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Supplementary information

Past abrupt changes, tipping points and cascading impacts in the Earth system

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Annex 1. Calculation of abruptness rates

Our approach to calculate abruptness of changes during abrupt event follows the recent method[1]: we compare the rate of changes before the event and during the event. We calculate a ratio of these rates for the variable under consideration, such as atmospheric CO_2 concentration, and compare it with the ratio for the orbital forcing. The procedure is as follows. We define the abrupt event period T_{ab}, t_1 to t_2, and calculate rate of changes in variable under consideration, V(t), during abrupt period. Because of interannual variability in V(t), we use an average of variable of up to 200 years before and after the change to calculate the rate

$$R_{ab} = (\bar{V}(t_2) - \bar{V}(t_1))/(t_2 - t_1) \quad \text{(A1)}$$

For the reference period, T_{ref}, t_0 to t_1, which is taken much longer than the period of abrupt changes, the rate of V changes, R_{ref}, is calculated as a slope of linear interpolation using Python package *lmfit*. The abruptness of changes relative to the reference period, A_{ab}, is calculated as a ratio R_{ab} / R_{ref}. The higher the value of A_{ab}, the more abrupt are changes relative to the reference period. Let us note that abruptness A_{ab} calculated in this way is not limited to time scale of changes, e.g. decadal or centennial, but is defined relative to the changes during the reference period.

To compare with the abruptness of the orbital forcing F(t), we do the same procedure with the orbital forcing as above using a computational algorithm of long-term variations of insolation[2]. We use the same reference and abrupt change periods T_{ref} and $T_{ab.}$, respectively. Because interannual variability in orbital forcing is negligible, we skip averaging of forcing before and after change and calculate the rate of changes in orbital forcing during the abrupt change period, O_{ab}, as

$$O_{ab} = (F(t_2) - F(t_1))/(t_2 - t_1) \quad \text{(A2)}$$

For the reference period, T_{ref}, t_0 to t_1, the rate of orbital forcing changes, O_{ref}, is calculated as a slope of linear interpolation using Python package *lmfit*. The abruptness of changes relative to the reference period, A_{orb}, is calculated as a ratio O_{ab} / O_{ref}.

Finally, we calculate abruptness of changes in the variable relative to changes in the orbital forcing, A, as a ratio A_{ab} / A_{orb}. The values of intermediate variables and final rates are provided in Table A1 and illustrated in the Figure A1. To explain the procedure, let us follow an example of the Case 1 in the Table A1. The variable is atmospheric CO_2 concentration from the West Antarctic ice core[3]. The steps of calculating abruptness A are as follows:

- Firstly, from the CO_2 record, we visually defined an abrupt change period, 14.8 to 14.6 ka BP. Calculating average values in CO_2 during 200 years before the abrupt change, i.e. during 15.0 to 14.8 ka BP, and after the change, i.e. 14.6 to 14.4 kyr BP, we find an increase of 11.1 ppm during the abrupt change period. The rate of change R_{ab} is therefore 11.1 ppm/0.2 kyr, or 56 ppm kyr^{-1}. The average concentrations before and after the change are shown as black horizontal lines in Fig. 1 (left), while the black line connecting them indicate a slope of change.

- Secondly, we linearly interpolate CO_2 concentrations during the reference period which we define as 16.0 to 14.8 ka BP. The rate of increase during the reference period, R_{ref}, is 5.9 ppm kyr^{-1}, while a total change during the reference period is 7.1 ppm. The interpolation is shown as a blue line on Fig. 1, left. Consequently, $A_{ab} = R_{ab} / R_{ref}$ = 56 ppm kyr^{-1}/5.9 ppm kyr^{-1}=9.5. For the orbital forcing, we assume that the relevant characteristic is an incoming solar radiation averaged over July at 65°N. Results of calculated changes during the abrupt change period and reference period are shown on Fig. 1 (right). The abruptness of orbital forcing, A_{orb}, is calculated as 1.08.
- Finally, an abruptness of changes in CO_2 concentration relative to the changes in orbital forcing, A, is A_{ab} / A_{orb} =9.5/1.08, or 8.8.

