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## Bulk Radiative-Convective Equilibrium Is Common Over Mid-Latitude Land

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### Key Points:

- Radiative-convective equilibrium (RCE) is a useful simplification of the atmosphere, usually employed in the tropics
- We show that “bulk RCE” is also a good approximation of annually-averaged mid-latitude land surfaces
- This result is explained by a simple energy balance argument

### Supporting Information:

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

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**Abstract** Radiative-convective equilibrium (RCE) is commonly used as an approximation of the time- and space-averaged tropical atmosphere. We examine two reanalyses to assess the extent to which column-integrated radiative cooling balances convective heating (“bulk RCE”) in the tropics and at higher latitudes. Our analysis shows that bulk RCE is a reasonable approximation of the tropics over ocean, but not land. Surprisingly, bulk RCE is often a reasonable approximation in mid-latitudes, especially over land. These findings are explained by a simple argument. Over land, the ground heat flux is small, and bulk RCE arises when the top-of-atmosphere net radiative flux is small, which occurs in mid-latitudes. Over ocean, the same mechanism applies but the ocean heat flux can be substantial and causes deviations relative to land. We conclude that bulk RCE is a surprisingly useful approximation of mid-latitude land climate, which permits the development of simple theory for land climate, more broadly.

**Plain Language Summary** Radiative-convective equilibrium (RCE) is a simple model used to understand the atmosphere. In RCE, the sun heats the surface which in turn heats the atmosphere through convection. This heating is balanced by radiation that is emitted by the atmosphere to space. Understanding where, and why, RCE is a good approximation of the Earth gives us a better understanding of the applications of simple RCE models. Typically, RCE is thought to apply in the tropics where there is abundant convective heating. We show that vertically-averaged radiative cooling approximately balances convective heating over mid-latitudes, particularly over land. We explain this result using a simple energy balance argument. This simplified picture of the atmosphere helps us understand mid-latitude climate over land, where much of the Earth's population is located.

## 1. Introduction

Radiative convective equilibrium (RCE) is an idealized state of the atmosphere in which radiative cooling is balanced by convective heating (Manabe & Strickler, 1964; Manabe & Wetherald, 1967). This simple idealization is foundational to our understanding of climate (Jeevanjee et al., 2022; Shaw & Stevens, 2025). It has been used to understand the hydrological cycle (Cronin et al., 2015; Dagan & Stier, 2020; Hohenegger & Stevens, 2018; McColl & Tang, 2024; Muller et al., 2011; O’Gorman & Muller, 2010; Romps, 2021; Silvers et al., 2024; Takahashi, 2009) and convective self-aggregation (Muller & Bony, 2015; Posselt et al., 2008; Prigent et al., 2011; Romps, 2021; Wing et al., 2017, 2020) among other applications (Beucler & Cronin, 2016; Kuang et al., 2005; Popke et al., 2013; Robe & Emanuel, 2001).

RCE only strictly holds in the time-averaged global mean. To what extent is it a reasonable approximation of climate at smaller spatial and temporal scales? Understanding where, and why, RCE is a reasonable approximation is important because its simplicity permits clear insight that is essential to basic understanding of climate (Emanuel, 2020; Jeevanjee et al., 2022). At high latitudes, RCE is a poor approximation, even after averaging in time and space. The dominant balance is between radiative cooling and advective—rather than convective—heating (Cronin & Jansen, 2016; Miyawaki et al., 2022). At low latitudes, RCE is often considered a reasonable approximation, although Jakob et al. (2019) (J19) provide a counterpoint to this common view, which we discuss in more detail below. In mid-latitudes, the atmosphere is dominated by quasi-geostrophic flows and large scale circulations which may seem to be at odds with RCE (Emanuel, 2008; Geerts, 2008). For this reason, it is uncommon to invoke RCE in understanding mid-latitude climate (Emanuel, 2008; Jakob et al., 2019).

A recent exception is Miyawaki et al. (2022) (M22) who argued that, in the zonal mean, RCE is a valid approximation in mid-latitudes, both in summer and in the annual mean. They based their definition of RCE on

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the column-integrated atmospheric energy budget, which does not require radiative cooling and convective heating balance at all heights, as RCE is classically understood. In this study, we will distinguish between classical RCE and “bulk RCE” (see Section 2.1 for more on this). In addition, while M22 provide important insights, their analysis raises several questions. First, M22 use an unusual definition of RCE, which includes cases in which cooling is primarily, or even solely, achieved by moist static energy (MSE) flux divergence, rather than radiative cooling. This seems inconsistent with any reasonable definition of RCE, in which radiative cooling must be the dominant cooling mechanism. Is their finding—that RCE is a valid approximation in mid-latitudes—simply an artifact of this unusual definition? Second, M22 focus on the zonal mean. To what extent does RCE hold at smaller spatial scales? Third, M22 combine land and ocean in their zonal mean. To what extent does RCE hold just over land, or just over ocean? This question is important because M22 argue that the presence of land is essential to creating bulk RCE in mid-latitudes, but we will show that bulk RCE is also common over mid-latitude oceans. This implies that a different mechanism is required to explain the existence of bulk RCE in mid-latitudes, which we provide.

