

Responses to the reviewer 2 are in blue color and the main changes in the manuscript are in red color.

RC2: The manuscript “Interaction between cloud-radiation, atmospheric dynamics and thermodynamics based on observational data from GoAmazon 2014/15 and a Cloud Resolving Model” general goal, as stated, is to understand the interactions between the dynamic and thermodynamic variables of the atmosphere and cloudiness in Central Amazonia.

For that, the authors used a set of observational data collected during GoAmazon IOP’s (dry and wet seasons) and carried out a set of simulations using a Cloud Resolving Model considering different spatial resolutions.

The first results are focused on the comparison between observed and modeled atmospheric variables (cloud fraction, rain rate, radiative fluxes, temperature, relative humidity, vertical velocity) looking at daily and diurnal variability.

The authors concluded that the model consistently simulated the observations

For the second part of the results, also focusing on the comparison between observations and modeling, the authors explore the relationship between cloud fraction and the atmospheric variables (short and long wave radiation, temperature, relative humidity and vertical velocity and liquid water content).

The authors concluded that shallow and deep convection clouds have significant impact on radiation fluxes in the Amazon region during wet and dry period, and that memory of previous day large-scale features (based on temperature, RH, and vertical velocity anomalies) have a good correlation with cloud fraction.

I would recommend authors to carry out a careful revision of the manuscript; it seems that several grammatical corrections are necessary.

Response AC2: We thank the reviewer for taking the time to read our manuscript. We are happy that the reviewer understood and indicated the main points of the work. For final review, a more careful assessment will be made regarding the manuscript's grammar. Below are the changes and answers to the questions and suggestions raised by the reviewer.

INTRODUCTION

RC2: The introduction and the problem contextualization are somehow dispersed, the authors mention several aspects related to the importance of clouds and their interaction with radiation, in some points they mention aspects of large-scale atmospheric dynamics, little talk about thermodynamic aspects, they mention the types of models, but again there is a lack of connection between the contents that points to an objective characterization of the problem to be studied.

Response AC2: Thanks for the comment. We have taken this comment on the introduction and reviewed all the manuscripts for improvement and clarification (pages 1-4, lines 25-106).

The interaction of radiation fluxes with clouds plays an important role in the Earth's atmosphere, through the direct forcing on the diurnal cycle of meteorological variables and convective processes (Yang and Slingo 2001). The physical processes associated with the formation of clouds produce disturbances in the atmosphere that interact with waves of different periods that propagate from the tropical region of the Pacific, influencing the cycles of active and passive convection in remote regions. The main waves that act in the tropical region are Rossby, Kelvin and inertial gravity waves that cover periods of a few days to several weeks (Matsuno 1966; Mather 2005). For this reason, weather and climate scales are strongly modulated by the presence of clouds that influence the energy balance of the Earth system (L'Ecuyer 2019).

The clouds play an important role in planetary albedo, reflecting solar radiative flux back into space, controlling the excessive heating of the planet (Wielicki 1995). Additionally, clouds behave as a barrier to longwave radiation emitted by oceans and continents, absorbing such radiation and emitting a part back to the surface, this process creates like a greenhouse effect in the atmosphere, and maintains the average temperature of the Earth planet (Chen 2000; Patnaude and Diao 2020). The effects of clouds on the warming/cooling climate system will depend on several factors: cloud base and top height, cloud fraction, optical properties, liquid or ice phase of the cloud

particle (Yi Wang et al. 2019; Liou 2002). These cloud-related factors will define the absorption, transmittance and scattering properties of longwave and shortwave radiation (Mardi et al. 2019; Maghrabi et al. 2019).

The variability of cloud type and composition depends on the region where clouds are formed (Giangrande et al. 2017). In the case of the Amazon region, the type and composition of clouds play a very important role in modulating the global and regional climate, especially over South America. It is a region with great convective activity, behaving as a great source of heat and humidity (Satyamurty 2012; Nunes et al. 2016; Yanai and Tomita 1998), these factors and the instability force the formation of different types of clouds.

