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Mapping potential surface contributions to reflected solar radiation

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Abstract

Modifying Earth’s albedo is one of the strategies considered to reduce its energy imbalance and slow global warming by reflecting solar energy. Atmospheric contributions to reflected solar radiation through stratospheric aerosols or cloud brightening have received considerable attention; however, the efficacy of surface interventions is less understood. We address this gap by estimating the potential for surface contributions to reflected solar radiation at approximately 30 km resolution using a simple radiative transfer model. Long-term average annual-mean incoming and outgoing top-of-atmosphere and surface solar fluxes are input to determine atmospheric shortwave optical properties (i.e., transmittance, absorptance, and reflectance), which can be used with surface albedo to estimate surface-reflected outgoing solar radiation. A comparison of reanalysis- and satellite-based input datasets shows good agreement. The results indicate global annual-mean surface-reflected outgoing solar radiation potential of 109 W m\textsuperscript{-2}, nearly a factor of five larger than the actual value, and local areas where it could be increased above 200 W m\textsuperscript{-2} with surface albedo enhancement. Regions with particularly strong potential include Andean South America, the Middle East, southwestern North America, southwestern Africa, Australia, and the sub-equatorial tropical oceans. Future research could extend the methods to account for seasonal variations and the potential to mitigate extreme heat events in particular.

1. Introduction

1.1. Motivation

The fate of solar irradiance reflected by Earth’s surface depends on atmospheric properties associated with clouds, aerosols, and gases that impede its passage back out to space, as well as surface properties associated with built and natural environments which interact with the fraction of surface-reflected sunlight reflected downward by the atmosphere. The efficacy of surface reflection has practical implications for efforts to mitigate urban heat islands and global warming. Because of the immediacy of its impact, albedo modification is joining measures such as greenhouse gas (GHG) emissions reduction \cite{1}, natural climate solutions \cite{2}, and GHG removal \cite{3} as an important climate risk reduction tool. All these measures aim to increase the Earth’s outgoing energy flows to reduce the planetary energy imbalance, which is the physical driver of global warming \cite{4}.

Top-of-atmosphere outgoing solar radiation (hereafter referred to as \textit{outsolation}) is composed of contributions from the surface and from the atmosphere. Outsolation represents approximately one-third of Earth’s outgoing energy. Outgoing longwave radiation emitted by Earth’s surface and atmosphere contribute the remaining two-thirds \cite{5}.

Interventions targeting longwave radiation have produced mixed results to date. Cirrus cloud thinning has been proposed to increase outgoing longwave radiation \cite{6}, and it remains in the domain of research \cite{7}. GHG removal has large potential capacity, however operating capacity will take many decades to scale up \cite{8}. Some countries have achieved GHG emission reductions in certain sectors \cite{9}, however global net emissions continue...
to rise, evidenced by the increasing atmospheric CO2 concentration and decadal mean atmospheric CO2 growth rate [10]. Thus, Earth’s energy imbalance and heating rate also continue to increase [11].

Outsolation strategies seek to adjust the net radiative forcing by increasing albedo to reflect more solar energy in the ultraviolet, visible, and shortwave infrared parts of the electromagnetic spectrum. Stratospheric aerosol injection and marine cloud brightening are atmospheric reflectivity interventions that have been proposed and studied [12, 13]. Surface reflectivity interventions such as reflective roofs (often called ‘cool roofs’), pavements, shade structures [14], water covers (e.g., stable, nondispersive foam [15, 16]), and landscape albedo modification have received less attention. Compared to atmospheric reflectivity interventions, which remain in the realm of research amid deep public controversy [17], surface reflectivity interventions are relatively low risk [18], and can be monitored via a variety of remote sensing platforms [19].

Lenton and Vaughan estimated the global radiative forcing potential of surface albedo modification broken down by surface type (e.g., desert, grassland, croplands, settlements), each with its own area, albedo change, and atmospheric transmittance factor [20]. However, to the best of the authors’ knowledge, no one has improved these estimates by determining the incoming solar radiation (hereafter insolation) intensity at each location on earth and the transmittance of reflections at each location back out to space. Doing so would provide policymakers, urban planners, real estate actors, and innovators with guidance on what locations offer the most potential for surface albedo increases.

