Adjusted Foreign Model for Crustal Source in Taiwan

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GMC TI-Team

Taiwan SSHAC Level 3 PSHA Study

Taipei, Taiwan

Outline

- **Foreign Crustal GMPEs to be adjusted to Taiwan GM Data**
- **Select data set for the adjustment**
- **GMPEs adjustment procedures**
- **GMPEs adjustment results**
  - Adjusted coefficients
  - Comparison of the original and adjusted GMPE.

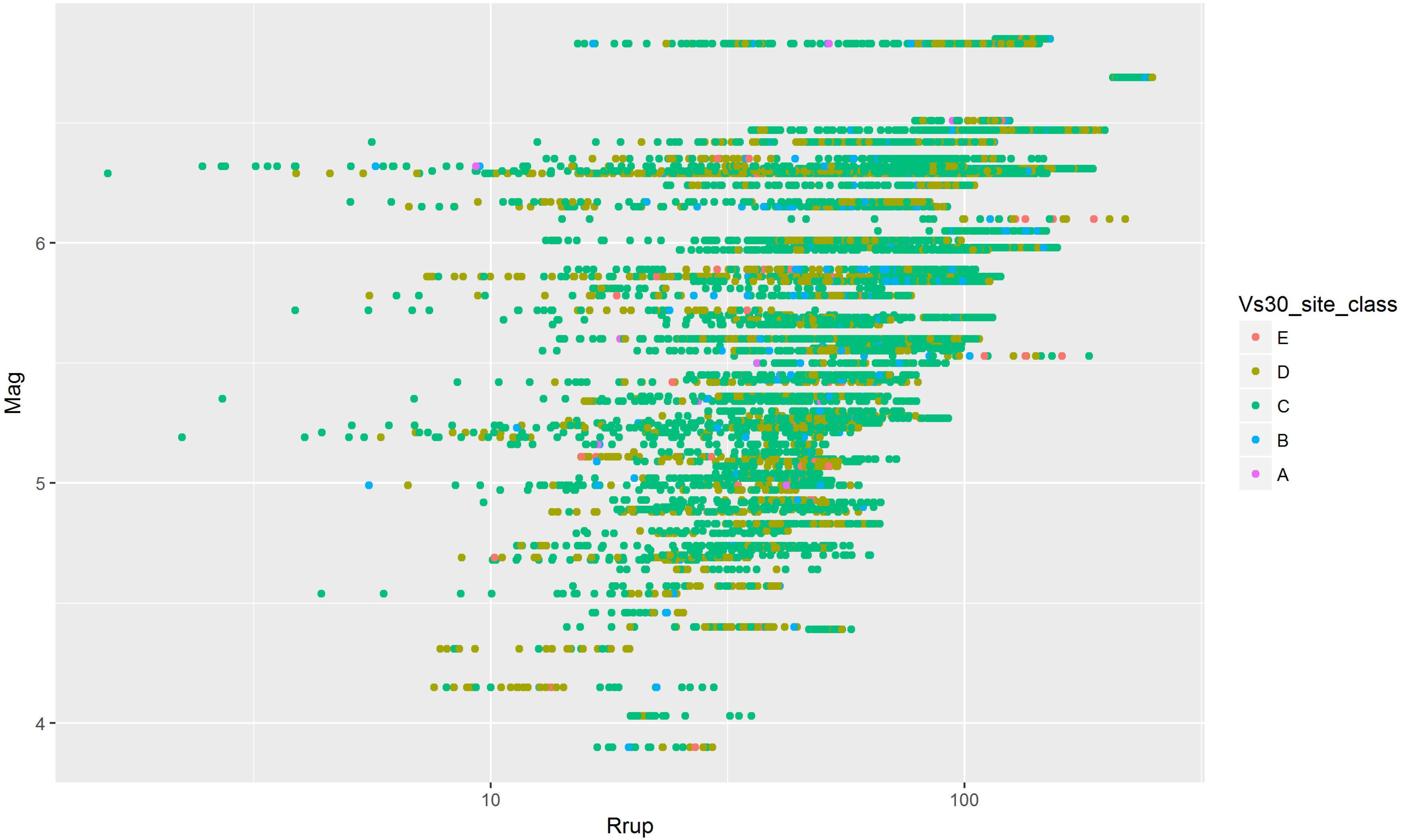
Foreign GMPEs to adjust

- **Crustal GMPEs – 7 GMPEs**
  - ASB14, ASK14, BI14, BSSA14, CY14, I14, CB14
- **24 Periods from 0.01 to 10 sec**
  - 0.01, 0.02, 0.03, 0.04, 0.05, 0.075, 0.1, 0.12, 0.15, 0.17, 0.2, 0.25, 0.30, 0.40, 0.50, 0.75, 1.00, 1.50, 2.00, 3.00, 4.00, 5.00, 7.50, 10.00
- **Add statistical uncertainties (e.g. Al-Atik and Youngs) to expand the range**

Select data set for adjustment

- Source type is either 'Shallow Crustal' or 'Deep Crustal'
- Exclude aftershocks
- Exclude 1999 ChiChi earthquake
- $R_{rup} \leq$ Rmax
- Number of recordings in an earthquake > 15
- Spectral period (T) < Longest usable period
- Result: 103 events with 8525 records

Data distribution



Modifications of the GMPE model

- **ASK14**
  - Use Taiwan's $E[Z_{1.0}|V_{S30}]$ as $Z_{1,reference}$
  - Extend the upper bound Z_{TOR} to 50km:
    - $f_6(Z_{TOR}) = a_{15}(\frac{Z_{TOR}}{50}, 1)_{min}$
- **Bi14**
  - 10-based logarithm was transformed to natural logarithm
  - Convert units from cm/s^2 to g
  - e_1 + sofS -> e_1
  - e_2 -> sofN – sofS
  - e_3 -> sofR – sofS
  - Change the anelastic attenuation term, from $-c_3*(R_{jb}-R_{ref})$ to $+c_3*(R_{jb}-R_{ref})$
- **BSSA14**
  - e_0 U + e_1 SS + e_2 NS + e_3 RS -> e_1 + e_2 NM + e_3 RV
  - SOF factor for UK (e_0) can not be estimated from Taiwan data
  - Normal slip factor: $e_2 - e_1$ -> e_2
  - Reverse slip factor: $e_3 - e_1$ -> e_3
  - F_{dZ1} = min(f7, f6 * $dZ_{1.0}$), and f6 and f7 are set to 0.0 if its original value is -9.900

Modifications of the GMPE model

- **CB14**
  - The f_{mag} function (Equation 2) was reformulated as:

```
ifelse(Mag <= 4.5, c0 + c1 * (Mag - 4.5),
       ifelse(Mag <= 5.5, c0 + c2 * (Mag - 4.5),
              ifelse(Mag <= 6.5, c0 + c2 + c3 * (Mag - 5.5),
                     c0 + c2 + c3 + c4 * (Mag - 6.5))))
```

    - The equivalence of coefficients between CB14 and the reformulated form is
      - c0 <- round(coef.CB14$c0 + coef.CB14$c1 * 4.5, 4)
      - c1 <- round(coef.CB14$c1)
      - c2 <- round(coef.CB14$c1 + coef.CB14$c2, 4)
      - c3 <- round(coef.CB14$c2 + coef.CB14$c3, 4)
      - c4 <- round(coef.CB14$c3 + coef.CB14$c4, 4)
    - c0, c1, c2, c3 were adjusted to Taiwan data; c4 was unchanged
- **ASB14, CY14, I14 (None)**

Modifications of the GMPE model

- **For Z_{TOR} or $Z_{1.0}$ effect,**
  - If the original GMM does not consider an effect, a term for that effect is not added even if the Taiwan data require such an effect
    - Z_{TOR} : BSSA14, ASB14, and Bi14
    - $Z_{1.0}$: ASB14 and Bi14

Regression analysis of adjusted coefficient

- Ground motion is modeled as a mixed-effect model with EQID and STAID as group factors
- The *VCA* method (Chen and Tsai, 2002) was used to estimate subset of model coefficients.
- In Run C01, variance is broken into three components: EQ-to-EQ, Station-to-Station, and the remaining component

Regression analysis of adjusted coefficient

- **Homoscedastic residual variances**
- **Estimated coefficients are not yet smoothed**
  - We will smooth only coefficients related to the prediction of ground motions from SS events
    - NM and RV faulting factors will not be smoothed here,
    - They will be smoothed in the integration phase for SOF factor branch of the GMC logic tree

