Strengthening Climate Information and Multi-Hazard Early Warning Systems for Increased Resilience in Azerbaijan

Annex 15

Appendices to Pre-Feasibility Study (Annex 2)

Appendix A: Details on the Design of Individual Hazard Forecasting and Warning Criteria, Multi-hazard integration, and Impact-based forecasting

This appendix provides a detailed design for the forecasting models/approaches and early warning criteria for each of the individual hazards identified. It further details the integration of a multi-hazard approach based on the individual underlying hazards.

Flood forecasting

As detailed in the climate rationale, floods are one of the most significant climate hazards in Azerbaijan. There are two main types of floods to consider in Azerbaijan, namely flash-floods and fluvial floods. The main difference regarding the forecasting approach for either flash-floods or fluvial floods resides in the lead time. Flash-floods are usually defined as flood events with a lead time of 6 hours or less, while fluvial floods have a lead time higher than 6 hours, and can be on the order of days for big catchments, such as the Kura River. In Azerbaijan there are several regions that are susceptible to flash-floods, due to topographical and climatic features, in the Lesser Caucasus and especially in Greater Caucasus. During the preparation of this proposal and feasibility study, an assessment of the lead time in the Greater Caucasus in three river basins and for several communities has been undertaken. The lead time is in between 1 and 5 hours. This is because of the proximity of some of these communities to the head of the catchments, and to the climatic conditions. Therefore, the implementation of the flood forecasting EWS in this area will consider this short lead time, and the possibilities for the implementation of the EWS.

Table 1. Lead time for communities in the Greater Caucasus

River Basin	Community	Lead Time (h)
Turyanchay	Bum	1.25
	Dandikh	1.62
	Gabala	1.48
	Imamli	2.57
	Kusnet	1.10
	Mikhliqovaq	2.23

	Mirzebeyli	3.97
	Mollali	3.90
	Qushlar	4.88
Kishchay	Sheki	1.37
Talachay	Tala	2.41
	Zagatala	1.38

Design of the flood forecasting system

The design of the flood forecasting system will consider the lead time for several catchments, the available input data (satellite data, automatic station data and meteorological forecasting data), modelling data (from local meteorological modelling, hydrological modelling and hydraulic modelling), and outputs (warnings levels). It should be noted that the existing resources within NHMS would be fully considered during the design phase, and that capacity building activities will be undertaken in order to ensure that NHMS has sufficient skills for both the implementation and the operation of the system. Also, as previously noted, the results from the risk knowledge component will be fully embedded into the forecasting approach.

Historical information

Historical information pertinent to the flood forecasting will be collected. This will include historical flood events and the related meteorological, climatic and river conditions. Special attention will be paid to the snow water equivalent contribution to several floods, and its greater impact due to climate change. Also, it should be noted that in some catchments in the Greater Caucasus, the impact of sediments in the flood events, as noted above, is significant, and this will also be considered. This information will be collected in close collaboration with the NHMS and with the support of national and international consultants. This information will be the basis for the product development task.

Product development

The main recommended approach for floods is summarised in Figure 1. During this phase, the full flood forecasting platform will be developed. It should be noted that the hydrological and hydraulic models used during the hazard assessment will be the base for the forecasting models.

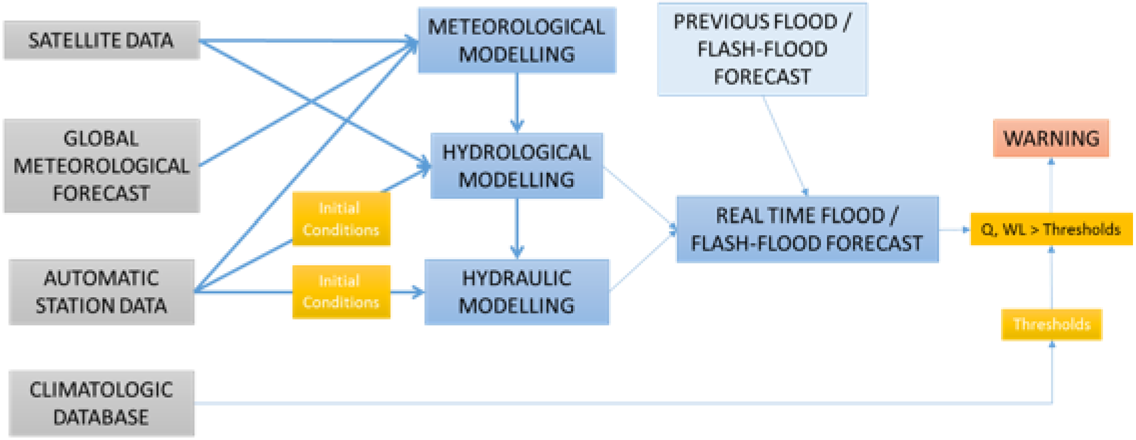


Figure 1. Main approach for flood forecasting

As above the key components of the flood forecasting approach are:

Satellite data – As previously noted, the NHMS is already using satellite data to complement some of their tasks and activities, especially for snow cover, cloud cover, and vapour content. Nonetheless, for flood forecasting purposes, it is recommended that the use of satellite resources is enhanced. This is especially the case for satellite precipitation data. These data can be very useful, especially in locations where there are no weather radar data available. There are different products worth noting here such as the Multi-sensor Precipitation Estimate (MPE) by EumetSAT or the Global Precipitation Measurement (GPM) by NASA and JAXA. The latter provides very high-resolution precipitation rates with 10 minutes latency whereas the former is the continuation of the successful TRMM mission. The use of both sources of data would supplement the automatic station data in regions where the density of stations is low.

Automatic Station Data – The new and existing automatic station data would serve as input for the meteorological (assimilation), hydrological, and hydraulic models (initial conditions and possibly assimilation).

Meteorological Modelling – The results from global resources and from the newly implemented local meteorological model outputs will be used in the flood forecasting platform as input data for the hydrological models, and also as direct output for warning purposes.

Hydrological Modelling – A hydrological model uses meteorological data and antecedent conditions to convert precipitation data into run-off (discharge) data. The hydrological model would supply information directly to the final forecasting results and also to the hydraulic model (where implemented). A snow water equivalent model will be linked to the hydrological model in relevant areas. Further, the assimilation of data will also be implemented.

Hydraulic Modelling – It is recommended that a hydraulic (flood inundation) model is implemented in some key areas in order to ascertain the proper routing of the flows derived from the hydrological model. The main components of a flood inundation hydraulic model are:

- Geometry information: such as cross sections, structures (bridges, culverts, levees, dams...), resistance information, etc. These data should be collected and processed during the implementation of the EWS (using the information from the hazard models). However, the model should be flexible enough to allow for the inclusion of sudden and/or temporary changes, such as bridge blockages.
- Initial conditions: water level and discharge initial conditions are also needed. They may be provided by either the monitoring network (ideally) or by previous runs.
- Boundary conditions: the implemented hydraulic model will require upstream (discharge) and downstream (water level) boundary conditions. Upstream boundary conditions will be provided by the hydrological model previously described, whereas the downstream will depend on the specific watercourse.

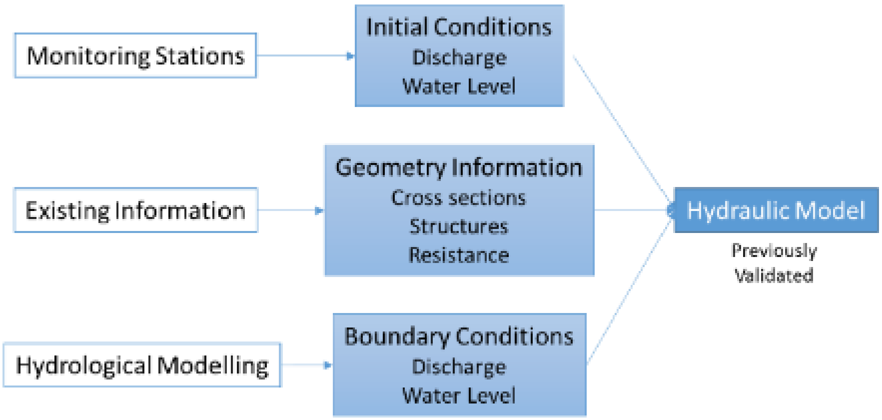


Figure 2. Hydraulic Modelling Approach

The assimilation of data will also be implemented in the forecasting platform.

- Forecasting – Combining the results from the meteorological, hydrological and the hydraulic models, in addition to the monitoring stations, forecasting will be compiled and issued. The hydrological and hydraulic models should be the main input to these forecasts, but the input from other sources should also be considered.

All of the data sources and models implemented and the data flow among the different modelling components will be managed using a forecasting platform.

Development of warning criteria

Using the information from the climatologic database and the selected thresholds, flood warnings can be issued. The warning levels will be based on a careful assessment undertaken during the modelling implementation and the testing of the forecasting platform. The table below shows an example of what the thresholds may look like, but it should be noted that the thresholds for the flood hazard will be location specific.

Table 2. Example of flood thresholds

		Green	Yellow	Orange	Red
Flood	Water Level at pre-defined locations (m)	<1m	>1	>2	>3
	Precipitation Threshold (mm)	<30mm in 24h	30mm – 50mm in 24h	50mm – 70mm in 24h	70mm or greater in 24h

Drought monitoring and forecasting

The drought forecasting capabilities at NHMS and the State Water Agency (SWA, within MOES) will be developed building upon its existing forecasting capabilities and utilizing some of the existing products.

Drought differs from other natural hazards in various ways. Drought is a slow-onset natural hazard that is often referred to as a creeping phenomenon. It is a cumulative departure from normal or expected precipitation, that is, a long-term mean or average. This cumulative precipitation deficit may build up quickly over a period of time, or it may take months before the deficiency begins to appear in reduced stream flows, reservoir levels, or increased depth to the groundwater table. Owing to the creeping nature of drought, its effects often take weeks or months to appear (Figure 3). Precipitation deficits generally appear initially as a deficiency in soil water; therefore, agriculture is often the first sector to be affected.

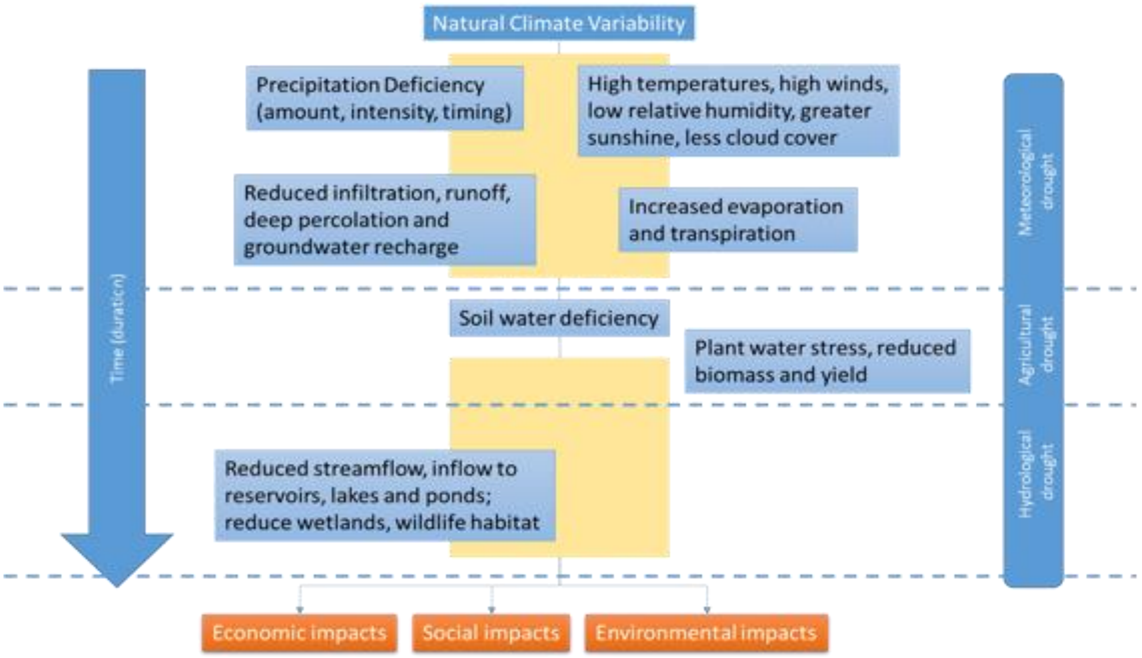


Figure 3. Sequence of drought occurrence and impacts

A drought early warning system is designed to identify climate and water supply trends and thus to detect the emergence or probability of occurrence and the likely severity of drought. This information can reduce impacts if delivered to decision makers in a timely and appropriate format and if mitigation measures and preparedness plans are in place. Understanding the underlying causes of vulnerability is also an essential component of drought management because the ultimate goal is to reduce risk for a particular location and for a specific group of people or economic sector.

There are numerous natural drought indicators that should be monitored routinely to determine the onset and end of drought and its spatial characteristics. Severity must also be evaluated on frequent time steps. Although all types of droughts originate from a precipitation deficiency, it is insufficient to rely solely on this climate element to assess severity and resultant impacts because of the factors identified previously. Effective drought early warning systems must integrate precipitation and other climatic parameters with water information such as stream flow, groundwater levels, reservoir and lake levels, and soil moisture into a comprehensive assessment of current and future drought and water supply conditions. Therefore, a comprehensive and integrated approach is required to monitor drought more effectively and provide early warning. Within this project, the monitoring systems will be enhanced, and the integrated and comprehensive approach will also be ensured through institutional set ups, especially noting the collaboration between the Ministry of Agriculture, SWA and NHMS.

Design of the drought forecasting system

Considering the existence of NHMS expertise and the available information, a drought forecasting product will be defined. Presently, most monitoring and early warning systems are based on a single indicator or climatic index, such as the Standard Precipitation Index (SPI). However, recent efforts to improve drought monitoring and early warning in some countries have provided new early warning and decision-support tools and methodologies in support of drought preparedness planning and policy development. Recent advancements will be thoroughly considered when designing the drought forecasting system.

Historical information

Historical information pertinent to the drought forecasting will be collected. This will include drought climatology, drought impacts, drought magnitude, and drought frequency. This information will be collected in close collaboration with the Ministry of Agriculture, SWA and NHMS and with the support of national and international consultants. This information will be the basis for the product development task.

Product development

As previously noted, the drought forecasting will be based on different products or indicators. Considering the uncertainties in the forecasting of droughts, for operative purposes it is better to combine the model predictions with other empirically based predictions.

The products developed will include:

- Soil Moisture Information: from remote sensing and from station data.
- Precipitation anomalies: from observational and forecasting data.
- Other meteorological data: such as temperature and evaporation will be collected from observational data too.
- Standard Precipitation Index: The Standardized Precipitation Index (SPI) is a tool which was developed primarily for defining and monitoring drought. The SPI allows an analyst to determine the rarity of a drought at a given time scale (temporal resolution) of interest for any rainfall station with historic data. It can also be used to determine periods of anomalously wet events. Mathematically, the SPI is based on the cumulative probability of a given rainfall event occurring at a station.
- Palmer Drought Severity Index: The Palmer Drought Severity Index (PDSI) uses readily available temperature and precipitation data to estimate relative dryness. The PDSI has been reasonably successful at quantifying long-term drought. As it uses temperature data and a physical water balance model, it can capture the basic effect of global warming on drought through changes in potential evapotranspiration

In order to enhance the prediction of droughts in a timely manner, all of the above products will be combined through the use of different models, such as regression, time-series, or probabilistic models (Figure 4). The model of choice will be decided with the support of international and national experts. It should be noted that both the SPI and the PDSI will have to be calibrated using historical data.

