (microscale mean wind speed):



If we compare the two values, we see the following:

Observed Value	Predicted Value
3.58	3.24
3.14	3.14
4.94	4.45

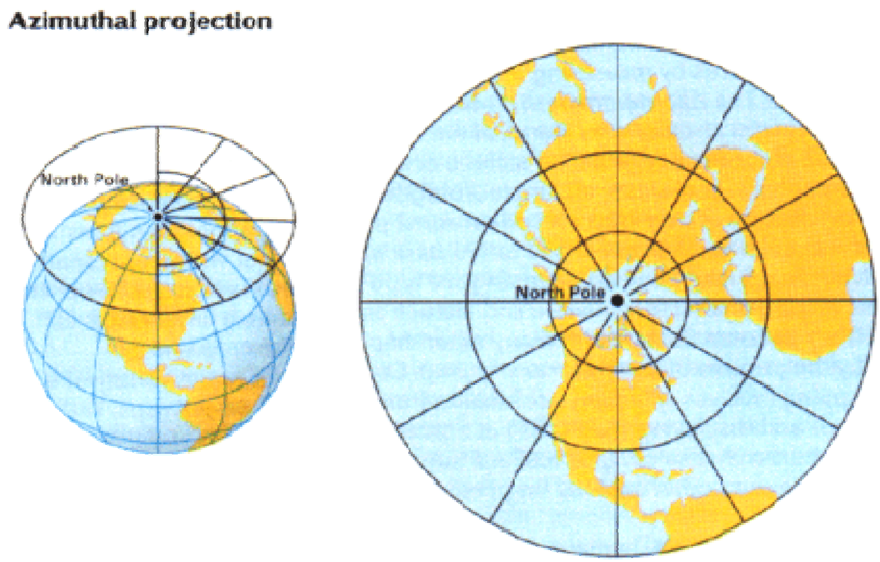
In this case, some of the difference might be the result of the accuracy of the stations' positions, which is accurate to within about one hundredth of a degree, i.e. about 1 km. Allowing for the positional error, we have effectively perfect results for two of the stations.

Appendix: The North Polar Stereographic Projection

The north polar stereographic projection is an azimuthal projection. It can be imagined as a plane touching the Earth's surface. If a light source inside the globe projects the graticule onto the plane, the result would be a planar—or azimuthal—map projection.

In AnemoScope, we define that plane as the one contacting the Earth at a latitude of 60º N with a projection made from a point at the South Pole. This projection can be viewed as seeing the Earth from above the North Pole. This projection is convenient for domains close to latitude 60º N, since deformations become important away from this latitude, especially near the equator. This projection is not recommended for any domain containing the tropics; in those cases, use a cylindrical projection instead.

In the event that a simulation is performed for a location in the Southern Hemisphere, geographical data used should be defined using a Polar Stereographic Projection with a latitude of 60º S.



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