Authors' Response to Referee Comment #2

To the authors' best understanding, the following 10 major concerns are extracted from the comments by the Anonymous Referee #2, which are listed and replied separately below.

Comment #1: In fact, the region under scrutiny has a seasonally dry climate, with the wetter season mostly coinciding with the growing season. Hence, it is not surprising that vegetation green up date is best described by hydrologic indices rather than by thermal ones. Low temperatures may delay green up, but in absence of water no green up can occur in such a dry climate. Because rainfall generally begins in May, it is likely that rainfall occurrence (and not temperature) is the main driver of vegetation activity (and indeed in very dry years green up does not occur at all).

Response: *It may be not surprising that vegetation green up can be best described by water indices rather than by thermal ones in Inner Mongolia. But it has no straightforward answer for general semi-arid areas. In fact, the searching for the dominant factors of vegetation phenology and its possible transition under climate change is important and attracted a lot of research attentions. The authors found the following papers discussing the dominance of factors over vegetation phenology in semi-arid area, i.e., Yu et al., 2003; Yu et al., 2010; Shen et al., 2011 (the detail bibliography is listed in the References part below). These work shows that the dominant factor varies among places with similar semi-arid climatic condition. For example, Yu et al (2003) studied response of seasonal vegetation development to climate variations in eastern central Asia, the results showed that for desert steppe both March temperature and May precipitation are significant variables contributing to the variance in the observed onset dates. While for typical steppe, precipitation in May and June is the most important factor determining the onset date of green-up. Yu et al. (2010) used an explanatory model for the beginning of the growing season for both steppe and meadow, the results indicate that onset of growing season on Tibetan Plateau is advanced by high temperature in May and June, while high temperatures during October and March have a delaying effect on spring phenology. Studies of Shen et al. (2011) on Tibetan Plateau grassland showed that the effect of precipitation on the onset of green-up onset were significant in areas with high mean annual precipitation index and low variation. And impact of temperature on vegetation phenology varied among parts of the plateau. Generally, the existing natural vegetation in an area is the result of long-term evolution and adaption to the environment including soil, climate, topography, hydrology and so on. Therefore, the vegetation should present some stable phenophases for a specific area, and be subject to variation due to the fluctuation of environmental factors. Also, for this reason the dominant factor for vegetation phenology could change year by year (as illustrated in Fig. 8 in the revised manuscript) and eventually present a new pattern in a region*

under the changed environment, i.e., water dominating could change to thermal dominating. The judgment of dominating factors and its change for a site and especially for a region is rather complex.

Therefore, in our following work we are developing a new method for the dominating analysis on vegetation phenology based on the proposed environmental indices (TSO and SMSO), which convert the controls of thermal and hydrological conditions on green-up to potential green-up onset dates and made it possible to compare the dominating controls directly. Here are some initial results:

$$\begin{cases} ADI = \sum_{i=1}^{n} DI_i \\ DI = 1 \quad if \quad TSO - SMSO > 0 \\ DI = -1 \quad if \quad TSO - SMSO < 0 \end{cases} \quad (1)$$

where, DI is the dominant index, ADI is the accumulated dominant index (the summed dominant index for a long time) , n is the number of years. If TSO is larger than SMSO, the potential green-up onset date controlled by temperature is later than that controlled by soil moisture, which means the dominant factor is temperature; otherwise the dominant factor is soil moisture. So, if DI=1, the dominant factor is temperature; if DI=-1, the dominant factor is soil moisture. Using ADI accumulating DI over the study period, we can get the long term dominant factor. Our results in Inner Mongolia is shown in the following figure, which indicates that there are 7 stations with ADI=-25 (stations in blue), means there was no fluctuation of dominant factor in the 25 years. The other stations experienced fluctuation more or less.
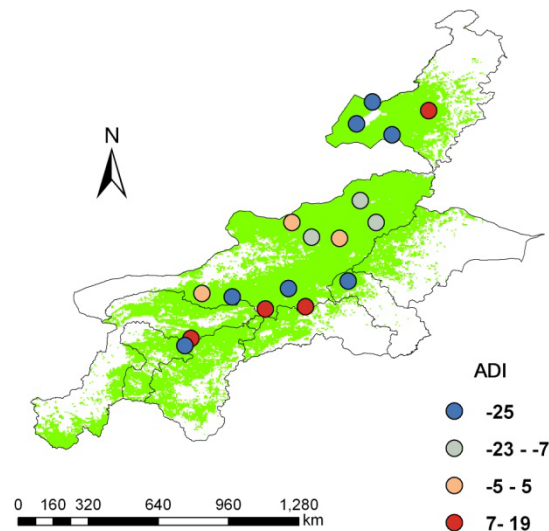

