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Changes in the fabric of the Arctic's greenhouse blanket

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Abstract

The Arctic is rapidly losing its permanent ice. While increases in greenhouse gases are believed to be the underlying cause of the melting, interactions among the Arctic's changing thermodynamic and dynamic processes driving ice loss are poorly understood. The emission of infrared radiation from the atmosphere to the surface has been recently implicated as an important factor governing the extent of summer perennial sea ice. In this study we use new satellite-derived products to investigate which atmospheric parameters are contributing to observed increases in the downwelling flux in longwave radiation (DLF) during spring in six regions around the periphery of the Arctic Ocean. In areas dominated by low clouds containing liquid water, we find that DLF trends are driven primarily by increasing cloud fraction and more abundant water vapor, and offset by lowering cloud-base heights. In ice-cloud dominated regions (seas north of Siberia), we find that changing water vapor assumes a more important role, while effects of changing cloud fraction and cloud-base height are reduced. Results highlight the need for improved information about Arctic cloud-base heights, cloud phase, and the height and strength of surface-based temperature inversions.

Keywords: Arctic, energy budget, clouds, radiation, sea ice

1. Introduction

The dramatic loss of Arctic sea ice, particularly during summer, is unprecedented in at least the past 50 years (Stroeve *et al* 2005, Serreze *et al* 2007). The minimum sea ice extent, as observed by passive microwave satellites, appears to be on an accelerating downward trend, as anomalies averaged over the past five years are approximately 23% lower than those in the early 1980s (figure 1). This apparent acceleration in ice loss fuels speculations that the much-anticipated ice–albedo feedback mechanism may now be in operation, i.e., enough ice has been lost to allow sufficient additional solar energy to enter the Arctic Ocean and affect ice growth through the winter, thereby resulting in a thinner and more easily melted ice cover the following spring (e.g., Serreze and Francis 2006).

Recent studies have investigated possible causes for the loss of Arctic sea ice. Rigor and Wallace (2004), by tracking the movement of ice-borne buoys, found that the ice cover is now much younger on average than it was in the 1980s. During the period from the late 1980s to early 1990s, when the Arctic Oscillation (AO) index resided in a mostly positive phase, they suggest that the change in atmospheric circulation shifted the trans-Arctic ice drift, flushing much of the thick multi-year pack ice out of the Arctic into the North Atlantic. This evidence supports findings by Francis *et al* (2005) and Francis and Hunter (2006) that variability in the summer-minimum ice edge position is highly correlated with anomalies in the downward longwave radiation flux from the atmosphere, particularly so in the period after 1992 when the ice cover was thinner and thus more susceptible to anomalies in the surface energy balance. These studies also found that the ice-edge retreat is *anti*correlated with anomalies in the incident solar radiation (i.e., increased retreat corresponds with negative insolation anomalies), suggesting that the observed increases in springtime cloudiness (Schweiger 2004, Wang and Key 2005b,

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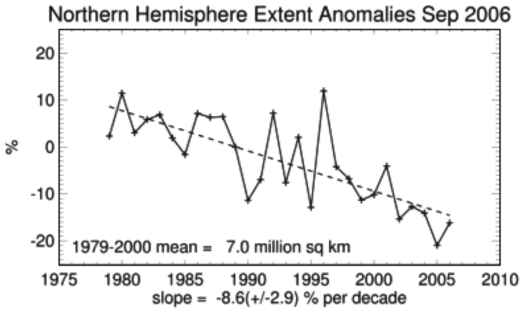

Figure 1. Sea ice extent anomalies in the Northern Hemisphere since 1979 derived from passive microwave satellite data. Values are expressed as a percentage difference from the mean extent from 1979 to 2000. (From the National Snow and Ice Data Center, www.nsidc.org)

2003) cause increased emission of longwave radiation to the surface that exceeds the increased reflection of incoming solar energy by the clouds back to space. Francis and Hunter (2006) also found that in the Pacific sector, approximately half of the variance in ice-edge position attributable to downward longwave radiation (DLF) anomalies results from the increasing trend in DLF during the melt season. This result begs the question, 'What is driving increases in DLF?' The study described in this paper addresses this question by combining new satellite-derived estimates of the likely factors contributing to DLF changes with model calculations of the DLF's sensitivity to the variables that affect it.

