

The Revised UNICON Configuration & The Responses to the Review Panel's Comments

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1. The differences between the NEW (revised) and OLD (original) UNICON configurations

In terms of physical formulation, there is no difference between the NEW and OLD UNICON configurations, except that (1) a couple of tunable parameters are adjusted within allowable ranges within UNICON, (2) instead of the original forward difference, a more accurate centered difference method is used in computing the production (evaporation) rate of convective precipitation within convective updraft (downdraft), and (3) a new cloud fraction generated from detrained convective condensate is added within the cloud macrophysics scheme.

A tuning exercise with the centered difference method was motivated by the fact that in contrast to the 1-deg simulation that was submitted to the review panel, the 2-deg UNICON simulation (with which I have done bunch of tuning exercises in order to save computation resources) produced a good ENSO, as was shown in the last AMWG meeting. When I increased the resolution from 2-deg to 1-deg to prepare simulations for the review panel, I tuned a few UNICON parameters additionally, in order to improve some minor aspects of cloud radiative forcing and precipitation, which resulted in unexpected degradation of ENSO in the 1-deg coupled simulation. Since UNICON is developed as a scale-adaptive scheme, however, I should not have done any additional tuning of UNICON parameters when the resolution changed. In this NEW 1-deg UNICON simulation being submitted to the review panel, most of the UNICON parameters are restored to those of the OLD 2-deg configuration that produced a good ENSO. As will be seen, this NEW 1-deg UNICON produces a desirable ENSO, implying that UNICON is scale-adaptive in terms of ENSO-related coupled variability.

The review panel also pointed out that the OLD UNICON simulates too small cloud fraction in the convective regime. I myself also recognized this problem when the OLD UNICON simulation was submitted to the review panel a half year ago. I speculated that this problem happened because UNICON did not compute cloud fraction generated by detrained convective condensate. In the OLD UNICON, I tried

to address this issue by decreasing critical relative humidity in proportion to the amount of detrained convective condensate by assuming that detrained convective condensate is homogeneously mixed with environmental air. However, this was not a realistic assumption, since in nature, detrained convective condensate is not subject to instantaneous homogeneous mixing with environmental air, but instead, holds its isolated identity for a while. This unreasonable approach in the OLD UNICON resulted in near complete evaporation of detrained convective condensate without producing enough cloud fraction. This failure was inevitable because the mean relative humidity in the cumulus regime is very low due to compensating subsidence, so that reducing critical relative humidity by convective detrainment was not enough to generate additional cloud fraction. In the NEW UNICON, instead of decreasing critical relative humidity, I directly computed an additional cloud fraction generated by detrained convective condensate (A_{det}), following the review panel's comment and previous studies (e.g., Teixeira 2001, *Monthly Weather Review*, 1750-1753, Volume 129):

$$A_{det} = (1 - A_{st} - A_{cu}) \cdot \left[\frac{M_{det} \cdot (q_{l,det} + q_{i,det})}{M_{det} \cdot (q_{l,det} + q_{i,det}) + c_{ero} \cdot (q_s - \tilde{q}_v) \cdot (\Delta p / g)} \right]$$

where A_{st} is stratus fraction that is a function of environmental relative humidity computed by a separate stratus macrophysics scheme; A_{cu} is cumulus fraction that is a function of cumulus mass flux and vertical velocity computed within UNICON; M_{det} is detrained convective mass flux; $(q_{l,det}, q_{i,det})$ are the liquid and ice mass of detrained convective condensate, respectively; q_s is saturation specific humidity; \tilde{q}_v is environmental relative humidity; and Δp is the layer thickness. Here, c_{ero} is a tunable erosion coefficient (the parameter '**coef_ero**' in **cldwat2m_macro.F90**) and following the previous studies, it is set to $c_{ero} = 1 \cdot 10^{-6} [s^{-1}]$. This formula is obtained by assuming an approximate balance between the production of cloud by convective detrainment and the dissipation of cloud by the mixing between detrained convective condensate and environmental air. The resulting net cloud fraction A_{tot} in each layer is $A_{tot} = A_{st} + A_{cu} + A_{det}$. This approach guarantees that A_{det} is not empty and $0 \leq A_{tot} \leq 1$. In order to prevent instantaneous mixing between detrained convective condensate and environmental air, I also set `cu_det_st = .true.` in the stratus macrophysics scheme (i.e., **macrop_driver.F90**). This new physics is added into **cldwat2m_macro.F90**. As will be seen, this process in the NEW UNICON successfully addresses the issue of too small cloud fraction in the convection region. I really appreciate the review panel's comments on this.

2. Responses to the *Two Major Comments* from the Review Panel

- ‘.....UNICON inflates the amplitude of ENSO cycle resulting in overly deterministic variation, a strong 3-year periodicity and excessive autocorrelation persistence. Make the highest priority the improvement of ENSO and the fully coupled simulation.....’

Below shows the ENSO power spectrum (Fig.1) and the interannual variance of NINO3.4 SST (Fig.2) from the observation, a large-ensemble CESM1, and the NEW and OLD UNICON simulations at 1-deg resolution. It is clear that in contrast to the OLD UNICON, *the NEW UNICON simulates reasonable ENSO*.

This drastic improvement of UNICON-simulated ENSO simply comes from the tuning that makes the convection strength in the NEW UNICON weaker than in the OLD UNICON, since the adaptation of the 2-deg UNICON parameters (which produced a good ENSO) in this 1-deg NEW UNICON simulation is virtually equivalent to making the convection strength weaker. In some senses, this is consistent with our conventional knowledge that as convective momentum transport decreases, ENSO becomes weaker. In principle, we need to use a longer analysis period for this kind of analysis, since the ENSO power spectrum may be sensitive to the analysis period. Not shown, however, the same analysis using 100-yr of coupled simulations showed similar robust improvement of ENSO in the NEW UNICON (please see the submitted simulation results on the web).

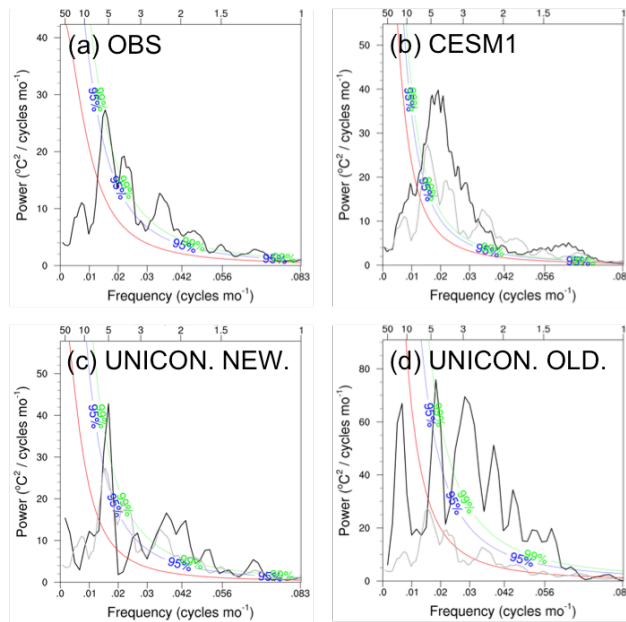


Figure 1. Power spectrum of NINO34 SST associated with ENSO. In panels (b)-(d), the gray lines are the identical observation from the panel (a). For the CESM1, 200-yr of coupled simulations are used while for the UNICON simulations, 50-yr are used.

