An updated CLIWAC model to investigate wet snow sleeve events on overhead lines in Italy by the end of the Century

P. Faggian[1], A. Trevisiol[1], G. Decimi[1]

[1] *Ricerca sul Sistema Energetico RSE S.p.A., Milan - Italy*

paola.faggian@rse-web.it, arianna.trevisiol@rse-web.it, goffredo.decimi@rse-web.it

Abstract— **An updated version of the CLImate Wet snow sleeve ACcretion model CLIWAC is presented. The novelty lies in: refining wet snow thermal range and the criteria to distribute daily cumulative precipitation on an hourly scale; taking into account the sleeve accretion in dry snow conditions and partial shedding and melting; using wind data instead of parametrized wind values.**

The comparison between the new estimates of Wet Snow Load (*WSL*) with the observations, acquired by the Wet snow Ice Laboratory Detection at Vinadio (Italy), showed better performance than previous results. In addition, the analysis of the new CLIWAC results, inferred from the MERIDA OI reanalysis, about the reconstruction of some Italian severe wet snow events in relation with the recorded failures in the energy supply, gave better results than before.

On the basis of daily data provided by 12 high-resolution (~12 km spatial resolution) Euro-CORDEX simulations, realized under the two emission pathways RCP8.5 and RCP4.5, CLIWAC was used to elaborate future projections of *WSL* on high voltage conductors (ACSR - d 31.5 mm) over Italy by 2100. To overcome the concept of "return time", obsolete in a climate change context, the two frequency indices *WSLD* (Wet Snow Load Days) and *WSLF* (Wet Snow Load Frequency) were also estimated to elaborate future scenarios at short-, medium and long-term to investigate the probability of *WSL* exceeding some infrastructural thresholds from 1 kg/m to 18 kg/m. Weighted ensemble scenarios were computed, and the statistical significance of the projected variations was investigated through the Wilcoxon test and the agreement among the models.

The results highlight a general reduction in intensity and frequency of the extreme wet snow episodes, especially in RCP8.5, as rainfalls will prevail over snowfalls due to global warming, except for high Alpine altitudes, so far spared by this kind of events.

Keywords— ***CLIWAC model, wet snow sleeve on overhead lines, regional climate models, climate extreme indices, Energy System resilience***

I. INTRODUCTION

Climate variability and change pose increasingly significant challenges to societies worldwide. Human influence on the climate system is unequivocal, and recent anthropogenic emissions of greenhouse gases are the highest in history [1]. WMO confirmed that 2023 was the warmest year on record, with the global average near-surface temperature at 1.45 ± 0.12 °C above the pre-industrial baseline. Moreover, it was the warmest ten-year period on record [2]. Over the last decade, European surface temperatures were more than 2 °C warmer than pre-industrial levels,[3]. The last bulletin of Copernicus[1] highlights that February 2024 was the warmest February on record globally, and recent climate changes have had widespread impacts on human and natural systems. In order to undertake efficient adaptation actions to withstand climate change impacts, climate information plays a crucial role in national development planning, for managing development opportunities and risks.

Heavy snowfalls represent one of the most serious hazards for electric grids because they trigger the formation of sleeves on overhead power lines whose loads may cause outages and sometimes prolonged disruptions of the energy supply. Hence stakeholders ask for information about future climate scenarios in planning actions to strength the resilience of the electric network against wet snow impacts.

The present study aims to improve on previous estimates [4] about the effects of climate change on the snow loads on overhead power lines, through an updated version of CLIWAC to assess future wet snow scenarios from state-of-art regional climatic simulations.

The datasets used and the methodology adopted to elaborate climate future projections are mentioned in Section II; main results are discussed in Section III and some conclusions are drawn in Section IV.

II. DATA SET, CLIWAC MODEL, AND METHODOLOGY

A. Variables and datasets

Hindcast and future projections of wet snow load (*WSL*) have been computed through an updated version of CLIWAC whose input consists of daily minimum T_n and maximum T_x temperature [°C], cumulated precipitation P [mm/d], and wind speed V [m/s]. These data have been inferred from 12 high-resolution (~12 km) region climate model (Table I) developed in the framework of the European Project Euro-CORDEX (https://euro-cordex.net/) by considering simulations realized under the Representative Concentration Pathways RCP8.5 and RCP4.5 representing respectively a pessimistic "*business as usual*" emission pathway, i.e. without reduction of green-house gas (GHG) and with partial reduction of GHG.

