ABSTRACT: Satellite observations reveal that decreasing surface albedo in both polar regions is increasing the absorption of solar radiation, but the disposition of this absorbed energy is fundamentally different. Fluxes of absorbed solar radiation, emitted thermal radiation, and net energy imbalances are assessed for both polar regions for the last 21 years in the Clouds and Earth’s Radiant Energy System record. Arctic absorbed solar radiation is increasing at 0.98 ± 0.69 W m⁻² decade⁻¹, consistent with the anticipated response to sea ice loss. However, Arctic thermal emission is responding at a similar rate of 0.94 ± 0.55 W m⁻² decade⁻¹. This is surprising since the radiative impact of ice loss would be expected to favor increasing solar absorption. We find however, that clouds substantially mask trends in Arctic solar absorption relative to clear sky while having only a modest impact on thermal emission trends. As a result, the Arctic net radiation imbalance has not changed over the period. Furthermore, variability of absorbed solar radiation explains two-thirds of the variability in annual thermal emission suggesting that Arctic thermal fluxes rapidly adjust to offset changes in solar absorption and re-establish equilibrium. Conversely, Antarctic thermal emission is not responding to the increasing (although not yet statistically significant) solar absorption of 0.59 ± 0.64 W m⁻² decade⁻¹ with less than a third of the annual thermal variability explained by accumulated solar absorption. The Arctic is undergoing rapid adjustment to increasing solar absorption resulting in no change to the net energy deficit, while increasing Antarctic solar absorption represents additional energy input into the Earth system.

SIGNIFICANCE STATEMENT: The polar regions of Earth are undergoing ice loss through ongoing global warming, reducing the ice cover and decreasing solar reflectivity, which would be expected to warm these regions. We use satellite observations to measure the trends in solar absorption and emitted thermal radiation over the Arctic and Antarctic for the last two decades. Arctic thermal emission is increasing at a compensating rate to solar absorption with a close relationship between these processes. Conversely, Antarctic thermal emission is not responding to solar absorption demonstrating that Antarctic surface temperatures are not significantly influenced by the region’s reflectivity. The Arctic is undergoing rapid adjustment to increasing solar absorption through warming, while increasing Antarctic solar absorption represents additional energy input into the Earth system.

KEYWORDS: Antarctica; Arctic; Cloud forcing; Climate change; Energy budget/balance; Radiation budgets

1. Introduction

Continual global warming through anthropogenic greenhouse gas emission has increased mean global air temperatures by over 1°C since preindustrial records. Through a series of geophysical feedbacks the Arctic has warmed by over 3°C (Eyring et al. 2021; Taylor et al. 2022). Observations over the

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The top of atmosphere (TOA) energy balance comprises two fluxes of energy, incoming/outgoing shortwave radiation from the sun and emitted longwave thermal radiation from the surface and atmosphere. In the polar regions, the thermal radiation emitted to space is up to 3 times greater than radiation received from the sun with the energy deficit being transported from lower latitudes primarily through large-scale atmospheric circulation (L’Ecuyer et al. 2015). A large partition of the incoming solar radiation in the poles is reflected back to space due to both the high albedo of the extensive snow/ice cover along with the ubiquitous cloud cover, which accounts for up to 80% of the total Arctic TOA albedo (Sledd and L’Ecuyer 2019). Variability and trends in snow, ice, and cloud cover will consequently modulate polar solar absorption. Due to the axial tilt of Earth, the solar input is confined to summertime in the polar regions, which is characterized by continuous but highly oblique incident solar radiation (Fig. 1). Conversely, the polar regions emit thermal radiation throughout the entire year, maximizing late in summer as the regions reach their maximum temperature (Fig. 1). Polar TOA outgoing thermal radiation variability may have multiple sources such as the surface temperature, the temperature of various levels in the atmosphere, cloud type, and the presence of water vapor (L’Ecuyer et al. 2021). It is the covarying effects of changes in surface ice cover, temperature, cloud cover, and water vapor that ultimately define the impacts of warming on the exchange of radiative energy within the polar regions.

The rapid warming in the Arctic, at least twice as fast as the global average, is occurring through a collection of processes known as Arctic amplification (Taylor et al. 2022). These effects result in warmer Arctic air temperatures (Lenssen et al. 2019), reduced sea ice concentration (Stroeve and Notz 2018), reduced sea ice age (Maslanik et al. 2011), longer melt seasons (Markus et al. 2009), and changes in surface–atmosphere interactions (Serreze and Barry 2011) paired with a wide variety of ecological, societal, and economic impacts (Smith and Stephenson 2013; Stephen 2018; Myers-Smith et al. 2020). Perhaps the most fundamental impact of Arctic amplification on the climate system is the changes to Earth’s TOA radiative balance. Indeed, quantifying the cascade of changes to the Arctic, including the changing Arctic energy balance, is a priority research goal identified by the Interagency Arctic Research Policy Committee (IARPC) 2022–26 Arctic Research Plan (IARPC 2021).

The observed Antarctic responses to a warming world are not nearly as explicit as the broad, statistically significant warming trends and sea ice decline observed in the Arctic. The contrasting geography (Salzmann 2017) accompanied by Southern Ocean heat uptake (Armour et al. 2016) and the radiative effects of South Pole stratospheric ozone depletion (Thompson et al. 2011) have led to a much weaker transient warming in Antarctica in the current observation period. In the satellite record, Antarctic sea ice appeared to be unchanging until 2015 (Meredith et al. 2019), but this has been followed by unprecedented declines in sea ice area in 2016 through to 2019 (and continuing through into 2023; NSIDC 2023), leading to an overall decline in sea ice area over the satellite record (Parkinson 2019). The recent loss of Antarctic sea ice is expected to have an impact on the Antarctic albedo and subsequently the absorption of solar radiation. If absorbed solar radiation is increasing then similar questions can be asked regarding the disposition of this energy as in the Arctic. Amplification of warming is certainly expected in Antarctica (Smith et al. 2019), especially through increased moisture...
transport and lapse-rate feedbacks (Hahn et al. 2021). The ice-albedo feedback is shown through modeling experiments to be of secondary importance (Hahn et al. 2021), however, the exact nature of this feedback and impact on the net Antarctica energy balance remains unexamined in the observation record.

