Module 4:
Creating a regional climate model ensemble using GIS and extreme events indices
Webinar Series

- **Module 1**: RICCAR regional climate modelling and hydrological modelling datasets: An introduction
- **Module 2**: Viewing NetCDF regional climate modeling datasets in GIS
- **Module 3**: Extracting tabular data from NetCDF climate files for use in other models and applications
- **Module 4**: Creating a regional climate model ensemble using GIS and extreme events indices
- **Module 5**: Accessing global and regional climate datasets and platforms
- **Module 6**: RICCAR integrated vulnerability assessment methodology
Module 4: Contents

- Benefits of ensemble analysis
- How to create a regional climate model (RCM) ensemble in GIS
- RICCAR extreme events indices and applications
<table>
<thead>
<tr>
<th>Model Name</th>
<th>Modelling Centre</th>
<th>Country</th>
<th>GCM Resolution (lon x lat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNRM-CM5</td>
<td>Européen de Recherche et Formation Avancée en Calcul Scientifique (CERFACS)</td>
<td>France</td>
<td>1.41° × 1.40°</td>
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<tr>
<td>EC-EARTH</td>
<td>EC-EARTH consortium published at Irish Centre for High-End Computing</td>
<td>Netherlands / Ireland</td>
<td>1.13° × 1.13°</td>
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<tr>
<td>GFDL-ESM2M</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory</td>
<td>USA</td>
<td>2.50° × 2.02°</td>
</tr>
</tbody>
</table>
Driving GCMs to RCM (RICCAR)

- CNRM-CM5
- EC-EARTH
- GFDL-ESM2M

Downscaling

Rossby Centre regional atmospheric model 4 – SMHI (RCA4)
Maps show differences in modelling outputs based on 3 different driving GCMs (CNRM-CM5, EC-EARTH, and GFDL-ESM2M) downscaled using the same RCM (RCA4).

Differences are most apparent in eastern North Africa and Sub-Saharan Africa.

More information is found in the RICCAR Technical Note from the Swedish Meteorological and Hydrological Institute (SMHI). Regional Climate Modelling and Regional Hydrological Modelling Applications in the Arab Region.
• Maps show differences in modelling outputs based on 3 different driving GCMs (CNRM-CM5, EC-EARTH, and GFDL-ESM2M) downscaled using the same RCM (RCA4).
• Differences are most apparent in Sub-Saharan Africa
• More information is found in the RICCAR Technical Note from the Swedish Meteorological and Hydrological Institute (SMHI). Regional Climate Modelling and Regional Hydrological Modelling Applications in the Arab Region.
Maps show differences in modelling outputs based on 3 different driving GCMs (CNRM-CM5, EC-EARTH, and GFDL-ESM2M) downscaled using the same RCM (RCA4).

Differences are most apparent in Mashreq and western Sahel.

More information is found in the RICCAR Technical Note from the Swedish Meteorological and Hydrological Institute (SMHI). Regional Climate Modelling and Regional Hydrological Modelling Applications in the Arab Region.
Maps show differences in modelling outputs based on 3 different driving GCMs (CNRM-CM5, EC-EARTH, and GFDL-ESM2M) downscaled using the same RCM (RCA4).

Differences are most apparent in the Horn of Africa.

More information is found in the RICCAR Technical Note from the Swedish Meteorological and Hydrological Institute (SMHI). Regional Climate Modelling and Regional Hydrological Modelling Applications in the Arab Region.
Why present results as an ensemble?

- Uncertainties in modelling outputs can include scenario uncertainties (RCPs), internal climate variabilities, and differing model assumptions.
How should ensemble be used?

- Recommended to use the largest possible model ensemble for evaluation and application of climate modelling outputs
- Minimum 3 model members but only 1 RCP scenario (multi-model ensemble)

Driving GCM: CNRM-CM5  
RCM: RCA4

Driving GCM: EC-EARTH  
RCM: RCA4

Driving GCM: GFDL-ESM2M  
RCM: RCA4

- Assess mean of all ensemble members over an extended period (i.e. 20 or 30 years)

RICCAR climate modelling output ensembles are based on 3 members as shown.  
RICCAR ensembles represent a 20-year mean. Results can either be annual or seasonal.
How should ensemble be used?