In addition, the meteorological data from the reanalysis dataset MERIDA OI, at 4-km spatial resolution covering the period 1990-2020 over Italy [5] (http://merida.rse-web.it; Optimal Interpolation version for temperature) have been also retrieved, in order to:

[1] https://climate.copernicus.eu/climate-bulletins

- remap climate model data from 12 km to 4 km and reconstruct the reference climatology;
- remove systematic temperature biases in climate model simulations to better identify the wet/dry snow thermal condition: T_n was bias-corrected (T_nAdj) at seasonal scale by using the Equidistant Quantile Mapping Technique. Then, T_x was bias-corrected according to the expression: $T_xAdj = T_nAdj + DTRAdj$, where $DTRAdj$ is the Diurnal Temperature Range bias-corrected at seasonal scale, too. Instead, P and V were used as raw data to maintain the temporal correlation between meteorological data, even if P bias may exceed 100% of the signal in cold months [6] and there is a great uncertainty about V values due to the great spread among the model (not shown).
- validate the new CLIWAC model.

TABLE I. LIST OF EURO-CORDEX SIMULATIONS. THE NAME IDENTIFIES THE GLOBAL CIRCULATION MODEL AND THE REGIONAL CLIMATE MODEL

Id	Climate model Simulation
1	*ICHEC-EC-EARTH_CLMcom-CCLM4-8-17*
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-CCLM4-8-17*
9	*CNRM-CERFACS-CNRM-CM5_SMHI-RCA4*
10	*IPSL-IPSL-CM5A-MR_SMHI-RCA4*
11	*MOHC-HadGEM2-ES_CLMcom-CCLM4-8-17*
12	*MPI_M-MPI-ESM-LR_CLMcom-CCLM4-8-17*

B. *The upgraded CLIWAC model*

The new version of CLIWAC have been achieved by modifying the wet snow thermal range, hourly precipitation distribution, sleeve accretion in dry snow conditions, partial shedding and melting, and wind contribution, in order to improve the reconstruction of the sleeve accretion events recorded at the WILD station[2], in comparison with the previous version of CLIWAC, as discussed in Section III.

It might be useful to recall here the characteristics of Makkonen model [7][8][9]. The resulting wet snow load at time i, L_i [kg/m][3] is the vectorial sum of the two components: Mi (linear mass component), and Wf_i (horizontal wind force acting on the iced conductor per length unit), which express the contributions to sleeve growth due to precipitation flow and wind action on the conductor, respectively:

$$L_i = \sqrt{M_i^2 + Wf_i^2}$$

The sleeve accretion is typically cylindrical and M_i [kg/m], at time i, is described by the equation:

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

where:

- M_{i-1} is the sleeve mass at time $i-1$
- $I_i = \beta\sqrt{V_i^2 + v_s^2} w_i$ is the flux [kg/(m^2·s)], i.e. the intensity of snow deposition around the cable, assuming a wind velocity orthogonal to it, where:
  β = is the sticking efficiency;
  V_i is the wind speed [m/s];
  v_s is the snowflake terminal velocity [m/s];
  $w_i = P_i / v_s$ is the mass concentration of snow in the air;
  P_i = total precipitation at time i
- D_{i-1} is the sleeve diameter at the previous time step $i-1$, whose evolution is described by:
  $D_i = \sqrt{4 \cdot \frac{M_i - M_{i-1}}{\pi \rho_s} + D_{i-1}^2}$, where:
  ρ_s [kg/m^3] is the snow density;
  D_0 = 0.0315 m is the high voltage cable diameter at the first timestep;
- Δt is the time step, assumed equal to 1 hour in this study.

The wind action component Wf_i is described by the formula:

$$Wf_i = 0.5/g \cdot \rho_{air} \cdot V_i^2 \cdot D_i$$

where:

- g = 9,8 m/s^2 is the gravitation acceleration;
- ρ_{air} is the density of the air [kg/m^3].

