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STUDY OF CONVECTIVE MOTIONS AND ANALYSIS OF THE IMPACT OF PHYSICAL PARAMETRIZATION ON THE WRF-ARW FORECAST MODEL

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Abstract. Optimizing the physical parametrizations of the Weather Research and Forecasting (WRF) model is one of the most challenging and complex tasks. In fact, it is not a simple operation to optimize the performance of a meteorological model capable of forecasting meteorological events, even extreme ones, in complex orographic areas such as that of Sicily. In this reference framework, the research activity of the group of meteorology and environmental modeling, established at the Department of Mathematics and Computer Sciences, Physical Sciences and Earth Sciences (MIFT) of the University of Messina, focuses on the development of a physical-mathematical model for the meteorological forecast. The WRF prediction model is evaluated on the ability to predict the development and evolution of a thunderstorm cell. After the definition of the domain under study and the choice of spatial resolution to be used, it was proceeded to the optimization of the physical parametrizations. In particular, in this paper, the performance improvements of the WRF model were evaluated, obtained by optimizing the convective parametrizations. As a case study, the meteorological event recorded in Sicily on 9 June 2016 was examined.

1. Introduction

The Sicilian territory is characterized by extreme weather events that often cause sudden flooding. In these episodes, the precipitation that occurs in a few hours overcomes the accumulations of rain that normally occur in several months. These extreme precipitations are connected to intense and quasi-stationary mesoscale convective phenomena that insist on the same area for several hours (Orlanski 1975; Wallace and Hobbs 1977; Pielke 2002). Their intensity is often determined by local factors such as the presence of orographic reliefs near the coast. Sicily, due to its geographical position and its complex orographic morphology, is often affected by extreme weather events.

One of the most important challenges of meteorological modeling is to develop models able to forecasting the development and evolution of the convective cell. In recent years, great progress has been achieved in meteorological forecasting. The development and optimization of limited area models, used in the main calculation centers, are often able to provide an adequate forecast performance. The Weather Research Forecast (WRF) model is a new generation of numerical weather prediction system designed for research needs and for operational forecasting of weather phenomena. This model is the result of a collaborative effort between the National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP) and the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration (NOAA). WRF is designed both for scientific purposes (for example for the numerical simulation of the atmospheric dynamics) and for applicative purposes, such as numerical weather predictions (Ooyama 1990; Laprise 1991; Pielke and Pearce 1994; Skamarock 2008). The "core" that governs the dynamics of the WRF model is constituted by:

- an Advanced Research WRF (ARW), calculation code developed by NCAR, able to simulate different types of meteorological events with different spatial resolutions;
- the not-hydrostatic Mesoscale Model (NMM), created by the NCEP, able to operate in both hydrostatic and non-hydrostatic mode.

The NMM core is used as operational model, while the ARW core, chosen in the case of WRF - UniMe, is dedicated to research applications. In order to improve the model performances, some progresses in the understanding of the mechanisms governing the formation and the localization of convective systems capable of producing large quantities of precipitation have been done. In this paper the convective phenomena and the physics parametrizations related to them are studied for the optimization of the WRF model. The convective phenomena are the central aspect linked to the process of condensation and evaporation. Convection affects the environment through the heating and cooling associated to condensation, evaporation, formation and melting of ice. The parameterization of convective phenomena assumes, therefore, a key role for a correct simulation of atmospheric dynamics. The case study examined the meteorological event that occurred in central Sicily in the early afternoon of June 9, 2016. This event was characterized by high atmospheric instability causing an afternoon thunderstorm that produced over 20 millimeters of rain in less than an hour (Fletcher 1962; Anthes 1983; Haltiner and Williams 1984; Anthes *et al.* 1989; Holton 1992; Walko *et al.* 1995).

