グローバル30分メッシュ可能蒸発散データセットの作成

Development of Global 30-minute grid Potential
Evapotranspiration Data Set

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論文要旨

蒸発散は様々な空間的、時間的スケールの気候学関連の研究において重要な要素である。これまで蒸発散推定のための経験式や解析のためのモデルの研究が行われてきたが、本研究では現在利用可能なグローバルデータセットを用いた蒸発散量を推定する方法を提案する。NOAA-EPA 作成の Global Ecosystems Database に含まれている温度、アルベド、日照率、標高データを用いて Priestley-Taylor 式に基づいた緯度/経度30分メッシュの月別グローバル可能蒸発散量の推定を行った。

Abstract: Evapotranspiration is a key element in climate related studies on all spatial and temporal scales. Recent studies have shown that evapotranspiration can be estimated with some degree of precision using semi-empirical and analytical models. By this study, a method for the estimation of evapotranspiration using the available global data sets has been proposed.

Monthly global potential evapotranspiration (PET) on 30-minute latitude-longitude grid was estimated based on the Priestley-Taylor method using global data sets including air temperature, albedo, cloudiness, elevation, which are parts of Global Ecosystems Database supplied by NOAA-EPA.

1. Introduction

Water is one of most precious natural resources and water management problems now represent key areas of applied science in the current worldwide economic and ecological situations. The imbalance of water demand and natural supplies in space and time is common problems in most region. It is generally found that periods of highest precipitation do not coincide with periods of maximum water demand. Increasing new water demand in irrigation as well as nonagricultural purpose results in stresses being placed on available water resources. These needs will grow in size with the increase in popula-

tion and industrialization. Agricultural output can be augmented by bringing new lands under cultivation and by improving existing agricultural and irrigation practices. Moreover, climate changes threaten agricultural production and water supplies, and they may induce the geographical shift of the potential area for cultivation. Growing population pushes one to seek for another cultivation areas. In this situation, knowledge of the precipitation, evapotranspiration, soil water etc. is important when seeking the potential area for cultivation.

Accordingly, the need to assess water resources in global scale has increased rapidly. A concentration of initial efforts at the broad scale provides an opportunity for identifying regions that are worthy of more detailed attention at the local scale.

In assessment of the global water resources, precipitation and evapotranspiration are an important

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key elements on climatological data sets. Although early works (UNESCO, 1978) on global water balance and the hydrologic cycle were carried out, their result is not proper for analysis by GIS (Geographic Information System) because they are not digital form and they are contour maps in various map projections with small scales. Recent development of global data sets and analytical technique provides a way more accurate estimates of climatological data such as precipitation, temperature. For example, Legates and Willmott (1990a, 1990b), Matthews (1983) and Leemans and Cramer (1991) have been compiled monthly precipitation, air temperature, albedo and cloudiness on 30-minute geographic (latitude/longitude) 360×720 grid.

For water resources analysis, evapotranspiration data set is required as stated above. In short, the knowledge of the evapotranspiration (ET) is of fundamental importance because of the following three reasons. Firstly, the latent heat of evaporation is one of the terms of the energy balance equation and its resolution gives much information for climatological and agrometeorological studies. Secondly, it is one of the main factors to be taken into account in hydrology when establishing water balances. Thirdly, the evaluation of evapotranspiration is important in agronomy because it permits the prediction of the harvest with the maximum saving of water.

Because it has been difficult to measure evapotranspiration, one estimate it from simplified parameterization. In response to this problem, a large number of empirical and semi-empirical methods have been developed to estimate the ET. Another concept widely used in studies of evaporation and evapotranspiration is potential evapotranspiration which has had major influence on geographic studies of world climate, on general hydrologic research, and on attempts to predict water needs in dry land and irrigation agriculture. For example, the difference between precipitation and potential evapotranspiration is frequently used, especially by geographer, as an index of aridity.

An important simplification to the problem of estimation of evaporation can be achieved through the concept of potential evapotranspiration, independently introduced by Penman and Thornthwaite in 1948. Since studies by Penman (1948) and Thornthwaite (1948), numerous approaches have been proposed and used for estimation of the actual evapotranspiration and for computation of the potential evapotranspiration. In general, actual evapotranspiration are determined by multiplying the potential evapotranspiration by a coefficient which depends usually upon crop growth stage, types of crop, availability of soil moisture.

