Biogeosciences, 13, 4271–4277, 2016
www.biogeosciences.net/13/4271/2016/
doi:10.5194/bg-13-4271-2016

Biogeosciences Open Access EGU

Technical note: 3-hourly temporal downscaling of monthly global terrestrial biosphere model net ecosystem exchange

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Received: 25 February 2016 – Published in Biogeosciences Discuss.: 14 March 2016
Revised: 13 June 2016 – Accepted: 22 June 2016 – Published: 29 July 2016

Abstract. The land surface provides a boundary condition to atmospheric forward and flux inversion models. These models require prior estimates of CO_2 fluxes at relatively high temporal resolutions (e.g., 3-hourly) because of the high frequency of atmospheric mixing and wind heterogeneity. However, land surface model CO_2 fluxes are often provided at monthly time steps, typically because the land surface modeling community focuses more on time steps associated with plant phenology (e.g., seasonal) than on sub-daily phenomena. Here, we describe a new dataset created from 15 global land surface models and 4 ensemble products in the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP), temporally downscaled from monthly to 3-hourly output. We provide 3-hourly output for each individual model over 7 years (2004–2010), as well as an ensemble mean, a weighted ensemble mean, and the multi-model standard deviation. Output is provided in three different spatial resolutions for user preferences: 0.5° × 0.5°, 2.0° × 2.5°, and 4.0° × 5.0° (latitude × longitude). These data are publicly available from doi:10.3334/ORNLDAAC/1315.

1 Approach

This technical note describes the methodological approach employed with temporally downscaling monthly terrestrial biosphere model (TBM) net ecosystem exchange (NEE) (i.e., net CO_2 flux between the land and atmosphere) output to 3-hourly time steps (Fisher et al., 2014). These data were created initially for NASA's Carbon Monitoring System (CMS) and are useful to the broader land surface and atmospheric scientific community (Fisher et al., 2011, 2012). The general downscaling approach follows Olsen and Randerson (2004) with modifications. The logic takes the components of NEE, i.e., gross primary production (GPP) and ecosystem respiration (Re), and links them with incident shortwave solar radiation (I) and near-surface (2 m) air temperature (T_a), respectively. I and T_a are provided at 6-hourly time steps from CRU-NCEP (Wei et al., 2014a, b), which we interpolated to 3-hourly time steps following cosines of solar zenith angle for I and linear interpolation for T_a. Hence, GPP and Re are temporally downscaled to 3-hourly and re-combined to form NEE at 3-hourly time steps.

The 6-hourly to two 3-hourly time steps from the solar zenith angle cosine interpolation follows this equation:

$$I_{t1} = \frac{I_t \times \cos z_{t1}}{\left(\frac{\cos z_{t1} + \cos z_{t-t1}}{2}\right)}, \; I_{t-t1} = \frac{I_t \times \cos z_{t-t1}}{\left(\frac{\cos z_{t1} + \cos z_{t-t1}}{2}\right)}, \quad (1)$$

where z is solar zenith angle and I_t is in units of W m^{-2}. As an example, if the 0–6 h I_t were 100 W m^{-2}, the 0–3 h z_{t1} were 0 (i.e., $\cos(z_{t1}) = 1$), and the 4–6 h z_{t-t1} were 60 (i.e., $\cos(z_{t-t1}) = 0.5$), then the 0–3 h I_{t1} would be 133.3 W m^{-2}, and the 4–6 h I_{t-t1} would be 66.7 W m^{-2}.

