nature portfolio

Peer Review File

Single-Chip Silicon Photonic Engine for Analog Optical and Microwave Signals Processing

Corresponding Author: Dr Hong Deng

This manuscript has been previously reviewed at another journal. This document only contains information relating to versions considered at Nature Communications.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The paper reports a single chip microwave photonic signal processor in silicon on insulator that contains all key compoonents, from laser, modulator, signal processor, switch, and photodetector, In my views this step alone is a significant demonstration in the field. Moreover, the authors demonstrate multifunctionality of this processor.

While this demonstration is important, the authors did not fully discuss the performance of the system. I noticed that this issue has been raised as well in previous reviews. For example, the authors added Table 1 to compare integration and performance of the system. But the table can be very misleading. Termed as recent demonstrations of integrated MWP systems, the table only includes certain tecnologies and completely left out other prominently used technology such as silicon nitride. I suggest to update the table to reflect more fair comparison.

One drawback of the approach presented here is the low performance when it comes to filter spectral resolution and the Rf metric such as noise figure due to the inherent limmitation of silicon photonics. Discussion of this topic is a bit hidden in the supplemetary material, but I think this is very important and should be moved to the main text.

If these issues are properly addressed and discussed, I believe that the manuscript merit a publication in Nature Communications.

Reviewer #3

(Remarks to the Author)
See attached

Version 2:

Reviewer comments:

Reviewer #3

(Remarks to the Author)
All comments have been thoroughly addressed, and I recommend the paper for publication.

Reviewer #1 Review
Remarks to the Author:
The authors have addressed the comments and critiques from my previous review. I also read the comments from the other two reviewers. We all share the same concern regarding the limited novelty of the work, although developing the reported integrated device is undoubtedly a challenging task.

1. Regarding the similarities with [6], the authors note that the filter architecture contains more tunable elements, and its integration with the configurable modulator allows for dual sideband processing. While this is true, I believe this point should be considered incremental, as it does not represent a significant difference.

The tunable elements not only ensure a large degree of freedom on our chip's operation, but also help to improve the performance of every single component, like the pure phase modulation with the used PN junction modulator. With this system, we showed several demonstrators, and we can imagine that many more applications can be implemented. This flexibility is not what can be done in [6], and this is what we put more efforts on during the chip design.
We also think that the dual sideband scheme can have significant benefits for future system flexibility (apart from not throwing away 50% of the modulated light right from the start).

2. With regard to the high (Note: not "low") noise figure (53.5 dB), the authors explained that it is due to the low power of the on-chip laser and the low modulation efficiency of the modulator. I agree that these are common factors affecting the NF performance of microwave photonic systems. However, I would expect the authors to propose potential remedies, particularly for the integrated solutions, to improve the NF performance.

To intrinsically improve the NF, we can add extra SOA with higher saturation power to boost the laser power in our system. While, higher optical may introduce nonlinearities in the used silicon waveguides, like two photon absorption. However, higher optical power may introduce nonlinearities in the silicon waveguides, such as two-photon absorption. Using wider silicon waveguides or SiN waveguides (now available in some silicon photonic platforms) can help mitigate the optical power limitations. Alternatively, we can employ a longer modulator or a dual-drive modulator to achieve higher modulation efficiency.
More discussion is added in our manuscript.

Other than the about two points, I am satisfied with the responses from the authors.

Reviewer #2 (Remarks to the Author):

The authors have responded to my review without any revision to the work. The authors only argue their points without any attempt to base them on scientific arguments. This makes it difficult to suggest anything more than what I already mentioned in my previous review. But nonetheless, I will try to continue this discussion:

We are sorry that the revised paper was not delivered. The manuscript was rejected after the first round of review. In response, we submitted a rebuttal email to the editorial team, which led to the opportunity for a second round. However, the rebuttal email was forwarded without the revised manuscript attached. While we submitted the updated manuscript subsequently, it appears that it was not delivered on time.

In their response, the author mentioned that the main novelty of their work is creating a flexible microwave photonics engine that can perform multiple functions by being reprogrammed. This is a very weak claim of novelty in the field. Here's a list of work that has exactly the same claim:

Refs 1, 3, 7, 14, 17 of the main text, https://doi.org/10.1364/OPTICA.2.000854, https://doi.org/10.1002/lpor.201800240, https://doi.org/10.1364/PRJ.476466 and some more works that should have been included in this manuscript. When programmability is combined with very high level of integration, as demonstrated in this work, indeed it is novel. But this is precisely my point, choosing this particular embodiment reported in this work, leads to poor performance.

