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Weather Research and Forecasting Model Simulation of a Snowfall Event in Southern Brazil

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ABSTRACT

This study evaluates the ability of the Weather Research and Forecasting (WRF) Model to simulate a snowfall event in the southern Brazil. The event in August 2013 was considered one of the most intense in recent years in the region with the highest topographic elevations between the states of Rio Grande do Sul (RS) and Santa Catarina (SC). The Snowfall in the mountain region of RS and SC was associated with the configuration involving a polar anticyclone and the intensification of an extratropical cyclone over the Atlantic Ocean. The WRF simulation results demonstrated the model's viability to predict the event, but without the magnitude representation of the phenomenon. The simulations represented few snow accumulations, with a maximum value of 1.2 mm, and occurred in only two meteorological monitoring stations among the seven evaluated, differently from what was reported in the media. These results may be linked to the simulation of the warmer air temperature near to the surface in relation to the observations, and consequently to the increase in the simulation of precipitation in liquid form. These results were attributed to the choice of WRF Single-moment 6-class (WSM6) microphysics and in the Noah Land Surface Model scheme. Despite these limitations, WRF has proved to be an important tool for predicting the spatial and temporal distribution of snowfall and precipitation in the higher regions of southern Brazil.

Keywords: snowfall; WRF; WRF Single-moment 6-class scheme; Atmospheric modeling.

Simulação do modelo Weather Research and Forecasting de um Evento de Precipitação de Neve no Sul do Brasil

RESUMO

Este estudo avalia a capacidade do modelo Weather Research and Forecasting (WRF) na simulação de um evento de precipitação de neve no sul do Brasil. O evento ocorrido em agosto de 2013 na região com as maiores elevações topográficas entre os estados do Rio Grande do Sul (RS) e Santa Catarina (SC) foi considerado um dos mais intensos dos últimos anos. A queda de neve na região da Serra dos estados do RS e SC foi associada à configuração envolvendo um anticiclone polar e à intensificação de um ciclone extratropical sobre o Oceano Atlântico. Os resultados do WRF demonstraram a viabilidade do modelo para prever o evento, porém não representando sua real magnitude. As simulações representaram poucos acumulados de neve, com valor máximo de 1,2 mm, e ocorrência em apenas duas estações de monitoramento meteorológico entre as sete avaliadas, diferentemente com o que foi veiculado na mídia. Estes resultados podem estar ligados a simulação da temperatura do ar mais quentes próximo da superfície em relação às observadas, e consequentemente do aumento na simulação da precipitação em forma líquida. Esses resultados estiveram associados à escolha da opção da microfísica WRF Single-moment 6-class (WSM6) e do esquema de superfície Noah Land Surface Model. Apesar dessas limitações, o WRF provou ser uma ferramenta importante para prever a distribuição espacial e temporal de precipitações em forma de neve e líquida nas regiões mais altas do sul do Brasil. Keywords: radiation, net radiation, photosynthetically active radiation, Caatinga, dry.

Palavras-chave: Precipitação de Neve; WRF; WRF Single-moment 6-class scheme; Modelagem Atmosférica.

Introduction

Brazil is known as a tropical country with high temperatures throughout the year. However, its large territorial extension, ranging from latitudes 5°N to 33° S, leads to climate diversification between the north and south of the country. The southern Brazil presents a humid subtropical climate with high thermal amplitude between summer and winter (Alvares et al., 2014). Parts of this region have considerable elevations, about 1800 meters. These two effects, latitude and altitude, lead to sporadic snowfall in southern Brazil. This phenomenon is poorly understood in this region with limited number of references, because it covers a small space area, with low population density and sporadic frequency of events. For this reason, added the lack of infrastructure of Brazil, the Brazilian Yearbook of Natural Disasters has listed snowfall as a Brazilian natural disaster (CENAD, 2014).

According to Nimer (1979), the highest regions of Rio Grande do Sul (RS) and Santa Catarina (SC) States are more likely to occur snowfall in Brazil (apud Fuentes, 2009). In addition to the terrain, these States also have a snow favorable pattern, due to the influence of extratropical synoptic systems advancing to subtropical latitudes, affecting temperature fields in the lower troposphere (Mitenguí et al., 2018). Fuentes (2009) detected seven synoptic and dynamic atmospheric patterns associated with snowfall in southern Brazil mainly based on the importance of the action of an extratropical cyclone in the coast of RS for the occurrence of the event.