Though the global maps of evapotranspiration were derived from the combination of global data sets and water balance model (Legates and Mather, 1992; Willmott and Rowe, 1985), their maps were not published.

In this paper, global 30-minute grid terrestrial distribution of monthly potential evapotranspiration was estimated using available global data sets.

2. Methods for Potential Evapotranspiration

Potential Evapotranspiration (PET) has been defined as the evapotranspiration rate of a "short green crop, completely shading the ground of uniform height and never short of water" (Penman, 1948). It is, in a sense, a measure of the evaporative power of the atmosphere. Therefore, potential evapotranspiration cannot exceed free water evaporation under same weather conditions (Rosenberg *et al.*, 1983).

There are many methods for computing potential evapotranspiration. They varies in their data demands from the simple (requiring only information on monthly average temperature) to the more complex (requiring daily data on maximum and minimum temperature, solar radiation, humidity, wind speed as well as characteristics of the vegetation). Temperature based methods depends on the generally reliable assumption that temperature is an

indicator of the evaporative power of the atmosphere. Although temperature based methods are useful when data on other meteorological parameters are unavailable, the estimates are generally less reliable than those which take other climatic factors into account. Rosenberg *et al.* (1983) explains detailed description of various methods. Each method has its own advantage and disadvantages for use in practical application. None of the methods being used is applicable under all conditions.

2.1 Penman combination method

The Penman combination equation for computing potential evapotranspiration is one which is theoretically sound and which has been widespread applications when sufficient data are available. It is superior to most empirical methods for potential evapotranspiration estimation. This method is described by the following equation.

$$PET = (\Delta \cdot Er + \gamma \cdot Ea) / (\Delta + \gamma) \quad (1)$$

where PET is potential evapotranspiration, Δ is the gradient of the saturated vapor pressure at a certain air temperature and γ is the psychrometric constant. The sum of weighting factor $\Delta/(\Delta + \gamma)$ and $\gamma/(\Delta + \gamma)$ is unity. A weighted estimates of potential evapotranspiration, PET, is derived from the evaporation rate computed from the rate of net radiation, Er , and aerodynamic methods, Ea .

The combination method of calculating evapotranspiration from meteorological data is the most accurate method when all the required data are available and the assumption is satisfied. However, there are some problems encountered in Penman method. The Penman method requires a variety of climatological data, such as maximum and minimum air temperature, relative humidity, solar radiation and wind speed. If some of these data are not available, alternative method must be used for potential evapotranspiration estimation.

2.2 Priestley-Taylor method

For evapotranspiration over very large areas,

energy balance is main affecting factor for the evaporation rate. For such cases, Priestley and Taylor (1972) found that the second term of the combination equation (1) is approximately 30 percent of the first, so that equation (1) can be rewritten as the Priestley-Taylor potential evapotranspiration equation

$$\begin{aligned} PET &= \alpha \cdot Er \cdot \Delta / (\Delta + \gamma) = \alpha \cdot (Rn - G) \cdot \Delta / (\Delta + \gamma) \\ &= \alpha \cdot ET_{eq} \end{aligned} \quad (2)$$

where Rn is net radiation and G is the soil heat flux. The coefficient α was suggested to have a value of 1.26 for large land areas with a nearly saturated surface. Other investigators have confirmed the validity of this approach. They reported that the value of α varies slightly from one location to another (Chow *et al.*, 1988). ET_{eq} is equilibrium evapotranspiration.

The equilibrium evapotranspiration (ET_{eq}) is defined as follows (Slayter and McIlroy, 1961):

$$ET_{eq} = \Delta \cdot (Rn - G) / (\Delta + \gamma)$$

where Rn , G , and γ are explained as previously. ET_{eq} defines the minimum possible evaporation rate from a moist surface and depends only on the temperature and available energy (Rosenberg *et al.*, 1983).

The Priestley-Taylor method can be considered as a simplified form of the Penman combination equation in which the additive aerodynamic term is replaced by the constant α . Priestley and Taylor (1972) obtained values for α between 1.08 and 1.34 with an overall mean of 1.26. Various studies (Barton, 1979; Davies and Allen, 1973; Williams *et al.*, 1978) have shown that α is related to surface soil moisture, though their studies do not lead to a relationship that is universally applicable. Although $\alpha = 1.26$ has been reported universally for open water surfaces, those value has not necessarily been obtained over bare soil or vegetated surfaces with unlimited soil water supply. The value for various surfaces was well summarized by Nakagawa (1984).