2. Methodology and data sources

The approach followed in this study consists of three main steps. The first is to calculate the sensitivity of the downward surface infrared flux in typical spring Arctic conditions to variations in atmospheric parameters that are likely to influence DLF. The baseline conditions are determined from a year of observations obtained during the Surface Heat Balance of the Arctic (SHEBA) field campaign conducted in 1997–1998 in the Beaufort Sea (Uttaletal 2002). Standard spring conditions for the sensitivity tests are as follows: cloud fraction = 57%, cloud-base height = 0.8 km, surface temperature = 258 K, precipitable water = 3.0 mm, and liquid (ice) water path = 49 (23) g m^{-2}. A forward radiative transfer model (Streamer; Key 2002) was run to determine the change in DLF resulting from varying each of these parameters individually over a realistic range while holding the others constant at typical Arctic spring values.

The second step is to calculate the observed trends in each of these parameters using new retrievals derived from satellite-borne sounding instruments. The Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) has flown continuously since mid-1979, providing global profiles of temperature and moisture along with cloud information and surface temperature (Scott *et al* 1999). Improvements in retrievals for Arctic conditions were developed and discussed by Francis (1994), Francis and Schweiger (2000); and Schweiger *et al* (2002). These fundamental retrievals have

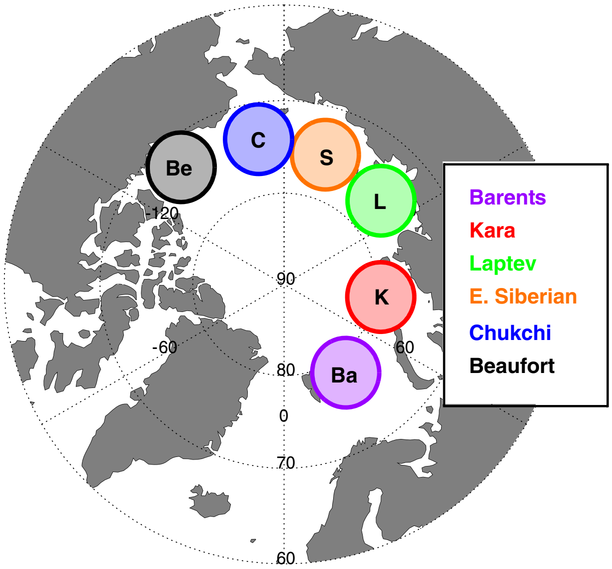

Figure 2. Six regions in Arctic peripheral seas where satellite-derived products are subsetted and trends calculated for spring (MAM) 1979–2005.

been used to generate new products for the Arctic climate system, including daily mean DLF, cloud-base height, and liquid/ice water path at a spatial resolution of (100 km)^2. As a part of the algorithm to calculate the DLF, the cloud-base height is estimated using brightness temperatures from pairs of infrared channels that differ in their sensitivity to cloud particles, thereby yielding a gross estimate of the cloud thickness. Combined with the retrieved cloud-top pressure, the cloud-base height is derived. The mean in-cloud temperature is then used to estimate the liquid/ice water path (LWP/IWP) based on published relationships between these parameters. Further details are available in Francis (1997).

The TOVS-derived DLF product has been validated with observations from SHEBA and from the Atmospheric Radiation Measurement (ARM) site at Barrow, AK, revealing biases of approximately 7 W m^{-2} and standard deviations of about 30 W m^{-2} over five years of year-round retrievals. Cloud-base height and LWP are more difficult to validate, as data from the ARM site are also estimated from remote sensing information. Nevertheless, the TOVS-derived LWPs are within 20 g m^{-2} of surface-based retrievals at the ARM site during spring, and cloud-base heights are within 0.5 km.