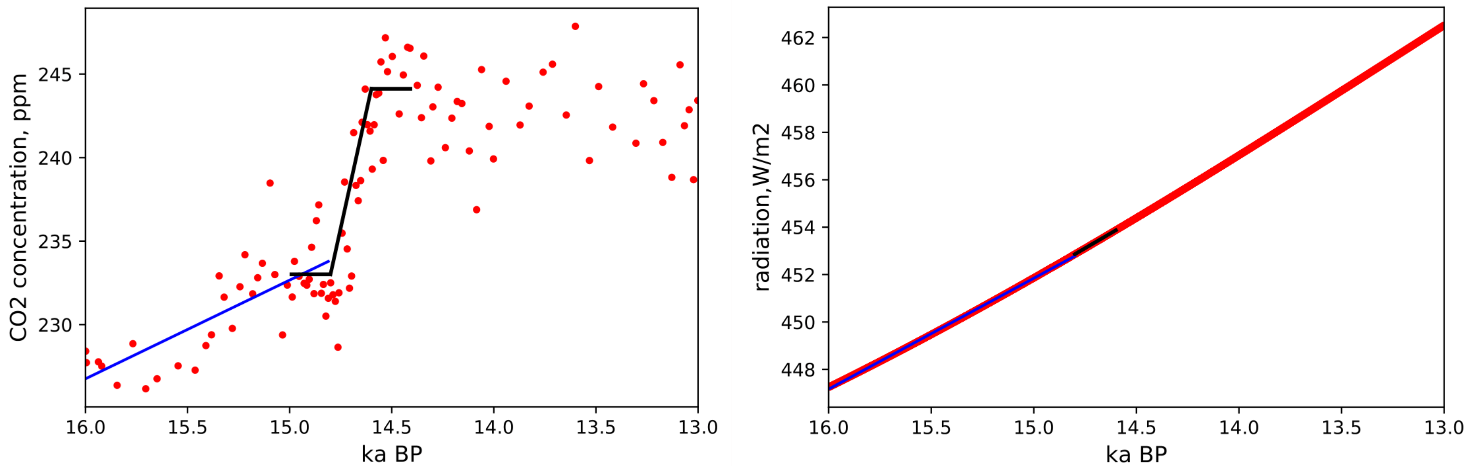
The abruptness of orbital forcing, A_{orb} is small (0.96-1.32), unless the reference period insolation change is small as for the case 7 of tree cover change in the Steel Lake record (2.45). Comparison of A_{ab} and A_{orb} shows that the change during the selected abrupt period is always substantially faster (3.4 to 89 times) than the change in orbital forcing. The abruptness A values in the Table A1 are in the range from 8 to 98, which we consider as significantly abrupt.

Table A1. Abruptness of changes for records shown in the Figure 3.