This manuscript is structured as follows. We construct a definition of bulk RCE based on the MSE budget and apply it in the annual and monthly mean at small spatial scales (0.25°). We use reanalysis data to determine where bulk RCE applies under this definition. We then investigate the seasonal pattern of bulk RCE over land and ocean. We find that bulk RCE is a reasonable approximation over the ocean in the tropics and, surprisingly, over land in mid-latitudes. Lastly, we use a simple conceptual argument to explain these findings.

## 2. Defining RCE

To test where RCE is a reasonable approximation, a quantitative definition is necessary. In traditional RCE, radiative cooling and convective heating are in exact balance at all heights in the atmosphere, such that:

$$\partial_p(g(\overline{F_R} + \overline{F_S} + \overline{F_L}) - \overline{\omega m}) = \partial_t \overline{m} + \nabla \cdot (\overline{\mathbf{v}m}) = 0, \quad (1)$$

where  $\mathbf{v}$  is horizontal velocity in  $\text{m s}^{-1}$ ,  $\partial_p(\omega m)$  and  $\nabla \cdot (\overline{\mathbf{v}m})$  are vertical and horizontal flux divergences of MSE in  $\text{W kg}^{-1}$ ,  $g$  is gravitational acceleration in  $\text{m s}^{-2}$ ,  $p$  is pressure in Pa,  $t$  is time in s, and  $F_R$ ,  $F_S$  and  $F_L$  are upward vertical radiative, sensible and latent heat fluxes, respectively, in  $\text{W m}^{-2}$ , and  $\overline{\bullet}$  denotes a horizontal average. The first equality in Equation 1 is the MSE budget, where MSE is  $m = s + \lambda q$ ,  $s = c_p T + gz$  is the dry static energy (DSE),  $c_p$  is the specific heat capacity of air at constant pressure,  $gz$  is the gravitational potential,  $\lambda$  is the latent heat of vapourization and  $q$  is specific humidity. MSE and DSE have units of  $\text{J kg}^{-1}$ .

This definition is implicitly enforced in steady-state RCE simulations with periodic boundary conditions, which impose zero horizontal flux divergence at each horizontally-averaged level, by design. A few assumptions are made in the derivation of the MSE budget. First, kinetic energy and kinetic energy loss to surface drag is ignored—this is a good approximation in long time averages (Adames Corraliza & Mayta, 2023; Neelin & Held, 1987). Second, the latent heat of freezing and ice budgets are ignored which may lead to small errors at high latitudes and elevations (Adames Corraliza & Mayta, 2023). Third, MSE is only conserved for displacements that are in hydrostatic balance, which is not strictly satisfied in the atmosphere. We shall also neglect the effect of water species on the specific heat of air when computing DSE and MSE.

### 2.1. Averaging in Space and Time

While Equation 1 almost never holds exactly at small temporal and spatial scales on Earth, it becomes a useful model of some regions after sufficient temporal and spatial averaging (Emanuel, 2008). Several recent studies have assessed this more precisely using reanalyses and observations. They base their analyses on a necessary but not sufficient condition for RCE to arise: column-integrated radiative cooling largely balances column-integrated convective (sensible and latent) heating (Jakob et al. [2019]; Miyawaki et al. [2022]). Vertically mass-weighted averaging each term in Equation 1 over the atmospheric column results in

$$\underbrace{Q_n}_{\text{Radiative cooling}} + \underbrace{H + \lambda E}_{\text{Convective heating}} = \underbrace{\langle \partial_t \overline{m} \rangle + \langle \nabla \cdot (\overline{\mathbf{v}m}) \rangle}_{\text{Storage and flux divergence, } R} = 0, \quad (2)$$



where  $p_s$  is surface pressure in Pa,  $\langle \bullet \rangle \equiv \frac{1}{g} \int_0^{p_s} \bullet dp$  denotes the mass-weighted column average,  $H \equiv F_s(p_s)$  and  $\lambda E \equiv F_L(p_s)$  are the surface sensible and latent heat fluxes in  $\text{W m}^{-2}$ , respectively, and  $Q_n \equiv F_R(p_s) - F_R(0)$  is the net radiative flux, equivalent to the difference between surface ( $Q_s \equiv F_R(p_s)$ ) and top-of-atmosphere ( $Q_t \equiv F_R(0)$ ) net radiation in  $\text{W m}^{-2}$ , with a negative value implying atmospheric radiative cooling. We define  $R \equiv \langle \partial_t \bar{m} \rangle + \langle \bar{\nabla} \cdot (\bar{\mathbf{v}} \bar{m}) \rangle$  as the sum of storage and horizontal flux divergence terms, although the storage term is negligible in the annual mean. Note that the vertical flux divergence term,  $\partial_p(\bar{\omega} \bar{m})$ , is not present because its column integral is zero, given boundary conditions  $\omega(p_s) = \omega(0) = 0$  (Neelin & Held, 1987).