ASB14

Summary of current adjust GMPEs – ASB14

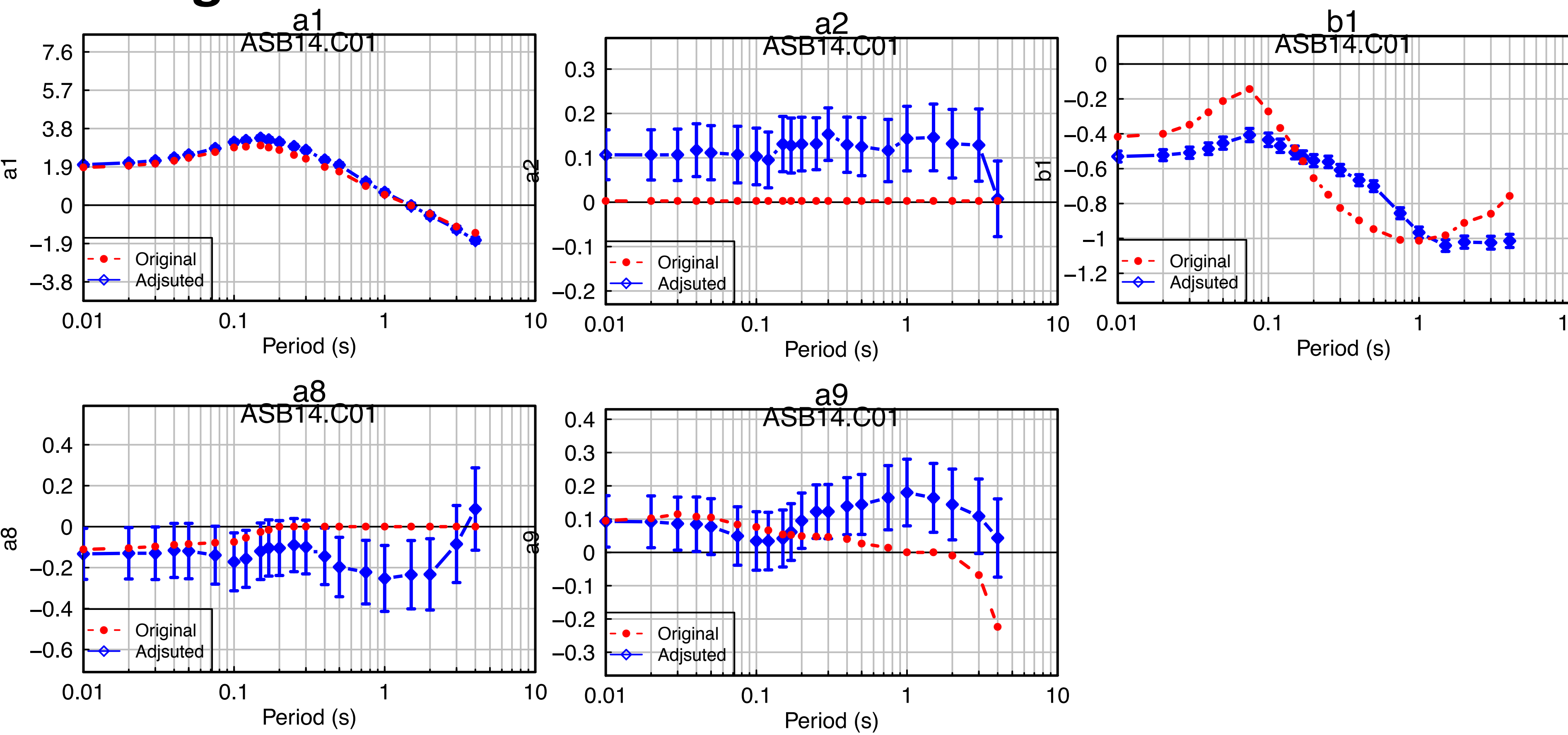
- **Adjusted coefficients**
  - a1, a2, a8, a9, b1

$$\ln(Y_{REF}) = \begin{cases} a_1 + a_2(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]\ln\left(\sqrt{R^2 + a_6^2}\right) \\ + a_8 F_N + a_9 F_R \quad\quad \text{for } M_w \leq c_1 \\ a_1 + a_7(M_w - c_1) + a_3(8.5 - M_w)^2 + [a_4 + a_5(M_w - c_1)]\ln\left(\sqrt{R^2 + a_6^2}\right) \\ + a_8 F_N + a_9 F_R \quad\quad \text{for } M_w > c_1 \end{cases}$$

$$\ln(S) = \begin{cases} b_1 \ln(V_{S30}/V_{REF}) + b_2 \ln\left[\frac{PGA_{REF} + c(V_{S30}/V_{REF})^n}{(PGA_{REF} + c)(V_{S30}/V_{REF})^n}\right] & \text{for } V_{S30} \leq V_{REF} \\ b_1 \ln\left[\frac{min(V_{S30}, V_{CON})}{V_{REF}}\right] & \text{for } V_{S30} > V_{REF} \end{cases}$$

Summary of current adjust GMPEs – ASB14

- Compare the adjusted coefficient (C01) with the original



Summary of current adjust GMPEs – ASB14

- **Notes:**
  - ASB14 does not cover T > 4 s

- **Notable Outcomes:**
  - Coef a_2 is roughly independent of period
  - Adjustment yields a coef a_2 that gives a (slightly) stronger **M**-scaling than the original ASB14, whereas adjusted NGA-W2 yields a much weaker **M**-scaling than the original
  - Homoscedastic residual variances
    - Intra-event variance is much smaller than the variances of ASB14
- **Residuals:**
  - Systematic over-prediction of short-period PSA at R_{JB} < 10 km range of **M** < 6.5 events
  - Large mismatch to Vs30 < 200 m/s sites
    - Require a different form of log(Vs30) scaling!
  - T=1 & 3 s
    - ASB14's nonlinearity is stronger than the curvature of EAF data in the 6th Vs30 bin
    - Total amp has a shallower slope than the linear amp!
- **Future works:**
  - Smooth adjusted coef
    - Model a2 as a T-independent constant
  - Original does not have anelastic attenuation term. Is a term needed?

ASK14

Summary of current adjust GMPEs – ASK14

- **Adjusted coefficients**
  - a1, a4, a6, a15, a11, a12, a10, a17, a43, a44, a45, a46

$$
= \begin{cases} a_1 + a_5(\mathbf{M} - M_1) + a_8(8.5 - \mathbf{M})^2 + [a_2 + a_3(\mathbf{M} - M_1)]\ln(R) + a_{17}R_{RUP} & for\, \mathbf{M} > M_1 \\ a_1 + a_4(\mathbf{M} - M_1) + a_8(8.5 - \mathbf{M})^2 + [a_2 + a_3(\mathbf{M} - M_1)]\ln(R) + a_{17}R_{RUP} & for\, M_2 \le \mathbf{M} < M_1 \\ a_1 + a_4(M_2 - M_1) + a_8(8.5 - M_2)^2 + a_6(\mathbf{M} - M_2) & \\ \quad + a_7(\mathbf{M} - M_2)^2 + [a_2 + a_3(M_2 - M_1)]\ln(R) + a_{17}R_{RUP} & for\, \mathbf{M} < M_2 \end{cases}
$$

$$
f_6(Z_{TOR}) = \begin{cases} a_{15}\frac{Z_{TOR}}{20} & for\ Z_{TOR} < 20 \text{ km} \\ a_{15} & for\ Z_{TOR} \ge 20 \text{ km} \end{cases}
$$

$$
f_7(\mathbf{M}) = \begin{cases} a_{11} & for\ \mathbf{M} > 5.0 \\ a_{11}(\mathbf{M} - 4) & for\ 4 \le \mathbf{M} \le 5 \\ 0 & for\ \mathbf{M} < 4.0 \end{cases}
$$

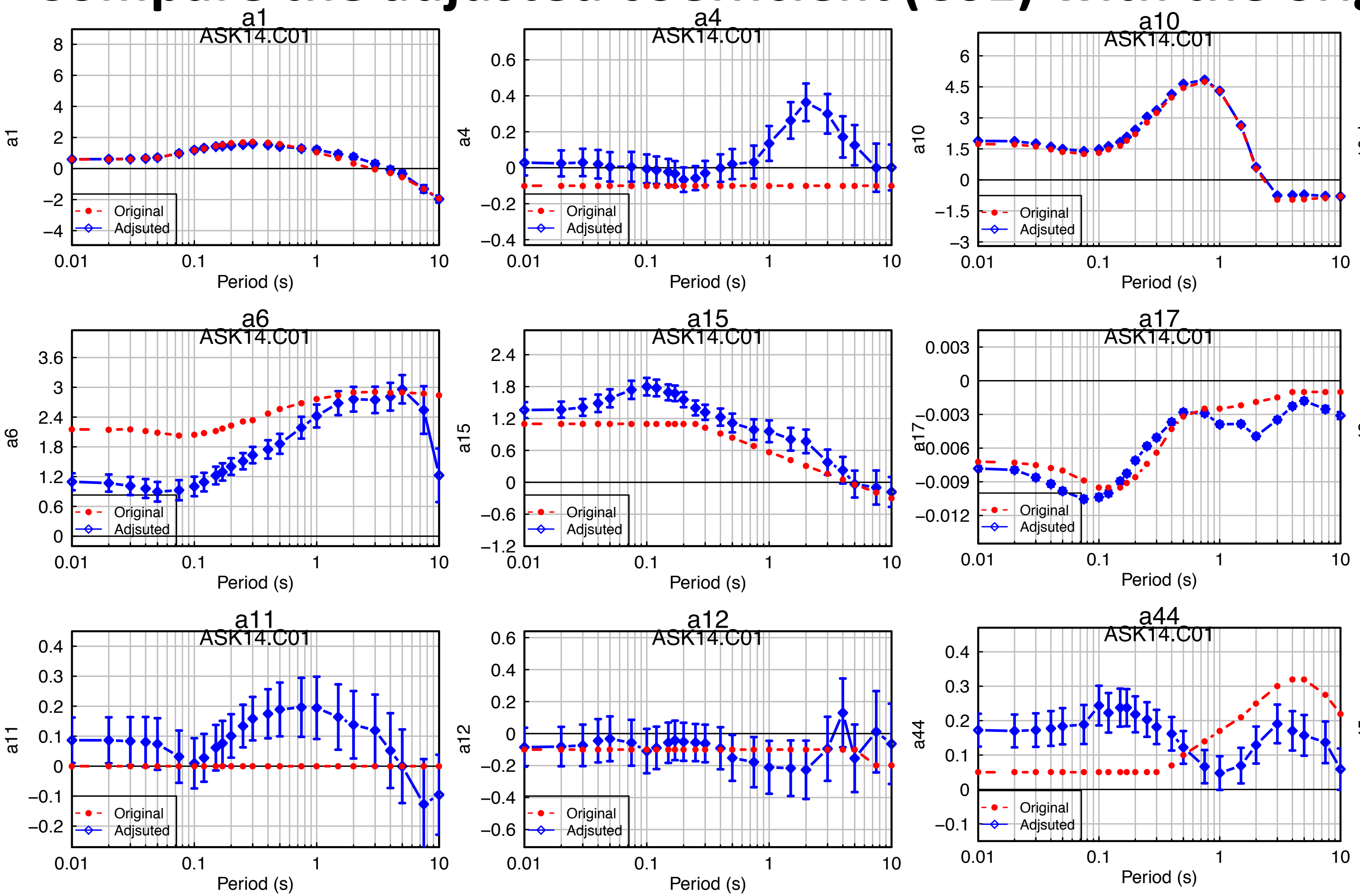
$$
f_8(\mathbf{M}) = \begin{cases} a_{12} & for\ \mathbf{M} > 5.0 \\ a_{12}(\mathbf{M} - 4) & for\ 4 \le \mathbf{M} \le 5 \\ 0 & for\ \mathbf{M} < 4.0 \end{cases}
$$

$$
f_{10}(Z_1, V_{S30}) = \begin{cases} a_{43}\ ln\left(\frac{Z_1 + 0.01}{Z_{1,ref} + 0.01}\right) & for\ V_{S30} \le 200 \\ a_{44}\ ln\left(\frac{Z_1 + 0.01}{Z_{1,ref} + 0.01}\right) & for\ 200 < V_{S30} \le 300 \\ a_{45}\ ln\left(\frac{Z_1 + 0.01}{Z_{1,ref} + 0.01}\right) & for\ 300 < V_{S30} \le 500 \\ a_{46}\ ln\left(\frac{Z_1 + 0.01}{Z_{1,ref} + 0.01}\right) & for\ 500 < V_{S30} \end{cases}
$$

$$
f_5(\widehat{Sa}_{1180}, V_{S30}) = \begin{cases} (a_{10} + bn)\ ln\left(\frac{V_{S30}^*}{V_{Lin}}\right) & for\ V_{S30} \ge V_{Lin} \\ (a_{10}) ln\left(\frac{V_{S30}^*}{V_{Lin}}\right) - b\ ln(\widehat{Sa}_{1180} + c) + b\ ln\left(\widehat{Sa}_{1180} + c\left(\frac{V_{S30}^*}{V_{Lin}}\right)^n\right) & for\ V_{S30} < V_{Lin} \end{cases}
$$