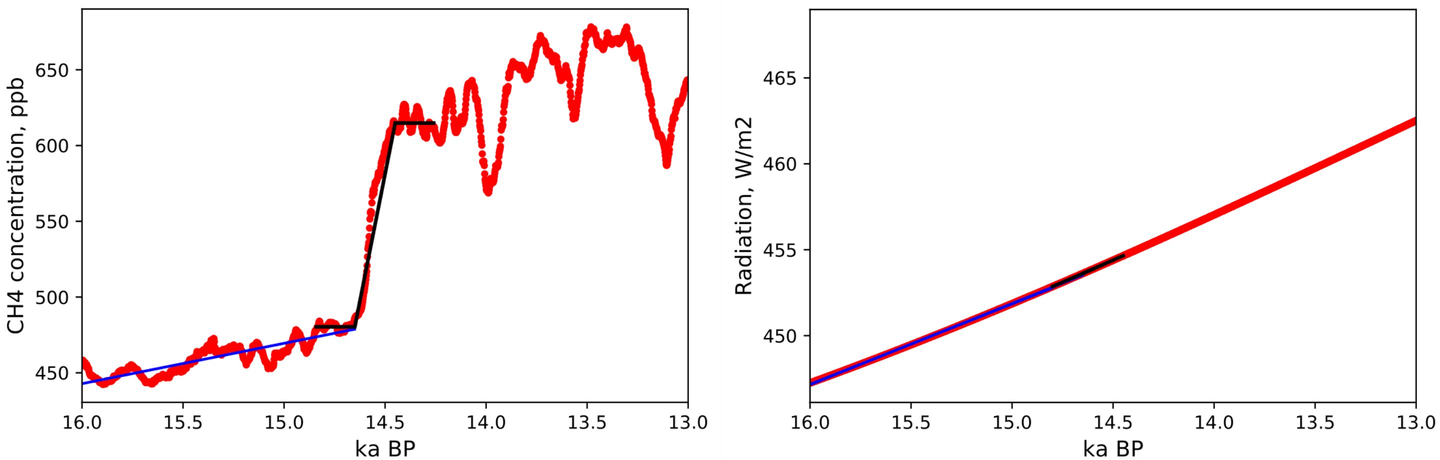
- The column “abrupt change period” shows: (i) the period with most abrupt changes, T_{ab}; (ii) the amplitude of changes during this period calculated as a difference between averages of periods before-and after change (shown as horizontal black lines on the Fig. A1); (iii) the rate of changes during abrupt period, R_{ab};
- The column “reference period” shows characteristics as above, but for the reference period T_{ref}, including rates of changes R_{ref};
- “Abruptness relative to the reference period”, A_{ab} is calculated as a ratio R_{ab} / R_{ref};
- “Abruptness of orbital forcing (latitude)”: A_{ref}, the ratio of rate of changes in the orbital forcing during the abrupt change period (black lines on Fig. A1 plots) to the rate of change in orbital forcing during the reference period (blue lines). In parentheses, a latitude used in calculation of the orbital forcing.
- “Abruptness relative to the orbital forcing”: A, or ratio A_{ab} / A_{ref}.

Case Nr.	Variable	Abrupt change period, amplitude of changes, rate of changes	Reference period, amplitude of changes, rate of changes	Abruptness relative to the reference period	Abruptness of orbital forcing (latitude)	Abruptness relative to the orbital forcing
1	Atmospheric CO_2 concentration, WAIS, ppm[3]	14.8 to 14.6 ka BP, 11.1 ppm, 56 ppm kyr^{-1}	16.0 to 14.8 ka BP, 7.1 ppm, 5.9 ppm kyr^{-1}	9.5	1.08 (65°N)	8.8
2	Atmospheric CH_4 concentration, WAIS, ppb[3]	14.65 to 14.45 ka BP, 134 ppb, 672 ppb kyr^{-1}	16.0 to 14.65 ka BP, 36 ppb, 27 ppb kyr^{-1}	25	1.09 (65°N)	23
3	AMOC strength, $^{231}Pa/^{230}Th$ ratio, ppt[4]	14.65 to 14.45 ka BP, 22 ppt, 107 ppt kyr^{-1}	16.0 to 14.65 ka BP, 1.5 ppt, 1.1 ppt kyr^{-1}	98	1.09 (65°N)	89
4	N. Pacific hypoxia, Bulimina exilis, %[5]	14.9 to 14.7 ka BP, 43%, 216% kyr^{-1}	16.0 to 14.9 ka BP, 3.7%, 3.4% kyr^{-1}	64	1.06 (55°N)	58
5	Sea level, Barbados, m[6]	14.4 to 13.6 ka BP, 23 m, 29 m kyr^{-1}	18.2 to 14.4 ka BP, 14 m, 3.7 m kyr^{-1}	7.8	1.35 (65°N)	5.8
6	Tree cover, Iberian margin, %[7]	15.0 to 14.5 ka BP, 27%, 54% kyr^{-1}	17.0 to 15.0 ka BP, 11%, 5.3% kyr^{-1}	10	1.1 (35°N)	9
7	Tree cover, Steel Lake, %[8]	8.3 to 7.9 ka BP, -41%, -103% kyr^{-1}	9.0 to 8.3 ka BP, -8.4%, -12% kyr^{-1}	8.6	2.45 (45°N)	3.4
8	Drought index, Chew Bahir basin, Africa[9]	7.9 to 7.7 ka BP, 1.11, 5.6 kyr^{-1}	9.0 to 7.9 ka BP, 0.41, 0.37 kyr^{-1}	15	1.32 (5°N)	11
9	Dust increase, ODP 658C, %[10]	5.6 to 5.3 ka BP, 13.5%, 45% kyr^{-1}	7.0 to 5.6 ka BP, 2.7%, 1.9% kyr^{-1}	24	1.10 (25°N)	22
10	Drought index (PDSI), Angkor[11]	0.63 to 0.6 ka BP, -3.6, -120 kyr^{-1}	0.7 to 0.63 ka BP, -0.87, -12.4 kyr^{-1}	9.7	0.96 (15°N)	10

