Reply to anonymous referee #1

We would like to thank our referee for the very helpful comments which will improve our manuscript! If not stated otherwise, our references to pages, figures, etc. are based on the submitted, not the revised manuscript in order to match the references of the reviewers. In the following, we quote the referee's comments one by one, each followed by our reply in italic font.

1.
The model contains a set of discrete coupled grid cells. A discussion of the continuum limit (increasing resolution of climate model) of the hot-spot idea would be relevant. This might also relate to the fundamental problem with climate models apparently incapable of showing multiple states.

We have added the following paragraph to Sect. 6:
"Models with higher spatial resolution could pose a more difficult challenge if hotspots consist of many grid cells whose signal is hard to distinguish from others. The demand of long time series to increase the significance of the results would be particularly problematic regarding the computing time for such higher resolution models. However, large hotspots can still be detected if the system is divided into larger parts (determined by parameter n_max) which would slow down the hotspot detection algorithm. As the increase in computing time of the algorithm results from the large number of possible combinations of elements that are considered independently, parallel computing could be applied to speed up the hotspot detection algorithm to some extent.

This issue relates to the problem of finding multiple steady states in the sense that they are difficult to find in complex models. Due to the vast number of variables in a global climate model, strategies like hysteresis experiments or choosing different initial conditions are no fail-proof methods. It can be speculated that this caveat is one reason why multiple steady states have not been found in the most complex models in contrast to low-dimensional models. The detection of different stable equilibria in PlaSim-VECODE turned out to be possible using our regression model. However, the applicability of such an approach is very limited: 1. In PlaSim-VECODE, the variability is large enough to sufficiently sample large parts of the phase space. 2. The regression can only be done in a limited area or for low resolution, otherwise too many regression coefficients would need to be estimated. 3. We based our regression model on the knowledge of V(P). In case of a more complex vegetation model, many more variables would be involved and the relationships would be less clear."*

2.
In the manuscript this is discussed in connection with the fact that the hotspot detection scheme cannot be applied directly to the climate model. Especially the sentence in p688, bottom seems to me to be central. The "claim" is that there might be multiple states, but internal variability is too large for the system to settle in any of these states. On which grounds can one argue that they are there?

There are several lines of evidence for our interpretation of multiple equilibria that are obliterated by the large variability:
1. PlaSim-VECODE, when coupled in equilibrium mode, shows multiple steady states depending on initial conditions. As the models are exactly the same as in transient mode, only that variability is reduced by the temporal averaging and return to equilibrium is immediate, we argue that the variability obliterates the multiple deterministic equilibria. This is what we refer to in the last paragraph on p. 688. Also see Bathiany et al. (2012a) for further explanations.

2. Without a large feedback that gives rise to multiple equilibria, there could be no vegetation collapse as the variability of P in PlaSim can be appropriately described by white noise. In this model, a collapse therefore implies a very strong P-V-feedback. Also see Bathiany et al. (2012a) for further explanations.
3. Equilibria can be determined in our regression models (which are based on experiments with PlaSim-VECODE in transient mode) and verified by choosing these solutions as initial conditions in equilibrium mode. This proves that the stability structure of the model is indeed the same in equilibrium and transient mode. See p693, l20-26 and p697, l13-26.

As the issue of different ways of coupling and the detection of multiple equilibria in PlaSim-VECODE has already been discussed in Bathiany et al. (2012a), while the focus of this manuscript is on the hotspot detection scheme, we have refrained from discussing these issues in more detail.

3.
The statement "Insofar, the prerequisit for an application of EWS-based analysis are in conflict with the case of PlaSim-VECODE-tr." and applying the method to the regression model as "an intermediate step" is unclear. As I understand it will never be possible to apply the method to the climate model, thus applying it to the regression model is the final step, where the results are then interpreted using the climate model. I might be mistaken, please clarify.

We agree and have removed the remark about the „intermediate step".

4.
Building simple effective models from GCMs is an important task. The RM1 and RM2 are interesting. It would, however, be nice to be able to judge their quality in equation (2) from scatter plots of P vs. V from which si and kij are obtained.

