MODELLING EXTREME METEOROLOGICAL PROCESSES POSING A RISK TO AGRICULTURE UNDER MODERN CLIMATE CHANGE

Teimurazi Davitashvili[1], Inga Samkharadze[2], Avtandil Amiranashvili[3]

[1]Ilia Vekua Institute of Applied Mathematics of Ivane Javakhishvili Tbilisi State University, GEORGIA
[2]Hydrometeorological Institute of Georgian Technical University, GEORGIA
[3]Mikheil Nodia Institute of Geophysics of Ivane Javakhishvili Tbilisi State University, GEORGIA
teimuraz.davitashvili@tsu.ge
inga.samkharadze562@ens.tsu.edu.ge
avtandil.amiranashvili@tsu.ge

Abstract

The phenomena associated with modern climate change have currently become an urgent problem in the South Caucasus region (Georgia), where frequent heavy rainfall, hail and flooding cause landslides that seriously endanger human safety and damage production and agriculture. To promptly control and prevent torrential rain, heavy hail and their consequences, it is necessary to provide environmental authorities, the scientific community and the population with scientific information on upcoming extreme regional and local events. This article emphasizes the importance of studying the thermodynamic state of the atmosphere during the formation of convective clouds in areas with complex orography. To this end, the Real-Time Environmental Applications and Display (READY) system, comprising the Meteor 735CDP10 meteorological radar and the Weather Research Forecast (WRF) v.4.5 model, was employed. The numerical values of instability energy throughout the day were determined and analyzed by carefully studying observational data and meteorological radars in certain regions of eastern Georgia. Analysis of the calculation results showed that, in some cases, the WRF model (using various microphysical parameterization schemes) did not correctly forecast showers and hail in some of the studied local territories. However, the thermodynamic state of the atmosphere was satisfactorily forecast by the ARL READY system compared with the meteorological radar data. Furthermore, the ARL READY system satisfactorily forecasted the stratification of the atmosphere (CAPE values) for the time interval between 13:00 and 19:00 local time in most cases.

Keywords: modelling, risk analysis, extreme processes, forecasting methods, climate change

I. Introduction

Modern climate change is caused mainly by an increase in anthropogenic environmental pollution, and this change in many regions of the Earth is expressed in frequent heavy rains and hail with destructive floods, accelerated melting of glaciers with avalanches and landslides, long-term droughts with increased desertification processes [1]. Climate change is in full swing in the Caucasus region and is well expressed in Georgia too [2]. Namely, climate change in Georgia is manifested, at a minimum, as a result of a pronounced accelerated melting of Georgian glaciers in the Caucasus with frequent avalanches and devastating landslides, an increase in the frequency of short-term heavy rains and hail with destructive floods and prolonged droughts in the summer [3,4]. Research has shown that over the past four decades, the number of extreme weather events and natural disasters (floods, landslides, storms, heavy rains, hail) has increased approximately two to three times compared to the 60-year period of the last century [4]. It should be noted that extreme meteorological processes in the Caucasus are largely due to the complex orography of the Caucasus and the consequences of regional climate specifics. Moreover, on the territory of Georgia, they are of a local nature and generally proceed differently due to the wide variety of features of the regional climate and locations [5]. Of particular importance among the frequent extreme meteorological processes in Georgia are heavy rains, hail, and subsequent floods and landslides. Frequent heavy rains and hail cause serious damage to agriculture (hundreds of vineyards in the Kakheti wine region in southeastern Georgia are especially destroyed) and also harm the population. To protect the entire Kakheti region, 85 anti-hail missile systems have been installed since 2015, but their effectiveness is not yet entirely satisfactory [6,7]. To effectively use a modern anti-hail system, it is necessary to timely predict extreme weather events, forecast local convective processes, and assess the thermodynamic state of the atmosphere and, accordingly, its stratification. It is clear that to warn operational authorities about the vagaries of nature and prevent extreme weather events, it is necessary to more effectively use modern scientific tools, such as ARL READY and Radar Meteor 735CDP10. At the same time, the Atmospheric Sounding Program (ASP) is a useful tool for assessing the state of the atmosphere, since ASP aerialgrams are the most useful means of displaying vertical profiles of thermodynamic quantities (temperature, humidity, and pressure profiles), for forecasting precipitation, boundary layer, clouds and the type of atmospheric convection [8]. In addition, fully automated ASP reduces operating costs and provides full coverage of upper-air meteorological observations, making it possible to compare convective available potential energy (CAPE) with standard instability indices for estimating convective atmospheric potential, such as lift index [9,10]. Over the past few decades, convective available potential energy (CAPE) has become a widely used variable to assess atmospheric instability, and atmospheric convective potential, since CAPE is independent of one specific atmospheric level (calculated using the integral of the atmospheric vertical profile). CAPE is widely used to model the developing thunderstorms (strength within a thunderstorm), showers, and hail [11, 12]. To improve the hail forecast model developed by the Laboratory of Atmospheric Physics of the University of León, the differences between groups of days with different levels of convective activity and the corresponding CAPE values were studied using morning radiosonde data [11]. The hail forecast results showed that CAPE should not be used as a single variable, but in combination with other parameters: in Leon, the maximum CAPE values were reached in the afternoon and did not exceed 2000 J/kg, while the average value of the entire sample was 132 J/kg.[11]. By systematically varying CAPE in a horizontally homogeneous reference environment, Lin and Koumdjian in [12] simulated hail formation under highly unstable supercell storms using a cloud1 model and a detailed 3D hail growth trajectory model. The results showed a non-monotonic relationship between hailstone residence time and CAPE due to changes in the upwelling wind field [12]. It should be noted that sometimes storms in high CAPE environments may produce smaller hail because the horizontal wind speed in the updraft becomes too high and the hailstones are prematurely thrown out of the optimal growth area [13]. Therefore, it is important to know the types of storm conditions that can cause large hail [14]. Therefore, it is important to know the types of storm conditions that can cause large hail. Among extreme meteorological processes for Eastern Georgia with complex orography, short-term, local, heavy hail and rain are of particular importance [4]. The strength and characteristics of the development of such processes are largely determined by the stratification of the atmosphere [10]. Besides, it is important to know temperature variability between the study regions. Therefore, when considering such processes, it is important to assess the thermodynamic state of the atmosphere in a local area and, accordingly, stratification [15-17]. The purpose of this article is to obtain additional information on extreme events (hail, and rain) in an area with complex orography (Georgia) to further develop an approach for predicting strong convection with hazardous precipitation and hail using modern forecasting tools.

