

Reply to reviewer#2

Please note that page and line numbers that we mention in this reply refer to our revised manuscript and not to the original ACPD paper. The changed and added texts in the revised manuscript are shown in red. The reviewer's comments are reproduced here in bold and the page and line number that he/she uses (in bold as well) refer to the original ACPD paper and not the revised manuscript.

Also, please note that because we added the three new figures after our revision, the numbering of the figures in the revised manuscript is different from that in the original one.

General comments:

This paper describes analysis of Borneo vortex and precipitation under cold surge conditions. The first part of the manuscript demonstrates the climatology of Borneo vortex and associated precipitation in the presence of strong cold surge. The second part presents dynamical analysis of Borneo vortex simulated in a semi-idealized numerical experiment. Based on budget analysis of vorticity and divergence, the authors try to explain generation and maintenance of meso-alpha scale cyclone (i.e., Borneo vortex) and meso-beta scale precipitating region that appear in the northeast quadrant of the vortex. They conclude that the deviatoric strain inherent in the confluent flow field was essential to the manifestation of both meso-alpha and meso-beta scale features. The motivation is clear and scientifically meaningful. The detailed analysis of dynamics provides new insights into the mechanisms of Borneo vortex.

We greatly appreciate the reviewer for his/her constructive comments on our manuscript.

In contrast, analysis of moist convection is less systematic and does not support some of the arguments. Critical problems appear to be;

1) Mechanisms of Borneo vortex and deep convection are rather separately discussed. Relationship between them is not fully elucidated by the dynamical analysis.

As the reviewer points out, our original manuscript did not explain the relationship between the vortex dynamics and thermodynamics of the moist cumulus convection. We added the new subsection titled "6.2 Dynamics-thermodynamics relationship in the meso- α cyclone core" in the revised manuscript. This point is related to reply to the reviewer's specific comment#2. Please see pages 23-24, lines 11-6 in the revised manuscript.

2) The discussion on deep convection is focused on the tail region of the comma-shaped rainband in the northeast quadrant. However, most intense convection appeared close to the cyclone center (i.e., comma-head). Which is essential to the whole system is not clear.

As the reviewer points out, the intense rainfall of the rainband is also found in the comma-head and northwest sector. We have since paid more attention to the rainfall northwestern sector and added the further investigation on this sector, because the strong convergence around the cyclone centre is mostly in the northwestern sector (the new Fig. 15). This point is related to the next comment and specific comment#11. Please see pages 27-28, lines 14-9 and pages 28-30, lines 18-2.

3) Hierarchical structure (meso-beta scale precipitating systems in the meso-alpha scale rainband) should not be limited in the northeast sector of the cyclone (e.g., comma-head and intense precipitation in the northwest sector). Separation by horizontal scale and by axisymmetry in the current manuscript is rather confusing.

As we reply to the previous comment, we added the further investigation of the rainfall in the northwestern sector close to the cyclone centre demonstrating that meso-beta precipitating systems are also present there. Please see pages 27-28, lines 14-9 and pages 28-30, lines 18-2.

4) Discussion on Borneo vortex (meso-alpha scale cyclone) in analogy with a tropical cyclone is inadequate in some points (not acceptable for publication). I recommend this manuscript to be eventually published in ACP after revision on these points.

One of our conclusions is that our simulated vortex is different from the typical TCs in terms of the vertical structure and its dynamics of the growth/maintenance. We have since emphasized the “differences” more clearly between our simulated vortex and the typical TCs in the revised manuscript. Please see page 20, lines 5-9 and page 28, line 6-9.

Specific comments:

1. p.80 L.9-10, L.12-17

These descriptions focus on the northeast sector of the cyclone. However, deep convection (upward motion, condensates, and intense precipitation) are most prominent close to the cyclone center (Figs. 10b, 11), where cyclostrophic balance is dominant (Fig. 13a,b). If this is important to the growth and maintenance of the whole system, it should be stated in the abstract.

As the reviewer noted, the intense rainfall around the cyclone centre is important for the convergence and the stretching term which is responsible for the vortex maintenance. We added the statement in the abstract and conclusion. Please see page 2, lines 10-18.

Moreover, intense precipitation in the northwest sector is also a major part of the comma-shaped rainband but in different dynamical conditions (i.e., meridional gradient of zonal wind is significant; p.96 L.1-3) from that in the northeast sector.