The continual, multidecadal record from the NASA Clouds and Earth’s Radiant Energy System (CERES) instruments offers an invaluable and unique documentation of Earth’s TOA radiative balance (Loeb et al. 2018). The CERES record is beginning to observe fundamental changes to the Earth system (Stephens et al. 2022). In the Arctic, CERES observations have been used to identify the increasing solar absorption (decreasing reflection) at a rate of $1.3 \pm 0.6$ W m$^{-2}$ decade$^{-1}$ (between 2000 and 2017; Duncan et al. 2020) along with the spatial pattern of absorption trends, maximizing over regions of extensive sea ice loss (Sledd and L’Ecuyer 2021). Using a combination of CERES and satellite microwave products, Pistone et al. (2014) estimate that between 1979 and 2011 the solar flux into the Arctic had increased by $6.4 \pm 0.9$ W m$^{-2}$ corresponding to a rate of between 1.7 and 2.3 W m$^{-2}$ decade$^{-1}$. Duncan et al. (2020) also briefly note that CERES indicates increasing thermal emission in the Arctic (north of 60°N) at a rate of $1.1 \pm 0.4$ W m$^{-2}$ decade$^{-1}$, comparable to the recorded trends in solar absorption. Peterson et al. (2019) examine the spectral dimension of these changes through analysis of the Atmospheric Infrared Sounder (AIRS, onboard NASA Aqua) demonstrating that Arctic trends in thermal emission are primarily driven by changes in surface temperature, rather than changes in water vapor or atmospheric properties. If changes in thermal emission are primarily driven by a change in surface temperature, then variable solar absorption would be expected to directly influence thermal emission if it warms the surface. The compensation between the TOA solar and thermal fluxes, the net radiative balance, is gradually increasing globally through greenhouse gas concentrations with considerable regional variability due to changes in cloud cover and surface snow/ice (Trenberth and Fasullo 2012; Loeb et al. 2021). The spatial nature of changes in polar thermal emission and its relation to changing albedo and solar absorption are both important outstanding questions that naturally follow from these prior studies.

Here, satellite observations of the TOA energy balance in both the Arctic and Antarctic are examined from the CERES record (2000–21), addressing shortwave and longwave fluxes along with the net energy deficit in the context of variable and reducing ice cover. Arctic solar absorption has received considerable attention as a changing aspect of the Earth system but to what extent the thermal emission offsets this trend requires further examination. Furthermore, with recent losses in sea ice cover in Antarctica, solar absorption is expected to respond accordingly in the region. Thermal emission in Antarctica has been offered little examination and remains as an important phenomenon to quantify to account for all radiative energy pathways in the polar regions. If the thermal emission does not offset the increasing solar absorption, then the polar energy deficit reduces, which will represent changing pathways of energy within the Earth system. Clouds are also known to considerably modulate Arctic solar absorption trends and their role in both solar absorption and thermal emission at both poles will also be quantified herein. Given the short 21-yr record, observed variability may not be representative of long-term trends and reported trends will be influenced by both internal variability (from annual to decadal scales) and anthropogenic forcing (Raghuraman et al. 2021; Loeb et al. 2022). The aim of this research is not to report on the exact nature of these trends but to compare the differing response in the radiative exchange at both poles, the importance of surface ice cover, and the role of clouds in modulating this exchange.

2. Methods

Observations of the polar TOA energy balance are retrieved from the Clouds and Earth’s Radiant Energy System Energy Balance and Filled (CERES-EBAF) version 4.2 (retrieved January 2024) derived primarily from the CERES instrument onboard the NASA Terra, Aqua, and NOAA-20 satellites (Loeb et al. 2018). The CERES record, starting in 2000 and providing monthly averages at $1^\circ \times 1^\circ$ resolution, is the authoritative measurement of Earth’s TOA balance. The Energy Balance and Filled (EBAF) product provides estimates of TOA radiative exchange consistent with global ocean heat uptake from in situ measurements (Loeb et al. 2018). While the absolute accuracy of the CERES instrument has TOA errors of up to 5 W m$^{-2}$ (less than 5% of the signal), the relative calibration stability is better than 0.3 W m$^{-2}$ decade$^{-1}$, demonstrating that anomalies in the TOA record are robust and serve as a direct observation of changes in Earth’s TOA radiative exchange (Loeb et al. 2009). Furthermore, the CERES-EBAF TOA cloud detection is based on the radiative properties of clouds present (Loeb et al. 2018), which would be expected to capture most of the radiatively important clouds and any clouds that escape this detection would only have a small influence on the reported monthly broadband trends.

To quantify emerging changes in polar radiative balance, TOA all-sky and total-region clear-sky absorbed shortwave ($SW_0 - SWT$) and outgoing longwave ($LWT$) fluxes from the CERES-EBAF 4.2 product are analyzed. Total-region clear-sky fluxes are used to maintain consistency between observational and model generated clear-sky fluxes (Loeb et al. 2018). The annual accumulated ($J m^{-2}$) absorbed solar radiation (ASR) and outgoing longwave radiation (OLR) for both regions are calculated as the spatially averaged and temporally integrated fluxes. Deseasonalized monthly anomalies ($W m^{-2}$) of absorbed solar and thermal emission are multiplied by the number of seconds in each month and integrated across the full region for both the Arctic and Antarctica. To examine how changes in these fluxes combine to influence variability in the polar energy deficits the net energy (ASR minus OLR), a value that is dominantly negative over the polar regions, is also computed. Results are presented in time integrated quantities, with spatial and temporal averaged quantities (e.g., $W m^{-2}$) presented in the supplemental material and text to aid comparison with other previous studies.
The monthly accumulated energy is then summed over half-yearly and annual time scales to determine year-to-year variability in the ASR to OLR relationship due to their differing relative importance over the polar day (summer) and polar night (winter). The annual (12-month) period considered for the polar energy accumulation begins at the start of summer, when the poles enter the period of continuous incident solar illumination (polar day), corresponding to March and September for the Arctic and Antarctic, respectively. The accumulated ASR and OLR is then summed through to February and August in the following year and assigned the year based on the start of the sum for analysis and interpretation. For the Arctic, the total period considered is March 2000–February 2021 and in Antarctica, September 2000–August 2021.

The polar regions in this study are defined as time invariant, contiguous regions centered at both poles where the climatological mean annual 2-m air temperature (from the Atmospheric Infrared Sounder 2002–16; AIRS 2019) is below 0°C (Fig. 2). This definition of the polar region is particularly important in the Arctic to remove the warm Atlantic water inflow in the Barents Sea which remains ice-free year-round and has a different thermodynamic behavior than the rest of the Arctic (Mayer et al. 2019; Sledd and L’Ecuyer 2019). The thermal definition is also important to capture changes in the Antarctic TOA energy exchange due to the vast extent of sea ice that extends equatorward of 66.5°S. Figure 2 shows the gridded regions at both poles that meet this definition and their close relation with the mean maximum sea ice extent in the Barents Sea which remains ice-free year-round and has a different thermodynamic behavior than the rest of the Arctic (Mayer et al. 2019; Sledd and L’Ecuyer 2019). The thermal definition is also important to capture changes in the Antarctic TOA energy exchange due to the vast extent of sea ice that extends equatorward of 66.5°S. Figure 2 shows the gridded regions at both poles that meet this definition and their close relation with the mean maximum sea ice extent in the Barents Sea which remains ice-free year-round and has a different thermodynamic behavior than the rest of the Arctic (Mayer et al. 2019; Sledd and L’Ecuyer 2019). The presented conclusions are relatively insensitive to the polar region definition as long as the broad extent of variable sea ice cover at both poles is contained within the respective boundaries (Fig. 1 in the online supplemental material).