We now present some scatter plots in Sect. 3.2, Fig. 4 in our revised manuscript. Yet, the quality of the regression models is hard to judge from such scatter plots alone where only one of 53 predictor variables can be shown at a time. We therefore now also discuss the robustness of the regression models in Sect. 3.2 (while the robustness of the hotspots is discussed separately in Sect. 4):

"The equilibria coincide well with the green and desert equilibria found with PlaSim-VECODE-eq (Bathiany et al., 2012) which indicates that the regression model is of sufficient quality."
(...)
"Fig. 4 indicates that the relation between a certain Pi and Vj is generally rather weak. However, the large variations can partly be explained with the influence of the other 52 predictor variables which are not taken into account in Fig. 4. As the residuals of our regression are not Gaussian distributed and their variance depends on the predictors (heteroscedasticity), we refrain from calculations of errors or confidence intervals. Instead, we test the robustness of our results towards changes in the predictor variables:
Excluding certain time slices from PlaSim-VECODE-tr (e.g. 9 k, 8.5 k and 8 k at the same time) and/or including the 5.5 k experiment to determine the regression parameters for RM1 leads to similar results with regard to the system's stability properties. Also, slight changes in the selected grid cells to build RM1 (for example, excluding the rather stationary cells near the mediterranean and the 4 most northern grid cells) do not alter the properties of the regression model substantially. This even holds true if we replace the original PlaSim-VECODE time series by a set of 20\,000 bootstrapped pairs of P and V (Efron, 1979). However, some of these alternative regression models show additional bifurcations in RM1. Nonetheless, the main bifurcation point at

which most elements of the system collapse in synchrony always occurs.
The persistent tendency of RM1 to show more bifurcations than PlaSim-VECODE may result from intrinsic limitations of our linear fit. For example, orbital forcing and its impact on annual precipitation does not change linearly over time.

In contrast, RM2 behaves more robustly as its 8 elements (80 coefficients) allow a more reliable regression than the 52 elements of RM1 (2808 coefficients). All elements in RM2 collapse in synchrony, regardless of the choice of time slices or the realization in our bootstrapping experiments.“

5.
I do not particularly like the term “toy model” (or “surrogate” for that matter) to characterize the regression model. Consider “simple model”, “low order model” or just “regression model”.

We now refer to the regression model and do not use the other terms anymore.

6.
Reference to a figure in another paper (not Part 1) is annoying. It would be nice with a P(recipitation)-V*(egetation) plot here. In this case perhaps with the modified VECODE shape of V*(P) (and thus omitting eq (1) which is not in use here (?)

We have included the figure as suggested (Fig. 1 in the revised manuscript).
However, we would like to keep Eq. (1) in the manuscript for several reasons:
1. to explain that the second condition is dropped in the regression models (p691, l5)
2. to explain how we treated the growing degree days (GDD0) when deriving the regression parameters and to explain why their fluctuations can be neglected (p691, l24 - p692, l8).
3. to explain how we determine the fixed points of RM2 (Fig. 5) and to allow reproducibility of these results.

7.
A discussion of the difference in running the model in the transient and the equilibrium modes would be nice. Especially what is the physics behind the different time scales of the vegetation.

We have added the following paragraph to Sect. 2:
“The asynchronous coupling corresponds to the limit of infinitely fast vegetation dynamics so that there is no timescale separation between P and V anymore. In addition, the variability of P (the fast subsystem) is averaged out and replaced by its mean response. This way, the stable deterministic equilibria of the slow part of the system can be identified as the system is always very close to these equilibria.
In this sense, the interactive timescale of several years in PlaSim-VECODE-tr and the large variability provide a more realistic case. However, the relationship of climate and vegetation timescale in the model is an empirical fit to observations from different ecosystems that may not be directly transferable to changes in time at one and the same location. As it is our aim to investigate the stability properties of PlaSim-VECODE rather than its realism, we accept this limitation as a side-effect of the model's simplicity.“

8.
Fig 1: “light red” is referred to as “orange” in text. “purple” is blue on my printer, consider helping readability by using less specific color nuances.

We now distinguish red and purple in Fig. 1, its caption and the text. We keep the purple area purple to avoid confusion with areas of different colour (in particular, blue) in the other figures. As red and purple are the only colours in Fig. 1, the purple area should be recognisable even if it may look blue on some printers or screens.

9.
Fig 2: Would you dare indicate curves for the supposed unstable steady state? (in panel 1 beginning at 0.3, merging with the stable equilibrium around 6K?)

Unfortunately the regression models cannot be solved analytically because of the nonlinear shape of V. Therefore, we use the numerical approach of choosing different initial conditions to find the stable equilibria. To find the unstable equilibria, more sophisticated methods would be needed. As our analysis focusses on the analysis of stable equilibria before their disappearance, we argue that the identification of the unstable equilibria would not add relevant information. We therefore do not show them.*