2. Physical parameterization of convective phenomena

In order to parametrize convective phenomena it is necessary to consider the statistical behavior of convective cloudy systems which are influenced by different large-scale conditions. Before tackling this problem it is important to introduce the potential temperature equation θ, defined as follows:

$$\theta = T\left(\frac{p_0}{p}\right)^{\frac{R}{c_p}} \tag{1}$$

where T is the temperature, p is the pressure, p_0 is ground pressure, R is the constant gas for dry air and c_p is the specific heat at constant pressure. In formulating the collective effect of convective clouds systems, one should consider a "closure problem" in which a limited number of equations that govern the statistics of a huge system are searched. The heart of the matter is then choosing the appropriate system closure conditions. A first classification of this conditions can be provided starting from the equilibrium equations of the potential temperature θ and the specific moisture q (where specific moisture q represents the ratio between water vapor mass and the fluid particle total mass) on large scale of pressure coordinates (Anthes 1977):

$$c_p = \left[\frac{\partial\overline{\theta}}{\partial t} + \overline{v}\cdot\nabla_h\overline{\theta} + \overline{\omega}\frac{\partial\overline{\theta}}{\partial p}\right] = \left(\frac{p_0}{p}\right)^{\frac{R}{c_p}} Q_1 \tag{2}$$

$$L = \left[\frac{\partial\overline{q}}{\partial t} + \overline{v}\cdot\nabla_h\overline{q} + \overline{\omega}\frac{\partial\overline{q}}{\partial p}\right] = -Q_2 \tag{3}$$

The marked variables indicate a large scale average and Q_1 and Q_2 are respectively the heat source and the moisture well. All the other symbols have the standard meaning assumed in literature. To simplify, these two equations can be rewritten respectively as:

$$\frac{\partial T}{\partial t} = \left(\frac{\partial\overline{T}}{\partial t}\right) + \frac{1}{c_p}Q_1 \tag{4}$$

$$\frac{\partial q}{\partial t} = \left(\frac{\partial\overline{q}}{\partial t}\right) - \frac{1}{L}Q_2 \tag{5}$$

where:

$$\left(\frac{\partial\overline{T}}{\partial t}\right) = -\left(\frac{p_0}{p}\right)^{\frac{R}{c_p}}\left(\overline{v}\cdot\nabla_h\overline{\theta} + \overline{\omega}\frac{\partial\overline{\theta}}{\partial p}\right) \tag{6}$$

and

$$\left(\frac{\partial\overline{q}}{\partial t}\right) = -\left(\overline{v}\cdot\nabla_h\overline{q} + \overline{\omega}\frac{\partial\overline{q}}{\partial p}\right) \tag{7}$$

To solve this two equation system:

$$\left(\overline{T}, \overline{q}, T' \equiv \frac{1}{c_p}Q_1, q' \equiv \frac{1}{L}Q_2\right) \tag{8}$$

you must have at least two types of closing conditions among the three possible choices (Emanuel and Raymond 1993):

- Coupling of terms $\frac{\partial T}{\partial t}$ and $\frac{\partial q}{\partial t}$;
- Coupling of terms Q_1 and Q_2;
- Coupling of terms Q_1 and Q_2 with the two terms $\frac{\partial T}{\partial t}$ and/or $\frac{\partial q}{\partial t}$.

The first choice is equivalent to assume a condition on the variation time of the system state (on a large scale) and is usually achieved by imposing a balance state condition. The coupling of source terms, on the other hand, is a condition for the humid-convective processes and is usually present in the form of a cloud parameterization model. The combination of these two types of closure represents the methodological basis for those parameterization schemes known as "adjustment schemes", like the schemes of Arakawa and Schubert (1974), Betts (1986) and Betts and Miller (1986) . The third type of choice requires a direct coupling between large-scale circulation and humid-convective processes. It represents the starting point for many schemes, such as the schemes of Kuo (1974), Anthes (1977), Fritsch and Chappell (1980) and the scheme of Kain and Fritsch (1992).

3. Impact of Cu parametrizations for forecast of mesoscale thunderstorm

The case study analyzed concerns a typical summer situation characterized (Ryan 1996) by high instability as a result of infiltration of cold air at altitude (Caccamo *et al.* 2017; Castorina *et al.* 2017; Colombo *et al.* 2017; Castorina *et al.* 2018a,b). In particular, during the course of the previous day, the afternoon thunderstorms had developed on the northeastern part of the island between Etna and the chain of the Peloritani. On 9^{th} June, after a morning with sky mostly clear, between 11 and 12 UTC, storm cells begin to develop both on the Ionian coast of Messina and on the central Sicily, between the provinces of Agrigento and Palermo (Fig1).