- Mashreq Domain modelling outputs expected starting in early 2021
- Driving GCMs are to be determined. One of them will be EC-EARTH.
- RCM to be used will be ALADIN (Aire Limitée Adaptation dynamique Développement InterNational) developed by CNRM. ALADIN is currently used by institutes from the ALADIN-HIRLAM consortium under the name HCLIM-ALADIN (SMHI).
How should ensemble be used?

Multi-model ensembles can have multiple GCMs and RCMs

Should be the same:

• Scenario/RCP
• Spatial and temporal resolution
• Modelling domain
• Bias-corrected or raw RCM outputs

• Multiple GCMs and RCMs can be used. For example for the MNA (Arab) Domain, there are raw RCM output projections available from CORDEX/ESGF that include (shown by GCM/RCM): (a) CNRM-CM5/RCA4, (b) EC-EARTH/RCA4, (c) GFDL-ESM2M/RCA4, (d) MPI-ESM-MR/RegCM4.3, and (e) HadGEM2-ES/RegCM4.3. All 5 modelling outputs can be used to create an ensemble.
• Spatial resolution of all ensemble members should be the same (i.e. all from 50 km / 0.44°)
• Temporal resolution of all ensemble members should be the same (i.e. all daily or all monthly)
• The modelling domain should be the same (i.e. all from Arab Domain) so that boundary conditions are identical
• Do not mix bias-corrected data with raw RCM outputs (not bias-corrected)
RICCAR Ensemble Outputs

3 models:
- CNRM-CM5
- EC-EARTH
- GFDL-ESM2M

RCP4.5
- Reference period (1986-2005)
- Near-century (2016-2035)
- Mid-century (2046-2065)
- End-century (2081-2100)

RCP8.5
- Reference period (1986-2005)
- Near-century (2016-2035)
- Mid-century (2046-2065)
- End-century (2081-2100)

Ensembles for RICCAR are based on the mean output of 3 modelling outputs for 4 different 20-year time periods for 2 different RCP scenarios.

Available in raster format from the RICCAR Regional Knowledge Hub data portal.
• Ensembles not available on the RICCAR Regional Knowledge Hub must be created manually
• Based on annual or seasonal data
• Minimum 3 model outputs, 20-year period (i.e. "2030", based on 2021-2040)
1. Extract each raster time slice
   a. Make NetCDF Raster Layer

   • Make NetCDF Raster Layer was discussed during webinar module 2.
   • RICCAR Training Manual on the Use of GIS to Analyse Climate Change Data Section 3.2.2.
1. Extract each raster time slice
   a. Make NetCDF Raster Layer
   b. Open Layer Properties and select time for the Band Dimension

- After selecting time as the Band Dimension, the Dimension Values field will turn blank.
1. Extract each raster time slice
   a. Make NetCDF Raster Layer
   b. Open Layer Properties and select time for the Band Dimension
   c. Save as Layer File

• Save layer file in user-defined location.
1. Extract each raster time slice
   a. Make NetCDF Raster Layer
   b. Open Layer Properties and select time for the Band Dimension
   c. Save as Layer File
   d. Download and use NetCDF Time Slice to Raster tool available from https://support.esri.com/en/technical-article/000011318

• Using the NetCDF_time_slice_to_Raster will automatically export each time slice from the NetCDF layer file as a single raster (.tif).
• Save the tool in a user-defined location.
Creating an ensemble in GIS

1. Extract each raster time slice
   a. Make NetCDF Raster Layer
   b. Open Layer Properties and select time for the Band Dimension
   c. Save as Layer File
   d. Download and use NetCDF Time Slice to Raster tool
   e. Open tool from user-defined location in ArcCatalog

   • NetCDF Time Slice to Raster tool may be located in a subdirectory under the user-defined location (NetCDF_time_slice_export.gdb > NetCDF_Time_Slice_Export > NetCDF_time_slice_export)
Creating an ensemble in GIS

1. Extract each raster time slice
   a. Make NetCDF Raster Layer
   b. Open Layer Properties and select time for the Band Dimension
   c. Save as Layer File
   d. Download and use NetCDF Time Slice to Raster tool
   e. Open tool from user-defined location in ArcCatalog
   f. Enter the NetCDF layer and user-defined Output Folder

- Select the Input NetCDF layer as saved during step 1.c.
- Once completed, select OK.
Creating an ensemble in GIS

1. Extract each raster time slice
   a. Make NetCDF Raster Layer
   b. Open Layer Properties and select time for the Band Dimension
   c. Save as Layer File
   d. Download and use NetCDF Time Slice to Raster tool
   e. Open tool from user-defined location in ArcCatalog
   f. Enter the NetCDF layer and user-defined Output Folder
   g. Execute tool