It was reported that the Priestley-Taylor method provided good estimates where humidities are high and large scale advection is low. However, it was

significantly underpredicted where advection can be substantial, and sensible heat fluxes and bowen ratios are often negative (Allen, 1986).

For the global evaluation of potential evapotranspiration, data availability is important to choose a method of estimation. Factors such as data availability, the intended use, and the time scale are important when choosing the calculation method of potential evapotranspiration. As the method proposed by Priestley and Taylor (1972) is physically sound and very simple to use, it requires little computational effort, many applications have been made over a variety of surfaces (Nakagawa, 1984). The Priestley-Taylor method can yield accurate results if the assumption of the model are met (Parlange and Katul, 1992). Because of that, the Priestley-Taylor method was chosen for global estimates of potential evapotranspiration in this study.

3. Used Global Data

For the estimation of potential evapotranspiration, the following data were used. These are parts of Global Ecosystems Database supplied on CD-ROM by NOAA-EPA (1992).

1. Temperature: Surface Air Temperature. This data represents long term (approximately 60 years) means between 1920 and 1980 (Legates and Willmott, 1990a).
2. Albedo: Seasonal Albedo as present integrated surface albedos for January, April, July, October for snow free conditions except for permanently snow-covered continental ice. This data represents average between 1950 to 1970 (Matthews, 1983)
3. Cloudiness: Average monthly "Cloudiness" (% Sunshine) expressed as percentage sunshine hour per month at the land surface (Leemans and Cramer, 1991). This data represents the average for 1931-1960.
4. Elevation: Global Gridded Elevation and Bathymetry (ETOPO5).

5. Precipitation: Gauge corrected average monthly precipitation. This data represents long term (approximately 60 years) means between 1920 and 1980 (Legates and Willmott, 1990b).

All data are resampled to the resolution of 30-minute in latitude-longitude projections (Plate Careé projections) introduced because of its ease of registering with other data sets in grid basis.

4. Estimation of Potential Evapotranspiration

Fig. 1 shows the data processing flow to estimate monthly potential evapotranspiration using global data sets.

Fig. 1 Data processing flow for estimation of monthly potential evapotranspiration.

As shown in equation (2), net radiation (R_n) is a major component of Priestley-Taylor method, and consequently the reliability of the potential evapotranspiration estimate is largely dependent on the accuracy of the net radiation. The estimation of net radiation is described in section 5. In equation (2), term G is difficult to calculate but crude approximation is adequate since it is one order smaller than R_n . For the period of 24-hr or more, G becomes zero at many sites since daytime positive value are counterbalanced by nighttime negative values.

The slope of the saturation vapor pressure versus temperature curve, Δ , and the psychrometric constant, γ , are nonspecific parameters and are independent of crop type.

The calculation of the saturation vapor pressure versus temperature curve (mb/°C) is presented Kotoda (1986) as follows :

$$\Delta = 4098.0258 \cdot 6.11 \cdot \exp(7.5T/(237.3 + T)) / (237.3 + T)^2$$

where T is air temperature(°C). T is obtained from the global data set described in section 3.

The psychrometric constant (mb/°C) is estimated using a simplified curvilinear relation between standard atmospheric pressure and site elevation (Kotoda, 1986).

$$\gamma = [1005(1013.25 - 0.11986E + 0.000005356E^2)] / [622(2501 - 2.37T)]$$

For the calculation of Δ and γ , Elevation (m), E , and Temperature, T , is obtained from global data set described in section 3.

Although, α varies surface and climate conditions, the value of 1.26 is used for the estimate of PET. That $\alpha=1.26$ shows that the advection-free conditions leading to an equilibrium state are extremely unlikely to occur, and large scale advection from extensive saturated surfaces account for roughly 30% of the evaporation rate (Parlange and Katul, 1992).

5. Estimation of Net Radiation

The sun supplies virtually all the energy received by the earth. This energy drives the processes of photosynthesis, heating of the soil, heating of the air, and evaporation. Net radiation represents the available energy for sensible heat, evapotranspiration, soil heat flux, and to a small extent, photosynthesis (Hu and Lim, 1983). It is defined as the algebraic sum of the downward and upward radiative fluxes including both the short and long wave components.