To scale GPP and Re to 3-hourly time steps, we followed Olsen and Randerson (2004) with modifications starting first with the calculation of scale factors based on I and T_a:

$$Q10_{3\,h} = 1.5^{\frac{T_{a,3\,h} - 30}{10}}, \quad (2a)$$

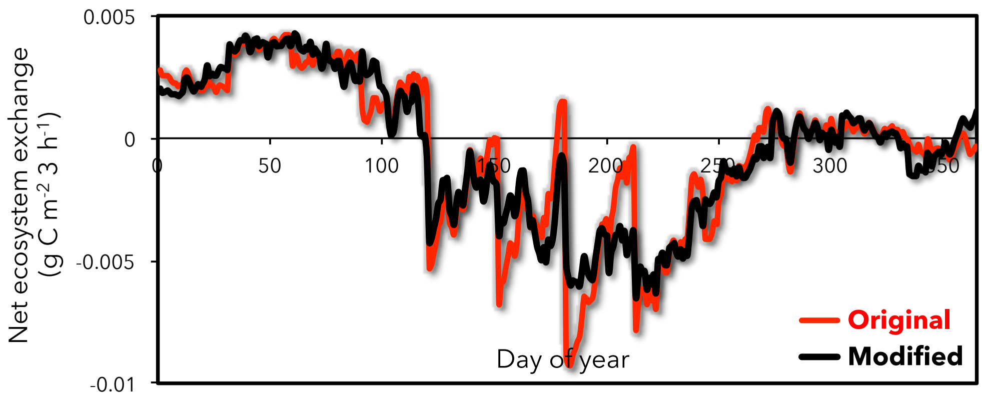

Figure 1. The original downscaling approach of Olsen and Randerson (2004) used monthly fixed values, which led to a "stair-stepping" behavior between months (red). This was eliminated by using a 30-day moving window and interpolating monthly input values to 3-hourly time steps (black). Example shown for Lund–Potsdam–Jena (LPJ) model global mean year 2005.

$$T_{\text{scale}} = Q10_{3\,\text{h}} \bigg/ \sum_{30\text{ day}} Q10_{3\,\text{h}}, \tag{2b}$$

$$I_{\text{scale}} = I_{3\,\text{h}} \bigg/ \sum_{30\text{ day}} I_{3\,\text{h}}, \tag{3}$$

where $Q10$ is the temperature dependency of Re, and T_a is in degrees Celsius (converted from kelvin, as provided by CRU-NCEP). Note that Olsen and Randerson (2004) originally used time integral periods of calendar months, but we observed that this caused unrealistic distinct shifts between months. Instead, we modified the integral period to a 30-day moving window (Fig. 1). For the first 15 days of January of the record and the last 15 days of December of the record, we used the last 15 days of December and the first 15 days of January, respectively, within the first (2004) and last (2010) years to complete the 30-day window.

The 3-hourly resolution scale factors are then multiplied by GPP and Re for each 3-hourly time step each month:

$$\text{Re}_{3\,\text{h}} = T_{\text{scale}} \times \text{Re}_{\text{month}}, \tag{4}$$

$$\text{GPP}_{3\,\text{h}} = I_{\text{scale}} \times \text{GPP}_{\text{month}}. \tag{5}$$

We modified Re_{month} and $\text{GPP}_{\text{month}}$ from Olsen and Randerson (2004) to be given at a 3-hourly time step, linearly interpolated to 3-hourly time steps based on the present, previous, and subsequent month, maintaining the original units ($\text{g C m}^{-2}\,\text{months}^{-1}$). $\text{Re}_{3\,\text{h}}$ and $\text{GPP}_{3\,\text{h}}$ are in units of $\text{g C m}^{-2}\,3\,\text{h}^{-1}$. This modification avoided using the same monthly value for the multiplier for all 3-hourly time steps per month as per Olsen and Randerson (2004) and instead provided a smooth transition from one month to the next. The result of this modification was to eliminate a "ramping" effect whereby values would, for example, increase steadily within a month, then suddenly shift to a new starting point at the beginning of the next month (Fig. 1). Note that the original nomenclature of Olsen and Randerson (2004) used $[(2 \times \text{NPP}_{\text{month}}) - \text{NEP}_{\text{month}}]$ in place of Re_{month} and $(2 \times \text{NPP}_{\text{month}})$ in place of $\text{GPP}_{\text{month}}$, where NPP is net primary production (GPP minus autotrophic respiration) and NEP is net ecosystem production (approximately equivalent to the inverse sign of NEE, with caveats; Hayes and Turner, 2012). The assumption here, therefore, is that $\text{GPP} = 2\times \text{NPP}$ and $\text{Re} = (2 \times \text{NPP}) - \text{NEP}$. The Re assumption misses CO_2 emissions other than respiration, e.g., fire, which we correct for at a later step.

