Methods to test the performance of a restricted area physical-mathematical model with variation of the physical parameterization of convective phenomena

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Abstract

In the restricted area physical-mathematical models, the physical parameterization of convective phenomena plays a key role. In this work, the extreme weather event of 25^{th} November 2016, occurring in Sicily, is considered as case of study. The heavy rainfalls recorded in this event were caused by cloudy systems of convective nature. For this reason, the performance of the restricted area physical-mathematical model, optimized for complex orography areas, has been tested varying the physical parameters of the convective phenomena. Performance were evaluated using appropriate verification methods.

Keywords: Weather Research and Forecasting model, Physical Parameterizations, Cumulus Parameterization.

Introduction

The central issue related to the condensation and evaporation processes is the convection phenomena. Convection influences the environment by diabatic heating and cooling due to the condensation, evaporation, formation and melting of ice through vertical flows of sensitive heat, humidity, and momentum and through horizontal pressure field disturbances.
Therefore, the parametrization of convective phenomena plays a fundamental role for a good simulation of the atmospheric dynamics. Physical processes associated with condensation of water vapor are essentially non-linear, so their overall effect can directly affect large-scale circulation. However, most of the convective clouds, where condensation processes take place, have horizontal dimensions ranging from 0.1 to 10 km, typically smaller than those the spatial grid usually account in restricted area models. Therefore, there is therefore a typical sub-grid phenomenon, which must be parameterized in terms of prognostic variables.

Physical parameterization of convective phenomena:

In order to parameterize 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:

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

where T is the temperature, p is the pressure, p_0 is the ground pressure, R is the gas constant for dry air and c_p is the specific heat at constant pressure.
In formulating the collective effect of convective cloud 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 most important aspect is the choice of the appropriate system shutdown conditions. A first classification of these conditions can be provided starting from the equilibrium equations of the potential temperature θ and the specific humidity q, which represents the ratio between the water vapor mass and the fluid particle total mass on large scale of pressure coordinates [2]

$$c_p\left[\frac{\partial\bar{\theta}}{\partial t} + \bar{\boldsymbol{v}}\cdot\boldsymbol{\nabla}_h\bar{\theta} + \bar{\omega}\frac{\partial\bar{\theta}}{\partial p}\right] = \left(\frac{p_0}{p}\right)^{\frac{R}{c_p}} Q_1$$

$$L\left[\frac{\partial\bar{q}}{\partial t} + \bar{\boldsymbol{v}}\cdot\boldsymbol{\nabla}_h\bar{q} + \bar{\omega}\frac{\partial\bar{q}}{\partial p}\right] = -\,Q_2$$

where 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

that take in literature. To simplify, it is possible to express these two equations respectively as:

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

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

where:

$$\left(\frac{\partial \bar{T}}{\partial t}\right) = -\left(\frac{p_0}{p}\right)^{\frac{R}{c_p}} \left(\bar{\boldsymbol{v}} \cdot \boldsymbol{\nabla}_h \bar{\theta} + \bar{\omega} \frac{\partial \bar{\theta}}{\partial p}\right)$$

$$\left(\frac{\partial \bar{q}}{\partial t}\right) = -\left(\bar{\boldsymbol{v}} \cdot \boldsymbol{\nabla}_h \bar{q} + \bar{\omega} \frac{\partial \bar{q}}{\partial p}\right)$$

To solve this system of two equations it is necessary to have at least two types of closing conditions among the three possible choices [3]

- 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 $\frac{\partial \bar{T}}{\partial t}$ and $\frac{\partial \bar{q}}{\partial t}$

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.
On the other hand, the coupling of source terms 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 Arakawa and Schubert [4] and Betts and Miller [5] [6]schemes. 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 Kuo [7] and Anthes [8] schemes and, starting from the Fritsch and Chappel [9] scheme, the Kain Fritsch [10] [3] scheme.

Case of study 25^{th} November 2016

This case of study involves the extreme weather event recorded in Sicily on 25 November 2016. In that event, the heavy rainfall recorded by the network of weather stations of the Sicilian Civil Protection Department (DRPC) was caused by a purely convective systems cloudy. For this reason it was considered appropriate to perform a re-analysis test to analyze and understand which physical parameterization of the convective phenomena provided the best performance. In particular, the Weather Research and Forecasting (WRF) model has been optimized for complex orography territories [1]. Simulations with spatial domains of 5km and time resolution were performed. The following physical parameters for convective phenomena have been considered:

- ***CU0***: *Explicit convection*
- ***CU1***: *New Kain Fritsch*
- ***CU2***: *Betts – Miller - Janic*
- ***CU3***: *Grell-Devenyi*
- ***CU5***: *Grell 3D*
- ***CU6***: *Tiedtke*
- ***CU14***: *New Simplified Arakawa – Schubert*

In the first analysis, the extrapolation of the rainfall accumulations recorded by the 13 weather stations examined was carried out. The choice of meteorological stations has been done accounting for the spatial localization of the extreme recorded meteorological event. In particular, the following stations have been chosen as reference: 5 stations in the north of Sicily (Castelbuono, Lascari, Pettineo, Polizzi and Cefalù), 4 in the northeast sector (Antillo, Fiumedinisi, Linguaglossa and San Pier Niceto) and 4 in the south - west (Bivona, Giuliana, Ribera and Sciacca).