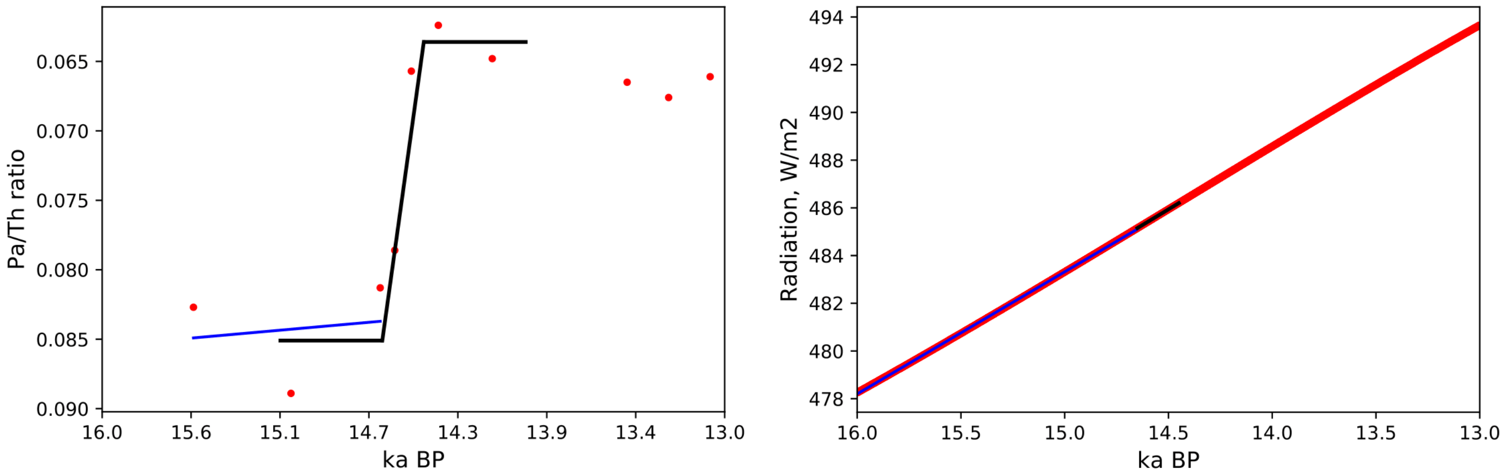
Figure A1. Graphical illustration of calculation of abruptness of changes in variables (left) and orbital forcing (right) for cases in Table A1. Red dots and lines are for variable and orbital forcing values, respectively. Blue line, trend in the reference period; black line – in the abrupt change period. For more details, see explanation of abruptness calculation above.