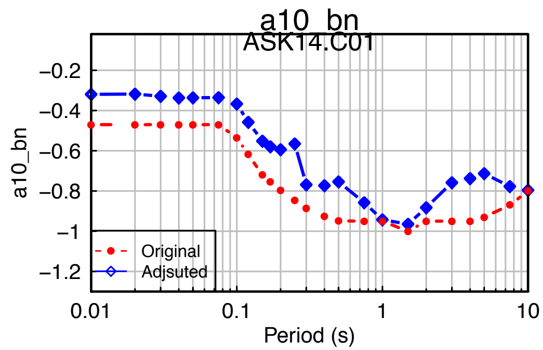
Summary of current adjust GMPEs – ASK14

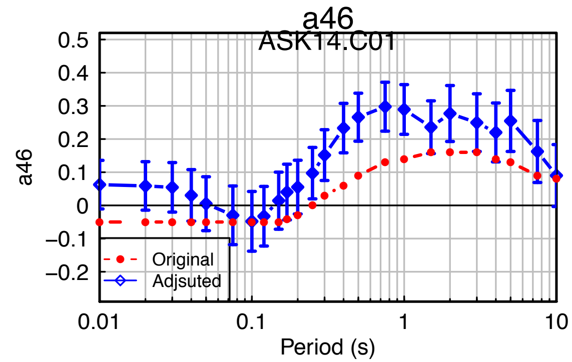
- **Compare the adjusted coefficient (C01) with the original**

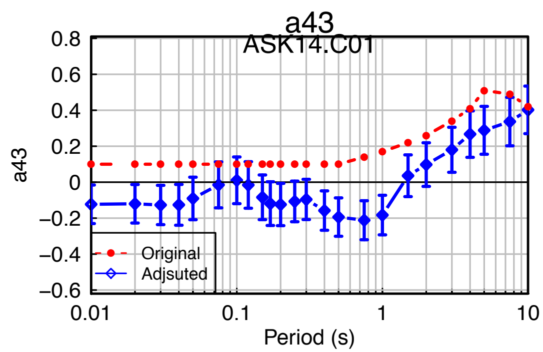


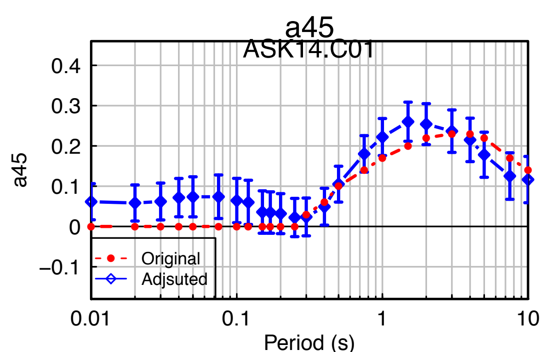
Summary of current adjust GMPEs – ASK14

- **Compare the adjusted coefficient (C01) with the original**









Summary of current adjust GMPEs – ASK14

- **Notes:**
  - Use Taiwan's E[$Z_{1.0}$|V_{S30}] as $Z_{1,\ reference}$
  - Extend the upper bound Z_{TOR} to 50km:
    - » $f_6(Z_{TOR}) = a_{15}(\frac{Z_{TOR}}{50}, 1)_{min}$ Notable outcomes
- **Notable Outcomes:**
- **Residuals:**
  - Soil Nonlinearity
    - Modifying b improves fits at the mid-range of rock-motion, but not enough for the higher-range of rock-motion
- **Decisions/Future Work:**
  - Should a_4 be a constant of spectral period?
    - In ASK14, a_4 was determined using PGA and set as a constant
    - In adjusted ASK14, a_4 is positive for T > 0.5 s. Is positive value acceptable? Is positive value indicative of an inadequate a8? a8 (along with a5) is NOT adjusted because we want to retain original M-scaling at M > 6.75

BI14

Summary of current adjust GMPEs – BI14

- **Adjusted coefficients**
  - e1, sofN, sofR, b1, c3, gamma

$$\log_{10} Y = e_1 + F_D(R, M) + F_M(M) + F_S + F_{sof}$$

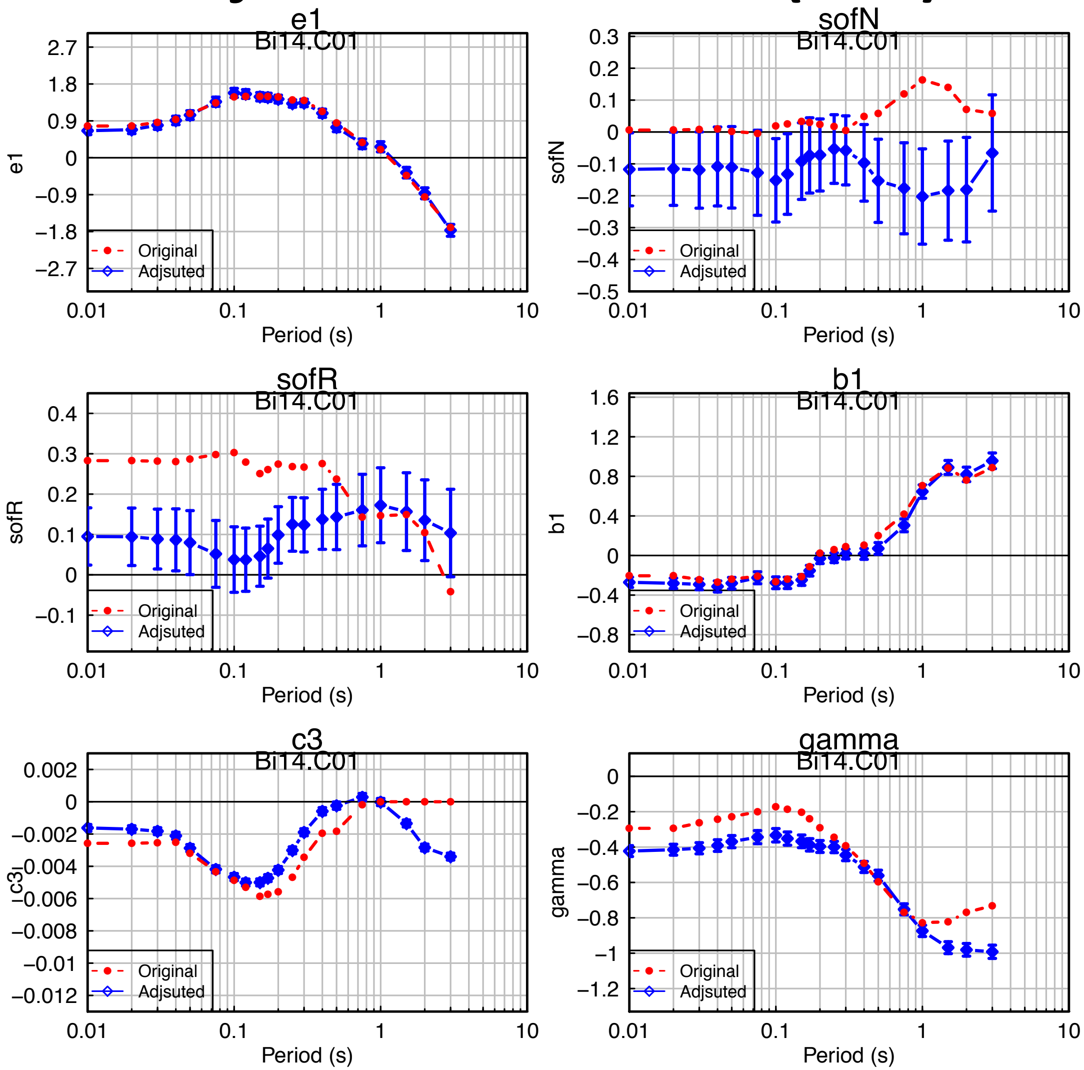
$$F_D(R, M) = \left[c_1 + c_2\left(M - M_{ref}\right)\right] \log_{10}\left(\sqrt{R^2 + h^2}/R_{ref}\right) - c_3\left(\sqrt{R^2 + h^2} - R_{ref}\right)$$

$$F_M(M) = \begin{cases} b_1\left(M - M_h\right) + b_2\left(M - M_h\right)^2 & \text{for } M \le M_h \\ b_3\left(M - M_h\right) & \text{otherwise} \end{cases}$$

$$\mathrm{F_S} = \gamma \log_{10}(\mathrm{Vs_{30}}/\mathrm{V_{ref}})$$

Summary of current adjust GMPEs – BI14

- **Compare the adjusted coefficient (C01) with the original**



Summary of current adjust GMPEs – BI14

- **Notes**
  - Does not cover T > 3 s and does not include nonlinear soil response
  - 10-based logarithm was transformed to natural logarithm
  - Change the anelastic attenuation term, from $-c_3*(R_{jb}-R_{ref})$ to $+c_3*(R_{jb}-R_{ref})$
  - Does not extrapolate well to large **M**, particularly at T=0.2s
- **Notable Outcomes**
  - Bi14, as is, fits the Taiwan data relatively well, compared to other GMMs
- **Residuals**
- **Decisions/Future Works**
  - Constrain c_3 to negative value