Arctic and Antarctic sea ice data are retrieved from the NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration product (version 4; Meier et al. 2021) on the Equal-Area Scalable Earth grid (EASE). Sea ice area (SIA) is calculated from the sea ice concentration (a fraction of area) in each grid cell multiplied by the area of the grid cell. Where the sea ice concentration is less than 15%, the sea ice area for that cell is set to zero due to limitations in the microwave sensitivity at low ice concentrations. Ocean and atmospheric reanalysis (ORAS5 and ERA5 respectively; Zuo et al. 2019; Hersbach et al. 2018) are utilized to provide an initial examination of the consequences of the presented observations. Area averaged ocean heat content and mean sea surface temperature from 2000 to 2021 are retrieved from ORAS5 for the ocean area identified in Fig. 2. Zonal mean, mass-consistent atmospheric heat (energy) transport (AHT; Mayer et al. 2022) is retrieved from ERA5 for the same period at 55°N and 55°S to provide an estimate of the AHT into both polar regions over the observation period. Due to the relatively short 21-yr record offered by the CERES-EBAF TOA measurements, assessing the statistical significance and interpretation of trends is enigmatic. An alternative approach is to calculate the time to emergence (TTE) to assess the time required for a trend in a given time series to emerge as significant given the observed variance and autocorrelation of the data (Weatherhead et al. 1998). The TTE is calculated following Chepfer et al. (2018) and Sledd and L’Ecuyer (2021) to account for the internal variability present within the record of annual radiation anomalies. To estimate the number of years required for an observed trend to emerge, simulated time series are generated based on the
Arctic thermal emission is increasing at a similar rate as solar and autocorrelation of the TOA radiation records. The statistically significant TTE (95% confidence) from each ensemble member is calculated as the amount of time for the magnitude of the trend to be twice that of the scaled standard deviation ($\sigma_v$):

$$\sigma_v = \sigma_N \left( \frac{\sqrt{N}}{1 - \phi} \right)$$

where $\sigma_N$ is the standard deviation, $T$ is the length of the time series, $dt$ is the time internal ($dt = 1$ for annual observations) and $\phi$ is the lag-1 autocorrelation. The TTE reported herein is the mean TTE from the 400 synthetic time series and the standard deviation of the TTE is also reported. Trends with a mean ensemble TTE values less than 21 years are said to have emerged in the observation period. For TTE values greater than 21 years, there has been no trend in the observed record and the interannual variability is greater than any measured trend. Any trend calculated from 21 years of data is unable to represent the low-frequency variability within the climate system, but it does represent a snapshot of how the system is currently changing in a warming world. This does not invalidate the observed TTE; however, it may be observed as a lower bound of the true emergence within the forced climate system since the signal-to-noise ratio may be overestimated in a truncated time series if periodicity exists.

3. Results

a. Arctic energy trends

Annual mean anomalies of ASR, OLR, and net energy relative to the 2000–20 (full-period) mean in the Arctic and Antarctic are shown in Fig. 3 for both all-sky and clear-sky conditions (equivalent time series at seasonal and monthly intervals are provided in supplemental Figs. 2 and 3). All-sky and clear-sky trends in ASR are increasing in the Arctic at rates of $99.6 \pm 70.3 \times 10^3$ and $205.5 \pm 89.9 \times 10^3$ PJ yr$^{-1}$, respectively, consistent with previously reported trends (supplemental Table 1; Sledd and L’Ecuyer 2021). Interestingly, Arctic thermal emission is increasing at a similar rate as solar absorption ($94.7 \pm 56.0 \times 10^3$ PJ yr$^{-1}$), implying that 95% of the ASR trend is offset by immediate increases in OLR. Since the OLR trend largely offsets the ASR trend, the all-sky net energy deficit of the Arctic has remained approximately constant over the CERES record ($4.8 \pm 48.9 \times 10^3$ PJ yr$^{-1}$) despite the ongoing rapid ice loss. This invariance in the net Arctic energy imbalance suggests that the energetic impacts of sea ice loss are confined to the Arctic and not transported to lower latitudes. Importantly, these trends are not dependent on the definition of the region, notably remaining consistent for regions bounded by 65°N/S (supplemental Fig. 1).

The clear-sky trends between ASR and OLR are not comparable, with clear-sky OLR ($127.2 \pm 57.9 \times 10^3$ PJ yr$^{-1}$) compensating only 62% of the ASR clear-sky trend, driven by disproportionate cloud influences. Clouds reduce the magnitude of the clear-sky ASR trends by 50% and OLR trends by only 25%, demonstrating that the dampening effect of clouds on the decadal trend is more dominant for ASR with only a minor effect on the trends of thermal emission. The amplified clear-sky ASR trend (being double the all-sky trend) drives a positive trend in the clear-sky net energy ($78.3 \pm 62.9 \times 10^3$ PJ yr$^{-1}$) that has emerged within the observation period (TTE of 18 ± 5 years). These results demonstrate that without the influence of clouds, the Arctic energy deficit would tend to become reduced in the absence of more rapid increases in SST; however, the dampening effects of clouds on the ASR trend inhibit Arctic Ocean warming.

Our confidence in these findings is reinforced by the fact that Arctic trends in both ASR and OLR have emerged within the 21-yr CERES record with TTE of 17 ± 4 and 12 ± 4 years, respectively, demonstrating that changes in the Arctic environment are detectable in observations of the interannual radiative exchange; more solar radiation is being absorbed and more thermal emission is being emitted. It is worth noting that, despite conventional wisdom concerning the effects of sea ice loss on solar reflection, the all-sky ASR trend was by far the last to emerge in the CERES record. Like, all-sky OLR, clear-sky ASR and OLR trends emerged within 12 ± 3 and 11 ± 3 years, respectively. This demonstrates that not only do clouds have a dampening effect on the rate of change in ASR, but clouds also reduce the detectability of the trend of ASR. Since cloud cover and sea ice concentration are not independent (Kay and Gettelman 2009; Taylor et al. 2015), it is important to note that the slower emergence of all-sky ASR may also be influenced by the interannual variability of sea ice. However, the difference between the clear-sky and all-sky ASR TTE indicates that sea ice variability alone is not increasing the all-sky ASR TTE since it would influence both records.