Researches of snowfall in Brazil subject is directly associated with climatological studies and atmospheric patterns, thus emphasizing the lack of studies evaluating the ability of numerical weather prediction (NWP) models to predict these events. Currently, the forecast and analysis of the weather conditions are made from computational systems, which are able to describe the atmospheric processes reliably based on the laws of physics. These systems have been evolving over the years, largely due to the increased understanding of the processes that control the evolution of the atmospheric state coupled with the technological advances in the processing of computers. Nowadays, a large number of NWP models are available in laboratories around the world, some of which are frequently used by large communities and for various applications (Giorgi, 2018). The forecast of these models has benefited many areas of society, such as: saving lives, supporting emergency management, mitigating the impact and

preventing economic losses in the extreme events cases, as well as creating substantial financial revenues in various sectors like energy, agriculture, transport and recreational sectors (as tourism) (Bauer et al., 2015).

The Weather Research and Forecasting (WRF) model is considered the state-of-the-art mesoscale weather forecasting system (Skamarock et al., 2008). The model is distinguished by the plurality of applications, due to the presence of multiple physical (parameterization) and dynamic options, allowing its use for simulations at different geographic locations, scale settings and focus of study. Studies from around the world use WRF to analyze snow events, especially in regions with complex terrain. Most of these studies address snowfall events in countries of the North American continents (Shi et al., 2010; Rasmussen et al., 2011; Miller 2012; Currier et al., 2017; Gordillo et al., 2019) Asian (Wang et al., 2011; Jung et al., 2012; Yu, 2013; Min et al., 2015; Norris et al., 2015; Tiwari et al., 2018; Liu et al., 2019; Kar & Tiwari, 2020) and localities in southern South America near of the Andes (Comin et al., 2018).

Maussion et al. (2011) evaluated WRF's ability to simulate rain and snow in a single event on the Tibetan plateau in China, the site of limited research on weather analysis. The authors emphasized the relevance of detailing the physical parameterization schemes employed. In the same region, Liu et al. (2019) study found that simulations precipitation of snow or melting snow depends on the surface air temperature, which depends on both the surface model parameterization and the boundary and initial conditions. Temperature has a large effect on cloud liquid water and ice content needed for producing snowfall in the model (Gordillo et al., 2019). The snow or ice melting below freezing level is determined by air saturation below freezing level (Min et al., 2015).

Comin et al. (2018) stated that the WRF model is a viable tool for predicting spatially and temporally precipitated snow distribution in steep terrain regions such as the Andes. In this study, the authors evaluated the sensitivity of the WRF model to the change in the microphysics parameterization and identified that the WRF Single-moment 6-class (WSM6) scheme showed better results compared to the others schemes. In regions of complex terrain the WSM6 scheme favors precipitation on the slopes of the terrain (Tiwari et al., 2018; Kar & Tiwari, 2020)

Jung et al. (2013) demonstrated the importance of topography data set resolution for snow event simulation with WRF. The authors mention that with an unrealistic topography, the model did not accurately simulate upward and downward movements along mountain ranges and valleys, resulting in a change in the reproduction of snow spatial distribution.

Rasmussen et al. (2011) showed that adequate spatial and temporal representations for snowfall with the WRF model could be achieved through appropriate choices of model grid spacing and appropriate parameterization. A key issue concerning the use NWP models is the availability of very high resolution, high quality data sets for the analysis and evaluation of the models. Thus, high-resolution data are needed to describe the details of the physiography of the region (Giorgi, 2018).

Considering the use of the numerical system to study phenomes such as snowfall implies the understanding of the event itself, which is not often in the Brazilian climate, such application and analysis are valid and can be significant.

Thus, the main objective of this study is to evaluate the ability of the WRF model to reproduce the episode of snow accumulation that occurred in the mountainous region of southern Brazil in August 2013, as well as to analyze the dynamics and atmospheric circulation patterns. This snowfall event was considered one of the most intense of the last 20 years (CLICRBS, 2019).

Data and Methods

In this study, the WRF model in version 3.7.1 was configured to simulate the period from August 23 to 29, 2013, designating the first day as a spin-up. The simulations were made from two nested domains with two-way interaction between grids, presented in figure 1, which had their format defined with a 1: 4 ratio. The domain 1 (D01), with a spatial resolution of 10 km, was set up to cover the Southern Region of Brazil, while Domain 2 (D02), with a resolution of 2.5 km, covering the RS and SC states highest elevations. D02 was used to obtain the results of the study.

