1-1-2014

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Recommended Citation

Wang, Dingbao and Tang, Yin, "A one-parameter Budyko model for water balance captures emergent behavior in darwinian hydrologic models" (2014). *Faculty Bibliography 2010s*. 6244.
https://stars.library.ucf.edu/facultybib2010/6244

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL060509

Key Points:
- Commonality of Budyko, abcd, and SCS models across time scales
- Derived a single-parameter Budyko equation from generalized proportionality
- A lower bound above the horizontal axis is identified for Budyko curve

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Citation:
Wang, D., and Y. Tang (2014), A one-parameter Budyko model for water balance captures emergent behavior in darwinian hydrologic models, *Geophys. Res. Lett.*, *41*, 4569–4577, doi:10.1002/2014GL060509.

Received 13 MAY 2014
Accepted 10 JUN 2014
Accepted article online 16 JUN 2014
Published online 2 JUL 2014

A one-parameter Budyko model for water balance captures emergent behavior in darwinian hydrologic models

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Abstract Hydrologic models can be categorized as being either Newtonian or Darwinian in nature. The Newtonian approach requires a thorough understanding of the individual physical processes acting in a watershed in order to build a detailed hydrologic model based on the conservation equations. The Darwinian approach seeks to explain the behavior of a hydrologic system as a whole by identifying simple and robust temporal or spatial patterns that capture the relevant processes. Darwinian-based hydrologic models include the Soil Conservation Service (SCS) curve number model, the "abcd" model, and the Budyko-type models. However, these models were developed based on widely differing principles and assumptions and applied to distinct time scales. Here, we derive a one-parameter Budyko-type model for mean annual water balance which is based on a generalization of the proportionality hypothesis of the SCS model and therefore is independent of temporal scale. Furthermore, we show that the new model is equivalent to the key equation of the "abcd" model. Theoretical lower and upper bounds of the new model are identified and validated based on previous observations. Thus, we illustrate a temporal pattern of water balance amongst Darwinian hydrologic models, which allows for synthesis with the Newtonian approach and offers opportunities for progress in hydrologic modeling.

1. Introduction

In hydrologic problems, conservation of mass (i.e., water balance) should always hold regardless of the time scale of interest. Yet, identifying the water balance behavior over various temporal scales remains a challenging research task. One reason for this is that the roles of controlling factors on rainfall partitioning vary with temporal scale. For example, rainfall intensity and topography are important factors for runoff generation at short-time scales [*Dunne and Black*, 1970; *Beven and Kirkby*, 1979], while climate aridity index is the dominant controlling factor affecting the ratio between evaporation and precipitation [*Budyko*, 1974]. To deal with this problem, various conceptual hydrologic models have been developed for capturing these dominant controls on rainfall partitioning specific to a particular temporal scale, i.e., long-term, monthly, or event scale [*Blöschl and Sivapalan*, 1995].

Hydrologic models can be categorized as being either Newtonian or Darwinian. The Newtonian approach builds a mechanistic model of hydrologic processes (e.g., evaporation, infiltration, surface runoff, and base flow) and their coupled components including initial conditions, boundary conditions, and model parameters. Hydrologic behavior is derived from Newton's laws of motion, specifically the momentum equation, and other conservation equations (mass and energy). For example, the infiltration process can be modeled by the Richards equation, which combines the continuity equation with Darcy's law, which represents the momentum equation. The Darwinian approach is not concerned with the physical processes in isolation and instead aims to explain the hydrologic behavior as a system [*Harman and Troch*, 2014]. The Darwinian approach involves identifying simple and robust spatial or temporal patterns in hydrologic behavior from a population of watersheds and postulating a theory for connecting the observed patterns—both similarities and variations—to the processes that created them [*Harman and Troch*, 2014]. Spatial or temporal patterns are also called emergent behaviors in complex systems, and many examples, such as self-similar phenomena, are encountered in other fields of the geophysical sciences [*Harte*, 2002; *Gentine et al.*, 2010].