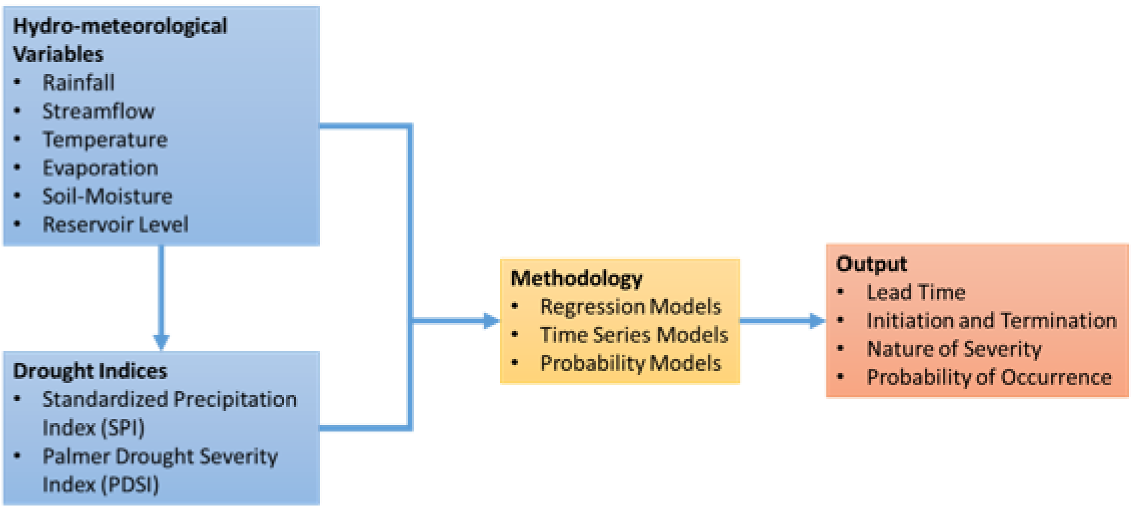


Figure 4. Components of drought forecasting

The information from the hydro-meteorological monitoring network will be combined with the selected drought indices through regressions, time-series, and probability models to produce the probability of a drought occurring and the nature of this drought, including the lead time, the severity, and the predicted initiation and termination of the drought.

Development of warning criteria

Based on the products defined above, and the different components of the drought forecasting, the drought warning criteria will be developed. To undertake this, historical data and hindcast scenarios will be analysed.

As a first approximation, and just considering the use at this stage of the SPI and PDSI indices, the following warning criteria is suggested (Table 3).

Table 3. Example of different drought indices thresholds for warning purposes

		Green	Yellow	Orange	Red
Droughts	Standardized Precipitation Evapotranspiration Index	>-0.5	<=0.5	<1.0	<=2.0
	Palmer Drought Severity Index	>=1.0	<=2.0	<3.0	<=4.0

Hail forecasting

For hail to be produced, deep moist convection is required in combination with these three basic situations:

- Adequate updraft to keep the hailstone aloft for an appropriate amount of time.
- Sufficient super-cooled water near the hailstone to enable growth as it travels through an updraft, and
- Particles of ice, snow or dust for it to grow upon.

There is no clear distinction, however, between storms that do and do not produce hailstones. Nearly all severe thunderstorms produce hail, although it may melt before reaching the ground. Multi-cell thunderstorms produce many hailstones, but not usually the largest hailstones. In the life cycle of the multi-cell thunderstorm, the mature stage is relatively short and therefore there is not much time for growth of the hailstone.

Supercell thunderstorms have sustained updrafts that support large hail formation by repeatedly lifting the hailstones into the very cold air at the top of the thunderstorm cloud. In general, hail 5cm or larger in diameter is associated with supercells, although non-supercell storms can produce “golf-ball” size hail.

In all cases, the hail falls when the thunderstorm's updraft can no longer support the weight of the ice. The stronger the updraft the larger the hailstone can grow.

It is important, from a forecasting point of view, to understand the meteorological conditions that can produce hailstorms in Azerbaijan.

Design of the hail forecasting system

Due to the existing forecasting capabilities for hail worldwide, the hail EWS will focus more on the monitoring component of the system. Many studies have demonstrated that dual-polarization weather radars are an effective tool for hail detection. Dual-polarization radar technology can help tell the difference between hail, ice pellets, and rain, and even determine hail size. There are studies using both C-band and X-band radars for the detection of hailstorms. However, in order to be able to properly detect hail-storms, the radar information has to be validated and calibrated extensively.

The type of radars in Azerbaijan should be considered too. Until recently, the weather radar network in Azerbaijan consisted of MRL-5 radars, with no dual-polarisation capabilities. These radars, although having the possibility of having wavelengths at two ranges (combination of a S and X radars), did not provide sufficient capabilities for hail identification. The NHMS, however, is currently modernising its radar network. While two C-Band dual-polarisation have been already acquired, they have not been deployed due to the Covid-19 situation. Considering that C-Band radars have an estimated 250km range, and considering the shape and the area of the territory of Azerbaijan, additional 3 radars would be required to ensure that the full area of Azerbaijan is covered. It should be added that it would be recommended that agreements with neighbouring countries are sought for radar data sharing. For instance, Georgia has two C-Band dual polarisation weather radars, one of them located in the East side of the country, that could be of great use for hail forecasting purposes.

Data from the weather radars will not be used just for hail forecasting purposes. Weather radar outputs can also be used for flash-flood, flooding, and strong wind purposes, and therefore this will be fully evaluated within the project implementation.

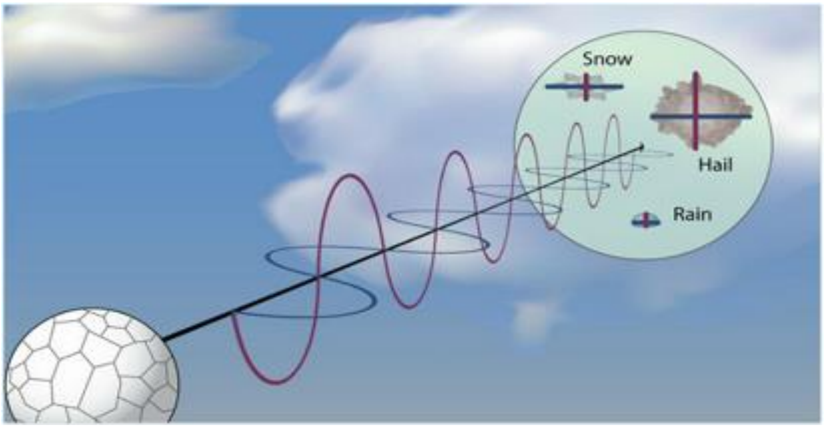


Figure 5. Dual Polarisation Radar

Historical information

As noted above, it is recommended that the hail EWS mainly relies and focuses on observations from weather radars. During the historical information stage, historical hail events will be studied in detail, from a meteorological forecasting point of view and to identify the conditions that led to those events. The possibility of using information from the NWP for pre-forecasting will also be analysed in detail.

Product Development

In addition to the use of weather radar outputs, from the hydro-meteorological classification, the use of NWP outputs will also be explored. As noted, the occurrence of hail-storms is preceded by certain pre meteorological conditions. During the product development, these pre-conditions will be fully explored, and the use of NWP for this will be fully explored. Nonetheless, the information from the weather radars will be the main input into the hail forecasting system.

The dual polar products include differential reflectivity (ZDR), correlation coefficient (CC), and specific differential phase (KDP), which provide an indication of the presence of hail and its size. These products are not available from all manufactures of radars.

<u>Differential Reflectivity</u>

The Differential Reflectivity (ZDR) shows the difference in returned energy between the horizontal and vertical pulses of the radar. Differential Reflectivity is defined as the difference between the horizontal and vertical reflectivity factors in dB units. Its value can range from minus 7.9 to plus 7.9 in units of decibels (dB). Positive values indicate that the objects are larger horizontally than they are vertical, while negative values indicate that the objects are larger vertically than they are horizontal. Values near zero suggest that the target is spherical, with the horizontal and vertical size being nearly the same (Figure 6).

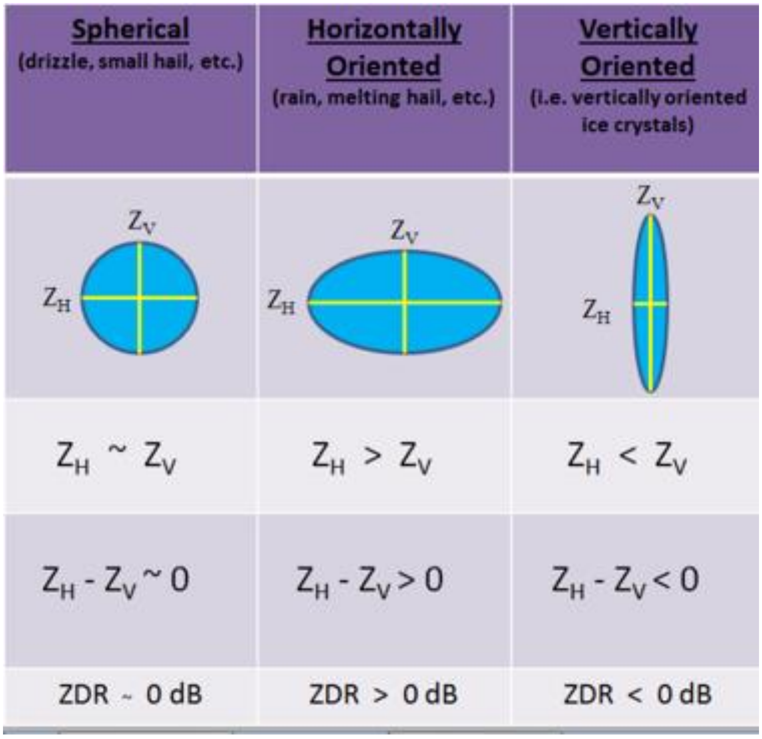


Figure 6. Differential Reflectivity Values. (Source: US NWS[1])

Differential Reflectivity values are biased toward larger particles. The larger the particle, the more it contributes to the resulting reflectivity factor. For example, raindrops are usually wider than they are tall, and yield a positive ZDR value. A scattering of large hailstones in the same volume of air being observed will yield a ZDR value closer to 0, because the spherical shape of the larger objects contributes more to the final reflectivity value. If the base reflectivity value is indicating high dB values, whereas differential reflectivity is returning values near zero, then the volume of air being observed is mostly likely filled with a mixture of hail and rain.

[1] Dual-Polarization Radar Training for NWS Partners https://training.weather.gov/wdtd/courses/dualpol/Outreach/ . NWS. Last accessed 10 December 2020

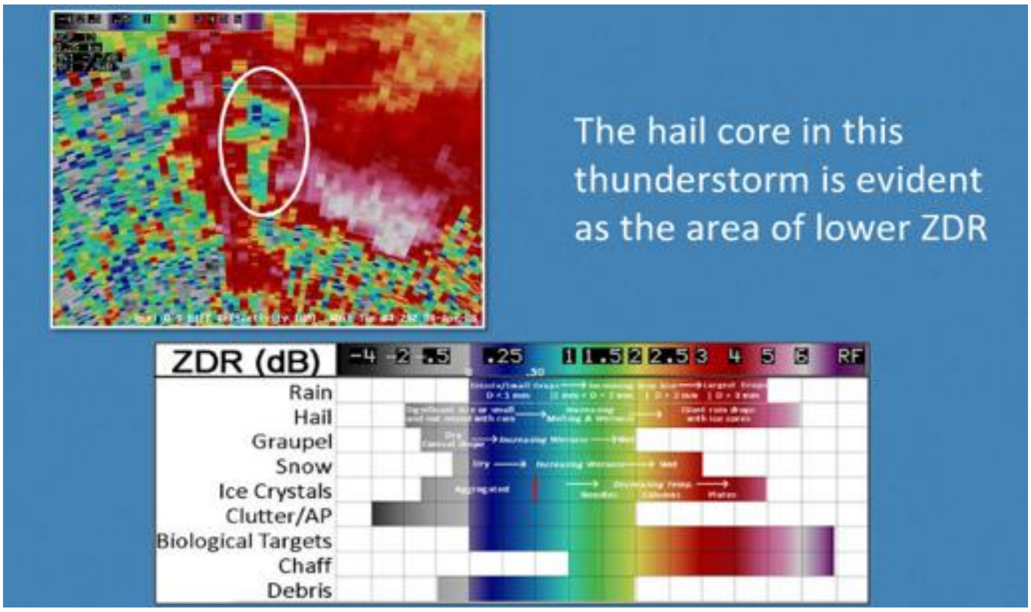


Figure 7. Differential reflectivity example. (Source: US NWS)

<u>Correlation Coefficient</u>

The Correlation Coefficient (CC) product is defined as the measure of how similar the horizontally and vertically polarized pulses are behaving within a pulse volume. The values range from 0 to 1 and are unit-less, with higher values indicating similar behaviour and lower values conveying dissimilar behaviour. The CC will be high if the magnitude or angle of the radar's horizontal and vertical pulses undergo a similar change from pulse to pulse; otherwise, it will be low.

Correlation Coefficient help distinguish objects of meteorological significance. Hail and melting snow are non-uniform in shape and thus cause a scattering effect and have more moderate CC values ranging from 0.8 to 0.97. Uniform objects such as rain and hail yield well-behaved patterns, and their CC from pulse to pulse generally exceeds values of 0.97.

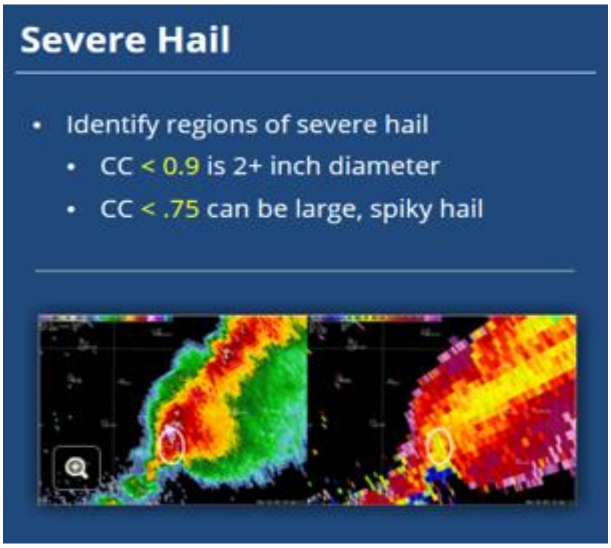


Figure 8. Correlation coefficient values for severe hail. (Source: US NWS)

The accuracy of the Correlation Coefficient product degrades with distance from the radar. The CC will also decrease when multiple types of hydro-meteors are present within a pulse volume. Thus, a volume with rain and hail will yield a lower CC value than the same volume with only rain.

Specific Differential Phase

Specific differential phase, technically classified as propagation differential phase shift, is the difference between the horizontal and vertical pulses of the radar as they propagate through a medium, such as rain or hail, and are subsequently attenuated (slow down). Due to differing shapes and concentration, most objects do not cause similar phase shifting in the horizontal and vertical pulses. When the horizontal phase shift is greater than the vertical, the differential phase shift is positive. Horizontally oriented objects will produce a positive differential phase shift, whereas vertically-oriented objects product a negative differential phase shift.

These positive differential phase values (horizontal) and negative values (vertical) are analogous to Differential Reflectivity (ZDR), however, there is a crucial distinction. The differential phase shift is dependent on particle concentration. That is, the more horizontally oriented objects within a pulse volume, the greater the positive differential phase shift. Thus, a high frequency of small raindrops would yield a higher differential phase value, then a lower concentration of larger raindrops. Differential phase shifting is unaffected by the presence of hail, and shifts in snow and ice crystals are typically near zero degrees.

Figure 9. Typical values of KDP. (Source: US NWS)

Specific Differential Phase (KDP) is defined as the range derivative of the differential phase shift along a radial. Values range from minus 2 to plus 7 in units of degrees per kilometre. The KDP value is used to detect heavy rain. Areas of heavy rain will typically have high KDP due to the size or concentration of the drops. Hail and snow/ice crystals have no preferred orientation and will yield KDP values near zero degrees.