Spatial subsets of each parameter in 400 km radius areas are extracted in six peripheral seas (figure 2), and linear trends are calculated from daily values for the period from 1979 to 2005. These trends for spring (March–April–May, abbreviated later as MAM) are tabulated in table 1. The regions shown in figure 2 are the same as those used to investigate factors driving variability in perennial sea ice extent by Francis and Hunter (2006). The TOVS-derived, 26-year trend in spring DLF over the Arctic Ocean is shown in figure 3. The pattern is very similar to the field calculated from the European Centre Medium-Range Weather Forecast (ECMWF) Reanalysis (ERA-40) product from 1982–2002 (not shown),

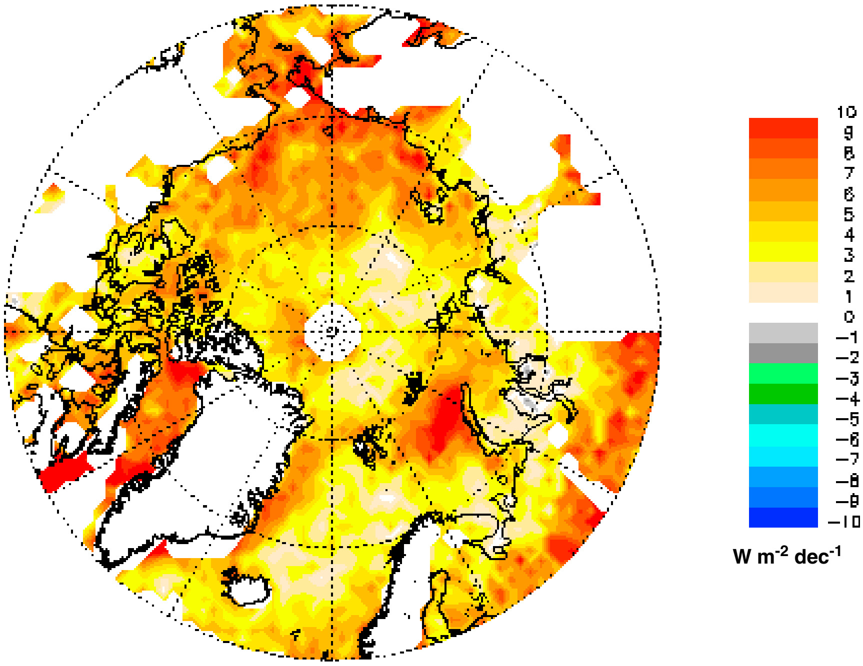

Figure 3. Decadal trend (W m^{-2} dec^{-1}) in TOVS-derived downwelling longwave radiation flux at the surface from 1980 to 2005 during spring (MAM).

Table 1. Linear decadal trends in atmospheric and surface parameters for six Arctic seas during spring (MAM) derived from satellite sounder retrievals from 1979 to 2005.

Parameter (units dec^{-1})	Barents	Kara	Laptev	E. Siberian	Chukchi	Beaufort
DLF (W m^{-2})	6.4	6.4	5.8	8.2	8.7	5.7
Cloud frac. (%)	4.0	3.0	2.9	7.2	5.7	6.5
Cld. base ht. (mb)	16.0	31.0	30.0	43.0	48.0	49.0
LWP/IWP (g m^{-2})	0.24	0.04	0.09	0.12	0.26	0.24
Precip. water (mm)	0.09	0.14	0.17	0.25	0.30	0.23
Surface temp. (K)	0.42	0.62	0.41	1.08	1.35	0.85
1000–700 hPa temp. (K)	0.43	0.44	0.38	0.94	1.25	0.84

although magnitudes in the Pacific sector are larger in the TOVS field, corresponding to the rapid ice loss in that area since 2002.

The final step in the analysis is to determine the amount of change in spring DLF that can be attributed to observed changes in the 'driver parameters,' i.e., cloud fraction, cloud-base height, liquid/ice water path, precipitable water (total-column water vapor), surface temperature, and lower-tropospheric air temperature. This is achieved by comparing the observed trends in these variables to the sensitivity calculations from step 1 to obtain the amount of DLF change that would result from a change in each parameter individually. These contributions are then summed, and the total is compared to the observed trend in DLF in each region.