The core novelty of our work lies in its high tuning flexibility and advanced level of integration. While this level of integration inevitably compromises certain performance metrics, such as the NF and operational bandwidth, it enables unique capabilities. In the main text, we also compare the performance of our system with previously published integrated photonic works.

When the author argue that their device performance is better compared to previously reported works, I didn't see this scientific comparison being included in the revised manuscript, so this remains a baseless argument.

Our integrated silicon photonic system includes on-chip lasers, modulators, filters, and photodetectors (PDs), thus we compare the results with those from other integrated components, as discussed in the main text. It is important to note that we can also leverage external active components, such as lasers, modulators, or PDs, to achieve improved performance. The microwave photonic link performance, including operational bandwidth, link loss, and noise figure, is primarily limited by these active components.

When answering point 2 of my review, again the authors give argument without any scientific background. The RF bandwidth of 26 GHz is relatively low when considering all the efforts of creating the RF photonics system, because this is simply can be achieve in integrated RF circuits (for example this 15-55 GHz phased array beamformer https://doi.org/10.1109/TMTT.2024.3421642)
The author did not scientifically address the other points I raised regarding performance, including the noise figure, system loss, and the spectral resolution.

There was a comment regarding the impact of research in MWP for 100 GHz and beyond, and I agree that creating solution for these high frequencies is one of the key opportunity for impactful MWP works. But even below 100 GHz, there's a wide range of frequencies between 26 GHz and

100 GHz, that can be used to show real impact of microwave photonics solutions.

With the advancement of integrated RF circuits, higher-frequency signals have become more accessible than before. In our case, the bandwidth of our microwave photonic (MWP) link is still limited by the traveling-wave Mach-Zehnder modulator and our basic packaging approach. Transitioning to high-bandwidth integrated photonic platforms, such as LNOI or BTO, could achieve higher modulation bandwidths, but the integration of other active components becomes more challenging.

On the other hand, photonic systems not only benefit from potentially higher operational bandwidths but also offer greater flexibility and lower optical transmission losses (especially when combined with fiber), compared to RF cables or radiation. In, we demonstrated an OEO (optical-electrical-optical) use case based on our photonic chip, showing a phase noise performance superior to that of commercial RF signal generators.

Reviewer #3 (Remarks to the Author):

Remarks to the Author:
After reviewing the authors' response to the previous comments, I appreciate the effort that went into revising the manuscript. However, I find that many of the concerns raised in the initial review have not been adequately addressed, which lead me to still not recommend the manuscript for publication in Nature Photonics.

Several of the responses, particularly around technical implementation and performance, are insufficiently detailed. For example, while the authors note the flexibility of their chip and the range of its potential applications, the discussion lacks concrete examples and quantitative analysis to substantiate these claims.

The flexibility and potential application of the proposed sample is ensured by its integrated functional blocks and a large amount of optical switches. The detailed performance and quantitative metrics of all functional blocks results, individually tested and packaged tested, are elaborated in the supplementary information. Most potential applications' performance can be estimated with the provided results. In the manuscript, we demonstrated an optical filter system, an RF filter system, and an OEO system, with all the detailed performances.

The comparison with previous works (such as [6]) still does not clearly differentiate the significance of this manuscript. Although some performance metrics are improved, the core novelty is still not convincingly justified, especially in light of the overlap with prior studies.

The comparison with previous works aims to demonstrate that the performance metrics we achieved are, at the very least, respectable—especially considering that most previous works were specifically designed for dedicated applications. The core novelty of this work lies in its hybrid integration and high tuning flexibility. While the level of integration inevitably compromises some performance metrics, such as the NF and bandwidth, we still achieve performance that is comparable to those prior efforts, even with these trade-offs.

