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Climate of the Past Discussions

Interactive comment on "The Aptian evaporites of the South Atlantic: a climatic paradox?" *by* A.-C. Chaboureau et al.

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RE: manuscript entitled " The Aptian evaporites of the South Atlantic: a climatic paradox ?" by A.-C. Chaboureau and co-authors.

Dear reviewers, we are grateful for your constructive comments on our manuscript. We reply here point to point to the raised questions.

First, in response to the comments of reviewers we have also modified the text of the manuscript to take their comments into account. We have:

(1) include a more detailed figure to better present the occurrence of the mineralogical distinct evaporites in the Central segment, and more discuss evaporites around the South Atlantic.

(2) included comments and about the initial used palaeogeography, modified from Sewall et al. (2007), and included a new figure showing the topography and bathymetry.

(3) Added a discussion about the results of our model, which show high precipitation rates compared to the data.

(4) Added a discussion about the calcium chloride brine in the text.

Comments by U. Wortman:

The MS by Chaboureau et al. aims to explain the mineralogical difference between evaporite salts found in the northern part of the opening South Atlantic and the more southern latitudes of this basin. They content that the northern evaporites have been deposited under wet humid conditions, and are likely of hydrothermal origin. As such, they caution that evaporites are not necessarily a good climate indicator. Their argument is primarily supported by the results of a climate model. The overall argument is believable, bur there are several shortcomings in the MS, which should be addressed in order to strengthen their argument:

- The occurrence of the mineralogical distinct evaporites is not well presented.

The figure 1 will be amended to better present the mineralogical repartition of the evaporites in the Central segment of the South Atlantic.

- The mineralogical differences and their significance is only touched upon. This requires a more substantial discussion which also incorporates more modern ideas about the origin of calcium chloride brines (e.g., Lowenstein et al. 2003).

Recent papers mention secular variations in the major ion chemistry and that the ocean chemistry was not constant over the past 600 M.y. (Hardie, 1996). The driving mechanism of the fluctuations of the seawater chemistry is debated, between (1) a mid ocean ridge hydrothermal brine flux influence (e.g. Hardie, 1996; Spencer and Hardie, 1990) or (2) be combined with the dolomitization of the platform carbonate (e.g. Holland et al., 1996). During the early Cretaceous, the seawater had a $CaCl_2$ – rich composition

(Lowenstein et al., 2001; 2003). According to Lowenstein et al. (2003), evaporation of this CaCl2-rich seawater in an arid climate would produce CaCl2 brines with elevated concentrations of Ca2+, Mg2+, K+, and Cl-. Such water chemistry had probably favored the presence potash evaporites in the Central segment. However, the presence of Seaward Dipping Reflectors (Mohriak et al., 1995) and of the high concentrations of Pb, Zn, Fe and Mn (Wardlaw and Nicholls, 1972) would also suggest an hydrothermal influence. Thus, these two combined control factors would explain the formation of these potash evaporites, under a less favorable climate). We added a discussion about this point in the text.

- Ground truthing a climate model is always difficult, but the authors should at least attempt to compare their results to other published models (e.g., Wold or Barron). I also miss some general benchmark values, e.g., the latitudinal temperature profile, or the resulting sea surface temperature. A discussion of these parameters (see e.g., Hay 2008, and much of Barrons work) would provide a useful context to judge the validity of their model.

The model FOAM has been used in several published studies (Pierrehumbert, 2004, Nature; Poulsen, 2003; Donnadieu, 2006a-b; Beaulieu, 2012, Nature Climate Change etc . . . see also: http://www.mcs.anl.gov/research/projects/foam/publications.html). It is based on the atmosphere of the NCAR's Earth system model. Description of the ocean component of FOAM can be found in Jacob (1997). We do agree that models remain a simplified representation of the real world. However, GCMs are used since 30 years, several intercomparison projects have been built (PMIP, CMIP, PlioMIP etc . . .) in order to check for validity each time it is possible. Unfortunately, none intercomparison projects exist on the climate of the Cretaceous. In addition, we do not attempt to compare our results with other published models for the following reasons. First, as fully explained in Donnadieu et al. (2006, EPSL), previous modelling studies (in particular Barron's work) were performed with a "mean geography" for the Cretaceous that lasts 80 Ma. Here, we use a continental configuration published by Sewall et al. that has

been designed for the Aptian time period. We even focus on the late Aptian, hence a shorter time period. Second, except for some papers published by Chris Poulsen and co-authors, most modellers have focused on the warmest period of the Cretaceous, i.e. the Cenomanian-Turonian, or on the Maastrictian (see Valdes, Otto-Bliesner etc. . .). It is thus not really comparable. Third, we do not attempt to fit the climate of the Aptian in this paper; our aim is rather to use a model to test if it is possible or not to have highly saline water at the equator.