II. Methodology and data

To assess the state of convection in the atmosphere, the particle method is used, where it is assumed that initially the particle and the surrounding atmosphere have the same temperatures, and if the particle moves upward, it moves dry adiabatically up to the condensation level. In the case of rising above the condensation level due to condensation and the release of latent heat of condensation, the particle temperature drops more slowly and the particle moves along a humid adiabata [9, 11, 12]. From the level of free convection (LFC) to the equilibrium level (EL) during the adiabatic rise of a unit volume of air, the work done by the particle is called convective available potential energy (CAPE), which can be represented as follows [9, 12,17],

$$CAPE = \int_{LFC}^{EL} g \frac{T_{parcel}-T_{env}}{T_{env}} dz, \quad (1)$$

where *Tparcel* is the temperature of the parcel and *Tenv* is the temperature of the environment, *g* is gravity acceleration.

It should be noted that LFC is the level above which the temperature of the environment falls faster than the temperature of the particle and EL is the level at which the temperature of the environment equals the temperature of the particle. The velocity W of an air particle at the level Zmax, where the temperature of the environment is equal to the temperature of the air particles is maximum and has the following from [9, 12,17],

$$W(Zmax)=(CAPE)1/2 \quad (2)$$

Formula (2) can be used to account for the relationship between instability energy and peak wind speed at maximum height. Theoretically, it is known that the state of the atmosphere can be divided into several stages depending on the energy of instability and the speed of the upward flow. When the instability energy CAPE>0 J/kg, the state of the atmosphere becomes unstable, and when CAPE>1000 J/kg, the state of the atmosphere changes from medium instability to extreme.

As already mentioned, to assess the degree of instability of the atmosphere, it is necessary to study its vertical structure and the processes developing in it. Today, the operation of a radiosonde is associated with certain financial costs, and its use in some developing countries is practically not carried out (including Georgia). To enable efficient and timely forecasting of atmospheric processes, the National Oceanic and Atmospheric Administration's (NOAA) Atmospheric Research Laboratory (ARL) has created the Real-time Environmental Applications and Display System (READY) (http://www.ready.noaa.gov). To study the thermodynamic state of the atmosphere on the days under consideration, we used data from the ARL archive with a horizontal resolution of 0.5^0 and constructed a particle state curve for each day under consideration. Numerical instability energy values were also taken from the ARL READY system archive with a horizontal resolution of 1.0^0 (~111 km)) [15]). The calculation results were compared with real data obtained from the Sighnaghi meteorological radar (Meteor 735CDP 10-Doppler Weather Radar), controlled by the Military Scientific and Technical Centre "DELTA", located in the village of Chotori, Sighnaghi municipality, through which the state of the atmosphere was studied throughout Kakheti.