The statistical relationship between annual ASR and OLR is examined to assess the dependence of emitted thermal radiation to absorbed solar radiation within a given year (Fig. 4). The interannual variability of all-sky OLR is well explained ($R^2 = 0.67$) by the variability in all-sky ASR in the Arctic with a slope of 0.69 (being statistically significant at the 95% level). The relationship is stronger for the clear-sky Arctic, with an increased $R^2$ of 0.76 (slope of 0.55 and statistically significant at 95%), demonstrating that 10% more of the OLR variability is explained by ASR in clear skies. Since clouds are removed in deriving the clear-sky relationship, it can be suggested that since the slope is not equal to unity, the remaining 35% of the increased ASR received at the surface within a given year is being sequestered into the ocean (or involved in ice–water phase changes) and away from the surface where it will not have an impact on the surface or atmospheric temperatures which contribute to the OLR.

b. Antarctic energy trends

In Antarctica, neither the ASR nor OLR has emerged as a detected trend over the CERES-EBAF record (Fig. 3). Antarctic all-sky ASR does have a positive trend ($74.3 \pm 81.2 \times 10^3$ PJ yr$^{-1}$;
supplemental Table 1) that is comparable to the Arctic ASR trend, but the TTE is 38 ± 5 years owing to larger interannual variability. Significant anomalies have been observed in recent years, and it would be expected that continual rapid sea ice loss in Antarctica may exacerbate these ongoing trends. Antarctic all-sky OLR is relatively invariant (−9.5 ± 65.5 × 10^3 PJ yr⁻¹), suggesting that thermal emission in this region does not compensate recent increases in ASR. Due to the relatively unchanging OLR over the 21-yr period, a reduction in the Antarctic net energy imbalance has emerged (TTE of 18 ± 5 years), clearly driven by recent increases in ASR. The Antarctic energy deficit is decreasing through local radiative exchange at 83.7 ± 67.4 × 10^3 PJ yr⁻¹, a reduction of 0.7% per decade.

As observed in the Arctic, clouds in the Antarctic also mask the underlying surface changes, reducing the magnitude of the ASR and OLR all-sky trends compared to clear-sky trend. The presence of clouds in Antarctic reduces the clear-sky ASR trend by 35%, slightly less than the reduction caused by clouds on Arctic ASR trends (50%). One notable feature of Antarctic fluxes is that clear-sky OLR has a negative (but not statistically significant) trend of appreciable magnitude (−36.7 ± 49.8 × 10^3 PJ yr⁻¹), which reduces in magnitude by about 75% compared to all-sky trends. This behavior is examined further in the following sections through examining spatial variability in the trends and the spatial impact of cloud cover. It is apparent that the trends in Antarctic radiative fluxes (especially ASR) are influenced substantially by the anomalously low SIA between 2016 and 2019 (up to 1 million km² smaller than the 21-yr mean). The unequal variability and unexpected trends of Antarctic SIA over the last four decades has prompted researchers to prescribe caution when interpreting trends (especially linear) in the Antarctic region (Hancock and Raphael 2020; Eyers et al. 2021). However, merely examining the time series themselves highlights the
different responses in Antarctic ASR and OLR to changing SIA compared to the Arctic.

The annual ASR–OLR relationship in Antarctica is very weak with an $R^2$ of 0.27 for all-sky and 0.11 for clear-sky (Fig. 4). The all-sky trend is statistically significant (at 95%) with a slope of 0.38, however, there are many more outliers in the relationship. The clear-sky trend is not statistically significant with a slope of 0.13, demonstrating that the variability of annual ASR has little impact on the variability of OLR. It is apparent that Antarctic ASR is closely related to the SIA, with the low sea ice years absorbing more solar radiation, but this does not necessarily correspond to increased OLR.

c. Land/ocean partitioning

While sea ice has been considered as a first-order control on the energy anomalies in Fig. 3, it is important to consider the individual roles of the land and ocean in the polar regions for varying the TOA radiative trends (Table 1; supplemental Figs. 4 and 5). In the Arctic (all-sky), 65% of the ASR trend and 55% of the OLR trend comes from ocean regions with the remaining 35% and 45% being driven by changes over...
TABLE 1. Characteristics of all-sky and clear-sky absorbed solar radiation (ASR), outgoing longwave radiation (OLR), and net energy balance for the Arctic and Antarctic over the entire domain (All) and the ocean–land surface types as defined in Fig. 1. Variables shown are trends shown with associated 95% confidence interval using Student’s t distribution, the standard deviation (Std dev), signal-to-noise ratio (SNR), the lag-1 (year) autocorrelation (Autocorr), and time to emergence (TTE) with the TTE standard deviation in parentheses.