Equation 2 is necessary for RCE (as traditionally understood) but not sufficient because horizontal transport may be considerable at individual levels in the column, but sum to zero in the column average. RCE traditionally refers to the scenario where the dominant balance is between radiation and convection at all heights (Equation 1). J19 used the column-integrated DSE budget to define RCE. In theory, it is possible to have significant height-dependent advective DSE tendencies that integrate to zero. However, in observations, the vertical velocity profile tends to have a first baroclinic structure with the same sign in the troposphere, and a small column-integrated DSE export typically implies that traditional RCE approximately holds. M22 defined RCE in terms of the column-integrated MSE budget (Equation 2). Unlike DSE, the vertical gradient of MSE changes sign from the lower troposphere to the upper troposphere such that significant height-dependent advective effects can be present with a small column-integrated MSE export. While M22 referred to this column-MSE-budget-based definition as RCE, we will use the term “bulk RCE” to differentiate it from the traditional view of RCE discussed above. Bulk RCE does not constrain and simplify the system as much as the traditional notion of RCE.

On the other hand, understanding where, and to what extent, bulk RCE holds is useful for a variety of reasons. For example, to the extent it holds, combining it with the surface energy balance implies that the difference between surface net radiation and the land/ocean heat flux is equal to the column-integrated radiative cooling, a major simplification of the system. Over ocean, this constrains ocean heat uptake. Over land, where the heat flux into the land surface is small, it determines surface net radiation (Section 3), which is proportional to potential evapotranspiration (PET) (Gallagher & McColl, 2025; Milly & Dunne, 2016; Tang & McColl, 2025). Changes in both of these quantities are important in the context of climate change. For these reasons, this study focuses exclusively on bulk RCE.

We will focus on annual and monthly means. Unlike the ocean, there are pronounced seasonal and diurnal cycles in terms in Equation 2 over land, implying that land adjusts to forcing over much shorter time scales than the ocean. Since the land adjustment time scale is clearly shorter than monthly or annual time scales, is it reasonable to focus on monthly and annual averages? Yes, to the extent that quantities of interest are approximately linearly related to terms in Equation 2. This is approximately true for PET, which scales quasi-linearly with surface net radiation (Gallagher & McColl, 2025; Milly & Dunne, 2016; Tang & McColl, 2025) and, in RCE,  $Q_n$ . More broadly, to a first approximation, many qualitative features of the near-surface atmosphere survive averaging over long time scales (Betts, 2000; McColl et al., 2019; McColl & Rigden, 2020).

## 2.2. Choosing a Threshold

Equation 2 is the strictest definition of bulk RCE, but there are at least two reasons to make the definition more flexible. First, as noted in J19, there are errors in reanalyses and observations, meaning observed terms in Equation 2 are unlikely to balance exactly, even for a region in bulk RCE. Second, the terms in Equation 2 needn't balance exactly for bulk RCE to be a useful approximation, and it may be acceptable to retain a small imbalance ( $|R| > 0$ ). In this work, we prescribe a non-zero relative threshold  $\epsilon$  and define a region as in bulk RCE when

$$|R| \leq \epsilon F, \quad (3)$$

where  $F = \max(|Q_n|, |H|, |\lambda E|)$ . We could instead have used an absolute threshold ( $|R| \leq \epsilon$ ), but using a relative threshold has two advantages. First, it takes into account the fact that observational errors are often proportional to the magnitude of fluxes. Second, it considers the relative contribution of flux divergences to the energy budget. For instance,  $20 \text{ W m}^{-2}$  may be a negligible component of the energy budget in the tropics but significant in high latitudes, regardless of observational errors.