BSSA14

Summary of current adjust GMPEs – BSSA14

- **Adjusted coefficients**
  - e1, e2, e3, e4, Mh, c3, cc

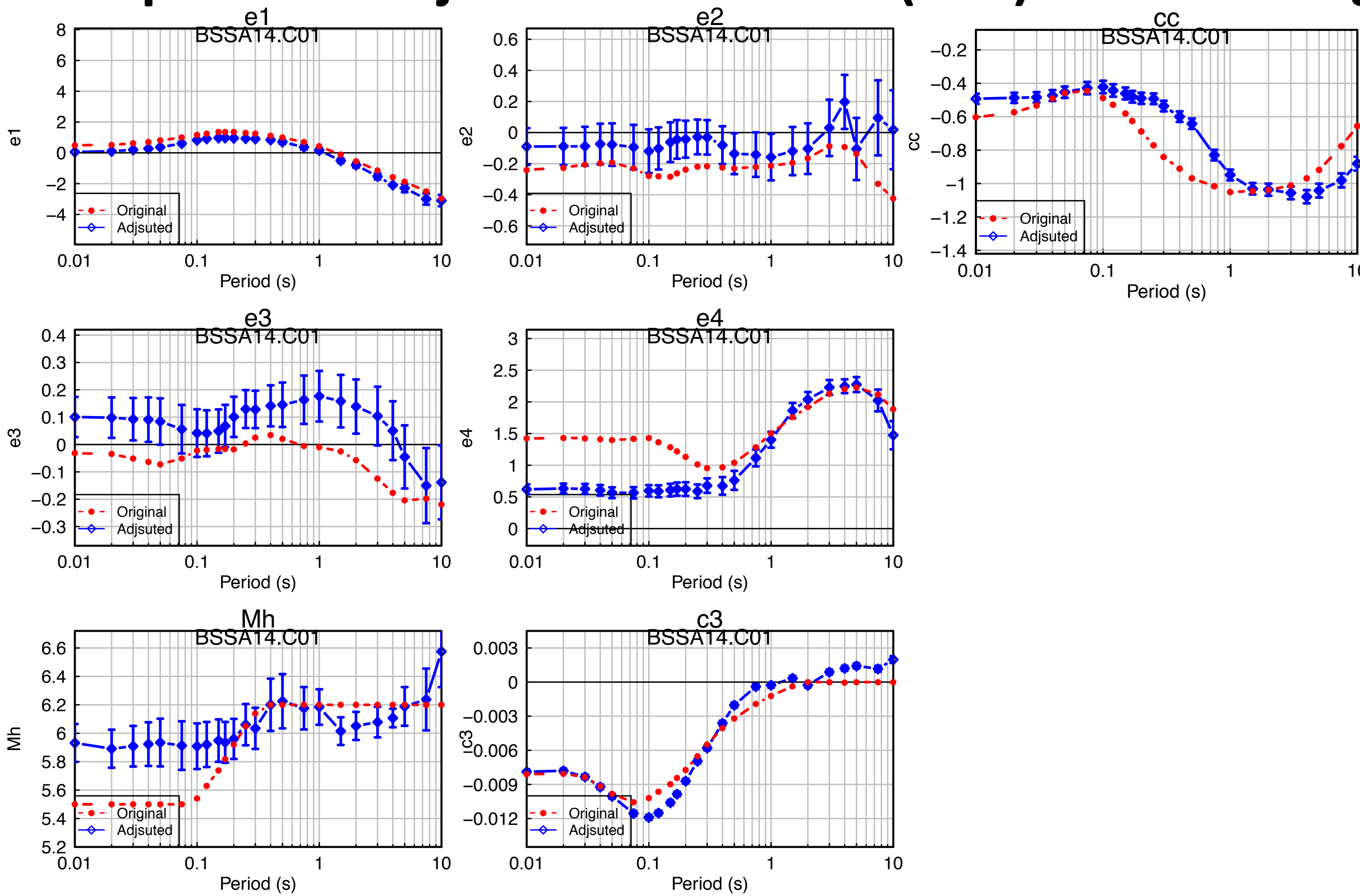
$$F_E(\mathbf{M}, mech) = \begin{cases} e_0 U + e_1 SS + e_2 NS + e_3 RS + e_4(\mathbf{M} - \mathbf{M}_h) + e_5(\mathbf{M} - \mathbf{M}_h)^2 & \mathbf{M} \leq \mathbf{M}_h \\ e_0 U + e_1 SS + e_2 NS + e_3 RS + e_6(\mathbf{M} - \mathbf{M}_h) & \mathbf{M} > \mathbf{M}_h \end{cases}$$

$$F_P(R_{JB}, \mathbf{M}, region) = [c_1 + c_2(\mathbf{M} - \mathbf{M}_{ref})] \ln(R/R_{ref}) + (c_3 + \Delta c_3)(R - R_{ref})$$

$$\ln(F_{lin}) = \begin{cases} c \ln\left(\frac{V_{S30}}{V_{ref}}\right) & V_{S30} \leq V_c \\ c \ln\left(\frac{V_c}{V_{ref}}\right) & V_{S30} > V_c \end{cases}$$

Summary of current adjust GMPEs – BSSA14

- **Compare the adjusted coefficient (C01) with the original**



Summary of adjusted GMPEs – BSSA14

- **Notes**
  - e_0 U + e_1 SS + e_2 NS + e_3 RS → e_1 + e_2 NM + e_3 RV
    - SOF factor for UK (e_0) can not be estimated from Taiwan data
    - Normal slip factor: $e_2 - e_1$ → e_2
    - Reverse slip factor: $e_3 - e_1$ → e_3
  - F_{dZ1} = min(f7, f6 * $dZ_{1.0}$), and f6 and f7 are set to 0.0 if its original value is -9.900
  - Coef e_5 (quadratic M-scaling at M < M_h) is retained because adjusting just e_4 and M_h is sufficient to match the **M**-scaling of Taiwan data
  - Also adjust the model for PGA for use in nonlinear soil model
- **Notable outcomes**
  - Re-estimated coef c_3 (anelastic damping) is positive at $T > 1$ s
  - Adjusted e_1 of short periods is much smaller than the original e_1
    - Change in e_1 reflects the changes in e_4 and M_h
  - For long periods (T > 1s), original M-scaling fits Taiwan EQ data well
    - T = 3 s, small difference in predicted median for low Vs30, large difference for high Vs30.
  - For short periods (T < 1s), original M-scaling does not fit Taiwan EQ data well
- **Decisions/future works**
  - Independent confirmation of the adjusted medians
    - T=3s, e4 and Mh are similar to BSSA14, but prediction is not.
  - Revise e_0 to be the weighted average of e_1, e_2 , & e_3
  - Force positive c_3 to be 0.0
  - Evaluate if $Z_{1.0}$ effect (at long perdios) is adequately modeled by BSSA14

CY14

Summary of current adjust GMPEs – CY14

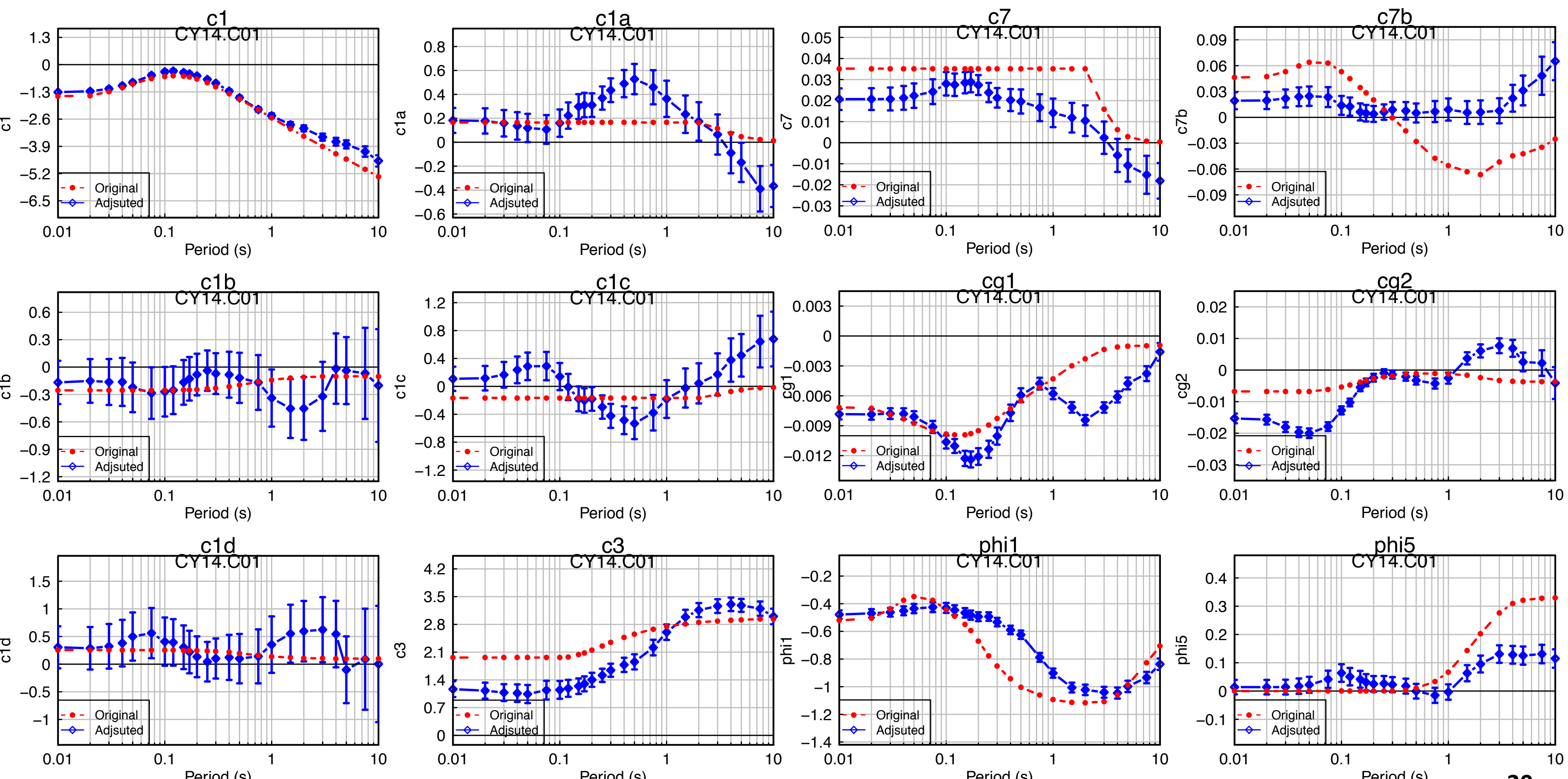
- **Adjusted coefficients**
  - c1, c1a, c1b, c1c, c1d, c3, c7, c7b, cg1, cg2, phi1, phi5