Hail Spikes

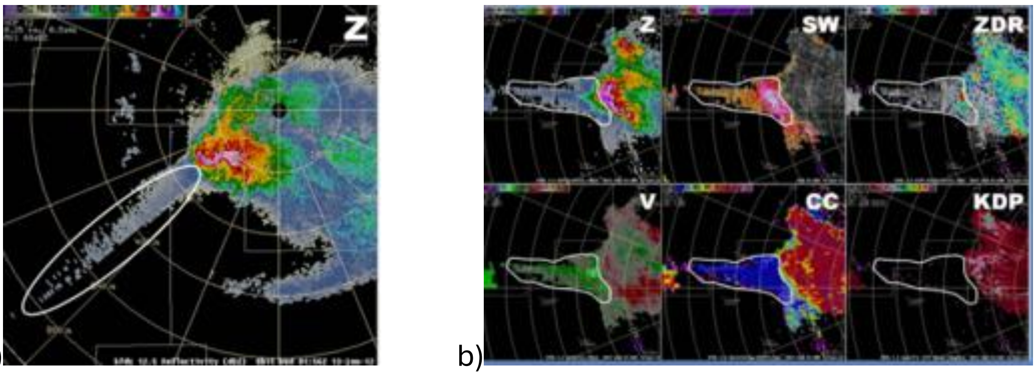
A hail spike or three body scatter spike (TBSS) is an artefact on a weather radar display, indicative of large hail. TBSS are identified by a spike of weak reflectivity echoes that extend out from a thunderstorm, and away from the radar site.

Generally known as hail spikes, the spikes are the result of energy from the radar hitting hail, or very heavy rain, being reflected to the ground, then reflect back to the hail and back to the radar. This results in the radar picking up the energy from these multiple paths at a later time than the energy that was directly reflected from the hail to the radar. However, both are on the same radial angle from the radar as the antenna did not have time to turn significantly.

The multipath echoes are shown on the radar display as echoes extending in a radial direction behind the actual location of the hail/heavy rain core. The loss of energy due to multiple reflections results in weaker return echoes. Thus, the hail spike region has comparatively weaker echoes than the echoes directly from the hail or heavy rain core.

Since hail cores are most intense at higher elevations, hail spikes usually appear at the levels that accompany the most intense hail. Because of this, hail spikes are usually not seen at lower elevations. Given the signal of the radar beam has to do multiple reflections, each time weakening the reflection, hail spikes are usually noticeable only when extremely large hailstone are present.

Because of their observed accuracy in indicating large hail stone events, TBSS's are used operationally to identify thunderstorms that could l produce large, severe hail (Figure 10).



a) b)

Figure 10. a) TBSS example. b) TBSS for the different dual-polarisation radar products. (Source: US NWS)

Hydro-meteor classification

A hydro-meteor classification algorithm provides information for the classification of hydro-meteors depending on the reflectivity, the differential reflectivity, the specific differential phase and the correlation coefficient (Figure 11).

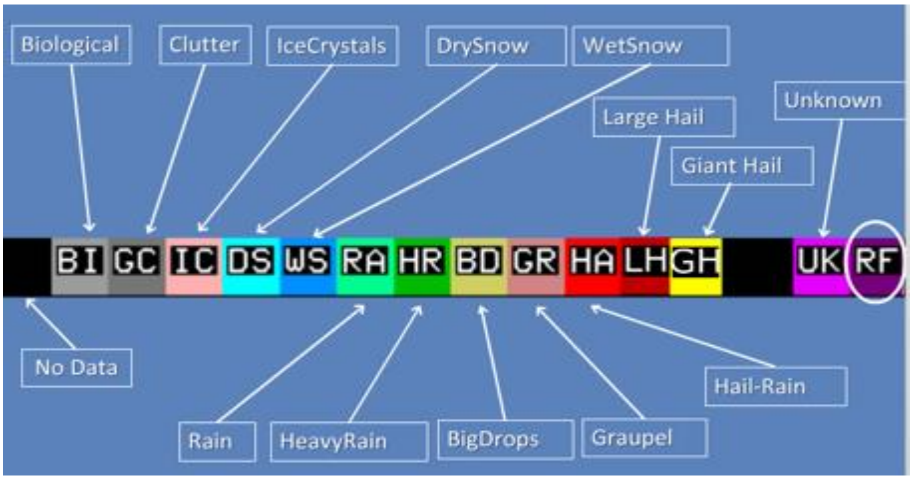


Figure 11. Hydro-meteor classification. (Source: US NWS)

Development of warning criteria

The warning criteria for hail-storms will be based on the information collected from the deployed radars. It should be noted that the main output from the radars regarding warnings will be hydro-meteor classification. Nonetheless, in order to support the warning procedures, other variables such as the differential reflectivity (ZDR), the correlation coefficient or the specific differential phase can be considered (Table 4).

Table 4. Example of different thresholds for hail warning purposes

		Green	Yellow	Orange	Red
Hail	ZDR	>1	<1	<0.5	<0.25
	Correlation Coefficient	>1.1	>1	>0.95	<0.95
	Specific Differential Phase	1	<0.6	<0.5	<0.3

Strong-wind forecasting

This project will develop NHMS capabilities to forecast extreme wind events. It should be noted that this will build upon the forecasting capabilities that will be developed within the framework of this project, especially in the meteorological forecasting capabilities. The strong winds EWS will be based on the use of forecasting information from numerical weather products and from local monitoring data.

Strong winds are due to a strong pressure gradient force. A pressure gradient is how fast pressure changes over distance. Thus, when pressure changes rapidly over a small distance, the pressure gradient force is large, and therefore strong winds almost always result from large pressure gradients. Most wind monitoring and warning applications are based on:

- Ground station data
- Satellite and weather radar data
- Weather Forecasting (numerical modelling)

The strong-wind forecasting will depend mainly on the direct products from the NWP models. As noted above, a new numerical weather forecasting product will be implemented in Azerbaijan within the framework of this project. Presently, there is no Local Area Model (LAM) implemented in Azerbaijan, and the predictions of the NHMS are based on global or regional models. The implementation of a LAM in Azerbaijan will increase the accuracy of the results from a forecasting point of view. This will especially be the case for the strong-wind forecasting. The accuracy of strong-wind forecasting from Global coverage models (GCM) as compared to LAMs have been the objective of several research initiatives. It should be noted that, while in some cases the GCM does provide better information in terms of the wind intensity, a LAM is able to capture all of the features and flow processes related to the wind dynamics. Therefore, if the implement LAM is coupled to a GCM, the accuracy of results of the wind forecasting will be enhanced. It should be noted that in addition to the implementation of the LAM, and especially for wind-forecasting, assimilation processed will be implemented. This is paramount for wind-forecasting, as it increases the reliability of the data. Furthermore, it should be added that the wind output will be one of the main inputs for the sea-wave forecasting.

Design of the wind forecasting system

The design of the system will be built upon the new meteorological forecasting capabilities of NHMS. The use of local meteorological forecasting products will be particularly important in this system. The new NWP model to be implemented in NHMS will produce several results, one of them being wind predictions at different altitudes.

Historical information

Historical information pertinent to the wind forecasting will be collected. At this stage, a validation (and calibration if required) of the to be developed meteorological products against observational data will be carried out. During this stage, the following will be accomplished:

- Data from different and significant strong-wind events will be collected. These data will be from:
    - Automatic weather station in Azerbaijan
    - Weather radar and satellite
    - Results from Global coverage models
- The collected data will be analysed with the following objectives:
    - To ascertain the quality of the GCM predictions.
    - To ascertain the reliability of the monitoring network data
    - To define thresholds for the wind forecasting.

Product Development

The product development of the wind forecasting will be based on the historical information collected on the previous implementation stage and the outputs from the implemented NWP model. Wind forecasting is a direct by-product of the meteorological forecasting. Meteorological forecasting models usually can provide different variables, including precipitation and wind speed and direction. The use of observational data will be considered here too, keeping in mind the accuracy of the historical data sources. This will provide more accurate wind information than the forecasted one. It should be noted that wind forecasting information is usually fairly accurate, especially if assimilation processes are implemented. The station data will also be used for assimilation purposes.

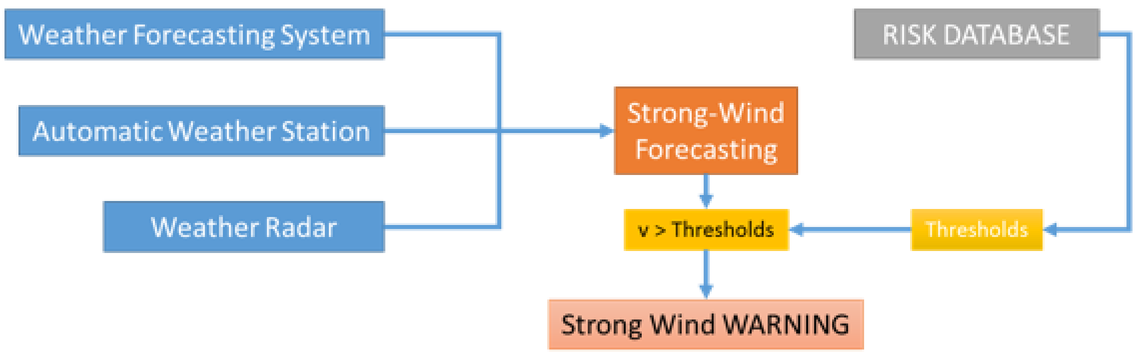


Figure 12. Strong Wind Forecasting Approach

Development of warning criteria

Based on the historical information and the product development, warning criteria will be defined within the framework of this project. An example of threshold values is given for the strong wind forecasting (Table 5). More information about strong wind threshold levels should be collected from previous events and these values should be adjusted.

Table 5. Example of different wind speed thresholds for warning purposes

	Green	Yellow	Orange	Red
Strong Wind	Gusts less than 80 km/h	Mean Speeds between 50 and 65 km/h	Mean Speeds between 65 and 80 km/h	Mean Speeds in excess of 80 km/h
		Gusts between 90 and 110 km/h	Gusts between 110 and 130 km/h	Gusts Speeds in excess of 130 km/h

Wave forecasting

Sea-surface waves are the result of forces acting on the sea. The predominant natural forces are pressure or stress from the atmosphere (especially through the winds), earthquakes, gravity of the Earth and celestial bodies (the Moon and Sun), the Coriolis force (due to the Earth's rotation) and surface tension. In the case of the Caspian Sea, and due to the limited surface available, the main driver for the sea-waves are the winds. Even if the available fetch area in the Caspian Sea is limited, significant wave heights (average wave height of the highest one-third of the waves) have a critical impact on offshore activities. The short period of the waves and the high significant wave heights can result in several activities being deeply disturbed. Therefore, a wave forecasting system will be implemented within the framework of this project.

Design of the wave forecasting system

Wave forecasting systems are based on the implementation of wave prediction models. As noted, as initial wave model will be implemented within the risk assessment stage of this project. The resulting wave model will be implemented in operational mode during the forecasting implementation. Regarding wave models, it should be noted that the two most important sources of information are the bathymetry and the wind fields. While the bathymetry of the Caspian Sea can be obtained from global sources (such as GEBCO (https://www.gebco.net/)) or from local sources, the wind fields will be obtained mostly from the NWP implemented within the framework of this project. It should be added that, given the peculiarities of the Caspian Sea, it is recommended that, for operational forecasting, two different models are implemented. One covering the whole Caspian Sea and with a larger resolution, and another one centered in the Azerbaijani coast, with a smaller horizontal resolution, and nested to the coarser resolution one.

Furthermore, the latest research shows that in some locations the ocean currents can have a significant influence on the wave dynamics. This is especially the case in locations with significant tide ranges and/or with high intensity currents (caused by differences in density). In this case, however, it is not believed that the currents on the Caspian Sea are significant enough to cause an impact on the wave dynamics. The implementation of a couple ocean current-wave model is not therefore considered necessary, although this will have to be ascertained during the historical information stage.

Historical information

A historical assessment of the wave regime will be undertaken, collecting information about significant and maximum wave heights during extreme events, as well as wind and pressure information during these events. It should be noted that the monitoring capacities of NHMS for waves are considered sufficient, with seven wave buoys deployed in the Azerbaijani coast. The inclusion of wind monitoring information in this wave buoys and the possibility of enhancing the real-time data transmission from these sensors will be fully explored too.

The main output from the historical analysis will be wave and climate information that will be used in the verification and validation of the forecasting model.

Product Development

The wave forecasting product will be based on the implementation of a wave model. This model, previously implemented during the risk knowledge component, will be used in hindcast mode to validate its suitability for forecasting purposes. The outputs of the meteorological forecasting model will be critical during this stage, because as noted the main forcing for the wave regime in the Caspian Sea is the wind. Information from the forecasting will be combined with observational data from the buoys and onshore wind monitoring stations. Assimilation of the wave observations into the wave forecasting platform will also be undertaken in order to increase the accuracy of the results.

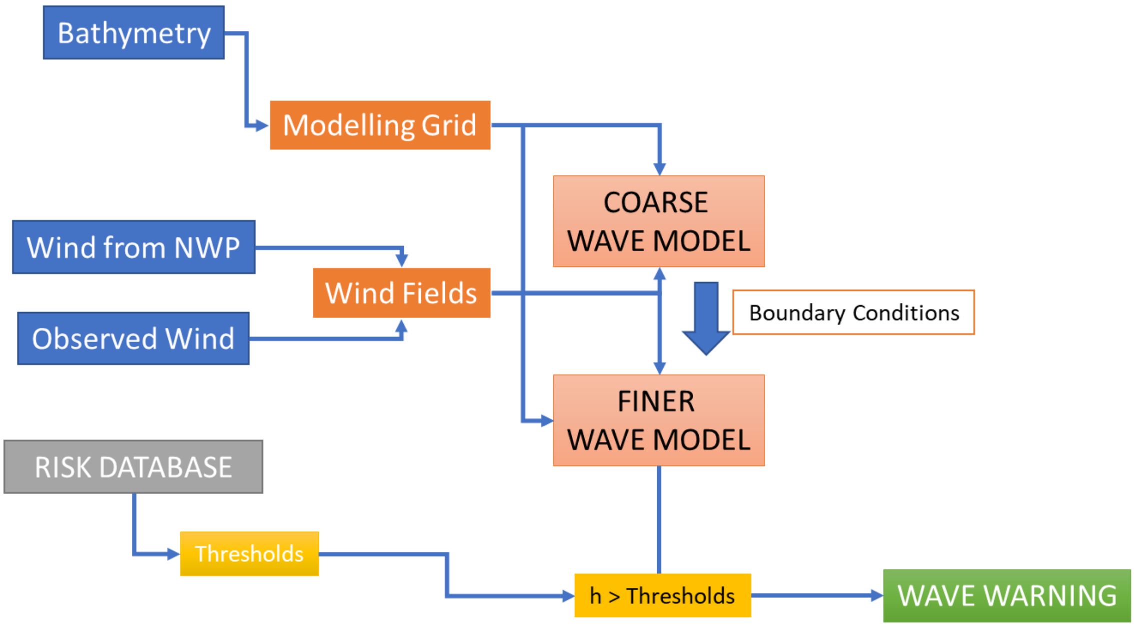


Figure 13. Wave Forecasting Approach

Development of warning criteria

The warning criteria for waves will be based on an analysis of the historical impact of waves on offshore activities. An example of threshold values is given for the wave forecasting (Table 6). More information about wave threshold levels should be collected from previous events and these values should be adjusted.

Table 6. Example of wave thresholds for warning purposes

		Green	Yellow	Orange	Red
Waves	Significant Wave Height (m)	<2	2.5	3	>4
	Maximum Wave Height (m)	<2.5	3.1	3.7	>5

Extreme Temperature Forecasting

This project will also develop NHMS capabilities to forecast extreme temperatures events. It should be noted that this build upon the new forecasting capabilities, especially in meteorological forecasting. The extreme temperature forecasting EWS will be based on the use of forecasting information from numerical weather products and from local monitoring data.