The initial NEE calculation simply subtracts GPP from Re:

$$\text{NEE}_{3\,\text{h}} = \text{Re}_{3\,\text{h}} - \text{GPP}_{3\,\text{h}}, \tag{6}$$

where $\text{NEE}_{3\,\text{h}}$ is calculated in units of $\text{g C m}^{-2}\,3\,\text{h}^{-1}$. However, we applied an additional unit conversion for the publicly available data to $\text{kg C km}^{-2}\,\text{s}^{-1}$, as these units are more readily ingestible by atmospheric inversion models (Deng et al., 2014).

Because the downscaling approach uses Re (e.g., autotrophic plus heterotrophic respiration) as the primary CO_2 efflux term, other ecosystem CO_2 loss components, such as fire and other disturbances (Hayes and Turner, 2012), are excluded in the downscale. Hence, the sum of the downscaled 3-hourly NEE fluxes in a given month did not necessarily equal the original monthly NEE flux. So, we included a per-pixel correction whereby we (i) calculated the difference between the sum of the downscaled 3-hourly NEE in a given month and the original monthly NEE, (ii) divided that difference by the total 3-hourly time steps in the month, and (iii) added that difference to each 3-hourly NEE flux. In so doing, the sum of the downscaled 3-hourly NEE fluxes subsequently summed exactly to the original monthly NEE. Nonetheless, this assumption smooths what could otherwise be punctuated fire or disturbance effluxes, so caution should be given when assessing these effluxes at 3-hourly time steps (e.g., relative to observations).