One of the great challenges of the scientific community is modeling correctly the formation, properties and feedback of different types of clouds (Zhang et al. 2005; Su et al. 2010; Bodas-Salcedo et al. 2014; Calisto et al. 2014;). Previous works found in the literature indicate that the deficiency of cloud simulation can generate weak or strong feedback in Global Climate Models (GCMs). Therefore, these shortcomings remain a major source of uncertainty in weather e climate forecasting and climate change simulation (Klein and Del Genio 2006; Del Genio 2012). Thus, understanding the processes that involve cloud formation and the interactions of clouds with radiation fluxes (called the cloud-radiation feedback process) is one of the main challenges for numerical modeling of the atmosphere, due to the characteristics and diversity of the types of clouds in the Earth's atmosphere (Giangrande et al. 2017; Chen et al. 2000).

The knowledge obtained through observed data on the different atmospheric physical processes related to the generation, development and dissipation of clouds, and the interaction of radiation with cloud cover are necessary to determine other phenomena that are not directly perceptible. Thus, new theories can be formulated helping to improve existing physical parameterizations in atmospheric circulation models. In this sense, several campaigns of data collection experiments realized in different regions will be useful in this work, for example, GoAmazon (Giangrande et al. 2017), DYNAMO (Feng et al. 2014; Fliegel and Schumacher 2012).

The results obtained in these campaigns of data collection experiments are being used to calibrate different types of radiative, convective and turbulent parameterizations (Ciesielski et al. 2017; Feng et al. 2015; Pujana et al. 2018; Moulin et al. 2018;) and explain meteorological phenomena at different weather and climate scales (Hagos et al. 2016; Rowe et al. 2019; Mather 2005). These field campaigns (GoAmazon and DYNAMO) helped to improve the understanding of cloud-radiation interaction processes and the physical processes responsible for the development of meteorological convective systems.

Numerical modeling is another methodology used to try to better understand the feedback of the interaction of radiation, cloud and turbulence. Numerical models have a hierarchy based on degree of precision of their parameterizations and simplifications in the dynamic equations (Frassoni et al. 2018; Jeevanjee et al. 2017), such as the General Atmosphere Circulation Model (AGCM-3D), Single Column Models (SCMs), Cloud Resolving Models (CRMs) and Large Eddy Simulation (LES). Each model has a scale domain that can be represented.

The LES and CRM models are high-resolution numerical models whose grid spacings are sufficiently refined to allow explicit simulations of turbulent eddies and individual clouds throughout the entire life cycle or part of it (Tao and Moncrieff 2009). The model (LES) is dedicated to the study of shallow, smaller and short-lived cumulus clouds and the model (CRMs) is suitable for the study of deep convective clouds with a longer life cycle (Frassoni et al. 2018; Tao and Moncrieff 2009).

Several works found in the literature show the efficiency of CRMs in simulating atmospheric phenomena (convective systems) with high resolution (Khairoutdinov et al. 2001, 2002, 2003; Mechem et al. 2018; Bretherton et al. 2017). More specifically for the Amazon region, which is the region of interest for this article, there are several studies carried out that use numerical models of the LES type (Dias-Junior et al. 2015; Neves et al., 2018; Chamecki et al. 2020) and CRM (Khairoutdinov and Randall 2006). However, for this region, no studies were found in the literature that uses forced CRMs with data from the GoAmazon 2014/15. Therefore, the use of CRMs for studies on the Amazon region, using more recent observational data, can provide detailed information on the

evolution of the cloud life cycle and the interaction of radiation with nebulosity that is not possible to obtain with observed data. This information can help improve cloud parameterizations used in atmospheric models.

In this sense, obtaining observed data or high-resolution modeling is essential to help understand how the physical processes of the atmosphere are related to the effects of cloud-radiation interaction that impact the development of convective systems in the tropical region. In the context of the problem of cloud representation in numerical models of weather and climate, the cloud fraction schemes are highlighted, which are mostly based on relative humidity thresholds, and some important parameters for cloud fraction diagnosis. These parameters are usually empirically calculated and the choice of these values can generate uncertainties in the representation of cloudiness (Park et al., 2016; Geoffroy et al., 2017). This work aims to obtain information on variables related to the cloud itself, such as water and ice content, and large-scale variables (temperature, omega and relative humidity) to understand the conditions for the formation, maintenance or dissipation of clouds.