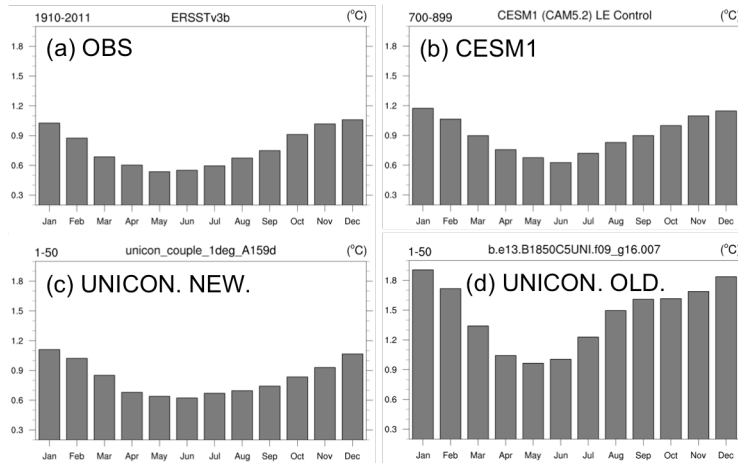


Figure 2. Interannual standard deviation of NINO34 SST for each month. The years used for the plot are denoted at the top of each panel.

- ‘.....make explicit plan regarding how to scientifically and infrastructurally combine the two schemes.....’

In the last AMWG meeting, I provided ‘*scientific*’ reason why UNICON cannot be combined with the other candidate scheme, so called, CLUBB: ‘*double counting*’. Fundamentally, UNICON is designed to simulate subgrid vertical transport by ‘*nonlocal asymmetric*’ turbulent eddies’ in the entire atmospheric layer. At the same time, the moist PBL scheme in the current CAM5 is designed to simulate subgrid vertical transport by ‘*local symmetric*’ turbulent eddies’ in the entire atmospheric layer. Thus, a combined use of UNICON and CAM5 moist PBL scheme is scientifically correct, preventing double counting.

To my understanding, however, CLUBB is designed to simulate both ‘local’ and ‘nonlocal’ turbulent transport in the entire atmospheric layer. Thus, CLUBB in itself is sufficient, and it should *not* be used in conjunction with any other convection schemes, since all the existing convection schemes – not only UNICON but also CAM5 shallow and deep convection schemes – are designed to parameterize subgrid ‘nonlocal’ transport. If CLUBB is used with UNICON or any other convection schemes, it inevitably induces a problem of double counting. In the next decade, GCM will be required to run at much higher resolution, and at that stage, this issue of ‘*double counting*’ will become even more important than now. I think that whenever possible, we should be faithful to the fundamental physical principle, rather than being driven by other practical reasons. If not, our GCM will quickly reach to the near saturation stage, at which we cannot expect any more meaningful progress regardless of how good schemes will be added.

3. Responses to the other Review Panel's Comments

- *'.....the model is very complicated: investigates multi-dimensional sensitivities in the context of climate sensitivities and SCM comparison, with a goal of simplifying the model.....'*

I admit that UNICON looks very complicated. Part of the reason is that UNICON is a *process-based* model (not *equilibrium-based* model which often overly simplifies the real phenomena with a very few non-realistic parameters), designed to simulate the observed convection as it is with a full inter-process consistency. Consequently, UNICON has detailed treatment of many new physical processes that have been neglected in the existing equilibrium-based convection schemes, such as the vertical tilting of cumulus updraft, treatment of various convective downdrafts, subgrid cold-pool and meso-scale organized flow, and its feedback on convective updraft – all of which have been speculated to be essential to simulate various atmospheric variabilities associated with convection (e.g., the diurnal cycle of precipitation and MJO). I tried my best to make UNICON simple, as long as it does not break the inter-process consistency between many new core physics.

When I wrote a pair of UNICON papers, I investigated multi-parameter sensitivities in the context of SCM through ensemble simulations. Although it was not possible to describe all of those parameter sensitivity simulations in the paper due to the limitation of page numbers, a set of UNICON parameter values used by the NEW UNICON for the review panel is carefully obtained through these multi-parameter sensitivity simulations. Investigating multi-dimensional sensitivities in the context of climate sensitivity is an important research subject. However, this requires extensive computational resources and times, since a series of Slab Ocean Model (SOM) and coupled simulations needs to be run. While it was not possible to thoroughly investigate this sensitivity within the given time frame, I have a plan to explore this climate sensitivity with other collaborators, hoping that it will be helpful to constrain several tunable model parameters within UNICON.

- *'.....a reduction in cloud amount and further aggravation of the too few, and too bright problem.....'*

Figure 3 shows CLDLow (low-level cloud fraction) from the NEW and OLD UNICON and the biases of SWCF (shortwave cloud radiative forcing) and LWCF (longwave cloud radiative forcing) against the observations. Thanks to the additional cloud fraction generated by detrained convection condensate (A_{det} as explained above), the NEW UNICON produces more CLDLow than the OLD UNICON, particularly in the stratocumulus and trade cumulus region. This results in the improvement of SWCF and LWCF in the NEW UNICON (the rmse of SWCF/LWCF against the observations are 8.3/6.4 Wm^{-2} in the NEW UNICON, while 10.3/7.1 Wm^{-2} in the OLD UNICON, about 20/10 % reduction from the

OLD to the NEW UNICON). If necessary, CLDLow can be further enhanced by decreasing a tunable erosion coefficient, c_{ero} from its default value of $1 \cdot 10^{-6} [s^{-1}]$. This addresses the concern regarding too small cloud fraction pointed by the review panel.

In the tropical continents, the NEW UNICON still simulates too strong SWCF/LWCF. This bias can be fixed by reducing aerosol concentration detrained from convective updraft in the upper troposphere (note that aerosols serve as ice nuclei for ice stratus in the upper troposphere), either by increasing the auto-conversion efficiency of updraft condensate into convective precipitation or by increasing wet scavenging coefficient of aerosols within convective updraft. Unfortunately, I did not have enough time to pursue this micro tuning. Ideally, this micro tuning should be performed in conjunction with a new ice nucleation routine before the formal release, if any.