Design of the extreme temperature forecasting system

The design of the system will be built upon the to be acquired meteorological forecasting capabilities of NHMS. The use of local meteorological forecasting products will be important in this system.

Historical information

Historical information pertinent to the temperature forecasting will be collected. At this stage, a validation (and calibration if required) of the existing meteorological products against observational data will be carried out.

Product Development

It should be noted that temperature forecasting is a by-product of the meteorological forecasting. Meteorological forecasting models usually can provide different variables, including precipitation, temperature, and wind speed and direction. The use of observational data will be considered here too. This will provide more accurate temperature information than the forecasted one. It should be noted that temperature forecasting is more accurate if assimilation processes are implemented. The station data could be used for these purposes.

Development of warning criteria

Based on the historical information and the product development, warning criteria will be defined within the framework of this project. More information about temperature threshold levels should be collected from previous events and these values should be adjusted. It should be noted that at this stage the collaboration between the Ministry of Agriculture and the NHMS is critical for the successful warning criteria definition. A suggested approach for the different warning criteria for extreme temperature is shown in Table 7.

Table 7. Example of different extreme temperature thresholds for warning purposes

		Green	Yellow	Orange	Red
Temperature	Mean daily temperature (ºC)	<20	>20	>24	>28
	Maximum daily temperature (ºC)	<27	>27	>30	>35

Air Quality Forecasting

The air quality forecasting product will be based on both, data from the air quality monitoring network, and the meteorological forecasting to be implemented. It should be noted that most NWP products available have air-quality modules that can be added to the NWP. This is the case, for instance, for the WRF (Weather Research Forecasting) NWP software, with the WRF-CHEM module available for air-quality forecasting.

Design of the air quality forecasting system

The implementation of the air quality forecasting platform will be embedded within the NWP implementation, including the air pollution dispersion add-ons. As noted above, there are several add-ons to NWP for air quality and pollution purposes. The implementation of the LAM NWP in Azerbaijan will serve several purposes, including the inclusion of local air quality forecasting products.

Historical information

Historical information pertinent to air quality-pollution forecasting will be collected. At this stage, a validation (and calibration if required) of the existing air quality products against observational data will be carried out. As noted above, the air quality monitoring network has recently been expanded in Azerbaijan, with the inclusion of additional air quality stations. There are plans for further extensions, in order to replace the old air quality monitoring stations with more up to date ones. The data from these stations, as noted above, will be ingested into the climate risk platform for dissemination, but it will also be used for assimilation and forecasting purposes within the air quality forecasting platform.

Product Development

As previously noted, the air quality forecasting is an additional product of meteorological forecasting. The implementation and calibration of the NWP will be critical to ensure that the air quality module is fit for purpose. The use of observational data will be considered here too. This will provide a more accurate air quality information than the forecasted one. The following information can be produced by the air quality module for most software applications:

- Anthropogenic emissions
- Biogenic emissions
- Surface biomass burning data
- Volcanic Ash emissions
- Aircraft emissions
- Green House Gas emissions

The choice of the output options outlined above will be decided during the implementation and considering the data available from the monitoring stations and the hazard and risk identified during the risk assessment stage.

Development of warning criteria

The warning criteria will be developed considering the information collected from the monitoring network, the historical analysis and the hazard and risk assessment results.

It is envisaged that thresholds values will be defined for PM2.5, PM10 and dust using those data sources.

Table 8. Example of different air quality thresholds for warning purposes

		Green	Yellow	Orange	Red
Air Quality	PM 2.5 (µg/m3)	<15	>15	>35	>50
	PM 10 (µg/m3)	<10	>10	>30	>50
	Dust (µg/m3)	<10	>10	>30	>50

Multi-Hazard Forecasting

<u>Approach</u>

There are several relationships to be considered in the multi-hazard approach. Apart from the fact that the monitoring hydro-meteorological network (to be upgraded within the framework of this project) will be used by different hazards, it should be noted that the occurrence of some of the hazards may trigger another, and therefore, this will be considered in the design. The following relationships can be identified (Table 9). It should be noted that some of these relationships address hazards that are not considered within the framework of this programme. Nonetheless, due to the multi-hazard approach, it is considered necessary to consider them for prevention and forecasting purposes; although as secondary hazards, just the ones considered within this programme are being addressed.

Table 9. MHEWS Relationships

		Secondary Hazard						
		Floods	Mudflows	Droughts	Strong Winds	Landslides	Hail	Sea-waves
Primary Hazard	Floods							
	Mudflows							
	Strong Winds							
	Landslides							
	Hail							
	Sea-waves							
	Earthquake							
	Subsidence							
	Extreme Hot Temperature							
	Wildfires							

Table 9 above should be reviewed more carefully once historical data is collected and more information is available regarding the relationships of several hazards in Azerbaijan.

Impact-Based Forecasting

Approach

The implementation of impact-based forecasting will be undertaken with great care within the framework of this project. The following stages will be followed.

- **Hazard Modelling**

The hazard modelling, within the risk assessment activities, will be the first activity to be undertaken for the impact-based forecasting. This activity will be critical for the implementation of the impact-based forecasting because in some cases the results from the modelling will have to be implemented directly in the impact-based framework.

Following with the flood example, the main approach for impact-based forecasting is described in Figure 14. While the flood forecasting will be undertaken considering the automatic station data (to be expanded within this project), the meteorological modelling/forecasting (to be implemented within this project), and the hydrological and hydraulic models (to be deployed within this project), among other system components; this information will be combined with the risk and vulnerability models (to be also implemented within this project). This will provide information, depending on pre-defined thresholds, for different warning levels.

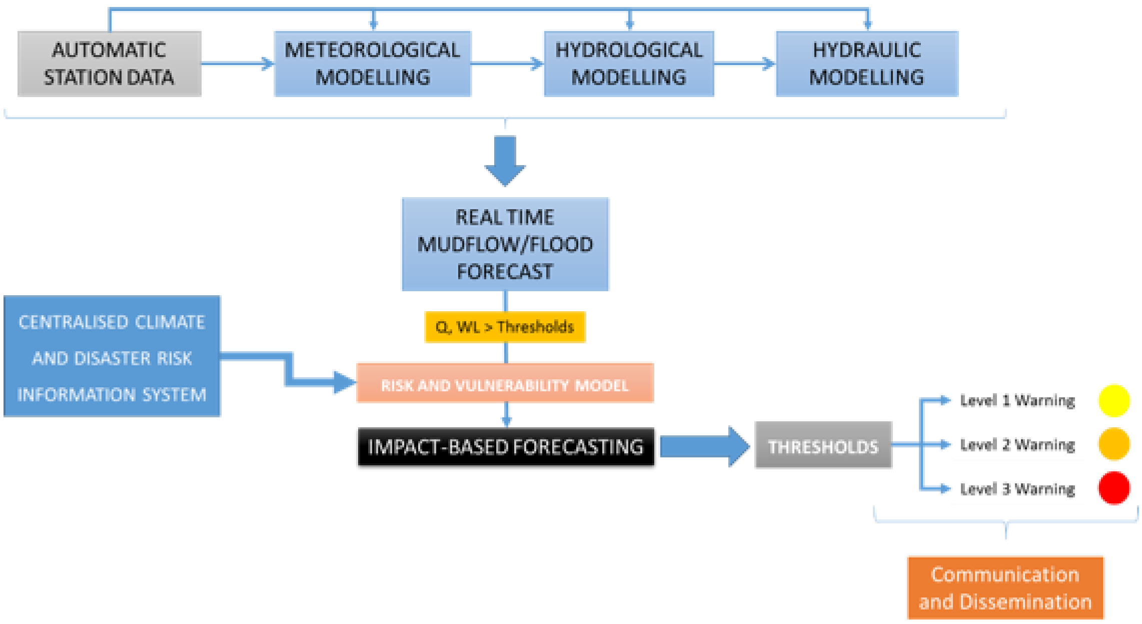


Figure 14. Impact-Based Forecasting System

However, the impact that any flood event is going to cause will need information about the water depth, water extent, water velocity, and all that information has to be combined with the information from the risk and vulnerability models. In some cases, to obtain the information of water depth, velocity and extent from a hydraulic model, it would be recommended that a 2D hydraulic modelling approach is followed. The simulation run-time of 2D models is significantly longer, and there are not usually 2D models implemented in operational mode. Therefore, it will be suggested that a range of scenarios per location are run to get the impact that any type of event may have.

- **Risk and Vulnerability Modelling**

The risk models implemented within the risk assessment activity will be used for the impact-based forecasting. As noted above, the information from the forecasting (either in pre-computed mode or in operational mode) will be combined with this model to produce impact results. It should be noted that the risk model should be maintain on a periodic basis to ensure that the information contained within this GIS model is up to date.

- **Implementation**

As previously noted, the implementation of the impact-based forecasting will depend on both the hazard forecasting and the risk model implemented. Also, when the hazard forecasting is not practical in a computational point of view (such as for 2D forecasting), pre-defined computational hazard impact will be used. In those cases, several scenarios will be hold by the impact-based forecasting platform and 'pulled-out' when the scenarios forecasted are equivalent.

- **Decision-making System**

One of the main reasons for the implementation of an impact-based forecasting is to better support decision-making procedures. To ensure this, the decision-making system will include information about the results from the impact-based forecasting.

- **Dissemination**

The dissemination of the impact-based forecasting is critical to ensure the sustainability of the system, as well as the correct application of the results. While the general population will receive warnings from a 'classical' point of view, relevant stakeholders will receive both types of information, classical warnings and impact-based warnings. The latter will be discretized depending on the sectors that the event is having on impact on.

Appendix B: Additional Weather Station Plots

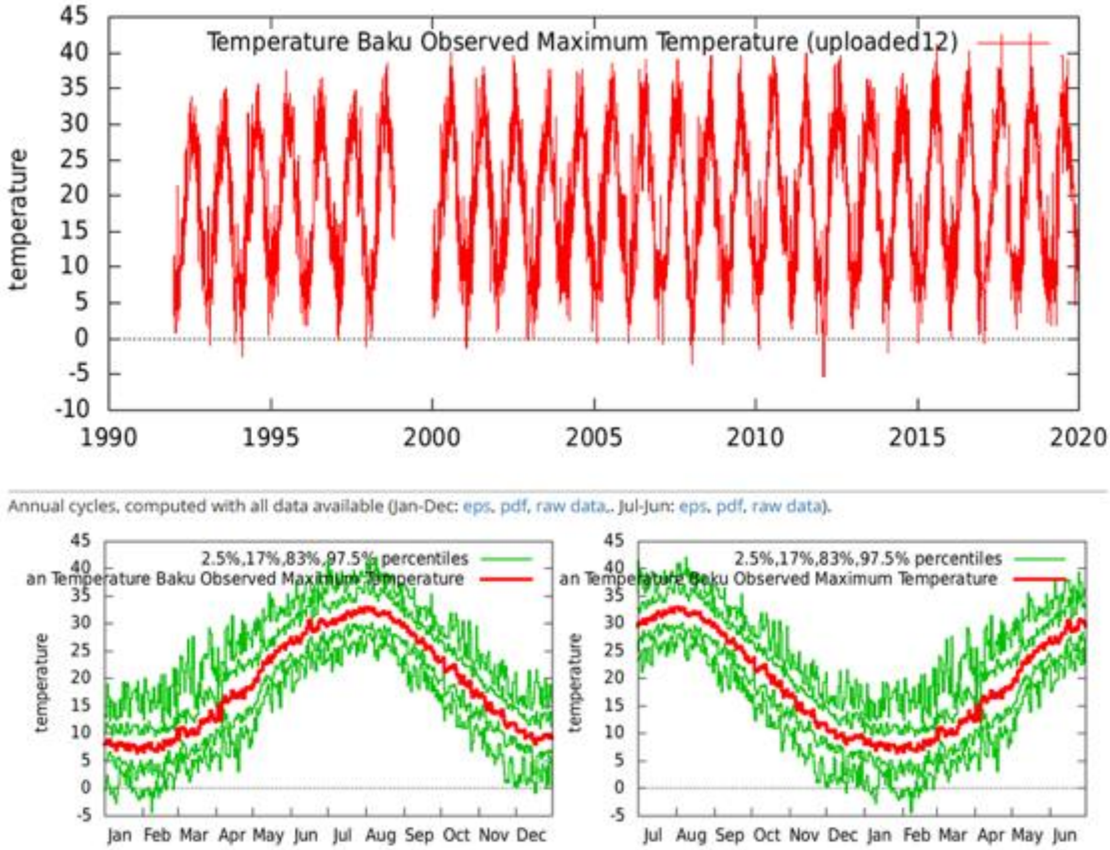


Figure 15. Observed Maximum Temperature (Baku)

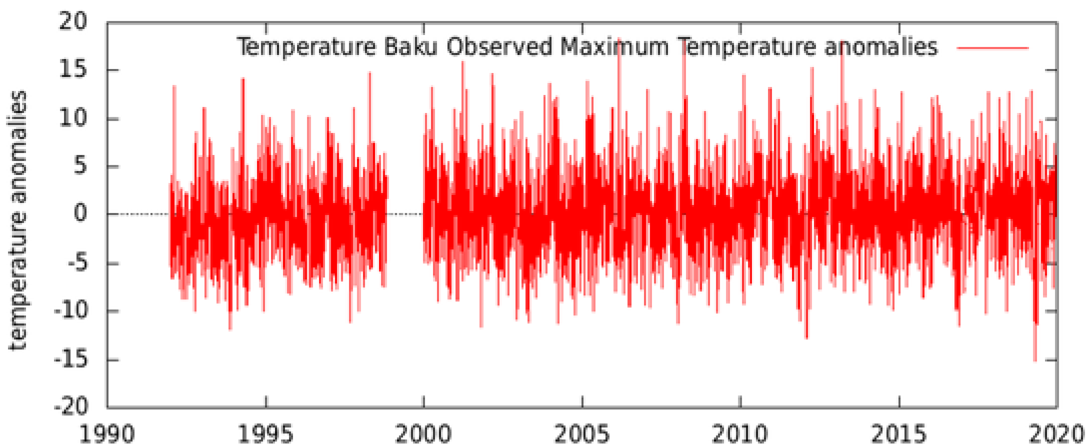


Figure 16. Observed Maximum Temperature Anomalies (Baku)