To investigate future wet snow load scenarios, CLIWAC model was developed by adapting the hourly accretion model to handle daily meteorological data, with the following approximations, similarly to old version:

- hourly temperature T_i is inferred from a sinusoidal-like evolution reconstructed between minimum T_n (imposed to 5:00 a.m.) and maximum T_x (at 2:00 p.m.) with continuity among consecutive days;
- ρ_{air} ranges between 1.170 kg/m^3 and 1.274 kg/m^3 depending on orographic height z, considering that 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 variations from the old version are listed here:

- wet snow accretion happens when temperature is between - 0.5° C (instead of - 1.0° C) and 1.5° C and it is a rainy day, with daily cumulated precipitation P > 1 mm/d (instead of 0 mm/d);
- dry snow accretion (not considered in the previous version) happens when T_i < - 0.5° C, P > 1 mm/d, and a sleeve is already grown at the previous time step;
- P is only evenly distributed during the hours of wet and dry snow conditions (instead of all 24 hours);
- V_i is equal to the daily V (instead of being parametrized between 1 and 1.5 m/s in 3 altimetric classes depending on model grid orography);
- v_s is fixed to 1.7 m/s and 1.1 m/s in wet and dry snow conditions respectively;
- referring also to [9], β and ρ_s are defined as follow.
  In wet snow conditions:

[2] The Wet snow Ice Laboratory Detection (WILD), sited at Vinadio (CN - Italy) at 960 m a.s.l. (44,298° N, 7,152° E) since the winter 2013-2014, is an open-air laboratory to measure the wet snow load on some high voltage conductors, integrated with a weather station.

[3] For simplicity, it is expressed in kilogram-force per meter of cable, as it is used by the TSO.

$$\begin{cases} \beta = 1 \quad ; \ \rho_s = 300 + 20 \cdot V_i \ \text{for} \ V_i < 1 \\ \beta = 1/\sqrt{V_i} \, ; \ \rho_s = 300 + 20 \cdot V_i \ \text{for} \ 1 \le V_i < 10 \\ \beta = 0.3 \quad ; \ \rho_s = 500 \ \text{for} \ 10 < V_i \end{cases}$$

In dry snow conditions:

$\beta = 0.3$; $\rho_s = 200$.

Spontaneous/stochastic ice shedding is difficult to simulate, but in the new CLIWAC model a partial shedding has been modelled by considering:

1) with precipitation (P > 1 mm/d):
- $M_i = 85\% \, M_{i-1}$, if $0.5° \text{ C} < T_i \leqslant 1.5° \text{ C}$ and T_i is rising with a gradient $\Delta T > 0.25°$ C/h;
- $M_i = 60\% \, M_{i-1}$, if $1.5° \text{ C} < T_i \le 2.5° \text{ C}$, for maximum 24 consecutive hours, after which $M_i = 0$.

2) without precipitation (P ≤ 1 mm/d):
- $M_i = M_{i-1}$, if $T_i < -0.5° \text{ C}$ (instead of - 1.0° C) for maximum 24 consecutive hours, after which $M_i = 0$;
- $M_i = 60\% \, M_{i-1}$, if $-0.5° \text{ C} < T_i \le 2.5° \text{ C}$, for maximum 24 consecutive hours, after which $M_i = 0$.

A total melting occurs if $T_i > 2.5°$ C.

Finally, as in the old version, a total breaking is described if M_i exceeds 20 kg/m or after a 3-days sleeve accretion, considering that no historical events recorded in WILD station lasted more than 3 days.

C. Methodology

The daily maximum wet snow load (hereafter *WSL*) values computed by CLIWAC were stored to study the climatology from 1990 to 2020 from MERIDA OI data, and to investigate the climate evolution from 1990 to 2100 from the regional models (Table I). The analysis periods were split into five 20-year time frames: the reference period 2001-2020 (REF), and four future scenarios 2021-2040, 2041-2060, 2061-2080, 2081-2100. The period 1990-2000 (VER) was also considered to characterize the climatological variations in the recent past. The climate scenarios were calculated at annual and seasonal scale neglecting summer, as wet snow events are very rare in Italy during warm months.

The WSL extreme values have been analysed by estimating three indices, already defined in [4]:

1) *WSL95*, i.e. the 95th percentile of *WSL* at annual/seasonal scale, computed filtering out the values lower than 0.05 kg/m. *WSL95* was computed, instead of mean values because *WSL* values, averaged over a twenty-year period, are very small, due to the very small temporal and spatial scale of the events. Moreover, as *WSL95* describes highest values, it is of most interest in investigating risks for overhead lines outages.

