Climate Change as a Challenge to Decision-Makers in the Management of the Brazilian Hydropower Systems

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Introduction

This work aims to contribute to the investigation of impacts of climate and land-use changes on the hydrological cycle in Brazil. The work provides new insights for two reasons. First, the hydrological model uses more realistic runoffs, precipitation and evapotranspiration that are generated from a biosphere model coupled with a regional climate model, thus incorporating land-use change and climate change into the assessment of future water resources for hydropower planning in Brazil. Second, this work promotes cutting-edge research and interactions among scientists, engineers, and also decision-makers who will participate in the beginning of this study and may influence the presentation of the results and the most sensitive variables to be analyzed.

Brazilian electric power generation is dominated by hydro which accounts for more than 80% of the production. One important historical challenge to the operation planning of the Brazilian interconnected electrical system has been the stabilization of the energy supply, due to the seasonal and annual uncertainty nature of hydro resources. Altogether, Brazil is building or planning more than 33 GW of new hydropower capacity in the next 10 years, most of it (75%) in the Amazon.

This paper will describe the work that has been done at Paraná River Basin and the ongoing work being done in the Tapajós river basin.

The Parana Basin was chosen primarily to address the valid concerns of practitioners that few if any of the plethora of climate models are credible because they make no effort to explain central features of Brazilian hydrology. In this particular case, the test was to see whether the results of the models would be able to explain “the Parana paradox”, namely a large secular increase in flows of the Parana River in recent decades.

The Tapajos Basin was chosen because there are major plans for development of this currently-undeveloped basin in coming decades. These plans include hydropower, but also navigation which is vital for a cheaper and more environmentally-friendly export of grains.

Thus, the present study investigates how the climate and vegetation models can be used credibly in conjunction with hydrological models in order to investigate the impacts of climate change on the hydrological cycle. This is an ongoing study and this article will cover the steps already completed and work planned for the next phases.

1. Background

Climate change studies and assessment of changes in land use are often used as the basis for generating scenarios that can assist in decision making in various sectors. However, practitioners show justified skepticism about these studies since the results vary so widely and since there are seldom efforts to show that the models can reproduce known hydrological features.

Many studies have been conducted to estimate and analyze the hydrological impacts of climate change and the changes in land use. There is great interest in this type of study in Brazil because: (i) more than 80% of the electric energy is produced by hydroelectric plants; (ii) hydropower will retain a dominant role in the foreseeable future, despite the fact that most new plants will be built in the Amazon; (iii) most of the new plants won't have regulating reservoirs due to the environmental constraints and flatness of the terrain, which means that the energy output will be more directly depended of the flow of the river, which in turn is directly linked to rainfall and soil characteristics and vegetation of the watershed[1].

Studies of climate change and its influence on the hydrological cycle suffer from the mismatch between the spatial scales characteristic to each model type. Global climate models (GCM) usually work in the range of 1 x 1 (approximately 120 x 120 km) and seek to represent the processes and relationships between the atmosphere, the vegetation and the soil. On the other hand, hydrological models are traditionally used to represent and simulate the processes of runoff generation and their propagation in the network of drainage in the catchment area. Most of these models consider only the processes of the land phase of the hydrologic cycle, using rainfall as input data. They usually work on scales of 5 x 5 km. An advantage in the use of regional climate models (RCM, such as BRAMS – Brazilian Regional Atmospheric Model) is that the current resolution (a scale of a few rather than hundreds of kilometers) enables them to capture the heterogeneity of the processes that influence the generation of the flow in the river basin scale without the need for disaggregation (downscaling). Both types of models - climate and hydrological - represent in different level of accuracy the interaction soil x climate x vegetation. In order to use them jointly, it is necessary to deal with the redundant representations. In this context, this study sought to investigate the best hydrological models that could contribute to the assessment of impacts in river flows, using as input the results of atmospheric models and vegetation.

This study seeks to innovate in another way. Common practice is for climatologists to run models, produce results that the climatologists find relevant and then suggest that water planners use the results. In many instances water planning models need different inputs from the climate models. Emerging good practice is to reverse this process, and start with an understanding of the sensitivity of the water planning models to different variables, and then run the climate and vegetation models to produce outputs which are useful for policy purposes (Brown, 2012). Accordingly, a key element of this study was to engage water and hydropower practitioners at the early stages. Interviews were conducted and a workshop was held in Brazil at the headquarters of the National Water Agency seeking to meet the decision-makers from the, electrical, environmental and water resources sectors, in order to present the initial studies and seek suggestions for the presentation of future results.