The Darwinian approach is exemplified by three hydrologic models, which were developed based on empirical data from a large number of watersheds: the Budyko curve for long-term or climatological water

Table 1. Three Budyko-Type Equations With a Single-Parameter

Budyko-type Equations	Parameter	References
$\frac{E}{P} = \left[1 + \left(\frac{E_P}{P}\right)^{-n}\right]^{-1/n}$	n	[*Turc*, 1954; *Mezentsev*, 1955; *Pike*, 1964; *Choudhury*, 1999; *Yang et al.*, 2008]
$\frac{E}{P} = 1 + \frac{E_p}{P} - \left[1 + \left(\frac{E_p}{P}\right)^{\omega}\right]^{1/\omega}$	ω	[*Fu*, 1981; *Zhang et al.*, 2004; *Yang et al.*, 2007]
$\frac{E}{P} = \frac{1 + w\frac{E_p}{P}}{1 + w\frac{E_p}{P} + \left(\frac{E_p}{P}\right)^{-1}}$	w	[*Zhang et al.*, 2001]

balance [*Budyko*, 1974], the "abcd" model for monthly or daily water balance [*Thomas*, 1981], and the Soil Conservation Service (SCS) curve number method for event-scale hydrologic runoff [*SCS*, 1972]. These hydrologic models have been successfully applied for water resources assessment at gauged and ungauged watersheds [*Yadav et al.*, 2007]. Due to the variable roles of controlling factors on rainfall partitioning across time scales, these models originated from distinct concepts and are based on different representations of the hydrologic physical processes. As a result, the structure and mathematical representations of these models are quite different, particularly between the Budyko model and the SCS model. The Budyko model is based on the concept of water and energy limits, which demonstrates that water is the limiting factor on evaporation when energy is unlimited, and vice versa. By contrast, the SCS model is based on the proportionality concept of direct runoff and continuing abstraction which represents post-ponding infiltration.

For a given watershed, physical properties such as vegetation, soil, and topography co-evolve under climate driving forces [*Sivapalan*, 2005]. Hydrological responses, such as evaporation and runoff, across time scales are signatures from the co-evolution of natural systems [*Newman et al.*, 2006; *Wagener et al.*, 2010; *Gentine et al.*, 2012; *Wang and Wu*, 2013; *Harman and Troch*, 2014]. Commonality, or linkage, exists among the behavior of rainfall partitioning across time scales and serves as an indicator of co-evolution. Therefore, the purpose of this paper is to recognize the general signature of rainfall partitioning by identifying the commonality of the three hydrologic models at the long-term, monthly, and event scales. The identified commonality, i.e., the generalized proportionality hypothesis, provides a hydrologic principle independent of any time scale from the Darwinian view, analogous to the role of the mass conservation principle from the Newtonian view. As a result of this study, a new single-parameter Budyko equation is derived for mean annual water balance, and a theoretical lower bound of the Budyko curve is identified.

2. Hydrologic Models Across Varying Time Scales

2.1. Budyko Hypothesis for Mean Annual Water Balance

In the mean annual or climatological water balance at the watershed scale, if water storage change is negligible, mean annual precipitation (P) is partitioned into runoff (Q) and evaporation (E). *Budyko* [1958] postulated that the partitioning of precipitation, to the first order, was determined by the competition between available water (P) and available energy measured by potential evaporation (E_p). Based on the data from a large number of watersheds, *Budyko* [1974] proposed a relationship between the mean annual evaporation ratio (E/P) and the mean annual potential evaporation ratio or climate aridity index (E_p/P):

$$\frac{E}{P} = \left[\left(1 - \exp\left(-\frac{E_p}{P}\right)\right)\frac{E_p}{P}\tanh\left(\frac{E_p}{P}\right)^{-1}\right]^{0.5} \tag{1}$$

To incorporate the impact of other factors on water balance, various functional forms have been proposed or derived in the literature as shown in Table 1 [e.g., *Turc*, 1954; *Mezentsev*, 1955; *Pike*, 1964; *Fu*, 1981; *Milly*, 1994; *Zhang et al.*, 2001; *Milly and Dunne*, 2002; *Yang et al.*, 2008; *Gerrits et al.*, 2009; *Wang and Hejazi*, 2011]. These models have advanced the understanding of the controls of vegetation, soil water storage, and climate seasonality on the water balance. The Budyko hypothesis for mean annual water balance results from the co-evolution of watershed vegetation and soils with climate [*Gentine et al.*, 2012; *Troch et al.*, 2013].