The main objective of this work is to understand the cloud-radiation interaction and the role of large-scale variables and liquid water/ice content in the development, maintenance and dissipation of cloudiness from observational data and high-resolution modeling. The results of this article will be used to improve the cloud fraction parameterization used in General Atmosphere Circulation Models (GACMs) in future work.

RC2: As the authors suggest developing and adjusting the parameterizations related to the cloud cover fraction, it would be interesting to discuss what are the limitations that they want to target, and the aspects that the proposed study would help to improve.

Response AC2: Thanks for the comment. As requested, we improved the contextualization of the introduction and in it we indicated the importance of representing cloud cover in atmospheric models and the main limitation of cloud fraction parameterizations. As well, we indicate how the results of this manuscript can be used in future works to improve the cloud fraction parameterizations. The text below was added to the introduction (page 3, lines 92-97) to clarify the limitations and what we are proposing in relation to cloud fraction parameterization.

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METHODS

RC2: Little is said about the site, about the presence of the city of Manaus, the characteristics of the region, circulation pattern, among other relevant information to reinforce the importance of the site. GoAmazon included several sites, each site was designed to meet different characteristics within the context of the interaction between the city of Manaus and the Forest, it would be interesting if the authors could describe a little more about the ARM site in the context of GoAmazon.

Response AC2: Thank for the comment. This part of the manuscript the following paragraphs were included on page 4, lines 110-118 and on page 4, lines 122-125 .

The Amazon region plays a very important role in modulating the global and regional climate, especially over South America, as it is a great source of heat and humidity for the development and maintenance of precipitating meteorological systems. Due to variation in the annual circulation pattern and thermodynamic structure, the region

has defined wet and dry seasons (Carneiro and Fisch, 2020), with annual rainfall totals of approximately 2200 mm (Marengo et al., 2018). The rainfall characteristics of the region are defined by the presence of different systems and meteorological phenomena throughout the year, such as the Intertropical Convergence Zone, Squall Lines, Friagens, River Breeze and Penetration of Frontal Systems and Convection Organization (FISCH et al., 1998). Due to the action of different meteorological systems together with local convection, the region has different types of clouds (Giangrande et al., 2017) and the interaction of these clouds with radiation is the focus of different studies and field campaigns carried out in the region.

RC2: In the method topic, the variables used are barely contextualized in the dataset description, The authors need to specify the macro and microphysical data that they are referring to.

Response AC2: The cloud microphysical variables that we refer are water and ice content, the cloud macrophysical variables are cloud fraction and cloud type. This part of the text will be modified as shown below (page 5, lines 144-151).

The data generated during the GoAmazon 2014/15 that were used in this article are related to the macrophysical (cloud fraction and type of clouds) and microphysical (water content and ice content) characteristics of clouds, downward longwave and shortwave radiation fluxes for clear and cloudy sky conditions and large-scale variables (temperature, omega, relative humidity). For the simulations carried out with the SAM model, large-scale forcing (horizontal advection of temperature and humidity) and as initial condition (surface pressure and profiles of temperature, specific humidity and U and V components of the wind) data from the Variational Analysis product - VARANAL (Tang et al., 2016). The list of observational data used in this article and the references where the methodologies adopted for the collection (instruments) or estimation (products) of each data can be found is found in Table 1.

RC2: Try to maintain consistency in relation to the description of the objective of the study, in the methods topic it is understood that what is intended is an analysis of the cloud-radiation interaction, but in the introduction the focus of the study is described as to understand the relationship between dynamics, thermodynamics and the cloud-radiation interaction.

Response AC2: Thanks for this comment. We have clarified it in the new version manuscript.