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[1] In other words, the future power plants will tend to be run-of-the-river, the same as the recently built or being built in the Madeira River (Jirau and Santo Antonio), Xingu River (Belo Monte), and Teles Pires River (Teles Pires and Colider).

1.1 Hydrographic regions studied - Parana and Tapajós River Basins

Fig. 1. Map showing the river basins studied.

1.1.1 Paraná river basin

For the initial investigation of the potential application of the EDBRAMS model (explained below), an analysis of the historical record of flow of the Paraná River was conducted. The average river flow after 1970 is 30% higher than the pre 1970 average flow. There is no consensus on the reasons for this dramatic and economically-important change. More than half of the installed capacity and population of Brazil are located in this region.

The Paraná River comprises a major part of the Rio de la Plata basin. In Brazil, the drainage area includes the southern states of São Paulo, Paraná, Minas Gerais, Goias and Mato Grosso do Sul with more than 800,000 km^2, it is a highland area (300 – 1200 m) with heavily seasonal rains (1000 – 2400 mm), and high temperatures. The ED model (explained below) is used to explore the separate and combined effects of precipitation and land use changes on the flows of the Parana at the Itaipu Dam with mean annual discharge of 10,203 m^{3}s^{-1}.

Tapajós river basin

The area of the Tapajós River lies between the 2nd and 15th parallels of latitude south and meridians 54 ° and 60 ° of longitude west, standing east of the Madeira River basin and west of the Xingu River basin, and being part of the North and Midwest Regions of Brazil. Its surface covers an area of 492,481 km^2 distributed between the states of Mato Grosso, Pará, Amazonas, and a small portion of Rondônia.

The Tapajós basin has an elongated shape from south to north, the main tributary rivers are Juruena and Teles Pires that after joining, near parallel 7 º, receives the name of Tapajós River. From this point on, after covering about 825 km, flows on the right bank of the Amazon River.

The area covered by the Tapajós basin is configured with a uniform pattern of mean air temperature with annual averages of 26.7 º C and a small seasonal variation, not being observed throughout the year monthly averages below 21 º C.

The precipitation regime is typical of tropical systems; the rainy season (November to April) is characterized by high intensity rainfall, when the total monthly precipitation exceeds 300 mm. The dry period is characterized by very low rainfall during drier periods, where typical total precipitations recorded are below 60 mm.

The spatial distribution of precipitation indicates a total annual average of 1,900 mm in the lower section of the basin and increasing amounts of rain as it heads upstream toward their trainers, respectively Juruena and Teles Pires.

In this particular portion of the basin, a regional rainy core is observed, where annual mean rainfall is about 2,700 mm.

2. Methods and Models

2.1 Biosphere model

On this study we use the Ecosystem Demography (ED) model (version 2). The ED model is a biosphere model incorporating hydrology, land surface biophysics, vegetation dynamics and soil carbon and nitrogen biogeochemistry (Medvigy et al., 2009). In a polygon that shares a same climate (e.g., temperature, precipitation, radiations), there are several patches defined according to the disturbance history. In this way, the ED model has been demonstrated to be ideal for investigating the impacts of land-use changes. Each patch is then subdivided into cohorts that represent different sizes and functional types of plants. Therefore, ED model is capable of simulating complicated fine-scale dynamics and heterogeneity of the terrestrial ecosystem composition, structure, and function, and this model is widely considered to represent the state of the art for vegetative models. The fast timescale fluxes of carbon, water, and energy between the land surface and the atmosphere are captured using leaf photosynthesis and soil decomposition modules coupled with a multi-leaf layer and multi-soil layer biophysical scheme (Kim et. al., 2012). . This more sophisticated representation of vegetation is of central importance in Brazil, both because a large fraction of rainfall in much of Brazil is derived from re-evaporation over the Amazon (e.g., van der Ent et al., 2010) and because of the massive land use changes that have taken place in recent decades and could take place in the future as a result of both deforestation and climate change.. The climate model used for both the Parana basin and the Tapajós basin is the BRAMS (Brazilian Regional Atmospheric Model), which is a numerical model designed to simulate atmospheric circulation at many scales. BRAMS features include, among others, an ensemble version of a deep and shallow cumulus scheme based on the mass flux approach (Grell and Devenyi, 2002) and daily soil moisture initialization data (Gevaerd and Freitas, 2006). Several biophysical parameters associated with the vegetation and soil parameterizations of BRAMS were adapted for tropical and sub-tropical biomes and soils, using observations or estimations obtained in recent field campaigns (Freitas et al., 2007).