- The northern part of the basin was rather small, and indeed smaller than the grid resolution of the model used by the authors. How will this affect the validity of their results?

Indeed, above the northern part of the Central segment, the atmospheric resolution of the model is lower than the width of the basin. FOAM uses a combination of an atmospheric and an oceanic model. As the numerical resolution of atmospheric processes is very time-consuming, the resolution of the atmospheric model (7.5° x 4.5°) is coarser than the oceanic resolution (2.8° x 1.4°). Hence, ocean and continental fractions are calculated from the high-resolution oceanic grid (e.g. Figure S1a). Then, the ratio is used to interpolate on the coarser atmospheric grid. In the case of the north of the Central segment, the land fraction is more important than the oceanic fraction within the atmosphere grid. This could potentially be an issue. However, in our particular case (which conditions can favour the formation of highly saline waters), we can assume that if we impose oceanic grid points over the northern part of the Central segment, moisture will be higher over this area, thus favouring the precipitations and creating much less favourable conditions for the formation of highly saline waters.

- Most importantly however, the authors reasoning depends critically on their choice of paleogeographical model. In most published paleogeographic reconstructions, the bulk of the evaporites was deposited between 10 and 40S, whereas Chaboureau et al. use the model by Moulin et al. 2010, which proposes paleolatitudes between 0 to 20S for the Aptian Salt basins. While it is beyond my abilities to judge the validity of

Moulin et al. 2010 paleolatitudes, it must be mentioned that paleolatitude estimates are particularly difficult and error prone. Since the main point of the MS, i.e., how to create evaporite deposits under tropical conditions, may not even exists if we choose another paleogeographical reference frame, the authors should provide a discussion, of why this particular paleogeographical model was chosen, what kind of confidence interval one can assign to the latitudinal values given in the model, and how that would affect their modelling efforts. In my view the authors should also supply model results for an alternative paleo-latitudinal model, and frame the discussion of their results accordingly.

Sewall et al. (2007) have built 4 maps covering the Cretaceous time period, one early Aptian, one early Albian, one Cenomanian and one Maastrictian. In our paper, the time period of interest is the late Aptian one. As explained below, because the evaporites have been deposited during the late Aptian, we use a modified version of the late Aptian continental map published by Sewall et al. (2007). Furthermore, we are not sure to understand what the reviewer means by writing that we have favoured the Moulin et al. paleolatitudes. In fact, we have used the Sewall continental configuration and we have not changed the latitude of South America and of Africa on our map (see Figure S1). Reconstructions of Sewall et al. account for most paleomagnetic, sedimentological data published in the literature. They basically use Scotese's work and Blakey's work. Hence, we do not choose a particular paleogeographical reference frame; we just used Cretaceous maps that seem to synthesize works from different authors. At early Aptian time, the Central segment of the South Atlantic is not yet opened and records a continental sedimentation, as depicted in Figure S1a (dotted square). This figure represents the global geography of Sewall et al. (2007) at the lower Aptian, scaled to the GCM resolution. At early Albian time, the Central segment is opened (Figure S1b) and records a marine sedimentation (Chaboureau et al., submitted ; Barbosa da Silva et al., 2007; Costa et al., 2007; França et al., 2007; Gontijo et al., 2007; Milani et al., 2007; Moreira et al., 2007; Netto et al., 2007; Rangel et al., 2007; Rodovalho et al., 2007; Winter et al., 2007; Braccini et al., 1997; Grosdidier et al., 1996; Teisserenc

and Villemin, 1990). Between these two palaeogeographic maps, the positions of the South America and Africa are very close, and no major rotation of one of these continents is observed (Figure S1c). Given these observations, we created an intermediate palaeogeography to model the evaporites of the Central segment of the South Atlantic, respecting the position of the South Atlantic according to the geography of Sewall et al. (2007), (Fig. S1d).