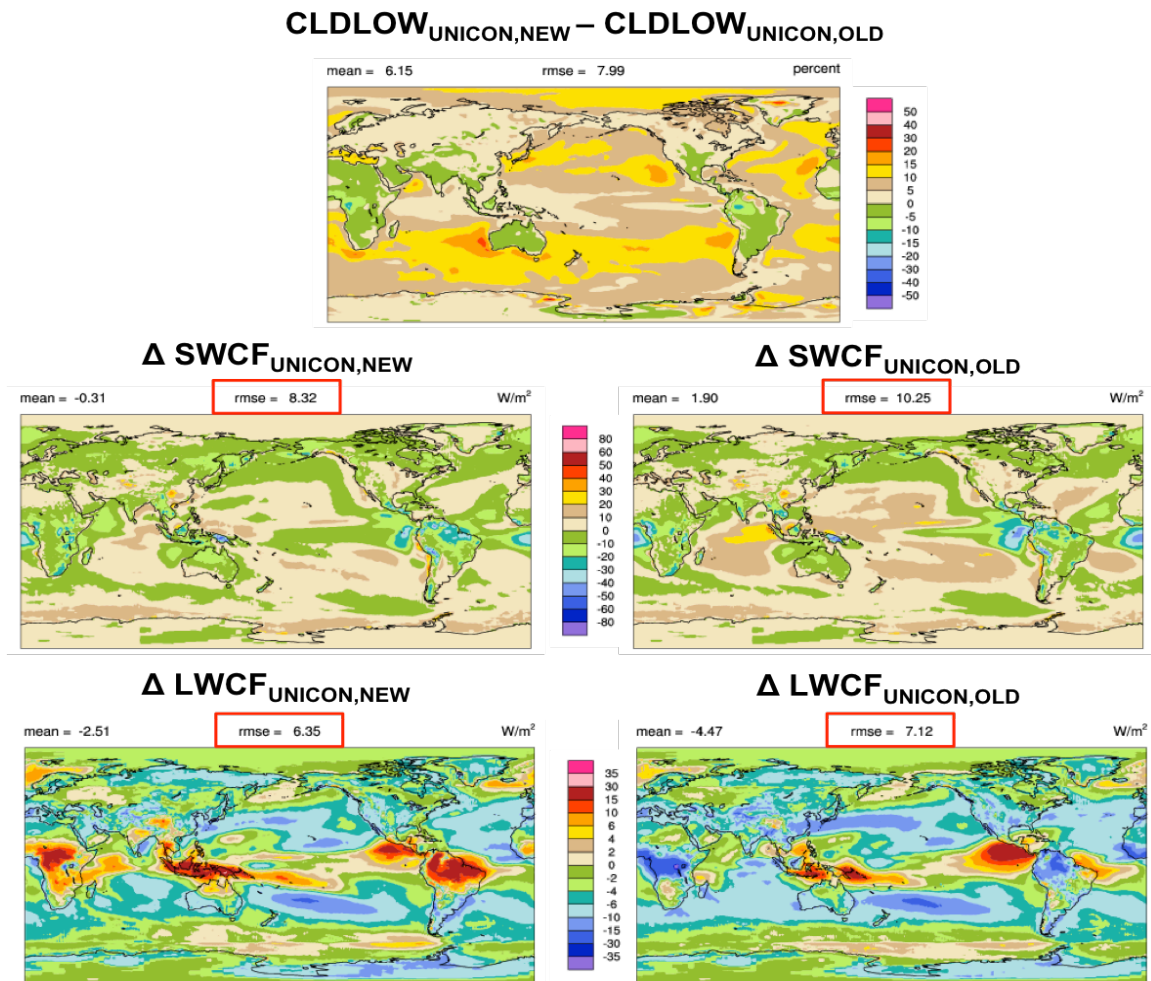


Figure 3. (Upper) The difference of CLDLow between the NEW and OLD UNICON; (middle) the biases of SWCF against the observation; and (lower) the biases of LWCF against the observation. All UNICON simulations are from the 27-yr of AMIP simulations.

- *'.....the excessive tropical humidity distribution...'*

Figure 4 shows the biases of water vapor specific humidity (ΔQ_v) and column-integrated water vapor (ΔPREH2O) against the ERA Interim observation from the NEW and OLD UNICON. As can be seen, the NEW UNICON reduces the positive and negative biases of Q_v in the tropical mid- and upper-troposphere. Improvement can also be seen in the horizontal plot of ΔPREH2O , where the NEW UNICON substantially reduces the strong biases of PREH2O in the eastern tropical and western Pacific warm pool regions that exists in the OLD UNICON. As a whole, this results in the reduction of PREH2O rmse from 1.86 to 1.74.

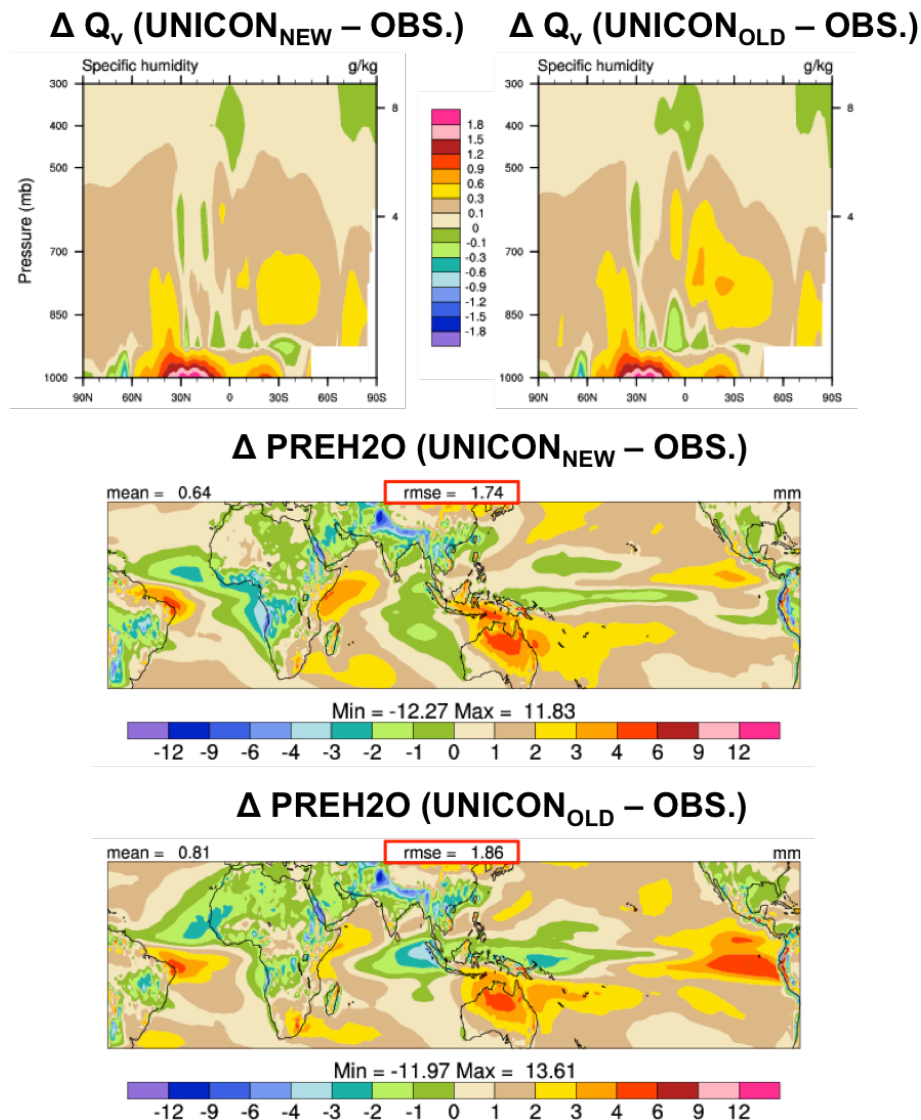


Figure 4. (upper) The biases of annual-mean water vapor specific humidity (ΔQ_v) against the ERA Interim observation, and (middle, lower) the biases of column-integrated water vapor (ΔPREH2O) against the ERA Interim observation. The simulations are from the 27-yr of AMIP simulation with UNICON.