1.2. Background
Although no one addressed the potential for location-specific modification of surface albedo, several authors have investigated the impact of surface albedo changes. Studies during the 20th Century tended to focus on (1) general relationships between surface albedo and climate, and (2) the impact of inadvertent albedo changes. Manabe and Wetherald employed a radiative-convective model of the global-mean atmosphere to investigate its sensitivity to changing various parameters including surface albedo [21]. Sagan, Toon, and Pollack built upon Manabe and Wetherald when they estimated the climate impact of global albedo change associated with historic human land use and environmental change [22]. Potter et al used the Lawrence Livermore Laboratory statistical dynamic climate model to investigate the climate impacts of albedo increases associated with desertification and tropical deforestation [23]. Hansen, Sato, and Ruedy leveraged a sector-type general circulation model with idealized geography to explore the climate response of various radiative forcings, including surface albedo changes [24]. Considered together, this research indicates that surface albedo plays a significant role in global climate and that humans can exert an influence on climate through surface albedo changes.

In contrast to these earlier studies, work published in the early 21st Century has tended to focus on the impacts of surface albedo modification strategies in the context of climate intervention. Using a static two-dimensional radiative transfer model, Hamwey provided some early evidence that increasing surface albedo in human settlements and grasslands could offset as much as 0.76 Wm$^{-2}$ of global-mean radiative forcing [25]. Akbari, Menon, and Rosenfeld estimated the radiative forcing from increasing roof and pavement albedos [26]. Menon et al used a land surface model in offline mode to estimate the impact of increasing urban albedo in terms of outgoing radiation and land surface temperature [27]. Zhang et al later revisited the potential climate impacts of global reflective roof deployment using a coupled Earth system model [28]. Beyond urban albedo modification, Carrer et al explored the radiative forcing potential of cover crops during the fallow period in European agriculture [29]. Bright et al investigated the radiative forcing and carbon-equivalence of albedo changes in land management contexts [30]. Gaskill and Reece proposed large-scale albedo enhancement of deserts by covering them with white plastic polyethylene film [31]. These studies suggest that combined urban and rural surface albedo increases could exert a modest negative radiative forcing globally and provide significant heat mitigation locally.

An increasing fraction of the land surface and global population is being exposed to heat extremes [32, 33]. Surface albedo modifications have thus also been studied as a regional heat mitigation strategy in urban settlements and rural landscapes. Ridgwell et al showed that increasing the canopy albedo of vegetation in specific cropland areas in a global climate model reduced summertime surface air temperature by more than 1 °C across a wide longitudinal band of North America and Eurasia [34]. Davin et al provided evidence that cropland albedo increases associated with no-till agriculture could reduce peak temperatures during summer heatwaves [35]. Yang and Bou-Zeid investigated the scale dependence of reflective and green roof cooling efficiency, concluding that increasing the area of these interventions beyond the city-scale produces diminishing returns for cooling in the city-center [36]. Vahmani et al used a satellite-supported version of the Weather Research and Forecasting (WRF) model coupled with a single-layer urban canopy model to investigate the climate impact of urbanization and demonstrated that reflective roofs could counter a substantial fraction of increased heat and associated building energy demand in Southern California [37]. Broadbent et al showed the positive efficacy of reflective roofs at reducing pedestrian-level air temperature with WRF model simulations of
reflective roof deployment in Phoenix, Atlanta, and Detroit under historical and future heat wave conditions [38]. Despite uncertainty regarding the net effect of global surface albedo interventions, these studies position surface brightening as a ‘low regrets’ local and regional adaptation strategy.

Notwithstanding the above-mentioned advances, the National Research Council noted a dearth of new research into surface albedo modification in 2015 [39]. A follow-on report featuring recommendations for solar geoengineering research and research governance left out surface albedo modification entirely [40]. These assessments are incongruous with the demonstrated cooling effectiveness and speed of reflectivity interventions [41], as well as the increase in infrastructure-based heat reduction modeling studies published in the early 21st Century [42].