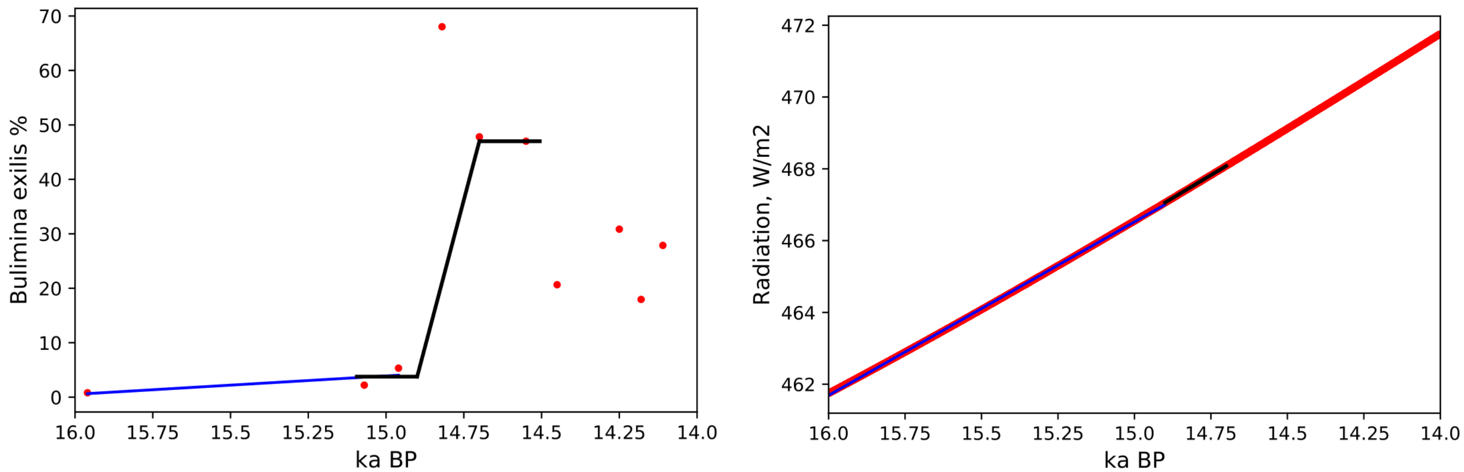
Case 1. Atmospheric CO_2 concentration, WAIS, ppm[3]. Abrupt series (left); orbital forcing (right).



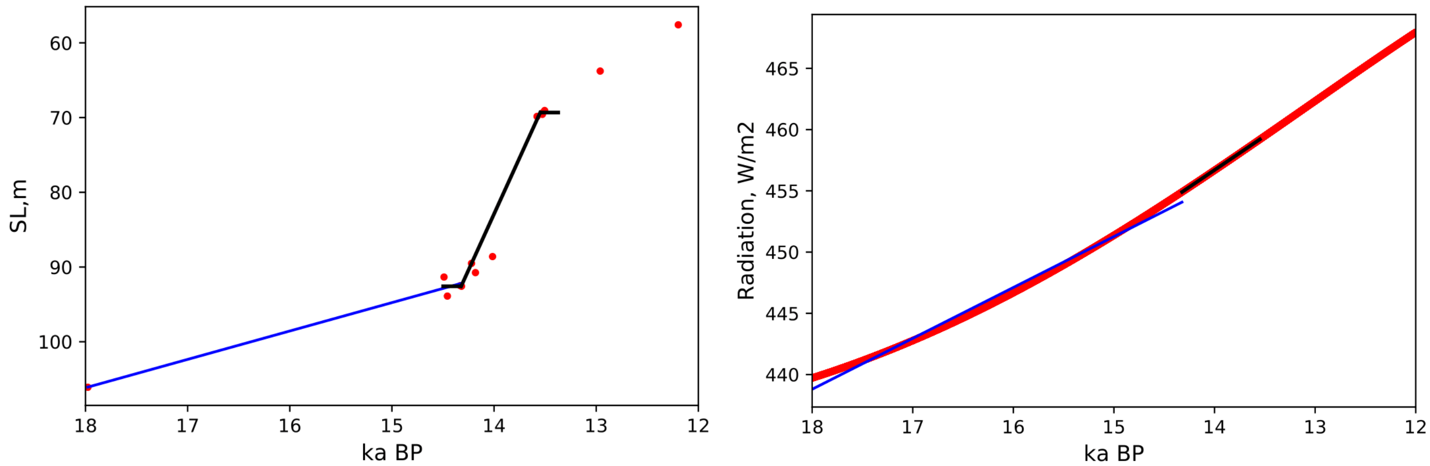
Case 2. Atmospheric CH_4 concentration, WAIS, ppb[3]. Abrupt series (left); orbital forcing (right)