RESULTS

RC2: The first part of the results focuses on evaluating the performance of the different model resolutions in relation to observation. I think that a statistical analysis to summarize the performance of each resolution would be helpful.

And it seems that an analysis separating different atmospheric scenarios, especially in the wet period, might bring interesting results. For example, in Figure 4 one can see that all resolutions fail in relation to the frequency of cloud cover fraction close to zero in the wet period, but at the other extreme, cases with a coverage fraction closer to 1 there is a resolution that seems to perform better than the others.

Response AC2: Thanks for the comment. One of the goals of the work is to analyze the behavior of the cloud fraction simulated by the SAM in the dry (IOP2) and wet (IOP1) periods, which are characterized by different circulation and precipitation patterns. Therefore, all analyzes and statistics are calculated separately for these two periods.

In Figure 4 it can be seen that the pattern of the distribution of different classes of cloud fraction is well simulated by the model, however there is difficulty in representing the frequency of the different classes of cloud fraction. Therefore, this is a shortcoming of the cloud fraction schemes used in CRMs, which generally depend on the

turbulent regime and microphysical processes. Any deficiencies in these processes produce an inaccurate cloud estimate. The SAM model consistently simulates the lowest cloud fraction values in both periods.

Indeed, the simulation with a horizontal resolution of 144p1km (green box) in Figure 4 is the closest to the observed data for maximum cloud fraction values (1). However, we can not define this resolution as the best configuration, just because it presents a good accuracy to simulate maximum cloud fraction values in IOP1, as it would not be representative for all cloud fraction classes.

On page 9, lines 277-287, a Table was inserted with the values of the correlation coefficient, bias and RMSE between the observed data and the simulations using the 4 different horizontal resolutions and the average between them (ensemble) for the variables precipitation, integrated cloud fraction and flux of incident shortwave radiation on the surface.

In Table 3, the correlation coefficient of precipitation and shortwave radiation between the observed and simulated data presents a good correlation, indicating that the variability of the observed data is well simulated by the model. However, the BIAS and RMSEs indicate that the data simulated by the SAM are overestimated in relation to the observation.

Statistical analysis of the cloud fraction does not show satisfactory values for the statistical indices, probably due to the methodology for calculating the cloud fraction obtained with observed data (Riihimaki et al., 2019) and how it is parameterized in the SAM model (Khairoutdinov and Randall, 2003), which produces cloud fraction values distinctly.

Thus, from the histogram of the distribution of the integrated cloud fraction (Figure 4) and the statistical analyzes (Table 3), it was not possible to define a better configuration of horizontal resolution to be used in the work, so it was decided to use the average among the 4 resolutions (ensemble) for the other analyses.

Tabela 3 - Summary of the statistical analysis. The correlation coefficient (r), BIAS and RMSE were calculated between the observed data and each simulation with different horizontal resolutions. For the wet (IOP1) e dry (IOP2) periods.

	PRP			CF			SW		
Simulations (IOP1)	r	BIAS	RMSE	r	BIAS	RMSE	r	BIAS	RMSE
SAM_144p2km	0,63	0,16	0,68	0,34	0,00	0,34	0,85	11,04	144,24
SAM_144p1km	0,62	0,16	0,69	0,33	0,03	0,36	0,81	8,56	160,72
SAM_144p500m	0,62	0,17	0,69	0,41	0,07	0,35	0,82	9,37	156,62
SAM_576p500m	0,65	0,17	0,67	0,36	0,02	0,34	0,83	13,04	152,05
SAM_Ensemble	0,64	0,17	0,68	0,38	0,03	0,34	0,83	10,50	151,12
Simulations (IOP2)	r	BIAS	RMSE	r	BIAS	RMSE	r	BIAS	RMSE
SAM_144p2km	0,24	0,19	0,39	0,17	0,05	0,30	0,94	7,79	106,16
SAM_144p1km	0,20	0,19	0,41	0,24	0,02	0,30	0,95	14,29	104,44
SAM_144p500m	0,24	0,20	0,42	0,27	0,01	0,30	0,95	18,24	106,44
SAM_576p500m	0,23	0,20	0,40	0,24	0,01	0,29	0,94	17,91	108,31
SAM_Ensemble	0,24	0,19	0,39	0,24	0,02	0,29	0,95	14,55	105,28

RC2: Regarding the two study cases, the analysis focused on two days seems to me limited in relation to the objective of extracting consistent and robust relationships between the atmospheric characteristics of the previous day and the properties of the clouds. The authors should evaluate a more robust alternative.

