

Supplemental Materials for: Impacts of land-use change and elevated CO₂ on the interannual variations and seasonal cycles of gross primary productivity in China

Binghao Jia^{1,2,3}, Xin Luo¹, Ximing Cai³, Atul Jain⁴, Deborah N Huntzinger⁵, Zhenghui Xie¹, Ning Zeng^{1,6}, Jiafu Mao⁷, Xiaoying Shi⁷, Akihiko Ito⁸, Yaxing Wei⁷, Hanqin Tian⁹, Benjamin Poulter¹⁰, Dan Hayes¹¹, Kevin Schaefer¹²

¹State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

²Key Lab of Guangdong for Utilization of Remote Sensing and Geographical Information System, Guangzhou Institute of Geography, Guangzhou, China

³Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

⁴Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, Illinois, USA

⁵School of Earth Sciences and Environmental Sustainability and Department of Civil Engineering, Construction Management, and Environmental Engineering, Northern Arizona University, Flagstaff, Arizona, USA

⁶Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, USA

⁷Environmental Sciences Division, Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

⁸Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Japan

⁹International Center for Climate and Global Change Research and School of Forestry and Wildlife Sciences, Auburn University, Auburn, Alabama, USA

¹⁰NASA GSFC, Biospheric Sciences Laboratory, Greenbelt, MD, USA

¹¹School of Forest Resources, University of Maine, Orno, Maine, USA

¹²National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, Colorado, USA

Correspondence to: Binghao Jia (bhjia@mail.iap.ac.cn)

1 Models and data

In this study, we used twelve terrestrial biosphere models (TBMs) that participated in the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) (Huntzinger *et al.*, 2013; Wei *et al.*, 2014a, 2014b) to investigate the effects of climate change, land use and land cover change (LULCC), and rising CO₂ concentration on the temporal changes in GPP. These models are Community Land Model version 4 (CLM4; Shi *et al.*, 2011; Mao *et al.*, 2012), CLM4 with Variable Infiltration Capacity Runoff Parameterization (CLM4VIC; Lei *et al.*, 2014), Dynamic Land Ecosystem Model (DLEM; Tian *et al.*, 2011, 2012), Global Terrestrial Ecosystem Carbon model (GTEC; Ricciuto

et al., 2011), Integrated Science Assessment Model (ISAM; Jain *et al.*, 2013), Lund-Potsdam-Jena Dynamic Global Vegetation Model, Swiss Federal Research Institute WSL modification (LPJ-wsl; Sitch *et al.*, 2003), Organizing Carbon and Hydrology in Dynamic Ecosystems (ORCHIDEE-LSCE; Krinner *et al.*, 2005), Simple Biosphere version 3 by Jet Propulsion Laboratory (SiB3-JPL; Baker *et al.*, 2008), SiB3 with Carnegie-Ames-Stanford Approach (SiBCASA; Schaefer *et al.*, 2008), Terrestrial Ecosystem Model version 6 (TEM6; Hayes *et al.*, 2011), Vegetation Global Atmosphere and Soil version 2.1 (VEGAS2.1; Zeng *et al.*, 2005), and Vegetation Integrative Simulator for Trace gases (VISIT; Ito and Inatomi, 2012), respectively. They were all forced by the same climate drivers, LULCC, and CO₂ data. The climate forcing data set was generated by combining the Climate Research Unit (CRU) data and the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) Reanalysis product (hereafter CRU-NCEP). Time-series data for atmospheric CO₂ concentration derived from observations were applied to SG3, and other simulations used constant CO₂. A merged product derived from a static satellite-based land cover product, SYNergetic land cover MAP (SYNMAP) (Jung *et al.*, 2006) and the time-varying land use harmonization version 1 (LUH1) data (Hurtt *et al.*, 2011) from the fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) were used to describe historical LULCC.

2 Analysis methods

The nonparametric Mann-Kendall method was used to determine the statistical significance of trends in Chinese and regional GPP (area-weighted), where the Sen median slope (Sen, 1968) was considered as the trend value in this paper. Trend analysis was based on annual values averaged from monthly values. The first step was to test for statistical significance of trends by computing the Mann-Kendall statistic S . Each data value was compared with all subsequent data values as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(GPP_j - GPP_k), \quad (1)$$

$$\text{sgn}(GPP_j - GPP_k) = \begin{cases} 1, & GPP_j > GPP_k \\ 0, & GPP_j = GPP_k \\ -1, & GPP_j < GPP_k \end{cases}, \quad (2)$$

where n is the length of the record for a given grid cell or region. The variance of S (Eq. (3)) was then calculated to test for the presence of a statistically significant trend using the Z -value (Eq. (4)):

$$\text{var}(S) = \frac{1}{18} [n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5)], \quad (3)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\text{var}(S)}}, & S < 0 \end{cases}. \quad (4)$$

where q is the number of tied groups and t_p is the number of data values in the p^{th} group. The statistic Z was compared with a tolerable probability (the default significance level was set to 0.05 in this study). If a linear trend was statistically significant, then the change per unit time was estimated using a simple nonparametric procedure developed by Sen (1968):

$$b_{\text{sen}} = \text{Median}\left(\frac{GPP_j - GPP_k}{j - k}\right), j > k. \quad (5)$$