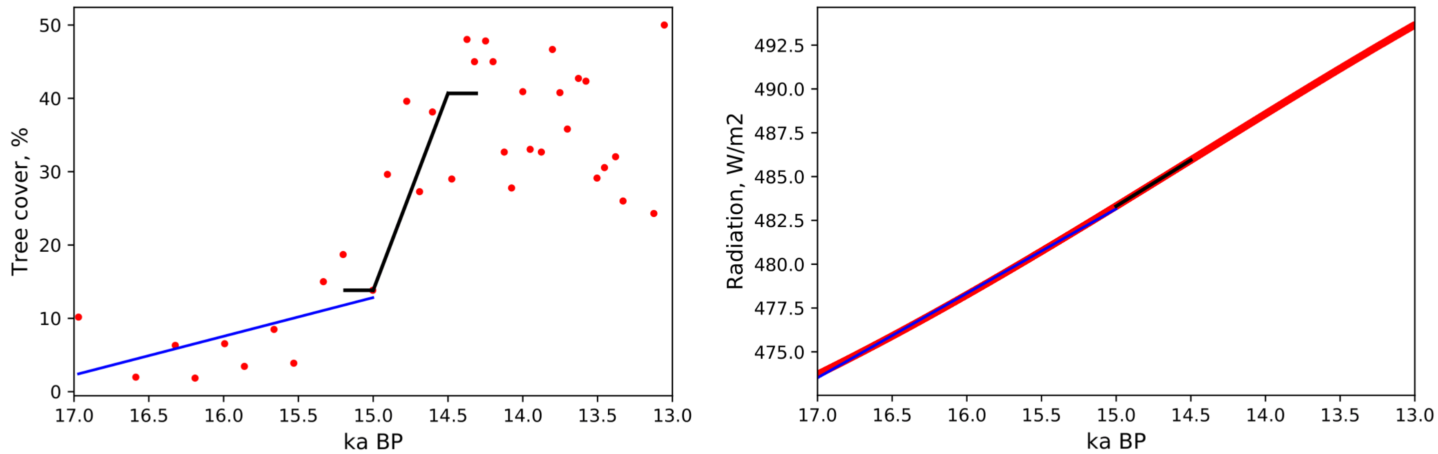
Case 3. AMOC strength, $^{231}Pa/^{230}Th$ ratio, ppt[4]. Abrupt series (left); orbital forcing (right)



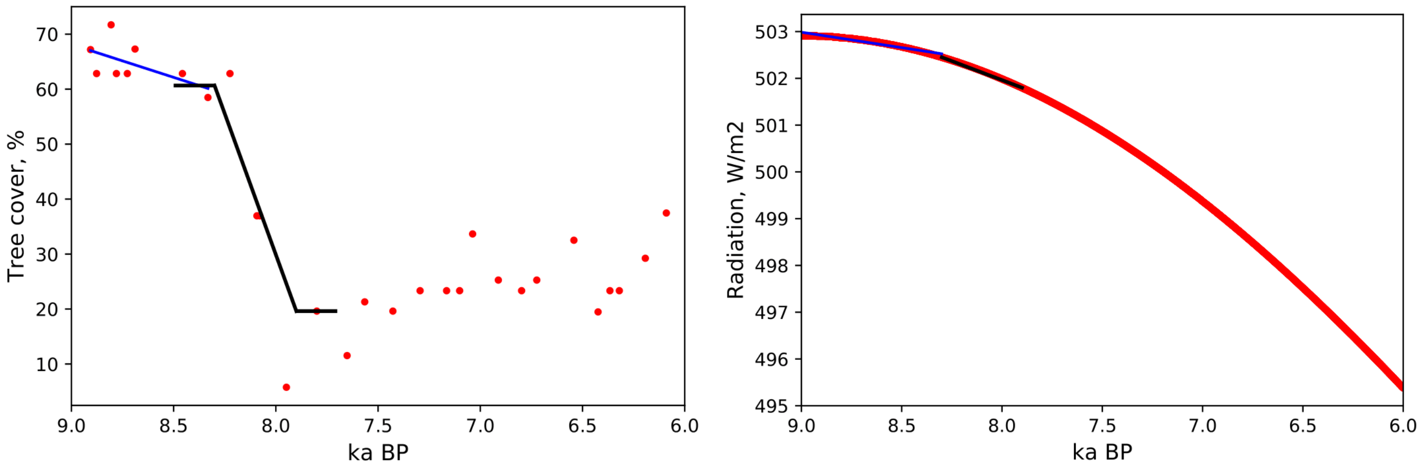
Case 4. N. Pacific hypoxia, Bulimina exilis, %[5]. Abrupt series (left); orbital forcing (right)



