Predicting drought propagation within peat layers using a three dimensionally explicit voxel based model

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Abstract. Peatlands are very vulnerable to widespread fires during dry seasons, due to availability of aboveground fuel biomass on the surface and belowground fuel biomass on the sub-surface. Hence, understanding drought propagation occurring within peat layers is crucial with regards to disaster mitigation activities on peatlands. Using a three dimensionally explicit voxel-based model of peatland hydrology, this study predicted drought propagation time lags into sub-surface peat layers after drought events occurrence on the surface of about 1 month during La-Nina and 2.5 months during El-Nino. The study was carried out on a high-conservation-value area of oil palm plantation in West Kalimantan. Validity of the model was evaluated and its applicability for disaster mitigation was discussed. The animations of simulated voxels are available at: goo.gl/HDRMYN (El-Nino 2015 episode) and goo.gl/g1sXPl (La-Nina 2016 episode). The model is available at: goo.gl/RiuMQz.

1. Introduction

Contribution of tropical peatland is of importance to the global climate, mainly due to its regulating services by storing a huge amount of carbon. Tropical peatland has been estimated as storing carbon of about 88.6 Gt C (range 81.7-91.9 Gt C), equal to 15-19% of the of the global peat carbon pool, where 68.5 Gt C of this is distributed in Southeast Asian region (77%), equal to 11–14% of the global peat carbon pool, with the largest share from Indonesia of about 57.4 Gt C or 65% of the tropical peat carbon pool, followed by Malaysia of about 9.1 Gt C or 10% of the tropical peat carbon pool [1].

Nevertheless, tropical peatland ecosystem is fragile, particularly to profound perturbations [2]; [3]. Stability of tropical peatland ecosystem is strongly determined by its hydrological system [2]; [1]; [4]; [5]. Drainage system applied to peatland can perturb its ecosystem functions, particularly on its hydrological function [4]. At sub-surface water levels of less than 40 cm below the peat surface and surface water levels of less than 100 cm above the peat surface, peatland is vulnerable to subsidence and fire [5].

Moreover, according to [6], CO₂ emitted from decomposition of drained peatlands was between 355 Mt year⁻¹ and 855 Mt year⁻¹ in 2006 of which 82% came from Indonesia, largely Sumatra and Kalimantan. Meanwhile, widespread peat fires in insular Southeast Asia resulted C emissions, with a conservative estimate of around 0.1 Gt year⁻¹ [3]. In addition, [7] estimated losses of tree species in peatland area of Central Kalimantan, Indonesia, of about 23% to 92% due to peat fires.

Meanwhile, monsoon plays an important role in determining seasonality of rainfall in humid tropical region, such as Indonesia, which inter-seasonal variability is associated with El-Nino Southern Oscillation (ENSO). During El-Nino years, the region can experience a longer dry season, while during
La-Nina years, the onset of the monsoon is usually earlier than normal [8]. Furthermore, increasing temperature during El-Nino years can potentially trigger wildfires.

The objectives of the study are: (1) to predict drought regime propagation within peat layers using three dimensionally model of peatland hydrology (the PEAT VOXEL model); and (2) to analyze vertical peat water behaviors under ENSO conditions.

2. Methods

2.1. Study area
The model was evaluated in a peatland restoration zone of oil palm plantation, located in Nataikuini Village, Kendawangan Sub-district, Ketapang District, West Kalimantan Province, Indonesia (110.896° -110.943° E, 2.831°-2.794° S) with total area of about 900 ha (Figure 1). Four land-cover types were identified: unburnt forest, shrub, burnt forest, and bareland (Table 1). We applied object-based image classification method using multi-resolution segmentation algorithm [9] to Landsat 8 imagery. Accuracy of the land-cover map was assessed using 38 ground truthing points with kappa accuracy of 0.89.

Figure 1. Map of the study area in a peatland restoration zone of oil palm plantation in Ketapang, West Kalimantan, Indonesia and the land cover map used in this study (the lower right corner).

| Land cover               | Description                                                                 |
|-------------------------|-----------------------------------------------------------------------------|
| Unburnt forests         |-dominated by vascular plants: Shorea balangeran (endangered according to IUCN Red List), Alstonia trees, and Combretocarpus rotundatus. |
| Shrub                   | dominated by fern and other vascular plants (at seedling stage).            |
| Bareland                | refers to non-vegetated fire-climax areas, mostly resulted by catastrophic wildfire in 2015 (based on reports by the oil palm plantation company). |
| Burnt forests           | refer to forest regrowth after experiencing wildfires in 2013.               |
2.2. Data
There are two data types used for parameterizing the model: spatial and tabular (Table 2). Tabular data consist of: (i) meteorological parameters, (ii) peat parameters, and (iii) land cover parameters. Spatial data consist of: (i) land cover map, classified from Landsat 8 imagery of path/row 120/62 with acquisition date of February 20th 2017, (ii) digital elevation model (DEM) based on SRTM, and (ii) peat thickness map, based on surface interpolation of ground measurement points. In this case, the spatial data were resampled into 60-m.