<table>
<thead>
<tr>
<th>Region</th>
<th>Trend (10^3 PJ yr⁻¹)</th>
<th>Std dev (10^4 PJ)</th>
<th>SNR (decade⁻¹)</th>
<th>Autocorr</th>
<th>TTE (yr)</th>
<th>Trend (10^3 PJ yr⁻¹)</th>
<th>Std dev (10^4 PJ)</th>
<th>SNR (decade⁻¹)</th>
<th>Autocorr</th>
<th>TTE (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Arctic</td>
<td>ASR 99.6 ± 70.3</td>
<td>109.8</td>
<td>1.12</td>
<td>0.00</td>
<td>17 (4)</td>
<td>205.5 ± 89.9</td>
<td>172.5</td>
<td>1.81</td>
<td>0.03</td>
<td>12 (3)</td>
</tr>
<tr>
<td></td>
<td>OLR 94.7 ± 65.0</td>
<td>93.3</td>
<td>1.34</td>
<td>-0.34</td>
<td>12 (4)</td>
<td>127.2 ± 57.9</td>
<td>108.8</td>
<td>1.74</td>
<td>-0.19</td>
<td>11 (3)</td>
</tr>
<tr>
<td></td>
<td>Net 4.8 ± 48.9</td>
<td>63.3</td>
<td>0.01</td>
<td>0.20</td>
<td>110 (24)</td>
<td>78.3 ± 62.9</td>
<td>94.6</td>
<td>0.98</td>
<td>0.09</td>
<td>18 (5)</td>
</tr>
<tr>
<td>Arctic Ocean</td>
<td>ASR 64.9 ± 40.7</td>
<td>67.3</td>
<td>1.23</td>
<td>0.23</td>
<td>17 (4)</td>
<td>133.1 ± 50.2</td>
<td>105.0</td>
<td>2.10</td>
<td>0.13</td>
<td>11 (3)</td>
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<td></td>
<td>OLR 51.9 ± 26.3</td>
<td>46.8</td>
<td>1.57</td>
<td>-0.19</td>
<td>12 (4)</td>
<td>70.2 ± 28.5</td>
<td>57.1</td>
<td>1.95</td>
<td>0.16</td>
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</tr>
<tr>
<td></td>
<td>Net 13.0 ± 31.4</td>
<td>41.4</td>
<td>0.33</td>
<td>0.13</td>
<td>41 (10)</td>
<td>62.8 ± 35.3</td>
<td>60.0</td>
<td>1.41</td>
<td>-0.01</td>
<td>14 (4)</td>
</tr>
<tr>
<td>Arctic land</td>
<td>ASR 34.7 ± 38.0</td>
<td>53.6</td>
<td>0.72</td>
<td>-0.20</td>
<td>19 (6)</td>
<td>72.4 ± 45.3</td>
<td>73.8</td>
<td>1.27</td>
<td>-0.08</td>
<td>15 (4)</td>
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<tr>
<td></td>
<td>OLR 42.9 ± 33.5</td>
<td>50.8</td>
<td>1.01</td>
<td>-0.39</td>
<td>14 (5)</td>
<td>57.0 ± 36.7</td>
<td>59.1</td>
<td>1.23</td>
<td>-0.39</td>
<td>12 (4)</td>
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<td>Net -8.2 ± 25.6</td>
<td>33.4</td>
<td>-0.25</td>
<td>0.28</td>
<td>53 (11)</td>
<td>15.4 ± 34.1</td>
<td>45.1</td>
<td>0.36</td>
<td>0.25</td>
<td>41 (9)</td>
</tr>
<tr>
<td>All Antarctic</td>
<td>ASR 74.3 ± 81.2</td>
<td>114.7</td>
<td>0.72</td>
<td>0.48</td>
<td>30 (5)</td>
<td>113.5 ± 128.7</td>
<td>180.6</td>
<td>0.70</td>
<td>0.39</td>
<td>29 (5)</td>
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<tr>
<td></td>
<td>OLR -9.5 ± 65.5</td>
<td>84.9</td>
<td>-0.11</td>
<td>-0.09</td>
<td>71 (20)</td>
<td>-36.7 ± 49.8</td>
<td>68.3</td>
<td>-0.58</td>
<td>-0.15</td>
<td>23 (7)</td>
</tr>
<tr>
<td></td>
<td>Net 83.7 ± 67.4</td>
<td>101.4</td>
<td>0.99</td>
<td>0.04</td>
<td>18 (5)</td>
<td>150.3 ± 169.8</td>
<td>169.8</td>
<td>1.08</td>
<td>0.34</td>
<td>21 (4)</td>
</tr>
<tr>
<td>Antarctic Ocean</td>
<td>ASR 51.5 ± 74.4</td>
<td>101.2</td>
<td>0.55</td>
<td>0.55</td>
<td>38 (5)</td>
<td>93.9 ± 121.3</td>
<td>167.2</td>
<td>0.61</td>
<td>0.45</td>
<td>33 (6)</td>
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<tr>
<td></td>
<td>OLR -5.4 ± 40.5</td>
<td>52.5</td>
<td>-0.11</td>
<td>0.05</td>
<td>83 (21)</td>
<td>-22.2 ± 27.7</td>
<td>38.4</td>
<td>-0.64</td>
<td>0.25</td>
<td>26 (6)</td>
</tr>
<tr>
<td></td>
<td>Net 57.0 ± 59.3</td>
<td>84.4</td>
<td>0.76</td>
<td>0.27</td>
<td>25 (5)</td>
<td>116.2 ± 100.9</td>
<td>149.0</td>
<td>0.91</td>
<td>0.42</td>
<td>24 (4)</td>
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<tr>
<td>Antarctic land</td>
<td>ASR 22.7 ± 17.3</td>
<td>26.5</td>
<td>1.01</td>
<td>-0.13</td>
<td>16 (5)</td>
<td>19.6 ± 21.6</td>
<td>30.5</td>
<td>0.72</td>
<td>-0.42</td>
<td>17 (5)</td>
</tr>
<tr>
<td></td>
<td>OLR -4.0 ± 28.1</td>
<td>36.5</td>
<td>-0.11</td>
<td>-0.26</td>
<td>65 (20)</td>
<td>-14.5 ± 30.3</td>
<td>40.1</td>
<td>-0.38</td>
<td>-0.32</td>
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</tr>
<tr>
<td></td>
<td>Net 26.8 ± 22.7</td>
<td>33.7</td>
<td>0.94</td>
<td>-0.21</td>
<td>17 (5)</td>
<td>34.1 ± 37.7</td>
<td>53.2</td>
<td>0.72</td>
<td>-0.38</td>
<td>17 (6)</td>
</tr>
</tbody>
</table>
land. Surprisingly, the Arctic ocean–land ratios are very similar for the clear-sky ASR trend (65% from ocean) and OLR trend (55%) demonstrating that clouds do not influence the relative importance of the ocean versus land. These results also demonstrate that changes in sea ice account for a two-thirds majority of the change in Arctic energy exchange with land flux changes accounting for one-third.

In Antarctica, the ocean has a similar dominant role in driving ASR increases, accounting for 69% of the increasing ASR all-sky trend and 83% for the clear-sky trend (Table 1). While the pan-Antarctic and ocean-only trends in ASR are not significant at the 95% level, an increasing ASR trend has emerged over the Antarctic ice sheet within the period. Even though snow and ice cover on the Antarctic continent is generally unchanging, leading to relatively low year-to-year variability in the time series, decreasing snow albedo has been observed through surface warming, especially in West Antarctica due to summertime heating (Seo et al. 2016). Thus, increasing Antarctic ASR trends over land have emerged within the 21-yr record (for both all sky and clear sky). The Antarctic clear-sky OLR trend has a TTE of 23 ± 7 years, representing a moderate reduction in the Antarctic OLR, driven mainly by changes over the ocean (60%). Since the magnitude of the OLR trend is small, net energy trends are dominated by the ASR changes in the ocean and the ocean-land ratio is similar to the ASR trend (69% and 83% from ocean all sky and clear sky, respectively).

