The Sun is the primary source of energy for the Earth. The small changes in total solar irradiance (TSI) can affect our climate on the longer timescale. In the evolutionary timescale, the TSI varies by a large amount and hence its influence on the Earth’s mean surface temperature ($T_s$) also increases significantly. We develop a mass loss dependent analytical model of TSI in the evolutionary timescale and evaluated its influence on the $T_s$. We determined the numerical solution of TSI for the next 8.23 Gyr to be used as an input to evaluate the $T_s$ which formulated based on a zero-dimensional energy balance model. We used the present-day albedo and bulk atmospheric emissivity of the Earth and Mars as initial and final boundary conditions, respectively. We found that the TSI increases by 10% in 1.42 Gyr, by 40% in about 3.4 Gyr, and by 120% in about 5.229 Gyr from now, while the $T_s$ shows an insignificant change in 1.644 Gyr and increases to 298.86 K in about 3.4 Gyr. The $T_s$ attains the peak value of 2319.2 K as the Sun evolves to the red giant and emits the enormous TSI of $7.93 \times 10^6$ W m$^{-2}$ in 7.676 Gys. At this temperature, Earth likely evolves to be a liquid planet. In our finding, the absorbed and emitted flux equally increases and approaches the surface flux in the main sequence, and they are nearly equal beyond the main sequence, while the flux absorbed by the cloud shows the opposite trend.

Abstract

The Sun is the largest energy source in the Earth’s atmosphere (Kren 2015; Kren et al. 2017). The small changes in total solar irradiance (TSI), which is also called the solar constant ($S_0$), is the energy radiated by the Sun that is incident on the Earth’s atmosphere. TSI varies by about 0.1% over the solar-cycle timescale (Fröhlich 2006; Kopp 2016). It varies with time and its tiny changes in TSI affect the Earth’s climate on the longer timescale (Eddy 1976). This idea is strengthened by many other studies (Haigh 2007; Lean & Rind 2008; Gray et al. 2010; Ineson et al. 2011; Ermolli et al. 2013; Solanki et al. 2013; Kopp 2016). Space-borne instruments have been measuring the TSI since 1978. Its average value is 1361 W m$^{-2}$ at 1 au (Kopp & Lean 2011).

In the evolutionary timescale, the Sun’s luminosity changes by a large amount. The term “evolution” refers to a star’s change over the course of time. Currently, the solar luminosity is increasing by 0.009% per million years (Hecht 1994). At this rate, the TSI increases by 0.1% in 10 million years. Following this rate, TSI is expected to increase by 10% in 1 Gyr at which time the Earth will become uninhabitable. In the same way, the luminosity will increase by 40% in about 3.5 Gyr (Hecht 1994; Kopp 2016). As Kopp (2016) indicated, the TSI increases as the solar luminosity increases in the evolutionary timescale. However, there is a limitation of the estimation of the TSI in the evolutionary timescale. Kasting (1988) estimated the TSI to be varying from 1.15$S_0$ to 1.45$S_0$. This variation is in about 1.1–3.5 Gyr as indicated by Sackmann et al. (1993) and Hecht (1994). However, to study the influence of the TSI on the Earth’s mean surface temperature ($T_s$) during the Sun’s lifetime, modeling of the TSI in relation to the evolutionary timescale is needed.

O’Malley-James et al. (2013) used time-dependent luminosity to study the TSI variability and found its influence on $T_s$ in the evolutionary timescale. However, the solar mass loss ($\Delta M$) has an influence on the solar luminosity on this timescale. Moreover, their work is limited to the next 3 Gyr, although further study is needed to understand the variability of an extended time interval. Schröder et al. (2001) presented a model of $T_s$ in which they include the effect of solar mass variation, and predict the $T_s$ of different planets including Earth over the lifetime of the Sun. They conclude that we can survive, although the maximum ratio of the future to the present temperature is about 6.6. However, in their modeling, they assume that albedo ($\alpha$) is constant, and neglect the effect of bulk emissivity ($\varepsilon$). However, $\alpha$ is expected to be changing, perhaps decreasing in the future. Therefore, in our model, we incorporate the climate parameters: non-constant $\alpha$ and $\varepsilon$. Moreover, in our modeling, we include the solar $\Delta M$ in both TSI and $T_s$ models.