$$
\begin{aligned}
\ln(y_{refij}) = c_1 &+ \left\{ c_{1a} + \frac{c_{1c}}{\cosh(2 \cdot \max(\mathbf{M}_i - 4.5, 0))} \right\} F_{RVi} \\
&+ \left\{ c_{1b} + \frac{c_{1d}}{\cosh(2 \cdot \max(\mathbf{M}_i - 4.5, 0))} \right\} F_{NMi} \\
&+ \left\{ c_{7} + \frac{c_{7b}}{\cosh(2 \cdot \max(\mathbf{M}_i - 4.5, 0))} \right\} \Delta Z_{TORi} \\
&+ \left\{ c_{\gamma 1} + \frac{c_{\gamma 2}}{\cosh(\max(\mathbf{M}_i - c_{\gamma 3}, 0))} \right\} R_{RUPij}
\end{aligned}
$$

$$
\begin{aligned}
\ln(y_{ij}) = \ln(y_{ref_{ij}}) &+ \eta_i \\
&+ \phi_1 \cdot \min\left(\ln\left(\frac{V_{S30j}}{1130} \right), 0 \right) \\
&+ \phi_2 \left(e^{\phi_3 (\min(V_{S30j}, 1130) - 360)} - e^{\phi_3 (1130 - 360)} \right) \ln\left(\frac{y_{ref_{ij}} e^{\eta_i} + \phi_4}{\phi_4} \right) \\
&+ \phi_5 \left(1 - e^{-\Delta Z_{1.0j} / \phi_6} \right) \\
&+ \varepsilon_{ij}
\end{aligned}
$$

Summary of current adjust GMPEs – CY14

- Compare the adjusted coefficient (C01) with the original



Summary of current adjust GMPEs – CY14

- **Notes:**
  - For style-of-faulting factor, the normal oblique slip event is grouped with the strike-slip event
- **Notable outcomes:**
- **Residuals:**
- **Decisions/Future Work:**
  - Should and how to improve the over-prediction at T=3s in the $6 < \mathbf{M} < 6.5$ bin at $R_{rup} < 20$ km?

I14

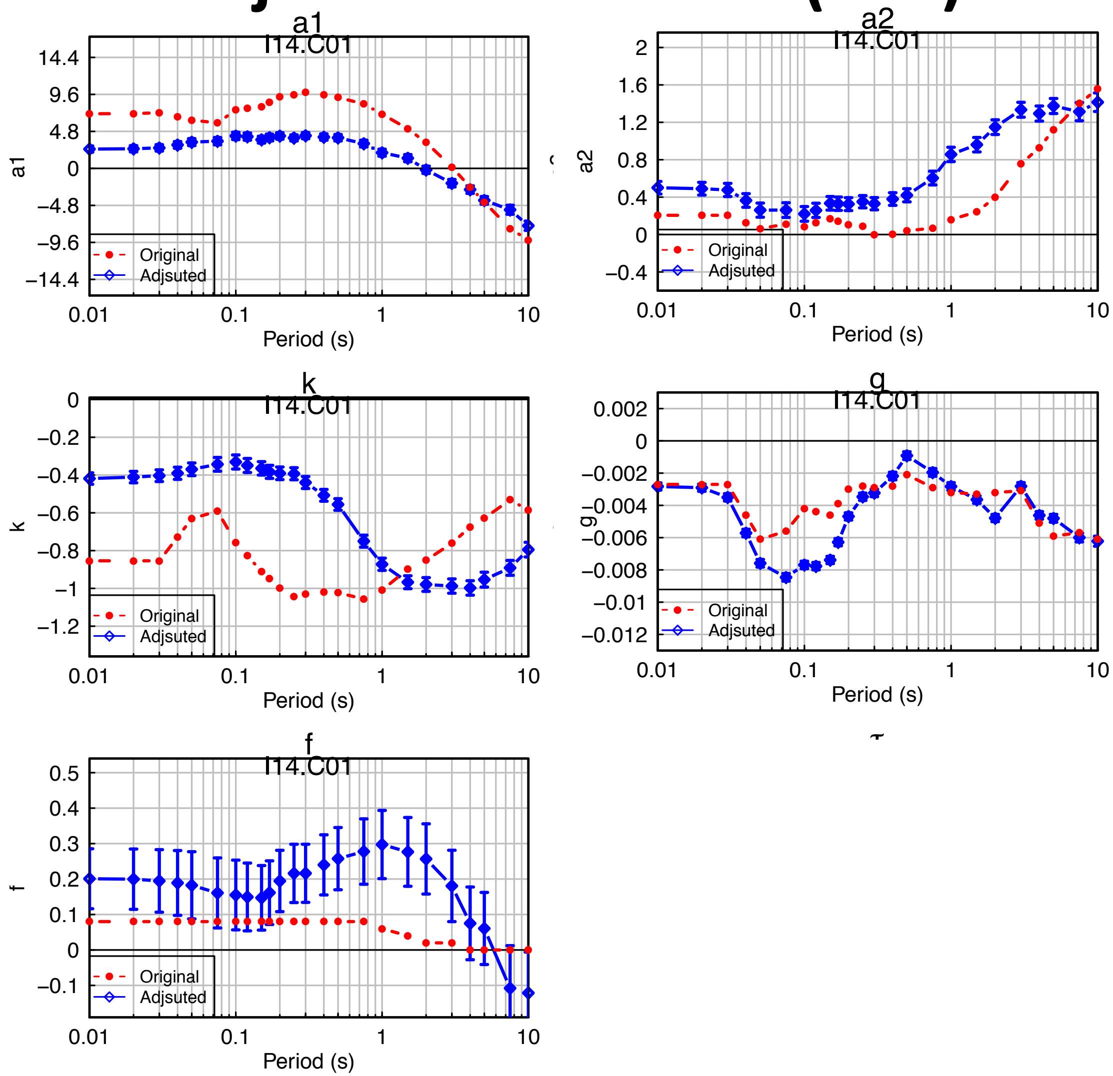
Summary of current adjust GMPEs – I14

- **Adjusted coefficients**
  - a1, a2, k, g, f

$$Ln[PSA] = \alpha_1 + \alpha_2\mathbf{M} + \alpha_3(8.5-\mathbf{M})^2 - [\beta_1 + \beta_2\mathbf{M}]Ln(R_{RUP} + 10)$$
$$+ \xi Ln(V_{S30}) + \gamma R_{RUP} + \varphi F$$

Summary of current adjust GMPEs – I14

- **Compare the adjusted coefficient (C01) with the original**



Summary of current adjust GMPEs – I14

- **Notes:**
  - Intercept (a_1) subsumes the reference Vs30
  - Original model applies to Vs30 > 450 m/s
- **Noted outcomes:**
  - Total sigma is much smaller than the total sigma of I14
- **Residuals:**
- **Decisions/Future Work:**

CB14

Summary of current adjust GMPEs – CB14

- **Adjusted coefficients**
  - c0, c1, c2, c3, c4, c8, c9, c11

$$f_{mag} = \begin{cases} c_0 + c_1\mathbf{M}; & \mathbf{M} \leq 4.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 4.5); & 4.5 < \mathbf{M} \leq 5.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 4.5) + c_3(\mathbf{M} - 5.5); & 5.5 < \mathbf{M} \leq 6.5 \\ c_0 + c_1\mathbf{M} + c_2(\mathbf{M} - 4.5) + c_3(\mathbf{M} - 5.5) + c_4(\mathbf{M} - 6.5); & \mathbf{M} > 6.5 \end{cases}$$

$$f_{flt} = f_{flt,F} f_{flt,M}$$

$$f_{flt,F} = c_8 F_{RV} + c_9 F_{NM}$$

$$f_{flt,M} = \begin{cases} 0; & \mathbf{M} \leq 4.5 \\ \mathbf{M} - 4.5; & 4.5 < \mathbf{M} \leq 5.5 \\ 1; & \mathbf{M} > 5.5 \end{cases}$$