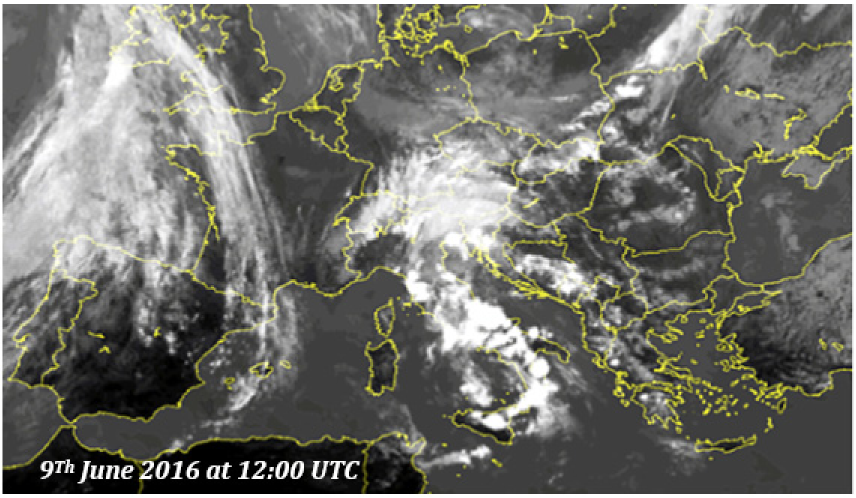

FIGURE 1. MSG thermal infrared image at 12.00 UTC on June 9^{th} 2016.The storm convection cell under development at the center of the Sicily region is clearly visible.

Between the hours 13 and 14 UTC the thunderstorm are fully developed and then begin to dissolve starting at 15 UTC. The total duration of the phenomenon can be estimated in 6 hours and the maximum accumulations of rain in the 24 hours were a little more than 30 millimeters with peaks of 31.2 in Mussomeli, 30.4 in Maletto, 27.2 in Cesarò (Fig2). From the map of the total rain accumulated in the 24 hours it is interesting to note that the southern and western sections of the island have not been affected by rain, and that only the internal areas have been subject to precipitations with two clearly visible maxima at Agrigento and in the northern part of Etna.

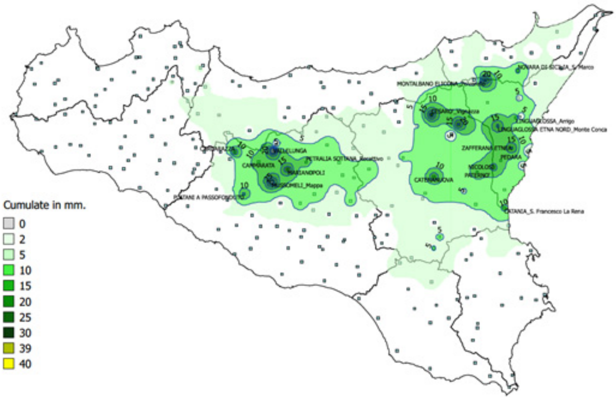

FIGURE 2. Map of the total rains recorded by the meteorological stations of the Regional Civil Protection Department of the SIcilia region. The total rains accumulated data refer from the hours 00 UTC to the 24 UTC on 09 June 2016. It is possible to notice that the south and west areas of the island were not affected by rain. Only internal areas have recorded rainfall accumulations. In particular, the province of Agrigento and the northern part of Etna recorded the highest rainfall accumulations.

The evaluations carried out in the present case study regard the performances of the WRF model (Fig3) when the different physics parameterization of the convective schemes are applied.

FIGURE 3. Map of the spatial domain used by the WRF model. The domain is centered on Sicily. The model is configured with horizontal grid spacing of 5km and a time interval resolution of 1h.

