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### Key Points:

- Land surface roughness anomalies caused by human activities can induce changes in climate
- Anomalous high roughness leads to greater sensible heat flux, triggering mesoscale circulations and precipitation
- This new mechanism may be relevant to storm formation over wind farms, cities and forests

### Supporting Information:

Supporting Information may be found in the online version of this article.

### Correspondence to:

K. A. McColl,  
[kmccoll@seas.harvard.edu](mailto:kmccoll@seas.harvard.edu)

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## Thermally Direct Mesoscale Circulations Caused by Land Surface Roughness Anomalies

Yu Cheng<sup>1</sup>  and Kaighin A. McColl<sup>1,2</sup> 

<sup>1</sup>Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA, <sup>2</sup>School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA

**Abstract** Deforestation, urbanization and construction of wind farms can change the land surface roughness, which can further influence surface heat fluxes and thus weather and climate. Land surface roughness anomalies can dynamically trigger convergence through changing mean wind speed. Here, we report a new mechanism, in which roughness anomalies cause thermally direct mesoscale circulations and anomalous precipitation. To study this mechanism, we conduct cloud-permitting simulations over an idealized land surface with prescribed surface roughness anomalies. Anomalous high roughness increases turbulent mixing near the surface, which decreases land surface temperature and outgoing longwave radiation. The additional surface net radiation partly goes into greater sensible heat flux, which triggers mesoscale circulations driven by differential heating. As a result, precipitation over the high-roughness anomaly is generally larger than that over the low-roughness background. This new mechanism, not present in climate models, may be relevant to storm formation over wind farms, cities and forests.

**Plain Language Summary** The Earth's surface roughness determines the turbulent exchange efficiency of momentum, heat, water vapor, and carbon dioxide between the atmosphere and surface, and thus serves as a key boundary condition for predicting weather and climate. Surface roughness can be modified by human activities, such as deforestation, urbanization, and construction of wind farms. It is recognized that land surface roughness anomalies can dynamically trigger convergence and precipitation anomalies through changing mean wind speed. Compared to its dynamical effects, the thermal effects of roughness anomalies have largely been overlooked. In this study, we report that higher roughness can lead to thermally direct mesoscale circulations and more precipitation. This new mechanism, neglected in previous coarse-resolution climate models, could be significant for predicting storms over wind farms, cities, and forests.

## 1. Introduction

Land surface modifications like deforestation, urbanization and construction of wind farms can change the surface roughness, which further influences turbulent exchange of momentum, heat, water vapor, and carbon dioxide between the atmosphere and the Earth's surface (Deardorff, 1972; Louis, 1979). At synoptic scales ( $O(1,000\text{ km})$ ), roughness anomalies caused by wind farms can trigger Rossby waves and induce anomalies in wind, temperature, and cloud cover (Kirk-Davidoff & Keith, 2008). At mesoscales ( $O(10\text{ km})$ ), changes in roughness caused by deforestation can generate “dynamically driven” mesoscale circulations (Khanna & Medvigy, 2014; Samuelsson & Tjernström, 2001), which are essentially horizontal divergence or convergence due to the speed change of mean horizontal winds over different roughness surfaces.

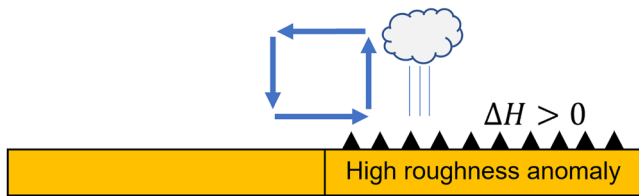
In contrast to the dynamically driven mesoscale circulations reported in previous studies (Khanna & Medvigy, 2014; Samuelsson & Tjernström, 2001), here we report a new mechanism: “thermally direct” mesoscale circulations caused by differential heating that arises in the presence of roughness anomalies. How can an anomaly in roughness cause anomalous heating? Consider a deliberately extreme, idealized example, used here to qualitatively illustrate the mechanism. An otherwise uniform domain is divided into two regions, one rough (denoted with “R” subscripts) and one perfectly smooth (denoted with “S” subscripts). In this idealized example, the roughness of the surface entirely controls the intensity of turbulent mixing near the surface, encoded in the “aerodynamic conductance” parameter ( $g_a$ ), and the aerodynamic conductance of the smooth region is zero.