While sensitivity tests were performed for both water- and ice-phase clouds, evidence from previous studies suggests that clouds containing water droplets are prevalent in spring in most areas (Intrieri *et al* 2002, Wang and Key 2005a). The exception may be the Kara and Laptev Seas, where the proximity to interior Siberia and low surface temperatures likely result in a predominance of ice clouds. This assertion is supported by retrievals of cloud-top phase from the Advanced Very High Resolution Radiometer (AVHRR) Extended Polar Pathfinder (APP-x) data (not shown) (Wang and Key 2005a). Clearly these assumptions are fairly crude, but little information exists to verify cloud phase anywhere but in the well-observed Beaufort Sea area. There is also evidence that water-containing Arctic clouds are becoming more prevalent (Wang and Key 2005b), which is consistent with the observed warming of the Arctic surface and atmosphere in recent decades (e.g., ACIA 2004). Based on this evidence, the sensitivity results for liquid clouds are used to assess contributions from each atmospheric variable to changing DLF, except in the Kara and Laptev Seas, where ice clouds are believed to be the predominant cloud type.

3. Results

The change in DLF resulting from observed spring trends in driver parameters is illustrated in a set of six histograms, one for each region. The individual bars in the histograms represent the change in spring DLF owing to the trend in

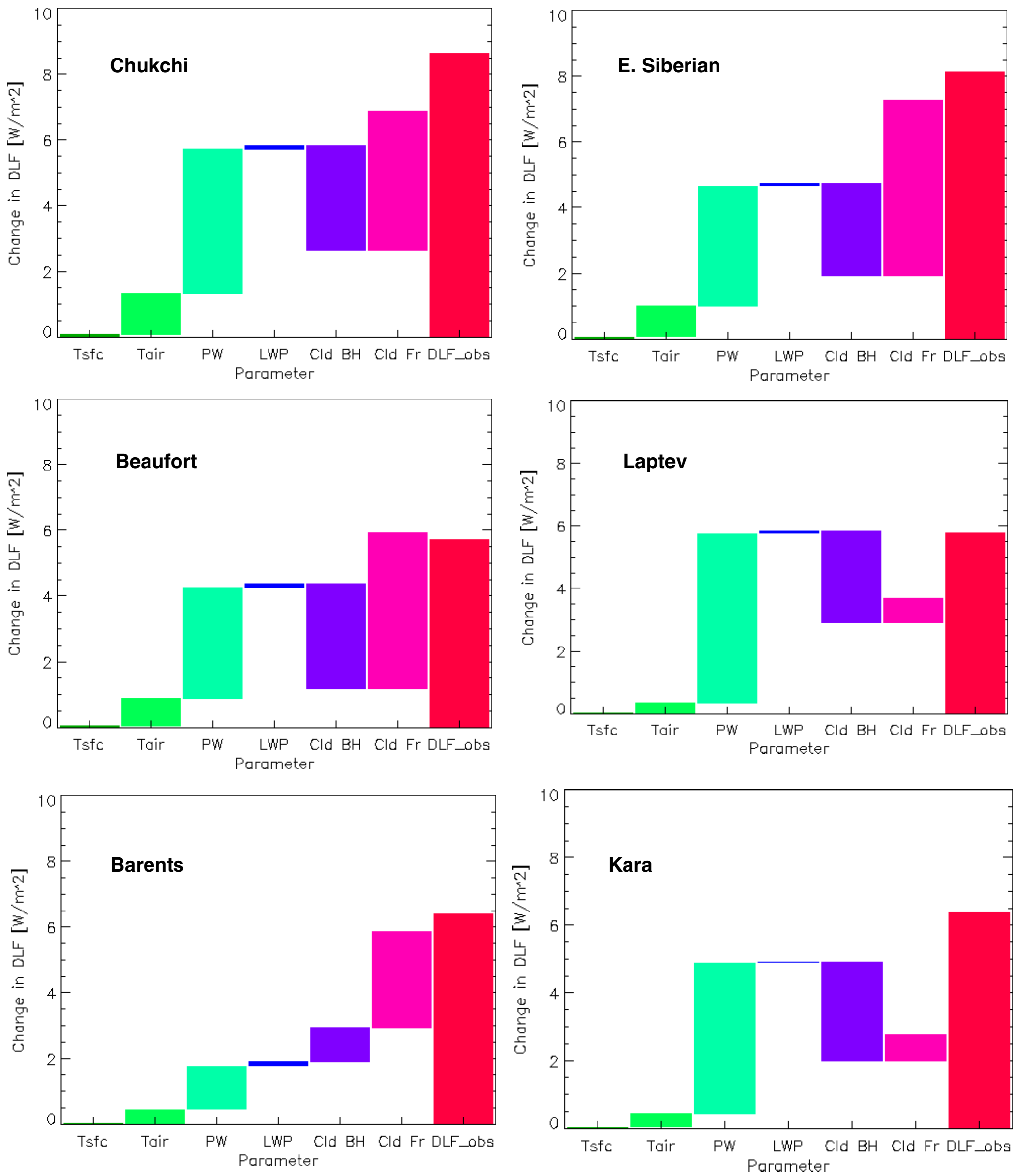

Figure 4. Histograms corresponding to each region shown in figure 2. Bars indicate the amount of change in DLF resulting from observed trends in each atmospheric parameter noted on the x-axis: surface skin temperature (Tsfc), lower-troposphere temperature (1000–700 hPa; Tair), precipitable water (PW), liquid/ice water path (LWP), cloud-base height (Cld BH), and cloud fraction (Cld Fr). The endpoint of each bar sums all those to its left, except for the final bar, which indicates the TOVS-derived trend in DLF for that region. Clouds are assumed to be composed of liquid droplets in all regions except the Kara and Laptev Seas, and cloud-bases are assumed to be located below the surface-based temperature inversion everywhere except the Barents Sea.

