Future projections and return levels of wet-snow load on overhead high voltage conductors

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Abstract—**Wet-snow conditions trigger the formation of ice sleeves on overhead power lines and promote the occurrence of heavy snowfalls whose effects may cause serious infrastructural damages and, consequently, prolonged disruptions on the National Transmission Grid. To develop action plans aimed to strength the resilience of the Power Network, probability maps about the formation of ice-sleeves and their loads on overhead power lines have been elaborated. Future scenarios over Italy have been computed on the basis of 12 high-resolution Euro-CORDEX models (spatial resolution ~12km), assuming a "Business-As-Usual scenario" (RCP8.5). The MERIDA meteorological reanalysis dataset (spatial resolution 4 km), spanning the period 1990-2020, was used to "bias-correct" model data by applying the "Equidistant Quantile Mapping". MERIDA dataset was also used to implement the "Makkonen model" to describe the growth of the ice-sleeve on high-voltage lines.**

After validating the codes by correlating the results with recorded failure in energy transmission during some serious event, the climate models' outputs have been elaborated to evaluate these phenomena until 2060 and to deduce future scenarios. Probability maps have been elaborated by means of the "Extreme Value Analysis" statistical technique, used to describe the expected values at the timeframes 2020, 2030, 2040 and 2050. The results point out that such phenomena will generally decrease as snowfall will turn in rainfall due to global warming. However, if the ice-sleeve loads are likely to reduce at low-medium altitudes, these events may intensify over the highest Alpine regions as, in a warmer climate, temperatures between -1.0 °C and +1.5 °C will be more likely thus allowing the occurrence of wet-snow events at those altitudes so far spared due to their typical cold temperatures.

Keywords— ***Resilience, wet-snow sleeve on overhead lines, regional climate model, return period, probability map***

I. INTRODUCTION

The heavy wet snowfalls occurred in February 2015 in Emilia Romagna region and in January 2017 in the Abruzzo region caused serious problems for the safety and operation of the Italian Electric System. During this last event, wet-snow sleeves on overhead lines reached 15 kg/m in areas whose design criteria was below 5 kg/m.

The frequency and intensity of these extreme phenomena have been increasing over the Italian territory in the last 15 years. As they may cause extensive damages, there is an urgent need to set up an appropriate Climate Change Resilience Planning for the national electrical sector.

The weather forecast system WOLF [1] supports the Italian electric stakeholders in the operative management by forecasting wet-snow events in the next 72 hours. But strengthening the resilience of the electric system in the coming decades is another important challenge to cope with climate change impacts within the lifecycle of energy infrastructures.

To bridge the gap between the climate models' results and the tailored information requested in planning a resilient power grid, future climate change projections have been elaborated on the basis of the state of art climate models.

The future scenarios concern the wet-snow load on overhead high voltage conductor (ACSR - diameter 31.5 mm) expected over Italy by 2050.

The datasets used and the methodology adopted to elaborate climate future projections are mentioned in Section II; future scenarios are analysed in Section III; the probability maps about the occurrences of the ice-sleeves, at different levels of intensity and timeframes, are discussed in Section IV; some conclusions are drawn in Section V.

II. METHODOLOGY

The analysis has been done over the whole Italy, based on 12 high-resolution (~12 km) region climate model (RCMs) (Table 1), whose performances have been checked in previous works [2]. Such simulations have been realized in the framework of the European Project Euro-CORDEX [3] under the Representative Concentration Pathways RCP 8.5, that is in a "Business-As-Usual scenario", i.e., without reduction of green-house gas emissions [4].