As detailed in Supporting Information S1, the heating differential between the rough and smooth regions is

$$\Delta H \equiv H_R - H_S = H_R \quad (1)$$

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**Figure 1.** Schematic of mesoscale circulations generated by differential heating due to a roughness anomaly.

where  $H$  is the sensible heat flux. This example shows that a surface roughness anomaly is capable of causing an anomaly in sensible heat flux, solely due to basic constraints imposed by the surface energy budget. Moreover, over land, the sensible heat flux is typically positive during the day outside high latitudes, and also in the daily, monthly and annual means. This implies that  $\Delta H$  is typically positive, and rough anomalies should heat the atmosphere more than their smoother surroundings, potentially triggering mesoscale circulations and precipitation (Figure 1).

These arguments are based on a deliberately simple and idealized model in which the region surrounding the rough anomaly is perfectly smooth with zero turbulent fluxes. Does the mechanism persist in less extreme cases? And, are the heating anomalies sufficient to trigger mesoscale circulations that cause precipitation? To answer these questions, we turn to cloud-permitting simulations.

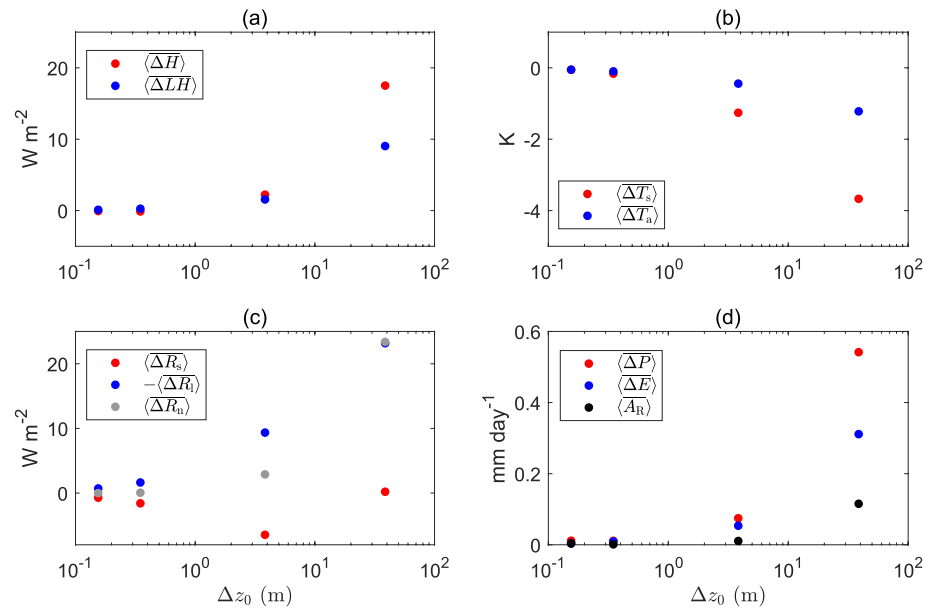
## 2. Numerical Simulations

We investigate climate responses to a roughness anomaly over an idealized tropical land surface using high-resolution cloud-permitting simulations (Khairoutdinov & Randall, 2003) coupled with a land surface model (Lee & Khairoutdinov, 2015), as detailed in Supporting Information S1. Cloud-permitting simulations are conducted over an idealized limited domain without vegetation, where a roughness anomaly is prescribed, similar to that shown in Figure 1. This idealized setup avoids evaporation differences due to vegetation differences. In addition, soil albedo is independent of soil moisture in our numerical simulations, although albedo changes with soil moisture in the real world (Idso et al., 1975; Rutherford et al., 2017). This setup is used to avoid the additional complexity due to soil albedo differences. In our simulations, the domain is centered at  $8^\circ\text{N}$ , and is  $25 \times 25 \times 22$  km (Figure S1 in Supporting Information S1) in the  $x$ ,  $y$  (horizontal) and  $z$  (vertical) directions, respectively. The domain is horizontally periodic and is divided into two equal patches with different roughness lengths in the  $x$  direction (Figure S1 in Supporting Information S1). The patch with the smaller roughness length has a value of  $z_0 = 0.0387$  m. The equivalent value for the rougher patch is a multiple of this value, and varies between experiments. For example, rough\_1\_5 denotes the experiment where the roughness length in the rougher patch is  $5z_0$ . The prescribed spatial resolution is 250 m in the horizontal direction. The vertical resolution is 30 m (200 m) near the surface (top). The simulations start on January 1 and were run for 500 days. Further descriptions of the land surface model and the cloud-permitting model are available in Supporting Information S1 and previous studies (Cheng et al., 2021; Khairoutdinov & Randall, 2003; Kiehl et al., 1998; Lee & Khairoutdinov, 2015).