- When executing NetCDF Time Slice to Raster tool, the .tif files will automatically named Band_(number). The numbers will be in chronological order from 1 to n, where n is the number of time slices. For daily precipitation and temperature, each RICCAR NetCDF will have 365 time slices (or 366 during leap years), representing each day of the year. For the extreme climate indices, there are 150 time slices, one for each year (1951-2100).
- Common error: If the NetCDF Time Slice to Raster output is only one file (Band_1.tif), it means that the user did not select time as the Band Dimension (step 1.b) before saving as layer file (Step 1.c).
- Note that tool execution may take several minutes depending on computer speed.
Creating an ensemble in GIS

1. Extract each raster time slice
2. Calculate annual (or seasonal) projections
   a. 1 NetCDF file (one model, one RCP scenario)

- Cell Statistics tool is located under Spatial Analyst Tools > Local
- Tool requires activation of the Spatial Analyst extension, available in ArcMap under Customize > Extensions
Creating an ensemble in GIS

1. Extract each raster time slice
2. Calculate annual (or seasonal) projections
   a. 1 NetCDF file (one model, one RCP scenario)

- Select raster files
- The table on the left is for normal calendar years and the table on the right is for leap years (with 29 February, i.e. 2020, 2024, 2028)
1. Extract each raster time slice
2. Calculate annual (or seasonal) projections
   a. 1 NetCDF file (one model, one RCP scenario)

- The raster files not listed in chronological order
- Because of this, it can be tedious to select appropriate raster bands (i.e. for January)
• Be sure to select complete raster file. There will be 5 files for each raster (.tif, .tif.aux.xml, .tif.ovr, .tif.xml, and .tfw).

• After this is completed, may get warning message indicating “Invalid drop item/One or more dropped items were invalid and will not be added to the control”. Disregard this message. It is because all 5 files per raster were selected, but all are not necessary to execute the tool.
Creating an ensemble in GIS

1. Extract each raster time slice

2. Calculate annual (or seasonal) projections
   a. 1 NetCDF file (one model, one RCP scenario)

- Output raster file name is user-defined
Cell Statistics: Overlay Statistic

For temperature data, the units of measurement do not include time (°C)

For precipitation, time is considered mm/day

- Mean is the default overlay statistic
- Selecting mean as the overlay statistic for temperature will calculate the average temperature of all the raster selected.
- If mean is selected as the overlay statistic for precipitation, the result will report the average precipitation in mm/day (because the NetCDF file and rasters are daily data)
For precipitation, more common to report units in mm/month or mm/year

- Select sum as the overlay statistic to sum monthly data or yearly data
To find the annual (or seasonal) average of monthly rainfall, select the monthly values as the input rasters and mean as the overlay statistic.

If reporting total yearly rainfall, this was completed in previous step, using the sum as the overlay statistic, selecting all 365 (or 366) raster files.
Exercise: Calculate seasonal precipitation (October-March)

1. Data: EC-EARTH, RCP8.5, year 2030 (extracted dataset)
2. Extract NetCDF to raster using tool
3. Sum monthly precipitation
4. Calculate mean monthly precipitation

- Note that October-March is calculated as January-March 2030 and October-December 2030.
- Result will be as shown when completed. (Adding color scheme and the background map is optional.) Results should range from 0 to 119.72 mm/month.
- Results for each month: Oct: 0 – 197.8; Nov: 0 – 135.28; Dec: 0 – 354.92; Jan: 0 – 47.01; Feb: 0 – 167.81; Mar: 128.43 mm/month
Creating an ensemble in GIS

1. Extract each raster time slice
2. Calculate annual (or seasonal) projections
   a. 1 NetCDF file (one model, one RCP scenario)
   b. Repeat for remaining NetCDF files in ensemble (all models, one RCP scenario)

- Models shown are the RICCAR GCMs/RCM. Note that ensembles can be composed of any GCM/RCM combination as long as the domain, spatial resolution, RCP scenario, and bias-corrected (or not bias-corrected) are the same.
- Smaller circles represent the mean precipitation (or temperature) for one year per GCM/RCM.
1. Extract each raster time slice

2. Calculate annual (or seasonal) projections
   a. 1 NetCDF file (one model, one RCP scenario)
   b. Repeat for remaining NetCDF files in ensemble (all models, one RCP scenario)
   c. Calculate mean for all models in ensemble
Creating an ensemble in GIS