- ‘.....distribution of convective and large-scale precipitation categories.....’

Since the amount of simulated *convective* and *stratiform* precipitation is a strong function of the model horizontal resolution, we need to be careful when comparing individual components of simulated precipitation against the individual components of observed precipitation. For example, in the case that the model horizontal grid becomes very small, the simulated subgrid convective precipitation approaches to zero, and so the comparison between the simulated and observed convective precipitation seems to be not much meaningful. I think that even at the current horizontal resolution of 1-deg, this problem exists. Thus, in my understanding, the only meaningful comparison between the simulated and observed precipitation can be made using ‘*total* precipitation’ (the sum of convective and stratiform precipitations).

- ‘.....the coupled simulation do not out-perform CESM-CAM5.3 configuration.....’

This is largely due to the fact that in contrast to CESM1 for which enormous amount of time has been spent to improve its skill score (e.g., extensive tuning), UNICON – a young daughter – has not been exposed to such kind of extensive training. It should be noted that in spite of the lack of intensive training, UNICON substantially improves the simulation of various atmospheric variability, such as MJO, diurnal cycle of precipitation, ENSO and tropical cyclone, without degrading the climatology, implying that somehow UNICON correctly captures fundamental physics controlling the observed atmospheric convection. It is likely that if more efforts and times are devoted to training UNICON, the skill score will be further improved.

It should be also noted that the submitted coupled simulation is from the Pre-Industrial era in Yr.1850, while the observations are from the Present Day. Thus, we cannot accurately assess the realism of the simulated coupled simulation against the observation. If necessary, there are two variables we can use for comparing the simulated coupled simulation with the observations: Pre-Industrial SST and Pre-Industrial sea-ice fraction, for which, UNICON shows similar performance as CESM1. Strictly speaking, for comprehensive comparison against the observations, we need to use the AMIP simulation instead of the Pre-Industrial coupled simulation. In fact, the NEW UNICON in the AMIP simulation shows superior performance than CAM5 (please see the simulation results on the web).

Figure 5 shows the Taylor diagram of the NEW and OLD UNICON obtained from the 1-deg coupled and AMIP simulations. The NEW UNICON shows slightly improved skill scores (e.g., smaller rmse) compared to the OLD UNICON. Similar improvement can be seen in the correlation table. Again, as mentioned above, the Taylor score of the AMIP simulation from the NEW UNICON is better than that of the default CAM5 (please see the submitted simulation results on the web).

Coupled Simulations. Yrs.31-50.

AMIP Simulations. Yrs. 1979-2005.

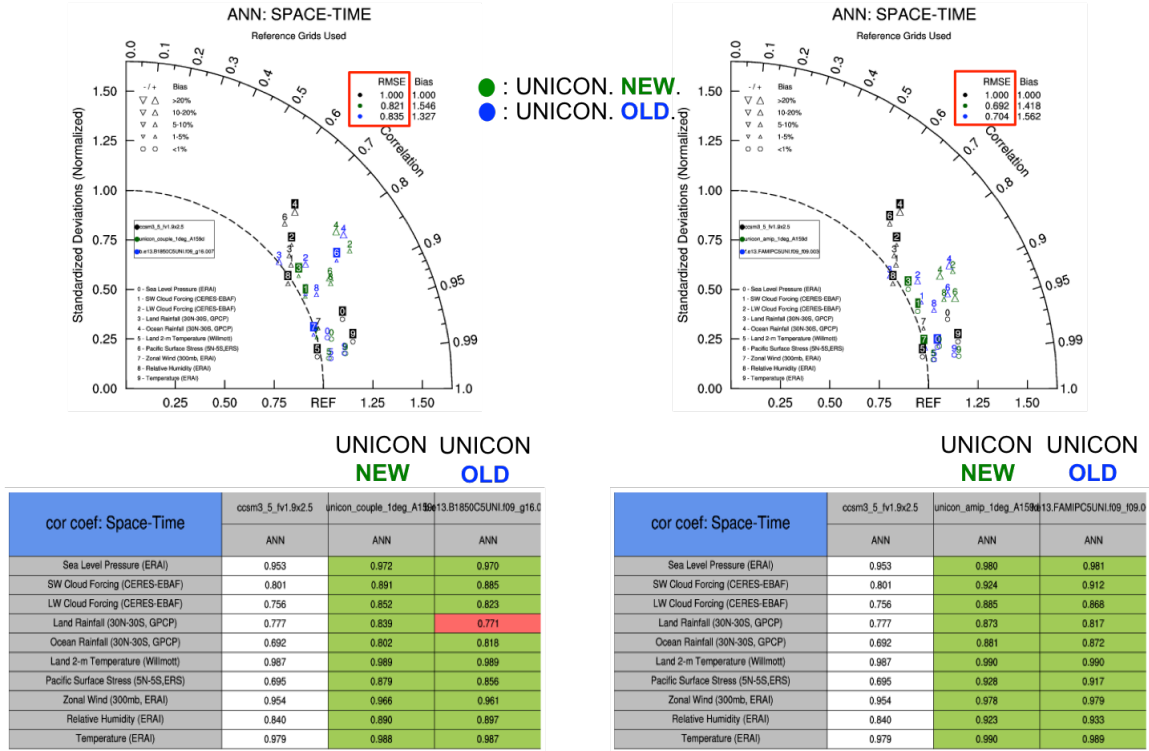


Figure 5. (upper) Taylor diagrams and (lower) correlation tables from (left) the 1850 Pre-Industrial coupled simulations and (right) the AMIP simulations. The simulations are from the NEW and OLD UNICON.

- ‘.....precipitation biases in the coupled simulation.....’

Similar to most GCMs, the precipitation biases in the UNICON simulation tend to be degraded from the AMIP to the coupled simulations. This may indicate some deficiencies in the underlying ocean model or the weakness of current UNICON in simulating the observed atmosphere-ocean interactions.