As the reviewer points out, the northwestern sector is also an important part of the rainband. The convergence due to the zonal component is dominant in the northwestern sector and this is responsible for the convection and rainfall in the northwestern sector adjacent to the cyclone center. This strong convergence is caused by the confluence of the background cold surge (that is wrapped around the vortex to acquire a westerly component) and the cyclonic flow (that has a easterly component). The basic mechanism is here similar to that in the northeastern sector.

We added more description on it in the abstract as well as added more detailed investigations and a figure on the northwestern sector close to the cyclone centre in section 6 (please see the new Fig. 17 and pages 27-28, lines 14-9, pages 28-30, lines 18-2, and page 32, lines 11-15). Actually, this added investigation can answer many of reviewer's specific comments and clarifies the relationship between Borneo vortex and meso-scale convective. Please see also our other replies to comments (#9, #11, #12).

2. p.80 L.10-11, L.16-18

The effects of moist convection indirectly appear in vorticity and divergence equations (e.g., acceleration of horizontal convergence and increase in horizontal pressure gradient force by latent heat release, etc.). Addressing the relationship between dynamics and moist convection is highly requested.

We agree completely with the reviewer. Our original manuscript did not mention much about the relationship between the dynamics and thermodynamics of the cyclone. We added a new subsection 6.2 and we investigated this relationship around the cyclone centre where the coupling between the two is the strongest (although the relationship exists in the rainbands away from the cyclone centre too). Please see page 2, lines 10-12, pages 23-24, lines 11-6, and page 26, lines 2-9. Because we did not output the diabatic heating rate from our NHM run, we show the mixing ratio of hydrometeors instead as the indication of the diabatic heating as an indication of where diabatic heating is likely to take place. But we recognize that the distribution of hydrometeors is affected by advection and falling.

Another point to take into account is that budget analysis in a quasi-stationary state (e.g., mature stage) explains balance among the forcing terms but not the reason for the growth of the quantity (Figs. 13, 16).

Yes, we did not use the correct word in this case. But we have also investigated the developing stage with similar results (new Fig. 13a-e) and in that case, the word of "growth" is correct. However, because main dynamical analysis is based on the mature stage, we replaced "growth" by "growth/maintenance" in the abstract.

3. p.81 L.16-22

In view of the mechanism of generation and organization of deep convection in the tropics, diagnosis of heat, moisture, and energy (e.g., Yanai et al. 1973) provides useful information.

We greatly appreciate for the constructive suggestions. We cited Yanai et al. (1973) in the revision and gave more explanation on our analysis in the introduction to justify our methodology. A part of this reply is related to the reviewer's comment#4. Please see page 5, lines 14-20.

If the authors prefer to confine their quantitative analysis to dynamical aspects, it is recommended to give explanations for 1) the selection of vorticity and divergence diagnosis and 2) how to understand the mechanisms of convective organization from the diagnosis, somewhere in the manuscript.

Our fundamental philosophy of the mechanism of generation of the Borneo vortex is different from the typical TCs. In the latter, the latent heat from the sea surface is responsible for the TC formation and maintenance. On the other hand, the former is caused by the cold surge mechanically. That is why our

diagnoses start from the vorticity budget analysis. The divergence tendency equation must be considered with the vorticity tendency equation, because they describe entirely the evolution of the vector flow field (just like the zonal and meridional momentum tendency equations together). Moreover, the form of the divergence equation is one of the newer aspects of this work. We propose that in the Borneo vortex, cumulus convection is initiated and organized by the low-level convergence, but we give equal emphasis to the idea that the latent heat release and forcing of vertical motion helps enhance the low-level convergence.

We added more explanation in the introduction. Please see page 6, lines 1-9.

4. p.86 L.12-19

Distributions of specific humidity (q) and convergence (upward motion) will be more relevant to the location of deep convection than moisture flux divergence. “Clausius- Clapeyron : : :” is difficult to understand. Additional explanations are requested.

The reviewer may be thinking of convection at cloud-resolving scales where horizontal convergence (of wind) is related to convection and the distribution of specific humidity at low levels increases the CAPE. But at the scales resolved by the reanalysis dataset ($1.25^\circ \times 1.25^\circ$), moist convection and the associated precipitation is maintained by the supply of water vapour and moist static energy. In particular, we would like to investigate, here, how the cold surges transport atmospheric quantities from the higher latitude to the equator, because the cold surge is responsible for the generation of the Borneo vortex. So, our analyses focus on the convergence of water vapour flux and moist static energy flux. To justify our fundamental philosophy, we added more explanation in the introduction. Please see page 5, line 14-20.