We set  $\varepsilon = 0.2$  in Equation 3 and test the sensitivity of this choice later in the study. This choice is based on the considerable uncertainty of all current products that measure energy balances, including satellite data, reanalyses, and climate models (Pokhrel et al., 2020; Tang et al., 2021; Yu, 2019). Flux uncertainty is on the order of tens of  $\text{W m}^{-2}$  for each individual flux, even for the ERA5 reanalysis which considerably outperforms other products (Pokhrel et al., 2020; Tang et al., 2021). Because the divergences are the residual of these individual fluxes, the error accumulates, with one study (Pokhrel et al., 2020) finding the root-mean-squared error of the flux divergence of MSE over three locations in the Indian Ocean to be about  $50 \text{ W m}^{-2}$ . This high uncertainty, which is higher in the tropics due to fewer in situ observations and greater fluxes (Pokhrel et al., 2020), is approximately equivalent to choosing  $\varepsilon = 0.3$  in the tropics. For this reason, we consider  $\varepsilon = 0.2$  to be a reasonable choice in discriminating between regions that are in bulk RCE, and those that are not. Choosing a smaller value for  $\varepsilon$  risks misclassifying significant areas where bulk RCE approximately holds as not in bulk RCE, simply due to errors in observations or reanalyses.

In the Supporting Information S1, we consider alternative definitions used in prior studies and provide justifications for not using them (SI: Alternative definitions in prior studies). While we consider Equation 3 to be the most reasonable definition of bulk RCE, we also examine results using definitions similar to those in M22 and J19 (SI: Sensitivity to using definitions from prior studies). Those results show that bulk RCE is common over mid-latitude land (this study's main finding), regardless of the definition used.

### 3. Theory

Where should we expect bulk RCE to hold? Basic physical arguments provide intuition, which we will use in interpreting more detailed analyses in the following sections.

In steady state, bulk RCE arises when  $\langle \nabla \cdot (\mathbf{v}m) \rangle$  is “small.” What determines  $\langle \nabla \cdot (\mathbf{v}m) \rangle$ ? The temporally- and spatially-averaged energy balance of a column of air is

$$\underbrace{Q_t - Q_s}_{\equiv Q_n} + H + \lambda E = \langle \nabla \cdot (\mathbf{v}m) \rangle, \quad (4)$$

where  $Q_t$  and  $Q_s$  are the top-of-atmosphere (TOA) and surface net radiation fluxes, respectively. The temporally-averaged surface energy balance for a land or ocean surface is

$$Q_s - H - \lambda E = G, \quad (5)$$

where  $G$  is the net land/ocean heat flux. Adding these two equations yields

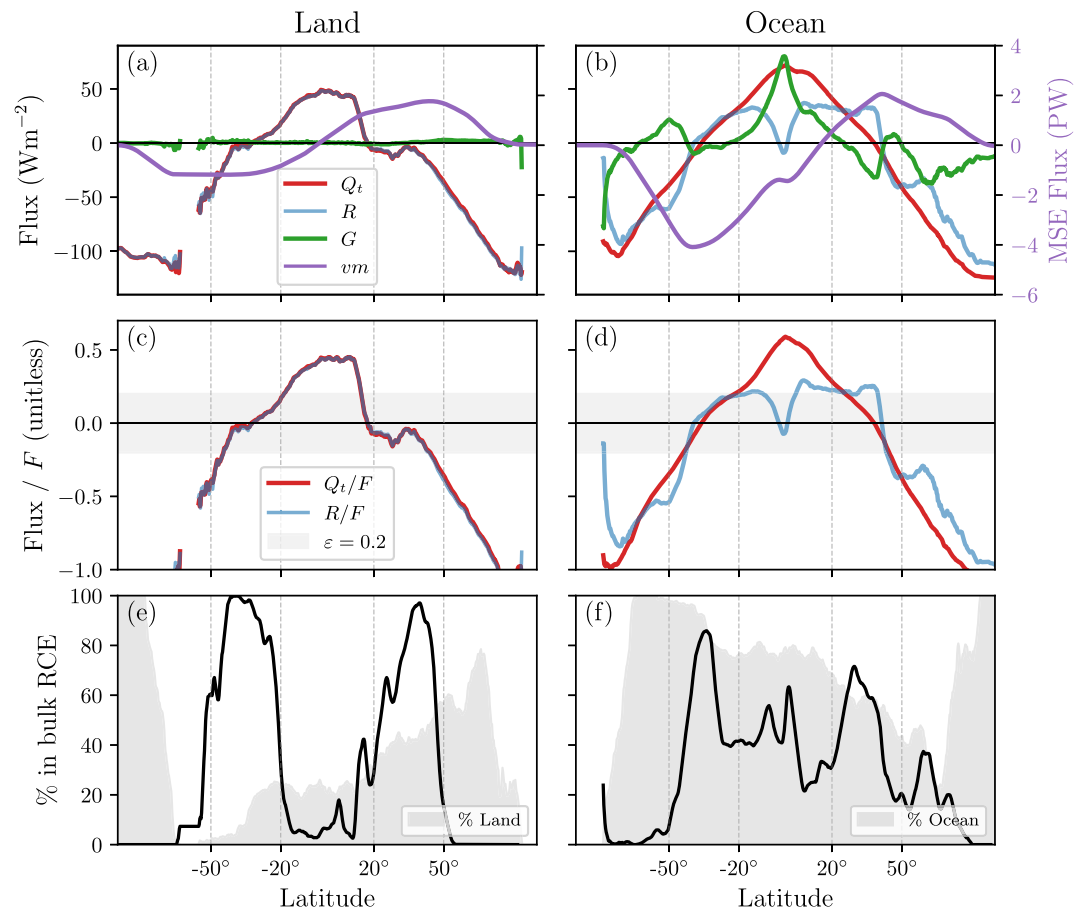
$$Q_t - G = \langle \nabla \cdot (\mathbf{v}m) \rangle. \quad (6)$$