The aim of this work is to model the TSI variability and $T_s$ in the evolutionary timescale and to study the link between the two parameters. In this study, we developed an analytical model of the TSI variability and $T_s$ in the evolutionary timescale. The base of our formulation is the models developed by Shukure et al. (2019). They developed a $\Delta M$ dependent solar luminosity in the evolutionary timescale. To calculate the solar $\Delta M$, they first...
calculate the solar mass reduction every 1 million years for the next 15 Gyr. Then, they calculate the $\Delta M$ at each interval of 1 million years by subtracting every newly reduced solar mass from the present-day solar mass. Following this method, we calculate the $\Delta M$ for 8.23 Gyr to model TSI in the evolutionary timescale. Using the newly formulated TSI model and zero-dimensional energy balance model (EBM), we formulate $T_s$. We used the numerical method to solve the newly formulated models by setting some boundary conditions to $\varepsilon$ and $\alpha$ that will be explained in detail in the method part.

2. Method

2.1. Mathematical Formulation

2.1.1. The Solar Mass Loss

In modeling TSI in the evolutionary timescale, considering the solar $\Delta M$ effect is mandatory. The solar mass reduction and solar $\Delta M$ are modeled by Shukure et al. (2019):

$$M(t) = M_0 e^{-\delta t},$$

where $M_0$ is the present-day solar mass and $\delta$ determines the rate of decay (Petter Langtangen 2016; Strang & Herman 2021) of the total mass of the star. It is defined as the ratio of a star’s mass-loss rate ($M$) to the star’s mass which is measured in per year (yr$^{-1}$). Equation (1) estimates the variation of the original mass of the Sun with time and $t$ is the time needed to change the original mass of the star. For $M(t=0) = M_0$, which is the original mass of the Sun. However, the solar $\Delta M$ is the difference between the original mass and the remaining mass ($M(t)$)

$$\Delta M = M_0 - M(t).$$

Equation (2) estimates the solar $\Delta M$ at any time $t$.

2.1.2. Luminosity–Mass Loss Relation

The $\Delta M$-dependent luminosity is:

$$L(\Delta M) = \frac{L_0}{1 + \frac{2}{5} \left(1 + \frac{1}{\varepsilon_0} \ln \left(1 - \frac{\Delta M}{M_0} \right) \right) - \frac{2}{5}},$$

where $L_0 = 3.85 \times 10^{26}$ W is the present-day solar luminosity, and $t_0 = 4.57$ Gyr is the present-day solar age (Dwivedi 2010; Feulner 2012). Equation (3) is used as an input to model TSI in the evolutionary timescale.

2.2. Modeling Total Solar Irradiance in the Evolutionary Timescale

The TSI for the present-day solar constant is (O’Malley-James et al. 2013):

$$S_0 = \frac{L_0}{4\pi Kd_E^2},$$

where $k$ is a constant ($k \approx 1$) and $d_E$ is the Earth–Sun distance. Equation (4) estimates the amount of energy which crosses an area $A = 1$ m$^2$ (one square meter). For our new model of luminosity in the evolutionary timescale, Equation (4) can be rewritten as:

$$S_{\text{evolution}} = \frac{L(\Delta M)}{4\pi Kd_E^2}.$$

Rewriting Equation (5) in terms of Equation (3), it becomes

$$S_{\text{evolution}} = \frac{S_0}{1 + \frac{2}{5} \left(1 + \frac{1}{\varepsilon_0} \ln \left(1 - \frac{\Delta M}{M_0} \right) \right) - \frac{2}{5}}.$$

Equation (6) estimates the TSI variability in the evolutionary timescale as solar $\Delta M$ significantly increases.