While the authors promise to add more details, the current presentation of figures, such as the filtering configurations in Figure 2, remains confusing and lacks sufficient distinction between the different plots. The authors' explanation about the Fano resonance and Lorentzian bandpass filter does not translate clearly in the figures provided. This weakens the overall clarity of the manuscript. The system-level analysis, particularly the discussion on crosstalk and the noise figure, is still vague and lacks sufficient data to support the conclusions. The issues related to the high noise figure (53.5 dB) remain inadequately addressed

The Fano resonance and Lorentzian bandpass filtering shape is a description in principle. Figure 2 has been updated in the revised paper, and the asymmetric Fano resonance shape can be easily identified.

The measured RF crosstalk is shown in the support information, which is about -60 dB. A more detailed discussion about the NF has been added to the discussion.

Several technical aspects raised in the previous review were acknowledged by the authors but have not been fully corrected or explained in the response. For instance, the justification regarding the short loop length and phase noise lacks supporting experimental data to demonstrate why longer fibers would lead to multi-mode oscillations.

We conducted several tests with longer fiber links. For instance, a 2 km fiber was used in combination with an external PD, and the resulting RF signal spectra are shown in the Figure (b) below. It can be observed that the sidelobe extinction ratio is only 8 dB (compared to 32 dB with a 500m fiber, shown in Figure (a)), indicating that stable single-mode oscillation was not achieved. Additional details regarding the multi-mode oscillations are provided in the supplementary information

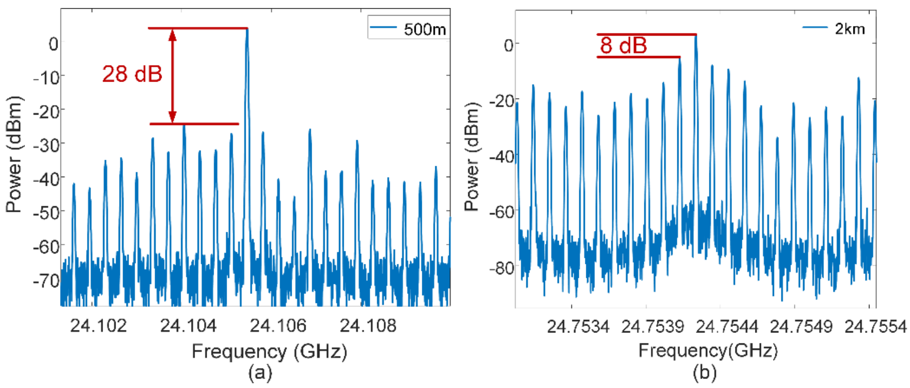

Figure (a) RF signal generated OEO system with 500m fiber, (a) RF signal generated OEO system with 22km fiber.

The manuscript emphasizes the novelty of the "single-chip" integration and flexibility, but this claim is undermined by the significant reliance on external components, such as the EDFA and photodetector. The extent to which the work represents a true single-chip solution remains questionable. Furthermore, the use of dual-sideband modulation, while presented as novel, does not stand out as a significant advancement, particularly given the current landscape of microwave photonics research. The lack of clear application scenarios and insufficient innovation in system performance further weakens the impact of the manuscript.

To clarify, the integration and flexibility of the system do not depend on external components. The presented chip can be configured and calibrated without requiring any external optical components. However, the absence of a TIA necessitates the use of an external EDFA to effectively demonstrate certain RF applications. Additionally, the external PD is employed to showcase the chip's potential performance if paired with a high-quality TIA. The dual-sideband modulation is utilized to map RF filter synthesis to established filter design algorithms. Unlike previous SSB-based microwave photonic filters, our approach introduces a simplified system with a more mature synthesis process. In addition, it reduces the overall system loss by not discarding 50% of the optical power immediately after modulation.

Reviewer #2 (Remarks to the Author):

The paper reports a single chip microwave photonic signal processor in silicon on insulator that contains all key components, from laser, modulator, signal processor, switch, and photodetector, In my views this step alone is a significant demonstration in the field. Moreover, the authors demonstrate multifunctionality of this processor.

The author thanks the reviewer for acknowledging our effort in the full integration of the system work.

While this demonstration is important, the authors did not fully discuss the performance of the system. I noticed that this issue has been raised as well in previous reviews. For example, the authors added Table 1 to compare integration and performance of the system. But the table can be very misleading. Termed as recent demonstrations of integrated MWP systems, the table only includes certain technologies and completely left out other prominently used technology such as silicon nitride. I suggest to update the table to reflect more fair comparison.