In particular both the forecasts of CAPE (convective available potential energy) at Trapani and the amount and the spatial distribution of rain during the event are compared. The physics parameterizations of the convective schemes analyzed are shown in the table 1:

Cu physics = 0	Explicit convection	No Cumulus scheme
Cu physics = 1	Kain-Fritsch scheme	Deep and shallow convection sub-grid schemeusing a massflux approach with downdrafts and CAPE removal time scale
Cu physics = 2	Betts-Miller-Janjic scheme	Operational Eta scheme. Column moist adjustment scheme relaxing towards a well-mixed profile
Cu physics = 3	Grell-Devenyi (GD) ensemble scheme	Multi-closure, multi-parameter, ensemble method with typically 144 sub-grid members
Cu physics = 4	Simplified Arakawa-Schubert	Simple mass-flux scheme with quasi-equilibrium closure with shallow mixing scheme
Cu physics = 5	Grell 3D scheme	It is an improved version of the GD scheme that may also be used on high resolution (in addition to coarser resolutions) if subsidence spreading is turned on
Cu physics = 6	Tiedtke scheme	Mass-flux type scheme with CAPE removal time scale, shallow component and momentum transport.
Cu physics = 14	New Simplified Arakawa-Schubert	New mass-flux scheme with deep and shallow components and momentum transport

TABLE 1. Physics parameterizations of the convective schemes analyzed

3.1. CAPE analysis: The Convective Available Potential Energy (CAPE) is a thermodynamic index that represents the potential convective energy, defined by the following equation:

$$CAPE = g \int_{z_f}^{z_n} \left(\frac{T_{part} - T_{env}}{T_{env}} \right) dz \tag{9}$$

where is:
g: gravitational acceleration;
z_f = free convection level height;
z_n = equilibrium level (neutral buoyancy);
T_{part}: Virtual temperature of the particle;
T_{env}: Virtual environment temperature.

It is a necessary parameter, but not sufficient, to understand the degree of instability of the air column. In other words, it gives information on the probability that there will be thunderstorms and their intensity. CAPE parameter depends on the temperature and moister of the air column between the ground and the upper troposphere; its unit is $[J/kg]$. High values indicate that the column of air has considerable convective energy and therefore, under an initial push, the convection will develop in a considerable way giving rise to strong storms. In particular, according to the numerical value which assumes the CAPE, one has that:

CAPE <500	absence of thunderstorms
500 <CAPE <1000	possibility of thunderstorms isolates
1000 <CAPE <2000	thunderstorms probable enough
CAPE >2000	strong enough probable storms

TABLE 2. numerical value of CAPE

As far as the CAPE predictions are concerned, obtained by varying convective parameterizations, as location for the forecasting the airport of Trapani has been chosen, since being the site of a radiosonde station, lends itself to a direct comparison between the observed data and the forecast data. As shown in the Figure 4, the numerical CAPE value is defined by the area enclosed between the temperature status curve and the adiabatic curve.

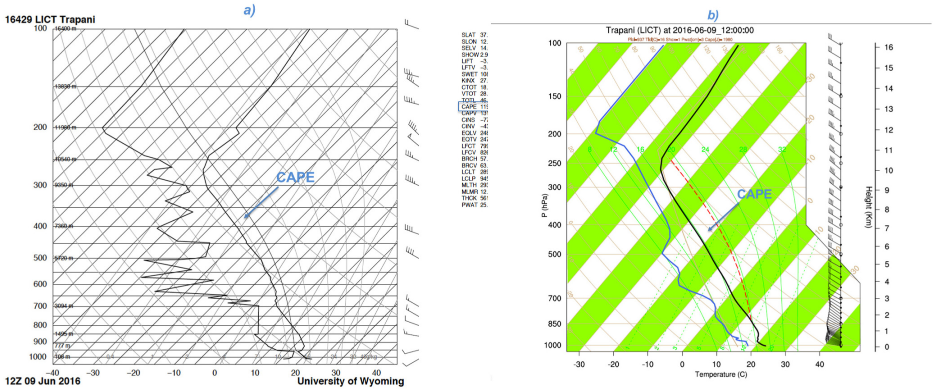

FIGURE 4. Comparison between Skew T graph observed (a) and forecast (b) at 12:00 UTC of the 09th June 2016.