Figure 1 ADI of the stations within Inner Mongolia grassland (1982-2006)

Comment #2: Furthermore, it is not surprising that soil moisture is a better predictor of green up (and plant water status in general) than cumulated precipitation.

Response: *Yes, we agree with the Referee that soil moisture is a straightforwardly better predictor of green up. Also, in the traditional vegetation phonology studies*

based on ground measurements, soil moisture is frequently used as the surrogate for water condition (e.g., Nielsen and Jørgensen, 2003). But in the recent regional scale vegetation phenology studies based on remote sensing technologies, water condition is surprisingly always represented by precipitation other than soil moisture. The possible reason could be the unavailability of soil moisture measurement at the larger (e.g. regional) spatial scale, which could be overcome by recent advances of macro-scale hydrological models. The purpose of this paper is just to explore the potential of simulated soil moisture by proposing a series of environmental indices.

Comment #3: Moreover, in its present form, the model cannot serve as a predicting tool, i.e., to explore the effects of climate change, as somehow implied by the authors in some sentences.

Response: *There are two places in the manuscript mentioning potential predictability of the method we proposed: (1) "The understanding about the relative controls on grassland phenology, and the effectiveness of alternative indices to capture these controls, are important for future studies and predictions of vegetation phenology change under climate change." on page 11642, and (2) "On the basis of the procedures adopted in this study to derive environmental indices, we can foresee their potential application for the prediction of Green-up Onset Date under future climate change." on page 11658.*
There might be some misunderstanding about the 'prediction' as to the comment. The term prediction here refers not to the prediction of vegetation green-up onset data itself, but to the prediction of the future potential green-up onset date, which is a reflection of control of factors in the future. To the authors' understanding, it is reasonable to predict future SMSO and TSO based on the hypothesis that the demand of thermal/hydrological conditions of a specific vegetation is stationary in the near future. However, the two sentences are revised as following to avoid confusion.
(1)"The understanding about the relative controls on grassland phenology, and the effectiveness of alternative indices to capture these controls, are important for future studies of vegetation phenology change under climate change."
(2) The sentence on page 11658 was deleted in the revised manuscript.

Comment #4: In fact, the length of the period over which the soil moisture, precipitation or temperature are summed up to obtain the index and the last day of summation depend on the observed green up day.

Response: *We agree with the Referee that the last day of summation depends on the observed green up day. But after that we still have the questions that on which day we should start the accumulation and how long the time span is. In the traditional degree-day concept, one assumes a threshold, i.e. 0 degree, if the temperature is above 0 then it can be accumulated. The question we would ask then is that how could we know that 0 degree is the "true" threshold for vegetation, and whether the time span determined by this threshold is a reasonable one. Besides, the current studies on*

the relationships between green-up onset date and various factors usually summed up temperature/precipitation over a fixed period (i.e. March-May), but the vegetation may already greened in the middle of May. The fixed period is not a good choice and would make the analysis more complicated. The problem is partially fixed by introducing a new optimization algorithm by Shen et al. (2011), which is the starting point of our study. It is based on the assumption that the requirement of thermal/hydrological accumulation before green-up is a certain value for a specific vegetation, and that it is still a relatively constant value in the near future under the current climate change condition. The methodology is illustrated in section 2.4.1 and 2.4.2.

Comment #5: Similarly, running VIC to get soil moisture will require information on plant status and, specifically, on transpiration rate, so that VIC itself requires an assumption/observation on the greening status of vegetation. As such, the proposed methodology can be used to assess which is the dominant driver in green up day at different locations (i.e., under different combinations of temperature and precipitation), but not in a prognostic manner as there is no guarantee that the results of the maximization algorithm will hold also under future climates. Nevertheless, as pointed out above, currently the manuscript achieves rather predictable results.