2) *WSLD* (*WSL* Days): the number of days on which the *WSL* exceeds the infrastructural damage thresholds 1, 2, 4, 6, 8, 10, 12, 14, 16, 18 kg/m on an annual scale in each analysis period.

3) *WSLF* (*WSL* Frequency): the number of years in which *WSL* exceeds the aforementioned thresholds, divided by the number of years of each time frame (20 years in this case).

To improve the accuracy of the future projections, among various model atmospheric approaches, referring to [10], a weighted ensemble mean (hereafter simply ensemble) has been considered with weights decreasing exponentially with respect to the *WSL* absolute bias between the model results and MERIDA estimate in the REF scenario, normalised with respect to the mean absolute bias of the *N* models:

$$p_{ens} = \sum_{i=1}^{N} a_i \cdot e^{-\left(\frac{b_i}{B}\right)^2} \cdot p_i$$

where:

p_{ens}: weighted ensemble mean projection for a given grid point

p_i: projection of the model *i* for the same grid point

a_i: normalisation coefficient

b_i: *WSL* bias between model *i* and MERIDA in REF

B: mean value of the absolute bias of the models.

The assessment about the future climate projections is carried out in term of anomalies (i.e. differences between future and reference scenarios) inferred from the weighted ensemble mean. The climate change signal was considered robust if 9 out of 12 models (75% model agreement) gave the same sign of anomalies.

III. Results

The performances of the new CLIWAC were first tested by comparing the outputs of the updated version, applied to the average daily meteorological variables recorded at the WILD station, with the wet snow loads measured at Vinadio. Then CLIWAC results, inferred from the MERIDA OI reanalysis at daily scale have been analysed by considering the *WSL* spatial patterns together with the location of faulted high voltage lines recorded during some serious wet snow events over Italy (*A.*). The historical climatology in REF and the future scenarios of *WSL95*, *WSLD* and *WSLF* are discussed in paragraph *B.*, C., and D. respectively.

A. Validation of the new CLIWAC model

The updated CLIWAC model shows better performances in the description of the phenomena. Such an example in Fig. 1 are reported the hourly diagrams of *T*, *P* and *L* in two wet snow episodes registered at WILD and calculated by the old CLIWAC on the left and by the new code on the right. The Fig. 1 shows the improvements in describing the shedding of the sleeve on 2015-02-21, and in evaluating the load on 2018-01-08 underestimated in the old version.

The improvement is also noticeable in Fig. 2 which depicts the faulted high voltage lines and the new *WSL* fields over Italy for the two severe episodes occurred in Emilia-Romagna region on 2015-01-06 and in Abruzzo region on 2017-03-05: now the recorded outages are better explained by the increased weight of the loads.

B. Analysis of WSL95

WSL95 historical variations were first calculated by using both reanalysis and model data. Fig. 3 shows the annual *WSL95* reconstructions inferred from MERIDA in VER (left) and REF (centre), and the ensemble values in REF (right). Compared to previous results [4], the updated *WSL95* values are higher and, therefore, more consistent with observations. In addition to the effect of the new parameterisations, the new, more satisfying results also depend on having imposed a threshold 0.05 kg/m, which removed small unrealistic values

in the cumulative distribution function from which *WSL95* was computed.

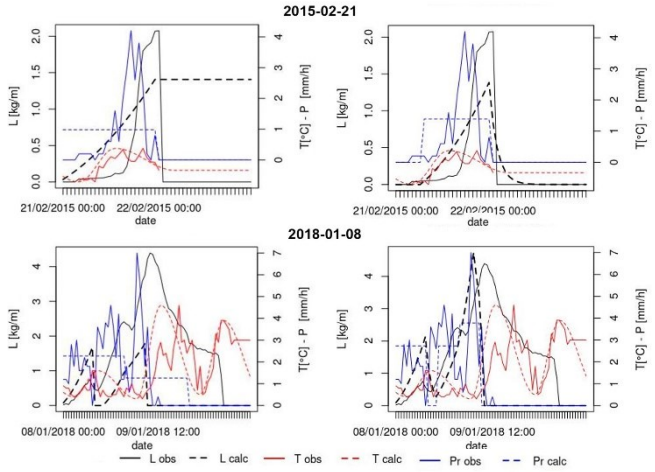

Fig. 1 Hourly *T*, *P* and *L* registered (continuous line) at WILD and calculated (dashed lines) by the old CLIWAC (left) and by the new CLIWAC (right) on 2015-02-21 (top) and 2018-01-08 (bottom).