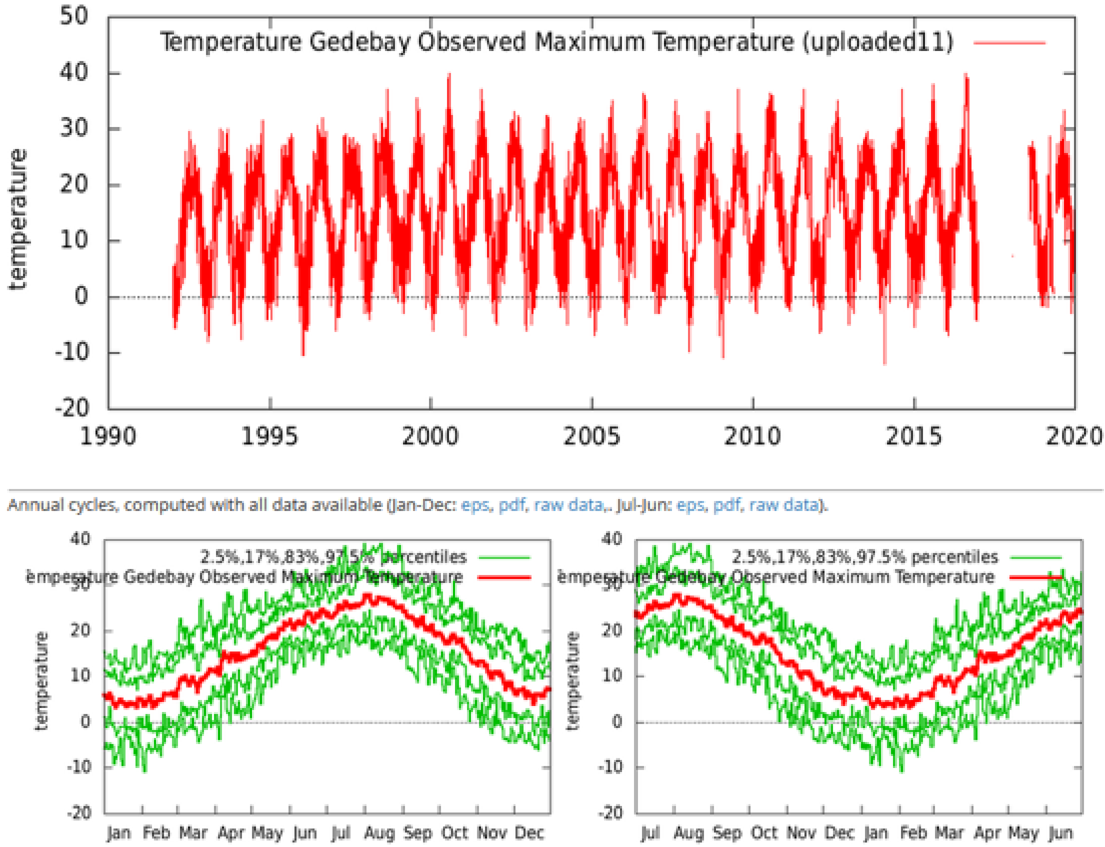


Figure 17. Observed Maximum Temperature (Gedebay)

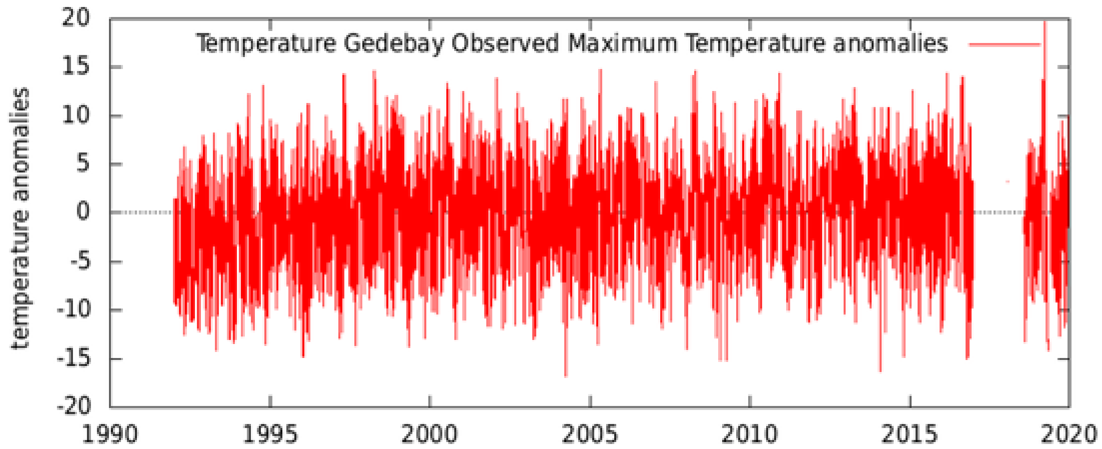


Figure 18. Observed Maximum Temperature Anomalies (Gedebay)

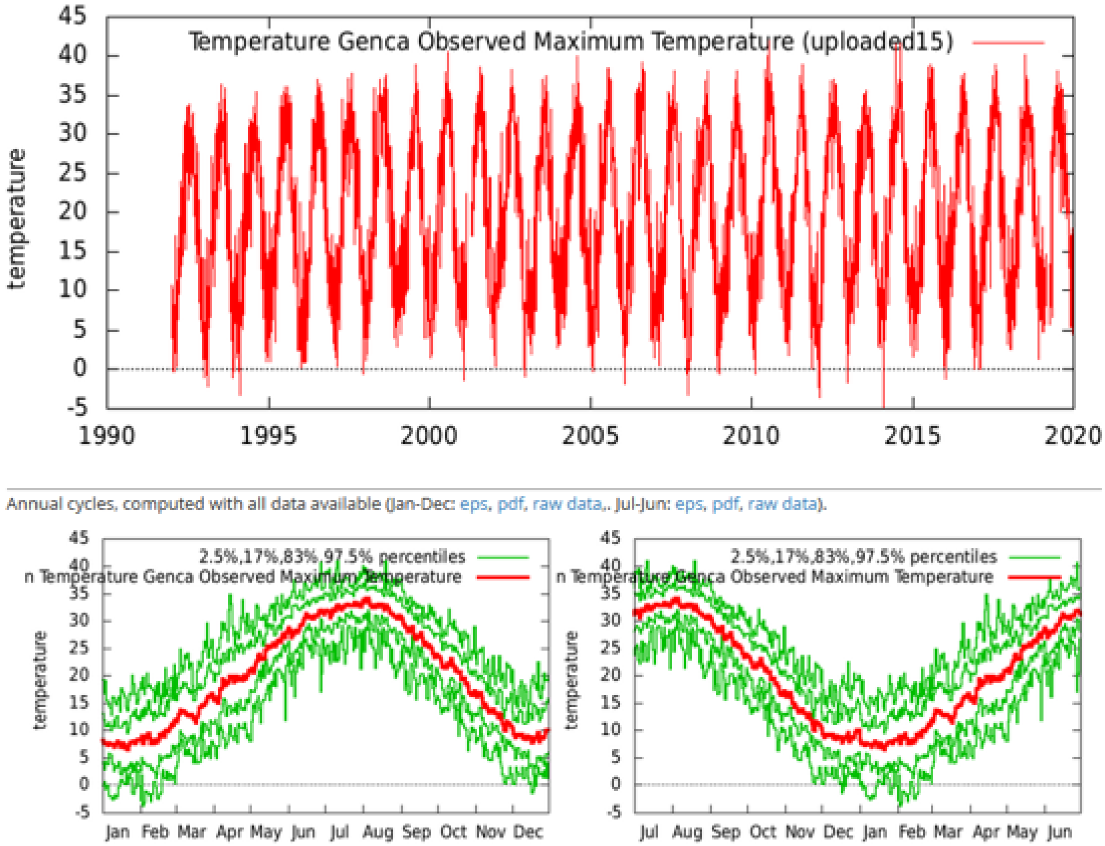


Figure 19. Observed Maximum Temperature (Genca)

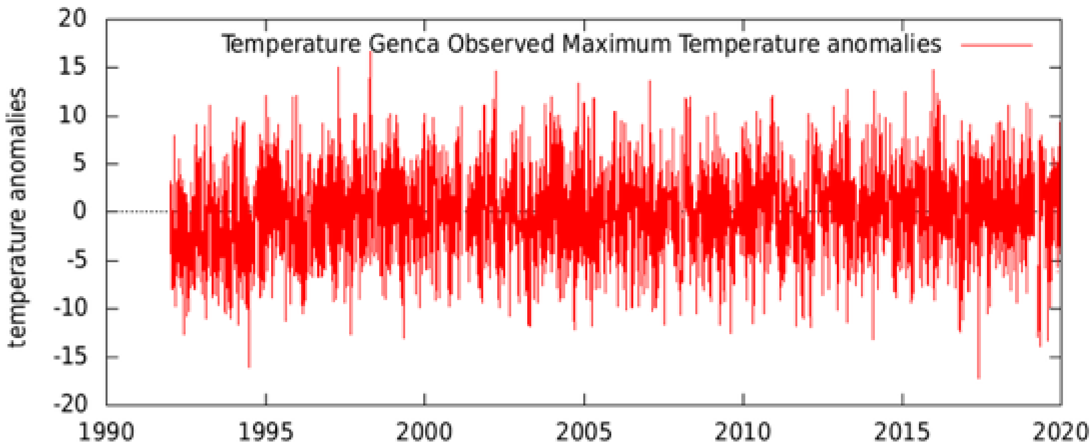


Figure 20. Observed Maximum Temperature Anomalies (Genca)

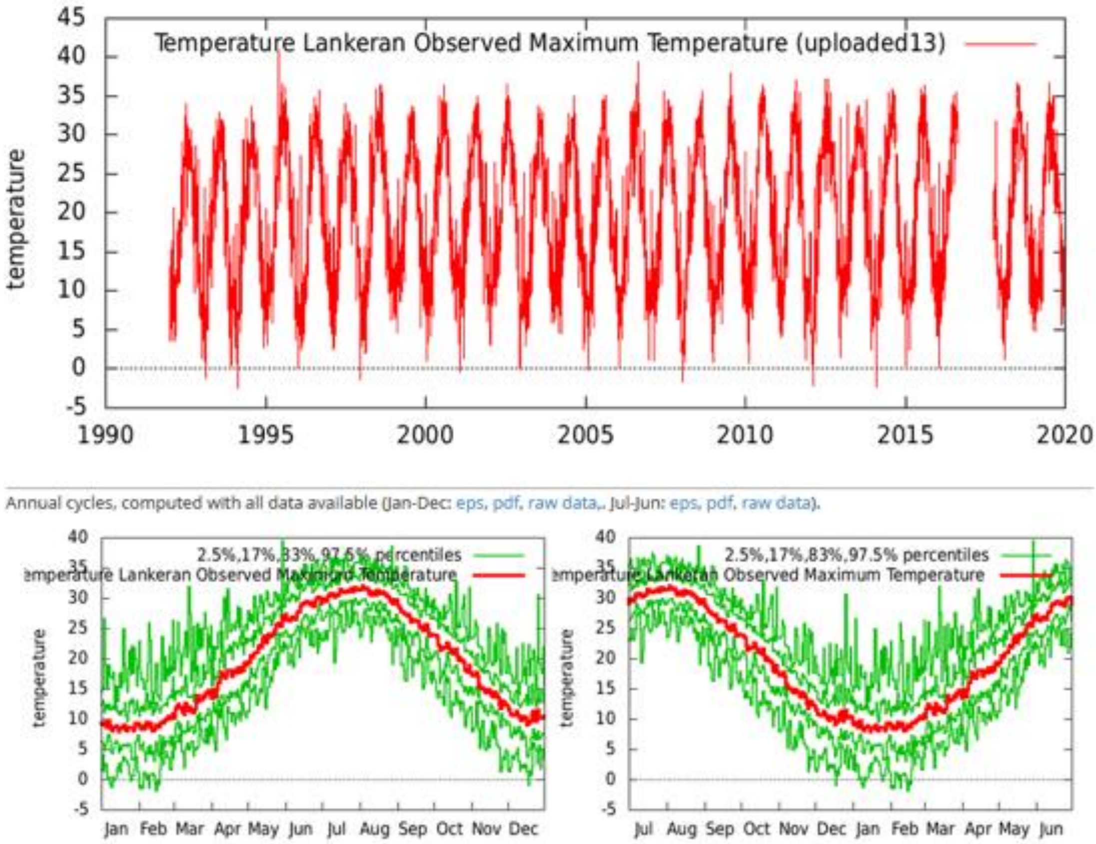


Figure 21. Observed Maximum Temperature (Lankeran)

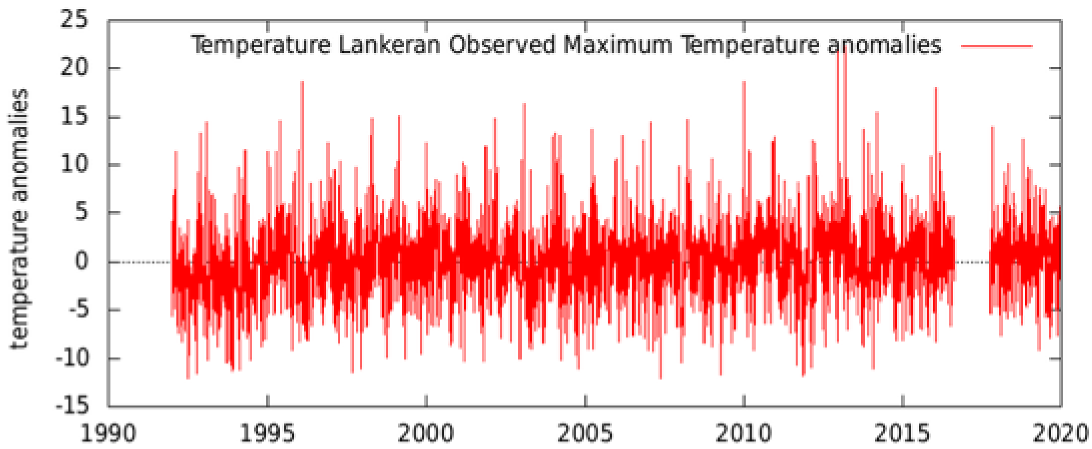


Figure 22. Observed Maximum Temperature Anomalies (Lankeran)

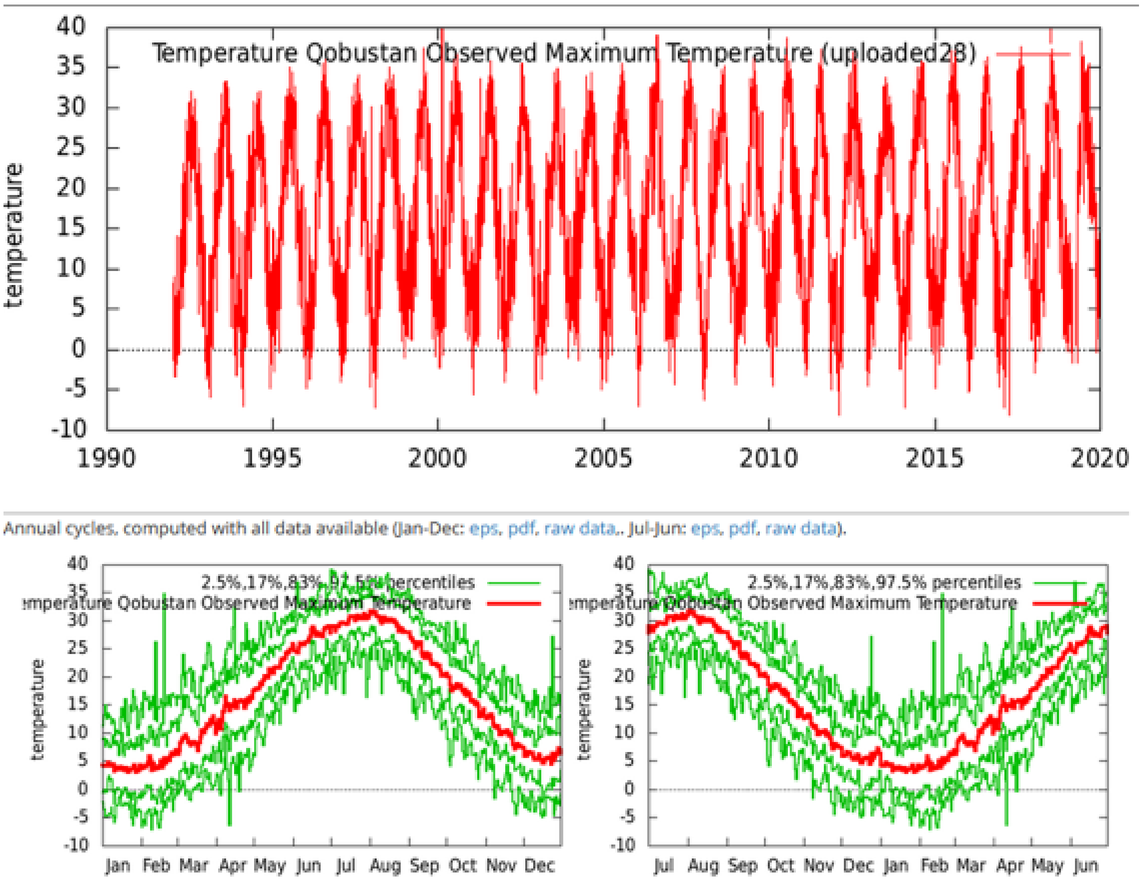


Figure 23. Observed Maximum Temperature (Qobustan)