Figure 6 shows the total precipitation rate simulated from the OLD and NEW UNICON in the coupled mode during the Pre-Industrial era. Since the observed precipitation is from the Present-Day, we need to be careful in assessing the realism of the UNICON-simulated precipitation biases shown here, as mentioned before. In addition, it is known that satellite observation underestimates the real precipitation by 10-15 %. With this caveat in mind, we can see that the NEW UNICON produces similar skill score as the OLD UNICON, with a slightly worse (better) rmse score during DJF (JJA). A notable improvement can be seen in the land precipitation over the South America in DJF (which can also be seen in the correlation table in Fig.5), while the precipitation over the western Pacific warm pool region in DJF is too strong in the NEW UNICON. We can reduce this positive precipitation bias by tuning some model parameters (e.g., by increasing the updraft plume radius at surface at the maximally organized state, say, from the

current default value of 4000 [m] to 5000 [m]). While it is clear that there are rooms for further reducing the precipitation biases through a tuning exercise, I want to leave it as a future research subject, since rigorous treatment of aerosol-precipitation interactions with a double moment cumulus microphysics in the convective updraft is likely to have more profound impact on the simulated precipitation. Similar to other existing convection schemes, current UNICON uses a very simple single-moment cumulus microphysics without considering aerosol activation and accretion processes.

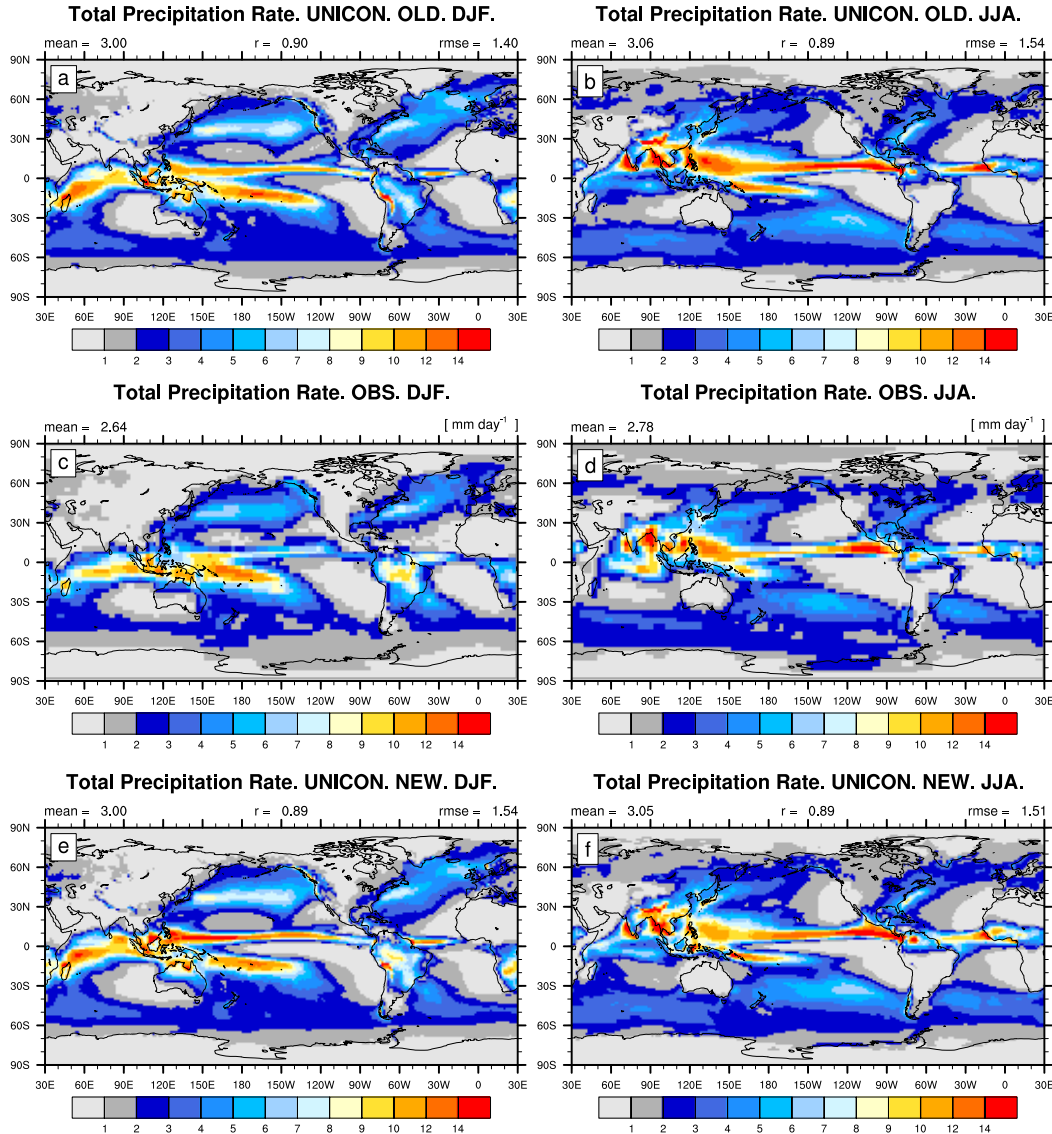


Figure 6. Total (convective plus stratiform) precipitation rate at the surface (PRECT) during (a),(c),(e) DJF and (b),(d),(f) JJA from (a),(b) the OLD UNICON, (c),(d) CMAP observations during 1979-1998, and (e),(f) the NEW UNICON. The simulations are from the coupled mode during the 1850 Pre-Industrial era in Yrs.31-50. The global-mean value is shown at the top-left of each plot. The pattern correlation and RMSE between the simulation and the observation are shown at the top center and the top right of an individual simulation plot, respectively.

- ‘.....the amplitude of diurnal cycle of precipitation is stronger in UNICON than observation.....’

Figure 7 shows UNICON-simulated diurnal cycle of total precipitation rate at surface. Roughly speaking, there is not much difference between the NEW and OLD UNICON. Within UNICON, the amplitude of diurnal cycle of precipitation can be easily reduced by decreasing the parameter k_* (the fraction of the cold pool available potential energy converted into the mesoscale kinetic energy within the PBL) from the current default value of 0.08; decreasing $\hat{A}_s(\Omega = 0)$ (updraft fractional area at surface at the non-organized state) from the current default value of 0.025 over land; or reducing the evaporation efficiency of convective precipitation. In other words, the strong amplitude of the diurnal cycle of precipitation in UNICON is not generic but a simple tuning issue.