2.2. The "abcd" Model for Monthly Water Balance

The "abcd" model is a nonlinear monthly water balance model that was originally proposed by *Thomas* [1981] for national water assessment. This model has been utilized for monthly streamflow predictions taking rainfall and potential evaporation as inputs [*Alley*, 1985; *Li and Sankarasubramanian*, 2012]. The "abcd" model defines W_t as available water and Y_t as evaporation opportunity. Available water is the summation of precipitation during month *t* and soil water storage at the beginning of month *t*; evaporation opportunity is the summation of actual evaporation during month *t* and soil water storage at the end of month *t*. Evaporation opportunity (Y_t) is postulated as a nonlinear function of available water (W_t):

$$Y_t = \frac{W_t + b}{2a} - \sqrt{\left(\frac{W_t + b}{2a}\right)^2 - \frac{W_t b}{a}} \tag{2}$$

The parameter a ($0 \le a \le 1$) represents the propensity for runoff to occur before the soils are fully saturated; the parameter b is the upper bound of storage in the unsaturated zone above the groundwater table [*Thomas*, 1981]. Equation (2) is the key component of the "abcd" model and was proposed simply because the limits of the derivative of Y should be 1 and 0 [*Thomas*, 1981]. *Sankarasubramanian and Vogel* [2002] modified the original model for understanding the role of soil water storage capacity on the annual water balance. The "abcd" model has been used to test the effectiveness of model calibration [*Vogel and Sankarasubramanian*, 2003] and diagnose model structure and performance [*Martinez and Gupta*, 2011].

2.3. SCS Direct Runoff Model at the Event Scale

Rainfall at the event scale is partitioned into direct runoff (Q_d) and soil wetting (W), where soil wetting includes initial abstraction (I_a) and continuing abstraction (F_a). The initial abstraction I_a is the amount of water lost before direct runoff is generated, such as infiltration and rainfall interception by vegetation. After initial abstraction, the remaining water of $P - I_a$ is partitioned into F_a and Q_d. The potential for continuing abstraction (S) is a function of soil properties, land use and land cover, and the antecedent soil moisture condition. Given that Q_d does not compete for I_a, the potential for direct runoff is (P-I_a). The proportionality hypothesis of the SCS method is that the ratio of continuing abstraction to its potential is equal to the ratio of direct runoff to its potential value [*SCS*, 1972]:

$$\frac{F_a}{S} = \frac{Q_d}{P - I_a} \tag{3}$$

This proportionality equation was obtained based on observed data from a large number of watersheds [*SCS*, 1985].

3. Generalized Proportionality Hypothesis

The proportionality hypothesis of the SCS method has been generalized by *Ponce and Shetty* [1995] as follows. A certain amount of water (Z) is partitioned into components X and Y (e.g., wetting and direct runoff in the SCS model). The quantity X is constrained by its potential value denoted as X_P (i.e., S in the SCS model), and X has a priority to meet the initial water demand of X_0, similar to I_a. The quantity Y is constrained by the total water availability of Z-X_0. The partitioning of Z is quantified by the generalized proportionality hypothesis:

$$\frac{X - X_0}{X_P - X_0} = \frac{Y}{Z - X_0} \tag{4}$$

The generalized proportionality hypothesis has been successfully applied for modeling the two-stage partitioning of rainfall and abstraction at the inter-annual scale [*Ponce and Shetty*, 1995; *Sivapalan et al.*, 2011].

In this paper, it is hypothesized that the generalized proportionality concept is applicable to any time period, from event to long-term average scale. To illustrate this, we show that the generalized proportionality is the commonality of three Darwinian hydrologic models across three time scales: the SCS model at the event scale, the "abcd" model for monthly water balance, and the Budyko hypothesis for long-term water balance. The generalized proportionality hypothesis provides a methodology to develop Darwinian models