TABLE I. LIST OF EURO-CORDEX SIMULATIONS CONSIDERED. THE NAMES OF SIMULATION IDENTIFY THE RESEARCH INSTITUTE, THE GLOBAL CIRCULATION MODEL AND THE REGIONAL CLIMATE MODEL

Id_mod	**Climate model Simulation**
1	*CHEC-EC-EARTH_CLMcom-CCLM4*
2	*ICHEC-EC-EARTH_KNMI-RACMO22E*
3	*ICHEC-EC-EARTH_SMHI-RCA4*
4	*MOHC-HadGEM2-ES_KNMI-RACMO22E*
5	*MOHC-HadGEM2-ES_SMHI-RCA4_*
6	*MPI-M-MPI-ESM-LR_SMHI-RCA4*
7	*CNRM-CERFACS-CNRM-CM5_KNMI-RACMO22E*
8	*CNRM-CERFACS-CNRM-CM5_CLMcom-CCLM4*
9	*CNRM-CERFACS-CNRM-CM5_SMHI-RCA4*
10	*IPSL-IPSL-CM5A-MR_SMHI-RCA4*
11	*MOHC-HadGEM2-ES_CLMcom-CCLM4*
12	*IPSL-IPSL-CM5A-MR_SMHI-RCA4*

The reanalysis dataset MERIDA [5], with spatial resolution of 4 km x 4 km from 1990 to 2020, has been used:

- to reconstruct the reference climatology;
- to compute the model bias-correction, as well as the model downscaling from 12 km to 4 km by applying the Equidistant Quantile Mapping (EQM) [6], which is a statistical bias-adjustment technique;
- to develop and validate the Makkonen model [7][8] in estimating wet-snow loads.

To estimate wet-snow load, the meteorological variables minimum (*Tn*) and maximum temperatures (*Tx*), and total precipitation (*P*) have been used. The wind intensity (*V*) has been parametrized at three different levels according to orographic height *z*.

The twenty years 2001-2020 has been considered as reference timeframe (REF). To investigate the climate change in the first half of the 21st Century, climate projections have been elaborated for the twenty years centred on the years 2030, 2040, and 2050. Such future scenarios have been analysed at annual and seasonal scales for the seasons:

- Winter or DJF (Dec, Jan, Feb)
- Spring or MAM (Mar, Apr, May)
- Autumn or SON (Sep, Oct, Nov).

as wet-snow events occur during the cold season.

The procedure can be outlined in four steps:

1) Generally, RCMs have systematic bias (i.e. errors with respect to observation) that should be removed. Models listed in Table 1 have been processed by applying EQM to reduce models' bias respect to MERIDA data in REF=2001-2020 (*training period*). Then a cross-validation has been performed to test the effectiveness of the process by applying the same bias-correction to the models in the verification period VER=1990-2000. Then the whole set of RCMs has been similarly corrected.

   The best meteorological configuration, as an input to study the events mentioned above, resulted in using:

   - *Tn* bias-corrected at seasonal scale (*TnAdj*);
   - *Tx* bias-corrected (*TxAdj*) computed as:

     $$TxAdj = TnAdj + DTRAdj$$

     where *DTRAdj* is the Diurnal Temperature Range bias-corrected at annual scale;
   - *P* without any correction to preserve the correlation between temperature and precipitation data.
2) The Makkonen model was implemented and validated:
   - by investigating the correlations between the ice-sleeve loads and the failures reported by Terna (Italian TSO) for some episodes;
   - by comparing the ice-sleeve dimensions with those observed by Terna for some notable events.
3) Single model and Multi-model mean future scenarios have been elaborated and analysed for the above mentioned twenty-years periods.
4) Probability maps have been elaborated by using the statistical technique "Extreme Value Analysis" (EVA) to describe the expected values at the different future timeframes and for different level of intensities [9].

A. Makkonen Model for climate analysis

In wet-snow conditions (i.e. when $-1.0\ °C \leqslant T_i \leqslant 1.5\ °C$, where T_i is the surface air temperature) snowflakes promote the growth of sleeve around the conductor.