From the analysis of the collected data (Fig5) it emerges that all the convective schemes underestimate the CAPE forecast for 12:00 UTC on 9^{th} June 2016. Infact, the value observed from the radiosonde was $1196 J/Kg$, while the values obtained by the models oscillate between 787 and $867 J/Kg$. The graph of the 00:00 UTC of the 10^{th} June instead shows an observed value of $266 J/kg$, caught by the 3D Grell scheme (Cu-physics = 5).

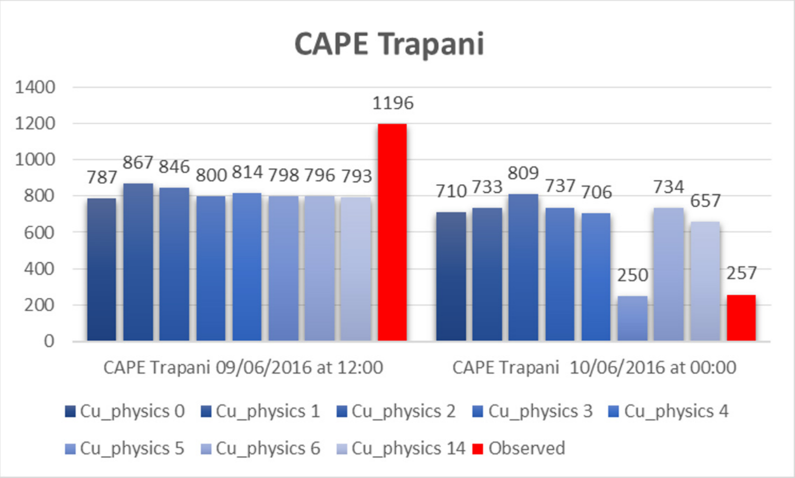

FIGURE 5. Comparison between forecasts and observed (red) CAPE. The value of forecast CAPE it is obtained by a WRF model with different physics parameterizations of the convective schemes.

3.2. Rain analysis: The analysis of the field of hourly rainfalls observed between the hours 12:00 and 18:00 of the 9^{th} June 2016 in Sicily, shows (Fig. 3) how the meteorological conditions has produced a convective thunderstorm on the Agrigento's area, and a minor cell between the northern slope of Etna and Siracusa. The analysis of hourly precipitation maps produced by the WRF and centered at the same hours (14:00 to 15:00 UTC), shows, by varying the convective patterns, results in some cases very discordant. In particular in the case of the Betts-Miller-Janjic (Cu-Physic = 2) convective schema, which in this specific situation underestimates in an excessive way the precipitation to the ground, providing hour maximum values that do not exceed 2 mm on the entire region. They allow to locate the thunderstorm cell in a very precise way the 3D Grell schemes (Cu-Physic = 5) and the New Simplified Arakawa-Schubert (Cu_Physics = 14). The latter in particular, in addition to a perfect spatial and time localization, provides in an optimal way the hourly rain quantities (Fig. 6).