Given the complexity of the topography of southern Brazil mountain region and the role of terrain in the processes of interaction between surface and atmosphere, the WRF simulation used different topographic data sets in each domain (Figure 1). The D01 was configured with the Global 30 Arc-Second Elevation (GTOPO) dataset, which has a spatial resolution of 30 arcsec (~1 km). The GTOPO dataset is the best resolution WRF default data set for topography. The D02 was configured with 1 arcsec (30 m) resolution topographic data sets from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER).

Table 1 shows the main simulation configurations in the two domains, including the physical parameters used. Attention was drawn to the choice of an advanced cloud microphysics parameterization scheme capable of solving precipitation processes in various types of hydrometeor classes. WSM6 (Hong & Lim, 2006) is a tested scheme for simulating various precipitation types, including snow (Yu, 2013; Min et al., 2015; Liu et al., 2019; Molthan & Colle, 2012; Sari et al., 2018; Yáñez-Morrón et al., 2018; Tiwari et al., 2018; Kar & Tiwari, 2020), being able to solve cloud physics in 6 types classes: water vapor, cloud water, cloud ice, snow, rain and graupel.

The initial and boundary conditions in the model are derived from the National Centers for Environmental Prediction (NCEP) model, Climate Forecast System Version 2 (CFSv2, Saha et al., 2011). This data is an evolution of the NCEP Climate Forecast System Reanalysis (CFSR) and surface, oceanic and atmospheric analyzed products are available in various spatial resolutions at 6-hour intervals. Because the scale of the event occurred is larger than that of the domains used, the CFSv2 data, besides initializing the model, were applied in order to characterize the synoptic configurations for event occurrence. We seek to establish the atmospheric pattern class for snowfall based on Fuentes (2009). To this end, atmospheric fields were analyzed using CFSv2 data at the time of the event, based on the low, medium and high atmospheric variables defined by the author.

Figure 1. Topography (in meters) for the simulation domains, D01 and D2, based on the GTOPO and ASTER data sets, respectively. The domains have spatial resolution of 10 km (D01) and 2.5 km (D02).

Table 1. WRF configuration for simulation between 23rd and 29 August 2013.

Option	Domain 1	Domain 2
Horizontal Resolution	10 km	2.5 km
Topographic dataset	GTOPO (~1 km) Gesch <i>et al.</i> (1999)	ASTER (30m) Yamaguchi <i>et al.</i> (1998)
Microphysics	WRF Single-Moment 6-Class Hong & Lim (2006)	
Long/Short Wave Radiation	Community Atmosphere Model Shortwave and Longwave Collins <i>et al.</i> (2004)	
Land Surface	Unified Noah Land Surface Model Tewari <i>et al.</i> (2004)	
Surface Layer	Revised MM5 Scheme Jimenez <i>et al.</i> (2012)	
Boundary Layer	Yonsei University Hong <i>et al.</i> (2006)	
Cumulus	Betts-Miller-Janjic Janjic <i>et al.</i> (2004)	-

The WRF simulation was evaluated in order to verify the model performance for the representations of the liquid precipitations occurred, and was made with data from meteorological monitoring stations of the Brazil National Institute of Meteorology (INMET). The model validation for the rainfall was performed by comparing the simulated precipitation with the values individually measured by the stations, using

the nearest grid point of the station. We apply the information registered by stations located in RS state: Teutônia (TT), Bento Gonçalves (BG), Canela (CN), Lagoa Vermelha (LV) and São José dos Ausentes (SJA); and in SC state: Morro da Igreja (MI) and São Joaquim (SJO). In the table 2 shows the geographic coordinates, the real topographic height of each station and the height based on the ASTER data set interpolated in D02.

Table 2. Location and real and interpolated in simulation grid altitude of the National Institute of Meteorology stations.