A cylindrical snow sleeve with mass M_i [kg/m] has a typically hourly evolution described by

$$M_i = M_{i-1} + I_i D_{i-1} \Delta t \tag{1}$$

where $\Delta t = 1h$

- M_{i-1} is the snow sleeve mass at the previous step $(i-1)$
- $I_i = \beta \sqrt{V^2 + v_s^2}\, w$ is the accretion intensity of snowfall over the conductor

  $\beta = 1/\sqrt{V}$ is the *sticking efficiency*

  v_s is the terminal velocity of the snowflakes ($v_s = 1.7\ m/s$)

  $w = P/\, v_s$ is the mass concentration of wet-snow in the air
- D_{i-1} is the diameter of snow sleeve at the previous step.

Moreover, the action on the conductor due to the wind is considered:

$$Svc = 0.5 \cdot / g \cdot \rho_{air} \cdot V^2 \cdot Di \tag{2}$$

- Svc = equivalent mass
- $g = 9.8\ m/s^2$ is the gravitation acceleration
- ρ_{air} ranging between $1.170\ kg/m3$ and $1.274\ kg/m^3$ depending on orographic height *z*, considering $1.219\ kg/m^3$ is the typical value of air density when air humidity is ~ 80% as in the case of wet-snow conditions.

The total snow load R_i is the vector sum of the two components:

$$R_i = \sqrt{M_i^2 + S_{vc}^2} \tag{3}$$

To investigate the future trend by using the model daily data, Makkonen model has been applied under the following approximations:

- hourly precipitation is $P_{ih} = P\ /24$ i.e. the daily precipitation equally distributed over the 24 hours
- hourly wind values range between 1 m/s to 1.5 m/s depending on orographic height
- hourly temperature T_{ih} is inferred from typical diurnal cycle between *TnAdj* and *TxAdj*.

Moreover, the shedding of the sleeve has been considered when its dimensions exceed the threshold equal to 20 kg/m.

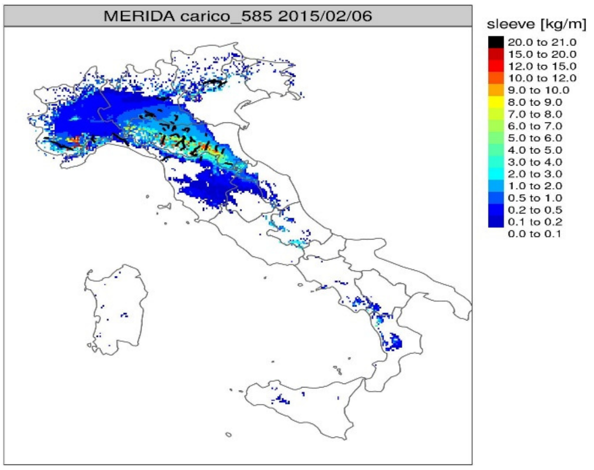

Fig. 1 Map of total snow loads [kg/m] for ACSR-585 mm^2 conductor and lines failures (black lines) for the event recorded on February 6, 2015

Lastly, a maximum time of 3-days during which the wet-snow accretion may occur has been fixed, after that a partial breaking of the sleeve is modelled.

Regarding the validation of the code, as an example Fig.1 shows the numerical reconstruction of snow loads for ACSR-585 mm^2 with the recorded lines failures occurred on February 6, 2015.

B. Extreme Values Analysis (EVA)

Extreme value theory evaluates the intensity and frequency of rare events that lie in the tails of the probability distribution of the variables, for example events that occur once in 20 years [10].

The extreme quantiles of interest are estimated by fitting an extreme value distribution. Two general methods can be used: one method, referred to as the "peaks-over-threshold" is used to represent the behaviour of exceedances above a high threshold. The second, the so-called "block maximum" (method used also in this study), considers the sample of extreme values obtained by selecting the maximum value observed in blocks of equal length. In this work blocks are one year, in accordance with the statistical theory that indicates the Generalized Extreme Value (GEV) distribution is appropriate for the block maxima when blocks are sufficiently large [9]. The maxima (each selected among 365 values) are assumed to be independent variables from a GEV distribution, whose parameters (location, scale, and shape) are to be estimated. Parameters can be estimated by different methods. Here the method of L-moments [11] has been used.