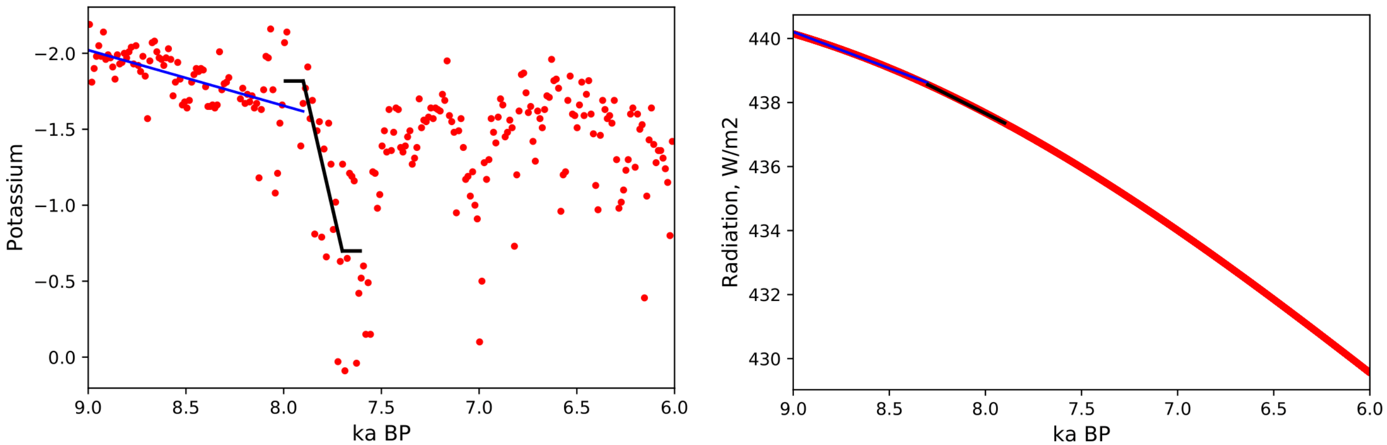
Case 5. Sea level, Barbados, m[6]. Abrupt series (left); orbital forcing (right)