1. p123 l23: To my knowledge, the bulk of the evaporites have been deposited during the Early Aptian (see e.g., Wortmann & Chernyavsky 2007). What is the relevance of the Mid-Cretaceous climate here?

Actually, the Aptian evaporites of the Central segment have been deposited during the Upper Aptian (Barbosa da Silva et al. 2007; Costa et al. 2007; França et al. 2007; Gontijo et al. 2007; Milani et al. 2007; Moreira et al. 2007; Netto et al. 2007; Rangel et al. 2007; Rodovalho et al. 2007; Winter et al. 2007; Teisserenc and Villemin, 1990; Grosdidier et al., 1996; Braccini et al., 1997). But, indeed we should rather mention the late Early Cretaceous here.

2. p 123 l 29, this is indeed interesting, and a location map would be really useful to support this point.

As mentioned above, a more detailed figure has been added.

3. p 124 l 23, why the upper Aptian? The majority of the salt extraction happened during the lower Aptian?

No, in the Central segment of the South Atlantic, the evaporites are deposited during the Upper Aptian along the brazilian and african margin (Barbosa da Silva et al. 2007; Costa et al. 2007; França et al. 2007; Gontijo et al. 2007; Milani et al. 2007; Moreira et al. 2007; Netto et al. 2007; Rangel et al. 2007; Rodovalho et al. 2007; Winter et al. 2007; Teisserenc and Villemin, 1990; Grosdidier et al., 1996; Braccini et al., 1997) and not during the lower.

4. p 125 l 6, the longitudinal resolution of the atmospheric model is smaller than or equal to the basin with. How will this affect the modelling of evaporation rates?

See discussion above.

5. p 125 l 14ff: If understand this correctly, the authors propose several important changes to the topographic model of Sewall 2007, and provide only scant justification why. More importantly, they do not provide model results based on the original Sewall 2007 model, so it is difficult to understand how these changes affect their model.

Changes in Sewall paleogeography have been made in order to initialize our model with a paleogeography as realistic as possible. Each change has been explained in the methods section with what we think are appropriate references. When interpolated on the model grid these modifications are too small to induce significant changes in simulated climate response. We have added a short comment in the text.

6. p 128 l 15: Is the model resolution really sufficient to evaluate whether local moisture uptake over the rift basin is sufficient to create substantial orographic rain at the rift shoulders? The comparison with India is not valid here, as the Indian monsoon has the hole Indian Ocean to fetch moisture, and a strong driving force (i.e., the trade winds). Furthermore, the moisture balance over land is critically controlled by vegetation. What kind of biomes where used in the model, and is there any evidence for comparable Aptian vegetation at these locations?

Actually, if we confer to diagnostic depicted by Braconnot et al (1999) to distinguish local moisture recycling from far-field advection in GCM simulations, our results show that most of moisture come from advection and not local uptake, and that the topography only acts as a barrier to set up vertical convection and precipitation. Concerning the comparison with India : Actually the trade winds are not the driving force for Indian monsoon. Indian monsoon is characterized by a surface flow reversal opposite to the direction of the trade winds. This moisture flow is driven by pressure gradients between the Indian ocean and the continent. What we meant in our comparison with

Fluteau et al. (1999) is that adding topography enhances such pressure gradients, ultimately increasing the moisture flux towards the continent. In the new version of the manuscript, we attempt to make it clearer. We totally agree that vegetation is crucial for the continental moisture balance. Here we used Sewall vegetation transposed on LPJ Plant Functional Types. Typically, in our region of interest, we use medium and tall grassland woodlands, short grassland, meadow and shrubland, deciduous forest, and tropical evergreen broadleaved forest, for the Gondwana continent.

7. p 131, l 6: why are clastic rocks a proxy for humid conditions? can this be substantiated?

Clastic pre salt sediments are more important to the North than in the South, where lacustrine carbonates persist. The more important detritical influx to the North is coherent with a more humid climate in this area. Here we not consider that clastic rocks are a proxy for humid conditions, but they are relevant when compared to the south. This is perhaps not clear in the text, and we have written this differently.

8. p 132 l 3: I miss a discussion of Lowenstein 2003?

Indeed, we include a discussion on this point.

9. p 132, l23: The rift shoulders around the Red Sea exceed 2.5km in elevation in many places – and this is under arid conditions. Intense rainfall would result in erosion and accelerated uplift. So why is 3km an extreme value?