**Table 2. Input parameters of the model.**

| Type           | Input parameters                      | Source                                                                 |
|----------------|---------------------------------------|------------------------------------------------------------------------|
| Tabular        | Meteorological parameters             | Daily precipitation Measurement by IOI Group from 1 rain gauge station using ombrometer\(^a\) |
|                | Tabular                               | Potential evapotranspiration\(^b\) NASA POWER data                      |
|                | Peat properties                        | Overland flow velocity [10]                                             |
|                |                                        | Hydraulic conductivity by land cover type [11]                          |
|                |                                        | Field capacity by land cover type [11]                                  |
|                |                                        | Saturated capacity by land cover type Authors’ defined                   |
|                | Land-cover properties                  | Potential evapotranspiration correction factor [12]                    |
|                |                                        | Drought resistance [12]                                                 |
|                |                                        | Interception effect on transpiration [12]                               |
| Spatial        | DEM                                   | SRTM                                                                   |
|                | Land-cover map                         | 4 categories Landsat 8 OLI 120/62                                       |
|                | Peat thickness map                     | IOI Group                                                               |

\(^a\)Since the study area is relatively flat, time series of daily precipitation based on measurement from 1 rain gauge station should represent the whole area [13].

\(^b\)Potential evapotranspiration was estimated using Penman-Monteith method [14].

To validate the PEAT VOXEL model, five instruments for water level measuring were constructed using Arduino micro-controller (Nano ATMega328) and ultrasonic HC-SR04 sensor, installed and distributed purposively to represent each land cover type in the study area, and recorded daily surface and sub-surface water levels for 2 weeks (30-March-2017 to 12-April-2017). Principally, the sensors transmit ultrasound pulse beams and calculate the return time of the signals from the peat surface level, thus depression of water level can be measured. The model goodness of fit [15] between daily simulated data and measured data was about 87%.

2.3. Model description
The PEAT VOXEL model was developed using NetLogo 3D agent-based modelling tool [16]. It captures spatio-temporal dynamics of surface water due to land-atmospheric interactions based on GenRiver conceptual framework [12] and spatio-temporal dynamics of sub-surface water due to water
diffusion within peat layers based on Darcy’s Law, which is three-dimensionally explicit. Temporal resolution of the model is daily, and three-dimensional spatial resolution of the model (xyz) is 60 m x 60 m x 0.1 m.

Assumptions of the model are: (i) surface water velocity is constant at 30 m/s [10]; (ii) total amount of sub-surface peat water within the entire peat layers is at equilibrium condition, i.e. water sinks from and leakages to outside (surrounding peat layers not under consideration) are assumed to be at equal rates [17]; and (iii) hydraulic conductivity and water retention capacity of peat layers are the main determinants of water diffusion within peat layer.

A diplotelmic peat characterization system, i.e. peat is categorized into acrotelm-catotelm layers ([18]; [19]) was used in this study. The acrotelm layer is the upper part of peat layers, with thickness of about 25 cm and relatively high hydraulic conductivity due to biological activities within the layers, such as vegetation rooting and microbial activities; while the catotelm layer is the deeper and more dense part of peat layers, with relatively low hydraulic conductivity due to low biological activities at its anaerobic condition [20].

In the PEAT VOXEL model, the movement of water on the surface is based on elevation-driven pixels neighbourhood rule, incorporating 8 pixel-neighbours, while the diffusion of water within peat layer is based on Darcy’s Law-driven voxels neighbourhood rule, incorporating 6 voxel-neighbours.