III. Results and discussion

On June 13, 2023, torrential rain and heavy hail caused damage to the villages of Samtskhe-Javakheti (southern Georgia), in particular, the villages of Shoraveli, Pkhero, and Zemo Enteli of the Adigeni municipality were affected. The disaster destroyed crops and a large harvest. Heavy hail occurred in six villages of the Akhalkalaki municipality. The hail began at 13:49 on 13/06/2023 and lasted 20 minutes but large hail caused significant damage to potato and barley crops, as well as destroying plantings. Fig. 1 shows forecast maps of convective accumulated precipitation in mm (Fig. 1, a), atmospheric temperature, and geopotential heights at 500 hPa at 12 UTC (Fig. 1, b), taken from the Wettercentrale NCEP Climate archive Forecast System Reanalysis (CFSR) at 0.5 resolution. Figure 2, a - shows that strong convective precipitation (20-25 mm) is recorded almost throughout the entire territory of Georgia at 12 UTC, while as can be seen from Figure 2, b, Georgia is located in an area of relatively low pressure (1005 hPa), therefore frontal processes are activated from the west, which caused strong convective precipitation throughout Georgia.

Testing of the physical parameterization schemes of the model WRFv.4.5.1 under conditions of strong convection that occurred on June 13, 2023, against the backdrop of the complex orography of Georgia showed a scatter in the values of the calculation results. The format of the article does not allow us to consider in detail all the results of the calculations (we are going to discuss this issue in a separate article), but in a nutshell, it should be noted that the calculations showed that none of the combinations of the Physical and Cumulus parameterization schemes were able to fully reproduce the deep convection that occurred on June 13 2023 in the Akalkalaki and Kakheti regions. According to ARL's READY system, the maximum value of instability energy for Akhalkalaki was (CAPE=1950 J/kg) at 12 UTC on June 13, 2023. Figure 2 shows radar data of cloud intensity in Eastern Georgia on June 13, 2023, the legend shows cloud reflectivity and the right and upper parts of the image show cloud height in km. According to radar data, on the same day a cold atmospheric front spread across the territory of Eastern Georgia and, as a result of local convective processes, the cloud system intensified even more throughout almost the entire territory of Kakheti (Sagarejo, Telavi, Akhmeta, Kvareli, Gurjaani, Lagodekhi, and Dedoplistskaro) (Fig. 2). For example, the maximum value of instability energy in Gurjaani was CAPE=2020 J/kg. According to Fig. 2, a cloud with a reflectivity of 55-60 dB, which corresponds to the dark red color in the image, was observed at 19:54 (local time) mainly in the territory of the municipalities of Sagarejo and Akhmeta and after that, the atmospheric front expanded and intensified in other regions and the upper the cloud boundary reached 10 km (in Fig. 2, the upper boundary of the cloud is clearly visible from the vertical section of the cloud, which corresponds to the upper and right parts of the picture).

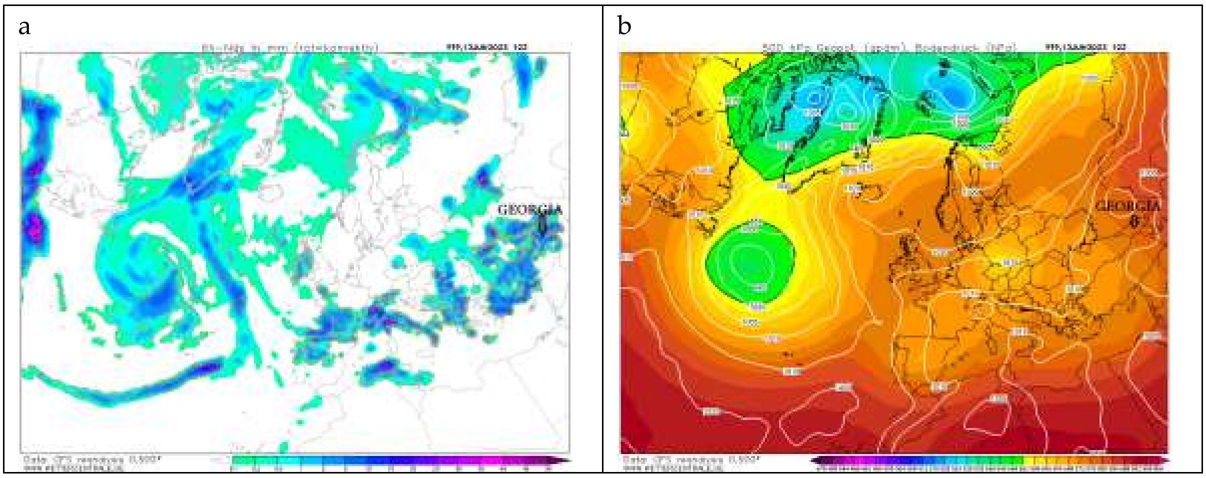

Figure 1: *CFSR 0.5 resolution forecast maps for 12 UTC (**a** - rainfall intensity in mm; **b** - 500 hPa geopotential heights contours).*

Fig. 3 shows the thermodynamic state of the atmosphere on June 13, 2023, in the period 09-12 UTC for geographic coordinates 41.73'N, and 45.33'E. (Gurjaani). As can be seen from Figure 4, the green area in Figure 3 accurately represents the numerical value of CAPE and shows that the Gurjaani region experiences strong instability between 09 and 12 UTC.