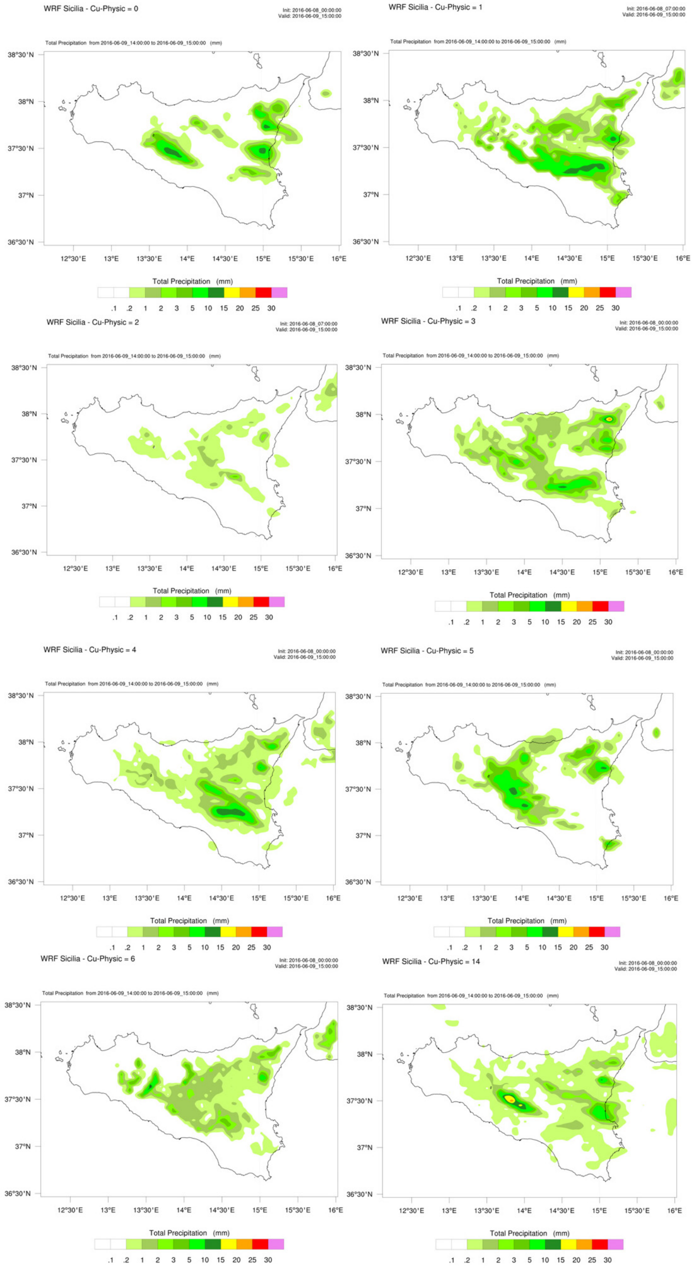

FIGURE 6. Comparison of different output in hourly rain forecast beetwen 00 and 15 UTC for different Cu-phisics parametrization.

Analyzing the performances obtained on the total rainfall in 24 hours (Fig. 7), should be noted that explicit convection (Cu-Phisics = 0) and the New Simplified Arakawa-Schubert (Cu_Physics = 14) overestimate the amount of rainfall. In fact, they forecast rainfall values above 50 millimeters. However, they are able to provide an excellent performance on the time and spatial location of the meteorological event under examination.

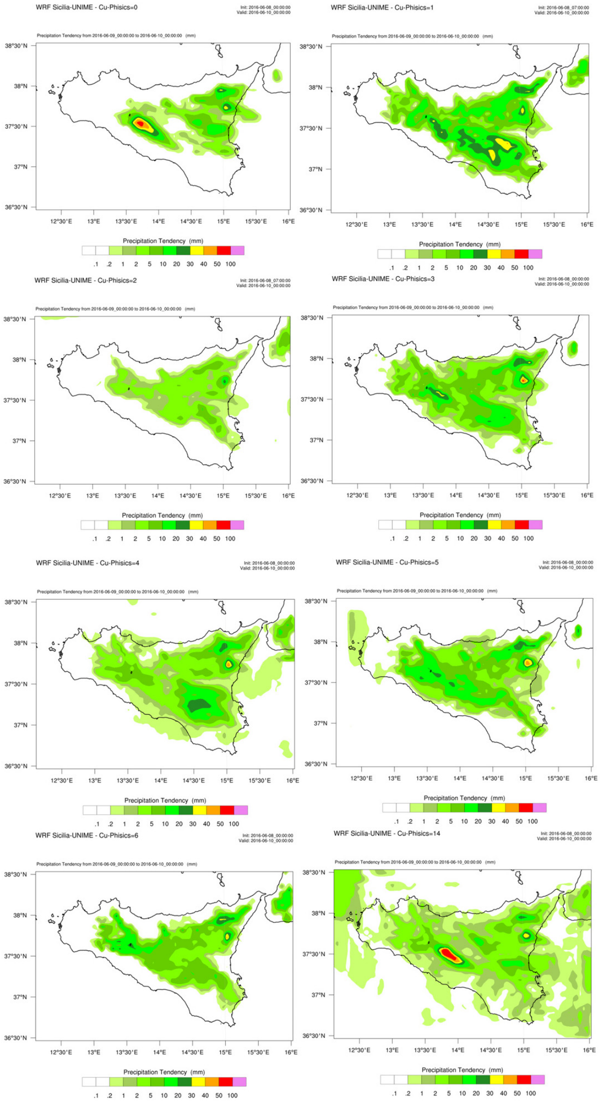

FIGURE 7. 24 hours total precipitation forecast for compared Cu-phisics parametrizations.