2.4. Mathematical model of PEAT VOXEL
Land-atmospheric interactions within the PEAT VOXEL model was conceptualized based on generic water balance model [12], incorporating precipitation, evapotranspiration, interception and infiltration, using the following equations.

\[
I_a = I_p (1 - \exp\left(\frac{P_g}{I_p}\right))
\]

(1)

Actual interception \((I_a)\) in mm is defined as water loss due to water evaporation from each land cover type to the atmosphere, determined by gross precipitation \((P_g)\) in mm and potential interception of each land cover type \((I_p)\) in mm.

\[
Inf = P_g - I_a, Inf < \min(SC - H)
\]

(2)

Infiltration \((Inf)\) is defined as water penetration from the surface into the sub-surface (peat layers), determined by net precipitation \((P_g - I_a)\) in mm, saturated capacity of peat layers \((SC)\) in mm, and actual water content of peat layers \((H)\) in mm. In this study, SCs of acrotelm and catotelm were parameterized to 200 and 150 mm per voxel, respectively.

\[
ETA = \beta \left[ETP \times k_o \right] - \left(c \times I_a \right)
\]

(3)

\[
\beta = \frac{H}{R_d \times \theta_{fc}}
\]

(4)

Actual evapotranspiration \((ETA)\) in mm contributes to water losses from peat surface and acrotelm layers. This parameter is determined by potential evapotranspiration \((ETP)\) in mm, evapotranspiration coefficient of each land cover \((k_o)\) in mm, actual interception \((I_a)\) in mm, interception effectiveness to transpiration \((c)\), and relative water content \((\beta)\) as averaged water content within acrotelm \((H)\) in mm, drought-resistance of each land cover type \((R_d)\), and field capacity \((\theta_{fc})\) in mm. In this case, \(c, \beta \) and \(R_d\) are fractional parameters, which values ranging from 0 to 1.

Sub-surface water diffusion within peat layers (acrotelm-acrotelm) is conceptualized based on Darcy’s Law, modified with regards to target voxels, incorporating 6 ordinal voxel neighbours of source voxels, using the following equation:
\[
\frac{dH}{dt}_i = -K \frac{(H - h_i)}{L_i}
\]  

(5)

Water diffusion within peat layers increases at higher hydraulic conductivity \((K)\), higher gradient of water between source voxels and their target voxels \((H - h_i)\), and shorter inter-voxel distance \((L_i)\). In this case, \(i\) denotes the 3D ordinal axes (xyz) of each voxel.

\[
w_i = \frac{\frac{dH}{dt}_i}{\sum_i \frac{dH}{dt}_i}
\]

(6)

Outflows from source voxels are weighted \((w_i)\) with regards to actual water contents of the target voxels.

\[
\theta = \sum_i^6 \left(\frac{dH}{dt}_i\right), \theta < H
\]

(7)

Total outflows from source voxels to target voxels \((\theta)\) is therefore limited by actual water content of the source voxels.

\[
\gamma_i = \theta w_i
\]

(8)

\[
H_{t+\Delta t} = H_t - \sum_i^6 \gamma_i + \sum_i^6 \alpha_i, \alpha_i < H_{\text{max}}
\]

(9)

Equation (8) describes the weighted outflows from target voxels \((\gamma_i)\). Furthermore, equation (9) describes peat water level of source voxels at time \(t + \Delta t\), where the total inflows from neighbouring voxels are limited by maximum capacity of the source voxels \((H_{\text{max}})\).

2.5. Drought propagations and vertical peat water distributions

Vertical peat water distributions within peat layers was evaluated using ratio of peat water content (mm) and saturated capacity (mm) of each layer. We visualized the ratio of peat water using filled contour plot that represented the temporal dynamics of peat water content within peat layers. Furthermore, drought propagations under different ENSO scenario was evaluated using standardized data [21] of precipitation, surface, and sub-surface peat water in acrotelm and catotelm zone so that we can predict the time travel of the deficit shifting throughout peat layers.

3. Results and Discussions

3.1. Peatland drought assessments

Based on the simulation results, peat water content ratio across peat layers was calculated as the voxel-averaged ratio between actual peat water content relative to its saturated water capacity, ranging from 0 to 1, indicating the wetness of the peat voxels (Figure 2). In addition, drought propagation from incoming precipitation to surface and peat layers [21] was evaluated based on standardized hydrological parameters (Figure 3).
Figure 2. Water content ratio within peat layers during: (a) 2015 El-Nino episode; and (b) 2016 La-Nina episode.

Based on water content ratio (Figure 2), relatively dry peat voxels during 2015 El-Nino episode were found at maximum peat thickness of ~80 cm from July to October; while during 2016 La-Nina episode, relatively dry peat voxels were found at maximum peat thickness of around 20-40 cm from July to September (on dry season). This peat water depression ignited wildfires in the study area during September to October 2015.\(^1\)

\(^{1}\) Based on Environmental, Health, and Safety Department wildfires report in 2015
Figure 3. Drought propagation from incoming precipitation to surface and peat layers during: (a) 2015 El-Nino episode; and (b) 2016 La-Nina episode. Yellow highlights indicate the deficiency period of hydrological parameters.