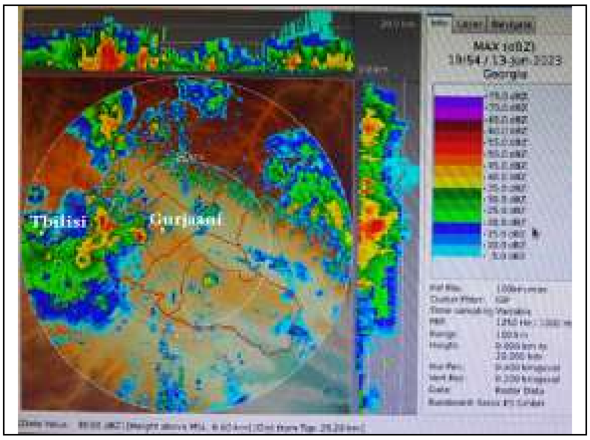

Figure 2: *Cloud intensity in Kakheti according to meteorological radar data (June 13, 2023).*

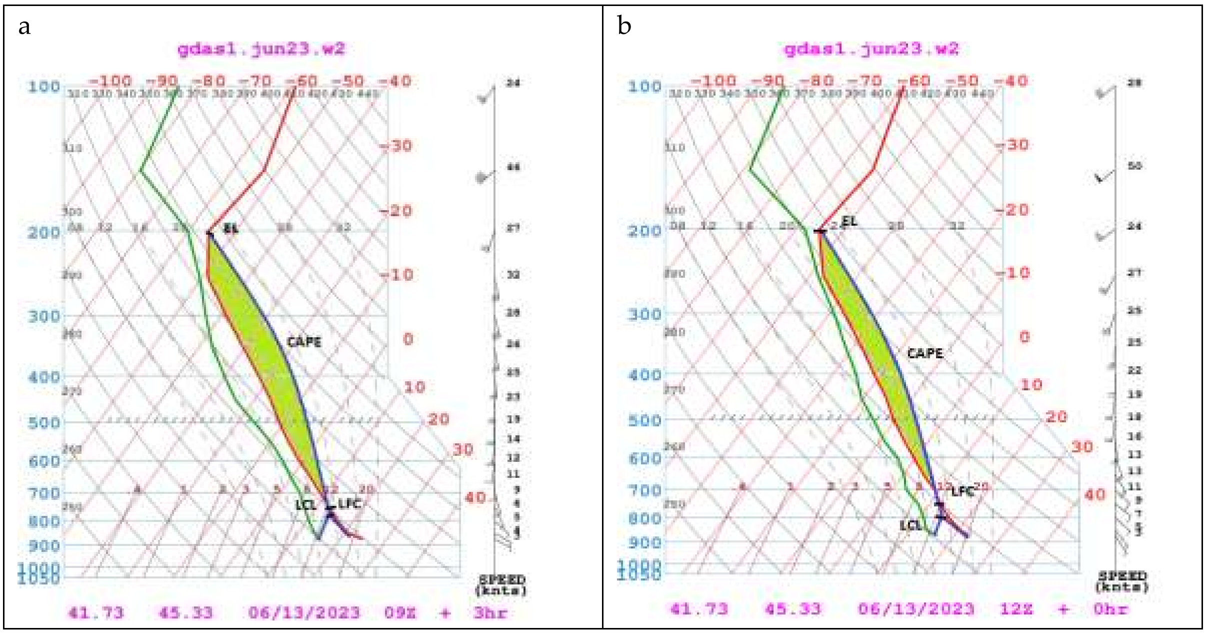

Fig. 3: *Aerological diagrams of Gurjaani.* ***a*** *- June 13, 2023, at 09 UTC;* ***b*** *- June 13, 2023, at 12 UTC.*

However, it should be noted that the numerical value of instability energy at 09 UTC (CAPE = 2020 J/kg) was greater than at 12 UTC (CAPE = 1500 J/kg, when heavy rain occurred). The right side of Fig. 3, a, and b shows the vertical distribution of wind in the territory of the Gurjaani municipality, it can be seen that at 09 UTC (Fig. 3, a), when CAPE is maximum, the wind speed at the level of 250 mb is 32 knots, and at 12 UTC (Fig. 3, b) when CAPE is comparatively lower, the wind speed is 27 knots. Thus, the study of the vertical distribution of wind speed is of great importance when assessing the energy of instability in the hail protection of the operational service.