Response AC2: Thank you for your comments about the number of days chosen for the study.

For the analyzes in section 3.2, they were evaluated every day within the periods of IOP1 (wet season) and IOP2 (dry season), however, to show in this work only two characteristic days were chosen (1 day of each period), in the which presented a well-defined diurnal cycle of different types of clouds, considering that the objective of this section was to evaluate the behavior of large-scale variables (temperature, omega and relative humidity) and the radiation flux in relation to the presence of different types of clouds. Furthermore, the performance of the SAM model (in this case using the ensemble between the 4 horizontal resolutions) in simulating the interaction between clouds and radiation fluxes and large-scale variables was evaluated. The importance of knowing whether the SAM model consistently and accurately simulates the role in cloudiness is due to the need to use model variables that are not possible to obtain observationally, in the case of this study, the liquid water and ice content.

In section 3.3, where the relationship between the large-scale variables, radiation flux and water/ice content with the cloud fraction is studied, aiming to propose the use of these variables in cloud fraction parameterizations, a larger sample of days was used, being 7 days for the wet period and 5 days for the dry period. These days were chosen by the presence and evolution of different types of clouds during the diurnal cycle.

On page 13, lines 390-396 and page 16, line 517, the paragraphs were improved in order to clarify the choice of only two days for section 3.2 and indicating the use of more days in section 3.3 where the relationship between the variables is evaluated.

RC2: To achieve the objective of integrating modeling as an element to understand the interaction between dynamics, thermodynamics, clouds and radiation, it seems that the model needs to be further explored. The presented design and analysis of the model output consisted essentially of an evaluation against observation.

Response AC2: Thanks for the comment. To clarify that in this work the SAM model was used mainly to complement the observational analysis, a paragraph was added on page 6, lines 169-172.

In this work, the SAM model is used, mainly, as a complement to the observed data. For this, the consistency of the model is verified in simulating the interaction between cloud cover and radiation fluxes and large-scale variables (temperature, relative humidity and omega) in order to use variables that are not available in the GoAmazon 2014/15, as well as to understand the importance of correctly simulating the cloudiness pattern in numerical models

RC1 and RC2: The discussions of the relationships between cloud fraction and the remaining atmospheric variables, in general, were focused on expected features, which make it difficult to identify a clear contribution regarding the needed development and improvement in cloud parameterization stated in the goals of the paper.

Response RC2: Thanks for the comment. To clarify, we have amended the introduction to better contextualize the limitations related to cloud fraction parameterization and the purpose of this work. At the end of the conclusion (on pages 18-19, lines 584-594), two paragraphs were added that indicate the contribution of this study to improve the cloud fraction parameterizations.

From the results of sections 3.1 and 3.2, it is evident the importance of correctly simulating the representation of cloud cover in a weather and climate model. The results of section 3.3 indicate that the cloud fraction is related to

the anomalies of the large-scale variables and to the liquid/ice water content. Therefore, we propose that the results found in section 3.3 be used to define thresholds for large-scale variables (relative humidity, omega and temperature) and water content in the development and calibration of cloud fraction parameterizations. These results are an attempt to better represent cloudiness in numerical models of weather and climate and thus reduce cloud-related errors.

The results of this article are part of the project to develop the Brazilian Atmospheric Model (BAM) (Coelho et al., 2021, 2022b, a; Guimarães et al., 2021; Figueroa et al., 2016). All the information obtained through this work is being used to develop and improve the parameterization of the cloud fraction used in the BAM model. A second article is being prepared with a focus on the description of the new parameterization of the cloud fraction and its validation.

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