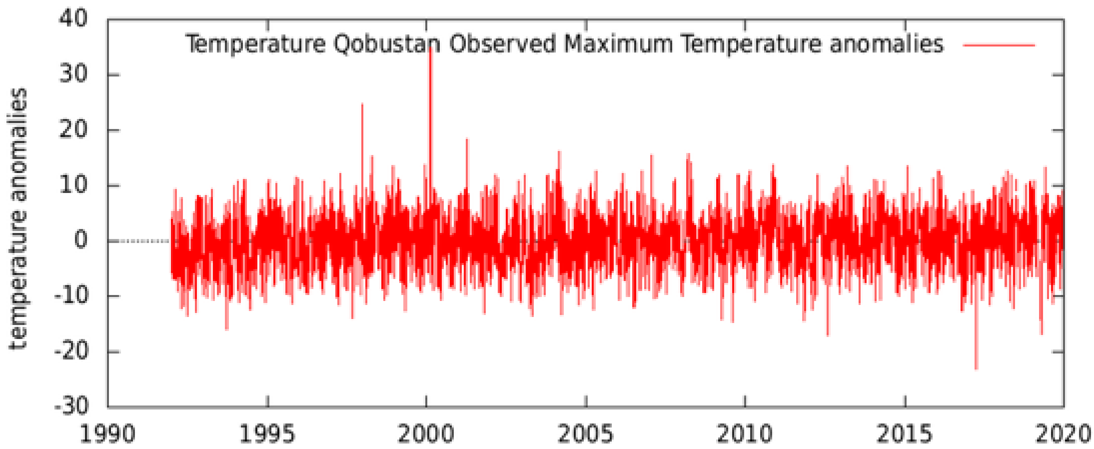
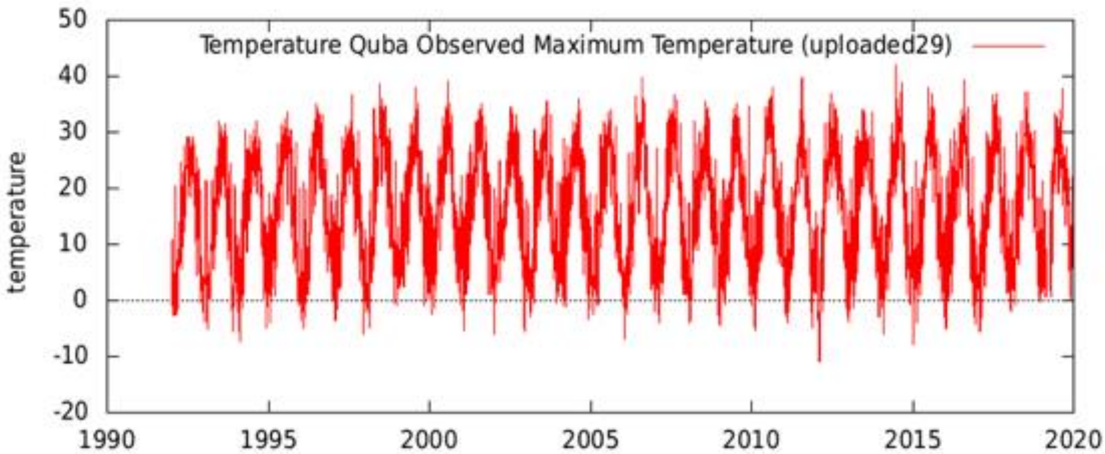


Figure 24. Observed Maximum Temperature Anomalies (Qobustan)



Annual cycles, computed with all data available (Jan-Dec: eps, pdf, raw data,. Jul-Jun: eps, pdf, raw data).

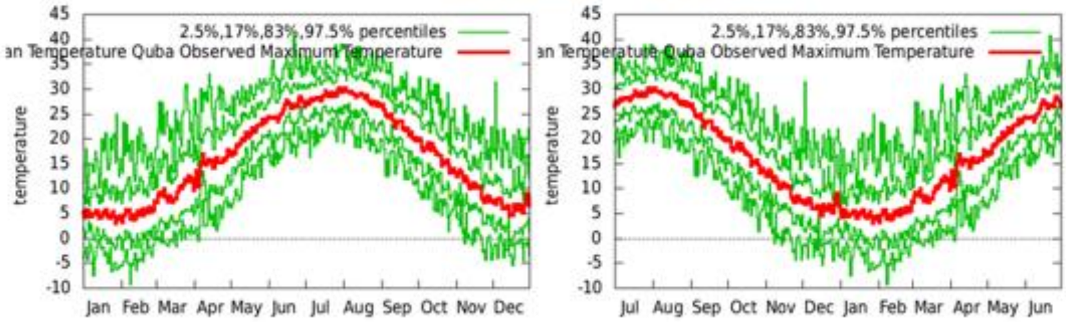


Figure 25. Observed Maximum Temperature (Quba)

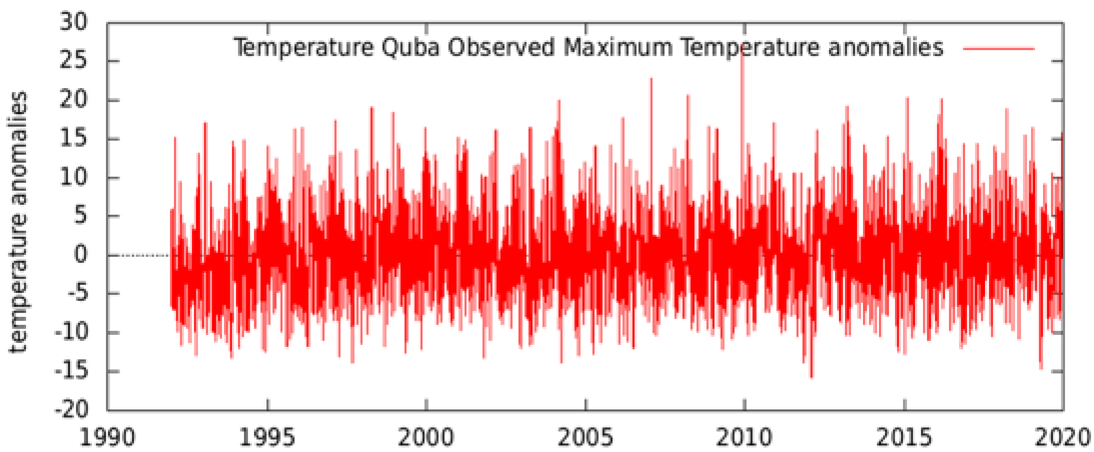


Figure 26. Observed Maximum Temperature Anomalies (Quba)

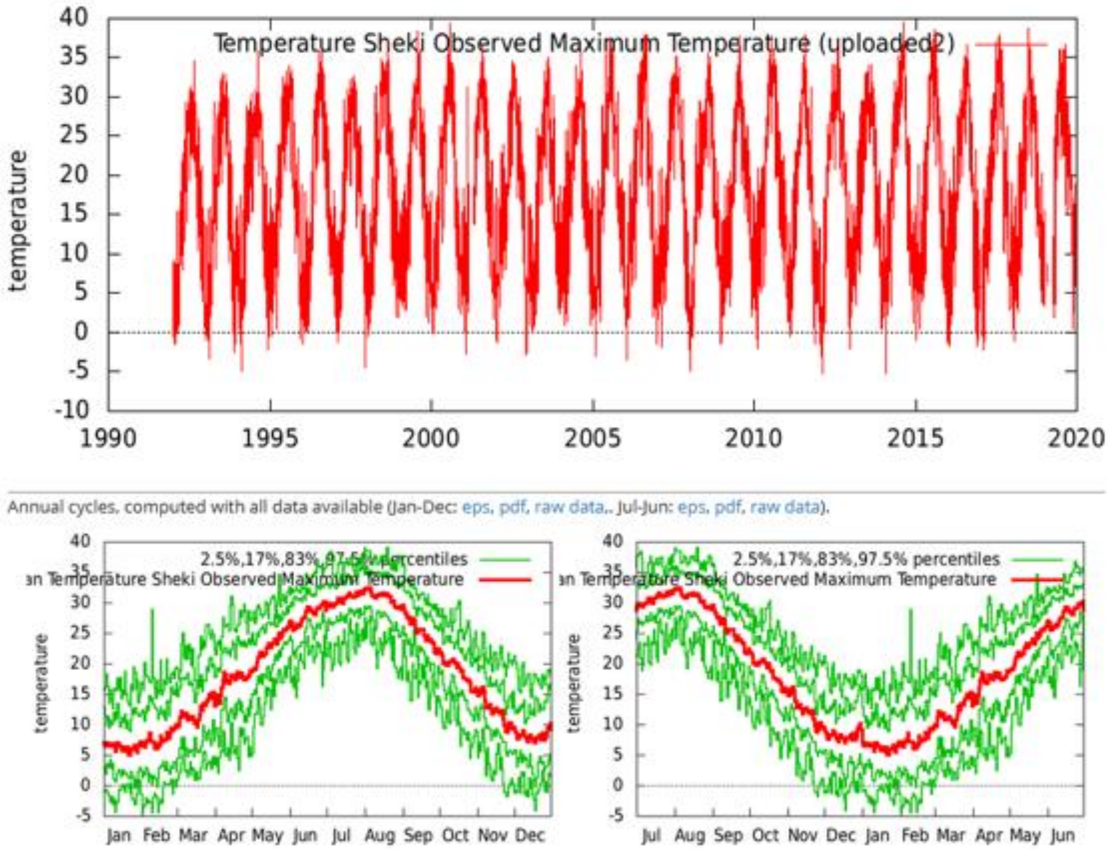


Figure 27. Observed Maximum Temperature (Sheki)

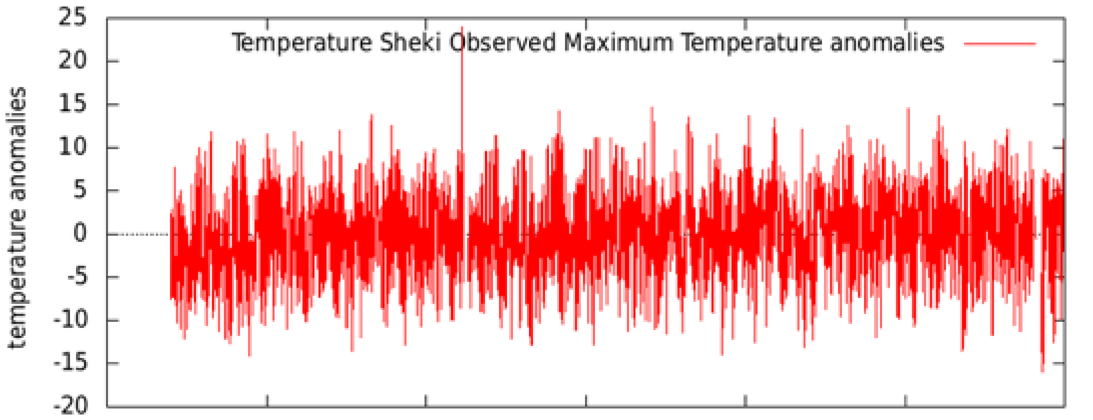
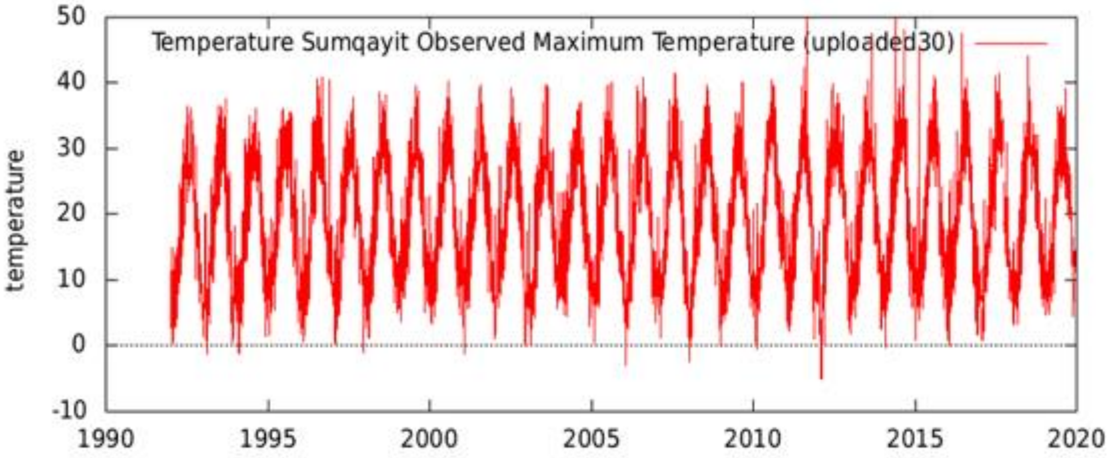


Figure 28. Observed Maximum Temperature Anomalies (Sheki)



Annual cycles, computed with all data available (Jan-Dec: eps, pdf, raw data,. Jul-Jun: eps, pdf, raw data).

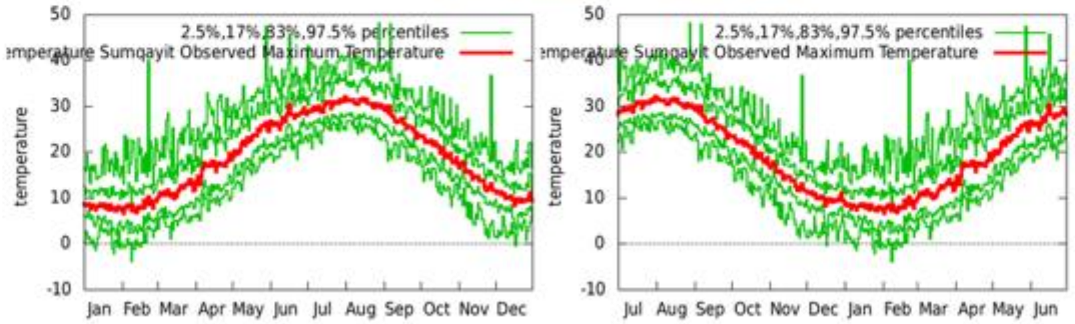


Figure 29. Observed Maximum Temperature (Sumqayit)

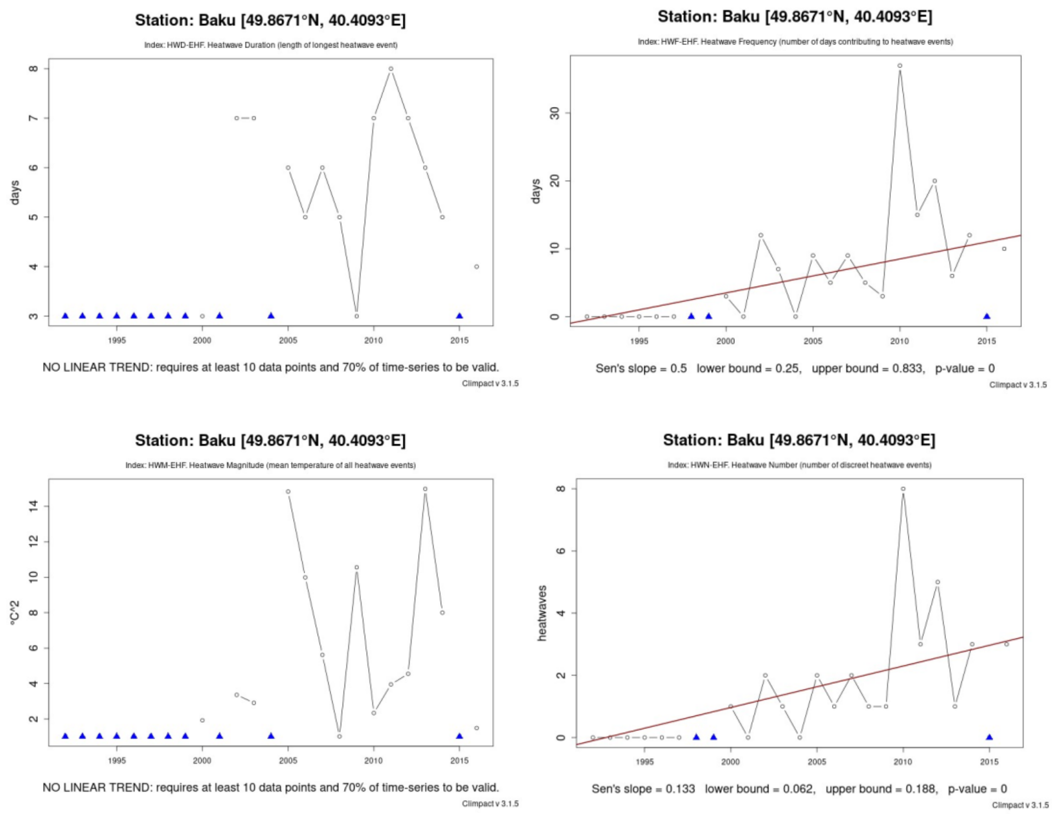


Figure 30. Excess Heat Factor (EHF) for Baku (duration, frequency, magnitude, number) 1992-2016