We apply the weak-temperature gradient (WTG) approximation (Abbott & Cronin, 2021; Anber et al., 2015; Raymond & Zeng, 2005; Sobel et al., 2001) to model the interaction between convection and large-scale forcing over an idealized tropical land surface. Cloud-permitting models coupled with the WTG approximation have been shown to reasonably simulate temporal variations of precipitation in the Amazon region (Anber et al., 2015). Our results are not qualitatively sensitive to the choice of atmospheric temperature reference profile used in the simulations (Supporting Information S1). The list of experiments prescribed with different roughness anomalies and initial soil moisture are available in Table S1 in Supporting Information S1. For each roughness anomaly experiment, simulations prescribed with different initial soil moisture constitute an ensemble. Surface roughness is characterized by the roughness length  $z_0$ . The largest roughness length is  $1000z_0 = 38.7$  m. This is not unrealistic since the roughness length can be of the order of  $0.1h$  (Leonardi & Castro, 2010; Macdonald et al., 1998; Placidi & Ganapathisubramani, 2015; Raupach, 1992), where  $h$  is the obstacle height. We focus on temporal- and ensemble-averages:  $\langle \cdot \rangle$  denotes long-term temporal averaging and overbars ( $\bar{\cdot}$ ) denote ensemble averaging (averaging across simulations prescribed with various initial soil moisture).

### 2.1. Surface Flux Anomalies Caused by Roughness Anomalies

A high roughness anomaly causes positive anomalies in both sensible and latent heat fluxes. Over a typical land surface,  $H > 0$  and  $T_s > T_a$  (outside high latitudes and night), where  $T_s$  is the land surface temperature. Introducing a high roughness anomaly increases turbulent mixing near the surface over the roughness anomaly, causing the temperature profile to become more uniform; thus  $T_s - T_a$  decreases over the high roughness anomaly. This



**Figure 2.** (a) The sensible heat flux anomaly  $\langle \Delta H \rangle$  and latent heat flux anomaly  $\langle \Delta LH \rangle$  plotted against the roughness anomaly ( $\Delta z_0$ ). (b) Soil temperature anomaly  $\langle \Delta T_s \rangle$  and near-surface air temperature (15 m above the ground) anomaly  $\langle \Delta T_a \rangle$  plotted against  $\Delta z_0$ . (c)  $\langle \Delta R_s \rangle$  (shortwave radiation anomaly),  $\langle \Delta R_l \rangle$  (longwave radiation anomaly) and  $\langle \Delta R_n \rangle$  (net radiation anomaly) plotted against  $\Delta z_0$ . At largest  $\Delta z_0$  of figure (c), the blue dot is covered by the gray dot, since the values represented by these dots are almost the same. (d) The precipitation anomaly  $\langle \Delta P \rangle$ , evaporation anomaly  $\langle \Delta E \rangle$ , and the horizontal convergence (net advection) of moisture into the atmosphere above the high-roughness anomaly ( $\langle \Delta A_r \rangle$ ) plotted against  $\Delta z_0$ .

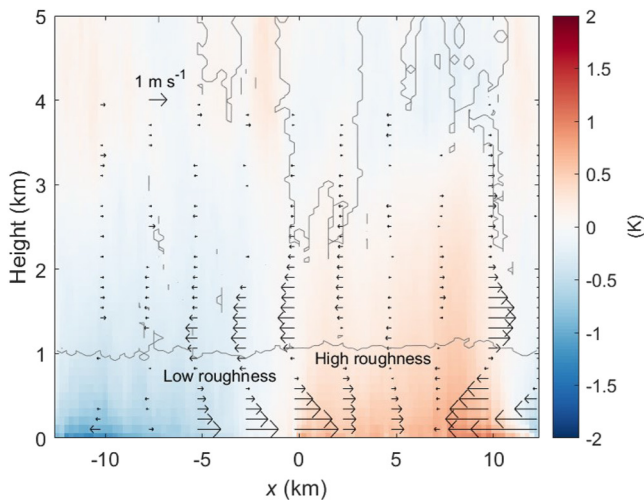
implies that  $T_s$  decreases and/or  $T_a$  increases. However, the atmosphere is well-mixed relative to the land surface, so  $T_a$  is less sensitive to changes in surface properties than  $T_s$ ; thus,  $T_s$  robustly decreases over the high roughness

anomaly. The decline in  $T_s$  over the high roughness anomaly causes a decline in outgoing longwave radiation from the surface. This means net radiation is greater over the high roughness anomaly, and so both sensible and latent heat fluxes are also greater over the high roughness anomaly.