From the fitted distribution, return values were calculated. In the case of a stationary climate, return values have a clear interpretation as the value that is expected to be exceeded on average, once every return period, or with probability 1/(return period) in any given year. In a changing climate, the return values are more difficult to interpret. In this study they were evaluated from the future projections by considering a stationary climate in each twenty-year scenario. Generally, confidence in a return level decreases rapidly when the period is more than about two times the length of the original data set.

III. ANALYSIS OF FUTURE SCENARIOS

At first, the reference values have been analysed by considering their spatial patterns over the analysis domain at seasonal scale to investigate the intra-annual variation of the phenomena. Then future climate change scenarios have been studied in terms of seasonal anomalies, i.e. differences between the climate future values and the reference ones.

The 95th percentile values have been considered, since snow-load events have very small temporal and spatial scales, so averages values over twenty-year period are very low and, therefore, uninteresting.

Analysing the total snow loads reconstruction in the past through the Makkonen model (Fig. 2), it is found a decreasing of the intensities of these events in the more recent past (2001-2020) respect to the more distant period (1990-2000), showing the same trend projected for the future scenarios (Fig.3) as precipitations will be more and more likely frequent as rains is expected instead of snowfalls due to the global warming [7].

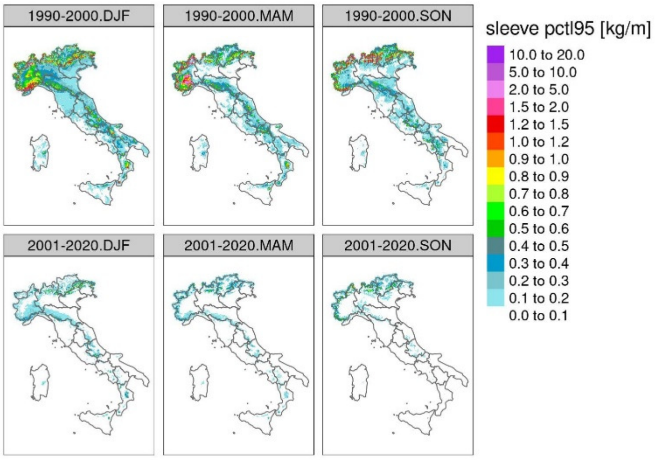

Fig. 2 Total snow loads [kg/m] (95th percentile values) inferred from MERIDA at seasonal scale (DJF, MAM, SON from left to right) for the periods 1990-2000 (top) and 2001-2020 (bottom)

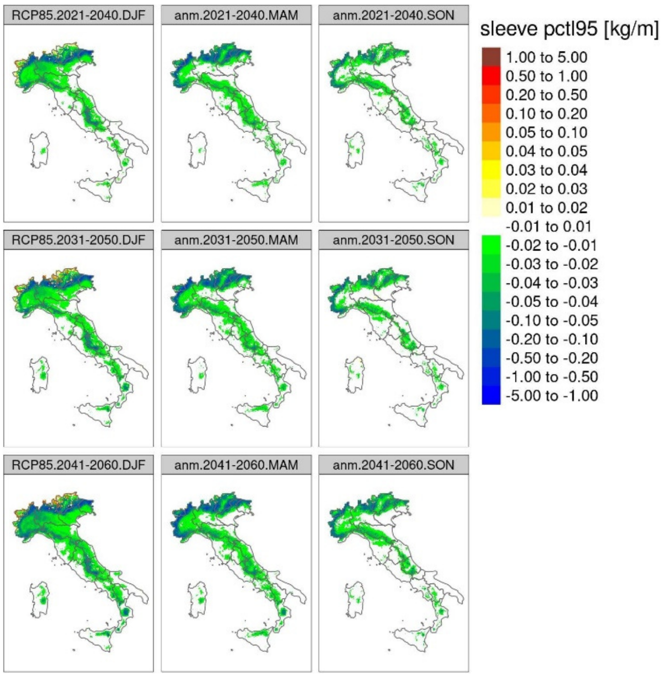

Fig. 3 Snow load change projections (anomalies) inferred by multi-model scenarios at seasonal scale expected for the future scenarios: 2030 (first row), 2040 (second row), and 2050 (third row)