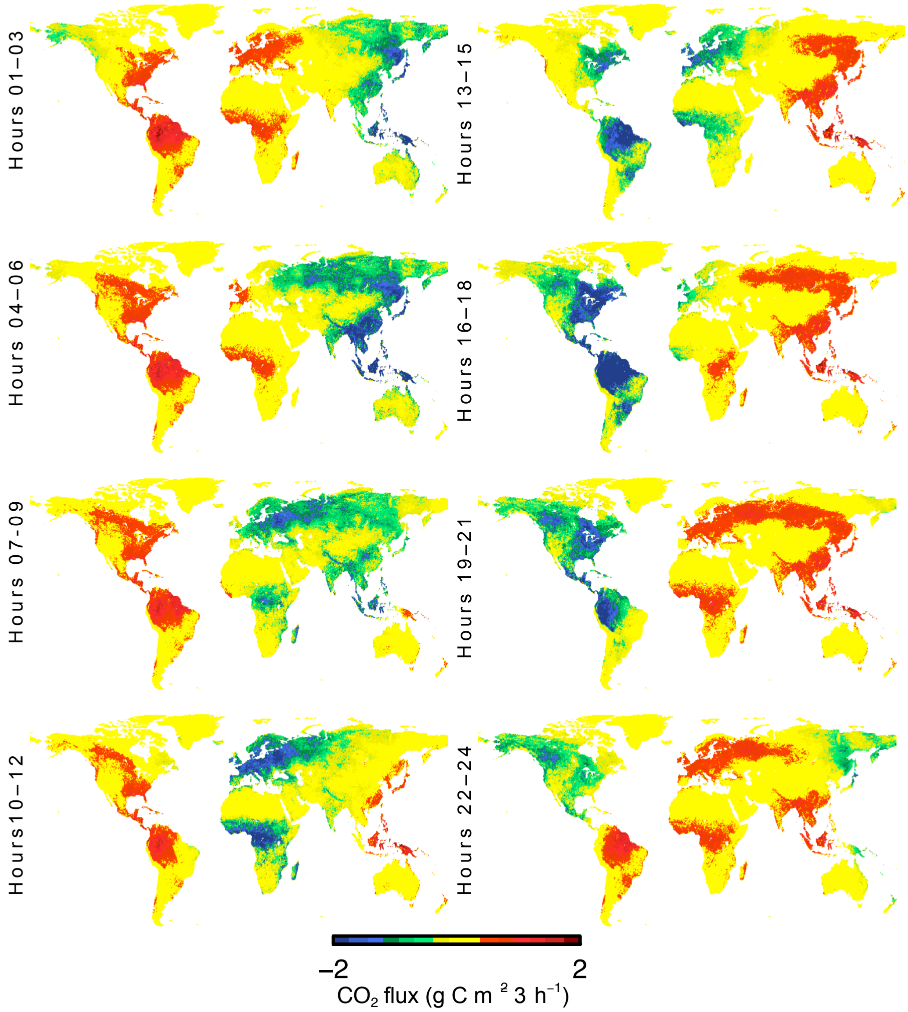

Figure 2. Vegetation productivity (e.g., blues/greens) follows the course of the Sun for a single day of net ecosystem exchange (NEE or net CO_2 flux; $g\,C\,m^{-2}\,3\,h^{-1}$) for each 3-hourly period. Shown here, for example, is 1 July 2007 for the weighted ensemble mean product.

All input data were given in a spatial resolution of $0.5° \times 0.5°$ (latitude × longitude); hence, we provide the 3-hourly NEE output at $0.5° \times 0.5°$ (Fig. 2). We also provide two additional sets of spatially upscaled NEE output at $2.0° \times 2.5°$ and $4.0° \times 5.0°$. These resolutions are used by the atmospheric modeling community, i.e., the GEOS-Chem atmospheric CO_2 transport model in the NASA CMS (Liu et al., 2014). To generate the coarser-resolution data, we (i) multiplied each pixel value by the land area of that pixel; (ii) summed the flux from all pixels that represent one pixel at coarser resolution (e.g., 8×10 pixels from $0.5° \times 0.5°$ comprise 1 pixel in $4.0° \times 5.0°$); (iii) calculated the total area covered by the pixels summed in step (ii); and (iv) divided the value in step (ii) by the value in step (iii). The regridding preserved the total sum flux of the finer grid cells as well as the total global flux. We provide a file containing the land area contained in each latitudinal band for each of the three resolutions (folder name: "latitude_area"). We provide two versions of the $2.0° \times 2.5°$ and $4.0° \times 5.0°$ resolution products – one version with consistent global resolution, and another that conforms to the GEOS-Chem setup whereby the northern- and southern-most latitudinal bands for the $2.0° \times 2.5°$ resolution are $1.0° \times 2.5°$, and for the $4.0° \times 5.0°$ resolution they are $2.0° \times 5.0°$. The orientation of the global grid in the NetCDF files is transposed (i.e., 90° S × 180° W at top left). The time vector represents the midpoint of each 3-hourly period.

Processing time in *R*, unparallelized, on a standard PC for a single year for the forcing data was as follows:

- interpolation of 6-hourly I and T_a to 3-hourly time step: 1 h per variable;
- 30-day moving window for I: 48 h;
- 30-day moving window for T_a: 68 h;