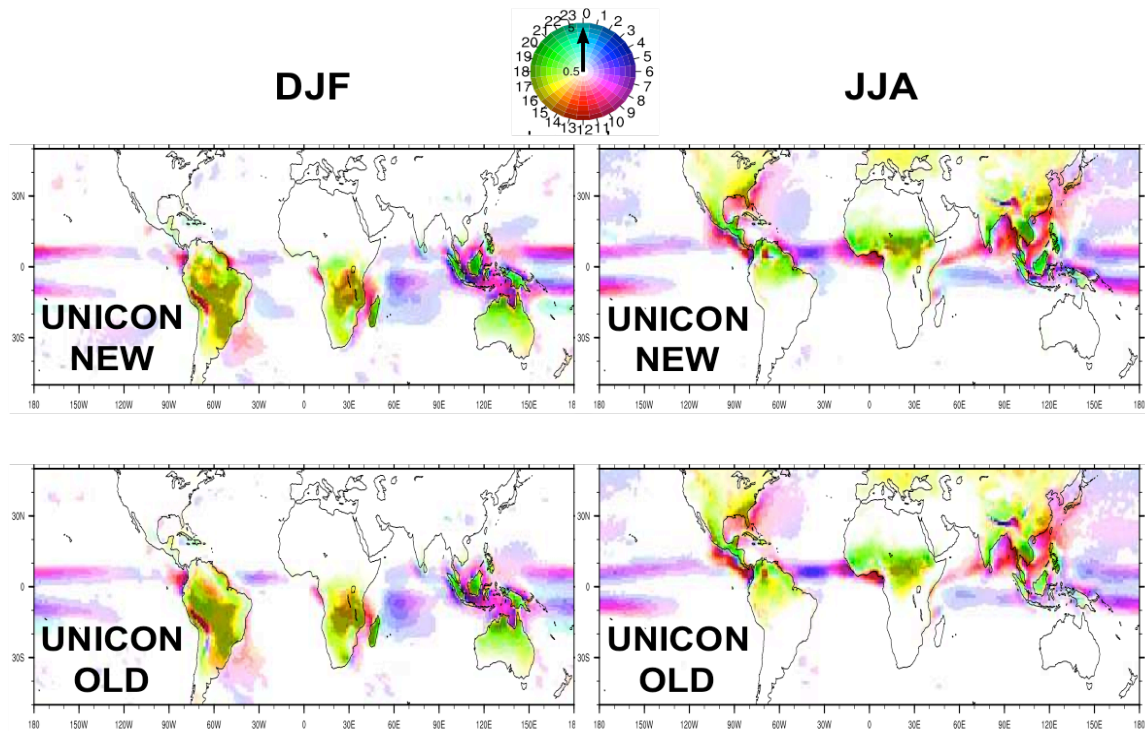


Figure 7. The diurnal cycle of the total precipitation rate at surface during (left) DJF and (right) JJA from (upper) the NEW UNICON and (lower) the OLD UNICON. The color scale denotes the local hour when the surface precipitation rate fitted to the first harmonic function is a maximum and the hue scale denotes the amplitude of the diurnal cycle.

- ‘.....Kelvin wave is too strong and too slow.....’ & ‘.....MJO amplitude is too weak.....’

Figures 8 and 9 are the MJO plots obtained from the standard MJO diagnostic package. The detailed description on each plot can be found in the captions. The review panel pointed out that the OLD UNICON simulated too strong and too slow Kelvin wave. As can be seen in Fig.8, the NEW UNICON simulates weaker Kelvin wave than the OLD UNICON with an improved phase speed too, addressing the review panel’s concern. Both the NEW and OLD UNICON shows a pronounced peak of OLR power in the MJO period of 30-60 days. In summary, the improvement of Kelvin wave does not come from the sacrifice of the MJO – both Kelvin wave and MJO are well simulated in the NEW UNICON.

The review panel also pointed out that MJO amplitude is too weak in the OLD UNICON. From the left panel of Fig.9, however, I could not find definite evidence indicating that the OLD UNICON simulates too weak MJO amplitude: in fact, the OLD UNICON simulates somewhat strong MJO power than the observation, except in the case of OLR during winter. We note that the interpretation of MJO can be sensitive to the analysis method, which may explain why the review panel’s comment is not consistent with the figures shown in Fig.9. Compared to the OLD UNICON, the NEW UNICON shows improvement in the simulation of the MJO power in the U850, but slight degradation in the OLR during winter (the right panel of Fig.9). It is speculated that this deficiency of the NEW UNICON in simulating MJO power of OLR during winter might be associated with the parameterization ice stratus (which is a part of ice cloud macro-microphysics) and ice nucleation process, as well as UNICON itself, since in contrast to OLR, the UNICON-simulated MJO power in U850 looks reasonable. More research is necessary to improve detailed aspects of the MJO.

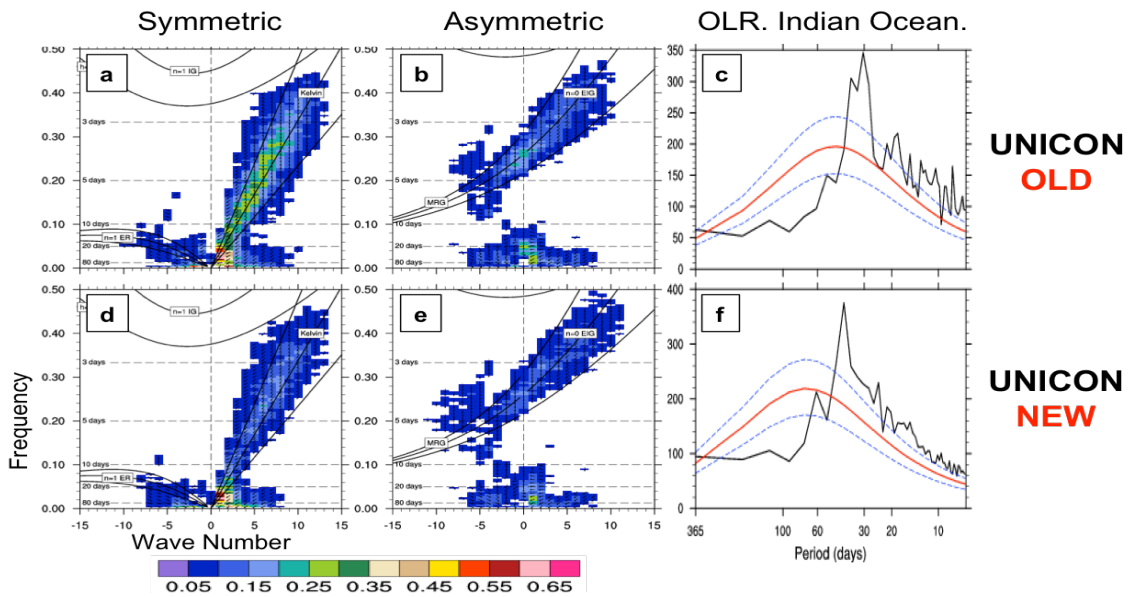


Figure 8. The (a),(d) symmetric and (b),(e) asymmetric components of coherence squared in wavenumber-frequency space obtained from the cross-spectrum analysis of daily anomalies of OLR and zonal wind at 850 hPa (U850) in the latitude band between 15°S and 15°N during the first 50-yr of

coupled simulation in the 1850 Pre-Industrial era from (a)-(c) the OLD UNICON and (d)-(f) the NEW UNICON. The power spectrum of daily OLR anomalies averaged over the Indian Ocean (10°S-5°N, 75°-100°E) is in (c),(f) with the null (red line), 5% (lower blue dotted), and 95% (upper blue dotted) red-noise significance levels.