IV. ICE-SLEEVE PROBABILITY MAPS

With the aim of providing the information required by the vulnerability model, some probability maps have been elaborated. The occurrences of the wet-snow load have been characterized at different levels of intensity and, as mentioned above, by assuming that the climate is essentially stationary within each twenty years period.

10 levels (Lev) have been considered to characterize snow load: 1, 2, 4, 6, 8, 10, 12, 14, 16, 18 [kg/m].

Considering that the probability of exceeding a certain threshold level is equal to 1/RT (Return Time), the ice-sleeve evolution has been described by considering the following RT: 1, 2, 3, 4, 6, 8, 10, 20, 30, 40, 50, 60, 70, 80, 100, 200.

The probability maps have been elaborated by applying the EVA statistical technique to daily data of snow sleeves.

At first the probability maps inferred from MERIDA data have been considered (Fig. 4) and, in the same way, probability maps have been elaborated by using the data of each climate model. Then the multi-model probability maps have been calculated and checked against the MERIDA maps over the same past period 2000-2020 (Fig. 5). It was also considered the standard deviations to evaluate the uncertainty degrees of the multi-model scenarios. The ensemble averages of probability maps have been obtained by averaging the probability map of each model and the deviations has been calculated according to their definition. Both mean and standard deviation have been computed by using the Climate Data Operators (CDO) software.

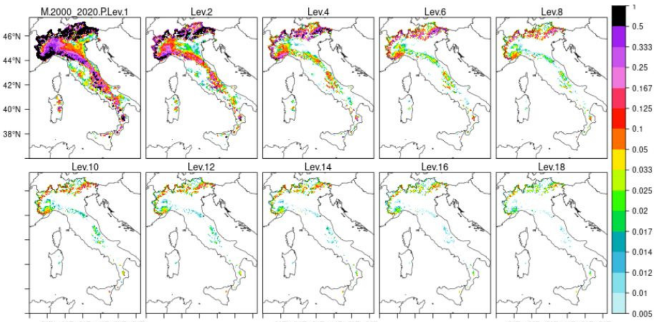

Fig. 4 Snow load probabiliy maps (one for each intensity level) inferred from MERIDA data for the period 2000-2020

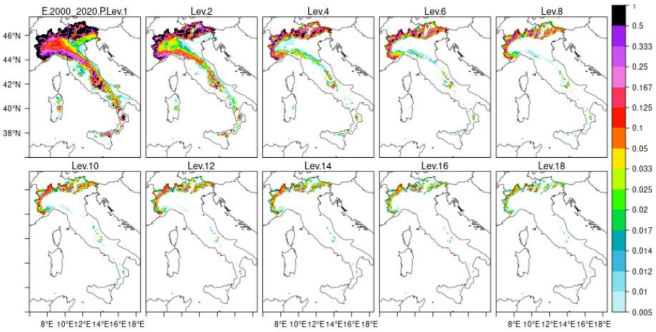

Fig. 5 Snow load probabiliy maps (one for each intensity level) inferred from the ensemble of the Euro-CORDEX models for the period 2000-2020

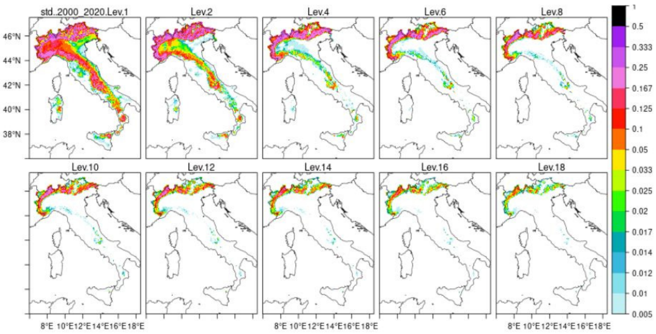

Fig. 6 Standard deviation of snow load probabiliy of the twelve Euro-CORDEX models for the period 2000-2020

As expected, the region with the greatest uncertainty concerns the western Po Valley, that is a region with a very complex orography and characterized by peculiar local wind circulations (Fig.6).