2.3. Earth’s Mean Surface Temperature Variation

The temperature of any planet varies as the Sun evolves. Our main interest in this section is to model $T_s$. In the modeling, we excluded the greenhouse effect on the $T_s$ variation. The base of our modeling is the energy balance model (EBM). The energy flux that crosses a unit area is estimated by Equation (4). If we consider the region of our Earth that faces the Sun as a circular area, the total amount of energy flux ($\phi$) that intercepts the Earth’s circular area is the product of the flux through the unit area ($S_0$) and the area of the circle:

$$\phi_{\text{intercept}} = S_0 \pi R_E^2,$$

where $R_E$ is the radius of Earth. However, the total surface area of Earth ($A_E$) is

$$A_E = 4\pi R_E^2.$$

The average energy absorbed by the Earth is the ratio of the total energy absorbed by the Earth to the surface area of the Earth and it is written as (Swift 2018):

$$\phi_{\text{absorbed}} = \frac{S_0}{4}.$$

Equation (9) can be the flux absorbed by a completely dark planet whose albedo is zero. However, planet Earth has an albedo different from zero. Hence, the absorbed $\phi$ by Earth is defined as (McGuire & Henderson-Sellers 1987; Swift 2018):

$$\phi_{\text{absorbed}} = \frac{S_0}{4} (1 - \alpha),$$

where $\alpha$ is the temperature-dependent Earth’s albedo taken to be varying in the interval $0 \leq \alpha \leq 1$. Energy emitted by Earth’s surface is estimated by the Stefan–Boltzmann law:

$$\phi_s = \sigma T_s^4,$$

where $\phi_s$ is the flux that escapes from the surface of the Earth, $\sigma$ is the Stefan–Boltzmann constant, and $T_s$ is the Earth’s mean surface temperature. However, Equation (11) needs a correction for the cloud absorption. The flux absorbed by clouds is:

$$\phi_c = \varepsilon \sigma T_s^4,$$

where $\phi_c$ is flux absorbed by cloud and $\varepsilon$ is the dimensionless bulk emissivity that can be in the interval $0 \leq \varepsilon < 1$ (Swift 2018). The flux radiated out of the atmosphere is:

$$\phi_{\text{emitted}} = (1 - \varepsilon) \sigma T_s^4.$$
When the energy of a planet is at thermal equilibrium, the absorbed and emitted $\phi$ by Earth become equal.

$$\phi_{\text{absorbed}} = \phi_{\text{emitted}}$$  \hspace{1cm} (14)

Substituting Equations (10) and (13) into Equation (14), one can calculate the $T_s$, as:

$$T_s = \left( \frac{S_0(1 - \alpha)}{4(1 - \varepsilon)\sigma} \right)^{\frac{1}{2}}.$$  \hspace{1cm} (15)

Equation (15) estimates the expected present-day Earth’s mean temperature. In the evolutionary timescale, the TSI is expected to be changing (i.e., $S_0 \rightarrow S_{\text{evolution}}$) and hence, it influences $T_s$. Therefore, the expected $T_s$ in the evolutionary timescale can be estimated by rewriting Equation (15) in terms of $S_{\text{evolution}}$:

$$T_s = \left( \frac{S_{\text{evolution}}(1 - \alpha)}{4(1 - \varepsilon)\sigma} \right)^{\frac{1}{2}},$$  \hspace{1cm} (16)

where $T_s$ changes as the Sun evolves. Since the Earth’s surface covered by ice will reduce in the future, this will result in the decrease of Earth’s albedo. Substituting Equation (6) into (16), $T_s$ is estimated as:

$$T_s = \left( \frac{(1 - \alpha)S_0}{4(1 - \varepsilon)\sigma} \right)^{\frac{1}{2}}$$  \hspace{1cm} (17)

Equation (17) predicts the $T_s$ of our planet in the evolutionary timescale.