Therefore,  $\langle \nabla \cdot (\mathbf{v}m) \rangle$  is set by the difference between two variables: the TOA net radiation,  $Q_t$ , and the land/ocean heat flux,  $G$ . Bulk RCE arises when the difference between these terms is small.

Alternatively, in bulk RCE, the two equations can be combined to yield  $Q_s - G = -Q_n$ . Over ocean, this implies that atmospheric radiative cooling constrains the ocean heat uptake ( $G$ ). Over land, where  $G$  is small, it implies the surface net radiation is essentially equivalent to the atmospheric radiative cooling in bulk RCE.

### 4. Methods

To determine where bulk RCE is a reasonable approximation, we analyze vertically- and temporally-averaged budgets (for the period 1980–2005, consistent with M22) of MSE, DSE and specific humidity ( $q$ ) in two reanalyses (ERA5 and MERRA-2). Further details on the reanalyses, and justifications for their use over more direct observations, are provided in SI: Reanalyses (Gelaro et al., 2017; Global Modeling and Assimilation Office, 2015a, 2015b; Hersbach et al., 2020, 2023; Raymond et al., 2009). Only results based on ERA5 are presented in the main text.



**Figure 1.** Panels (a) and (b) show a simplified schematic of the relation between the top of atmosphere radiation ( $Q_t$ ), the sum of the change in storage and the flux divergence of moist static energy ( $R$ ), and ground heat flux ( $G$ ) in the tropics, mid-latitudes, and at high-latitudes. Panels (c) and (d) show the zonal average of  $Q_t$  and  $R$  normalized by the maximum flux,  $F$ . The gray band shows  $\epsilon = 0.2$ , so when the divergence of MSE is within that band the zonal mean is in bulk RCE. Panels (e) and (f) show the percentage of  $0.25^\circ \times 0.25^\circ$  grid cells at each latitude in bulk RCE (without zonally averaging). The gray background is the percentage of each latitude that is land versus ocean. The left-hand plots (a, c, and e) are over land, while the right-hand plots (b, d, and f) are over ocean.

## 5. Results and Discussion

### 5.1. Annual Mean

In the annual mean, bulk RCE is most common in mid-latitudes, for both land (Figures 1c and 1e) and ocean (Figures 1d and 1f). This is true both in the zonal mean (Figures 1c and 1d) and at the  $0.25^\circ$  spatial scale provided by the ERA5 reanalysis (Figures 1e and 1f). Figures 1c and 1d show that  $R/F$  peaks in the tropics, reaches zero near the mid-latitudes, and decays sharply at high latitudes. The normalized top of atmosphere radiation balance,  $Q_t/F$ , follows  $R/F$  exactly over land (Figure 1c) but not over ocean (Figure 1d). Why? Over land surfaces,  $G$  is close to zero in the annual mean because of land's low heat capacity and low horizontal energy transfer through the ground (Figure 1a). That implies that, over land, Equation 6 is well approximated by

$$Q_t \approx \overline{\nabla \cdot (\mathbf{vm})}, \quad (7)$$

where the storage term is neglected because it is small after annual averaging. In other words, bulk RCE arises over land when TOA net radiation is small. Since there is a positive TOA net radiation balance in the tropics ( $Q_t > 0$ ; Figure 1a), and negative balance at high latitudes ( $Q_t < 0$ ; Figure 1a), it follows that  $Q_t \approx 0$  in mid-latitudes—exactly where RCE is most common over land (Figures 1c and 1e). It is also most common in mid-latitudes over ocean, although to a lesser degree than over land (Figures 1d and 1f). This is because  $G$  need

not be zero over the ocean, meaning  $\langle \nabla \cdot (\mathbf{v}m) \rangle$  can be large (and the system can be far from bulk RCE) even when  $Q_t \approx 0$ .