If there were n values of GPP_j in the time series, as many as $n(n-1)/2$ slope estimates could be obtained, and b_{sen} was taken as their median.

Each region's relative contribution to the interannual variation (IAV) and seasonal cycle amplitude (SCA) of China's GPP was also calculated based on the method proposed by Ahlström *et al.* (2015) and Chen *et al.* (2017). The regional contribution R_j ($j=1,2, \dots,9$) to the IAV of China's GPP was calculated using the following equations:

$$f_i = \frac{\sum_t \frac{A_i x_{i,t} |X_t|}{X_t}}{\sum_t |X_t|}, \quad (6)$$

$$X_t = \sum_i A_i x_{i,t}, \quad (7)$$

where $x_{i,t}$ is the GPP anomaly for region i in year t , A_i is the area of region i , and X_t is the area-weighted total GPP anomaly in the whole of China in year t . By this definition, f_i is the average relative area-weighted anomaly $A_i x_{i,t} / X_t$ for region i , weighted by the absolute regional area-weighted anomaly $|X_t|$. f_i ranges from -1 to 1. Higher positive f_i indicates that IAV in the region varies in phase with integral IAV and makes a larger contribution towards the IAV of China's GPP, whereas a smaller or negative f_i represents the opposite. In the same way, the regional contribution to the seasonality of China's GPP was calculated using Eq. (6), in which $x_{i,t}$ is the monthly GPP departure from the annual mean (seasonal anomaly) for region i in month t and X_t is the area-weighted total seasonal GPP anomaly for all China in month t .