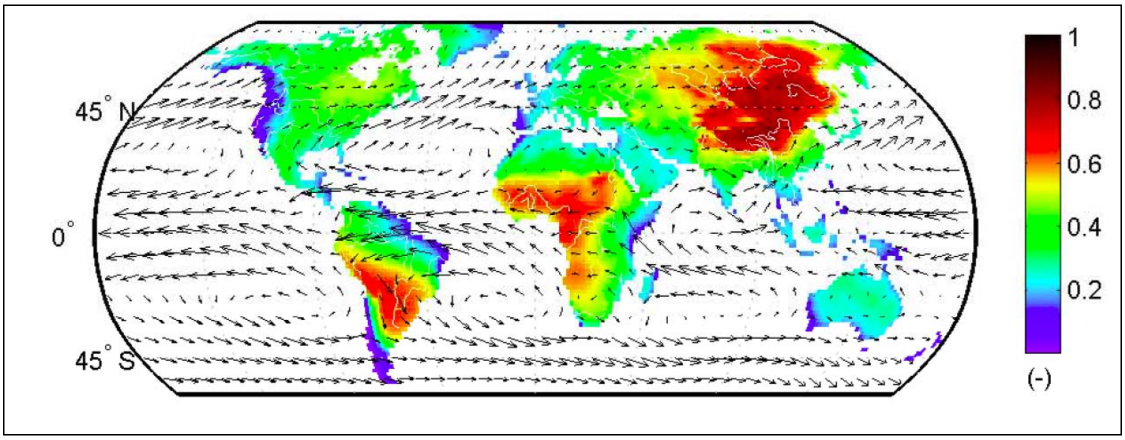

Fig. 2. Continental precipitation recycling ratio (Van der Ent. et.al.2010)

2.2 Hydrologic Models

Hydrological models are used to understand the operation of the water balance, the processes that control the movement of water and the impacts of changes in land use on the quantity and quality of water (Whitehead and Robinson, 1993). The importance of adopting a hydrologic basin as a unit is connected with the fact that its characteristics are closely related to water production. Traditionally, hydrological models of physical characteristic used just rainfall as input, the basin soil and vegetation characteristics to estimate the water balance, and the streamflow was obtained by a routing routine that uses topography to estimate the flows. However, with an enhanced climate knowledge and the advancement of the interactions between the airsheds (which may differ from the hydrographic basin), a new approach is needed, which is the use of the outputs of atmospheric models coupled with vegetation models as input to the flow propagation models to estimate the streamflows.

Thus, this study aims to analyze different hydrologic model options for use with the EDBRAMS output. Initially the rainfall - runoff IPH2 model (Tucci, 1998) was analyzed and despite being a widely used model that was developed seeking maximum parsimony so it could be used in basins of different sizes and characteristics, proved inadequate for this application. This was so because the IPH2 algorithms of losses through evaporation and interception of flow separation, propagation of surface runoff and groundwater propagation may not suit large river basins and do not allow the incorporation of the evapotranspiration and surface and sub-surface runoffs generated by the EDBRAMS model.

Likewise, the MGB model (Collischonn, W. 2001) was considered since it is widely used in large basins for hydrological studies and also with excellent results in Amazon Basins when coupled with atmospheric models. However, studies with this model also restrict the use of rainfall as input, since it internally details all the iterations involving soil, vegetation, subsurface storage and flow in the river. Thus, it was decided that a framework that would enable the use of outputs from state of the art vegetation-climate models (specifically EDBRAMS) was needed.