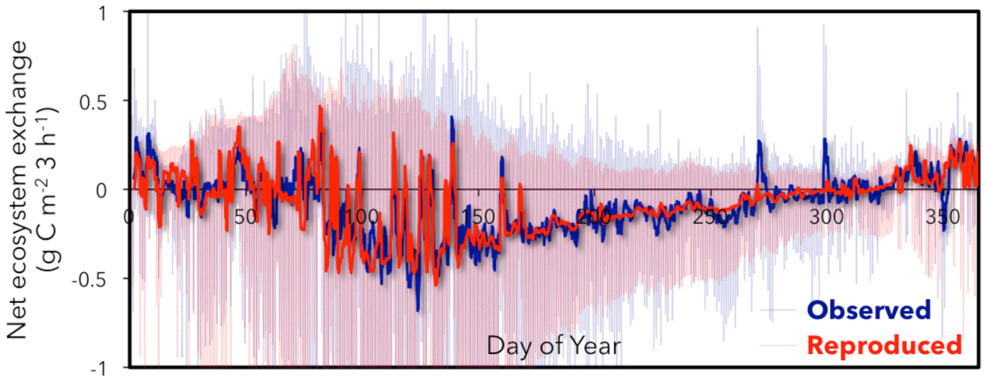

Figure 3. The observed net ecosystem exchange (NEE) (blue) and reproduced NEE (red) shown at the 3-hourly time step with daily moving window overlaid for a single year from the Tonzi Ranch AmeriFlux/FLUXNET site (Baldocchi and Ma, 2013).

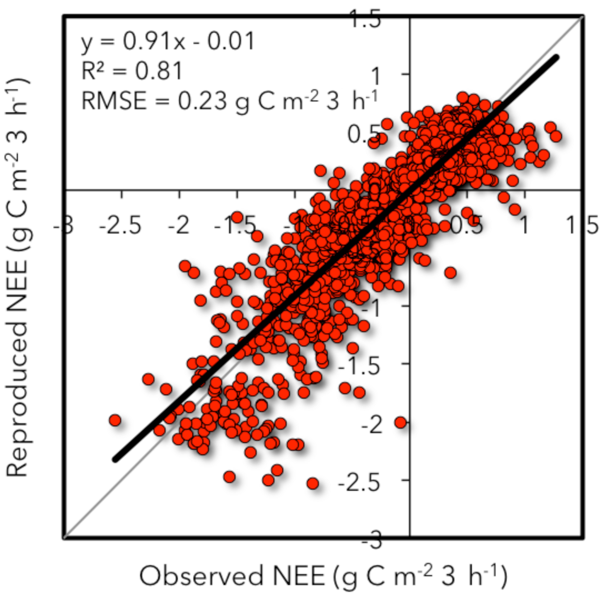

Figure 4. Observed versus reproduced net ecosystem exchange (NEE) at the 3-hourly time step for a single year at the Tonzi Ranch AmeriFlux/FLUXNET site (Baldocchi and Ma, 2013).

– total time to process forcing data for 7 years: $7 \times (1 \times 2 + 48 + 68) = 826$ h.

Processing time for the application of the modified Olsen and Randerson (2004) downscaling approach for a single model for a single year was as follows:

– monthly interpolation to 3-hourly time steps for GPP: 1 h;

– monthly interpolation to 3-hourly time steps for Re: 1 h;

– GPP and Re downscaling: 2 h;

– monthly NEE closure correction: 1 h;

Table 1. Global terrestrial biosphere models from the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) downscaled in this activity.

Model	Reference
BIOME_BGC	Thornton et al. (2002)
CLM	Mao et al. (2012)
CLM4VIC	Lei et al. (2014)
CLASS_CTEM	Huang et al. (2011)
DLEM	Tian et al. (2012)
GTEC	Ricciuto et al. (2011)
ISAM	Jain and Yang (2005)
LPJ-wsl	Sitch et al. (2003)
ORCHIDEE	Krinner et al. (2005)
SIB3	Baker et al. (2008)
SIBCASA	Schaefer et al. (2008)
TEM6	Hayes et al. (2011)
TRIPLEX-GHG	Peng et al. (2002)
VEGAS2.1	Zeng et al. (2005)
VISIT	Ito (2010)

– NetCDF generation with additional spatial resolutions: 2 h;

– total time to process all 19 products for 7 years: $7 \times 19 \times (1 + 1 + 2 + 1 + 2) = 931$ h.

The total storage size of the final NetCDF data products for all 19 products (15 models + 4 ensemble products) for all 7 years is 374 GB at 0.5° × 0.5°, 38 GB at 2.0° × 2.5°, and 10 GB at 4.0° × 5.0°.