Moreover, because the moist static energy flux rather than the moisture flux is more directly related to the moist convection, we replaced the divergence of moisture flux with the divergence of moist static energy flux in Fig.3 and revised our manuscript. The distribution of the moist static energy flux divergence coincides approximately with that of moisture flux divergence. This point is relevant to the next comment and reply.

The mention of Clausius-Clapeyron relation was removed following the revision.

5. p.86 L.20-23

This is not presented in Fig. 3. Again, description of moist static energy itself rather than flux divergence will be more informative.

This is an oversight. We should have written “(not shown)”. However, as in our reply to the previous comment, the moist static energy flux is more directly related to moist cumulus convection and we replaced the moisture flux divergence with the moist static energy flux divergence. Please see pages 10-11, lines 16-2. Actually, the distribution of the moist static energy flux divergence is similar to that in of the water vapour flux divergence because of the dominance of latent heat term in the moist static energy.

6. p.86 L.25 “diurnal cycle” I am not sure the diurnal cycle (Fig. 5 and 9b) is relevant to the objective of this study, although the findings here are quite interesting.

The diurnal cycle of rainfall is not the main theme of our study. However, the diurnal cycle is main contributor to the rainfall in the Maritime Continent and we should not avoid mentioning it in the manuscript. In fact, we found the difference in modification of diurnal cycle between over the equatorial South China Sea and Java Sea: While rainfall over the Java Sea intensifies only during midnight-morning time, rainfall over the equatorial South China Sea shows the diurnal cycle and is reinforced in the whole day. This difference indicates the different mechanism by which the rainfall is enhanced over two regions. This allows us to focus on the rainfall generated by Borneo vortices in the South China Sea during a cold surge without any worry that the Java Sea forms part of the same rainfall enhancement system.

In the new Fig. 10b, we gave some expression about the diurnal cycle of rainfall in order to show the consistency between the observations and our semi-idealized experiment. Please see page 17, lines 9-10. Moreover, we put the gray bars indicating 00 to 12 LST on the new Fig. 10b.

7. p.87 L.26-27

Colocation of vorticity flux convergence (Fig. 3a) and rainfall (Fig. 4) does not seem to be evident.

We apologize for our mistake: we meant to point out the relation between rainfall anomaly and absolute vorticity anomaly, not the anomaly in the absolute vorticity flux convergence. Please see the revised text, page 13, lines 1-3.

8. p.91 L.16-27

Precipitation in the northeast quadrant of the vortex center (Fig. 10b) is not necessarily clear in the composite TRMM precipitation (Fig. 7b). Since this is the major target of the discussion given in the following sections, the matching with observation is preferable. Are there any typical cases with a comma-shaped rainband in the 55 days of the composite analysis?

Our previous explanation was not so good on this point. The number 55 (days) is for the strong Borneo vortex based on JRA25/JCDAS data in December from 1981 to 2008. On the other hand, we have only 16 days of rainfall consistent with days of strong Borneo vortex in the TRMM composite picture, because TRMM 3B42 covers from 1998-2008. We added this explanation in the revised manuscript. Please see page 14, lines 1-2.

We agree that we need, to some extent, matching between our simulated vortex and observations. We checked the rainfall distribution for each of the 16 days and found that relatively intense rainfall on each day tends to be consistent with convergence around each Borneo vortex like Figs. 8, but no clear comma-shaped rainband is seen for these 16 days.

In fact, the Borneo vortices for the 16 days composited in the TRMM data record show different horizontal size, shape, and centre locations and the rainfall also has much spatial variance around the vortex centre. Conversely, our simulated vortex is one idealized case and has quite clear feature of a rainband. Nonetheless, some qualitative features such as that the relatively strong rainfall in the strong convergence zone northeast of the vortex centre is seen in both our simulation and the observations. We added these explanations in the revised manuscript. Please see pages 18-19, lines 20-3.

9. p.92 -93 meso-alpha cyclone, analogy with tropical cyclone

Warm core structure and maximum tangential wind in the lower troposphere are similar between the cyclone and a tropical cyclone (TC). In TCs deep convection (latent heat release) is maximized in the eyewall which is maintained by frictional convergence mechanism (Ooyama 1964; Yamasaki 1983). An eye is cloud free and warm by compensating subsidence. The cyclone in this paper was under cyclostrophic balance and warm anomalies were caused by convection which was more pronounced in the western part.