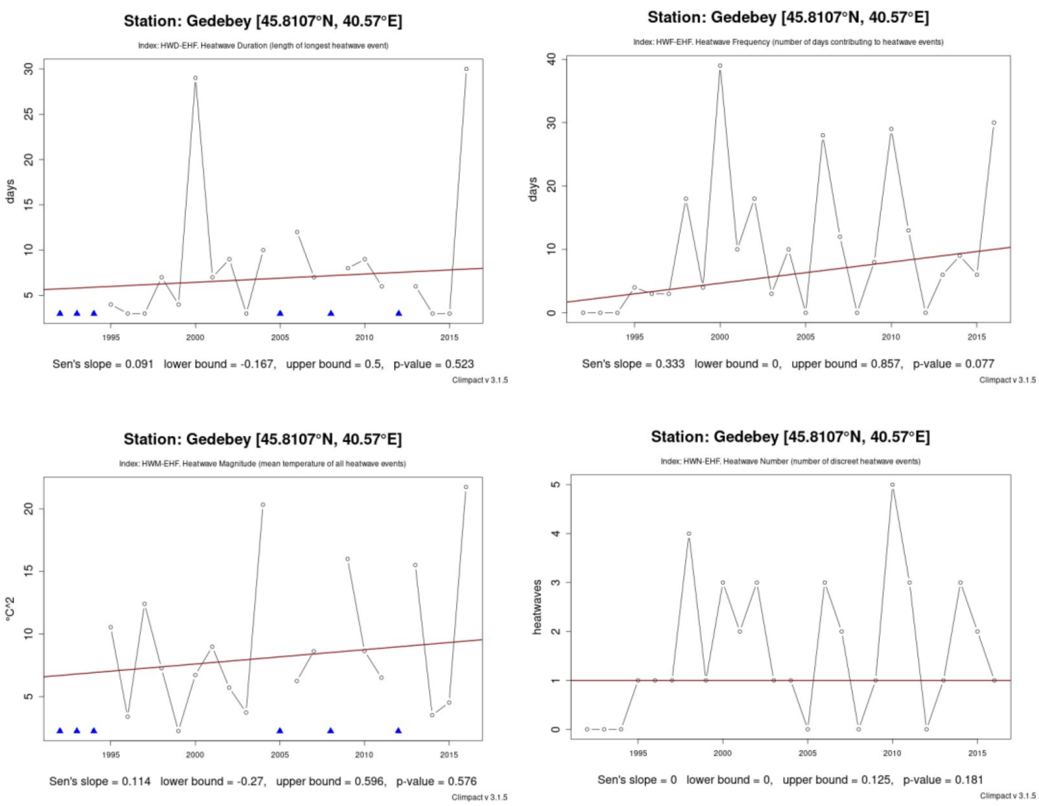


Figure 31. Excess Heat Factor (EHF) for Gedebey (duration, frequency, magnitude, number) 1992-2016

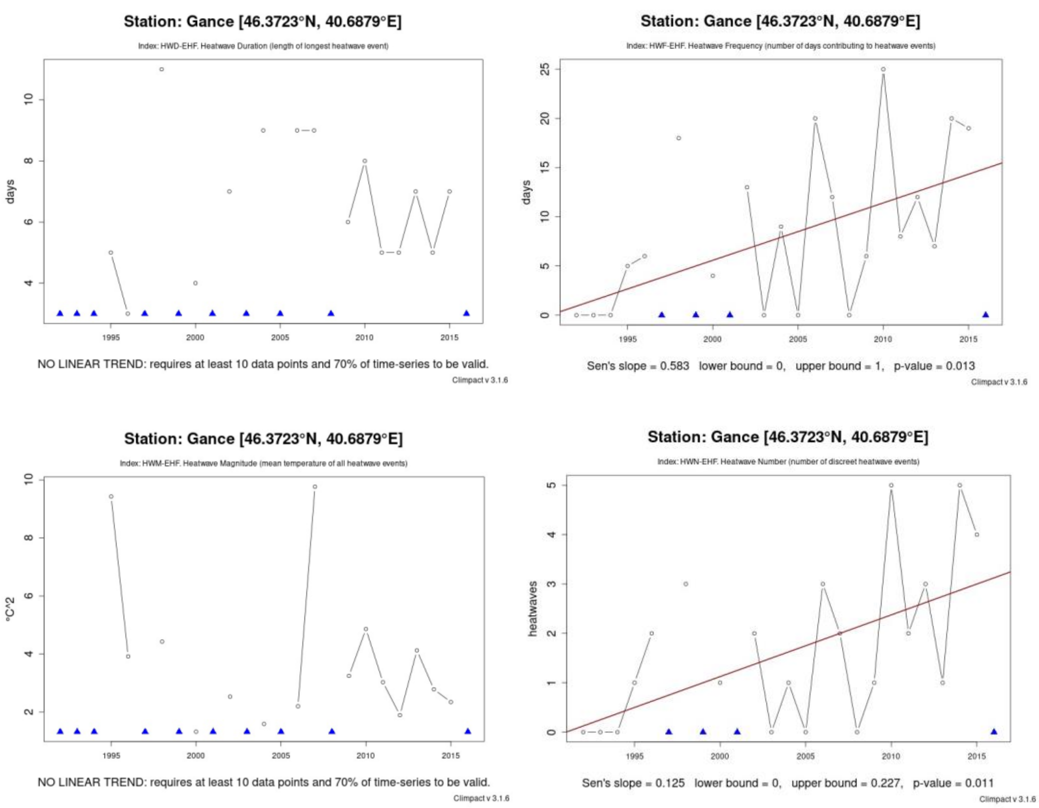


Figure 32. Excess Heat Factor (EHF) for Gance (duration, frequency, magnitude, number) 1992-2016

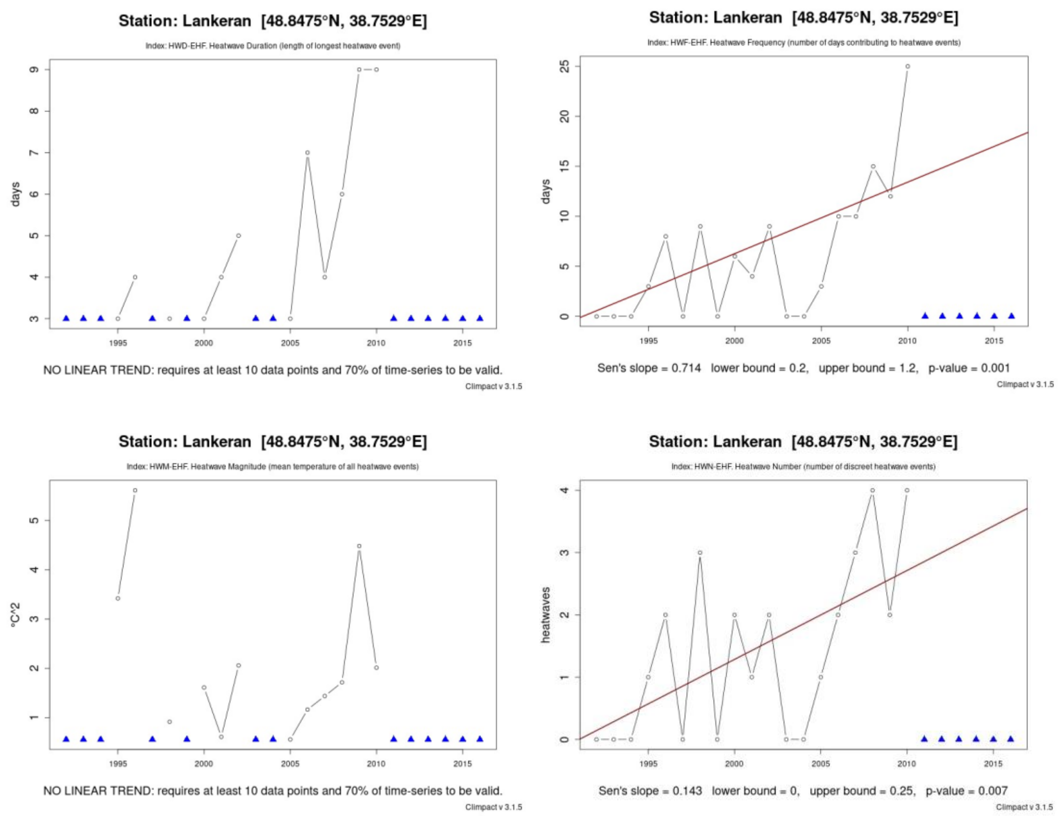


Figure 33. Excess Heat Factor (EHF) for Lankeran (duration, frequency, magnitude, number) 1992-2016

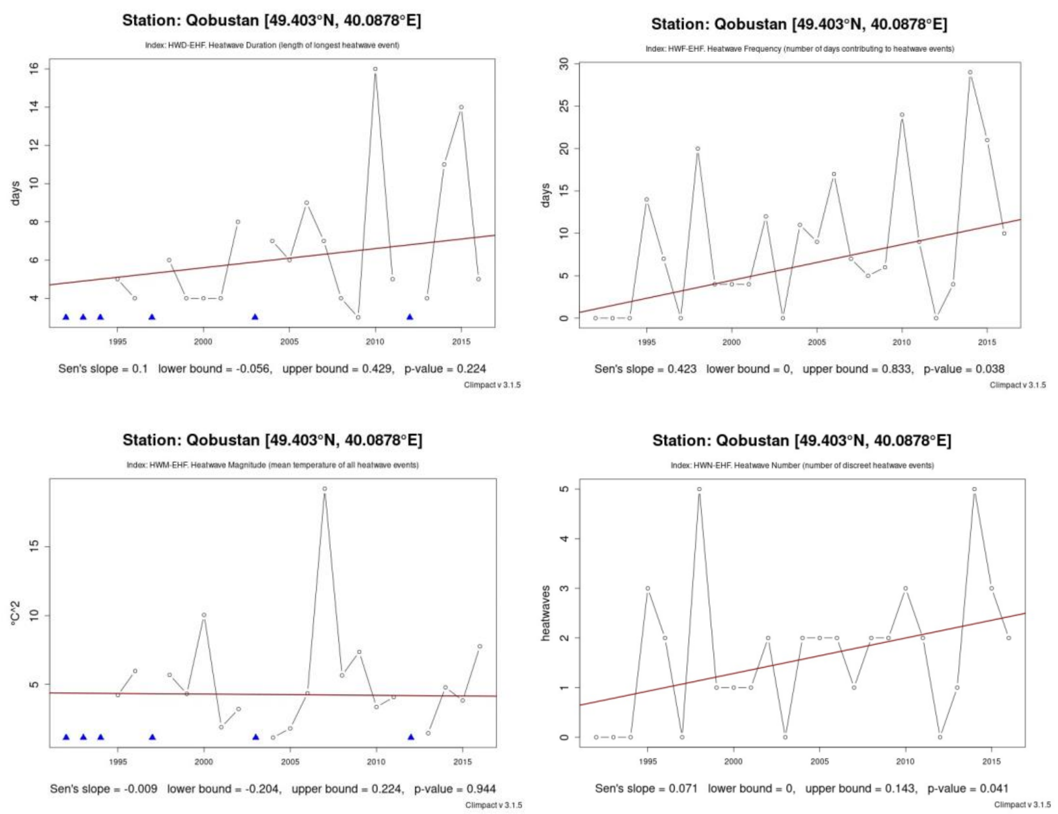


Figure 34. Excess Heat Factor (EHF) for Qobustan (duration, frequency, magnitude, number) 1992-2016

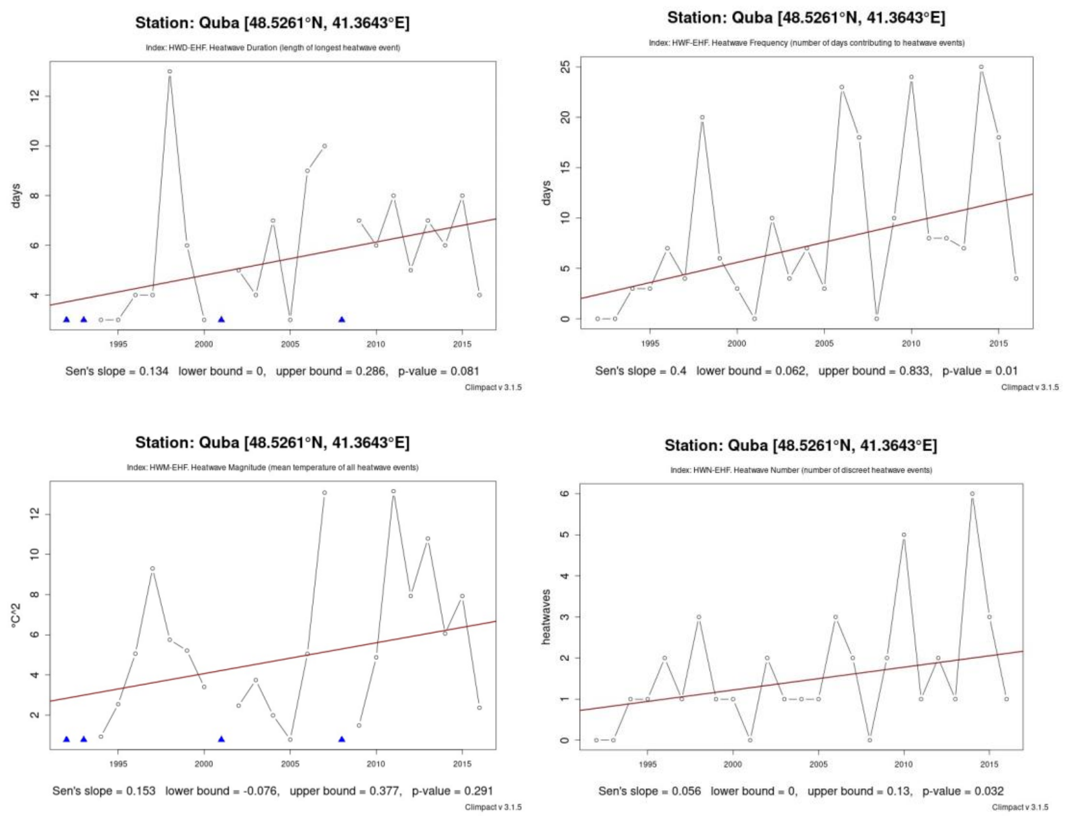


Figure 35. Excess Heat Factor (EHF) for Quba (duration, frequency, magnitude, number) 1992-2016