We sincerely thank the reviewer for their feedback and for reiterating this critical point about the completeness of Table T1. We agree that a fair and comprehensive comparison of MWP systems is essential, while many SiN-based demonstrations focus on fully passive components. In the revised manuscript, we have updated Table T1 to include SiN platforms its hybrid integration system, such as [DOI: 10.1109/JLT.2021.3089881, and 10.1088/2633-4356/ac168c] (see updated Table T1).

One drawback of the approach presented here is the low performance when it comes to filter spectral resolution and the Rf metric such as noise figure due to the inherent limitation of silicon photonics. Discussion of this topic is a bit hidden in the supplementary material, but I think this is very important and should be moved to the main text.

Indeed this part of discussion is very important for microwave photonic links. We moved this part from the supplementary material to the discussion part of the main text Page 11.

If these issues are properly addressed and discussed, I believe that the manuscript merit a publication in Nature Communications.

Reviewer #3 (Remarks to the Author):

The manuscript titled “Single-Chip Silicon Photonic Engine for Analog Optical and Microwave Signals Processing” demonstrates an integrated photonic system that combines lasers, modulators, photodetectors, and optical filters into a single chip. The authors claim programmability, flexibility, and novel dual-sideband modulation schemes as the main contributions. While the integration is a commendable achievement, the manuscript presents shortcomings in terms of novelty, performance justification, and reliance on external components.

Below are specific comments for the authors to improve their manuscript:

The authors thank the reviewer’s effort.

1. The authors position their chip as a “single-chip” solution, but the demonstrations depend heavily on external components, including EDFAs and off-chip photodetectors. The authors should reduce the dependence on external components or justify their necessity.

The proposed chip integrates most of the necessary components in a typical optical system. However, due to the lack of available transimpedance amplifiers (TIAs), the on-chip photodetectors (PDs) cannot be properly read out. This is the reason we incorporated EDFAs to enable the use of on-chip PDs or added external PDs to evaluate the performance of other components in the system. If a TIA were available, these external components would not be required. A clarification has been added to the revised manuscript to address this point.
This clarification is added to the revised manuscript Page 13.

2. The authors claim programmability and dual-sideband modulation as the core contributions. However, similar capabilities have been reported extensively in prior works (e.g., Ref. [6]: Fandiño, J., Muñoz, P., Doménech, D. et al. A monolithic

integrated photonic microwave filter. Nature Photon 11, 124–129 (2017). https://doi.org/10.1038/nphoton.2016.233), using dual-drive MZM in InGaAsP/InP. To strengthen the manuscript, the authors should clearly articulate the advantages of their method over existing approaches, providing a comprehensive comparison of performance metrics beyond the integration level.

The work in Ref. [6] indeed shares similarities with our optical engine in terms of microwave photonic filtering functionality and integration level. However, there are several key distinctions that underscore the unique advantages of our approach. Ref. [6] is implemented in the InGaAsP/InP platform, which intrinsically provides optical gain, whereas our work is based on the SOI platform, and it offers significantly lower fabrication costs and higher production yields at volume scales. To address the absence of optical gain, we employed micro-transfer-printing technology to integrate a III-V SOA on our chip, enabling comparable functionality while leveraging the benefits of SOI.

Beyond these platform-level differences, our optical engine demonstrates several additional advantages:

- **Programmability**: Thanks to the inclusion of tunable optical couplers, our system offers functionalities that extend far beyond microwave photonic filtering. Light can be guided in and out from every junction of our optical engine, enabling advanced functionalities such as tunable lasing and optical filtering. Furthermore, if higher performance is required, external devices can be used in place of on-chip components, offering enhanced results. This level of flexibility and programmability has not been achieved in previously reported works.
- **Dual-Sideband Modulation Scheme**: While Ref. [6] and similar works rely on a single-sideband (SSB) modulation scheme to achieve arbitrary microwave filtering shapes—requiring an SSB modulator and a complex optical filter—our approach utilizes a cascaded all-pass filter design (implemented with all-pass ring filters) to achieve the same functionality with greater simplicity and efficiency.
- **Performance Metrics**: Our chip demonstrates superior performance across multiple metrics compared to Ref. [6]. Specifically, our design achieves a higher

off-chip laser power (-3.5 dBm vs. -8 dBm in Ref. [6]), a broader modulation bandwidth (26 GHz vs. 6 GHz), a larger optical filter free spectral range (FSR) (107 GHz vs. 20 GHz), a narrower filter bandwidth (4 GHz vs. 6 GHz), more efficient thermal phase shifters (28 mW/π vs. 43 mW/π), and improved RF packaging (crosstalk floor up to 25 GHz vs. <1 GHz in Ref. [6]). Additionally, our design benefits from a more advanced photonic architecture, resulting in a smaller footprint (5 × 1.5 mm vs. 6 × 4 mm in Ref. [6]) and lower cost (SOI with transfer-printed SOA vs. full InP).