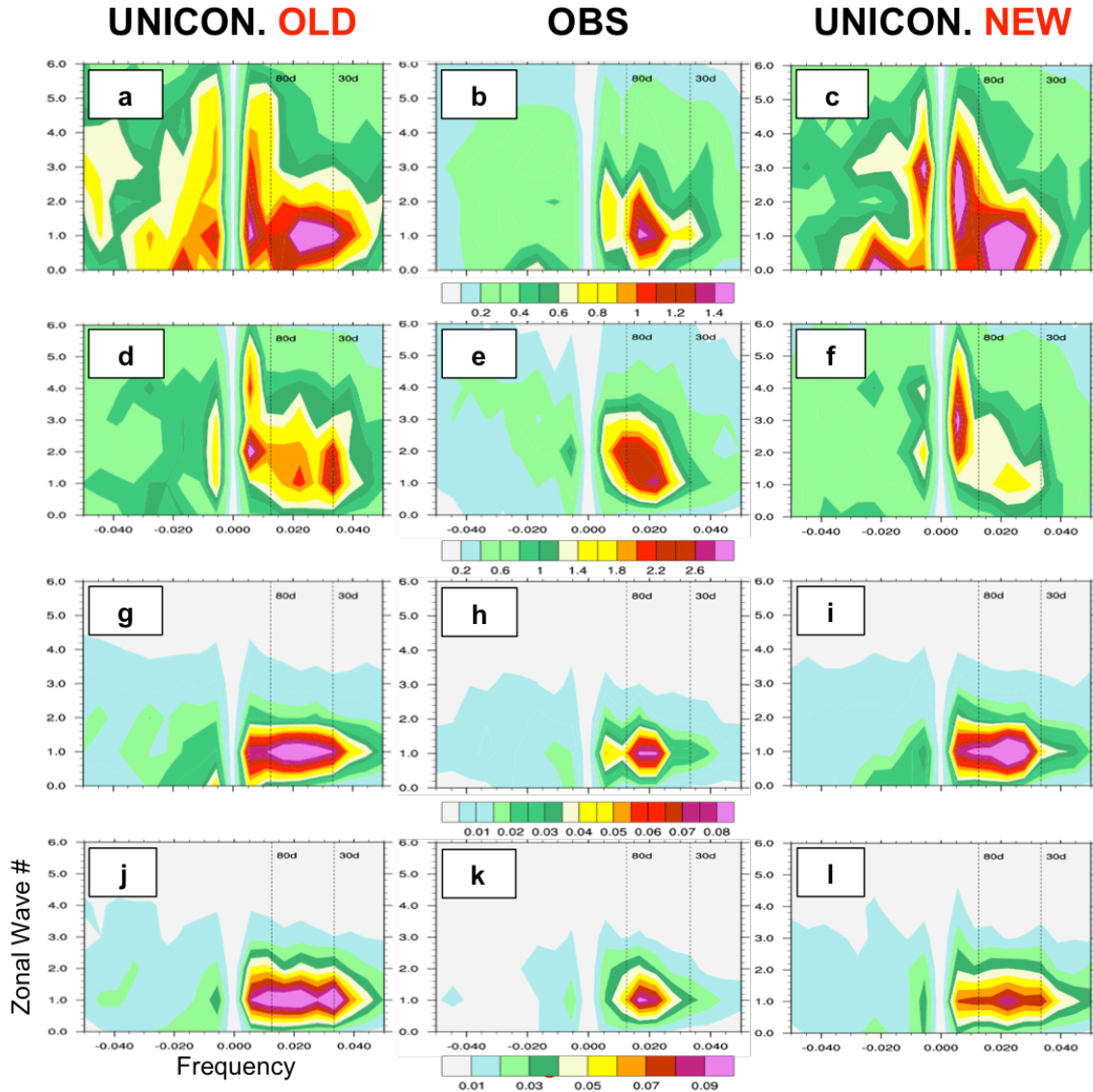


Figure 9. The wavenumber-frequency spectra of daily anomalies of (a)-(f) OLR and (g)-(l) U850 averaged over the latitude band between 10°S and 10°N during (a)-(c),(g)-(i) May-October and (d)-(f),(j)-(l) November-April for the period of January 1979-December 2005 from (center) AVHRR satellite observations and the NCEP-NCAR reanalysis, (left) the OLD UNICON, and (right) the NEW UNICON. The UNICON simulations are from the 50-yr of coupled simulations during 1850 Pre-Industrial era.

4. Comments on the other aspects

Although not pointed by the review panel, there was couple of aspects that made me uncomfortable in the OLD UNICON – (1) *occasional model crash*, (2) *too small sea-ice fraction in the coupled simulation*, and (3) *too expensive computation time* (currently, CAM5 with UNICON takes about 50% more computation time than the default CAM5). Since CAM/CESM is the community model used by various researchers with diverse expertise both in the research labs and universities, addressing these issues are important. Here, I will briefly explain how the NEW UNICON handles these problems.

- *Occasional Model Crash*

Following the review panel's recommendation, I shared UNICON code with other researchers after the AMWG meeting in 2015. A couple of collaborators (i.e., Drs. Po-Lun Ma and Jin-Ho Yoon at PNNL, DOE) reported me that when UNICON crashed, the concentration of some aerosol species (i.e., dust) became unreasonably large, which resulted in too large aerosol optics and model crash in the aerosol optics module. In CAM5, dust emission is a cubed function of near surface wind speed, so that if surface wind speed increases, for example, from 1 m s^{-1} to 10 m s^{-1} , dust emission increases by 1000 times. Although this model crash in the OLD UNICON may be able to be addressed by refining the crude parameterization of dust emission, I decided to do something within UNICON, since the default CAM5 with the same dust parameterization does not crash. After a detailed review of the code and the analysis of simulations, I tuned the fractional entrainment-detrainment rates between convective downdraft and environment (ϵ_d, δ_d) from 0 (in the OLD UNICON) to $1.5 \times 10^{-4} \text{ [s}^{-1}\text{]}$ (in the NEW UNICON). This reduces convective momentum transport from the upper atmosphere to the lowest model layer and prevents the model crash by suppressing the onset of too strong wind in the lowest model layer. In fact, this setting of $\epsilon_d = \delta_d = 1.5 \cdot 10^{-4}$ in the NEW UNICON is more consistent with the setting in other models (e.g., Tiedtke scheme uses $\epsilon_d = \delta_d = 2 \cdot 10^{-4}$) than the OLD UNICON. In addition, by considering that the treatment of aerosol processes in the current UNICON is somewhat crude due to its inability to separately handle interstitial and cloud-borne aerosols (note that improving this treatment is one of the future research subjects), I set the meso-scale perturbations of horizontal winds and aerosol species within the cold pool to be zero. This does not change the simulation much but stabilizes the system. As a whole, these modifications in the NEW UNICON stabilize the system and the model has not been crashed, at least, until today. But who knows what will happen tomorrow ?

- *Too small sea-ice fraction*

Below Fig.10 shows the biases of sea-ice fraction against the observation in the NEW and OLD UNICON and the difference of horizontal wind in the lowest

model layer between the NEW and OLD UNICON, obtained from the coupled simulations. The OLD simulation shows strong negative biases of sea ice fraction on the northern and eastern parts of the Arctic sea ice, especially, during JJA. These biases, however, are substantially reduced in the NEW UNICON. The magnitude of the sea ice fraction biases in the NEW UNICON is roughly similar to the biases in the default CESM1 (not shown).