Subsequently, using the restricted area model the rainfall data for each simulation in which only the physical parameterization of the convective phenomena were modified, have been calculated. These data were compared with the observed data, as shown in Figure 1:

Station name	24 H Rain mm	24 H Rain mm CU0	24 H Rain mm CU1	24 H Rain mm CU2	24 H Rain mm CU3	24 H Rain mm CU5	24 H Rain mm CU6	24 H Rain mm CU14
Castelbuono	74,1	2,3	12,2	3	1,7	8,5	18,5	7,6
Lascari	53,6	15,7	14,5	3,6	11,1	12,6	7,5	5,3
Pettineo	46,2	10,5	17,9	2,5	3,7	2,8	8,8	7,2
Polizzi	89,4	8,2	7,5	1,1	7,1	7,3	8,2	0,8
Cefalù	34,1	8,1	19,1	3	23,6	25,7	16,3	6,2
Antillo	159,5	40,1	10,8	5,2	22,1	19,8	9,6	1,5
Fiumedinisi	153,8	71,3	26,5	10,8	40	15,3	18,1	2,1
Linguaglossa	92,1	50,1	1,4	0	2,1	0,5	0,4	1,2
San Pier Niceto	98,6	22	18,6	2,9	9,4	10,6	4,5	6,6
Bivona	64,3	29,1	52,5	6,6	53	39,3	102,6	53
Giuliana	163,2	33,3	39	9,8	41,3	29,3	53,6	53,6
Ribera	198,4	7,5	52,4	5	28,5	29,2	74,5	12,9
Sciacca	132,3	13,2	50,8	9,9	37,8	46,2	46,6	21

Figure 1: *Observed rainfall data (24H Rain mm) and predicted by the WRF varying the physical parameterization of convective processes.*

Performance Testing Method:

In order to establish which of the simulations provided the best performance, it is necessary to use statistical methods. The performance of a forecast model can be calculated using one or more scalar verification indices. A possible method to obtaining these indices is provided by the dicotomic predictions, yes/no. In order to calculate these indices it is necessary place the data in a table of I **x** J elements, called *"contingency table"*, which contains the absolute frequencies of all possible combinations of the observed and predicted data pairs. Considering the case I = J = 2, as shown in Figure 2, a indicates the number of cases in which the event was expected to occur and its actually happening, b is the number of cases in which the event was expected to happens but it did not occur, c represents the number of cases in which the event occurred but was not expected and finally d represents the number of cases in which the absence of the event was properly scheduled.

		Observed		
		yes	no	
Forecast	yes	a	b	a + b
	no	c	d	c + d
		a + c	b + d	N

Figure 2: *Contingency Table Schedule*

Dividing by $N = a+b+c+d$, it is possible to obtain the combined distribution of prediction relative frequencies and the observed data; a perfect forecast have zero values only for the elements on the diagonal of the table.
From the contingency table it is possible to define the categorical indexes used to quantify the yield of the simulations performed with this model, in particular:

- ***Hit rate***: defined as the ratio between the number of cases in which the event was correctly predicted and the total number of cases considered, n. The value 0 indicates a bad forecast, on, the value 1 indicates a perfect forecast.

- ***Threat score***: is an alternative to the hit rate, useful when the event considered has a substantially lower occurrence frequency than non-occurrence. If the threat score assumes the value 0, the forecast will be bad, otherwise, if it assumes the value 1, the forecast will be perfect.

- ***Bias***: It represents the ratio between the predicted and observed data average.

  $B = 1 \Rightarrow$ the event was predicted the same number of times that it was observed;
  $B > 1 \Rightarrow$ *overforecasting*, the model predicts events with greater frequency than real;
  $B < 1 \Rightarrow$ *underforecasting*, the model predicts events with a lower frequency than real.

- ***False Alarms Rate***: is designed to highlight the tendency to predict events that will not happen. It is especially useful to verify the prediction ability of extreme events. If it assumes the value 0, the forecast will be perfect, if it assumes value 1 there will be the prediction of events that will not happen.

- ***Equitable Threat Score***: is based on TS. By definition ranging from -1/3 to 1 (perfect prediction)

- ***Hanssen-Kuipers Discriminant***: is given by the ratio between the events correctly predicted and those actually occurred less the probability of having a false alarm. By definition ranging from -1 to 1 (perfect prediction,)

Figure 3 shows the index values obtained for the case considered:

	CU0	CU1	CU2	CU3	CU5	CU6	CU14
Accuracy	0,68	0,53	0,45	0,54	0,53	0,51	0,52
TS	0,49	0,43	0,12	0,38	0,35	0,30	0,26
Bias	0,95	1,47	0,49	1,13	1,07	0,91	0,73
ETS	0,22	0,04	-0,06	0,05	0,03	0,01	0,01
POD	0,64	0,74	0,16	0,58	0,54	0,44	0,36
FAR	0,33	0,50	0,67	0,48	0,50	0,51	0,51

Figure 3: *Numeric values of categorical indexes calculated for each simulation performed by modifying the physical parameterization of the convective processes of the mathematical physical model*

Conclusions

The analysis shows that the *explicit resolution* of convective processes ($CU = 0$) is the most reliable and accurate solution with the highest accuracy in term of *Threat Score* and *Equitable Threat score.*
The *Betts-Miller-Janic* scheme ($CU = 2$) is the worst and is the one that also generates the highest number of false alarms *(FARs).*
The *New Simplified Arakawa-Schubert* ($CU = 14$) and *Tiedtke* ($CU = 6$) schemes are only slightly better than the *BMJ* ($CU = 2$).
New Kain Fritsch schemes ($CU = 1$), *Grell-Devenyi* ($CU = 3$) and *Grell 3D* ($CU = 5$) show only small differences and they are the only ones that tend to

overestimate the rain.
The *New Kain Fritsch scheme* ($CU = 1$), excluding an excessive *BIAS* overlapping, has good overall behavior and is the one that shows the maximum *POD (Probability Of Detection)*.

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