The THMB (terrestrial hydrological model with biogeochemistry) model was chosen because it has been widely used in this type of exercise. It is a routing model that is intended for modeling the flow of water in the drainage network in order to obtain the flow of rivers, estimates flood events and their influence on floodplains, and the magnitude of the hydrographic network. Basically this model takes as input the prescribed paths river and floodplain morphology derived from a digital elevation model of the terrain and the outputs of the land surface sub-surface drainage runoff from coupled climate vegetation models and calculates the streamflow using the conservation of mass principle. The flux to downstream cells (discharge) is based on the volume of water in the river reservoir and river geomorphic characteristics, such as slope and hydraulic radius. The inundation of the river floodplain is a function of the flux of water from the stream channel to the floodplain, the vertical water balance, and the geomorphic characteristics of the river and floodplain. (Coe et. Al., 2007).

3. Parana River Basin Exercise – A Credibility Check

As described earlier, the team chose to start the analysis with a “credibility check”, namely whether the model produced results that were consistent with the dramatic changes in flow in recent decades in the Parana Basin. The model was run with a prescribed meteorology to simulate a change in the vegetation and hydrological variables such as soil evaporation and plant transpiration. To represent the change in land use two scenarios called CLU1970 and CLU2008 (Current Land Use) were adopted. The maps are based on the use of land prepared by Hurtt (2006), which are reconstructed using two data sets of land use: SAGE and HYDE (Goldewijk, 2001) and contemporary farming maps based on satellite data and historical data inventories of farmland.

Two decades were chosen as representative of the analyzed period, 1969-1978 and 1999-2008. Thus, Table 1 summarizes the simulated scenarios.

Figure 3 illustrates the observed paradox in this chosen period. When comparing the average annual flow in the decades of 1969-1978 and 1999-2008, it is clear that there is an increase in flow rates of approximately 10%, whereas the precipitation decreased approximately 7% in the same period. Table 1 presents a summary of simulations and Figure 4 summarizes the results.