To advance understanding of surface albedo contributions to urban heat island and climate change interventions, we break out existing global-mean estimates of potential surface-reflected outstory into a full global map with approximately 30 km resolution. Using a model of reflected solar radiation, we have determined the potential gain from reflectivity modification for each location on earth. This data provides insights on radiative properties of surfaces and the atmosphere across a wide range of spatial and temporal scales. The data allow us to characterize the areas with highest annual-average potential and will enable further research regarding the radiative forcing potential, cooling efficacy, and costs of surface reflectivity interventions across all locations and times of year as well as during periods of greater vulnerability to extreme heat such as heat waves.

2. Methods

2.1. Data

Atmospheric data used in this study are derived from incoming and outgoing solar radiation flux fields at the surface and top of atmosphere from the fifth generation of the European Centre for Medium-range Weather Forecasting (ECMWF) atmospheric reanalysis (ERA5) and the Clouds and the Earth’s Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) top-of-atmosphere (TOA) and surface dataset version 4.1. We obtained ERA5 hourly all-sky solar flux fields for the years 1991 through 2020 from the Copernicus Climate Change Service (C3S) Climate Data Store at https://cds.climate.copernicus.eu/ [43]. C3S provides ERA5 fields with hourly time resolution and approximately 30 km horizontal resolution (at the equator, narrowing toward the poles) from 1959 to present. ERA5 is based on the ECMWF Integrated Forecasting System (IFS) Cy41r2 and data assimilation based on a hybrid incremental 4D-Var scheme with an ensemble component. The system produces state-of-the-art, spatiotemporally complete, dynamically consistent estimates of the state of the atmosphere, land, and ocean [44]. ERA5 solar flux fields correspond roughly to the wavelength range from 0.2 to 4 μm.

Compared to previous generations of reanalyses, ERA5 includes improved external forcings through the provision of CMIP5-recommended long-term forcing fields representing total solar irradiance, aerosols, greenhouse gases, and ozone. The result is in better agreement with observational estimates of global-mean energy budgets at the surface and top-of-atmosphere [45]. Yang and Bright compared surface downwelling solar flux estimates from global satellite- and reanalysis-based products with station observations from the Baseline Solar Radiation Network (BSRN) [46]. They found that ERA5 outperforms another reanalysis product (MERRA-2) in terms of bias and root mean square error but exhibits larger error statistics than satellite-derived products such as Solcast and CERES.

We obtained CERES EBAF monthly all-sky solar flux fields for the years 2001 through 2020 from the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) CERES ordering tool at http://ceres.larc.nasa.gov [47]. NASA LaRC provides CERES EBAF fields with monthly time resolution and 111 km (1°) horizontal resolution (at the equator) from March 2000 to a few months prior to the present. Among other goals, the CERES program aims to provide a long-term, integrated global climate data record for observing changes in Earth’s radiation budget from the surface to the top-of-atmosphere. Its instruments fly on a series of polar orbiting, sun-synchronous satellites that measure filtered radiances including the shortwave range from 0.3 to 5 μm. These measurements are converted into unfiltered shortwave radiances and TOA radiative fluxes as described by Loeb et al [48]. The surface irradiances are computed nearly independently with satellite-derived cloud and aerosol properties and vertical profiles of temperature and specific humidity from reanalysis. EBAF-TOA irradiances are used to constrain surface irradiances. More details on the CERES EBAF algorithms can be found in Loeb et al and Kato et al [48, 49].

CERES EBAF has been utilized for many climate research applications relevant to this study, including analyzing Earth’s energy imbalance [11] and surface albedo trend detection [50]. The TOA fluxes are accurate to within 2%, a factor of 2 or more improvement over the CERES predecessor ERBE [51]. Zhang et al evaluated the accuracy of surface incident shortwave fluxes from four satellite-based products including CERES EBAF against...
global ground-based measurements. They found that CERES EBAF had the best accuracy, which they attributed to its incorporation of improved cloud information from active instruments [52].