one of the variables. Each bar in the histogram begins at the end-value of the previous one, thus the bar for the final parameter represents the total change in DLF resulting from all the variables combined. The right-most bar displays the TOVS-observed change in DLF for that region. This method treats the contributions from each variable as being independent and therefore can be added to obtain a total DLF change. This assumption was tested using the radiative transfer model to compare the DLF change computed from the standard conditions with the trends in all variables included to that derived from summing the individual contributions as described above. The DLF change computed using the two methods differed by approximately 10%, or less than 1 W m^{-2}, suggesting that to a first approximation the contributions from each changing variable can be added linearly.

The histograms shown in figure 4 are arranged according to their relative location around the Arctic basin. The primary factors contributing to positive DLF trends in all regions appear to be increased cloudiness and precipitable water, while lowering cloud-base heights offset the DLF trend. The mean cloud-base height of 0.8 km, determined from lidar measurements at the Barrow ARM site (not shown) and at

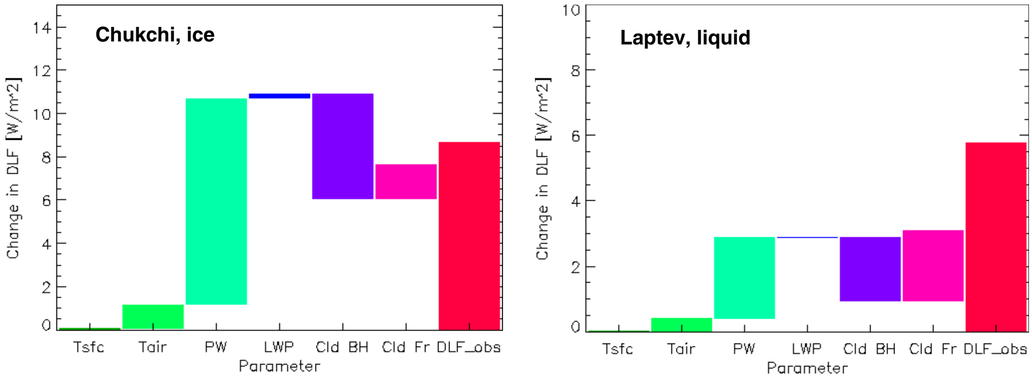

Figure 5. Same histograms as in figure 4, but assuming the opposite cloud phase in two regions to illustrate the effect of phase on the results. The left plot is for ice clouds in the Chukchi Sea, and the right is for liquid clouds in the Laptev Sea. Note the change in vertical scale for ice clouds in the Chukchi Sea.

the Surface Heat Balance of the Arctic (SHEBA) base camp (Intrieri *et al* 2002), is below the top of the nearly ubiquitous surface-based Arctic temperature inversion (Serreze *et al* 1992, Liu *et al* 2006). A lowering cloud base in these conditions, therefore, results in a colder cloud-base temperature, which reduces the downwelling longwave emission and offsets the augmenting effects of increased cloud fraction and precipitable water. The exception is in the Barents Sea, where satellite-derived inversion strengths are low (Liu *et al* 2006) owing to the advection of warm air and water by frequent storms and a predominant flow of moisture from the southwest (Groves and Francis 2002). Here it is assumed that a lower cloud base is warmer.