Figures

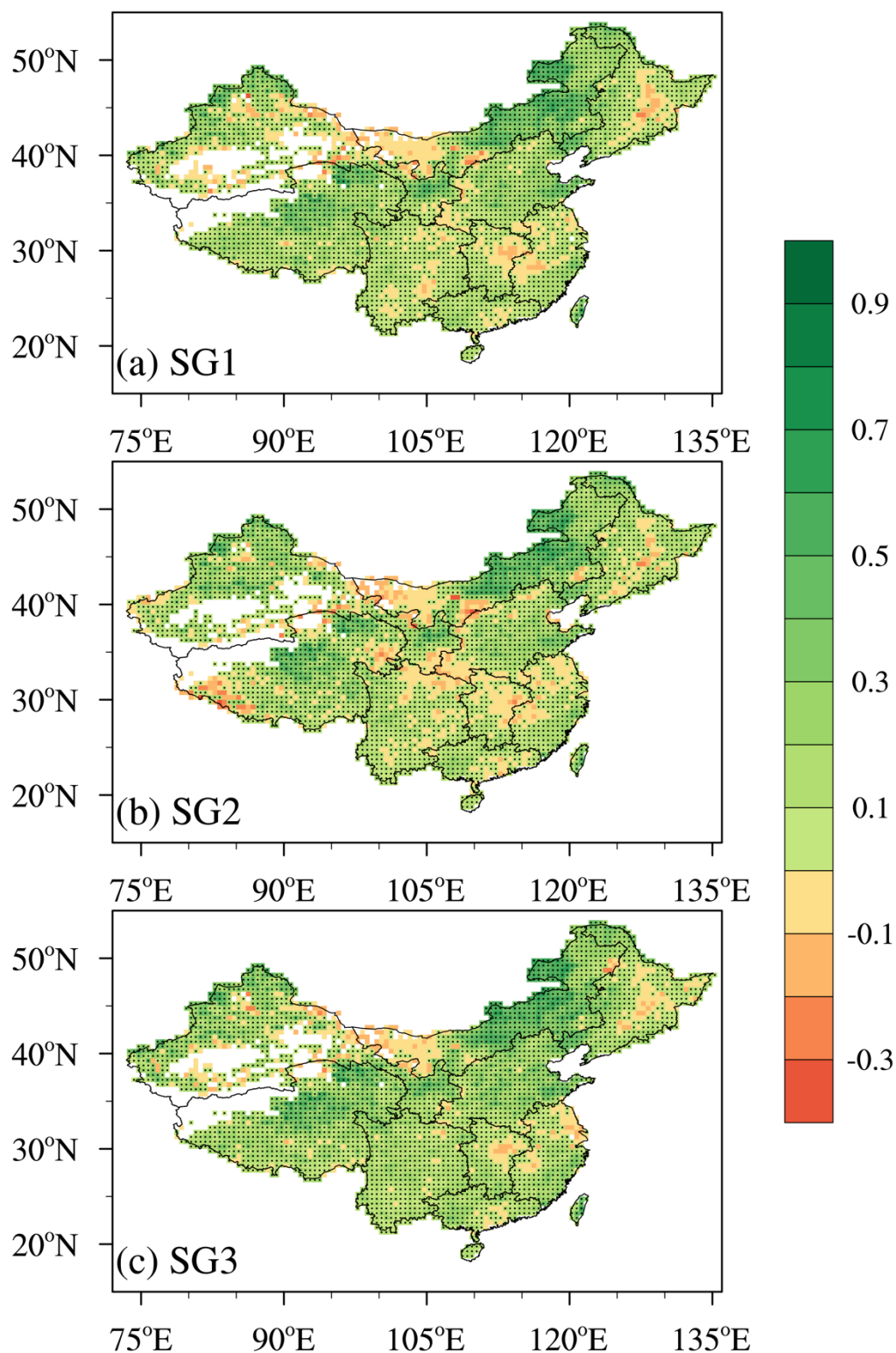


Figure S1. Spatial patterns of temporal correlation coefficients between annual GPP from MTE and that from ensemble mean of MsTMIP simulations for the period of 1982–2010, including: (a) SG1, (b) SG2, and (c) SG3. Stippling highlights regions with significant correlations ($p < 0.05$).