Response: *It is difficult to get regional observation data of soil moisture, so the distributed hydrological model maybe best choice at hand. We agree with the Referee that there is a logical conflict to predict the potential change of vegetation phenology with the assumption that vegetation is stationary in the VIC model. We acknowledge that the final solution for such conflict is to develop the fully coupled eco-hydrological model as illustrated by the pioneering work by Eagleson in his famous book titled by "Ecohydrology: Darwinian Expression of Vegetation Form and Function". The authors also developed a state-of-the-art fully coupled model for a hyper-arid riparian vegetation system (see Liu et al., 2012), but without the consideration of phonological phases of vegetation. In fact, it is really difficult to develop such fully coupled model considering the phenology at the regional scale, and it is a reasonable simplification for such analysis under current situation, just like what the researchers have done in relating variations in runoff to variations in climatic conditions and catchment properties (see Roderick and Farquhar, 2011; and Wang and Hejazi, 2011).*

Comment #6: There are some indications of interannual variability in temperature rise and rainfall occurrence. For this reason (and two avoid issues with observed trends – see below), it would be a lot more interesting and probably also more correct to consider the problem year by year, developing a methodology that does not require optimization over multiple years and that allows presenting results relative to single years as opposed to averages over more than two decades. This would allow clarifying the dominance level of the factors at play year by year.

Response: *As we have explained in Response to Comment #4, the optimization process is aiming at looking for the best time span and corresponding accumulation threshold. Once we have the threshold and time span, the following calculation of SMSO and TSO is independent of the optimization and can indeed be carried out year by year. We totally agree with the Referee's comment to develop a methodology that could present results at annual scale, which is what we are doing following this study as described in the Response to Comment #1 (we could get the dominant index for each year by the newly proposed method).*

Comment #7: I also have some concerns regarding the method itself: - While dehardening processes may indeed be driven by cumulated degree days, the same concept may not be fully applicable to precipitation. In fact (as also shown by the results of the paper) plants respond to soil water availability: precipitation is the main input to the soil water balance, but losses via runoff or deep infiltration may reduce soil water availability with passing time; hence, cumulated rainfall is likely not to be a good predictor of green up, unless the focus is on a very short period of time.

Response: *We agree with the Referee that the accumulation method may be not appropriate for precipitation, because it is not the exact water that vegetation could make use. But in the current large scale vegetation phenology studies, precipitation is usually used by summing up over a certain period to analyze its control on phenology change. Here in our study we summed precipitation in the optimal time span just for comparison purpose with the soil moisture based index, and our results proved that soil moisture is a better choice than precipitation when analyzing the control of water condition on grass green-up.*

Comment #8: The typical values of optimal summing period, Nmax, are not reported in the manuscript, but figure 3 suggests that Nmax may span several weeks. - The results are presented as averages over the period 1982-2006, with the optimization algorithm trying to maximize the agreement between model prediction and observed days of green up over the entire period. However, as clarified in Fig. 8, the area witnessed an increasing trend in temperature over the period, with possible repercussions on the most dominant driver and timing of green up. I wonder if this averaging over the period is appropriate given this clear trend.

Response: *Our study is based on the hypothesis that the requirement of thermal/hydrological condition for a specific vegetation is constant in decades. That means the threshold and optimal time span we achieved from the maximizing process are inherent characteristics and can be applicable at the time scale we concerned. Given the threshold and time span, if the area gets warmer, the TSO will happen earlier (the threshold and time span will not change).*
For the Nmax, we didn't report Nmax in manuscript or in figures. The final potential green-up dates relating to soil moisture, precipitation, and temperature are reported and compared in the figures.

Comment #9: As noted also by the authors, it is most likely that Mongolian grasses respond to a combination of thermal and hydrologic cues, and that the dominance of one or the other likely varies from year to year. The authors include the combination of thermal and hydrologic indices in section 2.5, but it remains obscure to me how this result is achieved and whether the methodology can provide information on the degree of dominance of one factor over the other.