On June 15, 2023, at 18:39, a cold atmospheric front entered Eastern Georgia and the cloud system locally intensified in most regions of Kakheti (Akhmeta, Sagarejo, Gurjaani, Telavi, Kvareli, Lagodekhi, and Sighnaghi). Half an hour later, due to torrential rain and heavy hail (accompanied by strong winds), the streets of Gurjaani were flooded so much that the water almost flooded the cars and flooded the offices on the ground floor (Fig. 4).

The results of the WRFv.4.5.1 model calculations performed with different schemes showed that although the background synoptic situation occurring in Georgia was modeled quite well, the local convective processes that occurred on June 15, 2023, over Kakheti were not modeled well enough.

a b

Figure 4: *Disaster in the Gurjaani municipality of Kakheti, June 15, 2023. Streets of Gurjaani,* ***a****-June 15, 2023, 16:00, b- June 15, 2023, 17:00.*

Fig. 5, a - shows radar data of cloud intensity in Eastern Georgia on June 15, 2023, at 17:04, where the legend indicates the reflectivity of the clouds, and in the right and upper part of the image the cloud height in km is indicated. As can be seen from Fig. 5, a, in the vicinity of Gurjaani (in Fig. 5, a - the locations of Tbilisi, Sagarejo, and Gurjaani are indicated) there is a massive cloud system and the main part of the clouds is spreading from the northeast to the southwest, across the territory of the Gurjaani and partly Kvareli districts, on June 15 at 17:04. According to Fig. 5, a, a cloud with a reflectivity of 55-60 dB, which corresponds to the dark red color in the image, was recorded by 17:04 mainly in the territory of the municipalities of Gurjaani and Kvareli and the upper boundary of the cloud is 12 km (Fig. 5, a - the upper boundary of the cloud is clearly visible from the vertical section of the cloud corresponding to the upper and right parts of the image).

Fig. 5, b - presents the aerological diagram of June 15, 2023, obtained by ARL READY at 12 UTC for the Gurjaani region, when strong convective clouds formed. On all the presented aerological diagrams, we have constructed the curve of the state of the particle (blue), the location of which determines the value of the instability energy and, accordingly, the strength of local convection processes.

a b

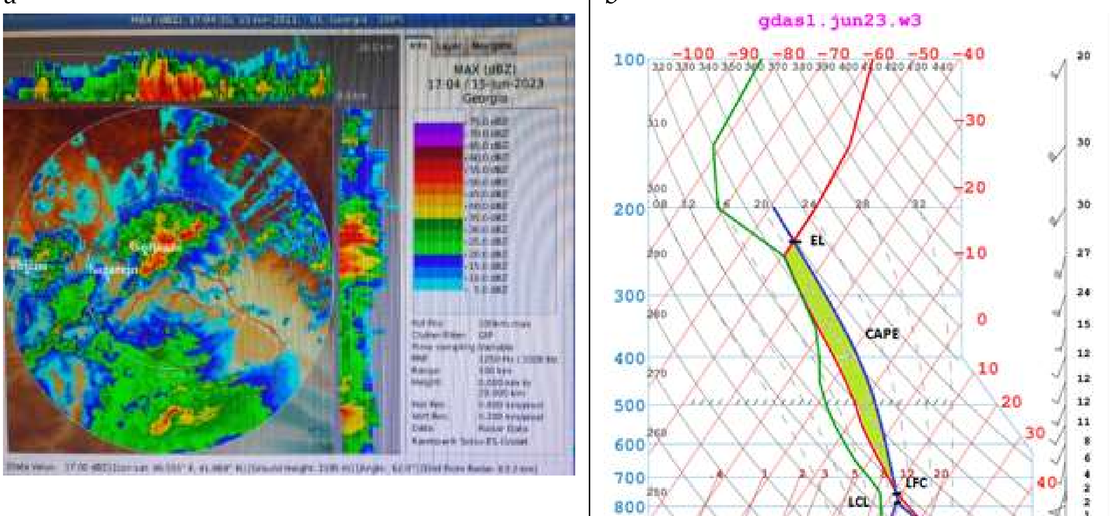

Figure 5: ***a*** *- Cloud intensity in Kakheti according to meteorological radar data. (June 15, 2023);* ***b*** *- Aerological diagram of Gurjaani on June 15, 2023 (12 UTC).*

The area of the green figure (between the LFC and EL levels) is the value of the instability energy. For the day under study, the maximum values of instability energy (CAPE=1450 J/kg) were recorded at 12 hours UTC, and the wind value in the vertical direction was maximum up to the level of 200 mb and amounted to 30 knots.