Indeed, in the Red sea, the rift exceeds 2.5 km in elevation in many place, but rarely reaches 3 km. Actually, two markers record occurrence of rift shoulder: (1) alluvial fans associated with active normal faults and (2) the nature of the sediments and solutes coming from inland and preserved in the rift. According to these proxies, the maximum of the rift flank was probably reached during Valanginian time, and then had decreased (Chaboureau et al. submitted) and was probably flattened during Aptian time, at the end of the rift activity. Furthermore, the geochemical data of Harris (2000) and Harris et al. (2004) suggest, on African side, a decrease of the upstream relief during the Barremian. For these reasons, we believe that 3km is an extreme value.

Thank you for all of your comments.

Comments by J. Trabucho-Alexandre:

This manuscript by Chaboureau and coworkers deals with an extremely interesting aspect of Cretaceous palaeogeography which is the presence of evaporites at equatorial latitudes. Evaporites are not (in any significant volumes) present at these latitudes at present and, therefore, this requires some explanation. The authors address this problem from a climate modelling perspective. They conclude, based on their modelling results and on latitude-related changes in evaporite mineralogy, that evaporites in the northern South Atlantic region are of hydrothermal origin. Therefore, they are not related to climate, which, according to the results presented here, was humid in the northern South Atlantic.

- I think this is an interesting manuscript dealing with an interesting problem that has not really been addressed before (as far as I know). My main criticism of the manuscript is a lack of more background information. In my opinion, the authors should include a figure (and perhaps a table) with a compilation of known evaporite deposits in the South Atlantic region for the time interval studied. Moreover, the authors could discuss the problematic of evaporites at equatorial latitudes a bit further, and include literature on vegetation at low latitudes during the Cretaceous (see, for a starting point, the paper by Beerling, 2000 and the paper by Spicer et al., 1993; as well as Chumakov et al., 1995 which the authors already refer to).

The Equatorial and Central segment of the South Atlantic are separated by the Romanche Fracture Zone. Most of the significant Aptian salt is located along the Eastern Brazilian margin, and along the conjugated African margin. The Central segment is thus distinguished from the equatorial segment by the presence of the widespread and thick salt layer, up to 2 kilometers. Such deposits are not found in the adjacent

segments north and south. For these reasons, we focused on the Central segment. However, indeed, evaporites deposits are locally deposited in some basins of the equatorial margin (Grajau, Sao Luis, Ceara), and in the Potiguar basin, and also raises the problem of the presence of evaporites at the equator. Precisions will be added in the manuscript, and location of these evaporites have been specified. Indeed, these equatorial evaporites are mainly characterized by anhydrite and gypse (Davison, 2007; Zalan, 2007, Paz et al., 2005;). The most soluble salt recorded in the equatorial margin is the halite and is only recorded in the Ceara basin (Conde et al., 2007; Davison, 2007) and none potash salt are recorded in the equatorial margin. In our simulation, this part of the South Atlantic is also affected by a seasonality created by the movement of the ITCZ. Low precipitation during the dry season could provide adequate conditions to the development of evaporites and is coherent with the sedimentary record (Santos and de Carvalho, 2009). Absence of potash salt in this segment at the Upper Aptian, adjacent to the Central segment, indicates a climate not sufficiently favorable and no geodynamic control which could compensate.

- The P–E data which is modeled compares well with data for the present-day equatorial region, I think (the authors may correct me if I'm wrong). This raises the interesting question: why was vegetation xeromorphic in those regions (see Spicer et al., 1993)? In fact, the biomes used by the authors in the model (see Sewall et al., 2007) reflect this knowledge. Yet, climate appears to have been humid following the model results. This certainly warrants discussion.

Indeed, this point deserves discussion, thank you for raising it. A bias of the model is that our results show a humid climate in the equatorial region, whereas the vegetation was rather xeromorphic (Beerling et al., 1990; Chumakov et al., 1995; Sewall et al., 2007; Spicer et al., 1993) . A new paradox is highlighted here that it is difficult to give an answer. An explanation would be the resolution of the model, which might not adapted to the characteristics (e.g. evapotranspiration rates) of Cretaceous vegetation. Such a feature has been highlighted in recent studies and should be considered in the future development of past vegetation models (Boyce et al., 2010). Other explanation could be linked to by the global control versus the regional control. Physical processes like the Intertropical Convergent Zone, orographic rainfall, or proximity of large water body could be predominant to a local effect of the vegetation. This point has been added and discussed in the text.