d. Spatial distribution

The spatial nature of these polar radiative trends is presented in Figs. 5 and 6 to aid in understanding the geophysical drivers of these trends. In the Arctic, ASR is increasing broadly across the entire Arctic basin at rates of about 10–20 MJ m$^{-2}$ yr$^{-1}$ in all-sky conditions (Fig. 5a). Clear-sky trends reveal the fundamental role of sea ice reduction in increasing the ASR, with the regions of greatest increase of ASR aligning with the locations of enhanced sea ice loss close to the coastlines (supplemental Fig. 6) on the order of 20-30 MJ m$^{-2}$ yr$^{-1}$, reaching maxima in the Kara Sea, Laptev Sea, Beaufort Sea, and along the Denmark Strait (Fig. 5b). Increasing ASR is also observed over northern Siberia and Alaska in clear-sky conditions. There are regions of declining ASR (not significant) in the Labrador Sea along with northeast Russia and eastern Hudson Bay. These regions align with regionally isolated increases in sea ice cover (supplemental Fig. 6), which, paired with changes in timing of freeze and melt (Gupta et al. 2022), increases the amount of reflected solar radiation. The difference between the all- and clear-sky ASR trends reveals the locations where clouds either enhance or mask the changes to the underlying surface reflectivity (Fig. 5c). As previously reported by Sledd and L’Ecuyer (2021), clouds reduce the magnitude of ASR trends by about 50%, with the greatest reductions of about 20 MJ m$^{-2}$ yr$^{-1}$ over the Barents and Kara Seas. Isolated positive differences between all- and clear-sky ASR represents regions of increasing snow and ice cover, where clouds are maintaining a more constant (subdued) albedo than the changing surface beneath (in the Labrador Sea and northeast Russia).

Arctic OLR trends are much more homogenous in magnitude and spatial extent, demonstrating broad increases of 4–16 MJ m$^{-2}$ yr$^{-1}$ across the Arctic Ocean and northern Siberia for both all sky and clear sky. Increases in OLR in the Arctic Ocean are well confined to the locations of variable sea ice area, providing evidence for the relationship between ASR, surface temperature, and OLR (similar to that observed by Sledd et al. 2023). It is also notable that all- and clear-sky trends are of very similar magnitude. The spatial difference between the isolated maxima in ASR trends and the broadly uniform OLR trends suggests an efficient redistribution of energy within the Arctic Ocean. Furthermore, in the Arctic, clouds primarily act to reduce the OLR trends, particularly in the coastal regions of the Kara Sea, Chukchi Sea, Beaufort Sea, and the Denmark Strait (Fig. 5f).

While the pan-Arctic net energy is not changing, there are regions where the energy imbalance is changing with statistical significance (increasing and decreasing) through local processes. Positive trends in the net energy represents regions where the ASR trends exceed the OLR trends, such as in the Kara Sea, Southern Greenland, the Canadian Archipelago, and the Beaufort Sea (Figs. 5g,h). These regions appear in both the all-sky (at about 4–8 MJ m$^{-2}$ yr$^{-1}$) and clear-sky trends (reaching trends of 24 MJ m$^{-2}$ yr$^{-1}$). Regions of negative net energy trends appear in northeast and northwest Russia and eastern Hudson Bay where increasing snow and ice cover may be increasing the albedo (reducing the ASR) while the OLR remains relatively constant. The difference between the all-sky and clear-sky net energy trends highlights the masking effect of clouds over regions of changing surface cover, reducing the magnitude of all trends by up to 50% (Fig. 5i). These variations in local net radiative balance would be expected to be indicative of variations in local circulations in the Arctic region since energy flows down gradient from regions of increasing absorption (positive net trends) to regions of increased thermal emission (negative net trends).

Antarctic ASR exhibits large opposing regions of increasing absorption in the Ross and Amundsen Seas along with the eastern Weddell Sea and southern Indian Ocean (Fig. 6a). Intriguingly, there are regions of decreasing ASR, most apparent in the clear-sky trends (Fig. 6b) in the coastal waters of the Antarctic continent, especially adjacent to Wilkes Land. There are also regions of reducing ASR toward the sea ice edge in the Bellingshausen Sea and around the Antarctic Peninsula. A reducing ASR trend suggests that the albedo at the surface is increasing in these regions. These likely reflect regions which remain covered with sea ice for longer periods of time (as demonstrated in supplemental Fig. 7). In contrast to the Arctic, the clear-sky trends of appreciable magnitude are entirely confined to within the region of variable sea ice, demonstrating the roughly unchanging albedo of the Southern Ocean. There are variations in all-sky ASR trends beyond the marginal sea ice zone that must be associated with changing cloud properties over the Southern Ocean. Indeed, a wave-number-2 pattern of alternating cloud effects is apparent over the Southern Ocean (Fig. 6c), with increased solar absorption
from clouds in the southern Atlantic and south of Australia and reducing solar absorption from changing cloud properties in the South Pacific and Indian Oceans.

The OLR trends in Antarctica are of very small magnitude compared to the ASR. The clear-sky OLR is increasing in the Amundsen and Ross Seas with much of the Antarctic continent exhibiting reducing OLR. Notably, Wilkes Land (East Antarctica) and Marie Byrd Land have statistically significant decreasing OLR trends, indicating reducing thermal emission in these regions. While these may be related to local temperature trends (Nicolas and Bromwich 2014), the melting and refreezing of snow cover would also produce such radiative trends even without a change in temperature (L’Ecuyer et al. 2021). The mid- and far-infrared emissivities of water and ice

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**FIG. 5.** Arctic trends in (a),(b) absorbed shortwave radiation (ASR), (d),(e) outgoing longwave radiation (OLR), and (g),(h) net energy calculated for (left) all-sky and (center) clear-sky conditions over 2000–20. Stippling demonstrates regions where the trend has emerged in the observational record with 95% confidence. (c),(f),(i) The differences between the trends in all-sky and clear-sky conditions. The magenta line indicates the mean extent of August sea ice area (over 15% concentration).
are considerably lower than the emissivity of snow, so if the snowpack were to melt and refreeze from an anomalous weather event the new ice surface would have a lower net thermal emission even at the same temperature. There is also a region of decreasing clear-sky OLR close to the historical winter ice edge in the Amundsen-Bellingshausen Seas, which may be expected as a result of ice advection from the Amundsen Sea low, which is paired with an ASR dipole in the same region. Since the trends in Antarctic ASR are almost tenfold greater than the OLR trends, it is clear that changes in the net energy are dominated by the pattern of ASR variability which is demonstrated in the similarity between the net and ASR Antarctic trends (Figs. 6g–i).