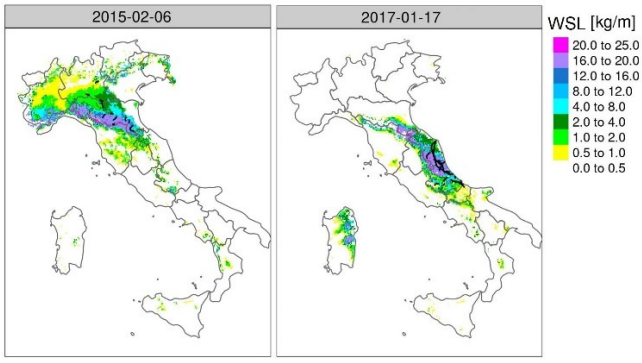

Fig. 2 *WSL* maps and high voltage lines failures (black lines) for the events recorded in Italy on 2015-01-06 (left) and 2017-03-05 (right).

Confirming the previous results [4], the new estimates highlight a significant ($p < 0.05$ from Wilcoxon test) positive trend of *WSL95* over most of Italy in the recent past (REF) compared to the more distant period (VER), in particular over the Apennine ridges, due to more abundant precipitation and an increase of minimum temperature in the last decades. The ensamble scenario in REF is characterised by comparable or slightly lower values than those described by the reanalysis and reproduces the complex spatial pattern in a completely satisfactory manner (Fig. 3).

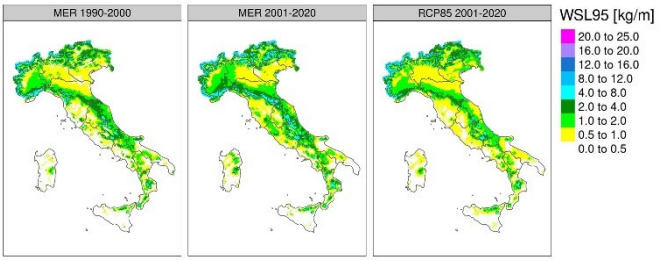

Fig. 3 Annual climatology of *WSL95* in the past: MERIDA OI in VER = 1990–2000 (left); MERIDA OI in REF = 2001–2020 (centre); ensemble in RCP8.5 in REF (right).

About future projections, very small decreases (within 0.5 kg/m) are inferred at short term (not shown). The decrease is accentuated in the second half of the Century at the lower-middle elevations (above 2 kg/m), whereas the events are expected to increase locally over high alpine regions (within 1 kg/m). Fig. 4 represent the *WSL95* evolution under the RCP8.5 hypothesis, but very similar results are inferred in RCP4.5. The noteworthy differences concern the scenario 2081-2100 in which the downward trend of *WSL* is slightly reduced (about 1 kg/m) on the Apennines and Alps. These long-term differences may be explained by the lower warming and more intense precipitations expected in RCP4.5 configuration compared with RCP8.5 [6].

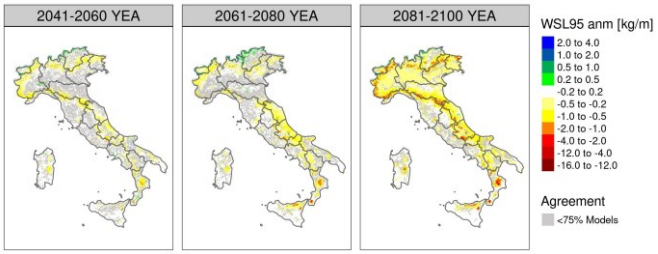

Fig. 4 Annual anomalies of *WSL95* for the ensemble mean in RCP85, from left to right: 2041-2060; 2061-2080; 2081-2100 scenarios. The grey colour represents areas where the agreement among models in the sign of anomaly is lower than 75%.

C. *Analysis of WSLD*

As mentioned above, *WSLD* index points out the number of occurrences of wet snow events exceeding some infrastructural damage thresholds. The maximum annual values of $WSLDmax = max\ (WSLD_i)$ $(1y \leq i \leq 20y)$ are here discussed to investigate the trend of serious wet snow events.