$$f_{hyp} = f_{hyp,H} f_{hyp,M}$$

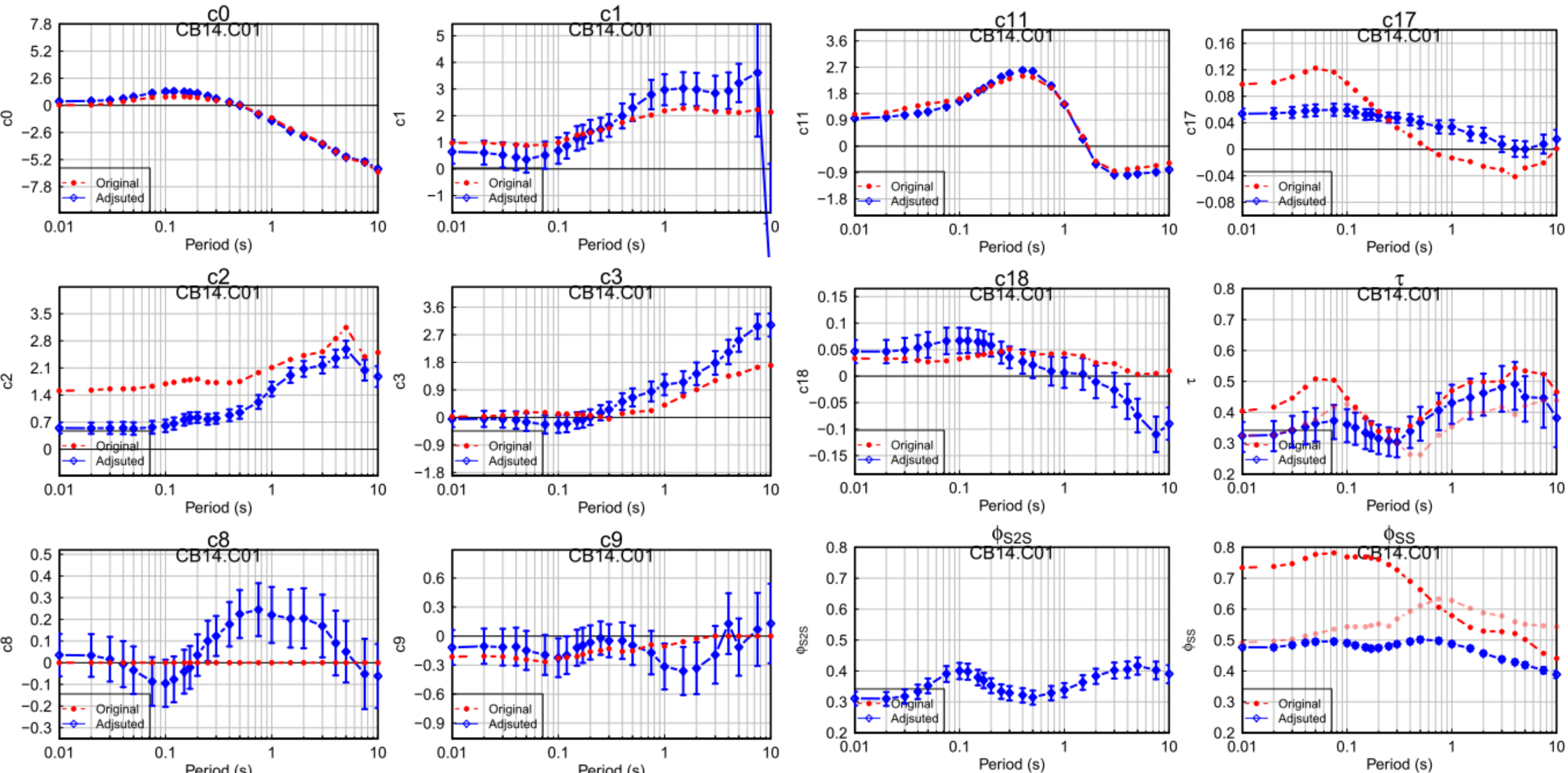
$$f_{hyp,H} = \begin{cases} 0; & Z_{HYP} \leq 7 \\ Z_{HYP} - 7; & 7 < Z_{HYP} \leq 20 \\ 13; & Z_{HYP} > 20 \end{cases}$$

$$f_{hyp,M} = \begin{cases} c_{17}; & \mathbf{M} \leq 5.5 \\ [c_{17} + (c_{18} - c_{17})(\mathbf{M} - 5.5)]; & 5.5 < \mathbf{M} \leq 6.5 \\ c_{18}; & \mathbf{M} > 6.5 \end{cases}$$

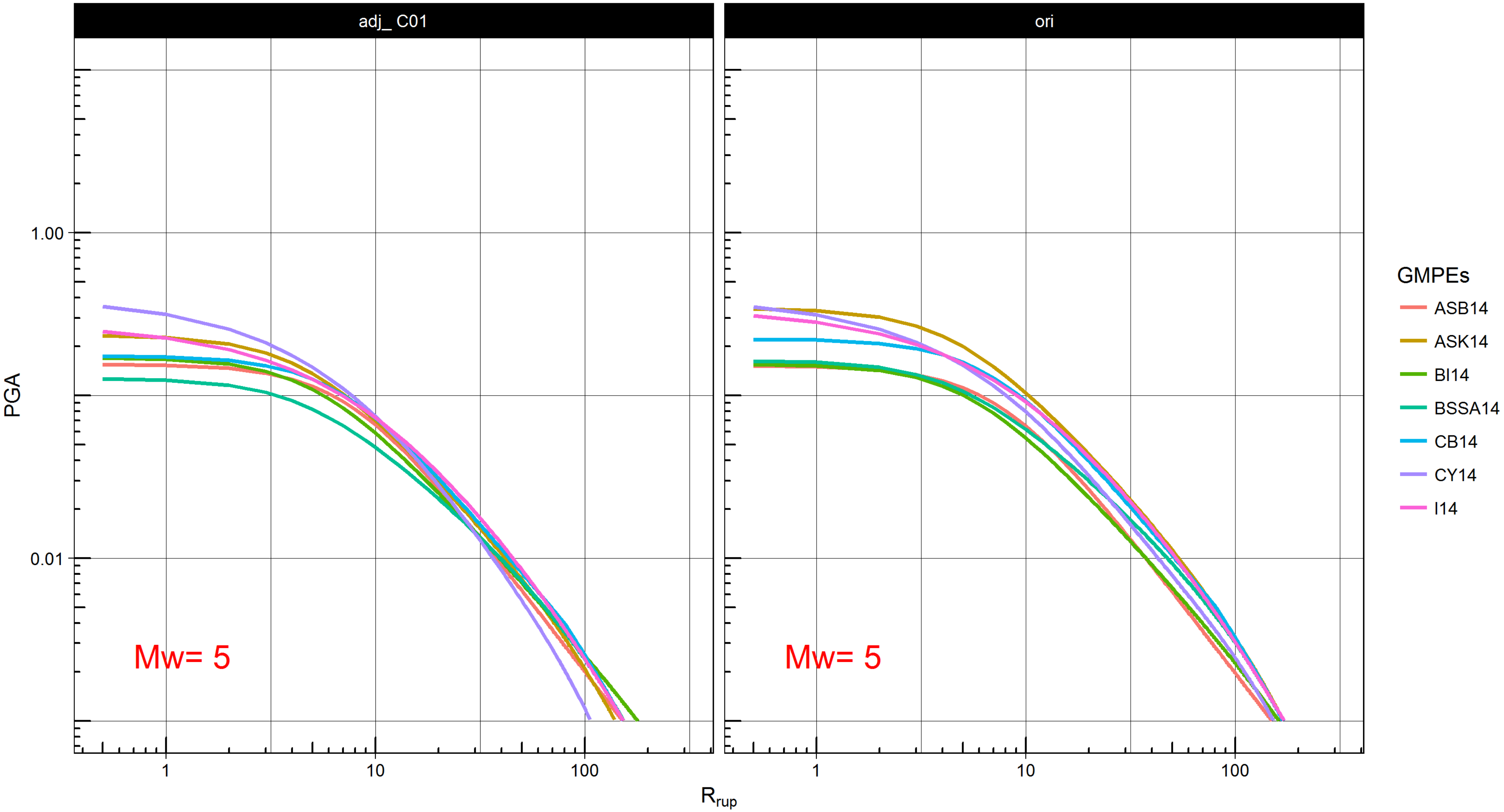
$$f_{site,G} = \begin{cases} c_{11} \ln\left(\frac{V_{S30}}{k_1}\right) + k_2\left\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln[A_{1100} + c]\right\}; & V_{S30} \leq k_1 \\ (c_{11} + k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right); & V_{S30} > k_1 \end{cases}$$

Summary of current adjust GMPEs – CB14

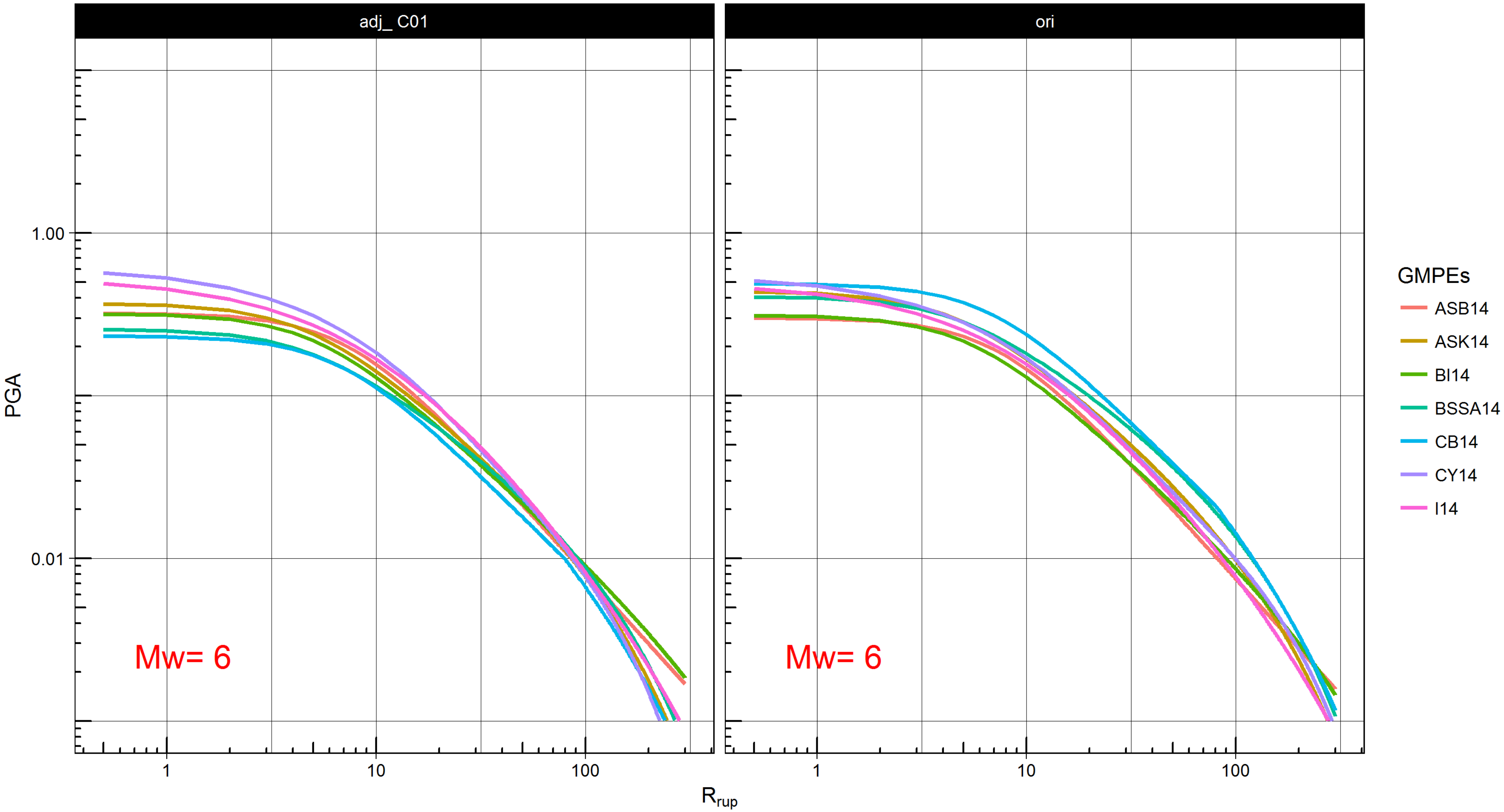
- **Compare the adjusted coefficient (C01) with the original**