We tested the robustness of our results by repeating our analysis on the ERA5 and CERES EBAF datasets. Both datasets account for surface type and latitude-dependent solar zenith angle when formulating solar fluxes. The higher temporal and spatial resolution of ERA5 solar fluxes motivated our choice of ERA5 as a primary dataset and the higher accuracy of CERES EBAF solar fluxes motivated our choice of CERES EBAF as a validation dataset.

2.2. Model of reflected solar radiation
To estimate surface contributions to outsolation, we implement a radiative transfer model like the one described by Donohoe and Battisti [53] and reformulated by Stephens et al [54]. Loeb et al [55] also extended the Stephens formulation in a study that isolated atmospheric and surface contributions to the variability in solar fluxes.

The model features a single-layer atmosphere that accounts for three radiative processes that are assumed to be isotropic: reflection, absorption, and transmission. These intrinsic properties account for atmospheric attenuation of solar radiation on its path from the top-of-atmosphere down to a reflecting surface and back out to space (see figure 1). Of the incident solar radiation, some fraction is reflected by the atmosphere, some fraction is absorbed by the atmosphere, and the remainder is transmitted to the surface. Of this transmitted radiation reaching the surface, some fraction is reflected upward by the surface. Of this surface-reflected solar radiation, some fraction is reflected downward by the atmosphere, some fraction is absorbed by the atmosphere, and some fraction is transmitted out to space. For the fraction reflected downward, these processes are repeated for a very large number of reflections and approximated by a convergent infinite series.

Following Stephens et al [54], the model assumes that the atmospheric optical properties can be combined with the surface optical properties to determine optical properties of the system of the atmosphere plus surface. In other words, the system (atmosphere and surface), the atmosphere, and the surface each have optical properties.

The system reflectance (i.e., planetary albedo) is defined as the ratio of outsolation to insolation (i.e., incoming solar radiation) at the top-of-atmosphere:

\[ R = \frac{F_{\text{TOA}}}{F_{\text{TOA}}} \] (1)

The system transmittance is defined as the ratio of downwelling solar radiation reaching the surface to the insolation at the top-of-atmosphere:
The system absorptance is one minus the system reflectance:

\[ A = 1 - R \]  

The surface reflectance (i.e., surface albedo) is defined as the ratio of upwelling solar radiation to downwelling solar radiation at the surface:

\[ \alpha = \frac{F_{Sfc}}{F_{Sfc}} \]  

The atmospheric properties relate to the downwelling and upwelling fluxes of solar radiation via the interaction principle which describes the relationship between radiation incident upon and emergent from a medium \[ [56] \]. In this model, atmospheric properties are assumed to be independent of direction:

\begin{align*}
F_{TOA}^i &= rF_{TOA}^i + tF_{Sfc}^i \\
F_{Sfc}^i &= tF_{TOA}^i + rF_{Sfc}^i
\end{align*}  

Atmospheric absorption is one minus the atmospheric reflectance minus the atmospheric transmittance:

\[ a = 1 - r - t \]  

The system properties and atmospheric properties can be related by combining equations (1), (2), (4), and (5b):

\begin{align*}
T &= \frac{t}{1 - r \alpha} \\
R &= r + \frac{\alpha^2 t}{1 - r \alpha}
\end{align*}  

And since the system properties are known from the inputs, the atmospheric properties can be determined by inverting equations (7a) and (7b):

\begin{align*}
t &= \frac{1 - \alpha R}{1 - \alpha^2 T^2} \\
r &= R - t \alpha T
\end{align*}  

The model has several useful qualities for our application. It is computationally efficient and requires only a few inputs that are readily accessible from observations or numerical models. It can be applied flexibly to individual locations or area-averages, as well as to different time-averages (e.g., daily, monthly, annual averages).