In the tropics, the ocean is often in bulk RCE (Figures 1d and 1f), but not land (Figures 1c and 1e). Little land in the tropics is in bulk RCE because  $Q_t > 0$  and  $G \approx 0$ . But, unlike land, there is a strong net transfer of heat into the ocean, particularly at the equator. Upwelling at the equator due to Ekman pumping brings cool water which readily accepts energy. This means that, over tropical oceans,  $Q_t > 0$  and  $G > 0$  (Figure 1b) such that  $Q_t - G$  is small and the system is in bulk RCE, according to Equation 6.

Neither land nor ocean are in bulk RCE at high latitudes (Figures 1c–1f). In fact, high latitudes are closer to radiative-advective equilibrium than to RCE (Cronin & Jansen, 2016; Miyawaki et al., 2022). However, some exceptions arise in parts of the ocean, in which the ocean circulation transports warm water that provides a heat source for convective surface fluxes, and causes  $G < 0$  (Figure 1b).

Overall, bulk RCE is common over mid-latitude land at annual time scales, even at a  $0.25^\circ$  spatial scale (Figure 2). Approximately 43% of mid-latitude land ( $30^\circ$ – $60^\circ$  N/S) is in bulk RCE. The precise fraction varies depending on the definition of “mid-latitudes” used: using a range of alternative definitions from prior studies, the fraction ranges between 43% and 62% (Figure 2a). It also depends on the choice of  $\epsilon$ , with the fraction varying between 27% and 39% for  $\epsilon = 0.1$ , and 57% and 79% for  $\epsilon = 0.3$  (Figure 2a). While somewhat sensitive to definitional choices, it is clear that bulk RCE is common over mid-latitude land. Bulk RCE is rarer over mid-latitude oceans (38% over  $30^\circ$ – $60^\circ$  N/S, varying between 38% and 48% depending on the definition of “mid-latitudes”; Figure 2c), but still sufficiently common to result in bulk RCE being common over combined land and ocean surfaces (40% over  $30^\circ$ – $60^\circ$  N/S, varying between 40% and 52%; Figure 2e). The fraction of land in bulk RCE in mid-latitudes exceeds that in the tropics, regardless of definitional choices (Figures 2a and 2b). The fraction of ocean, and the combination of land and ocean, in bulk RCE in midlatitudes generally exceeds that in the tropics for  $\epsilon \leq 0.2$ , and remains similar for  $\epsilon > 0.2$  (Figures 2c–2f).