Further investigations carried out on the study case involved the selection of a predictor Storm parameter, able to provide useful information about the spatial and time localization of convective storm cells. The forecast of thunderstorms is in fact of great interest especially for meteorological forecasting for civil protection purposes and in the preservation and safeguarding of the territory. In addition to the CAPE they were taken into account the Cross-Total Index, the Total-Totals Index and the S Index. To complete the comparison, it took also into account the Absolute Vorticity 500 Hpa and the Storm Relative Helicity (SRH), a mathematical quantity derived from:

1 shear speed (how much wind speed increases with height) between the surface and 3 km above;
2 directional shear (how much wind speed direction changes with height) between the surface and 3 km above;
3 The strength of the low level wind directly into the speed and directional wind shear.

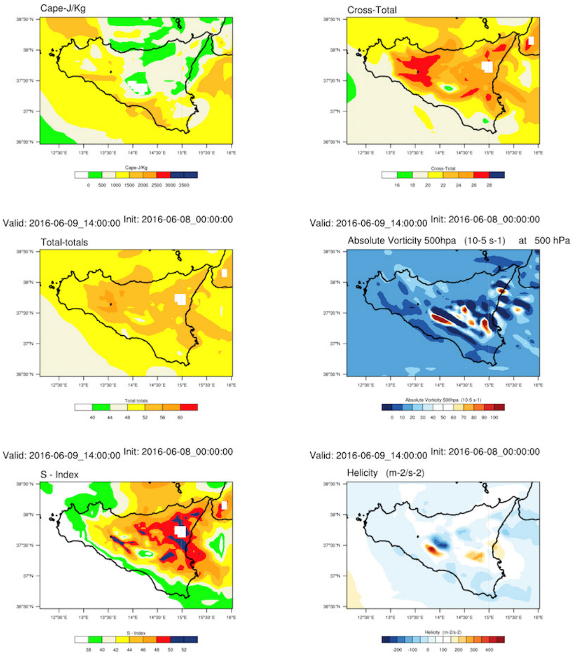

FIGURE 8. Comparison between the various indices. The CAPE index is necessary but not sufficient to make a forecast of the storms. The S index can provide useful guidance on the area of a probable storm cell development. The two diagnostic variables Absolute Vorticity and Helicity would allow to give indication both on the site and on the moment in which the time cell would develop.

The stronger each of these components is the higher the helicity. $150-300$: supercell development possible with large CAPE, 300-450: supercell development possible with small CAPE, > 450: large risk for supercell development, risk for violent tornadoes. The comparison between the various indices shows how the only CAPE index is inappropriate to make a forecast of thunderstorms. Among the other indices used, only the S Index can give useful indications on the area of a probable storm cell development. A different discussion holds for the two diagnostic variables Absolute Vorticity and Helicity. In this case, the simultaneous analysis of the two variables would allow to give some useful guidance both on site and on the time when the thunderstorm cell would develop, as evidenced by the panels in Fig. 8.