We have added more detailed information regarding these comparisons and advantages in the revised manuscript Page 10 , 11, and 12.

3. It is acknowledged that the devices' performance degrades in the system compared with their single unit, and I believe the authors have made considerable efforts to mitigate this issue. For instance, on page 9, the authors mentioned that "With this system, RF signals can be generated with a frequency tunable from 4 GHz to 24 GHz and −116 dBc/Hz phase noise at 100 kHz offset frequency, shown in Fig. 6c. And with the on-chip PD, the generated signal can be tuned from 3.3 GHz to 11.6 GHz with −84 dBc/Hz phase noise at 100 kHz offset frequency, shown in Fig. 6d." To clarify, the authors should provide a detailed explanation of the factors contributing to the observed system performance degradation and suggest practical methods to improve the overall performance of the integrated system, such as better RF isolation, reduced thermal crosstalk through optimized phase shifter designs, improved packaging, or higher-efficiency on-chip photodetectors.

We sincerely thank the reviewer for acknowledging our efforts in the migration process. The performance degradation observed in the demonstrations is primarily attributed to two factors: the readout system and RF crosstalk. As noted in the PDK manual, the on-chip PD exhibits an efficiency of 0.6 A/W with a bandwidth exceeding 50 GHz, which is nearly identical to that of the off-chip PD. Since the entire system, apart from the PD, remains consistent across all demonstrations (including the optoelectronic oscillator

(OEO) and others), the performance differences are largely due to the readout system (PD related) and RF crosstalk (space related).

Regarding the readout system, the absence of a proper TIA necessitated direct wirebonding of the on-chip PD to the PCB, followed by signal amplification through an electrical amplifier after approximately half a meter of coaxial cable. The PD's impedance is not optimized for 50-ohm matching, and the lengthy connection introduces significant RF signal reflection and loss, severely degrading the signal integrity.

Additionally, the compact size of the chip works against us, exacerbating the RF crosstalk. While we achieved a high RF isolation of -60 dB (exceeding the -30 dB requirement specified in SFP standards), crosstalk remains a challenge. Combined with the high RF loss in the readout system, the signal-to-noise ratio (SNR) of the on-chip PD is limited, which impacts the performance of all demonstrations.

To address these issues, the most effective solution would be the integration of a proper TIA near the output of the on-chip PD. This could be achieved through monolithic integration, micro-transfer-printing, or SMD assembly with wirebonding. A TIA would enable proper RF signal readout from the PD and significantly improve the SNR. Furthermore, RF wirebonding could be employed to reduce crosstalk by minimizing radiation.

We have added a detailed discussion of these challenges and potential solutions to the main text in Page 14.

4. The authors employed tunable lasers based on micro-transfer-printing technology to realize on-chip lasers, which is a notable aspect of the integration in this work. However, the manuscript does not provide sufficient details regarding the performance of these lasers. Additionally, the authors should discuss how the performance of these on-chip lasers impacts the overall system performance.

The novelty of this work is in the integration of the components into a circuit and system, and the demonstration of that functionality. For this, we rely on a transfer-printed laser process developed in our group, and for which the first results have already been reported in [doi:10.1364/OE.505112].

As this paper does not focus on the tunable laser, we included the detailed information about the laser design, lasing conditions, output power, tuning range, and phase noise in the Supplementary Information rather than the main text. This decision was made to maintain the manuscript's focus on the core contributions of the work.