1. Extract each raster time slice
2. Calculate annual (or seasonal) projections
3. Compare to reference period

- Ensemble projections are frequently reported as a change in value to quantify climate change, compared to a reference period.
- Reference period used for RICCAR is 1986-2005, defined by IPCC AR5.
- Figure shown is from the RICCAR Arab Climate Change Assessment Report - Main Report, Figure 21, RCP8.5 showing mean change in annual precipitation
Creating an ensemble in GIS

1. Extract each raster time slice
2. Calculate annual (or seasonal) projections
3. Compare to reference period

- To compare projected values to the reference period, use the Raster Calculator, found under Spatial Analyst > Map Algebra.
- Note that the Spatial Analyst extension must be active.
Creating an ensemble in GIS

1. Extract each raster time slice
2. Calculate annual (or seasonal) projections
3. Compare to reference period

- Note that raster files must be added to ArcMap project to use in the Raster Calculator (shown in Layers and variables).
- Subtract the reference period value from the projected value to calculate the change.
- Recommended to provided a user-defined Output Raster rather than leave the default name to help facilitate future access of the raster file. Note that ArcMap often limits the number of characters in the file name (shown as “change” in the example).
### Extreme climate indices

<table>
<thead>
<tr>
<th>ID</th>
<th>Indicator Name</th>
<th>ID</th>
<th>Indicator Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD0</td>
<td>Frost days</td>
<td>WSDI</td>
<td>Warm spell duration indicator</td>
</tr>
<tr>
<td>SU25</td>
<td>Summer days</td>
<td>CSDI</td>
<td>Cold spell duration indicator</td>
</tr>
<tr>
<td>ID0</td>
<td>Ice days</td>
<td>DTR</td>
<td>Diurnal temperature range</td>
</tr>
<tr>
<td>TR20</td>
<td>Tropical nights</td>
<td>RX1day</td>
<td>Max 1-day precipitation amount</td>
</tr>
<tr>
<td>GSL</td>
<td>Growing season length</td>
<td>Rx5day</td>
<td>Max 5-day precipitation amount</td>
</tr>
<tr>
<td>TXx</td>
<td>Max Tmax</td>
<td>SDII</td>
<td>Simple daily intensity index</td>
</tr>
<tr>
<td>TNx</td>
<td>Max Tmin</td>
<td>R10</td>
<td>Number of heavy precipitation days</td>
</tr>
<tr>
<td>TXn</td>
<td>Min Tmax</td>
<td>R20</td>
<td>Number of very heavy precipitation days</td>
</tr>
<tr>
<td>TNn</td>
<td>Min Tmin</td>
<td>Rnn</td>
<td>Number of days about nn mm</td>
</tr>
<tr>
<td>TN10p</td>
<td>Cool nights</td>
<td>CDD</td>
<td>Consecutive dry days</td>
</tr>
<tr>
<td>TX10p</td>
<td>Cool days</td>
<td>CWD</td>
<td>Consecutive wet days</td>
</tr>
<tr>
<td>TN90p</td>
<td>Warm nights</td>
<td>R95p</td>
<td>Very wet days</td>
</tr>
<tr>
<td>TX90p</td>
<td>Warm days</td>
<td>R99p</td>
<td>Extremely wet days</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PRCPTOT</td>
<td>Annual total wet-day precipitation</td>
</tr>
</tbody>
</table>