![Fig. 6. Antarctic trends in (a),(b) absorbed shortwave radiation (ASR), (d),(e) outgoing longwave radiation (OLR), and (g),(h) net energy calculated for (left) all-sky and (center) clear-sky conditions over 2000–20. Stippling demonstrates regions where the trend has emerged in the observational record with 95% confidence. (c),(f),(i) The difference between the trends in all-sky and clear-sky conditions. The magenta line indicates the mean extent of February sea ice area (over 15% concentration).](image-url)
4. Discussion

Satellite observations of the Arctic TOA radiative exchange from 2000 to 2021 reveal that both absorbed solar radiation and emitted thermal radiation are increasing at remarkably similar rates that exceed the interannual variability of $0.98 \pm 0.69$ and $0.94 \pm 0.55$ W m$^{-2}$ decade$^{-1}$ for ASR and OLR respectively (Fig. 7). Figure 4 also demonstrates that this compensation generally occurs within a given year, with 67% of the annual accumulated OLR variability explained by the accumulated ASR. These results reveal the efficient conversion of ASR to heat in the Arctic, and the retention of that heat in a location that is able to emit to space such as the ocean surface or atmosphere. These trends agree with those previously reported by Duncan et al. (2020) from CERES-EBAF (between 2000 and 2017) of $1.3 \pm 0.6$ and $1.1 \pm 0.4$ W m$^{-2}$ decade$^{-1}$ for ASR and OLR, respectively, for the region poleward of 60°N. The rates presented herein are calculated from four more years of data collection, demonstrating stability and confidence in these estimates.

The locations that are losing ice cover rapidly are the same locations that are absorbing more solar radiation (Fig. 5). The surface temperature of the Arctic must then be increasing at a rate directly comparable to the rate of increasing absorption. It is known that the ice-albedo feedback currently accounts for up to 60% of observed Arctic warming (Taylor et al. 2022). Change in sea ice area alone is not the only change that is occurring to albedo in the Arctic region, with the albedo of persistent multiyear ice declining through thinning (Riihelä et al. 2013) and snow cover change over Arctic landmasses also varying surface albedo (Duncan et al. 2020). These other surface changes allow for interpretation of the Arctic clear-sky ASR trends especially in Siberia and over regions of constant ice cover in Fig. 5. Snow cover has not been assessed here, first due to the sparse record of year-round satellite retrieved Arctic snow cover and the dominance of the Arctic Ocean in driving the observed trends, accounting for 65% of the ASR trend.

It is notable that the trend in thermal emission is much more spatially uniform across the Arctic region than the regionally concentrated ASR maximums, suggesting a possible redistribution of the heat across the entire Arctic basin either through ocean or atmospheric transport. This effective mixing of heat within the Arctic region has been previously discussed by Timmermans and Marshall (2020) and Guemas et al. (2016), through the Beaufort and Laptev Sea gyres, affirming these results with geophysical explanations. The thermal inertia of the Arctic Ocean is well known, with ocean heating occurring in the summer being a sink of energy that is then emitted from the ocean in the fall and winter (Screen and Simmonds 2010; Steele and Dickinson 2016; Boeke and Taylor 2018). From modeling experiments, Boeke and Taylor (2018) further highlight the importance of the relatively shallow Arctic Ocean mixed layer for trapping solar heating at the surface in the Arctic. Enhanced ocean surface heating increases the upper ocean stability, disallowing mixing of heat downward and encouraging the development of sea surface temperature maximums, which increases the outgoing thermal radiation following absorption of solar radiation (Boeke and Taylor 2018). Indeed, Blanchard-Wrigglesworth et al. (2011) and Landy et al. (2022) both demonstrate predictability of growth season (winter) sea ice area and volume from melt season (summer) characteristics primarily through ocean temperature anomalies, providing further evidence for the dependence of year-round thermal emission on variable ASR through heat storage in the Arctic Ocean. The fact that the

![FIG. 7. Schematic of the changing top-of-atmosphere radiative balance in the polar regions (as defined by Fig. 1). The yellow and red arrows represent the annual mean flux of absorbed solar radiation and emitted thermal radiation respectively (presented trends have only emerged in the Arctic). The theoretical transports of energy to fulfill the energy deficit are shown with the pink (oceanic transport) and purple (atmospheric transport) arrows. The bathymetry is shown in blue with the vertical scale exaggerated to highlight the fundamental difference between the polar regions.](image-url)
Arctic net radiation is not changing demonstrates that changes to the radiative balance through ASR increases are being balanced effectively by OLR, suggesting that radiatively, the Arctic is acting as a self-contained system [in agreement with Stuecker et al. (2018)]. Through this understanding, we describe the Arctic Ocean as a “shallow bathtub,” that is, an enclosed basin with low connectivity to mix with lower latitudes and a small amount of water available for warming, primarily due to a shallow, stable mixed layer that re-emits the vast majority of absorbed energy within a given year (Fig. 7).

The lack of significant trends in Antarctic ASR and OLR is unsurprising given the complex relationship between global warming, regional surface temperature, and sea ice loss in this region (Parkinson 2019). The presented TOA radiative record shows very little alignment between trends in absorbed solar radiation and the amount of thermal emission in the region, with no statistically significant relationship in the clear-sky record and very low $R^2$ for the all-sky record. Antarctic ASR is increasing at $0.59 \pm 0.63 \text{ W m}^{-2} \text{ decade}^{-1}$ and the OLR trend is effectively zero at $-0.07 \pm 0.50 \text{ W m}^{-2} \text{ decade}^{-1}$ (however both these trends are not statistically significant). These results align well with results from modeling experiments demonstrating that Antarctic amplification will be driven by other feedbacks apart from the ice-albedo feedback, such as changes in moisture transport (Goosse et al. 2018; Smith et al. 2019; Hahn et al. 2021). This appears to be consistent with the presented observational results, demonstrating that varying solar absorption due to variable sea ice cover does not currently contribute to surface warming. The spatial structure of Antarctic ASR and OLR trends requires additional examination. While the region wide clear-sky ASR and OLR trends do not appear to align, the region of maximum solar absorption in the Ross Sea is collocated with a region of increased thermal emission, which aligns with an isolated region of surface warming (Armour et al. 2016). In contrast, the increasing absorption between the Weddell Sea and southern Indian Ocean is not associated with increasing OLR and is associated as a location of substantial ocean heat uptake and transport (Huguenin et al. 2022).