This mechanism is supported by our simulations. As expected, the high roughness anomaly reduces  $T_s$  in our simulations. Specifically, as the prescribed roughness anomaly increases,  $\langle \Delta T_s \rangle \equiv \langle T_{s,R} - T_{s,S} \rangle$  decreases, with  $\langle \Delta T_s \rangle$  decreasing more than  $\langle \Delta T_a \rangle$  (Figure 2b). This causes outgoing longwave radiation to decline over the high roughness anomaly, where land surface temperature is lower, resulting in greater net radiation (Figure 2c). Both sensible and latent heat flux anomalies increase with increasing roughness anomaly, consistent with increasing surface net radiation (Figure 2a).

## 2.2. Thermally Direct Mesoscale Circulations Driven by Surface Flux Anomalies

The resulting sensible heat flux anomalies cause thermally direct mesoscale circulations to form. An example is shown in Figure 3. At 1:30 p.m. local time on day 500 of experiment rough\_1\_100, the sensible heat flux over the high-roughness anomaly is about  $68 \text{ W m}^{-2}$  larger than that over the low-roughness background (Figure 3), leading to a transient air temperature anomaly of  $+1.3 \text{ K}$  near the surface. A thermally direct mesoscale circulation is then generated by a pressure anomaly around 12 Pa near the surface due to the temperature anomaly. This thermally direct mesoscale circulation leads to precipitation preferentially over the high-roughness anomaly. The zonal velocity fluctuation (Figure 3), which is the difference between zonal



**Figure 3.** Presence of mesoscale circulations in numerical simulations.  $x$ - $z$  diagram at 1:30 p.m. local time of  $y$ -averaged quantities for the experiment rough\_1\_100 on day 500. The color contours denote temperature anomaly. The black arrows denote zonal velocity fluctuation, that is, the difference between zonal velocity and its mean at each height. Note that the zonal velocity fluctuation is only presented for those with a magnitude not less than  $0.1 \text{ m s}^{-1}$ . The arrow below “ $1 \text{ m s}^{-1}$ ” in the figure is not a real velocity but just used as a reference velocity scale. The gray isolines denote non-precipitating cloud ice and water equal to  $10^{-5} \text{ g kg}^{-1}$ . The  $x$  axis denotes the distance from domain center in  $x$  direction.

velocity and its mean at each height, clearly indicates horizontal convergence near the surface and divergence above 1 km over the high-roughness anomaly, consistent with a mesoscale circulation driven by the prescribed roughness anomaly.

The higher air temperatures over the high-roughness anomaly in Figure 3 may appear to contradict the finding that air temperatures are lower, on average, over the roughness anomaly (Figure 2b). The difference is explained by the diurnal cycle. The transiently positive  $\langle \Delta T_a \rangle$  shown in Figure 3 coincides with the diurnal peak in  $\langle \Delta H \rangle$  (Figures S3 and S4 in Supporting Information S1). Thus, the anomalously high sensible heat flux over the roughness anomaly causes air temperatures to transiently rise during the day, which triggers mesoscale circulations. But, the transient increase in air temperatures quickly recedes, resulting in lower air temperatures over the high-roughness anomaly, on average.

The mesoscale circulations trigger uplift and greater precipitation over the high-roughness anomaly (positive  $\langle \Delta P \rangle$ , Figure 2d). Net advection of moisture into the high-roughness anomaly (positive  $\langle A_R \rangle$ , Figure 2d) is consistent with this mechanism. The high precipitation anomaly only occurs when the atmosphere is sufficiently wet (Figure S6d in Supporting Information S1).