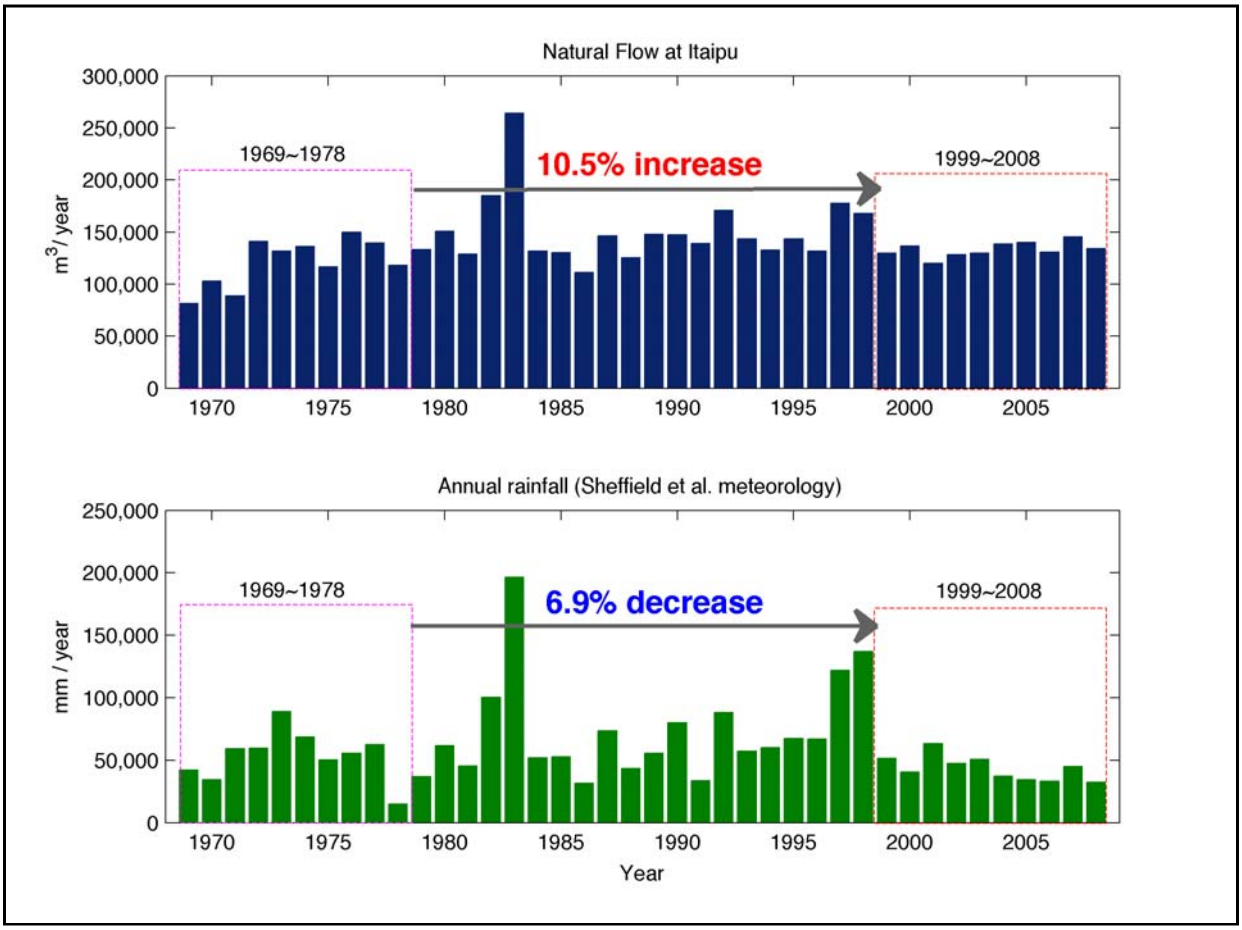

Fig. 3. Comparison between the average annual natural flow at Itaipu dam and average annual rainfall in the region of Paraná

Table 1. Simulations and results

Land Use\Precipitation	**(1969-1978)**	**(1999-2008)**
CLU 1970	Case 1	Scenario A
CLU 2008	Scenario B	Case 2