Station	Latitude	Longitude	Real altitude (m)	WRF altitude (m)
Teutônia - RS (TT)	-29.450334°	-51.824283°	80	67
Bento Gonçalves - RS (BG)	-29.164581°	-51.534202°	623	603
Canela - RS (CN)	-29.368788°	-50.827231°	831	682
Lagoa Vermelha -RS (LV)	-28.222381°	-51.512845°	834	789
São José dos Ausentes - RS (SJA)	-28.748615°	-50.057869°	1229	1197
Morro da Igreja – SC (MI)	-28.126992°	-49.479610°	1790	1304
São Joaquim – SC (SJO)	-28.275640°	-49.934617°	1400	1372

Results and Discussion

Event Description

Initially, we investigated the motivations for the snow phenomenon to occur in August of that year, based on an analysis of the previous atmospheric circulation. On August 24, 2013, a cold front was active in SC state combined with a low-pressure center in Atlantic Ocean, at 28°W-47°S (Figure 2a). The presence of the 0 °C isotherm at 850-hPa was observed, which indicated air with polar characteristics, reaching the boundary between Uruguay and the extreme south of RS. Due to the configuration, between the frontal system and the high pressure located ahead, there was a slight advance over the 4 days (between 24th and 27 August) and, consequently, slight advance of the cloudiness, which remained on RS state until the 27th (Figure 2). The stationary condition of the frontal system detains the advancement of the cold air mass located behind frontal system. The 0°C isotherm between the 24th and 26th days remained in the extreme south of RS (Figure 2a, 2b and 2c). On day 26th it was observed the presence of low-pressure area on the coast between the south and southeast of Brazil, associated with a cyclonic circulation at 850-hPa, which was responsible for the moisture advection of ocean to the continent (Figure 2c). At dawn on the 27th, the system displaced to the ocean, along with the cyclonic circulation on the coast, allowed the polar air mass to penetrate the extreme south of Brazil (Figure 2d). The 0°C isotherm was located in the northeast

of RS and the SC border, causing negative temperatures in its rear, at the 850-hPa level.

In the following, the atmospheric circulations occurring at the moment of the snow precipitation event from low, medium and high-level synoptic charts, based on the first pattern defined by Fuentes (2009) and on suggested variables, are discussed. Figures 3 correspond to the atmospheric fields of 06Z on August 27, 2013, approximate time of the beginning of the snowfall. As shown in figure 3a, the surface post-frontal anticyclone was displaced in north of Argentina and Paraguay and an extratropical cyclone was observed on the coast at 42°W-28°S, between the South and Southeast of Brazil, which was responsible for the moisture advection in the RS and SC mountain range region (Figure 3a and 3b). At the 250-hPa level, a trough was observed that gave a dynamic contribution to the advection of negative surface temperatures over Uruguay and RS state (Figure 3c). The high, medium and low-level fields (Figure 3a, 3b and 3c) reflected the system's baroclinic structure (intensification of the extratropical cyclone), with the altitude trough over the continent and the low-pressure center over the inflection point, between the trough and the surface anticyclone ridge. These atmospheric configurations contributed to the high relative humidity indices in southern and southeastern Brazil, largely above 90% (Figure 3d). Figures 3e and 3f show that temperatures were negative at the 700-hPa level in practically all Southern Brazil while at the 850-hPa level they were negative over RS and western SC states.

Figure 2. Mean Sea Level Pressure (hPa, continuous black lines), Temperature and Streamlines (m/s) at 850-hPa level at 00Z on (a) August 24, 2013, (b) August 25, 2013, (c) August 26, 2013 and (d) August 27, 2013. The red solid line indicates the location of the 0°C isotherm at 850-hPa level.

Figure 3. Atmospheric Fields at 06Z August 27, 2013 from (A) Atmospheric Pressure (hPa) at Surface Level, (B) Geopotential Height (m) at 500-hPa level, (C) Jet and Streamlines (m/s) at 250-hPa level, (D) Relative Humidity (%) of 925-hPa level and Air Temperature (°C) (E) 700-hPa and (F) 850 hPa-level.

WRF Experiment

Rainfall Validation

Figures 4 show the accumulated 3-hour precipitation measured and simulated at RS and SC states stations. The simulation of the model represented the temporal evolution of the rainfalls, showing the accumulated between the 24th and 27th of August. In general, the model demonstrated a good coherence in the representation of the accumulated precipitation in the observed times. The correlation coefficients for TT (Figure 4a), BG (Figure 4b), CN (Figure 4c), LV (Figure 4d), SJA (Figure 4e), MI (Figure 4f), and SJO (Figure 4g) stations were 0, 53, 0.64, 0.54, 0.43, 0.47, 0.72 and 0.56, respectively. The model represented the continuous rainfall measured in the stations located in RS state, as well as the reduction of accumulated volumes between the 24th and 25th in the SC state stations. No evident trends between underestimation and overestimation were observed