### 3. Summary and Discussion

We report thermally direct mesoscale circulations driven by a land surface roughness anomaly. The mechanism promotes precipitation over high roughness anomalies at mesoscales. To our knowledge, this mechanism is new, and is distinct from “dynamically driven” mechanisms reported in previous studies (Khanna & Medvigy, 2014; Samuelsson & Tjernström, 2001). Although the effects of land surface heterogeneities on climate have been studied in terms of deforestation (Khanna & Medvigy, 2014; Khanna et al., 2017; Winckler et al., 2019), urbanization (Li et al., 2021; Rajeswari et al., 2021; W. Wang, 2009; Zhu et al., 2016), and construction of wind farms (Baidya Roy et al., 2004; Fiedler & Bukovsky, 2011), these studies do not identify the thermally direct mechanism shown here. Studies using coarse-resolution climate models do not resolve mesoscale circulations at all (Davin & de Noblet-Ducoudré, 2010; Dickinson & Henderson-Sellers, 1988; Lean & Warrilow, 1989; Li et al., 2018; C. Wang & Prinn, 2010; Winckler et al., 2019), so higher resolution simulations must be used instead. Of those studies, some include an imposed mean wind, in which the “dynamically driven” mechanism likely dominates and obscures the thermally direct mechanism (Claussen, 1989; Courault et al., 2007; Huang & Margulis, 2009; Khanna & Medvigy, 2014; Li et al., 2021; Lin & Glendening, 2002; Maronga & Raasch, 2013; Miller & Stoll, 2013; Rajeswari et al., 2021; Stoll & Porté-Agel, 2006; Wright et al., 1998). Others do not include an interactive surface energy budget, instead prescribing surface temperatures or surface fluxes, which precludes the mechanism identified here (Claussen, 1989; Huang & Margulis, 2009; Lin & Glendening, 2002; Maronga & Raasch, 2013; Miller & Stoll, 2013; Stoll & Porté-Agel, 2006; W. Wang, 2009; Wright et al., 1998; Zhu et al., 2016). Figure S7 in Supporting Information S1 highlights key differences between our study and previous literature.

Our proposed roughness-anomaly mechanism may moderate warming in urban environments caused by coincident anomalies in surface albedo and vegetation transpiration (Bounoua et al., 2015; Grimmond, 2007). The proposed mechanism predicts that the high roughness anomaly caused by urban areas will enhance turbulent mixing and decrease surface and near-surface temperatures, on average, potentially offsetting some urban heat island effects (Figure 2b).

Our work is subject to limitations. We have deliberately focused on an idealized representation of land surface roughness ( $z_0$ ) to understand the most essential features of the mechanism. However, an important next step is to quantitatively evaluate the mechanism with more realistic roughness schemes, including parameterizations of forest canopies (Bonan et al., 2018), urban canopies (Santiago & Martilli, 2010) and elevated momentum sinks (Fitch et al., 2013; Wu & Archer, 2021) for forests, cities and wind farms, respectively. Wind farms, in particular, induce important changes in near-surface turbulence that go beyond simple increases in  $z_0$  (Fitch et al., 2013; Wu & Archer, 2021).

For maximum simplicity, our study also does not include a mean wind. It is plausible that a sufficiently large roughness anomaly may obstruct the mean wind flow, decreasing the mean wind speed, and thus decreasing the sensible heat flux anomaly. This dynamical weakening of the sensible heat flux anomaly acts against the proposed thermally direct mechanism proposed here, and should be investigated in future work. In addition,

our study also deliberately treats soil albedo as independent of soil moisture, even though soil albedo typically decreases as soil moisture increases (Idso et al., 1975). In our numerical simulations, the high roughness anomaly leads to a larger sensible heat flux, more precipitation, and higher soil moisture. If the effects of soil moisture on soil albedo are considered, the high roughness anomaly will lead to lower soil albedo, which further strengthens the mechanism proposed here.

A variety of scale-dependent climate responses to the presence of wind farms likely exist, beyond the mechanism presented here (Baidya Roy et al., 2004; Fiedler & Bukovsky, 2011; Fitch et al., 2013; Zhou et al., 2012). Our study focuses on mesoscale roughness heterogeneity ( $O(10\text{ km})$ ) without considering changes in large-scale forcings. However, a roughness anomaly at larger spatial scales may trigger changes in large-scale forcings and thus lead to different precipitation responses. For example, large-scale urbanization ( $O(1,000\text{ km})$ ) may influence the summer monsoon system in China (Chen et al., 2016). Conversion of land cover from forest to croplands over the Indian subcontinent and Southeastern China weakens the Asian summer monsoon circulation (Takata et al., 2009). In addition, the precipitation response to continental-scale tropical deforestation depends on the spatial scale (Lawrence & Vandecar, 2015). Nevertheless, this work identifies a basic new mechanism by which wind farms, cities, and forests may trigger storms, by inducing thermally-direct mesoscale circulations solely caused by roughness anomalies.

## Data Availability Statement

The dataset used for this study is available for public access on the Harvard dataverse (<https://doi.org/10.7910/DVN/R1J7FQ>).

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