Δ Case2 - Case1	+8,5%
Δ Scenario B – Case 1	+24,4%
Δ Case2 - Scenario B	-11,3%

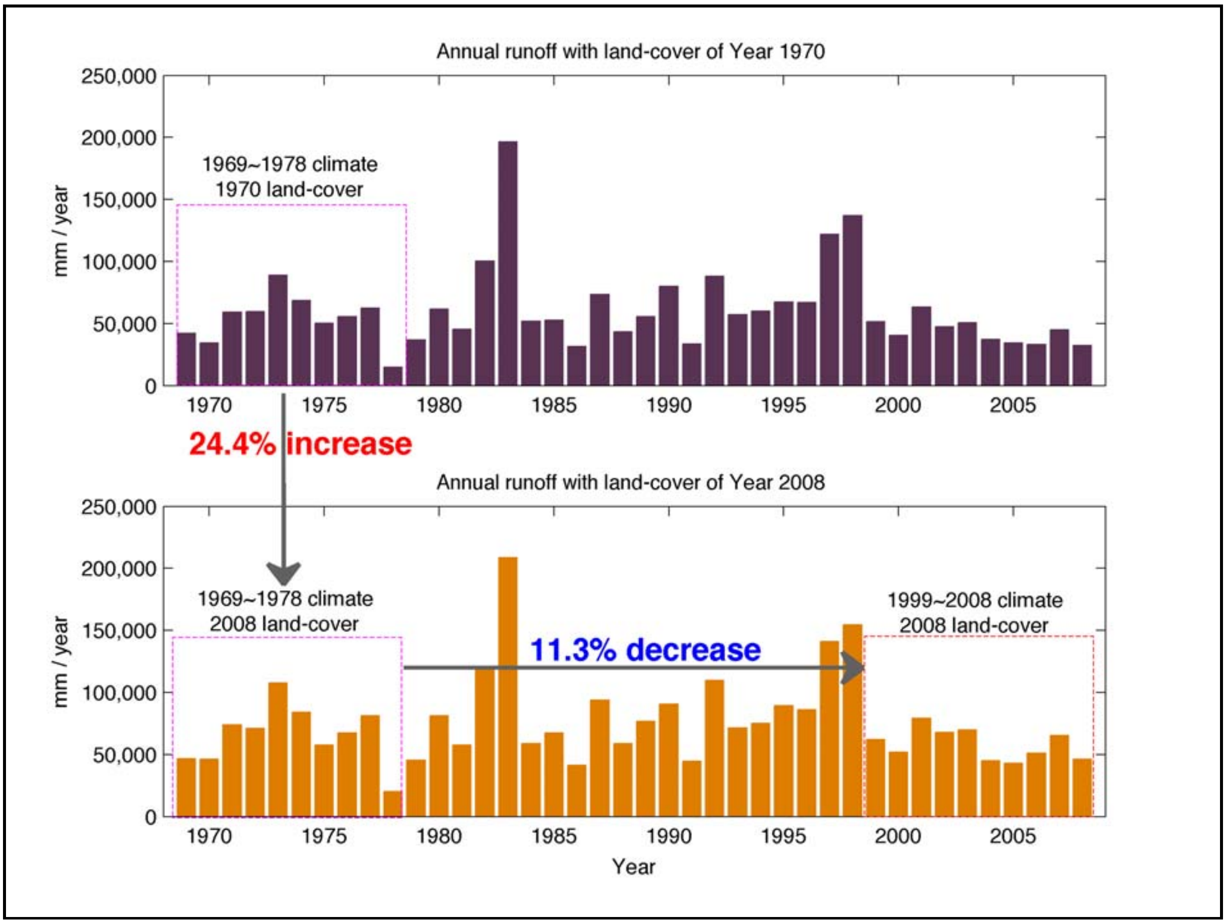

Fig. 4. Summary of Simulations

As shown in the Figures, the model results reproduce the central feature of the Parana paradox: namely a modeled increase of 8.5% versus a real increase of 10.5%. The isolated effect of land use shows that the effect of the change is significant (for the same pattern of rainfall in the decade of 1969-78 there was an increase of 24.4% in flows if the land use was changed. The effect of changing the pattern of rainfall (analyzed separately, or maintaining the same scenario of the soil) shows that there was an 11.3% reduction in flow rates. That is, the combined effect of precipitation and change in land use results in increased flow, but the change in the weight of the land use is so strong that it overrides the fact that the rainfall was lower and it is predominant in explaining the phenomenon presented.

This work also allowed an analysis of a phenomenon that has been occurring recently in the hydrological cycle of this region, which is a change in the seasonality of streamflows with a delay in the start of the rainy season (delay of two up to three months in some years) as well as the intensification ds extreme events (both floods as droughts). This phenomenon has serious social and economic consequences. For the energy sector there is concern with the operation of reservoirs aiming flood control, as well as with the operating procedures that support short term decision-making for early operation of the thermal power plants (fossil fuel).

Brazilian energy sector uses optimization models that have the assumption of stationarity of hydrological series. Thus the advancement of this type of study and greater knowledge of these changes in the pattern of hydrological series can be useful as a stimulus for the revision of the assumptions of energy models used in Brazil.

4. Work in Progress

For the Tapajós basin we are currently doing the validation of the rainfall generated by the model coupled with EDBRAMS for the period 2001 - 2009 in comparison with the data observed in some key positions in the basin. Additionally, the THMB model is under validation and adaptation of parameterization for the Tapajós basin.
The next steps of the study for the Tapajós region are:

1. Improvement of the parameterization of the THMB model for theTapajós basin
2. Execution of future runs of the EDBRAMS models (up to 2050)
3. Generation of scenarios for future streamflows for fluviometric stations (using the results obtained in step 2.) and evaluation of the energy generation of the hydropower plants planned for the Tapajós region through energy simulations with the MSUI model.
4. Analysis of impacts on the operation and design of plants and recommendations for energy planning (using the results obtained in step 3).

5. Conclusions and Recommendations

The next steps of this research are to analyze future scenarios of land use and interaction with climate change in the coming decades, in order to provide a basis for decision-making in the management of water resources, especially for the Brazilian energy sector that has hydroelectricity as the basis of its generation.

The research shows that hydrological models coupled with ecosystem models and atmospheric circulation models can successfully model the hydrological response of large basins to the impacts of changes in land use and surface cover taking into account the interactive processes between climate and vegetation, thus providing a credible framework with which to evaluate the ways in which water and energy planning can take account of future changes in both climate and land use.

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Acknowledgements

This work was conducted while the first author was a Giorgio Ruffolo Fellow in the Sustainability Science Program at Harvard University. Support from Italy’s Ministry for the Environment, Land and Sea is gratefully acknowledged.

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