2.4. Numerical Computations of the Model

In the numerical analysis, we assumed that the present-day position of the Earth’s orbit does not change as the Sun evolves. We numerically solved Equation (6) by setting $\delta$ to vary as $10^{-13}$ yr$^{-1} \leq \delta \leq 6 \times 10^{-11}$ yr$^{-1}$ based on the present-day value of $\dot{M} = 10^{-13}$M$_e$ yr$^{-1}$ reported by Feulner (2012). We also assumed the value of $\dot{M} = 6 \times 10^{-11}$M$_e$ yr$^{-1}$ during the red giant phase and we used the solar observables to be $S_0 = 1361$ W m$^{-2}$ (Kopp & Lean 2011; Schmutz et al. 2013), $M_e = 1.99 \times 10^{30}$ (Kaplan & Union 1981), and the present-day solar age as initial time $t_\odot = 4.57 \times 10^9$ (Bahcall et al. 1995; Feulner 2012). The solar mass reduction is calculated for about 8.23 Gyr from now. The new mass of the Sun, $M(t)$, is recorded at the intervals of every 1 Myr based on Equation (1) resulting in a total of 8231 numerical values. The total numerical values are used for further analysis.

Similarly, the solar $\Delta M$ in the same time interval is calculated using Equation (2). Each of the new numerical values is subtracted from the present-day mass of the Sun in each time step (1 Myr). The new values of $\Delta M$ are used as an input to calculate the TSI in the same time intervals.

To solve Equation (17) we set some boundary conditions of $\alpha$ and $\varepsilon$. We set the present-day values of the Earth’s $\alpha$ and $\varepsilon$ to be 0.3 and 0.407, respectively, as initial boundary conditions. By assuming the future Earth’s atmosphere to be the present-day atmosphere of Mars, we set the final boundary condition to be 0.250 and 0.0038, respectively, for $\alpha$ and $\varepsilon$ (Swift 2018).

We numerically solved Equation (17) for the next 8.23 Gyr by using the numerical solution of TSI as an input. Our program determines the $T_s$ every 1 million years. We then calculate $\phi_{\text{absorbed}}$, $\phi_{\text{f}}$, $\phi_{\text{e}}$, and $\phi_{\text{emitted}}$ based on Equation (10), (11), (12), and (13), respectively, by using the $T_s$ solution as an input.

3. Result and Discussion

3.1. Total Solar Irradiance Variability in the Evolutionary Timescale

Figure 1 shows the TSI variability as the Sun evolves. Figure 1(a) indicates that the TSI increases to 1448.1 W m$^{-2}$ in the first 1 Gyr from now, representing an increase of 6.4% with respect to the present-day value. At about 1.42 Gyr from now, the TSI changes to 1497.1 W m$^{-2}$, which is about a 10% increase compared to the present value. At this value of TSI, the Earth will lose water (Hecht 1994). However, according to our model, the 10% variability achieved at about 1.4 Gyr lags by 0.32 Gyr as compared with Hecht’s finding.

In 3,374 Gyr, the TSI increases to 1905.4 W m$^{-2}$, and it is about a 40% increment. This is the Kasting (1988) flux at which an ocean evaporates entirely. This value is achieved at about 3.5 Gyr, as indicated by Sackmann et al. (1993) and Hecht (1994). In our model, the 40% increment of the TSI occurs before 3.5 Gyr.

At the end of the time in the main sequence, TSI increases to 2994.2 W m$^{-2}$ at about 5.23 Gyr from now. As compared to $S_0$ it increased by about 120%. Beyond the main sequence, the TSI increases enormously. Figure 1(b) shows the peak value of $7.93 \times 10^9$ W m$^{-2}$ at about an age of 7.676 Gyr from now. This
age is the age at which the Sun approaches the final stage of RGB (Sackmann et al. 1993). Equation (1) predicts that the present-day Sun’s mass reduces to 0.46 $M_{\odot}$ in the next 8.23 Gyr. According to Sackmann et al. (1993), an object which approaches this solar mass is a low-mass white dwarf. At this age, the dwarf will have the TSI of $-1.13 \times 10^4$ W m$^{-2}$. The negative sign indicates the TSI is below the present-day value of the Sun.