Surprisingly, even though the LWP appears to have increased dramatically in recent decades (table 1), the DLF shows little sensitivity. This is because the clouds are already nearly opaque in the infrared, so adding cloud mass has little effect on the cloud emissivity. Observed increases in temperature at the surface and in the lower troposphere also have little effect on the DLF. This result is consistent with the sensitivity studies of Chiacchio and Francis (2002), who found that the DLF was only slightly affected by perturbations in the temperature profile.

The assumption of cloud phase has a substantial influence on the relative contributions to DLF trends. Figure 5 shows results for two of the seas shown in figure 4 but with the opposite cloud phases. A comparison of the plots in the two figures suggests that in ice clouds the effect of changing cloud fraction is weaker than if water clouds are assumed, while the influence of trends in precipitable water is larger in ice clouds. This occurs because thick water clouds mask changes in emission from the water vapor above.

4. Conclusions

Anomalies and trends in the downwelling longwave radiation flux have been implicated as important drivers of perennial sea ice loss (Francis and Hunter 2006). In this study we attempt to determine which of the many possible atmospheric parameters are responsible for the changes in DLF during spring. Products derived from the TOVS satellite sounder are used to make this assessment by subsetting them for six regions around the Arctic Ocean. Because passive satellite radiances cannot directly retrieve parameters such as cloud-base height, liquid water path, and cloud phase below cloud top—all of which are important drivers of DLF—this analysis is clearly not a definitive attribution of change in the surface radiation balance. Arctic change is dramatic and rapid, however, thus it is important to obtain a first-order understanding of the causes for the change using information available today. New active satellite sensors, additional data from the International Polar Year field campaigns, and improved models should provide an opportunity to refine this assessment.

The accumulation of contributions to DLF change based on the factors considered here—cloud fraction, cloud-base height, liquid/ice water path, precipitable water, surface skin temperature, and lower-tropospheric temperature—captures most of the total retrieved trend in DLF. We can conclude, therefore, that the observed DLF trend is driven by changes in these six variables. The relatively poor agreement between accumulated and observed DLF trends in the Kara and Laptev Seas (figure 4) is likely due to the baseline conditions from the SHEBA campaign (Beaufort Sea) used in the sensitivity calculations in step 1 not being representative of typical spring conditions along the Siberian coast. As this work continues, we will attempt to acquire baseline atmospheric data from each region.

If clouds are assumed to be composed of liquid water droplets, the primary factors contributing to trends in DLF appear to be cloud fraction, cloud-base height, and precipitable water. If one assumes clouds are composed of ice particles, the dependence of DLF trends on changes in cloud fraction is reduced, but the role of changing precipitable water is enhanced. An unexpected result is the weak dependence of DLF trends on changing surface temperature, lower-tropospheric temperature, and liquid/ice water path, especially given that these variables have increased substantially in recent decades. Changing atmospheric temperatures have little effect because the Arctic atmosphere is so dry and thus has a low emissivity, and the DLF is relatively insensitive to

LWP/IWP changes because most Arctic clouds are already nearly optically thick in the infrared.

Cloud fraction and precipitable water are fundamental quantities retrieved from satellite sounders, and their accuracy has been verified through validation with available ground-based observations. An important but sobering finding from this assessment is the key role played by cloud-base height. Even though the TOVS-derived estimates of cloud-base height appear reasonably accurate as compared with ground-based retrievals at the Barrow ARM site, their accuracy elsewhere in the Arctic is less certain. In addition to the general lack of knowledge about cloud-base heights in the Arctic, we find from this study that knowing whether the cloud base is located above or below the top of a surface-based temperature inversion is also essential. Based on this work that highlights cloud-base height as a key parameter for determining the Arctic surface energy balance, we recommend that new satellite systems, such as CloudSat and Calipso, develop a cloud-base climatology for polar regions, in particular. We also suggest that this type of attribution study may be useful for identifying parameters that drive change in other climate parameters, thus prioritizing the deployment of resources. Finally, relationships among variables, such as those identified in this study, may be used to assess whether models simulate change correctly and for the right reasons.

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