Net radiation is defined by following formula.

$$Rn = Rs - r \cdot Rs + Ld - Lu = (1 - r)Rs + Ld - Lu$$

where Rs is total (direct+diffuse) shortwave solar radiation, Ld is downward longwave radiation, Lu is upward longwave radiation and, r is albedo.

As net radiation is a very useful quantity for the study of energy balance in agriculture, it has been found necessary to estimate this quantity from empirical formulae.

Net radiation (Rn): In the estimation of Rn using Penman (1948), Chang (1970), Wright's (1982) formulae, a knowledge of saturation vapor pressure at dew point temperature is necessary but it is not available from global data set. Therefore, the equation developed by Linacre (1968) which requires only two parameters of temperature and cloudiness is used for estimating Rn . As a matter of course, it would be rather unjustifiable to assume that Linacre's formula would still yield the best result for all month as well as all conditions. Linacre's formula is

$$Rn = (1 - r)Rs - 1.11(0.2 + 0.8n/N)(100 - T) \quad (3)$$

where Rs is total (direct and diffuse) shortwave solar radiation, n/N is the ratio of actual (n) to maximum possible (N) sunshine hours (percent possible sunshine ; cloudiness). T is temperature (°C) and r is albedo. Rn and Rs are in W/m². The values of r , n/N , T are obtained from the global data set described in section 3.

The formula (3) requires amount of short wave radiation, Rs . The amount of solar radiation reaching a unit area of the earth's surface depends on a number of factors which include the intensity of radiation emitted by the sun, astronomical considerations determining the position of the sun in the sky, and the general transparency of the atmosphere (Rosenberg *et al.*, 1983).

Total (direct and diffuse) Radiation (Rs): If there were no atmosphere, the total shortwave radiation reaching the surface of the earth, extraterrestrial solar radiation, would be easily computed in any place and any time. That is, the total radiation can be calculated by simple equation from the solar constant and the geographical and astronomical coordinates,.

However, it is evident that the total short wave

radiation reaching the surface is always lower than extraterrestrial shortwave radiation because of the absorption and the diffusion in the atmosphere. In atmosphere, two factors control the extinction of solar radiation. One is the path length through the atmosphere which depends on the solar elevation angle and azimuth, and the other is the extinction effects due to atmospheric gases, dusts, water vapor, and other suspended materials.

A tabulation of daily radiation incident through a cloudy atmosphere onto a flat surface is given for value of atmospheric transmissivity. The calculation will be for either direct incident radiation or for the total radiation. To calculate the short wave radiation, so-called correlation method based on relationship between solar radiation and other meteorological variables has been studied much in the past. The ratio of the bright sunshine (n/N) has been used most frequently as one of the pair for the correlation with total short wave radiation because the results is usually better and the calculation is easier than employing any other meteorological variable (Tena and Tinaut, 1986).

Since Angstrom (1924) proposed a relationship between total short wave radiation and duration of sunshine, a varieties of empirical formulae have been developed to estimate solar radiation from sunshine data. A general form, known as Angstrom's formula is

$$Rs = (a + b \cdot n/N) \cdot R \tag{4}$$

In equation (4) a and b are empirical constants which depends on the location, and R is extraterrestrial solar radiation. The method to derive extraterrestrial solar radiation, R , is explained in the Appendix.

The value of a and b are affected by the optical properties of the cloud cover, ground reflectivity, and average air mass (Iqbal, 1983). The sum of the coefficient a and b in equation (4) is considered a measure of the transparency of the atmosphere for the solar radiation under clear sky (Rao and Bradley, 1983). This means that, with total cloudiness ($n/N=0$), $a\%$ of the possible radiation is received.

When constant a and b are known, this formula can be applied to other locations with climatological characteristics similar to those from where the original data are obtained. The values of a and b were found to vary from month to month, and they are attributed to changes in the optical air mass.

For choosing the value of a and b , several papers are examined and summarized in Table 1. For example, Glover and McCulloch (1958), based on their analysis of the daily records from several sites (33.9°S~51.5°N) proposed that b might be considered a constant with a mean value of 0.52 and a considered a function of latitude, Φ , which is $0.29 \cos(\Phi)$.