Vertical profile of hydrometeor class simulation

The next section aims to verify the model performance to represent the simulated vertical conditions during the snowfall period. For this, figures 5, 6, 7 and 8 show the temporal evolution (between 21Z of 26 August to 21Z of 27) of the simulation of hydrometeors in liquid water phase (qrain, left) and snow (qsnow, right) and vertical

in the simulations of station measurements. However, there was an underestimation of rainfall on the 24th in LV and SJO stations and overestimation at 06Z of the same day in CN (Canela) and MI (Morro da Igreja) stations.

Figures 4 also show the simulated precipitation accumulations in snow form at the grid points corresponding to the stations. At the CN (Figure 4c), SJA (Figure 4e) and SJO (Figure 4g) stations at dawn on August 27, between 03Z and 12Z, small snow accumulated were simulated. Volumes were simulated more intensely within 3 hours (between 06Z and 09Z) at SJA and SJO points, with values of 1.2 mm and 0.6 mm, respectively. A smaller simulated volume was observed at the CN station point, with a maximum accumulation value of approximately 0.1 mm between 06Z and 09Z. The snow simulations were consistent with the synoptic descriptions discussed earlier, coinciding with the period when the system moved to the ocean and the cold air mass incursion into southern Brazil.

Figure 5. 3-hour precipitation accumulated (blue column) and simulated by the WRF model (orange column) at the stations of: (a) Teutônia - RS, (b) Bento Gonçalves, (c) Canela - RS, (d) Lagoa Vermelha - RS, (E) São José dos Ausentes - RS, (F) São Joaquim - SC and (G) Morro da Igreja - SC. In addition, the accumulated snowfall simulated by the WRF (gray line).

air temperature (°C) over CN, SJA, SJO and MI station points. To contribute to the analysis, Figure 9 shows the variations in air temperature at 2 meters from the surface measured and simulated by the respective stations. These analyzes were defined on the stations where snow was simulated (Canela, São José dos Ausentes and São Joaquim stations) and on the point where no snow was observed (Morro da Igreja station), but located on

one of the highest regions from the southern Brazil mountain range region.

The temporal evolution of the vertical profile showed the presence of grain near the surface of about 21Z of four stations 26 until the morning of day 27 (9Z) (Figures 5a, 6a, 7a and 8a). In the MI station, a higher grain concentration was simulated in relation to the others (above 20 mg/m³) (Figure 8a), a condition consistent with the high simulated rainfall accumulated in this station (Figure 4f).

From 06Z on the stations of São José dos Ausentes-RS (Figures 7) and São Joaquim-SC (Figures 8) the effect of the cold air mass incursion was represented in the model simulation, with the decay of the isotherm of 0°C and negative surface temperature representation. Along with the negative surface isotherms, qsnow was observed in

these stations, with the snow hydrometeors extending from the surface for about 4 km vertically.

At the points of Canela - RS (Figures 6) and Morro da Igreja - SC (Figures 9) stations, the model did not estimate surface temperatures below 0°C. However, even with the small concentration of liquid hydrometeors at Canela station it was possible to observe the simulation of small volumes of snow over the point of the station (as seen in figure 4c). The same condition was not observed for the MI station point, since the model simulated an intense grain zone in a layer contiguously below the 0°C isotherm. This may be due to the conversion of qsnow to rain hydrometeor after passing through the melt layer (Sari *et al.*, 2018).

Figure 5. Vertical profile of temperature and mixture ratio of (a) liquid (grain) and (b) snow (qsnow) precipitation in Canela - RS.

Figure 6. Vertical profile of temperature and mixture ratio of (a) liquid (grain) and (b) snow (qsnow) precipitation in São José dos Ausentes - RS.

Figure 7. Vertical profile of temperature and mixture ratio of (a) liquid (qrain) and (b) snow (qsnow) precipitation in São Joaquim - SC.

Figure 8. Vertical profile of temperature and mixture ratio of (a) liquid (qrain) and (b) snow (qsnow) precipitation in Morro da Igreja - SC.