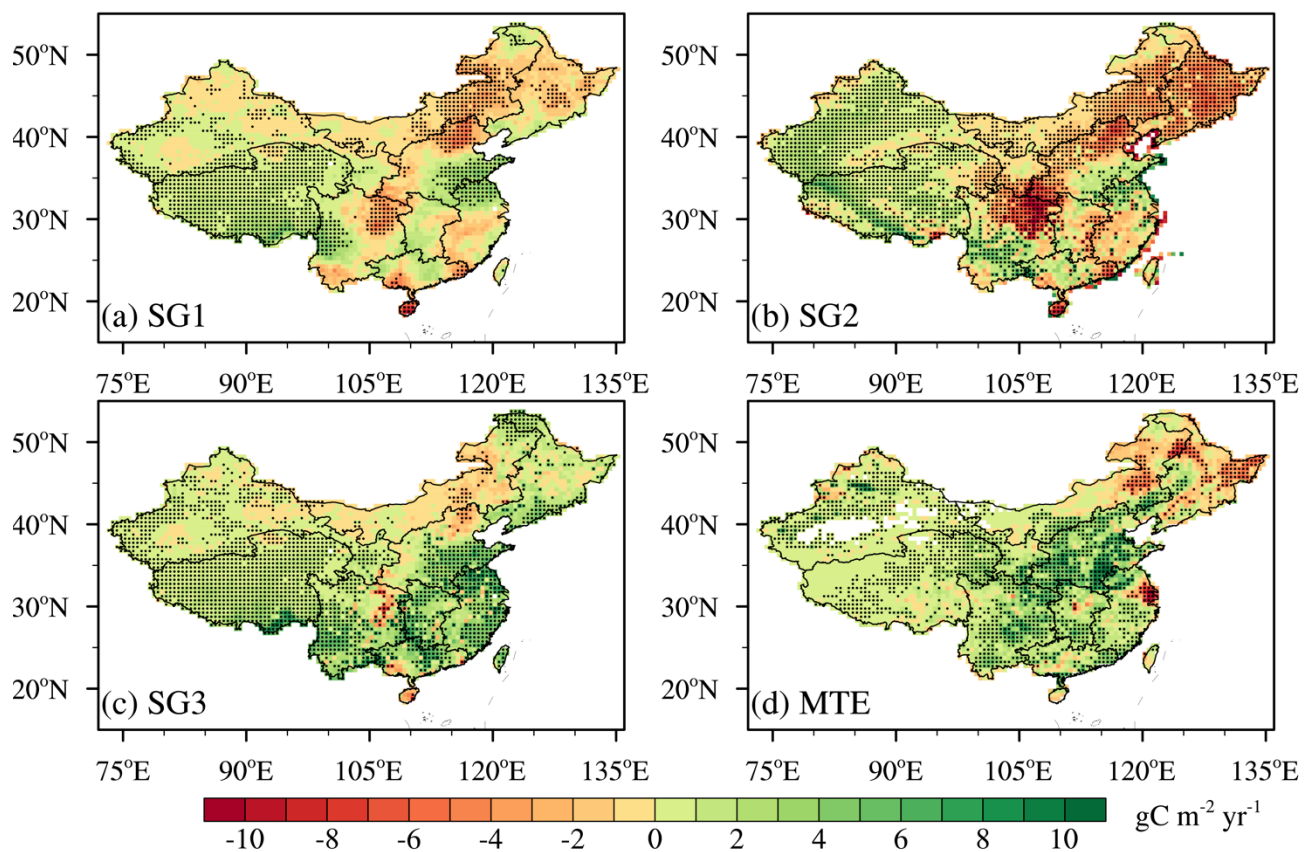


Figure S2. Trends in annual GPP between 1982 and 2010 from the ensemble mean of MsTMIP simulations: (a) SG1, (b) SG2, (c) SG3 and (d) MTE. Stippling highlights regions with significant trend ($p < 0.05$).

References

- Ahlström, A., Raupach, M., Schurgers, G., Smith, B., Arneth, A., Jung, M., Reichstein, M., Canadell, J., Friedlingstein, P., Jain, A., Kato, E., Poulter, B., Sitch, S., Stocker, B., Viovy, N., Wang, Y., Wiltshire, A., Zaehle, S., and Zeng, N.: The dominant role of semi-arid ecosystems in the trend and variability of the land CO₂ sink, *Science*, 348(6237), 895–899, 2015.
- Baker, I. T., Prihodko, L., Denning, A. S., Goulden, M., Miller, S. and da Rocha, H. R.: Seasonal drought stress in the Amazon: reconciling models and observations, *J. Geophys. Res.*, 113, G00B01, doi: 10.1029/2007JG000644, 2008.
- Chen, M., Rafique, R., Asrar, G. R., Bond-Lamberty, B., Ciais, P., Zhao, F., Reyer, C. P. O., Ostberg, S., Chang, J., Ito, A., Yang, J., Zeng, N., Kalnay, E., West, T., Leng, G., Francois, L., Munhoven, G., Henrot, A., Tian, H., Pan, S., Nishina, K., Viovy, N., Morfopoulos, C., Betts, R., Schaphoff, S., Steinkamp, J., and Hickler, T.: Regional contribution to variability and trends of global gross primary productivity, *Environ. Res. Lett.*, 12, 105005, 2017.
- Hayes, D. J., McGuire, A. D., Kicklighter, D. W., Gurney, K. R., Burnside, T. J. and Melillo, J. M.: Is the northern high-latitude land-based CO₂ sink weakening? *Global Biogeochem. Cycles*, 25, GB3018, doi: 10.1029/2010GB003813, 2011.
- Huntzinger, D. N., Schwalm, C., Michalak, A. M., Schaefer, K., King, A. W., Wei, Y., Jacobson, A., Liu, S., Cook, R. B., Post, W. M., Berthier, G., Hayes, D., Huang, M., Ito, A., Lei, H., Lu, C., Mao, J., Peng, C. H., Peng, S., Poulter, B., Ricciuto, D., Shi, X., Tian, H., Wang, W., Zeng, N., Zhao, F., and Zhu, Q.: The North American Carbon Program Multi-scale Synthesis and Terrestrial Model Intercomparison Project: Part 1: overview and experimental design, *Geosci. Model Dev.* 6, 2121–2133, 2013.
- Hurt, G. C., Chini, L., Frolking, S., Betts, R., Edmonds, J., Feddema, J., Fisher, G., Goldewijk, K. K., Hibbard, K., Houghton, R., Janetos, A., Jones, C., Kinderman, G., Konoshita, T., Riahi, K., Shevliakova, E., Smith, S. J., Stefest, E., Thomson, A. M., Thornton, P., van Vuuren, D., and Wang, Y.: Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands, *Clim. Change*, 109, 117–161, doi:10.1007/s10584-011-0153-2, 2011.
- Ito, A., and Inatomi, M.: Water-use efficiency of the terrestrial biosphere: A model analysis focusing on interactions between the global carbon and water cycles, *J. Hydrometeorol.*, 13(2), 681–694, 2012.
- Jain, A. K., Meiyappan, P., Song, Y., and House, J.: CO₂ emissions from land-use change affected more by nitrogen cycle, than by the choice of land-cover data, *Global Change Biol.*, 19, 2893–2906, doi: 10.1111/gcb.12207, 2013.