Beyond 1.644 Gyr from now, the temperature of Earth is observed to be rising significantly (see Figure 2(a)). This could be due to an increase in moisture in the Earth’s atmosphere that causes an increase in the temperature, which influences the $T_s$ (O’Malley-James et al. 2013). At about 3.374 Gyr, when TSI increases to 1905.4 W m$^{-2}$ (40% increase from present-day value), part of this energy absorbed by the Earth’s atmosphere raises the $T_s$ to 298.86 K. According to Kasting (1988), the oceans would evaporate entirely when the TSI become 1905.4 W m$^{-2}$. $T_s$ rises by 3% as predicted by Equation (17). The equation also predicts the $T_s$ to be 326.72 K in 5.23 Gyr from now when the Sun completes its main sequence life. This happens when the TSI becomes 2994.2 W m$^{-2}$ (increases by 120%).

If we consider the assumption of Schröder et al. (2001), that all forms of life will be extinct when $T_s$ has reached 380 K, Equation (17) predicts that this will happen at the age of 7.13 Gyr (see Figure 2(b)). This shows our equation predicts this phenomenon happens 0.1 Gyr before the Schröder et al. prediction. This is because, in our model, we included $\varepsilon$ and $\alpha$ parameters and let them vary. However, humans will have to leave much sooner, similar to the present-day situation, perhaps before the model temperature reaches 291.9 K in 2.2 Gyr, as our model predicts. Figure 2(b) also shows that $T_s$ attains a peak value of 2319.2 K, where the ratio is 7.7 as the Sun evolves to the red giant phase. This value is much greater than the melting points of rocks and minerals as investigated by Eppelbaum et al. (2014). This finding indicates the bad news that our planet Earth will have the probability of disappearance or have a chance of evolving into the liquid planet due to the extreme temperature increment in the next 7.676 Gyr during the Sun’s red giant stage. However, beyond this age the good news is that since the Sun’s energy output is observed to be decreasing, the $T_s$ also decreases and becomes 311.34 K at the end of 8.23 Gyr from now. The decrease in the temperature of the planet may have allowed our planet to revert to a solid state. The link between the TSI and $T_s$ in the presence of greenhouse effect in the same timescale will be considered in our future work.

### 3.3. Earth’s Flux Variation Surface to Top of Atmosphere

#### 3.3.1. Variation in the Main Sequence

So far we discussed the $T_s$ variation due to solar evolution. Since the magnitude of an energy flux entering into Earth’s atmosphere is expected to vary with the altitude of our

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**Figure 2.** $T_s$ relative to its present temperature, which is produced based on Equation (17). (a) The predicted variation for the next 5.23 Gyr of the Sun’s life, up to the end of the main sequence. (b) On the expansion of the Sun on the RGB. The maximum ratio is about 7.99.
atmosphere, we estimate the energy flux at different levels by assuming that $T_s$ is independent of the atmospheric altitude.

Figure 3(a) shows the energy flux variation at different levels of Earth’s atmosphere. The $\phi_{\text{absorbed}}$ and $\phi_{\text{emitted}}$ that are produced based on Equations (10) and (13), respectively, are equal in the figure. Their present-day value is 238.41 W m$^{-2}$ that shows the energy balance of the system. The two values increase as the Sun evolves in the main sequence, and approach the values of $\phi_s$ whose present-day value is 401.91 W m$^{-2}$ based on Equation (11). This value is shown to be greater than $\phi_{\text{absorbed}}$ since it is dependent only on the $T_s$ of the Earth. The $\phi_s$ does not show significant change for the next 2.83 Gyr. If the $T_s$ varies according to the prediction of our model, the life on the Earth’s surface would have a probability of surviving up to 2.83 Gyr from now. This result is close to that of O’Malley-James et al. (2013), which predicts the maximum lifetime for the life on our planet is 2.8 Gyr from now. The $\phi_c$ is found to be decreasing from the present-day values of 163.58 W m$^{-2}$. This is because we assumed the cloud emissivity to be decreasing until it becomes equal to the present-day value of Mars. The values of the fluxes at different time intervals are illustrated in Table 1.