According to the Kakheti weather radar, on August 2 and 3, 2023, a cold atmospheric front entered Eastern Georgia from the southwest, which spread to almost the entire territory of Kakheti (Sagarejo, Telavi, Akhmeta, Kvareli, Gurjaani, Sighnaghi, and Lagodekhi), but the cloud was especially enhanced by local convection in the Kvareli region.

Indeed, Fig. 6 shows that the strongest cloudiness (with a reflectivity of 60 dB) was recorded in the territories of the municipalities of Gurjaani and Kvareli, the upper boundary of the cloud reached 18 km, and the maximum size of hailstones in the cloud reached 47 mm. Numerical calculations performed using the WRF model were able to approximately correctly predict the maximum hailstone size, but the location of the hailstone was not accurately predicted.

From Fig. 7, presented aerological diagrams constructed for the Kvareli district (geographic coordinates 41.57'N, 45.49'E), it is clear that for the presented days the maximum values of instability energy (CAPE=1400, 1200 J/kg) are fixed at 15 UTC.

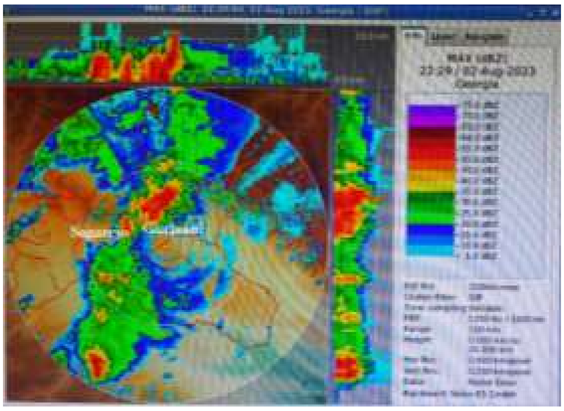

Figure 6: *Cloud intensity in Kakheti according to meteorological radar data at 22:29 August 2, 2023.*

On the right side of the diagrams, where the vertical wind distribution is presented, the maximum wind speed is presented at 200 mb and is 82 knots in Fig. 7, a), and in Fig. 7, b - maximum wind speed at the same level 68 knots. Despite the different values of instability energy, the magnitude of the wind in the cloud plays a very important role in assessing the ascending convective flows, and the aerological diagrams constructed for the Kvareli region well reproduce the real situation that took place on August 2 and 3. 2023.

An additional search was also carried out for days when heavy precipitation (hail, rain) came to the territory of Eastern Georgia in the summer of 2021 and 2022. For the 25 days tested, 14 days were chosen when the energy of heavy precipitation (hail) was unstable and exceeded 1000 J/kg (CAPE>1000 J/kg.

For simplicity, Table 1 presents the numerical values of the instability energy (CAPE > 1000 J/kg) and the corresponding updraft velocities at the EL level during hazardous meteorological processes that developed in 2022 in some regions of Eastern Georgia. As can be seen from Table 1, during dangerous meteorological processes that developed in 2022, the numerical values of instability energy increased and reached their maximum in the time interval 09 UTC-15 UTC, this is about 13-19 hours local time, which is when the soil temperature and vertical velocities are high and, among other favorable reasons, a favorable time comes for the formation of local convective clouds [6,7,9,12]. It should be noted that the calculations showed that in all cases we had different levels of instability and the difference was noticeable. Indeed, sometimes storms with high CAPE conditions produce less hail because the horizontal wind speed in the updraft becomes too high

[13] and, conversely, some calculations have shown that storms with low CAPE conditions produce heavy rain and hail, but in any case, energy instability reached its maximum in the time interval 09 UTC-15 UTC. That is why, when forecasting local convective processes in regions with complex orography, together with regional forecasting models (WRF), it is necessary to study the thermodynamic state of the atmosphere in the time interval 09:00-12:00 UTC (based on CAPE and the aerological diagrams of the ARL READY system), and if unstable energy with a significant lift index appears, then there is a high probability of causing an adverse atmospheric event.