Extreme meteorological conditions area

Extreme weather conditions, such as heavy rains, strong winds, maximum or minimum temperatures, can be recorded in different parts of the earth. Extremely extreme weather events rarely occur. However, in some places on Earth, extreme weather conditions occur frequently (Caccamo *et al.* 2016; Caccamo and Magazú 2019). For example, the places of the Earth with the highest average annual rainfall are Mawsynram and Cherrapunji (India). These two cities are 15 km apart from each other. Both have the highest officially measured rainfall in the world. Mawsynram gets 11.873 mm per year (20 times more than in London) while Cherrapunji gets 11.430 mm. The village of Mawsynram has no weather station, unlike Cherrapunji. Measurements show that Mawsynram records more rain than Cherrapunji, although the results are disputed due to less scientific measurement methods.In some years the precipitation is much higher (up to 24.555 mm) in Cherrapunji.In these two places, most of the rains are recorded between the months of June and August, the period of the rainy season. The city of Lloro (Colombia) has the highest average annual rainfall (13.300 mm per year), but this data has not been scientifically proven. Contrary to Cherrapunji and Mawsynram, here it rains every day and there is no a specific rainy season. The most extreme hailstorm, in all probability, was recorded in Roopkund (India). More than 500 skeletons of pilgrims were found in this glacial lake. These people died here around the 12th-15th century AD. Further studies on the damage to their skulls showed that these people died by sudden hail storm: there was no shelter and the people died due to a violent fall of ice balls. The world's most acidic area is to be found in the Poás volcano (Costa Rica). Here the tropical forest is located next to a lifeless landscape created by acid fog. At the peak of the volcano there is Hot Lagoon (or Laguna Caliente in Spanish), one of the most acidic natural lakes in the world. The pH of this lake is often close to 0 (for example in 1993, 1994 and 2000). Laguna Caliente is chaotic, with water temperatures that can oscillate within hours and magmatic channels that run beneath the lake, giving rise to frequent geyser eruptions. Recently, researchers at the University of Colorado Boulder have discovered microbes living in this extreme environment. The driest place on Earth is Yungay, a part of Atacama Desert (Chile). This is highly unusual place which has attracted attention of scientists from all over the world due to high similarity to Mars environment. Only recently, after extensive research have been found some microorganisms, called extremophiles, such as the Selaginella lepidophylla.This plant that synthesizes the trehalose (Branca *et al.* 2002; Minutoli *et al.* 2008; Magazú *et al.* 2013), is able to adapt to the conditions of prolonged drought in this environment. Moreover, it can live about 50 years in total dehydration without being damaged and, after a rehydration process, it regenerates. There are several areas of the land that contend for the title of "warmer place", but Gandom Beryan in the Lut Desert (Iran), is one of the few places where it has been demonstrated by scientific methods. From 2003 until 2005 the surface temperature of the Earth was mapped. The NASA satellite "Aqua" with the help of the Moderate Resolution Imaging Spectroradiometer (MODIS) has recorded the temperature of the surface of the soil of the entire planet. The results of this study show that in 2004 and 2005 the hottest place on Earth was exactly the Lut desert. It is logical to suppose that the dark-colored Gandom Beryan, plateau is the hottest place here. MODIS data indicate that temperatures often reach even the temperature of $71°C$. In a saline river in the Lut desert, researchers found traces of extremely halophile archaea. Traces of mesophilic and halotolerant strain of Kocuira Polaris have been found in Gandom Beryan. All these extremophiles synthesize trehalose (Minutoli *et al.* 2007; Barreca *et al.* 2013; Magazú *et al.* 2018) to survive these extreme environments. The coldest place on Earth is in one of the highest places in Antarctica - on Dome A (Dome Argus). Dome A is about 600 m higher than Vostok (Russian station where the lowest temperature was recorded in 1983: $-89.2°C$). The automatic weather station was installed in Dome A in January 2005. In July 2005, a temperature of $-82.5°C$ was recorded, but scientists believe it could drop to $-102°C$. In extreme environments where temperatures are so low, it is possible to find the Arctic Megaphorura. This extremophile survives at temperatures below $0°C$ through a de-trekation mechanism dependent on trehalose (Jannelli *et al.* 1996; Branca *et al.* 2005; Magazú *et al.* 2010, 2012).

4. Conclusion

The study undertaken in the present paper wants to point out as the choice of convective parameterization determines the goodness of the prediction obtained by the WRF model. This study allowed to evaluate the performance on a particular territory, namely Sicily in which, the complex Orography and to the presence of seas with bathymetric and thermodynamic characteristics often very different, can play a decisive role in the development or not of convective storm cells. The case study of the June 9th represents was the typical thermo-convective cell of summer storms, which developed because of excessive heating of the soil and favored in his ascension by the presence of unstable air. Some convective parameterizations in the model are able to grasp and adequately reproduce what then in reality occurred, others were deficient both concerning the time and spatial location, as well as for the estimation of forecast precipitation amounts. This paper has allowed to define the parameter settings that allow the model to have the best performance.

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