In REF, the highest values of *WSLDmax* characterize the Alpine region (by about 50 to 100 days at level 1 kg/m), as expected and in close agreement with MERIDA field. The first row of Fig. 5 represents *WSLDmax* for the multi model ensemble under RCP8.5 hypothesis for the threshold levels = 1, 4, and 10 kg/m. The future anomalies at medium- and long-term (2nd and 3rd row of Fig. 5, respectively) indicate that, where the agreement among the model is > 75%, the *WSLDmax* trend is negative (blue colours) everywhere and becomes more pronounced along the Century, with reductions for each threshold level. The positive trend (red colours) affects only few points over the Alps in the future. Analogous results are found in RCP4.5 hypothesis with smaller anomalies (1-2 days, not shown).

D. *Analysis of WSLF*

According to its definition, the *WSLF* represents the relative frequency of wet snow events above the thresholds of interest, therefore *WSLF* fields can be considered probability maps of exceedance of some threshold values in a year.

Fig. 6 represents the *WSLF* values for the ensemble mean under RCP8.5 hypothesis for the threshold levels as in Fig. 5. In REF (1st row of Fig. 6), the probability of occurrence of low *WSL* is very high over Northern Italy and Apennine regions. Regarding more serious levels (≥10 kg/m), the frequency continues to be high only for high-altitude regions in close agreement with MERIDA results and confirming the Italian critical areas highlighted in the previous work [4].

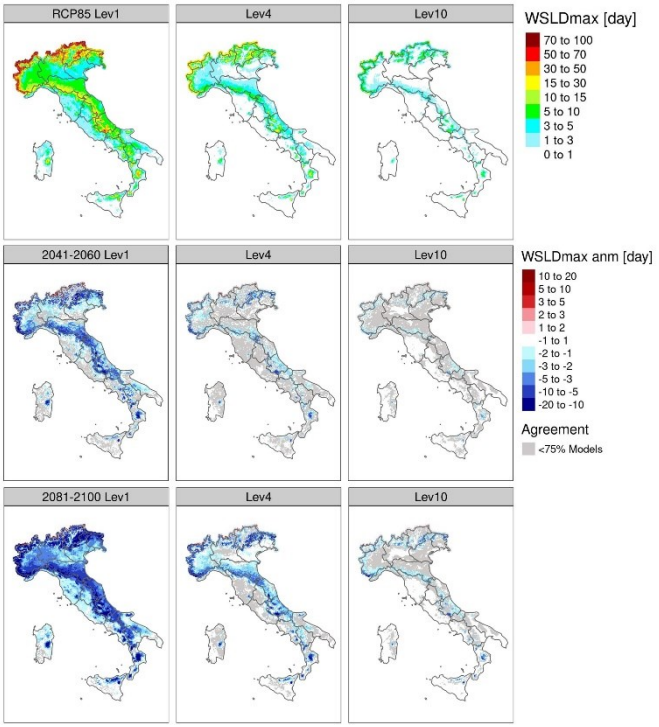

Fig. 5 *WSLDmax* ensemble mean in RCP85 in REF (1st row) and corresponding anomalies [day] in 2041-2060 (2nd row) and 2081-2100 (3rd row). The grey colour represents areas where the agreement among models in the sign of anomaly is lower than 75%.