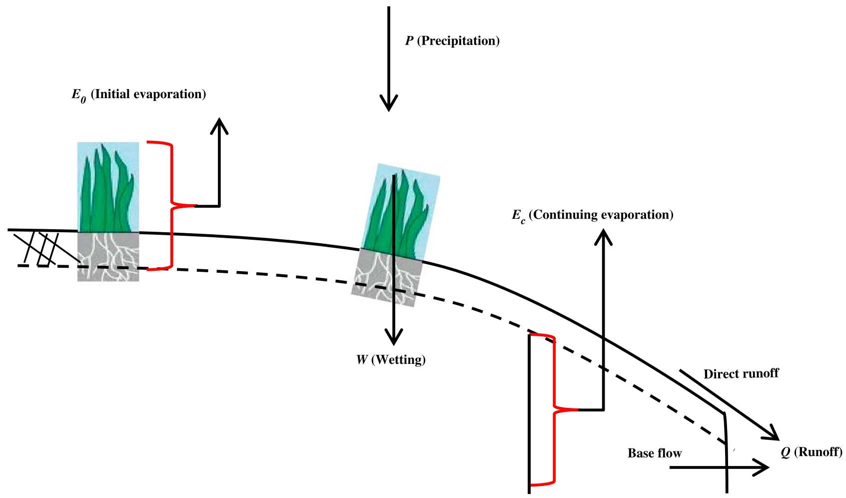

Figure 1. Partitioning of precipitation into evaporation (initial evaporation and continuing evaporation) and runoff.

that are independent of temporal scale and therefore serves a purpose similar to the water balance principle from the Newtonian view.

4. Proportionality Application for Mean Annual Water Balance

For mean annual water balance, water storage change is negligible, and precipitation is partitioned into evaporation and runoff. At the first stage of the partitioning, precipitation is partitioned into wetting and direct runoff [*L'vovich*, 1979]; at the second stage of the partitioning, wetting is partitioned into evaporation and base flow from groundwater discharge [*Sivapalan et al*., 2011]. Total runoff is the summation of direct runoff and base flow. As shown in Figure 1, a portion of wetting is only available for direct evaporation, such as that which occurs due to vegetation interception and water storage in top soils. Evaporation from this portion of wetting is defined as initial evaporation (E_0). Following the initial abstraction concept of the SCS method, initial evaporation is represented as a percentage of wetting:

$$E_0 = \lambda W \tag{5}$$

where λ is the initial evaporation ratio and λW is the amount of water storage which is not available for competition between runoff and evaporation. The remaining rainfall (P - λW is partitioned into continuing evaporation (E - E_0) and total runoff (Q). Continuing evaporation is defined as the portion of evaporation that is lost through competition with runoff. For example, the interaction between root zone depth and the shallow water table dynamics affects the magnitude of continuing evaporation.

As precipitation increases unbounded, continuing evaporation is bounded by atmospheric evaporation demand and asymptotically approaches a constant value of $E_p - \lambda W$, where E_P is mean annual potential evaporation aggregated from daily or monthly values. Runoff increases unbounded with precipitation but is constrained by $P - \lambda W$. Applying the generalized proportionality, we obtain:

$$\frac{E - E_0}{E_p - \lambda W} = \frac{Q}{P - \lambda W} \tag{6}$$

Substituting equation (5) and $Q = P - E$ (assuming no storage change on long time scales) into equation (6):

$$\frac{E - \lambda W}{E_p - \lambda W} = \frac{P - E}{P - \lambda W} \tag{7}$$

The ratio between evaporation and wetting is called the Horton index, $H = E/W$ [*Horton*, 1933; *Troch et al*., 2009], and is a catchment signature that is predominantly controlled by vegetation [*Troch et al*., 2009;

Voepel et al., 2011]. Dividing the numerator and denominator of both sides of equation (7) by P and substituting in H, we obtain:

$$\frac{E/P - \frac{\lambda}{H}E/P}{E_p/P - \frac{\lambda}{H}E/P} = \frac{1 - E/P}{1 - \frac{\lambda}{H}E/P} \tag{8}$$

The ratio between λ and H is denoted as $\varepsilon = \lambda/H$. Based on the definitions of λ and H, ε can be interpreted as the ratio between initial evaporation and total evaporation, E_0/E. A quadratic function for $\frac{E}{P}$ is obtained by manipulating equation (8):

$$\varepsilon(2-\varepsilon)\left(\frac{E}{P}\right)^2 - \left(1 + \frac{E_p}{P}\right)\frac{E}{P} + \frac{E_p}{P} = 0 \tag{9}$$

Since $\frac{E}{P}$ is positive and less than 1, the root for $\frac{E}{P}$ is obtained as:

$$\frac{E}{P} = \frac{1 + E_p/P - \sqrt{(1+E_p/P)^2 - 4\varepsilon(2-\varepsilon)E_p/P}}{2\varepsilon(2-\varepsilon)} \tag{10}$$

Equation (10) quantifies $\frac{E}{P}$ as a function of $\frac{E_p}{P}$ with a single parameter, ε. This equation is a single-parameter Budyko-type equation. The parameter ε is the ratio of two dimensionless numbers, i.e., the ratio of the initial evaporation ratio to the Horton index. When $\varepsilon = 1$, equation (10) represents the upper bound of the Budyko curve, i.e., $\frac{E}{P} = \frac{E_p}{P}$ when $\frac{E_p}{P} \leq 1$, and $\frac{E}{P} = 1$ when $\frac{E_p}{P} > 1$.