The model and our assumptions introduce a few caveats and limitations. First, we assume that the same percent of absorption takes place on every incoming and every outgoing pass through the atmosphere. Other authors, such as Taylor \textit{et al} \[ [57] \], have assumed that absorption only occurs on the first incoming pass through the atmosphere based on the theory that wavelengths that are absorbed by molecules in the atmosphere are fully absorbed on the way in and there is nothing more to absorb on the way out. Although the subsequent passes of wavelengths that were significantly absorbed on the first pass have less flux that can be absorbed after reflection than other wavelengths, Donohoe and Battisti \[ [53] \] pointed out that radiative transfer model calculations have shown that atmospheric absorption of multi-pass radiation increases as the surface albedo is increased from 0 to 1 \[ [58] \], supporting our assumption. If the true absorption of reflected solar energy is less than used in our model, our estimate of potential surface-reflected solar energy may be understated.

Second, we assume that the atmospheric radiative properties are isotropic (i.e., independent of direction) and no correction is required at high latitudes. However, Winton provided some evidence that upward and downward reflectivity of the atmosphere are not equivalent in many parts of the globe \[ [59] \]. The more accurate 4-parameter method of estimating atmospheric radiative properties described by Winton requires additional model diagnostics that are not available from ERA5 or from observations. Another alternative, which Winton termed ALL/CLR, leverages differences between all-sky and clear-sky fluxes to estimate upward atmospheric reflectivity. This method would not estimate upward absorptivity and cannot be used to estimate the top-of-atmosphere shortwave flux change due to a surface albedo change. Hence, we are limited to the isotropic assumption regarding atmospheric radiative properties. More accurate estimates of potential surface-reflected outpsolation would be facilitated by provision of the model solar flux diagnostics required for Winton’s 4-parameter model or by global observational estimates of upwelling and downwelling atmospheric radiative properties.
2.3. Estimating potential surface contributions to albedo modification

We partition outgoing solar radiation fluxes into contributions from the surface and from the atmosphere by implementing the above-described radiative transfer model, which takes as inputs incoming and outgoing solar radiation fluxes at the top-of-atmosphere and surface. First, we apply the model to estimate the values of atmospheric radiative properties and the observed surface-reflected outsolation using long-term-mean solar fluxes for every data grid cell. Then we estimate the potential surface-reflected outsolation associated with surface albedo modification by repeating the computation assuming a 100% surface albedo. The difference between the actual and potential surface-reflected outsolation represents our estimate of the negative radiative forcing achievable with surface albedo modification.

When estimating the radiative forcing associated with surface albedo increases, we consider the albedo of a horizontal reference surface \( \alpha^\text{h} \), like a flat roof or pavement, separate from the surrounding area albedo \( \alpha \), which is assumed to remain unchanged. Thus, the surface contribution to outsiolation is:

\[
F_{\text{TOA}} \cdot \frac{\alpha^\text{h} t^2}{1 - r\alpha}
\]

where the reference surface albedo in the numerator represents the initial reflection of downwelling solar radiation and the surrounding area albedo in the denominator represents subsequent reflections between the surface and atmosphere. This is akin to the approach taken by Salamanca \textit{et al} \cite{60}. Whereas they aimed to validate radiative forcing associated with actual reflective roof installations at two locations in India, our objective is to estimate the radiative forcing associated with potential reflective surface installations anywhere in the world. We compute the actual surface-reflected outsiolation using a reference surface albedo equal to the surrounding area albedo \( \alpha^\text{h} = \alpha \). We compute the potential surface-reflected outsiolation assuming a reference surface albedo of unity \( \alpha^\text{h} = 1 \). This choice is supported by the development of surface coatings with installed surface albedo above 90% \cite{61, 62}. Notwithstanding our definition of theoretical potential, estimates of operational potential may prefer to use a weathered surface albedo value. We fix the values of the intrinsic atmospheric radiative properties \((a, r, t)\) and large-scale albedo \((\alpha^\text{h})\), ignoring any atmospheric feedbacks associated with increased reference surface albedo \( \alpha^\text{h} \).