### 3.3.2. Variation Beyond the Main Sequence

The variation of various energy fluxes in the Earth’s atmosphere beyond the main sequence is shown in Figure 3(b). Unlike in the main sequence, all fluxes except $\phi_c$ have almost the same values. For example, at about 5.43 Gyr, $\phi_{\text{absorbed}}, \phi_{\text{emitted}}$, and $\phi_s$ has the values of 590.97 W m$^{-2}$, 590.97 W m$^{-2}$, and 687.96 W m$^{-2}$, respectively. However, $\phi_c$ has the value of 96.99 W m$^{-2}$. At about 12.25 Gyr, when the Sun gets its peak expansion, all the fluxes attain their peak values as indicated in the figure. Additional values of the fluxes at different time intervals are shown in Table 1.

### 4. Conclusion

We modeled the TSI variability in the evolutionary timescale. It shows a significant influence on the Earth’s mean

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**Table 1**

| Age (Gyr) | TSI (W m$^{-2}$) | $T_s$ (K) | $\phi_{\text{absorbed}}$ (W m$^{-2}$) | $\phi_s$ (W m$^{-2}$) | $\phi_c$ (W m$^{-2}$) | $\phi_{\text{emitted}}$ (W m$^{-2}$) | $\alpha$ | $\varepsilon$ |
|----------|------------------|---------|--------------------------------------|----------------------|---------------------|----------------------------------|------|--------|
| 4.570    | 1361.908         | 290.160 | 238.334                              | 163.578              | 401.912             | 238.334                          | 0.300| 0.407  |
| 5.990    | 1497.552         | 289.889 | 265.301                              | 135.113              | 400.414             | 265.301                          | 0.291| 0.337  |
| 7.944    | 1905.465         | 298.908 | 343.221                              | 109.400              | 452.621             | 343.221                          | 0.280| 0.242  |
| 9.800    | 2995.261         | 326.615 | 547.963                              | 97.287               | 645.251             | 547.963                          | 0.268| 0.180  |
| 11.700   | 12089.574        | 452.832 | 2246.597                             | 137.543              | 2384.139            | 2246.597                         | 0.257| 0.058  |
| 12.246   | 7925489.4        | 2277.903| 1479360.5                            | 47234.825            | 1526595.300         | 1479360.500                      | 0.253| 0.031  |
| 12.247   | -34065380.000    | 2319.196| -6358646.800                          | -202694.910          | -6561341.700        | -6358646.800                      | 0.253| 0.031  |
| 12.800   | -11308.673       | 311.247 | -2120.376                             | -8.088               | -2128.464           | -2120.376                        | 0.250| 0.004  |
surface temperature. The following are the conclusions from the above analysis.

1. The TSI varies by 6.4% in 1 Gyr increasing from 1361 to 1448.1 W m$^{-2}$
2. The TSI increases to 1497.1 W m$^{-2}$ (by 10%) from a present-day value in 1.42 Gyr from now.
3. The TSI increases by 40% at the end of 3.4 Gyr from now.
4. The model also predicts the TSI variability when the Sun is at the end of the main sequence to be about 2994.2 W m$^{-2}$ at about 5.23 Gyr from now.
5. The Earth’s mean surface temperature does not change significantly, with a value of 290.16 K at 1.644 Gyr from now.
6. At about 3.4 Gyr, when TSI increases to 1905.4 W m$^{-2}$, the Earth’s surface temperature increases to 298.86 K.
7. The maximum Earth’s temperature is predicted when the Sun becomes an RGB to be 2319.2 K, turning Earth into a liquid planet.
8. The absorbed flux and emitted flux are observed to be increasing equally and approach the surface flux at the end of the main sequence, while the flux absorbed by clouds is found to be decreasing.
9. Beyond the main sequence, the surface flux, absorbed flux, and emitted flux become nearly equal attaining a peak value at about 7.676 Gyr from now. However, the flux absorbed by the clouds decreases relative to others, although it peaks at the same points as other fluxes.

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