We provide the data in NetCDF with a separate file for each day per product at doi:10.3334/ORNLDAAC/1315 (Fisher et al., 2016). Each file contains the global gridded data with the eight 3-hourly intervals in the day. Open-water pixels are set to 0, as this was desired by the atmospheric modeling community. However, we realize that NEE values can conceivably be 0 (though unlikely as our precision is to 16 decimal places); nonetheless, there are some pixels over land that are calculated as 0, but this is due to missing forcing data (e.g., I at the high latitudes during winter). Our code is set up such that we can easily provide a different file output structure and missing value mask by request (contact the corresponding author: jbfisher@jpl.nasa.gov).

Model output (GPP, Re, and NEE) was from the Multi-scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) (Huntzinger et al., 2013, 2016), version 1. Fifteen models were included: (1) BIOME_BGC, (2) CLM, (3) CLM4VIC, (4) CLASS_CTEM, (5) DLEM, (6) GTEC, (7) ISAM, (8) LPJ-wsl, (9) ORCHIDEE, (10) SIB3, (11) SIBCASA, (12) TEM6, (13) TRIPLEX-GHG, (14) VEGAS2.1, and (15) VISIT (Table 1). All models were driven by CRU-NCEP meteorological forcing data, hence our use of the same data source for the downscaling approach applied here. We note that there are other meteorological forcing datasets also available at 3-hourly time steps for those interested in applying our downscaling approach with different data (Sheffield et al., 2006; Weedon et al., 2011, 2014). Although some models are capable of output at sub-monthly time steps, the standard MsTMIP output is at the monthly time step. Additionally, four ensemble products were included: (1) unweighted (naïve) ensemble mean, (2) unweighted (naïve) ensemble standard deviation, (3) weighted (optimal) ensemble mean, and (4) weighted (optimal) ensemble standard deviation. Weights for model ensemble integration were derived based on model skill in reproducing GPP and biomass (Schwalm et al., 2015). Model output was obtained from ftp://nacp.ornl.gov/synthesis/2009/reutlingen/CMS/20141006/.

To test and confirm that our downscaling approach was applied correctly, we tested our method on a set of ground-truth data of measured NEE (and forcing variables) from the FLUXNET database (Baldocchi et al., 2001). We show, for example, a single year for a single site (3-hourly in background with daily-moving window overlaid) (Fig. 3) and the scatterplot of calculated versus observed NEE values at the 3-hourly time step for that site and year (Fig. 4). A full uncertainty analysis of the approach is beyond the scope of this technical note, intended to describe the methodological detail of the downscaling.

2 Data availability

The data are available for download in NetCDF at doi:10.3334/ORNLDAAC/1315.

Author contributions. Joshua B. Fisher, Deborah N. Huntzinger, and Christopher Schwalm formulated the idea; Joshua B. Fisher and Munish Sikka designed the research; Munish Sikka performed the research; Deborah N. Huntzinger and Christopher Schwalm provided data; all authors contributed to the writing of the paper.

Acknowledgements. Funding for this work was provided by NASA's Carbon Monitoring System (CMS) and NASA's Carbon Cycle Science (CARBON) programs. We thank the MsTMIP modeling teams for providing the model output. Access and information about MsTMIP model output can be found at http://nacp.ornl.gov/mstmipdata/, along with model and model team participant information. Funding for the MsTMIP activity was provided through NASA ROSES grant no. NNX10AG01A. Data management support for preparing, documenting, and distributing MsTMIP model driver and output data was performed by the Modeling and Synthesis Thematic Data Center at Oak Ridge National Laboratory with funding through NASA ROSES grant no. NNH10AN681. We thank Dennis Baldocchi and Siyan Ma for providing the Tonzi Ranch AmeriFlux/FLUXNET data; funding for AmeriFlux data resources and core site data was provided by the U.S. Department of Energy's Office of Science. Two reviewers provided useful suggestions on how to improve the paper. The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.

The authors declare no conflict of interest.

Edited by: P. Stoy
Reviewed by: Z. Zhang and one anonymous referee

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