For optical signal filtering and detection, the performance of the on-chip laser does not significantly impact the results. However, for microwave photonic applications, the on-chip laser performance plays a critical role in determining system performance. Specifically:

- Optical Power: The on-chip laser power directly influences the RF gain of the system, particularly in the absence of additional optical amplification. Higher laser power enhances the overall system gain, which is essential for achieving optimal performance in microwave photonic applications.
- Phase Noise: The phase noise of the on-chip laser contributes to the accumulated phase noise of the signal within the system. Minimizing laser phase noise is therefore crucial for maintaining high signal integrity and system performance.

This information is added to the revised manuscript Page 13

5. On Page 11, The authors use dual-sideband modulation, claiming reduced system loss and simplified filter design. However, the discussion does not adequately explain why this technique was chosen over traditional single-sideband modulation. It is better to provide a simplified explanation of the advantages of dual-sideband modulation, supported by quantitative comparisons.

The commonly used SSB modulation scheme for arbitrary RF filtering requires filtering out one sideband of the RF-modulated signal, throwing away half of the modulated signal. Even in an ideal case this results in an intrinsic 3 dB RF loss. Also, the SSB scheme maps an arbitrary optical filter into the RF domain, which typically necessitates a ring-loaded Mach-Zehnder interferometer (MZI).

In contrast, our chip is based on a double-sideband modulation scheme, keeping all the modulated RF power, as it eliminates the need for an additional optical filter for SSB suppression, saving at least 3 dB in both optical and RF power. In addition, we can perform arbitrary RF filtering only cascaded all-pass filters. In our demonstrations, we used two cascaded ring filters to achieve the RF filtering shapes shown in Fig.4 . The cascaded ring filter and its tuning process are also significantly simpler than the ring-loaded MZI used in other works.

This information is added in the revised paper in Page 12.

6. On Page 13, the authors briefly mention the power consumption of the system; however, the details provided are insufficient for a comprehensive evaluation. More details could be provided.

Our system contains two lasers, one modulator, and around 52 phase shifters (each tunable coupler contains two phase shifter). To fully operate the system, we will need to drive one laser, the modulator, and 23 phase shifters, including 17 tunable couplers (only one arm driven is needed for each tunable coupler), and 6 phase shifters for offset phases. The transfer-printed laser unit consumes about 300mW of electrical power, and the 23 thermal phase shifters would cost around 812 mW at the worst case, (thermal efficiency of 28 mW/pi. Altogether, the photonic engine would demand roughly 1112 mW maximumly.

This information is updated in revised manuscript Page 13.

7. On Page 13, the discussion on optical, RF, and thermal crosstalk is qualitative and lacks quantitative metrics. For instance, the reported thermal drift and optical reflections are briefly acknowledged without detailed analysis.

The optical crosstalk would mainly because of the leaked light from the tunable couplers. As can be seen in Fig.S3.7, our tunable couplers can reach a 40dB extinction ratio, corresponding to a 0.01% optical crosstalk.

The RF crosstalk from RF input to RF output is shown in Fig. S2.3. It shows that the RF crosstalk (measured between the input connector and the output connector) is around -60dB.

The thermal crosstalk of the phase shifters is around 5.4%. The generated heat spreads over the surrounding waveguides, inducing a phase shift. This can be extracted from the Ring's tuning response, as shown in Fig.S3.14. When applying an additional 2pi phase shift to one arm of the tunable coupler (i.e. getting the same coupling ratio) this consumes 55.6mW extra. At that point the ring phase shifter needs an extra 3mW to maintain its resonant wavelength (i.e. 5.4% of 55.6mW).

The thermal crosstalk from the on-chip laser has not been fully characterized in our tests. Since the laser remains constantly powered on, all tuning operations are performed in the presence of the laser's heat source.

The optical reflection is mainly due to the used grating coupler. The transmission of the grating coupler pair is also shown in Fig. S2.3. We can roughly fit the spectrum with a FP cavity response, and estimate the reflection of the grating coupler as 1.6%. Other components like directional couplers and waveguides can only introduce back scattering.

It should be noted that the temperature dynamics and optical reflections are challenging to measure precisely, as they vary due to fabrication non-uniformities and imperfections. Our sample, with complete thermal, optical, and electrical packaging, demonstrates high repeatability. Thanks to the thermal tuners integrated into the optical system, we can effectively compensate for thermal drifts and optical reflections, ensuring consistent and reliable results.

This discussion is added to the revised manuscript Page 13 and 14.

REVIEWER COMMENTS

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