- Jung, M., Henkel, K., Herold, M., and Churkina, G.: Exploiting synergies of global land cover products for carbon cycle modeling, *Remote Sens. Environ.*, 101, 534–553, doi:10.1016/j.rse.2006.01.020, 2006.
- Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P.,
5 Sitch, S., and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, *Global Biogeochem. Cycles*, 19, GB1015, doi: 10.1029/2003GB002199, 2005.
- Lei, H., Huang, M., Leung, L. R., Yang, D., Shi, X. Mao, J., Hayes, D. H., Schwalm, C. R., Wei, Y., and Liu, S.: Sensitivity of global terrestrial gross primary production to hydrologic states simulated by the community land model using two runoff parameterizations, *J. Adv. Model Earth Syst.*, 6, 658–679,
10 2014.
- Mao, J., Thornton, P. E., Shi, X., Zhao, M. and Post, W. M.: Remote sensing evaluation of CLM4 GPP for the period 2000–09, *J. Clim.*, 25, 5327–5342, doi:10.1175/JCLI-D-11-00401.1, 2012.
- Piao, S., Fang, J., Ciais, P., Peylin, P., Huang, Y., Sitch, S., and Wang, T.: The carbon balance of terrestrial ecosystems in China, *Nature*, 458, 1009–1013, 2009.
- 15 Ricciuto, D. M., King, A. W., Dragoni, D. and Post, W. M.: Parameter and prediction uncertainty in an optimized terrestrial carbon cycle model: effects of constraining variables and data record length, *J. Geophys. Res.*, 116, G01033. doi: 10.1029/2010JG001400, 2011.
- Schaefer, K., Collatz, G. J., Tans, P., Denning, A. S., Baker, I., Berry, J., Prihodko, L., Suits, N., and Philpott, A.: Combined Simple Biosphere/Carnegie-Ames-Stanford Approach terrestrial carbon cycle
20 model, *J. Geophys. Res.*, 113, G03034, doi: 10.1029/2007JG000603, 2008.
- Sen, P. K.: Estimates of the regression coefficient based on Kendall’s tau, *J. Amer. Stat. Assoc.*, 63, 1379–1389, 1968.
- Shi, X., Mao, J., Thornton, P. E., Hoffman, F. M. and Post, W. M.: The impact of climate, CO₂, nitrogen deposition and land use change on simulated contemporary global river flow, *Geophys. Res. Lett.*, 38, L08704. doi: 10.1029/2011GL046773, 2011.
25
- Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplans, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K., and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, *Global Change Biol.*, 9, 161–185, 2003.
- 30 Tian, H., Chen, G., Zhang, C., Liu, M., Sun, G., Chappelka, A., Ren, W., Xu, X., Lu, C., Pan, S., Chen, H., Hui, D., McNulty, S., Lockaby, G., and Vance, E.: Century-scale responses of ecosystem carbon storage and flux to multiple environmental changes in the southern United States, *Ecosystems*, 15, 674–694, 2012.

- Tian, H., Xu, X., Lu, C., Liu, M., Ren, W., Chen, G., Melillo, J., and Liu, J.: Net exchanges of CO₂, CH₄, and N₂O between China's terrestrial ecosystems and the atmosphere and their contributions to global climate warming, *J. Geophys. Res.* 116, G02011, doi: 10.1029/2010JG001393, 2011.
- Wei, Y., Liu, S., Huntzinger, D. N., Michalak, A. M., Viovy, N., Post, W. M., Schwalm, C. R.,
5 Schaefer, K., Jacobson, A., Lu, C., Tian, H., Ricciuto, D., Cook, R. B., Mao, J., and Shi, X.: The North American Carbon Program Multi-scale Synthesis and Terrestrial Model Intercomparison Project—Part 2: Environmental driver data, *Geosci. Model Dev.* 7, 2875–2893, 2014a.
- Wei, Y., Liu, S., Huntzinger, D. N., Michalak, A. M., Viovy, N., Post, W. M., Schwalm, C. R.,
Schaefer, K., Jacobson, A. R., Lu, C., Tian, H., Ricciuto, D.M., Cook, R.B., Mao, J., and Shi, X.:
10 NACP MsTMIP: Global and North American Driver Data for Multi-Model Intercomparison, ORNL DAAC, Oak Ridge, Tennessee, USA. <https://doi.org/10.3334/ORNLDAAAC/1220>, 2014b.
- Zeng, N., Mariotti, A. and Wetzel, P.: Terrestrial mechanisms of interannual CO₂ variability, *Global Biogeochem. Cycles*, 19, GB1016, doi: 10.1029/2004GB002273, 2005.