We appreciate the reviewer for the detailed explanation of the feedback in the TCs and suggestions on the mechanism of our simulated vortex.

As in our reply to the general comment above, our simulated vortex is different from the typical TC. Therefore, we emphasize the difference between our vortex and the typical TCs on page 20, lines 5-9 and page 28, lines 6-9.

The positive feedback between vertical motion (upward transport of moisture and low-level convergence that transport angular momentum to accelerate tangential wind) and deep moist convection (latent heat release) occurred close to the cyclone center (large contribution from the deep convection in the western part is expected). This may drive the growth of the cyclone (may appear in SELF term in the divergence equation).

As in our reply to the reviewer's comment #2, we added section 6.2 and investigated the relationship between the dynamics and thermodynamics close to the cyclone centre. We agree with the suggestion that the effect of the moist cumulus convection is hidden in the SELF term. We added more description on it. Please see page 26, lines 2-9.

The question is the role of the STRN term to the establishment of this feedback system.

As in our reply to the comment #2, we show the dynamics-thermodynamics relationship near the cyclone centre in Section 6.2.

However, these processes are not inherent at the formation stage, but subsequent, because the initiation of the Borneo vortex is caused primarily by the cold surge mechanically (as in our reply to the comment #3). The convection near the cyclone centre is organized by the low-level convergence itself after the meso-alpha cyclone forms. Our conclusion is that the STRN term is likely to be the seed for the whole system. We added more explanation about this point in the revised manuscript. Please see page 26, lines 6-9.

10. p.94 L.11-13

The effects of deep convection primarily appear in stretching term in the vorticity equation (Eq.1). Large contribution of stretching term in the western part of the cyclone (Fig. 12) is consistent with the low-level convergence (Figs. 13, 14a) and organization of deep convection (Figs. 10b, 11, 14d) there. It is recommended to state this fact in the manuscript.

We agree totally with reviewer's suggestion. The stretching term is located consistently with the intense upward motion and rainfall in the comma-head. As in our reply to the comment #2, we added the investigation of the dynamics-thermodynamics relation. Please see pages 23-24, line 11-6.

11. p.97 L. 1-2

The generation of deviatoric strain by the northeasterly surge and northwesterly crossing the equator (to the west of the cyclonic center; Fig. 14f) is not fully explained. Does the turning of zonal wind component enhance zonal convergence? The dynamics here seem to be quite different from those in the northeastern sector.

Yes, our previous explanation was not enough. In fact, the strong convergence in the northwestern sector around the cyclone centre is contributed mostly by zonal component which is shown in the new Fig. 16b. This strong convergence seems to be induced by drastic gap of zonal wind component between -200 and 0 km (zonal direction) in the northwestern sector (which is evidenced by the new Figs. 16a and 16d).

In the western (eastern) sector to -100km within the northwestern sector, the zonal wind component is almost zero or weakly easterly (strongly easterly). While the strong easterly can be mostly attributed to the cyclonic flow itself, the modest zonal wind component in the outer region (<-100km) seems to include the background cold surge that has wrapped around the vortex. That is, the strong convergence in the northwestern sector is also generated by the confluence of background cold surge and cyclonic flow. This confluence is responsible for the STRN term in the northwestern sector, and not surprisingly, the convergence zone of the zonal component is consistent roughly with the intense STRN term (the new Fig. 15). Therefore, we modified our explanation of the contribution of the STRN in the new section 6.3 and more detailed investigation on northwestern sector has been added in the new section 6.4. Please see page 26, lines 17-19 and page 27-28, lines 16-9.

This reply is related to comments and replies #1, #9, and #12.

12. p.97 L.25-p.98 L.2

Transport of rain cells that formed in the northeast sector to the northwest sector is not evidenced by the materials presented here. The distribution of horizontal divergence suggests that deep convection was also organized in the downstream parts of the comma-shaped rainband (i.e., low-level convergence in the western part of the cyclone). This description should be carefully reexamined.

We have removed references to such transport of rain cells. As in the last reply above, the intense rainfall in the northwestern sector around the cyclone centre is induced by low-level horizontal convergence after our further diagnostics in response to the reviewer's comments. Please see pages 28-30, lines 18-2.