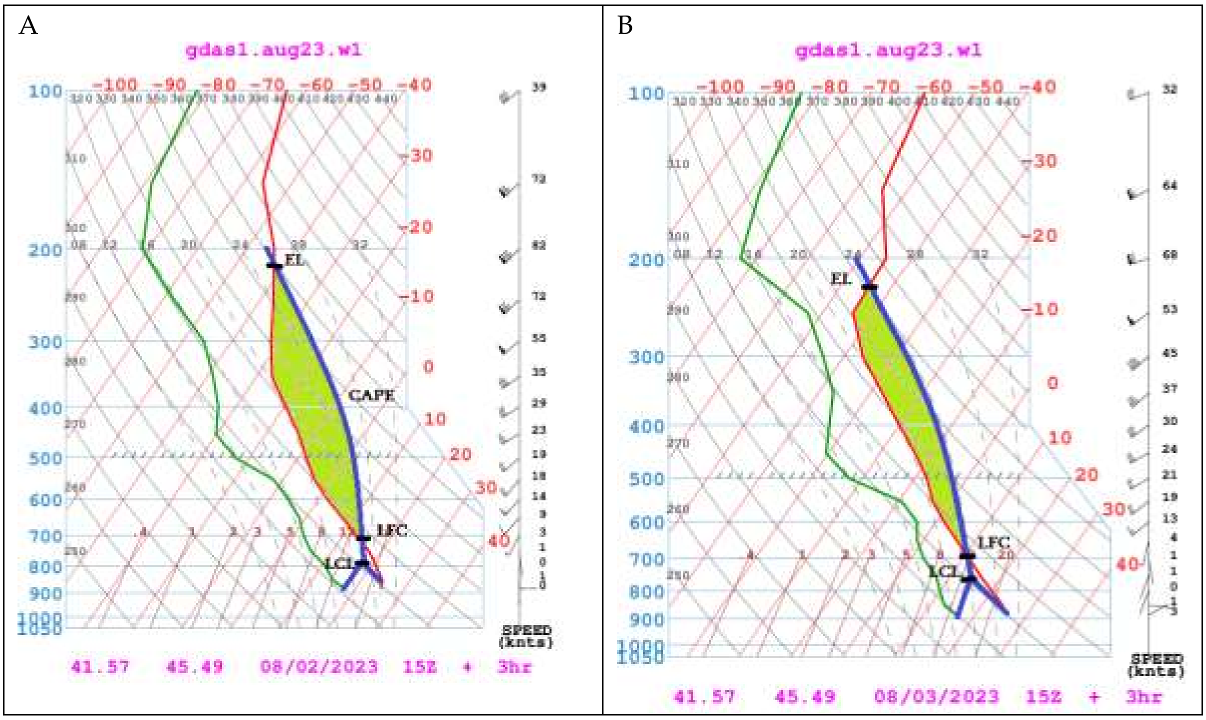

Figure 7: *Aerological diagrams of Kvareli.* ***a*** *- on August 2, 2023, at 15 UTC;* ***b*** *- on August 3, 2023, at 15 UTC.*

Table 1: *Numerical values of instability energy (CAPE > 1000 J/Kg) and vertical velocity of upward airflow (Wzm) during dangerous meteorological processes developed in some regions of Eastern Georgia in 2022.*

Day	06/06	13/06	28/06	29/06	31/06	02/07
CAPE 00UTC	174	0	3	70	30	288
CAPE 06UTC	200	600	730	730	437	873
CAPE 09UTC	1300	1100	1120	1170	1100	1040
CAPE 12UTC	1050	1150	1200	1180	900	1225
CAPE 15UTC	1740	710	1390	1260	800	950
CAPE 18UTC	800	77	323	464	104	580
W_{zm} m/s	**59**	**46**	**53**	**50**	**46**	**49**

V. Conclusion

This article presents a comparative study of the results of numerical calculations performed by the WRF v.4.5.1 model and the READY system in comparison with weather radar data. The study was conducted against the background of three exceptional local short-term heavy rainfall events (with hail) that occurred in eastern Georgia in the summer of 2023. The instability energy (based on CAPE and upper-air diagrams of the ARL READY system) of all exceptional local short-term heavy precipitation (with hail) that occurred in Eastern Georgia in the summer of 2021 and 2022 was also studied. Analysis of the calculation results showed that almost none of the combinations of the MP and CPS schemes in the WRF v.4.5.1 model could accurately predict real deep moist convective atmospheric phenomena in Kakheti (the famous wine-growing region). The aerological diagrams (ARL READY system) constructed for the cases discussed accurately showed the instability of the atmosphere over the study area. Although we had different levels of instability in all cases, the difference was exactly the same as the actual meteorological conditions of the day in question (as measured by the weather station and weather radar). To test our findings for the above three cases, all hazardous heavy precipitation events in 2021–2022 were examined. In particular, one of the main thermodynamic characteristics of atmospheric instability CAPE was studied (at times: 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 UCT) on the specified days. Analysis of the calculation results showed that the numerical values of CAPE were completely different, but for all 25 events, the maximum CAPE values were observed in the time interval 09:00-15:00 UTC. It should be noted that maximum CAPE values were recorded 15 times at 12:00 UTC and 5 times at 09:00 and 15:00 UTC, respectively. Thus, for forecasting local convective atmospheric processes, the CAPE value obtained in the time interval 09:00-15:00 UTC (11:00-19:00 local time, when the values of unstable energy show their maximum) is one of the best indicators to assess atmospheric instability and expected adverse atmospheric events. Indeed, along with all other favorable conditions, the temperature of the Earth's surface during this period reaches its maximum and the most favorable conditions are created for the development of local convective processes. Thus, when forecasting local convective processes together with regional forecasting models (WRF), it is desirable to study the thermodynamic state of the atmosphere in the time interval 09:00-12:00 UTC (based on CAPE and the aerological diagrams of the ARL READY system), and if unstable energy appears, then there is a high probability of an unfavorable atmospheric event.