Like the Budyko-type equations in Table 1, equation (10) satisfies the boundary conditions:

$$\frac{E}{P} \to 0 \textit{ when } \frac{E_p}{P} \to 0 \tag{11-1}$$

$$\frac{E}{P} \to 0 \textit{ when } \frac{E_p}{P} \to \infty \tag{11-2}$$

Observed data from real watersheds are typically clustered around the deterministic Budyko curve (equation (1)), which overlaps with the curve given by equation (10) when ε is approximately 0.6. When $\varepsilon = \frac{2-\sqrt{2}}{2} \approx 0.29$, the functional form of equation (10) is the same as Fu's equation, with the parameter $\omega = 2$ [*Fu*, 1981].

4.1. Lower Bound of *E/P*

It should be noted that equation (10) can mathematically simulate the entire domain between the upper bound and the horizontal axis ($E/P = 0$). However, since initial evaporation (E_0) cannot exceed total evaporation (E), the physical range of ε is between 0 and 1 ($0 \leq \varepsilon \leq 1$). When ε approaches zero, the limit of equation (10) can be obtained:

$$\lim_{\varepsilon \to 0} \frac{E}{P} = \left[1 + \left(\frac{E_p}{P}\right)^{-1}\right]^{-1} \tag{12}$$

Equation (12) is the same as the Turc equation with $n = 1$ [*Turc*, 1954] and the equation by *Zhang et al.* [2001] with $w = 0$. Setting $\varepsilon = 0$ is equivalent to setting $E_0 = 0$, in which case equation (6) reduces to the following:

$$\frac{E}{E_p} = \frac{Q}{P} \tag{13}$$

As a result, the lower bound of the Budyko curve corresponds to the condition when the ratio of evaporation to potential evaporation equals the runoff coefficient. The lower bound is equivalent to the constraint of $\frac{E}{E_p} = \frac{Q}{P}$.

The theoretical lower bound of *E/P* is compared with reported data from real watersheds in the literature. Figure 2a plots the data for over 470 watersheds around the world from *Zhang et al.* [2004], and the lower

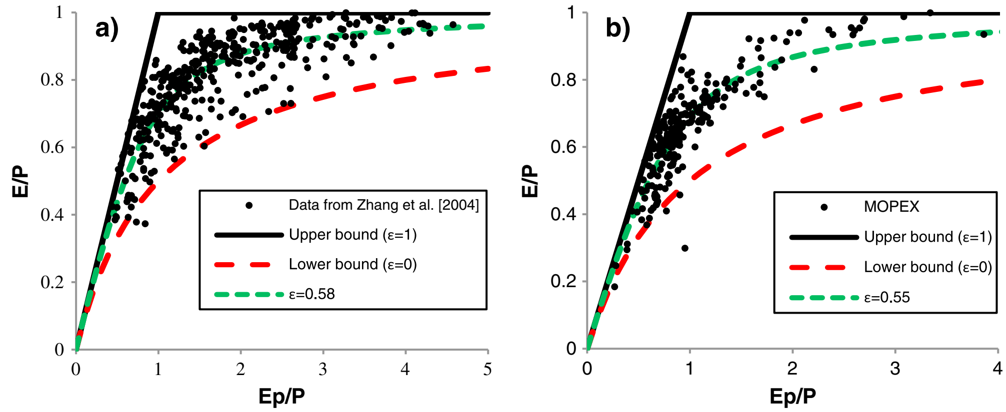

Figure 2. The theoretical lower and upper bounds of the Budyko curve and observed E/P and E_p/P data in watersheds: (a) around the world [*Zhang et al.*, 2004], and (b) Model Parameter Estimation Experiment (MOPEX) data set. Equation (10) is plotted in both cases with the respective best fitted values for ε.