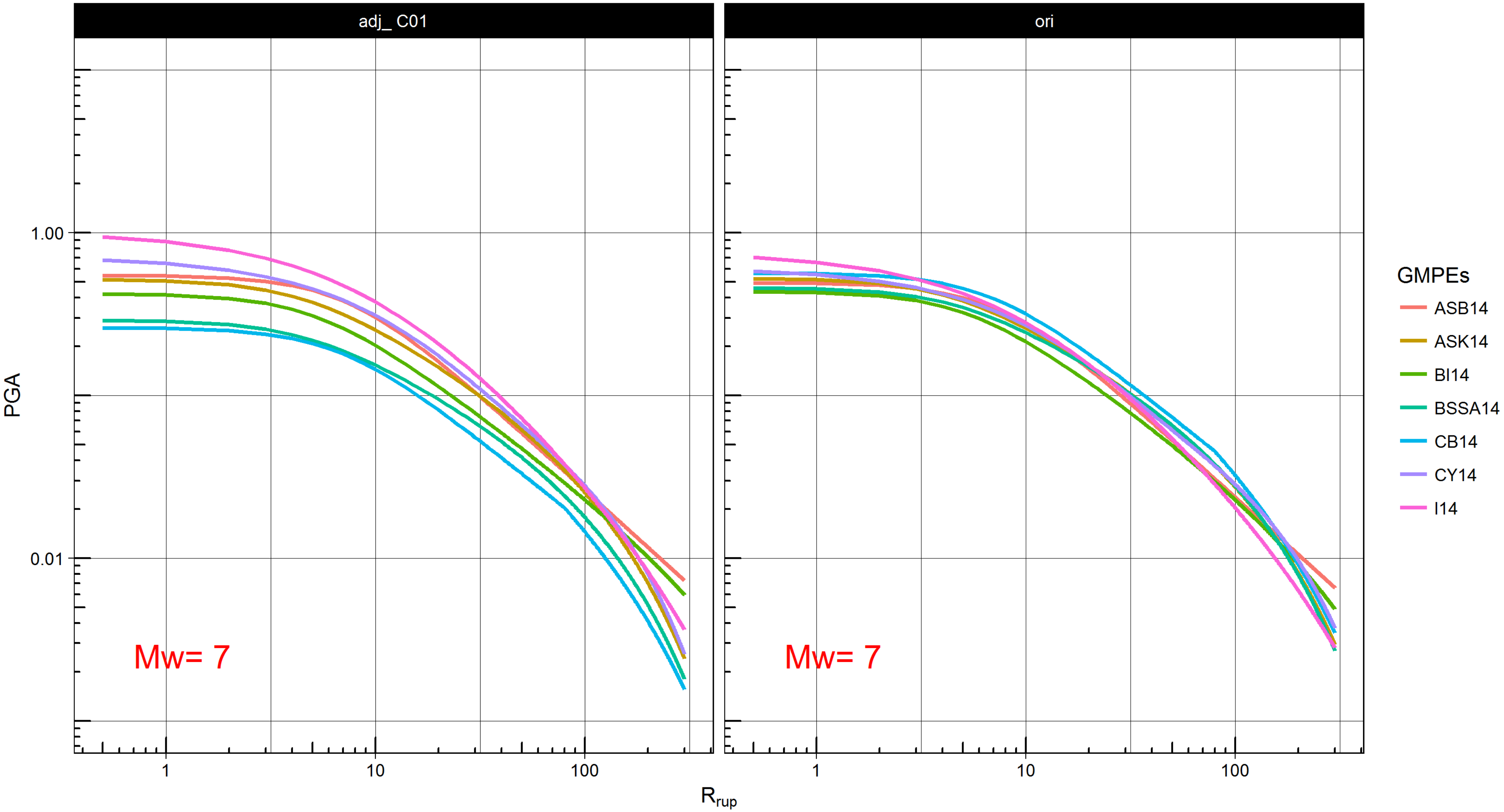
Comparison of the adjusted GMPEs



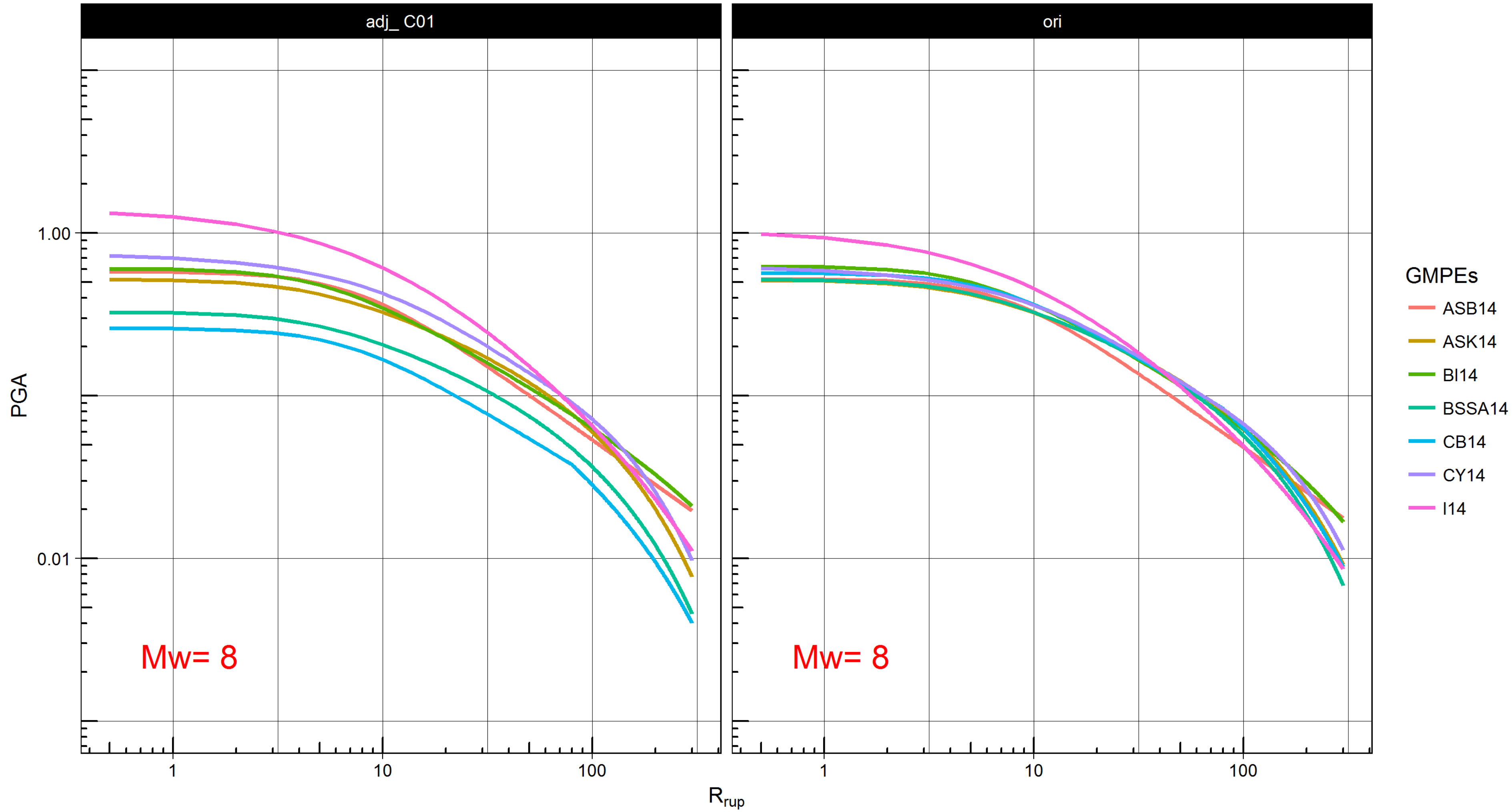
Comparison of the adjusted GMPEs



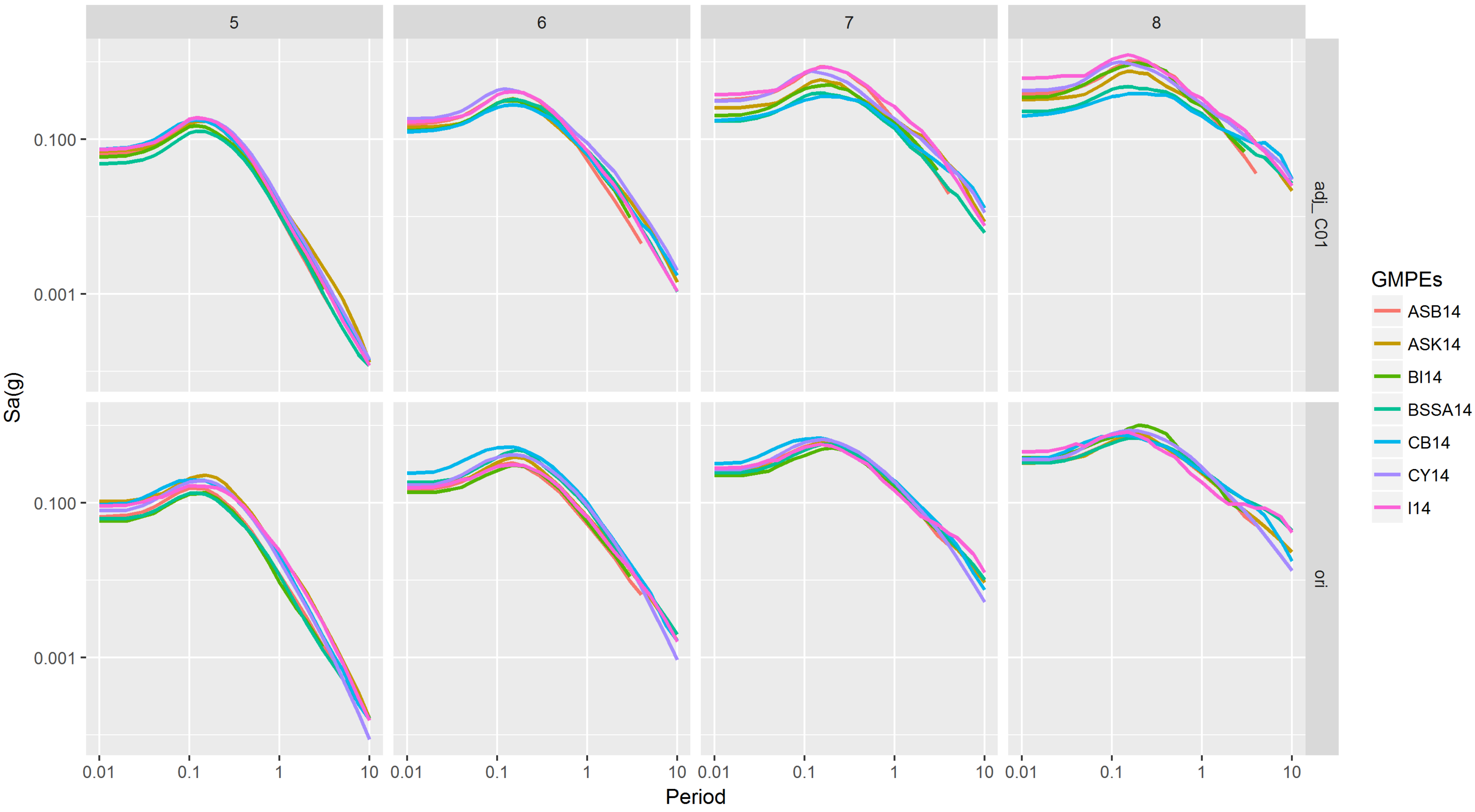
Comparison of the adjusted GMPEs



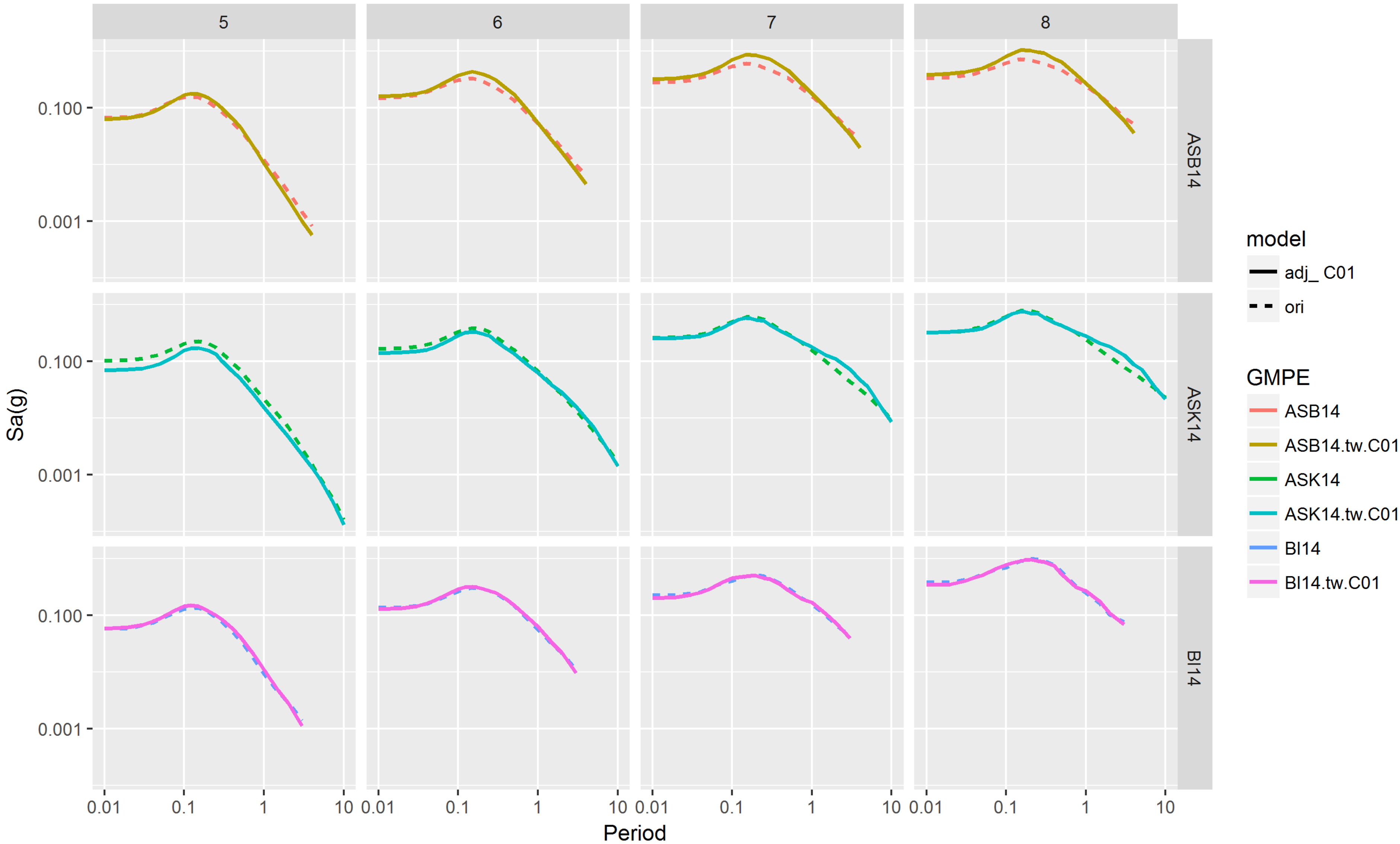
Comparison of the adjusted GMPEs



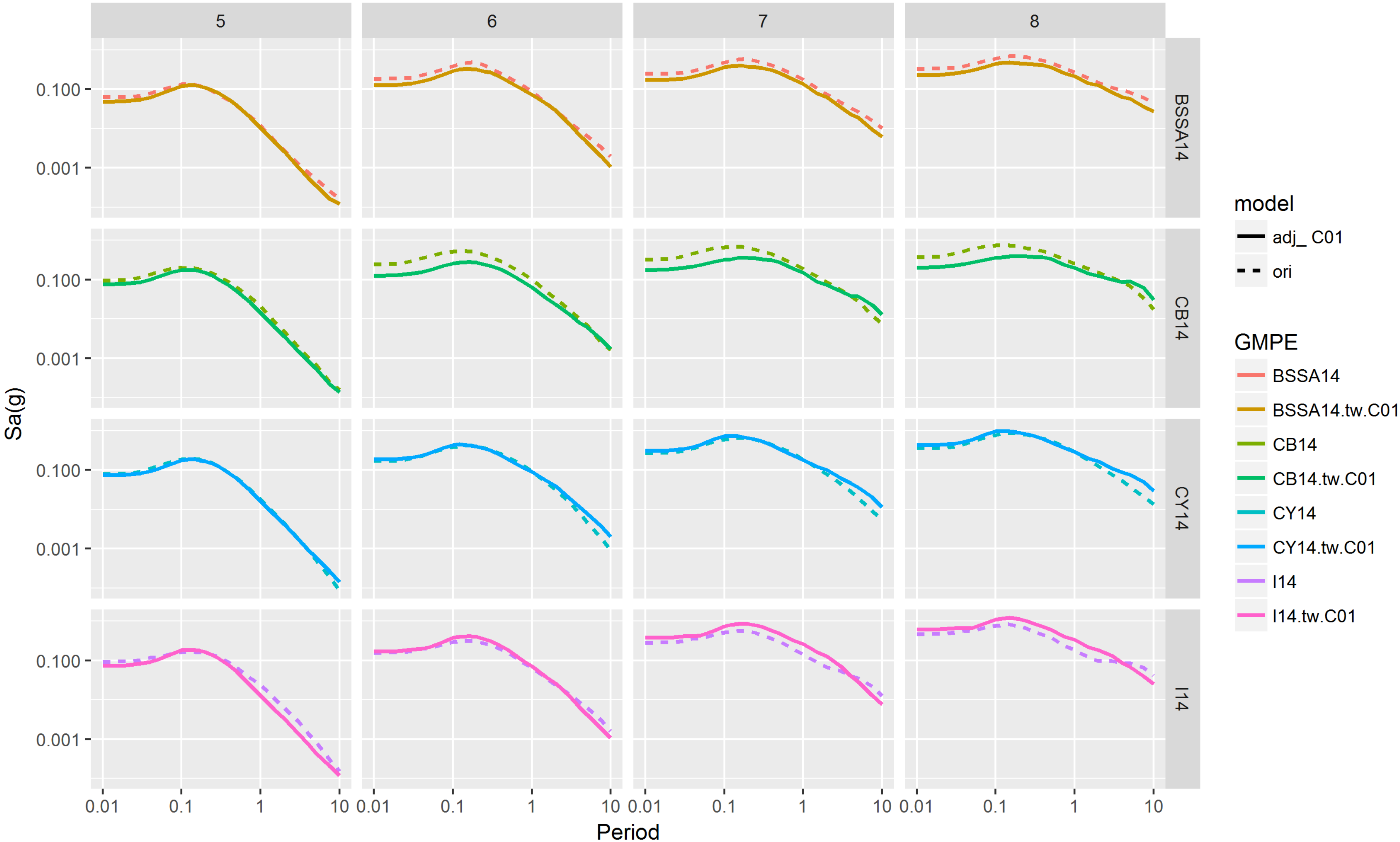
Comparison the spectrum of the adjusted GMPEs



Comparison the spectrum of the adjusted GMPEs



Comparison the spectrum of the adjusted GMPEs



Future work

- **Using the updated GM database.**
- **For GMPEs not defined to 10 sec, extrapolate the original GMPE to 10 sec (ASB14, BI14) and then adjust to Taiwan data**
- **Adjustment to the rest of the Crustal GMPEs: GK14, KAAH15**
  – Adjusting GK14 will be a challenge. It’s not certain it can be done.

Thank You for Your Attention !!

Questions ?