In figure 9, it is confirmed that the model represented warmer near-surface temperatures during the event compared to the data observed in the stations. The temperature variation curves at 2 meters from the simulated surface observed in the CN stations, and especially in MI, showed that the model was not able to represent the cooling occurred in the measurements of these stations. Simulated minimum temperatures of 0.8 °C in CN and 2 °C in MI were identified, while the thermometers of these stations marked minimum 0.1 °C and -1.3 °C, respectively. These

overestimations of surface temperatures indicated the non-simulation of the snow precipitation model. Regarding the simulated temperatures over the SJO and SJA stations, the model reproduced the cooling level with good performance in relation to the observed, demonstrating the necessary conditions for snow precipitation over the station's points. Results, demonstrating the effect caused by the simulation of warmer temperatures in the production of liquid water and ice clouds influencing the snow precipitation are seen in Gordillo et al. (2019).

Figure 9. Evolution of air temperature at 2 meters from the surface observed and simulated by the WRF at the stations of Canela-RS (CN), São José dos Ausentes - RS (SJA), São Joaquim - SC (SJO) and Morro da Igreja - SC (MI).

Conclusions

In this study, the WRF model was applied to verify the representation of a snowfall event in the southern Brazil mountain region in August 2013. The studied event demonstrated characteristics similar to the first-class dynamic snowfall defined by Fuentes (2009) with configuration of a polar anticyclone and an intensifying extratropical cyclone over the Atlantic Ocean.

The model presented a good performance for temporal representation of liquid and snow precipitation. The simulations of the model were in phase with those observed in the seven meteorological stations of RS and SC, being verified similarities between the observed period of liquid precipitation and the simulated period. However, the WRF simulation underestimated the results for the accumulated and area of the snowfall region, which may be linked to overestimations of surface and vertical air temperature and liquid water precipitation. These results can be attributed mainly to the sensitivity of the model to the choice of microphysics parameterizations (Yu, 2013; Fernández-González *et al.*, 2015; Min *et al.* 2015; Comin *et al.*, 2018; Liu *et al.*, 2019) and in the surface model scheme (Yu, 2013; Liu *et al.*, 2019).

It was found that the use of the WSM6 microphysics scheme in the simulation demonstrated efficacy for the reproduction of snow hydrometeors over the region. However, the high grain production, and consequently more liquid phase precipitation, may have been characterized

due to a possible overestimation of snow melt level. The melting level of snow or ice is the transition height between solid and liquid precipitation (Heuvel *et al.*, 2018) and is dependent on the air temperature of the layer below this level. Thus, the simulation of small snow accumulations and high precipitation were mainly related to the physics linked to the vertical temperature profile. This condition was verified when observed the simulations of warmer near-surface air temperatures compared to those observed in the meteorological stations, which triggered the simulation of a higher melt level in relation to the surface, thus causing an increase in precipitation production of liquid and reduction of snow precipitation, results also observed in the studies by Jin & Miller (2007), Saha *et al.* (2017) and Gordillo *et al.* (2019). These errors are directly related to the choice of Noah LSM scheme.

In summary, this study demonstrates that the WRF model was able to simulate the snowfall event, but underestimated the original magnitude of the event. However, this work is embryonic and more events need to be studied to increase understanding of snowfall in southern Brazil. In order to obtain better future results, we intend to focus mainly on cloud microphysics schemes that are responsible for partitioning atmospheric water into vapor, cloud liquid water, cloud ice etc. leading either to solid or liquid precipitation (Kar & Tiwari, 2020), as well as the use of surface models.

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References

- Alvares, C.A., Stape, J.L., Sentelhas, P.C., Gonçalves, J.L.M., Sparovek, G., 2014. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* 22, 711–728.
- Bauer, P., Thorpe, A., Brunet, G., 2015. The quiet revolution of numerical weather prediction. *Nature* 525, 47–55.
- CENAD - Centro Nacional de Gerenciamento de Riscos e Desastres. 2014. Anuário brasileiro de desastres naturais: 2013. Available in: <http://www.mi.gov.br/defesacivil/publicacoes>. Accessed: 28 Feb. 2019.
- CLICRBS. 2019. Neve de 2013: Relembre um dos Fenômenos Mais Intensos em Quase 20 Anos. Available in:

<https://gauchazh.clicrbs.com.br/ambiente/noticia/2019/07/neve-de-2013-relembre-um-dos-fenomenos-mais-intensos-em-quase-20-anos-cjxoxd4el05jfo9mtmsxyte.html>>. Accessed: 28 Feb 2019.