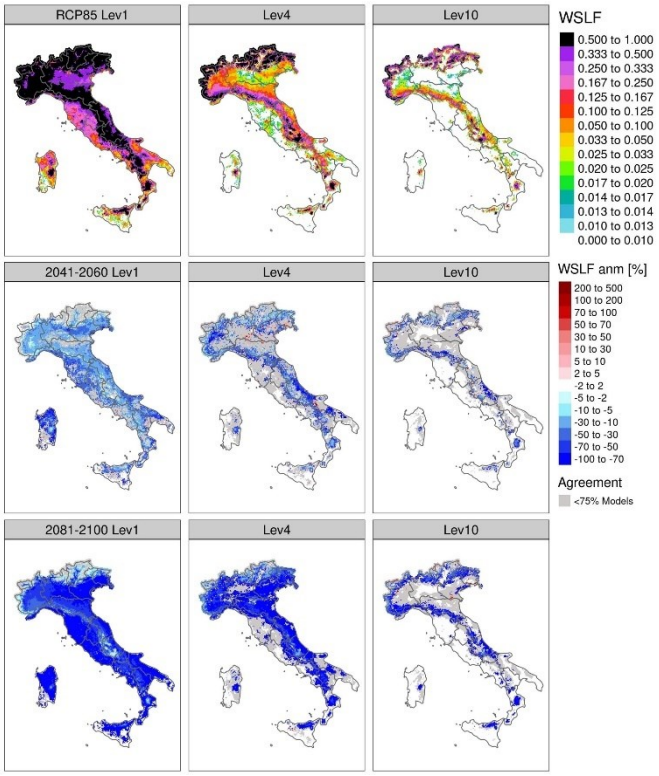

Fig. 6 *WSLF* ensemble mean in RCP85 in REF (top) and corresponding percentage anomalies [%] in 2041-2060 (2nd row) and 2081-2100 (3rd row). The grey colour represents areas where the agreement among models in the sign of anomaly is lower than 75%.

In the future a decrease of *WSLF* is projected elsewhere from medium- to long-term (2nd and 3rd row of Fig. 6, respectively). The confidence in the results decreases at low-medium altitude, where the topographic features such as elevation and terrain shading may be described in different way by the different climatic models (grey areas Fig. 6) and, therefore there is more uncertainty in the results. A slight increase of the *WSLF* is expected strictly in some locations.

Analogous results are found in RCP4.5 scenarios (not shown for the sake of brevity).

IV. Conclusions

Following the methodology developed in [4] and by applying an updated CLIWAC model, a new investigation of wet snow sleeves on overhead lines in Italy by the end of the Century has been carry out.

Wet snow events are related to topographic features. However, their frequency is projected to decrease in general from short- to long-term, as shown through the analysis of *WSLD* and *WSLF* indices, because rainfalls will prevail over snowfalls due to global warming. The *WSL95* analysis also highlights a general decrease in the intensity of extreme wet snow loads, except for the higher Alpine regions so far spared because of their historical cold temperatures. This negative trend is expected to be more pronounced in RCP8.5 than in the RCP4.5 pathway. Unlike previous results, the Apennine region will also be characterized by a reduction of the events.

The methodology developed and the results could directly impact on the decision-making process of electric user to cope with climate change impacts, and on the revision of Eurocodes.

Acknowledgment

This work has been financed by the Research Fund for the Italian Electrical System under the Three-Year Research Plan 2022-2024 (DM MITE n. 337, 15.09.2022), in compliance with the Decree of April 16th, 2018.

References

[1] IPCC, 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896, 2391 pp.

[2] World Meteorological Organization 2024: State of the Global Climate 2023. https://wmo.int/publication-series/state-of-global-climate-2023

[3] European Environmental Agency, 2023. Trends and projections in Europe 2023. DOI 10.2800/595102

[4] P. Faggian, A. Trevisiol, G. Decimi, Future projections of wet snow frequency and wet snow load on overhead high voltage conductors over Italy, Cold Regions Science and Technology, vol. 217, 103980, 2024.https://doi.org/10.1016/j.coldregions.2023.103980.

[5] Bonanno, R., Lacavalla, M., Sperati, S., 2019. A new high-resolution Meteorological Reanalysis Italian Dataset: MERIDA. Q. J. R. Meteorol. Soc. https://doi.org/ 10.1002/qj.3530.

[6] Faggian, P., 2021. Future Precipitation scenarios over Italy. Water MDPI J 13 (1335), 1–17.

[7] Makkonen, L., 1989. Estimation of wet snow accretion on structures. Cold Reg. Sci. Technol. 17 (1), 83–88.

[8] Makkonen, L., Wichura, B., 2010. Simulating wet snow loads on power line cables by a simple model. Cold Reg. Sci. Technol. 61 (2–3), 73–81. https://doi.org/10.1016/j. coldregions.2010.01.008.

[9] Nygaard, B.E., ´Agústsson, H., Somfalvi-T´oth, K., 2013. Modeling Wet Snow Accretion on Power Lines: Improvements to previous Methods using 50 years of Observations. J. Appl. Meteorol. Climatol. 52, 2189–2203. https://doi.org/10.1175/JAMC-D-12- 0332.1.

[10] E. C. Massoud, V. Espinoza, B. Guan, D. E. Waliser, «Global Climate Model Ensemble Approaches for Future Projections of Atmospheric Rivers,» *Earth's Future,* vol. 7, p. 1136–1151, 2019. https://doi.org/10.1029/2019EF001249