The ERA5-based input fields are computed by averaging hourly fluxes over 24 h, then averaging daily-means over the calendar year, then averaging annual-means over a range of years. The CERES EBAF-based input fields are computed by averaging monthly fluxes over the calendar year (weighting by days in the month), then averaging annual-means over a range of years. See the supplementary materials figures S1 (available online at stacks.iop.org/ERC/4/065003/mmedia) through S3 to compare these input fields.

3. Results

Daily-mean solar fluxes highlight the salient shortwave radiative properties of the Earth system. ERA5 solar fluxes at the top-of-atmosphere and surface for 22 September 2020 are shown in figure 2. The equator to pole gradient in top-of-atmosphere insolation is evident in figure 2(a). Downwelling solar radiation at the surface is less than top-of-atmosphere insolation. Spatial variations in figure 2(b) are suggestive of the attenuating influences of the atmosphere, particularly clouds on that day. Except for deserts and ice-covered polar and high-altitude regions, upwelling solar radiation reflected by the surface shown in figure 2(c) is much lower than the downwelling solar radiation at the surface, indicative of Earth’s generally low surface albedo \cite{5}. Outsolation at the top-of-atmosphere shown in figure 2(d) is largely the inverse of the downwelling solar radiation at the surface, which illustrates atmospheric reflectivity.

In the process of estimating the actual surface-reflected outsiolation, the simple radiative transfer model estimates broadband shortwave atmospheric radiative properties: transmittance, reflectance, and absorptance. The long-term means of these properties based on ERA5 are shown in figure 3. Atmospheric solar absorption is low, varying from 13% over Antarctica and high-elevation regions of North America, South America, and Asia to 30% over tropical South America and Africa, southern Asia, and central Europe. These magnitudes and spatial variations are consistent with previously published estimates \cite{63}, and are attributable to the distribution of surface elevation, water vapor, aerosols, and surface albedo \cite{63, 64}. Atmospheric solar reflectance is higher than absorptance, varying from 4% over the Sahara Desert to 47% over the subpolar oceans and southeast Asia, attributable to cloud fraction, cloud optical depth, and backscattering aerosol optical depth \cite{65}. Atmospheric solar transmittance is high, varying from 27% over the Arctic Ocean to 82% over the dry, high-elevation regions of North America, South America, and Asia. The patterns of these properties are qualitatively similar between ERA5 and CERES EBAF, and quantitative differences are within 10% (see figure S4).

The distribution of annual-mean surface-reflected outsiolation based on ERA5 is shown in figure 4. Potential surface-reflected outsiolation is largest over the tropical deserts, high-elevation regions of South America and Asia, and subequatorial oceans. The lowest potential is evident over the Arctic Ocean, Greenland Sea, Barents
Sea, and Southern Ocean. Over land, low potential areas include the Arctic Tundra, and south-central China. Actual surface-reflected oustolation is maximum over the Sahara Desert, Andes Mountains, and Tibetan Plateau, with local maxima over Antarctica and Greenland. The difference between actual and potential shows values approaching 200 Wm$^{-2}$, notably over the Andean Plateau. Other areas with appreciable differences

Figure 2. Daily-mean solar radiation fluxes (Wm$^{-2}$) from ERA5 on 22 September 2020: (a) incoming at the top of atmosphere, (b) downwelling at the surface, (c) upwelling at the surface, and (d) outgoing at the top of atmosphere.
between potential and actual surface-reflected outsolation include Western Australia, southwestern Africa, southwestern North America, and the subequatorial oceans.

Table 1 shows area-average values for the globe and both hemispheres, including disaggregations for land and ocean areas, in watts per square meter. The difference between potential and actual outsolation represents the unrealized gain that may be achieved with surface albedo modification. This view illustrates the potential to increase surface-reflected outsolation by nearly a factor of five globally. The low albedo ocean surface presents slightly larger unrealized gains in surface-reflected outsolation than land.