Acknowledgements. The research was funded by Shota Rustaveli National Scientific Foundation Grant No. FR-22-18445.

References

[1]. IPCC, CLIMATE CHANGE 2023, Synthesis Report-A Report of the Intergovernmental Panel on Climate Change, 2023, p. 146. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

[2]. Westphal, M., Mehtiyev, M., Shvangiradze, V., Tonoyan, V. Regional Climate Change Impacts Study for the South Caucasus Region - Science, 2011, 62 pages.

[3]. Shengelia, L., Kordzakhia, G., Davitashvili, T., Begalishvili, N. The Possibilities of using Remote Sensing Technologies to Assess the Impact of Climate Change on the Glaciers of the Caucasus - Sci. and Techn., 6, 2012, pp. 24-27.

[4]. Fourth National Communication of Georgia to the UNFCCC, 2021, p. 426. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

[5]. Davitashvili, T. On Some Aspects of Climate Change in Georgia - Inter. J. of Ener. and Envir., 12, 2018, pp. 80-86.

[6]. Amiranashvili, A., G., Chikhladze, V., A., Dzodzuashvili, U., V., Ghlonti, N., Ya., Sauri, I., P. Reconstruction of Anti-Hail System in Kakheti (Georgia) - Journal of the Georgian Geophysical Society, Issue B. Physics of Atmosphere, Ocean and Space Plasma, v. 18B, 2015, pp. 92-106.

[7]. Davitashvili, T., Samkharadze, I., Megreladze, L., Kvatadze, R. Using Modern Technology to Protect Vineyards from Hail Amid Climate Change - E3S Web of Conferences 234, 00034, 2021. https://doi.org/10.1051/e3sconf/202123400034 ICIES 2020.

[8]. Nielsen-Gammon, J. Weather Observation and Analysis. Chapter 5. Soundings. Texas A&M University, 2007. http://www.met.tamu.edu/class/ATMO251

[9]. Blanchard, D., O. Assessing the Vertical Distribution of Convective Available Potential Energy - Weather and Forecasting. 13, 1998, pp. 870-877. NOAA/National Severe Storms Laboratory, Boulder, Colorado.https://doi.org/10.1175/15200434(1998)013<0870:ATVDOC>2.0.CO;2

[10]. Wei, L., Jiangping, H. Study and Development on Fully Automated Sounding System - WMO, IOM-109, TECO, 2012.

[11]. López, L., Luis, M., J., Luis, S., J., Amaya, C., Fraile, G. CAPE Values and Hailstorms on Northwestern Spain - Atmospheric Research, Vol. 56, Iss. 1–4, 2001, pp. 147-160.

[12]. Lin, Y., Kumjian, M., R. Influences of CAPE on Hail Production in Simulated Supercell Storms - Journal of the Atmospheric Sciences, 79(1), 2022, pp. 79-204. https://doi.org/10.1175/JAS-D-21-0054

[13]. Kunz, M., Blahak, M., U., Handwerker, J., Schmidberger, M., Punge, H. J., Mohr, S., Fluck, E., Bedka, K., M. The Severe Hailstorm in Southwest Germany on 28 July 2013: Characteristics, Impacts and Meteorological Conditions // Quart. J. Roy. Meteor. Soc., 144, 2018, pp. 231–250. https://doi.org/10.1002/qj.3197

[14]. Huang, J., Ji, M., Xie, Y. Wang, S., He, Y., Ran, J. // Climate Dynamics, 46, (3-4), 2016.

[15]. Rolph, G., Stein, Ar., Stunder, B. Real-time Environmental Applications and Display System: READY. Environmental Modelling & // Software. 95, 2017, pp. 210-228. www.elsevier.com/locate/envsoft.

[16]. Gkikas, A., Basart, S., Hatzianastassiou, N., Marinou, E., Amiridis, V. Mediterranean Intense Desert Dust Outbreaks and their Vertical Structure Based on Remote Sensing Data - // Atmospheric Chemistry and Physics, 16 (13), 2016, pp. 8609-8642.

[17]. Davitashvili, T., Samkharadze, I., Sharikadze, M. Modeling of Extreme Events and Regional Climate Variability on the Territory of the Caucasus (Georgia) - Applic. of Math. and Infor. in Natural Sci. and Eng. Jaiani G., Natroshvili D. (eds) AMINSE 2019. Springer Proc. in Math. & Statis, 334, 2020.