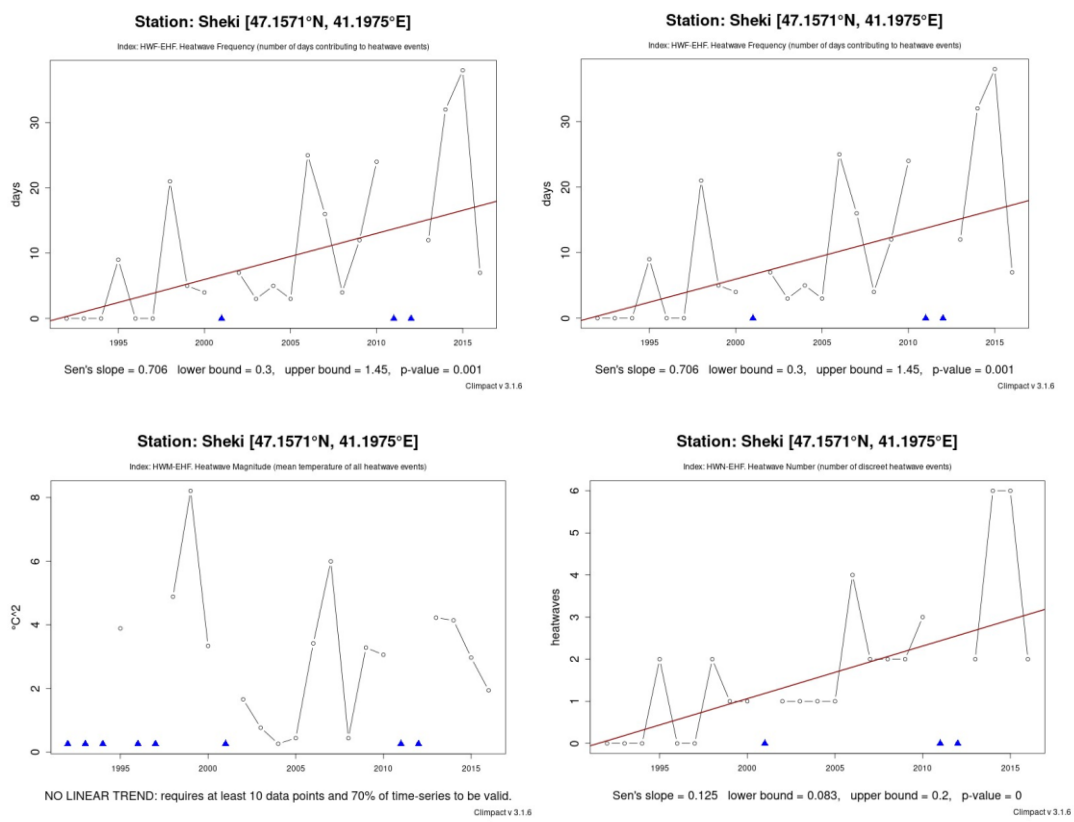


Figure 36. Excess Heat Factor (EHF) for Sheki (duration, frequency, magnitude, number) 1992-2016

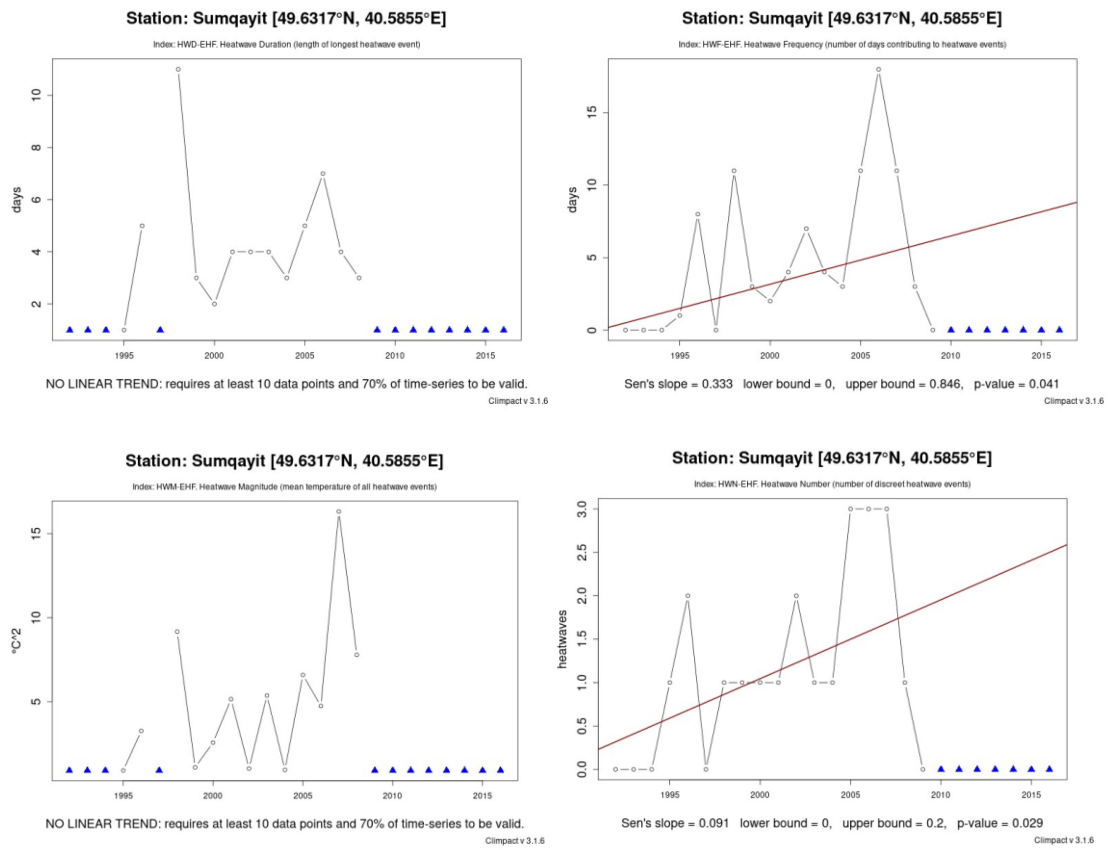
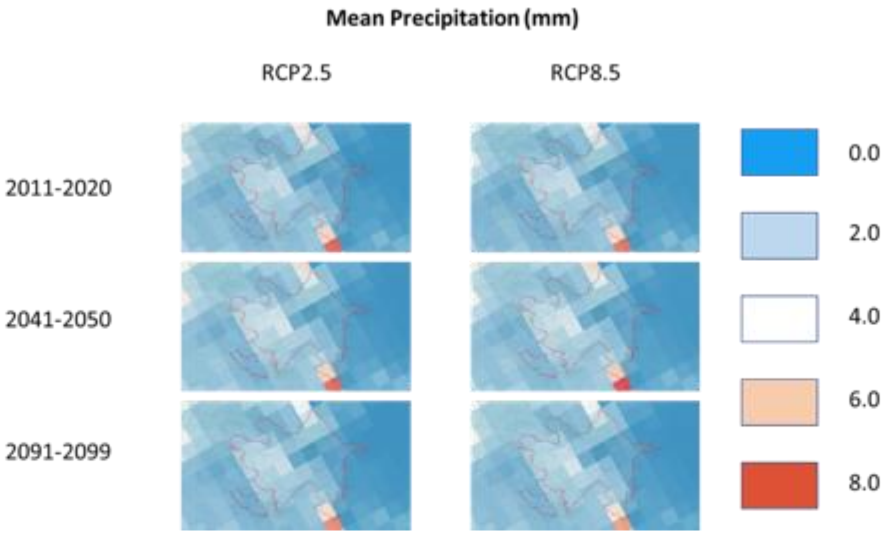
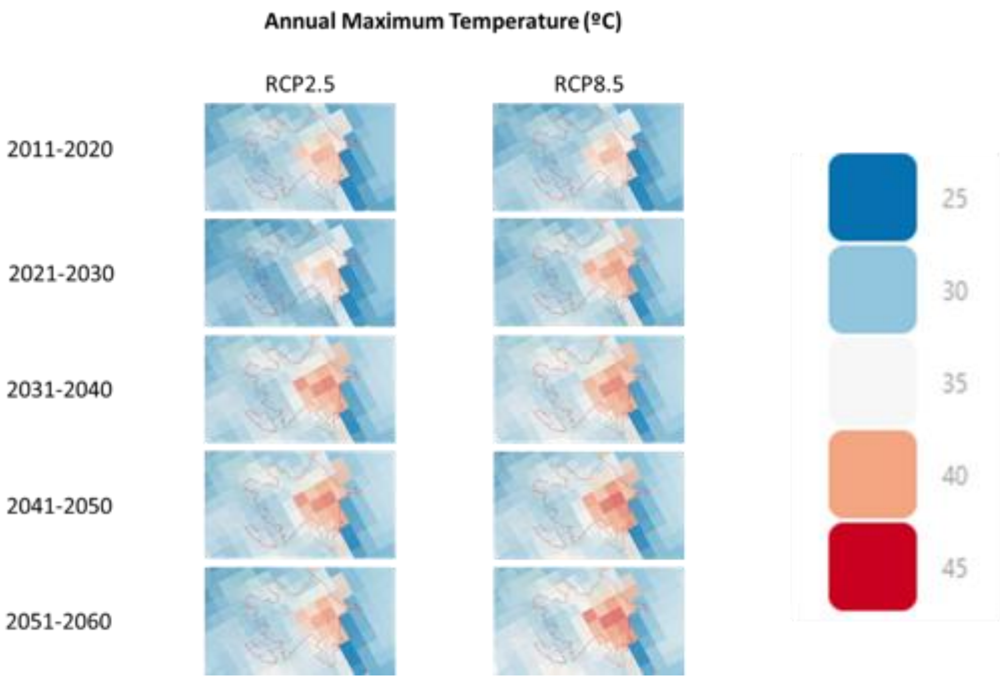


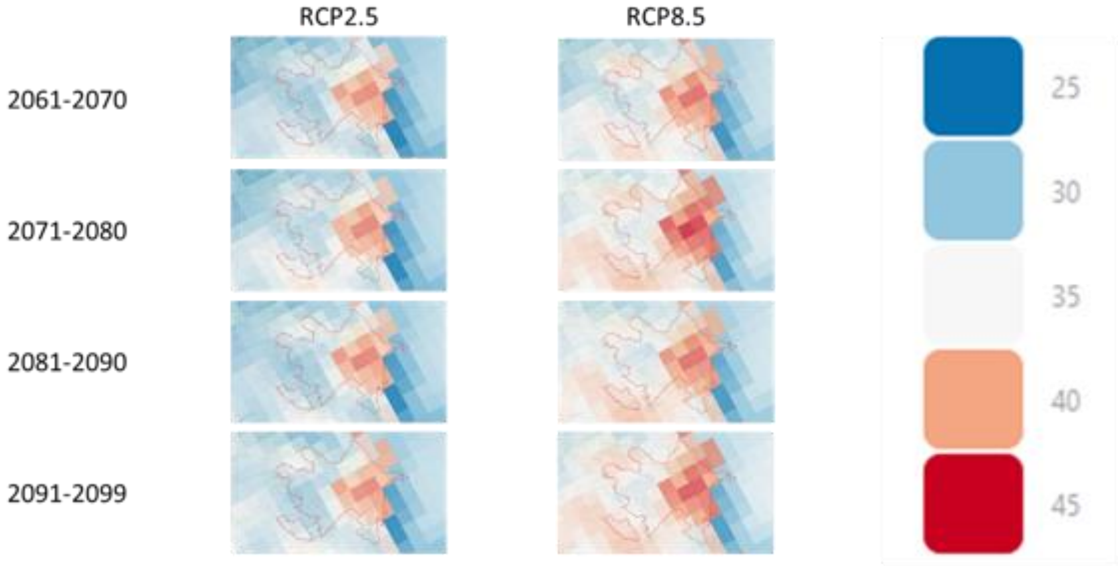
Figure 37. Excess Heat Factor (EHF) for Sumqayit (duration, frequency, magnitude, number) 1992-2016

Appendix C: Additional Spatial Projections for Precipitation and Temperature

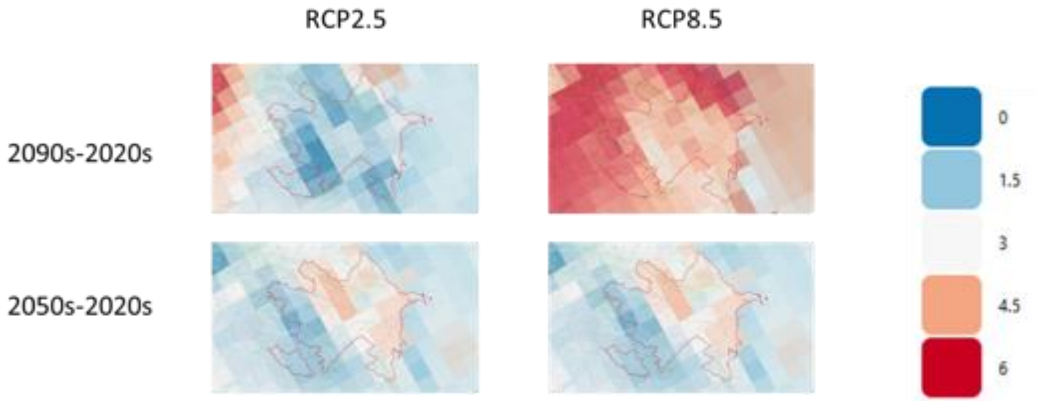




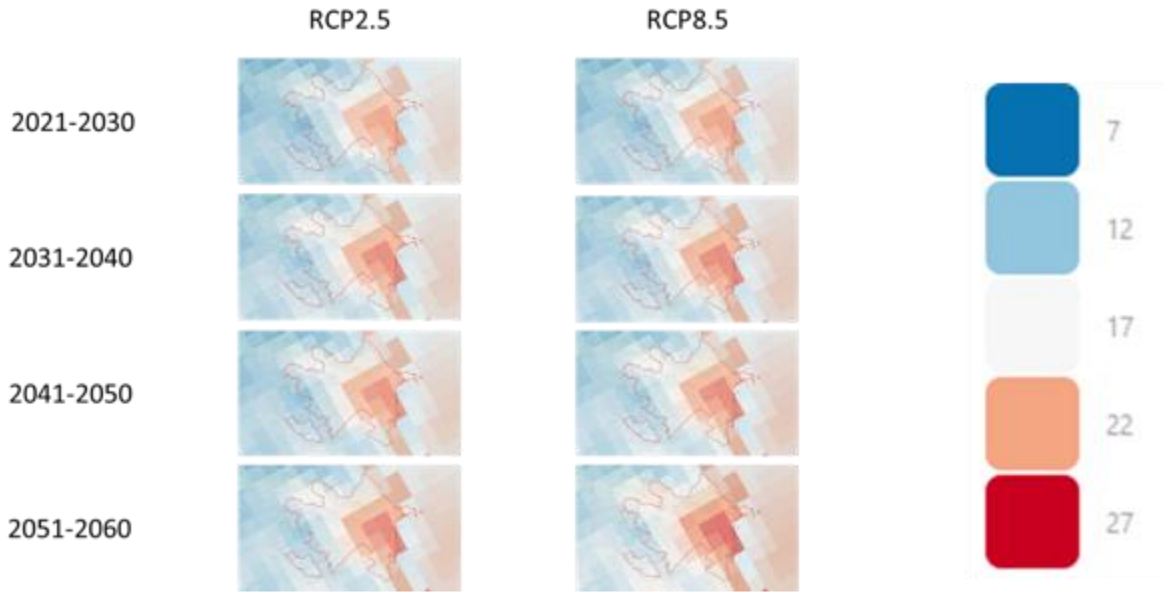
Annual Maximum Temperature (ºC)



Difference Annual Max Temperature (ºC)



Mean Maximum Temperature (ºC)



Mean Maximum Temperature (ºC)