The results shown in figure 4 are not particularly sensitive to the choice of dataset, as evidenced by figure 5, which shows CERES EBAF-based results and differences relative to ERA5-based results using a concurrent period 2001 through 2020. The most salient differences in potential appear over the marine stratocumulus regions off the western coasts of North America, South America, and Africa as well as the Southern Ocean. ERA5 exhibits lower atmospheric reflectivity than CERES EBAF and higher transmissivity in these regions. Loeb et al [55] suggested that reanalysis treatment of clouds is a primary driver of differences between satellite-based products and two reanalysis products. Over land, differences between the ERA5 and CERES EBAF are primarily explained by differences in surface albedo, wherein ERA5 has higher albedo than CERES EBAF, notably over

Figure 3. Intrinsic atmospheric broadband solar radiative properties based on annual-mean ERA5 solar fluxes 1991 through 2020: coefficient of (a) reflectance, (b) absorptance, and (c) transmittance.
Figure 4. Long-term average (1991–2020) annual-mean surface-reflected outgoing solar radiation at the top of atmosphere (W m$^{-2}$) inferred from ERA5 solar radiation fluxes using a simple model of reflected radiation: (a) potential assuming a reference surface albedo equal to 1, (b) actual based on the ERA5 surface albedo, and (c) their difference.

Table 1. Area-averaged surface-reflected solar radiation statistics (W m$^{-2}$) based on annual-mean ERA5 solar fluxes 1991 through 2020 for global-mean, Northern Hemisphere (NH)-mean, and Southern Hemisphere (SH)-mean, as well as disaggregated statistics for land and ocean areas.

|                | Potential | Actual | Difference |
|----------------|-----------|--------|------------|
| Global-mean    | 105.6     | 21.7   | 83.9       |
| Land           | 109.2     | 42.8   | 66.4       |
| Ocean          | 104.0     | 12.2   | 91.8       |
| NH-mean        | 106.6     | 24.6   | 82.0       |
| Land           | 107.2     | 41.9   | 65.3       |
| Ocean          | 106.1     | 12.2   | 93.9       |
| SH-mean        | 104.7     | 18.8   | 85.9       |
| Land           | 113.3     | 44.7   | 68.6       |
| Ocean          | 102.6     | 12.2   | 90.4       |
high-elevation regions such as the Tibetan Plateau, southern Andes, and eastern Greenland (not shown). This is also consistent with Loeb et al [55].

4. Discussion

Past research has increasingly focused on atmospheric albedo modification as a primary means to reflect solar radiation, either through stratospheric aerosols [66] or marine cloud brightening [39]. While the atmosphere presents a larger opportunity to reflect incoming radiation, our results show that the opportunity at the surface is nontrivial. If surface albedo interventions were applied across a large area, our results show that there is enough potential surface-reflected solar radiation to diminish anthropogenic effective radiative forcing (2.72 Wm$^{-2}$ in 2019 [67]).

General circulation model experiments provide some support and caution for large-scale surface albedo modification. For example, Gabriel et al [68] reported on a geoengineering modeling experiment (G4Foam) where the albedo of the ocean surface was increased over the Southern Hemisphere subtropical ocean gyres. This resulted in a global average forcing of $-1.5$ Wm$^{-2}$, surface cooling amplified through positive cloud feedbacks, and an anticipated equatorially asymmetric precipitation response associated with a shift in the southern Hadley cell. Seneviratne and coauthors focused on land-based radiation management and showed modeling results that suggest regionally variable land surface albedo modifications in agricultural and urban areas could reduce mean and extreme temperatures with modest effects on precipitation [69]. This echoed earlier modeling experiments including urban, crop, and desert surface albedo interventions by Irvine et al [70]. They found that the cooling effect of surface albedo modification is concentrated over the applied region, yet not confined to those areas. Their global desert experiment produced some dramatic local cooling and large changes in precipitation.
throughout the tropics and subtropics, although their urban and crop experiments produced continental-scale cooling with minimal shifts in precipitation.

Considered together with these modeling studies, our results confirm the ability of surface albedo modifications to contribute to cooling as part of a broader set of climate intervention strategies and suggest specific geographies with particularly high potential. Although large-scale surface albedo modification has the potential to change precipitation patterns, modeling specific deployments could help anticipate and minimize negative impacts. As a ‘soft’ geoengineering strategy [18], surface albedo modification may deliver unambiguous benefits at the local and regional scale with broader social acceptance and faster implementation than so-called ‘hard’ strategies deployed in the atmosphere.