The presented conclusions are supported by trends in region wide ocean heat content (OHC), SST, and atmospheric heat transport (AHT) into the region (Fig. 8; from ORAS5 and ERA5 reanalysis). The Antarctic region OHC has increased at significant rates in the last 20 years, much greater than the OHC increases in the Arctic. Importantly, while Arctic OHC is increasing at a much lower rate than the Antarctic, the Arctic summertime SST is increasing at a greater rate. This easily demonstrates that the warming that is occurring in the Arctic Ocean (through increasing ASR) is doing so primarily at the ocean surface (or mixed layer), which will contribute to TOA OLR. Comparatively, the lack of increasing SST in Antarctica, given the rapid increase in OHC (equivalent to an increase of $0.65 \text{ W m}^{-2} \text{ decade}^{-1}$), indicates that the heating is occurring at some depth below the surface and therefore not contributing to the emitting radiation from the ocean surface. Antarctic Ocean ASR is increasing at $0.6 \text{ W m}^{-2} \text{ decade}^{-1}$ (supplemental Table 2), demonstrating that OHC increases in the Southern Ocean are consistent with ASR trends. These findings firmly corroborate the importance of ocean heat uptake in Antarctica, identifying a significant sink of energy, which is increasing in magnitude over time, especially as sea ice area reduces. Morrison et al. (2016) and Armour et al. (2016) describe this effective ocean heat uptake around Antarctica and the equatorward advection and downwelling of this energy, facilitating warming at lower latitudes and in the subsurface Southern Ocean driven by the Antarctic Circumpolar Current. With this understanding, we describe the ocean surrounding Antarctica as an “energy sink” due to its effective ability to absorb solar radiation (of increasing amounts) and sequestering the energy deep into the Southern Ocean (Fig. 7). The consequence of this absorption and accumulation of energy into the Earth system remains a fundamental question in our understanding of ongoing anthropogenic climate change.

The lack of appreciable change in the Arctic net energy implies that either the poleward heat transport isunchanging or that any change is being effectively compensated for by other processes (other than emission to space). This conclusion would demonstrate that there is low connectivity to energetic variability outside of the region, which would be expected to modulate the ASR–OLR relationship [as examined by Steele et al. (2010), Steele and Dickinson (2016), and Stuecker et al. (2018)]. Reanalysis suggests that poleward AHT may have increased slightly by $0.01 \text{ PW decade}^{-1}$ (although not significant) or $0.6 \text{ W m}^{-2}$ into the Arctic region over the last two decades (Fig. 8), which could be expected to have an influence on TOA OLR. It may be true that some sequestered ASR into the Arctic Ocean is being compensated by this increasing AHT, allowing for OLR to match the ASR. However, it would indeed be surprising if the increasing rate of the AHT is increasing the OLR to so closely match the observed increasing rate of ASR. Importantly, the lack of significant trend in AHT into both the Arctic and Antarctic emphasizes the importance of local radiative exchange in driving changes observed in the TOA energy balance.

5. Conclusions

Analysis of the CERES-EBAF TOA satellite record in both polar regions has quantified the variable rates of solar absorption and thermal emission in both the Arctic and Antarctica over the last 21 years. Arctic all-sky ASR is increasing at $0.98 \pm 0.69 \text{ W m}^{-2} \text{ decade}^{-1}$, corroborating previous studies. All-sky OLR trends are remarkably similar at $0.94 \pm 0.55 \text{ W m}^{-2} \text{ decade}^{-1}$. These compensating trends result in no significant trend in Arctic energy uptake despite rapid ice loss and increasing solar absorption demonstrating rapid adjustment of the regions temperature to solar absorption. The effective re-emission of ASR in the Arctic is attributed to heat uptake in the Arctic Ocean mixed layer with little mixing downward or equatorward, keeping absorbed energy within the Arctic basin and emitting as OLR within a given year. The observations further indicate that clouds mask Arctic solar absorption trends (50%) far more effectively than thermal emission trends (10%). In the absence of clouds, Arctic sea ice loss results in considerably larger trends in ASR ($2.01 \pm 0.88 \text{ W m}^{-2} \text{ decade}^{-1}$) than thermal emission ($1.24 \pm 0.56 \text{ W m}^{-2} \text{ decade}^{-1}$). Clouds...
substantially mask trends in Arctic solar absorption relative to clear sky while having only a modest impact on thermal emission trends. As a result, the Arctic net radiation imbalance has not changed over the period due to the unequal impact of clouds on solar and thermal radiation. The presented conclusions regarding the importance of cloud cover are drawn from the observed role of clouds and therefore act as a thought experiment. The true response of the cloud-free Arctic to changes in sea ice is complicated by numerous other factors, including heat transport from lower latitudes and exposure of new moisture sources; further modeling experiments are required to fully untangle the complexities of changing sea ice on cloud cover.

These conclusions do not hold true for Antarctica where all-sky ASR trends far exceed OLR trends, decreasing the energy deficit through local radiative exchange at a rate of 0.7% per decade. The Antarctic thermal emission remains relatively unchanged even with recent reductions in sea ice area causing increased solar absorption. While some regions in the Ross Sea exhibit increased thermal emission, a large region between the Weddell Sea and the southern Indian Ocean is absorbing more solar radiation without a
compensating thermal emission. The resultant increasing TOA net energy budget (reducing polar deficit) demonstrates an implied pathway of energy into the Southern Ocean that is increasing in magnitude over the satellite record. The all-sky time to emergence of the Arctic for ASR and OLR is within the 21-yr record demonstrating emergence of these trends, while neither ASR nor OLR has emerged in Antarctica.

Importantly, there is substantial interannual variability in the net energy at both poles of comparable magnitude and following energy conservation; this must be accompanied by a compensating pathway of energy, either through oceanic or atmospheric meridional energy transport. Discerning between the oceanic and atmospheric components of this variability remains an important, ongoing focus of study, connecting polar energy deficits to the general circulation of the atmosphere. We presented an initial examination of reanalysis heat transport and storage to support the discussion but a robust comparison between observations, reanalysis, and model output is required to understand how well these conclusions are represented from different data sources. The presented research also highlights the importance of continuity in the measurement of Earth’s energy budget to quantify the changing disposition of energy within the Earth system, providing timely justification for NASA’s first Earth Venture Continuity mission, Libera (Pilewskie and Hakuba 2020). The quantified trends in polar energy balance over the last two decades provide a benchmark for both climate model validation and to track the observed changing geophysical processes in these sensitive regions.

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Data availability statement. Top of atmosphere flux data (CERES-EBBF 4.2) were sourced from the NASA CERES data repository (https://ceres.larc.nasa.gov/data/). Sea ice data (NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, version 4) were sourced from NSIDC repository (https://nsidc.org/data/g02202/versions/4). AIRS data were retrieved from the NASA Goddard Earth Sciences Data and Information Services Center—GES DISC (https://disc.gsfc.nasa.gov/datasets/AIRX3STM_7.0/summary).

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