It is very interesting to note that even though all the NEW and OLD UNICON and the default CESM use the identical sea ice parameters, a few tuning in the *convection* scheme from the OLD to the NEW UNICON leads to substantial changes of the simulated sea ice fraction. In order to understand why this happened, we need to recognize that UNICON simulates both the dry and moist convection. Over the open ocean in the Arctic area where surface buoyancy flux is upward, dry convection simulated by UNICON plays an important role on the vertical transport of heat, moisture and horizontal momentum. As explained before, a set of tuning exercises from the OLD to the NEW UNICON forced the overall convection to be weaker. Thus, dry vertical transport in the NEW UNICON is likely to be weaker than those in the OLD simulation, which may cause weaker wind speed near the surface and improve the simulation of Arctic sea ice. In fact, the NEW UNICON shows weaker wind speed in the lowest model layer over the northern and eastern portion of the Arctic than the OLD UNICON (see the right panel of Fig.10). This suggests one way to further improve the simulation of sea ice fraction with UNICON in future – by further reducing the strength of dry convection within UNICON, downward transport of horizontal momentum can be reduced, which may further improve the simulation of Arctic sea ice fraction.

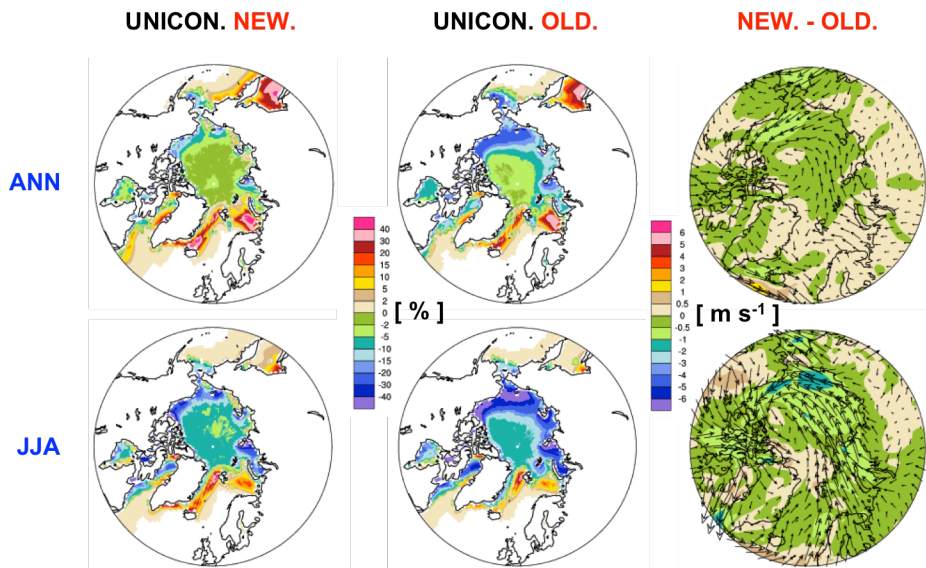


Figure 10. The biases of Arctic sea-ice fraction against the observation from (left) the NEW and (center) the OLD UNICON simulations, and (right) the JJA difference of wind vector and wind speed in the lowest model layer during annual mean (upper) and JJA (lower) from the 50 yrs of 1850 coupled simulations.

- *Improving computational efficiency*

Although the power of computing machine is expected to increase rapidly, it is still important to develop a computationally efficient GCM. This is particularly important since the majority of university community does not have strong enough computing facility to perform their own in-house GCM experiments. Computationally, our CAM5/CESM1 is already heavy. Unfortunately, UNICON makes the situation worse even though it is designed to simulate both shallow and deep convection at the same time. The good news is that about 50% or more of UNICON computation time is consumed for the initialization of variables at the beginning of UNICON. This looks very strange but according to our in-house software engineer, this may be fixed in a relatively easy way. Although I did not have enough time to address this issue of computational efficiency within a given time, I expect that experienced software engineers can solve this problem in a very near future before the formal release of UNICON, if any.

5. Summary and Concluding Remarks

The NEW UNICON shows *improvements* over the OLD UNICON in various aspects, e.g., *ENSO*, *low-cloud fraction* and associated *SWCF/LWCF*, *Kelvin wave*, *tropical humidity distribution* and *sea ice fraction*. In addition, the NEW UNICON is stable *without being crashed*. The diurnal cycle of precipitation and the MJO simulated by the NEW UNICON is similar to those of the OLD UNICON. The overall precipitation climatology simulated by the NEW UNICON is similar to the OLD UNICON with some regional improvements (e.g., land precipitation) and degradations (e.g., too strong precipitation over the western ITCZ during DJF). Compared to the default CAM5/CESM1, the NEW UNICON shows superior performance in simulating the diurnal cycle of precipitation, MJO and SWCF; similar or slightly improved performance in simulating ENSO, Kelvin wave, sea-ice fraction, and other aspects of climate. The NEW UNICON substantially weakens the double ITCZ, which has been a long-standing issue in the modeling community, including our CESM1.

Other than the improvement of low-cloud fraction and SWCF/LWCF (which is due to the addition of detrained cumulus fraction), all the improvements from the OLD to the NEW UNICON listed in the above paragraph are associated with *a few tuning* of UNICON parameters that makes the overall strength of convection weaker. Since the tuning parameters in the NEW UNICON are not necessarily optimized, I expect that additional tuning in future will further improve the UNICON. A set of systematic parameter sensitivity simulations based on the uncertainty quantification technique will be an ideal approach. Collaboration on this subject has already been initiated with other researchers (e.g., Drs. Hui Wan, Po-Lun Ma, Yun Qian, William Gustafson, Jin-Ho Yoon, and Phil Rasch at PNNL). In terms of improving physical formulation of UNICON, I set the highest priority

on refining the treatment of aerosol-precipitation processes within convective plumes, on which intensive collaboration is also planned with Prof. Xiaohong Liu at the University of Wyoming, Drs. Steve Ghan and Phil Rasch at PNNL. Various research proposals have been submitted with other scientists, and the UNICON code is available on the trunk. I hope this addresses the recommendation of the review panel to *allow a broader range of users to evaluate, use and develop the code*.

As a concluding remark, I want to stress that the improved performance of UNICON over CAM5/CESM1 is deeply rooted on its solid conceptual and physical background, not on the intensive tuning exercises for a long time. Unlike the usual convection schemes based on a certain equilibrium assumption, UNICON is a process-based model simulating all dry-moist, forced-free, and shallow-deep convection within a single framework in a seamless, consistent and unified way. By construction, UNICON is scale-adaptive and well compatible with the CAM5 moist PBL scheme without double counting. I hope that UNICON proved its capability to simulate various atmospheric variability without degrading the mean climate.

I admit that UNICON is inexperienced in many aspects. However, she is a candid and promising child with a good potential for further improvement. After a long struggle, now I have a good feeling that my daughter is ready to leave her parents and fly to the community.

I really appreciate the review panel's service.