The study also found that drought propagation time lags into sub-surface peat layers after drought events occurrence on the surface were about 2.5 months during 2015 El-Nino episode and 1 month during 2016 La-Nina episode (Figure 3). Drought propagation explains drought transformation processes from meteorological drought (i.e. precipitation deficiency) to hydrological drought (i.e. catotelm water deficiency). Assessment of drought propagation in this study was carried out based on methods developed by [21].

4. Conclusion
The PEAT VOXEL model captures the spatio-temporal dynamics of surface and sub-surface peatland hydrology with relatively high performance with average of about 87%. Results from scenario-based simulations suggest that drought propagation from surface into sub-surface of peat layers had a time lag of about 2.5 months during El-Nino period and 1 month during La-Nina.

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References
[1] Page S E, Rieley J O, and Banks C J 2011 Global and regional importance of the tropical peatland carbon pool Glob. Chang. Biol 17 (2) 798–818
[2] Page S E and Baird A J 2016 Peatlands and Global Change: Response and Resilience Annu. Rev. Environ. Resour. 41 (1) 35–57
[3] Page S E and Hooijer A 2016 In the line of fire: the peatlands of Southeast Asia Philos. Trans. R. Soc. B Biol. Sci. 371 (1696) 20150176
[4] Ritzema H 2008 The Role of Drainage In The Wise Use of Tropical Peatlands Restor. Trop. Peatlands 78–87
[5] Wöstjen J H M, Clymans E, Page S E, Rieley J O, and Limin S H Peat-water interrelationships in a tropical peatland ecosystem in Southeast Asia Catena 73 (2) 212–224
[6] Hooijer A, Page S, Canadell J G, Silvius M, Kwadik J, Wöstjen H, and Jauhiainen J 2010 Current and future CO2 emissions from drained peatlands in Southeast Asia Biogeosciences 7 (5) 1505–1514
[7] Shiodera S, Atikah T D, Apandi I, Seino T, Haraguchi A, Rahajoe J S, and Kohyama T S 2015 Peat-fire impact on forest structure in peatland of central Kalimantan Tropical Peatland Ecosystems 197–212
[8] Hamada J I, Yamanaka M D, Matsumoto J, Fukao S, Winarso P A, and Sribimawati T 2002 Spatial and Temporal Variations of the Rainy Season over Indonesia and their Link to ENSO J. Meteorol. Soc Japan 80 (2) 285–310
[9] Blaschke T 2010 Object based image analysis for remote sensing ISPRS J. Photogramm. Remote Sens 65 (1) 2–16
[10] Holden J, Kirkby M J, Lane S N, Milledge D G, Brookes C J, Holden V, and McDonald A T 2008 Overland flow velocity and roughness properties in peatlands Water Resour. Res. 44 (6) 1–11
[11] Mustamo P, Hyvärinen M, Ronkanen A K, and Kløve B 2016 Physical properties of peat soils under different land use options Soil Use Manag 32 (3) 400–410
[12] van Noordwijk M, Farida A, Suyamto D, Lusiana B, and Khasanah N 2015 Spatial variability of rainfall governs river flow and reduces effects of land use change at landscape scale: GenRiver and SpatRain simulations Modsim 2003 Int. Congr. Model. Simulation (1–4) 572–577
[13] Dingman S L 2015 Physical hydrology ( Illinois US: Waveland Press, Inc.)
[14] Allen R G, Pereira L S, Raes D, Smith M, and a B. W 1998 Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56 Irrig. Drain 1–15
[15] Costanza R 1989 Model goodness of fit: A multiple resolution procedure Ecol. Modell 47 (3–4) 199–215
[16] Wilensky U and Rand W 2015 An Introduction to Agent-Based Modeling
[17] Xie Z H, Di Z H, Luo Z D, and Ma Q 2012 A Quasi-Three-Dimensional Variably Saturated Groundwater Flow Model for Climate Modeling J. Hydrometeorol. 13 (1) 27–46
[18] Holden J 2005 Peatland hydrology and carbon release: why small-scale process matters Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 363 (1837) 2891–2913
[19] Holden J and Burt T P 2003 Hydrological studies on blanket peat: The significance of the acrotelm-catotelm model J. Ecol. 91 (1) 86–102
[20] Ballard C E, McIntyre N, Wheeler H S, Holden J, and Wallage Z E 2011 Hydrological modelling of drained blanket peatland,” J. Hydrol. 407 (1–4) 81–93
[21] Van Loon A F 2015 Hydrological drought explained Wiley Interdiscip. Rev. Water. 2 (4) 359–392