- What would happen to the modelling results if the Andes were higher? I cannot help but wonder.

Sensitivity experiments to low and high Andes have been run with high resolution GCMs by one of the coauthors. The results show that in a present-day configuration, changes in the Pacific SSTs driven by changes in surface wind patterns occur when Andes are lowered. Ultimately, these mechanisms drive changes in rainfall over the Amazonian basin and Patagonia (Sepulchre et al., 2009, 2010). In this particular paleogeogrpahic context of the Aptian, we could expect changes in rainfall along the cordillera and maybe as far 20-15°W, but inferring changes in the central segments would be speculative.

- Another interesting question can be raised by comparing the mineralogical distribution of evaporites given by the authors and the data presented in Paz et al. (2005). In their manuscript, Paz and coworkers document gypsum, anhydrite (locally) and black shales from NE Brazil. Based on their analyses, the authors determined that these are upper Aptian continental deposits. However, the studied region falls under the area in which the present model shows highest P–E values. This also warrants discussion (and therefore I suggest the authors include more detailed data on the evaporite deposits around the South Atlantic).

A discussion has been added (see discussion above), and a more detailed figure will present the evaporites deposits along the equatorial margin.

Page 128, ln 11: I think SO is SW? Yes, thank you for seeing it.

Page 129, 3: How would varying orbital parameters affect the ITCZ position? See also page 132, ln 19 where you mention that climate would always be more humid to the north. Is that really so (if you vary orbital parameters)?

We have carried out four additional simulations with different positions in the precessional cycle (orbital conditions and climatic effects for one complete precessional cycle are well described by Floegel et al. (2005)). The other values of orbital parameters were kept constant, and fixed to the present-day values. According to the simulations, changes in precipitation rates between the five simulations are more marked from March to July. However, the main results are not dependent on the orbital parameters as the highest values of the rainfall are found during October. The magnitude of precipitation for the different precession sensitivity tests are very close to those obtained with current settings (Fig. S2). In addition, seasonality is not affected, and the wet and dry seasons are still simulated.

Page 130, ln 1: Evaporites. Yes, thank you.

Page 130, ln 17: Please be more specific than just adding the reference. We will more develop.

Page 132, ln 23: Rift flank? Yes, thank you.

Page 133, ln 1: How does this inferred reduction in relief compare to clastic deposition in the basin prior to salt? The maximum growth of clastic deposits (alluvial fans) occurs at the beginning of the rifting (during Valanginian time) and then decreased after the early Barremian, before the salt deposit (Chaboureau et al., submitted).

A figure could be add showing topography and bathymetry. Yes, a figure will be added.

In figure 3 the caption mentions TopoB. I think it should be TopoHigh. Yes

I hope you find my review fair and my comments useful. Yes, thank you for these interesting and constructive remarks, and for this careful review.

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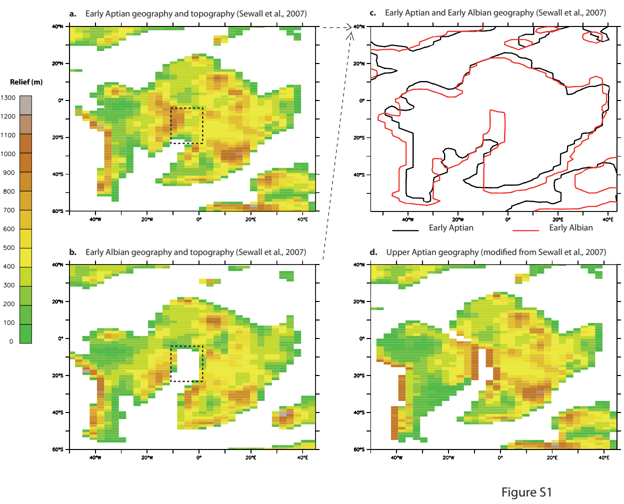

Fig. 1.

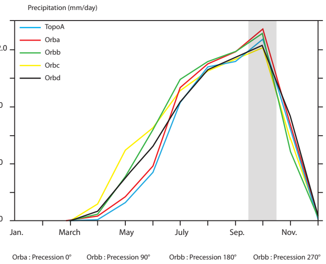

Figure S2

Fig. 2.