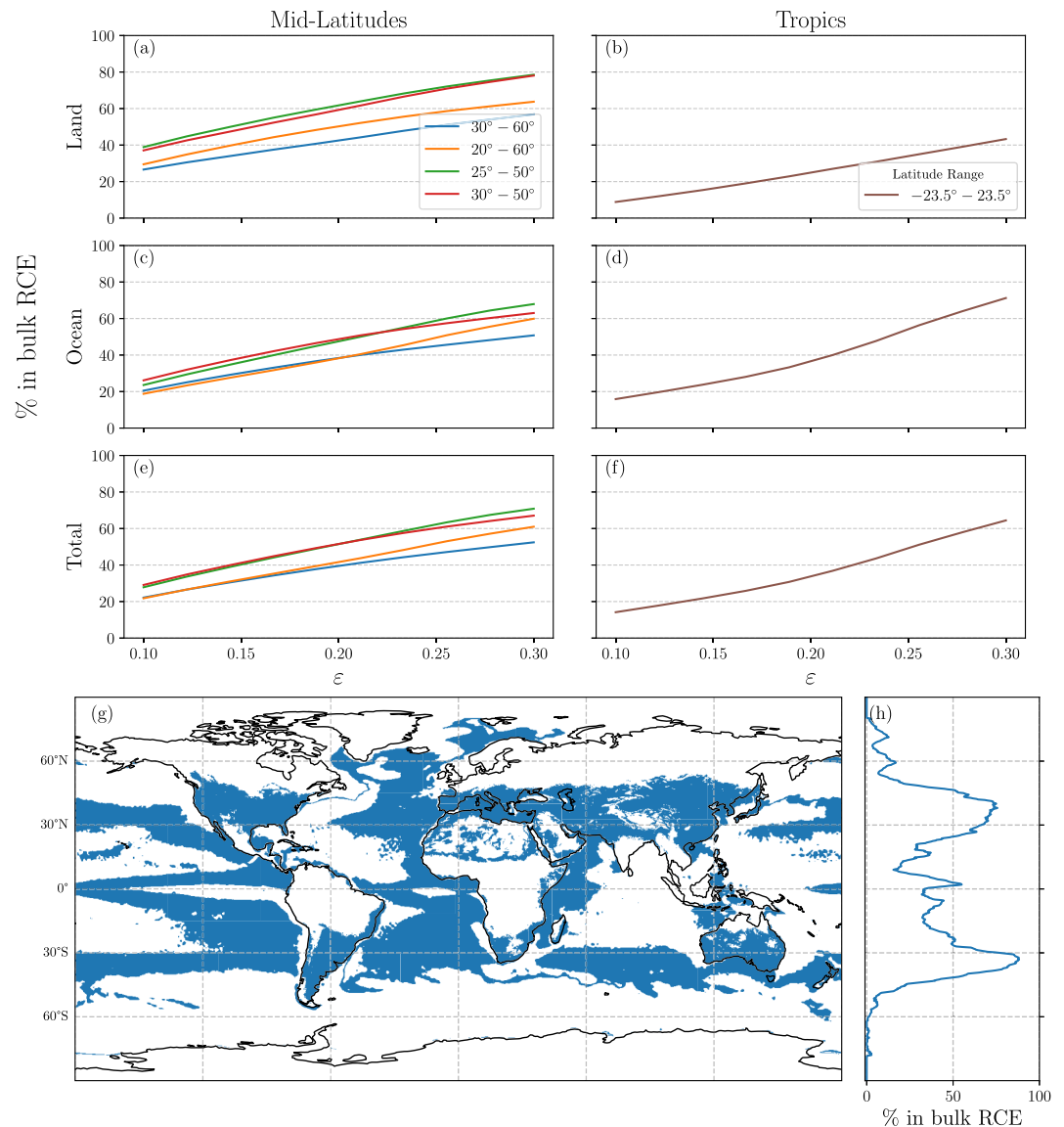
## 5.2. Seasonal Cycle

There is a strong seasonal cycle in  $R/F$  over land, but not over ocean (Figure 3). From Equation 6, this is largely driven by  $Q_t$  over land since  $G \approx 0$ .  $Q_t$  itself is the difference between net incoming shortwave radiation and outgoing longwave radiation (OLR). In the summer as peak insolation shifts north, OLR changes significantly less, leading to maximum  $Q_t$  approximately following maximum solar insolation (Stephens et al. (1981); Figure S5 in Supporting Information S1). The region in bulk RCE migrates up to  $65^\circ$ N over land at the peak of summer, and returns to  $20^\circ$ N in the winter (Figure 3a). However, the latitude band in which bulk RCE holds is relatively narrow. This means that, in any given month or season, including summer, most mid-latitude land is not in bulk RCE (Figure 3a), even though most mid-latitude land is in bulk RCE after averaging over a full seasonal cycle (i. e., in the annual mean). This implies that bulk RCE is most relevant to understanding the annual mean climatology of mid-latitude land, rather than shorter time scales.

In contrast, over ocean, the seasonal cycle in  $Q_t$  is not visible in the seasonality of  $R/F$  (Figure 3b). Since there is a strong seasonal cycle in  $Q_t$  over both ocean and land (Figure S5 in Supporting Information S1), it must be counteracted by an equally large seasonal cycle in  $G$  to maintain bulk RCE. That is, the ocean must be a net sink of heat in each hemisphere's summer and source in their winter. This is possible because of the large heat capacity and currents of the ocean. An interesting exception to this arises around  $50^\circ$ N, with the region in bulk RCE during the winter but not in the summer (Figure 3b). This implies that the ocean provides a surplus of heat in the winter ( $G > 0$ ), but not in the summer. The source of this heat is the western boundary currents, which are known to supply significant heat in winter (Trenberth & Solomon, 1994).

## 5.3. Limitations

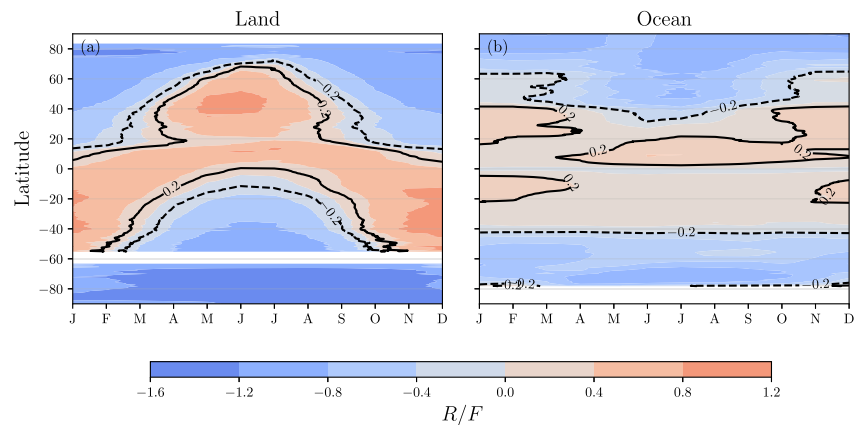
Our study is subject to several limitations, beyond those already discussed. Some humility is warranted in analyzing atmospheric energy budgets globally in reanalyses, since most budgets do not close in reanalyses (e. g., Trenberth et al. [2011]). Further, uncertainty of all fluxes is much higher in regions with scant observations (tropical ocean) compared to well observed regions (mid-latitude land). This calls into question the use of a single threshold to represent uncertainty over the whole earth (Adames Corraliza & Mayta, 2023; Lavers et al., 2022; Tang et al., 2021). However, our approach maintains consistency with previous studies which use a constant