13. p.98 L.22-27 (Fig. 15)

This is a very good approach to understand the convective organization. Figure 15 support the argument that the positive feedback between the rising motion (low-level convergence) and the deep convection (latent heat release) at the thermodynamical front was essential to the growth and maintenance of the rainband system. The effects of deep convection mainly appear in self

enhancement (SELF), pressure Laplacian (LAP), and vertical advection (VMOM) terms in the divergence equation (Eq. 2), of which SELF was dominant representing the positive feedback described above. The deviatoric strain (meridional confluence) may contribute to the formation of the frontal structure, but thermodynamical aspect seems to be most important here.

We agree with the reviewer's comment that thermodynamic aspect is important to cumulus convection and convergence along the confluence line, as thermodynamic indicators such CAPE, LCL and LNB show in new Figs. 17. We have mentioned this in the new paragraph in Section 6.4. Please see pages 27-28, lines 16-9. However, the SELF term, which is the main contributor to the maintenance of front, is expected to be the subsequent effect because it can work only if the primal convergence "seed" exists (done by STRN), as we also replied to the comment #9. While the contribution ratio of SELF to the maintenance is larger than that of STRN, we feel that STRN plays the dominant role in triggering frontogenesis.

Technical comments

1. p.80 L.12 "rainfall patches"

Please use meteorologically well-defined terms.

We replaced this word with "rainfall cells".

2. p.80 L.17 "deviatoric strain"

This term would be unfamiliar to many of readers. Substitution by explanatory description may increase readability. "deformation less the effect of the horizontal divergence" (p. 95, L21; Appendix B) is difficult to understand.

While we appreciate that some reader may be unfamiliar with "deviatoric strain", the concept of deviatoric components of stress and strain tensors is quite elementary in continuum mechanics and is introduced in a standard text like (Allan. F. Bower, Applied Mechanics of Solids).

3. p.80 L.26

Fig. 2g is cited before Fig. 1.

We moved Fig. 2g to Fig. 1a.

4. p.81 L.1

monsoon -> monsoonal flow?

Corrected.

5. p.87 L.22-24.

This description is difficult to follow.

We improved explanation on rainfall over the Java Sea with new figures (new Fig.6), following the other reviewer's comment. Please see page 12, lines 6-18 and the new Fig.6.

**6. p. 90 L.22
Figure 10 -> Figure 8l?**

Yes. This was a typographical error. Corrected.

**7. p.93 L.5
“cloud cluster can be categorized as the anvils”
“cloud cluster” is a category of convective system, whereas “anvil” is a category of cloud type, and these do not match.**

We appreciate your correction. Corrected.

**8. p. 93 L.8 “not unlike”
Please write in a straight manner.**

Corrected.

**9. p.94 L.5
Figure 10l -> Figure 8l?**

Yes, this was a typographical error. Corrected.

**10. p.96 L.5
It is recommended to state that positive (negative) values in these terms indicate acceleration of divergence (convergence), which at 850 hPa roughly means downward (upward) motion in the free atmosphere.**

We appreciate your recommendation. We added a statement. Please see page 25, lines 6-8.

**11. p.97 L.9-10
and but -> but?**

Yes, corrected.

12. p.98 L.28-29 This sentence is difficult to understand.

We have removed this sentence.

13. p.99 L.26

southwesterly cyclonic wind → southeasterly? (inconsistent with the description in abstract)

Corrected.

Figures

1. Fig. 2

It is recommended to indicate the area of CS Index (described in the caption of Fig1).

Following the reviewer technical comment #3, we moved the old Fig. 2g to the new Fig. 1a and indication of CS Index has been added in the new Fig. 1a.

2. Fig. 3

The former (d) in the captions of contour intervals will be (c).

This is a typographical error. The contour intervals of (c) were wrong. Corrected now.

3. Fig. 5

It is recommended to indicate the area of average in Fig. 4.

The indicating boxes have been added in the new Fig. 4a.

4. Fig. 6 caption

Marine the Borneo vortex → the Marine Borneo vortex?

Yes, corrected.

5. Fig. 13 caption

(c)-(h) are not properly captioned.

Corrected.

6. Fig. 15 caption
the confluence line in Fig. 14e -> the confluence line (zero meridional lines in Fig.14e)?

Yes, corrected.

7. Fig. 16
It is recommended to indicate the domain of Fig. 16 in Fig. 14d.

We added a black box in the new Fig. 16d for the explanation.