Surface albedo modification may not be as cost-effective as atmospheric approaches and the rate, scale, and ecosystem implications of land use modification for climate mitigation has generally been of significant concern [71]. However, the subset of surfaces that are man-made (like buildings and pavements in cities) can still generate significant co-benefits at the local and regional scales [72]. These areas are already under active human management with fewer concomitant ecosystem concerns.

Albedo modification assessments have tended to downplay surface-based albedo modification techniques based on cost and their inability to offset a large fraction of anthropogenic radiative forcing [39, 40]. However, there is little doubt that surface albedo modification can produce negative radiative forcing and decreased surface temperature, regardless of the observation that historical examples are largely the result of inadvertent land use changes [73, 74]. Viewed from this perspective, the operative question is not ‘can surface albedo modification offset a large fraction of anthropogenic radiative forcing?’ but rather ‘what and where can surface albedo modification cost-effectively contribute toward reducing anthropogenic radiative forcing?’

A growing body of urban climatology research shows that reflective surfaces including roofs, walls, and pavements can mitigate urban heat islands [27, 37, 38]. This suggests that surface albedo modification may play a larger role in human-managed environments like cities and agricultural landscapes where local radiative forcing is larger than the global-mean. Our results indicate that the metropolitan area with the largest population in the Middle East, Cairo–Giza, has a surface-reflected outolation potential of 164 Wm$^{-2}$; the city of Saudi Arabia with the largest population, Riyadh, has a surface-reflected outolation potential of 174 Wm$^{-2}$; and the Middle Eastern city with the highest potential is Aswan, Egypt at 191 Wm$^{-2}$. The city with the highest potential in the world is Calama, Chile, on the edge of the Atacama Desert, with a potential of 228 Wm$^{-2}$.

The method of Stephens et al [54], which we extended to estimate the surface contribution to outolation, considers a contribution from surface re-reflection of solar energy reflected down to the surface by the atmosphere (i.e., the denominator of the second term in equation (7b)). Prior research that assumed only a two-way transmissivity (i.e., the numerator of the second term in equation (7b)) may have underestimated the actual surface-reflected outolation [20, 75, 76]. Potential refinements to our approach include testing the isotropic assumption with the 4-parameter method of Winton [39], exploring how the spectral characteristics of surface-reflected solar radiation affect its transmission out to space, or investigating climate feedbacks associated with surface albedo modification.

5. Conclusion

We have presented a novel map of the potential surface contributions to reflected solar radiation using a radiative transfer model. Results indicate regions where surface albedo modification is likely to produce the largest annual-mean gain in outolation. Comparison of two independent datasets show the robustness of results and suggest regions and physical processes that reanalysis and satellite product developers might investigate while improving their dataset quality.

Our results show that there is opportunity for surface-based albedo interventions, particularly in the tropics and subtropics. International, national, and local policymakers could use these estimates to evaluate different climate action options. Although we have not explored particular surface-based inventions, reflectivity practitioners could leverage our methods to estimate the reflectivity potential and observed performance of their applications.

Future research could extend our results beyond the annual-mean to investigate seasonal variations in surface-reflected outolation potential. While the middle and high latitudes did not exhibit much potential viewed from the perspective of the annual-mean, those regions may have sufficient summertime potential to justify deploying reflective surfaces. The benefits of reduced extreme heat days alone may be sufficient to motivate surface albedo changes. Our methods could be combined with high resolution albedo estimates for particular surfaces to quantify the reflectivity improvement potential for particular roofs and pavements within cities, reflective crops, water covers, and reflective shade structures across agricultural landscapes.
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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.6652323.

Author contributions

Brian V Smoliak: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft; Writing - review & editing.

Michel Gelobter: Conceptualization; Investigation; Project administration; Resources; Supervision; Writing - review & editing.

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