The coefficient a and b shows seasonal, geographical difference (Glover and McCulloch, 1958). Tena and Tinaut (1986) and Hu and Lim (1983) showed that the sum of $a + b$ may be considered nearly constant throughout a year. That is the sum of a and b , is equal to 0.71. It means that the atmospheric transmittance to solar radiation, assumed 0.71 (moderate haze atmosphere conditions), and the incoming shortwave radiation does not exceed about 70% of the total extraterrestrial radiation.

Glover and McCulloch methods in Table 1 is reasonable because it takes the effect by latitude into account. The authors modified the Glover and McCulloch method by defining a and b as:

$$a = 0.29 \cos(\Phi)$$

$$b = 0.71 - 0.29 \cos(\Phi)$$

The sum of a and b by this method becomes 0.71.

Table 1 Comparisons of coefficient a and b in equation (4)

a	b	$a + b$	Source	Remarks
0.18	0.55	0.73	Penman(1948)	
0.25	0.50	0.75	Doorenbos and Pruitt(1977)	
0.24	0.51	0.75	Rao and Bradley(1983)	U.S.A.
0.18	0.62	0.80	Rietveld(1978)	$n/N < 0.4$
0.24	0.43	0.71	Mabuchi and Sato(1990)	Japan
0.26	0.44	0.70	Hu and Lim(1983)	Malaysia
0.34	0.51	0.75	Chuah and Lee(1981)	Malaysia
0.25	0.46	0.71	Chia(1969)	Singapore
0.27	0.44	0.71	Tena and Tinaut(1986)	Spain
0.37	0.39	0.76	Firzpatrick and Stern(1965)	Australia
$0.29 \cos(\Phi)$	0.52	$0.52 \sim 0.81$	Glover and McCulloch(1958)	$\Phi < 60^\circ$

6. Results

The authors developed 12 monthly datasets of potential evapotranspiration in this study. Those datasets are based on 30-minute latitude-longitude grid. Fig. 2 shows the estimated potential evapotranspiration (mm) in January, April, July, October within developed 12 months datasets.

In January (Fig. 2a), almost parts of the Northern Hemisphere shows the low potential evapotranspiration, and the higher latitude in the Southern Hemisphere has larger potential evapotranspiration. In April (Fig. 2b), high potential evapotranspiration is shown in the areas of tropical Africa, India, South-east Asia, and Central America because of high solar and net radiation.

In July (Fig. 2c), relatively high potential evapotranspiration extends in a vast area of the Northern Hemisphere while the Southern Hemisphere has low values because of the winter. In October (Fig. 2d), middle and high latitudes in the Northern Hemisphere, net radiation is much lower than April largely because of the lower incoming

solar radiation in autumn. Therefore, the Northern Hemisphere in October has more area with low potential evapotranspiration than April. High potential evapotranspiration values are shown in north Australia and northeast Brazil.

7. Accuracy of estimation

Sensitivity analysis of mathematical models are needed to explore their validity and to understand the interactions of their various components (Camillo and Gurney, 1984).

Coleman and Decoursey (1976) examined the sensitivity of various evaporation models to understand the effect of variations meteorological factors and introduced to computing error variances as follows :

$$\sigma^2(E) = \sum_i \{ \partial E / \partial P_i \cdot \sigma^2(P_i) \} \quad (5)$$

where $\sigma^2(E)$ is the expected variance in evaporation, as a function of the analytical derivatives of the model E with respect to the input data P and the variances of these data $\sigma^2(P)$. The equation (4) assumes independence among the input variables.

To apply Priestley-Taylor method, equation (5) is

Fig. 2 Estimated monthly potential evapotranspiration (mm) based on Priestley-Taylor method using global data sets by NOAA-EPA (1992).

rewritten as follows :

$$\sigma^2(\text{PET}) = \frac{\partial \text{PET}}{\partial (r)} \cdot \sigma^2(r) + \frac{\partial \text{PET}}{\partial (n/N)} \cdot \sigma^2(n/N) + \frac{\partial \text{PET}}{\partial (E)} \cdot \sigma^2(E) + \frac{\partial \text{PET}}{\partial (T)} \cdot \sigma^2(T) \quad (6)$$

For the sensitivity analysis of Priestley-Taylor method with global data set, variances of air temperature (T), cloudiness (n/N), albedo (r) and elevation (E) are assumed to be 1°C , 0.01, 0.01 and 100m, respectively.