Then the probability maps in the three future periods have been analysed together with the corresponding standard deviations. For sake of brevity only the probability maps elaborated for the scenario 2030 are reported.

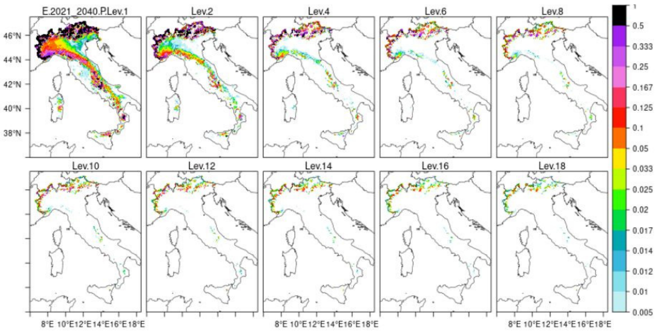

Fig. 7 Snow load probabiliy maps (one for each intensity level) inferred from the ensemble of the Euro-CORDEX models for the period 2021-2040

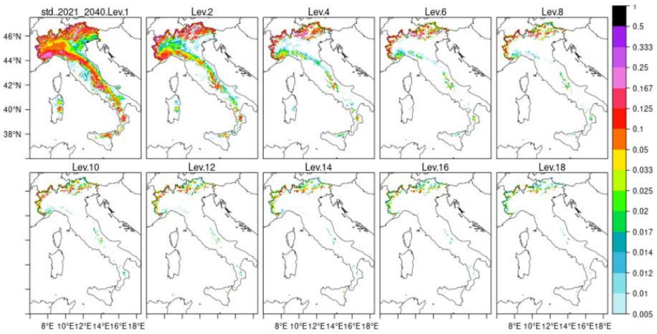

Fig. 8 Standard deviation of probabiliy snow load of the twelve Euro-CORDEX models for the period 2021-2040

The occurrences of sleeves are expected to decrease in general (Fig. 7). It is worth noting that sleeves with loads ≥ 8-10 kg/m are projected to occur with RT <10 years in the future scenarios over Alpine Regions. Analogous results have been found out for the other periods.

V. CONCLUSIONS

Network system will have to cope with very serious climate conditions characterized by extreme meteorological events, projected to increase in both frequency and intensity. A better understanding of vulnerabilities of electric system is necessary to define measures to increase the resilience against threats from climatic changes.

Focusing on the meteorological hazards occurring in wet-snow conditions, 12 high resolution regional climate models (listed in Table 1) have been analysed to elaborate future scenarios about the snow sleeve loads on overhead high voltage conductors.

Each model has been investigated separately then multi-model mean scenarios have been computed to improve the accuracy and the reliability of probabilistic projections compared to any projection inferred from single model realizations.

The work points out the phenomena are expected in general to decrease because, with the increasing temperature, the precipitations will be more likely rains instead of snowfalls. Instead, the same phenomena are expected to intensify over high-altitude regions so far saved from these phenomena because were characterized by cold temperatures, as visualized by Fig. 3 in the winter season.

The methodology presented may be extended to study other hazards as floods or heatwaves to provide useful material to decision-maker in planning action to increase the resilience of the national electric system.

ACKNOWLEDGMENT

This work has been financed by the Research Fund for the Italian Electrical System in compliance with the Decree of Minister of Economic Development April 16, 2018.

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