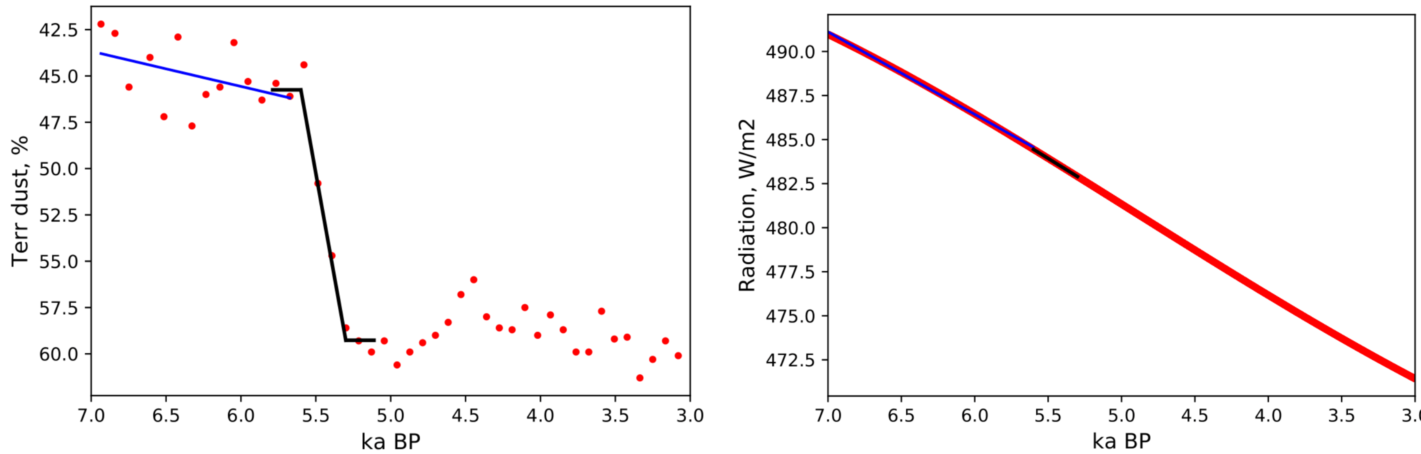
Case 6. Tree cover, Iberian margin, %[7]. Abrupt series (left); orbital forcing (right)



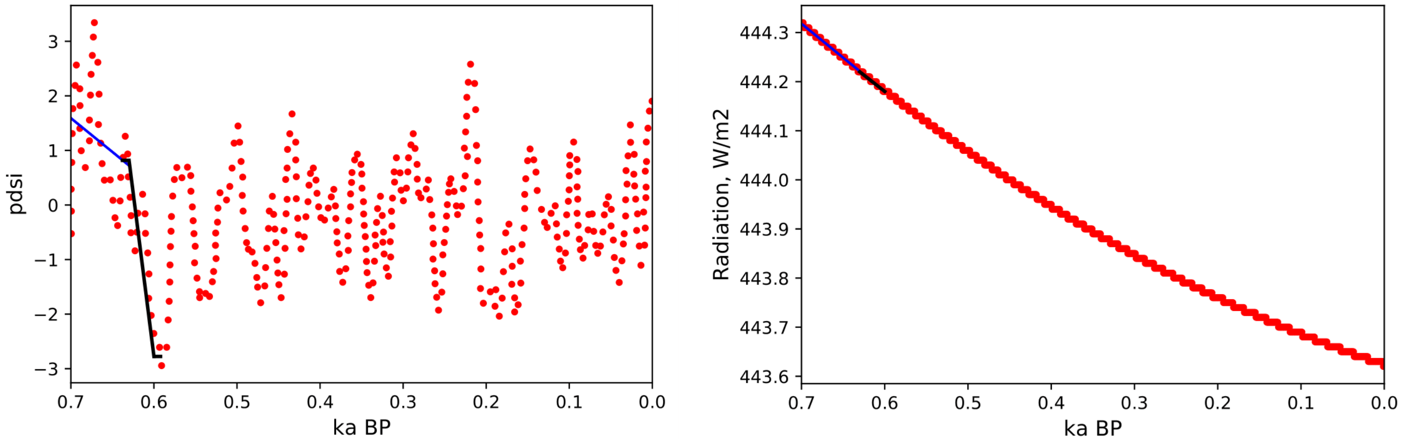
Case 7. Tree cover, Steel Lake, %[8]. Abrupt series (left); orbital forcing (right)



Case 8. Drought index, Chew Bahir basin, Africa[9]. Abrupt series (left); orbital forcing (right)



Case 9. Dust increase, ODP 658C, %[10]. Abrupt series (left); orbital forcing (right)



Case 10. Drought index (PDSI), Angkor[11]. Abrupt series (left); orbital forcing (right)

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