Zonally average of potential evapotranspiration and standard deviation, σ (PET), were computed one degree latitudinal belts in the land area in January, April, July and October. They are shown in Fig. 3 with corresponding precipitation. The broken lines along estimated potential evapotranspiration are $\pm$ one standard deviation, the root of σ^2 (PET) in the equation (5).

The accuracy is approximately 20% in $0^\circ \sim 20^\circ\text{N}$ and 18% in $30^\circ \sim 50^\circ\text{N}$ of estimated potential

evapotranspiration. This accuracy is calculated under the assumption that the used model based on Priestley-Taylor method is correct.

8. Conclusions

Global potential evapotranspiration was estimated based on the Priestley-Taylor method using global datasets, air temperature, albedo, cloudiness, elevation in the Global Ecosystems Database supplied by NOAA-EPA (1992).

The developed datasets of global potential evapotranspiration has the following characteristics.

- Monthly, 12 datasets were developed.
- 30-minute latitude-longitude grid. The number of pixels is 720 by 360.
- The developed datasets represent approximately period during 1950 and 1970 because the periods

Fig. 3 Zonally average (one degree latitude belt) monthly precipitation, potential evapotranspiration and $\pm$ one standard deviations of estimated potential evapotranspiration.

of input data are 1950~1970 (Albedo), 1931~1960 (Cloudiness) and 1920~1980 (Temperature).

By the analysis of accuracy, it is found out that the accuracy (standard deviation) of the estimated potential evapotranspiration is approximately 20% of an estimated values. This accuracy includes only the assumed accuracy of input data and their sensitivity to the result. Further research is necessary to estimate the accuracy of the used model itself.

In order to estimate more detailed estimates of potential evapotranspiration, the more reliable data base and empirical formulae are necessary. With the improvement of global data sets, the method in this study can readily be applied to various parts of the world for estimating mean monthly and annual net radiation and potential evapotranspiration, which have many practical applications.

Therefore, the highest priority for future research must be placed on the development of world-wide information of precipitation, net radiation, potential and actual evapotranspiration, soil moisture with better resolution and accuracy. Until globally applicable formulae have been completed, the full utility of these database of potential evapotranspiration for standard surfaces remains still to be realized.

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Appendix

Monthly average extraterrestrial radiation (R) :

The monthly average extraterrestrial radiation is obtained by the summation of daily extraterrestrial radiation, H_o .

$$R = \sum_{n1}^{n2} H_o$$

where $n1$ and $n2$ are the day numbers at the beginning and end of the month. In this equation, H_o is obtained as following

$$H_o = (24/\pi) E_o \cdot I_{sc} [\omega_s \cdot \sin(\Phi) \cdot \sin(\delta) + \cos(\Phi) \cdot \cos(\delta) \cdot \cos(\omega_s)] \quad (7)$$

where ω_s is the sunrise hour angle (in radians), I_{sc} is the solar constant at mean distance of the earth from the sun ($=4921 \text{ KJ/m}^2\text{hr}$), E_o is the square of the ratio of the mean distance between earth and sun to the actual distance between earth and sun and δ is solar declination.

The value of each variables in equation (7) were calculated as follows (Iqbal, 1983) :

$$E_o = 1.00011 + 0.03422 \cos(\Gamma) + 0.00128 \sin(\Gamma) + 0.000719 \cos(2\Gamma) + 0.000077 \sin(2\Gamma)$$

In these equation, Γ , in radians, is called the day angle. It is represented by

$$\Gamma = 2\pi(dn - 1)/365$$

where dn is the day number of the year, ranging from 1 on 1 January to 365 on 31 December. February is always assumed to have 28 days. solar declination may be determined in radian as follows :

$$\delta = 0.006918 - 0.399912 \cos(\Gamma) + 0.070257 \sin(\Gamma) - 0.006758 \cos(2\Gamma) + 0.000907 \sin(2\Gamma) - 0.002697 \cos(3\Gamma) + 0.00148 \sin(3\Gamma)$$

At sunrise, solar zenith angle is equal to 90° . Therefore, sunrise hour angle, ω_s , is given by

$$\omega_s = \arccos(-\tan(\Phi) \cdot \tan(\delta))$$