Response: *To solve the fixed time span problem, in this research we adopted concept of TSO (Shen et al., 2011), and developed a similar index SMSO to depict the soil moisture controls on the green-up. From the calculation processes of the two indices we could see that they have different optimal time spans, i.e., N_T and N_{SM}. The regression model we used in section 2.5 is based on hypotheses of a dominant factor, and the variables in that regression equation will be accumulated over the optimal time span of the dominant environmental factor. As shown in equation (12) of the manuscript, both soil moisture and temperature are summed up over time span of N_{SM}, as we assumed that soil moisture is the dominant factor. Then we could decide a better assumption by comparing the regression efficiencies, i.e., the environmental factor with the highest regression efficiency is the dominant factor in the study period. Compared with the current regression models, the advantage of the model we proposed in section 2.5 is that it avoid the fixed time span problem by using the variables summed over the optimal time span. Indeed, we acknowledge that the regression model in section 2.5 could not tell us the degree of dominance of one factor over the other. The new work should be done to quantify the dominance level, which is our ongoing work as illustrated in Response to Comment #1.*

Comment #10: Finally, I would like to add a few comments on the presentation of material. Several sections are unnecessarily long, including general definitions (e.g., of phenology beyond the case of vegetation) and details, that are not very relevant for the problem at hand. At the same time, the (many) figures are generally only briefly described and over-detailed with respect to the amount of information provided in the text and figure caption. Therefore, I suggest that number of figure should be reduced and the remaining figures should be described in more detail. Figures 1 and 4 are two examples of figures that could be removed without loss of information (Fig. 4 could be easily substituted by a measure of the agreement between observed and modeled discharges). Figure 3 is good example of a very detailed figure lacking explanations, both in the caption and text.

Response: *Many thanks to the Referee for the suggestions about the presentation of material, and we revised the manuscript by following the suggestions.*
(1)The suggestion about Fig. 4 is quite right, and we delete it in the revised version.
(2)About Fig. 3, we add more explanations in the text (see section 2.4.2 in the revised manuscript)
For the definition of phenology, since the readers in HESS are mostly hydrological

persons and may be not familiar with phenology terms, the authors think that it is necessary to describe the concept at the very beginning of this paper. We would like to keep it to avoid possible difficulties for the readers.

For the Figure 1, it shows the location of the study area and basic information of meteorological and hydrological stations, as well as the distribution of grassland. Though there is not much interesting information, this kind of figure is useful to give a general knowledge to the readers as frequently adopted in the literature. So we would like to keep it in the revised manuscript.

References

[1] Liu, D., Tian, F., Hu, H., Lin, M., and Cong, Z.: Ecohydrological evolution model on riparian vegetation in hyperarid regions and its validation in the lower reach of Tarim River. Hydrol. Process., 26, 2049-2060, doi:10.1002/hyp.8313, 2012.

[2] Nielsen, C.N., F.V., Jørgensen.: Phenology and diameter increment in seedlings of European beech (*Fagus sylvatica L.*) as affected by different soil water contents: variation between and within provenances. For. Ecol. Manage., 174, 233-249, doi: 10.1016/S0378-1127(02)00042-7, 2003.

[3] Roderick, M. L., and Farquhar, G. D.: A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties. Water Resour. Res., 47, doi:10.1029/2010wr009826, 2011.

[4] Shen, M., Tang, Y., Chen, J., Zhu, X., and Zheng, Y.: Influences of temperature and precipitation before the growing season on spring phenology in grasslands of the central and eastern Qinghai-Tibetan Plateau. Agric. For. Meteorol., 151(12): 1711-1722, 2011.

[5] Wang, D., and Hejazi, M.: Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States, Water Resour. Res., 47, doi:10.1029/2010wr010283, 2011.

[6] Yu, F., Price, K.P., Ellis, J., and Shi, P.: Response of seasonal vegetation development to climatic variations in eastern central Asia. Remote Sens. Environ., 87(1): 42-54, 2003.

[7] Yu, H., Luedeling, E., and Xu, J.: Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. PNAS, 107, 22151-22156, doi:10.1073/pnas.1012490107, 2010.