- Collins, W.D., Rasch, P.J., Boville, B. A., Hack, J.J., McCaa, J.R., Williamson, D.L., Kiehl, J. T., Briegleb, B., Bitz, C., Lin, S.-J., Zhang, M., Dai, Y., 2004. Description of the NCAR Community Atmosphere Model (CAM 3.0). In: NCAR TECHNICAL NOTE 464.
- Comin, A.N., Schumacher, V., Justino, F., 2018. Impact of different microphysical parameterizations on extreme snowfall events in the Southern Andes. *Weather and Climate Extremes* 21, 65–75.
- Currier, W.R., Thorson, T., Lundquist, J.D., 2017. Independent Evaluation of Frozen Precipitation from WRF and PRISM in the Olympic Mountains. *Journal of hydrometeorology* 18, 2681–2703.

- Fernández-González, S., Valero, F., Sánchez, J.L., Gascón, E., López, L., García-Ortega, E., Merino, A., 2015. Numerical simulations of snowfall events: Sensitivity analysis of physical parameterizations. *Journal of Geophysical Research*, 120, 10130–10148.
- Fuentes, M.V., 2009. *Dinâmica e Padrões da Precipitação de Neve no Sul do Brasil*. Doctoral Thesis, Rio Grande do Sul Federal University, Porto Alegre, Brazil. 191p.
- Gesch, D. B.; Verdin, K. L. & Greeblee, S. K. 1999. New land surface digital elevation model covers the Earth. *American Geophysical Union*, 80:69–70.
- Giorgi, F., 2018. Thirty years of regional climate modeling: Where are we and where are we going next? *Journal of Geophysical Research: Atmospheres* 124, 5696–5723.
- Gordillo, N., Smith, E., Taziny, A., 2019. Using WRF to determine the effects of natural sensitivities on orographic precipitation. *SOARS*, 1-12.
- Heuvel, F.V.D., Gabella, M., Germann, U., Berne, A., 2018. Characterization of the melting layer variability in an Alpine valley based on polarimetric X-band radar scans. *Atmospheric Measurement Techniques Discussions* 11(9), 1–37.
- Hong, S.-Y., Lim, J., 2006. The WRF single-moment 6-class microphysics scheme (WSM6). *Journal of the Korean Meteorological Society*, 42, 129–151.
- Hong, S.-Y., Noh, Y., Dudhia, J., 2006. A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly Weather Review* 134, 2318–2341.
- Kar, S. C., Tiwari, S., 2020. Impact of Cloud Microphysical Processes on the Dynamic Downscaling for Western Himalayas Using the WRF Model. In: DIMIRI, A.P., Bookhagen, B., Stoffel, M., Yasunari, T., (Eds.) *Himalayan Weather and Climate and their Impact on the Environment*. Springer Nature Switzerland AG 2020, pp. 91-107.
- Janjic, Z.I., 1994. The Step-Mountain ETA Coordinate model: Further developments of the convection, viscous sub-layer and turbulence closure schemes. *Monthly Weather Review* 122, 927–945.
- Jimenez, P.A., Dudhia, J., Gonzalez-Rouco, J.F., Navarro, J., Montavez, J.P., Garcia-Bustamante, E., 2012. A revised scheme for the WRF surface layer formulation. *Monthly Weather Review* 140, 898–918.
- Jin, J., Miller, N. L., 2007. Analysis of the impact of snow on daily weather variability in mountainous regions using MM5. *Journal of Hydrometeorology* 8, 245–258.
- Jung, S.H., Im, E.S., Han, S.O., 2012. The effect of topography and sea surface temperature on heavy snowfall in the Yeongdong Region: A case study with high-resolution WRF simulation. *Asia-Pacific Journal of Atmospheric Sciences* 48, 259–273.
- Liu, L., Ma, Y., Menenti, M., Zhang, X., Ma, W., 2019. Evaluation of WRF Modeling in Relation to Different Land Surface Schemes and Initial and Boundary Conditions: A Snow Event Simulation over the Tibetan Plateau. *Journal of Geophysical Research: Atmospheres* 124, 209–226.
- Maussion, F., Scherer, D., Finkelnburg, R., Richters, J., Yang, W., Yao, T., 2011. WRF simulation of a precipitation event over the Tibetan Plateau, China - An assessment using remote sensing and ground observations. *Hydrology and Earth System Sciences*, 15, 1795–1817.
- Miller, D.K., 2012. Near-term effects of the lower atmosphere in simulated northwest flow snowfall forced over the southern Appalachians. *Weather and Forecasting*, 27, 1198–1216.
- Min, K.H., Choo, S., Lee, D., Lee, G., 2015. Evaluation of WRF cloud microphysics schemes using radar observations. *Weather and Forecasting* 30, 1571–1589.
- Mintegui, J.M., Puhales, F.S., Boiaski, N.T., Nascimento, E.L., Anabor, V., 2018. Some mean atmospheric characteristics for snowfall occurrences in southern Brazil. *Meteorology and Atmospheric Physics* 131, 389–412.
- Molthan, A.L., Colle, B.A., 2002. Comparisons of Single-and Double-Moment Microphysics Schemes in the Simulation of a Synoptic-Scale Snowfall Event. *Monthly Weather Review* 140, 2982–3002.
- Nimer, E., 1979. *Climatologia do Brasil*. Brazilian Institute of Geography and Statistics, Rio de Janeiro – RJ, Brazil.
- Norris, J., Carvalho, L.M.V., Jones, C., Cannon, F., 2015. WRF simulations of two extreme snowfall events associated with contrasting extratropical cyclones over the western and central Himalaya. *Journal of Geophysical Research* 120, 3114–3138.
- Rasmussen, R., Liu, C., Ikeda, K., Gochis, D., Yates, D., Chen, F., Tewari, M., Barlage, M., Dudhia, J., Yu, W., Miller, K., 2011. High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. *Journal of Climate* 24, 3015–3048.

- Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., Becker, E., 2011. NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products. Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory. Available in: <<https://doi.org/10.5065/D61C1TXF>>. Accessed: 28 Oct 2018.
- Saha, S.K., Sujith, K., Pokhrel, S., Chaudhari, H., Hazra, S., 2017. A. Effects of multilayer snow scheme on the simulation of snow: Offline Noah and coupled with NCEP CFSv2. *Journal of Advances in Modeling Earth Systems* 9, 271–290.
- Sari, F.P., Baskoro, A.P., Hakim, O.S., 2018. Effect of different microphysics scheme on WRF model: A simulation of hail event study case in Surabaya, Indonesia. *Proceedings of the AIP Conference Proceedings; American Institute of Physics Inc.* 1987(1), 0200021-02000211.
- Shi, J.J., Tao, W. K., Matsui, T., Cifelli, R., Hou, A., Lang, S., Tokay, A., Wang, N.Y., Peters-Lidard, C., Skofronick-Jackson, G., Rutledge, S., Petersen, W., 2010. WRF simulations of the 20-22 January 2007 snow events over eastern Canada: Comparison with in situ and satellite observations. *Journal of Applied Meteorology and Climatology* 49, 2246–2266.
- Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.-Y., Wang, W., Powers, J.G., 2008. A Description of the Advanced Research WRF Version 3. In: NCAR TECHNICAL NOTE 475, 113p.
- Tewari, M., Chen, F., Wang, W., Dudhia, J., LeMone, M.A., Mitchell, K., Ek, M., Gayno, G., Wegiel, J., Cuenca, R.H., 2004. Implementation and verification of the unified NOAA land surface model in the WRF model. In: 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction, pp. 11–15.
- Tiwari, S., Kar, S.C., Bhatla, R. 2018. Dynamic downscaling over western Himalayas: Impact of cloud microphysics schemes. *Atmospheric Research* 201, 1-16.
- Wang, H., Yu, E., Yang, S., 2011. An exceptionally heavy snowfall in Northeast china: Large-scale circulation anomalies and hindcast of the NCAR WRF model. *Meteorology and Atmospheric Physics* 113, 11–25.
- Yamaguchi, Y., Kahle, A., Tsu, H., Kawakami, T., Pniel, M., 1998. Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). *IEEE Transactions on Geoscience and Remote Sensing*, 36(4), 1062–1071.
- Yáñez-Morroni, G., Gironás, J., Caneo, M., Delgado, R., Garreaud, R., 2018. Using the Weather Research and Forecasting (WRF) Model for Precipitation Forecasting in an Andean Region with Complex Topography. *Atmosphere* 9, 1–23.
- Yu, E.T. 2013. High-resolution seasonal snowfall simulation over Northeast China. *Chinese Science Bulletin* 58, 1412–1419.