bound is found to accurately constrain the vast majority of the data points. The best fit for these data points is achieved with equation (10) when $\varepsilon = 0.58$, as is also shown in Figure 2a, where the fitted relationship overlaps with the deterministic Budyko curve given by equation (1). An additional 246 watersheds from the Model Parameter Estimation Experiment (MOPEX) data set [*Duan et al.*, 2006] provide a second data set for verifying the lower bound, as is shown in Figure 2b, along with the best fit curve of equation (10) where $\varepsilon = 0.55$. This second data set is also nearly entirely constrained by the theoretical lower bound; of the 246 watersheds in this data set, 242 are located above the lower bound determined by the proportionality hypothesis. The reported watershed data in other studies, using the equations in Table 1, are also located above the lower bound with a few exceptions [*Yang et al.*, 2007; *Roderick and Farquhar*, 2011; *Donohue et al.*, 2011].

4.2. Vegetation and Rainfall Frequency Control on ε

As discussed earlier, the parameter ε in equation (10) has a physical meaning from the process perspective. From the soil wetting perspective, ε can be interpreted as the ratio between initial evaporation ratio (λ) and the Horton index (H). From the evaporation perspective, ε is the ratio between initial evaporation and total evaporation, where initial evaporation is the component of the wetting which is not available for runoff competition. Here, the physical control on ε is analyzed through the dimensionless numbers λ and H.

The Horton index provides a measure of water use efficiency of vegetation in response to change in precipitation [*Brooks et al.*, 2011]. The Horton index is relatively constant from year to year despite

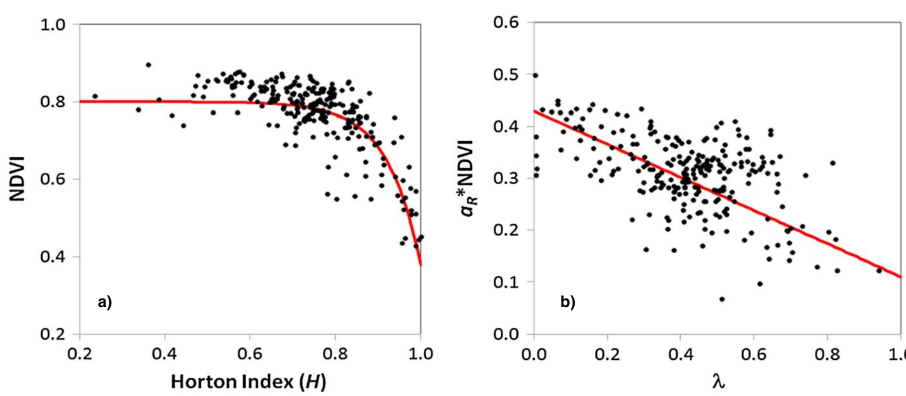

Figure 3. (a) The vegetation control (Normalized Difference Vegetation Index (NDVI)) on the Horton index, and the fitted red line represented by $NDVI = 0.8(1 - e^{-12.82(1.05 - H)})$; (b) the vegetation and rainfall frequency (α_R) control on $\lambda = E_0/W$, and the fitted red line represented by $\alpha_R \cdot NDVI = 0.43 - 0.32\lambda$.

fluctuations in annual precipitation, indicating that vegetation adapts to lower water availability by increasing water use efficiency [*Troch et al*., 2009]. In this study, soil wetting is computed by taking the difference between precipitation and direct runoff, which is obtained by base flow separation [*Sivapalan et al*., 2011]; bimonthly Normalized Difference Vegetation Index (NDVI) for the MOPEX watersheds are obtained from the satellite remote sensing data [*Tucker et al*., 2005]. Figure 3a presents the relation between average value of annual maximum NDVI and the Horton index, and the pattern is the same as the one reported by *Voepel et al*. [2011]. Water use efficiency of vegetation, represented by the Horton index, is close to 1 in water-limited regions.

The initial evaporation ratio (λ) is the ratio of initial evaporation (E_0) to total soil wetting (W). Vegetation affects both soil wetting and initial evaporation. W increases with NDVI as shown in *Voepel et al*. [2011], and E_0 may also increase with NDVI since interception loss increases with vegetation coverage. Over shorter time scales, E_0 is affected by the frequency of rainfall events. To evaluate the impact of rainfall variability on λ, the long-term average fraction of rainy days is computed for the MOPEX watersheds. The fraction of rainy days is computed from daily rainfall data as the ratio between the number of rainy days (N_R) and the total number of days in a year (N). As shown in Figure 3b, the initial evaporation ratio increases when $\alpha_R \cdot DVI$ declines. Therefore, soil wetting increases faster than initial evaporation when NDVI increases.