- 27 Core Indices defined by ETCCDI (Expert Team on Climate Change Detection and Indices)
- The 7 indices highlighted were used for RICCAR, plus SU35 and SU40. Note that the indicator name may differ slightly.
- Definitions and units of measurement:
  - FD0 – Annual count when TN (daily minimum) < 0 °C (days)
  - SU25 – Annual count when TX (daily maximum) > 25 °C (days)
  - ID0 – Annual count when TX (daily maximum) < 0 °C (days)
  - TR20 – Annual count when TN (daily minimum) > 20 °C (days)
  - GSL – Annual count (1 Jan to 31 Dec in northern hemisphere, 1 Jul to 30 Jun in southern hemisphere) between first span of at least 6 days with daily mean temperature > 5 °C and first span after 1 Jul (1 Jan in southern hemisphere) of 6 days with daily mean temperature < 5 °C (days)
  - TXx – Monthly maximum value of daily maximum temperature (°C)
  - TNx – Monthly maximum value of daily minimum temperature (°C)
  - TXn – Monthly minimum value of daily maximum temperature (°C)
  - TNn – Monthly minimum value of daily minimum temperature (°C)
  - TN10p – Percentage of days when minimum temperature < 10th percentile (days)
• TX10p – Percentage of days when maximum temperature < 10\textsuperscript{th} percentile (days)
• TN90p – Percentage of days when minimum temperature > 90\textsuperscript{th} percentile (days)
• TX90p – Percentage of days when maximum temperature > 90\textsuperscript{th} percentile (days)
• WDSI – Annual count of days with at least 6 consecutive days when maximum temperature > 90\textsuperscript{th} percentile (days)
• CSDI – Annual count of days with at least 6 consecutive days when minimum temperature > 10\textsuperscript{th} percentile (days)
• DTR – Monthly mean difference between daily maximum and daily minimum temperature (°C)
• RX1day – Monthly maximum 1-day precipitation (mm)
• RX5day – Monthly maximum consecutive 5-day precipitation (mm)
• SDII – Annual total precipitation divided by the number of wet days (precipitation ≥ 1.0 mm) (mm/days)
• R10 – Annual count when precipitation ≥ 10 mm (days)
• R20 – Annual count when precipitation ≥ 20 mm (days)
• Rnn – Annual count when precipitation ≥ nn mm (nn is user-defined threshold) (days)
• CDD – Maximum number of consecutive days with precipitation < 1 mm (days)
• CWD – Maximum number of consecutive days with precipitation ≥ 1 mm (days)
• R95p – Annual total precipitation when daily precipitation > 95\textsuperscript{th} percentile (mm)
• R99p – Annual total precipitation when daily precipitation > 99\textsuperscript{th} percentile (mm)
• PRCPTOT – Annual total precipitation in wet days (precipitation ≥ 1 mm) (mm)
• Can calculate indices from NetCDF files using CDO or from time series data (.txt) for single point location using RClimDex (http://etccdi.pacificclimate.org/software.shtml)
**Why are extreme climate indices important?**

<table>
<thead>
<tr>
<th>Change in mean annual precipitation</th>
<th>Mid-century RCP8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -10</td>
<td>Precipitation decreasing (or increasing slightly) while intensity increasing</td>
</tr>
<tr>
<td>10 to -8</td>
<td></td>
</tr>
<tr>
<td>8 to -6</td>
<td></td>
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<tr>
<td>6 to -4</td>
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<td>4 to -2</td>
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<td>2 to 0</td>
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<td>0 to 2</td>
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<td>6 to 8</td>
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<td>8 to 10</td>
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<tr>
<td>&gt; 10</td>
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<table>
<thead>
<tr>
<th>SDII</th>
<th>Mid-century RCP8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; -2.5</td>
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</tr>
<tr>
<td>2.5 to -2</td>
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</tr>
<tr>
<td>2 to -1.5</td>
<td></td>
</tr>
<tr>
<td>3.5 to -1</td>
<td></td>
</tr>
<tr>
<td>3 to -0.5</td>
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</tr>
<tr>
<td>0.5 to 0</td>
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<tr>
<td>0 to 0.5</td>
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<tr>
<td>0.5 to 1</td>
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<tr>
<td>1 to 1.5</td>
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</tr>
<tr>
<td>1.5 to 2</td>
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</tr>
<tr>
<td>2 to 2.5</td>
<td></td>
</tr>
<tr>
<td>&gt; 2.5</td>
<td></td>
</tr>
</tbody>
</table>
Why are extreme climate indices important?

Temperature increasing such that intense heat waves (> 40 °C) more likely.
Why are extreme climate indices important?

Monthly (or annual) averages can mask out important information on “extremes” which can be useful for sector applications.

Use of extreme climate indices can help with mitigation, adaptation, risk reduction, and policy planning.
Potential applications:
Temperature extreme climate indices

- Heat wave duration
- Heat-related illnesses
- Fire risk
- Livestock heat stress
- Agricultural productivity decline
Potential applications:
Precipitation extreme climate indices

- Intense rainfall and flash flood
- Deforestation
- Agricultural drought
- Flood risk and urbanization
- Water scarcity
Thank You

Marlene Ann Tomaszkiewicz
Regional Advisor for Climate Change Analysis using GIS
Water Resources Section
Climate Change and Natural Resource Sustainability Cluster
UN Economic and Social Commission for Western Asia (ESCWA)
tomaszkiewicz@un.org
www.riccar.org

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