In summary, the dominant controlling factors on ε are vegetation and rainfall. The physical meaning of ε is the ratio of initial evaporation, which is not through the competition process with runoff such as evaporation from vegetation interception and top soil, to total evaporation. The magnitude of ε decreases with increasing α_R. The control of vegetation on ε is complex because both λ and H decline with increasing NDVI. The relationship between ε and NDVI is non-monotonic since vegetation affects the processes of wetting, initial evaporation, and total evaporation.

5. A Temporal Pattern for Darwinian Hydrologic Models

Dividing by W_t on both sides of equation (2), the key equation of the "abcd" model can be written as:

$$\frac{Y_t}{W_t} = \frac{1 + \frac{b}{W_t} - \sqrt{\left(1 + \frac{b}{W_t}\right)^2 - 4a\frac{b}{W_t}}}{2a} \tag{14}$$

This equation has the same functional form as equation (10). Over a monthly period, W_t is partitioned into Y_t and runoff, and b is the potential value of Y_t. Therefore, the concept of the "abcd" model is the same as the SCS and Budyko models, and equation (14) can be obtained from the generalized proportionality principle. As the above mentioned, the generalized proportionality is the commonality between the SCS and Budyko models, since the Budyko equation can be derived from the generalized proportionality hypothesis originating from the SCS model. In summary, the generalized proportionality hypothesis is identified as the commonality of the three Darwinian hydrologic models: the Budyko model for mean annual water balance, the "abcd" model for monthly water balance, and the SCS model for direct runoff at the event scale.

6. Conclusions and Future Research

In this work, the generalized proportionality hypothesis has been identified as the commonality of three hydrologic models across a range of time scales: the Budyko model at the long-term scale, the "abcd" model at the monthly scale, and the SCS model at the event scale. The Newtonian hydrologic modeling approach is independent of time scale; the generalized proportionality provides a hydrologic principle independent of time scales from Darwinian view. This commonality among rainfall partitioning across time scales is a signature of the co-evolution of climate, vegetation, soil, and topography as well as hydrologic responses. A single-parameter Budyko-type equation was derived based on the generalized proportionality hypothesis: the ratio of continuing evaporation to its potential equals the ratio of runoff to its potential.

The temporal pattern of water balance or proportionality hypothesis emerges from the analysis of observed data based on the Darwinian approach. Reliable generalization of the pattern calls for identifying the underlying mechanisms based on the Newtonian approach in order to go beyond pattern to process. This research provides a basis for the synthesis of Newtonian and Darwinian approaches, presents opportunities for important progress in hydrologic research [*Sivapalan*, 2005; *Harman and Troch*, 2014; *Chen et al*., 2013], and could also expedite progress in other disciplines of geosciences [*Harte*, 2002].

In practice, spatial or temporal patterns and process-based equations could co-exist in hydrologic model development. Laws or patterns based on the Darwinian approach could provide one component of a developed hydrologic model when Newtonian modeling is not achievable for some processes due to the limitation of observations or knowledge of mechanisms. Future research will investigate the linkage of rainfall partitioning between the event scale and long-term scale from a hydrologic processes view. Model structures, capturing temporal or spatial patterns and obeying the Newtonian laws, could be developed for reliable predictions.

Acknowledgments
This research was funded in part under Award NA10NOS4780146 from the National Oceanic and Atmospheric Administration (NOAA) Center for Sponsored Coastal Ocean Research (CSCOR) and Award NA10OAR4170079 from Florida Sea Grant. Data supporting Figure 2 are obtained from NOAA National Weather Service MOPEX data set (http://www.nws.noaa.gov/oh/mopex/mo_datasets.htm) and *Zhang et al*. [2004]. The authors acknowledge the Editor (Dr. Bayani Cardenas) and the two anonymous reviewers for their very constructive comments and suggestions that have led to substantial improvements over an earlier version of the manuscript.

The Editor thanks two anonymous reviewers for assistance in evaluating this manuscript.

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