**Figure 2.** (a–f) Sensitivity of the percentage of mid-latitudes and tropics in bulk radiative-convective equilibrium (RCE) to various definitions of mid-latitudes and to  $\epsilon$ . The various definitions of “mid-latitudes” shown above are representative of definitions used in prior literature, and include 25°–50° (Dommenget & Latif, 2002; Grose et al., 2019), 30°–50° (De Vrese et al., 2021; Francis & Vavrus, 2012; Routson et al., 2019), 20°–60° (Hénin et al., 2019), 30°–60° (Blackport & Screen, 2020; Swann et al., 2012; Zheng et al., 2025). (g) Regions in bulk RCE with  $\epsilon = 0.2$ . (h) Latitudinal profile of the percentage of land and ocean in bulk RCE with  $\epsilon = 0.2$ .

percentage of a relevant flux to measure water and energy budget closures (Dagan & Stier, 2020; Miyawaki et al., 2022). Furthermore, the main results, particularly over land, are qualitatively insensitive to choice of  $\epsilon$  for  $0.1 \leq \epsilon \leq 0.3$  (Figure 2, Figure S3 in Supporting Information S1). The methods were also repeated with another reanalysis (MERRA-2 instead of ERA5) and found to be very similar, but with more of the tropical ocean under RCE when using MERRA-2 (Figure S1 in Supporting Information S1). Lastly, even when repeated with the strictest definition of bulk RCE, requiring closure of DSE, MSE, and moisture budgets, bulk RCE still applied over a large fraction of mid-latitude land (Figure S2 in Supporting Information S1; SI: Sensitivity to using definitions from prior studies). This suggests that the result that bulk RCE holds over mid-latitude land is robust to reasonable modifications to definitions.





**Figure 3.** Zonally averaged  $R/F$  for each month. Plot (a) shows just land and plot (b) shows just ocean. Black solid and dashed contours show  $\epsilon = \pm 0.2$ , so the regions between the contours are zonally in bulk radiative-convective equilibrium that month.

#### 5.4. Summary and Implications

We have examined the prevalence of bulk RCE over land and ocean. Our main findings are as follows:

- Section 5.1: In the annual mean, bulk RCE is most common in mid-latitudes, for both land and ocean. This is true both in the zonal mean, and at smaller scales ( $0.25^\circ$ ). It is more common over mid-latitude land than mid-latitude ocean, although this result is a little sensitive to the precise definition of “mid-latitude” and “bulk RCE.” In the tropics, the ocean is often in bulk RCE, but not land. Neither land nor ocean are in bulk RCE at high latitudes, as expected.
- Section 5.2: At shorter time scales, bulk RCE is much less common over land. In particular, it is a poor approximation of most mid-latitude land during summer. In contrast, over ocean, the seasonal cycle is weaker and, to the extent bulk RCE holds in the annual mean, it also tends to hold at shorter time scales.
- These results are explained by a simple argument (Section 3). Combining energy budgets for the surface and the atmospheric column implies that the MSE flux divergence is equal to the difference between TOA net radiation and the land/ocean heat flux. Since RCE arises when the MSE flux divergence is small, it must arise when TOA net radiation balances the land/ocean heat flux. The land heat flux is typically small, implying bulk RCE arises over land when TOA net radiation is small (Equation 7), which occurs in mid-latitudes. The same mechanism makes bulk RCE common over mid-latitude ocean, but less so than land, because the ocean heat flux can be substantial and causes deviations from this argument (Equation 6).

That bulk RCE is a good approximation of mid-latitude land is surprising given its typical employment in the tropics. Unlike the tropics, the mid-latitudes are typically thought of in terms of large scale flows with significant advection. We have provided a simple argument for why we should expect bulk RCE to apply over mid-latitude land surfaces that remains consistent with the existence of large advective fluxes (Equation 7). Our explanation can also be understood in terms of poleward atmospheric energy transport. Since the poleward atmospheric energy flux peaks in mid-latitudes, the divergence of that flux will be zero in mid-latitudes (Figures 1a and 1b), implying the dominant terms in the atmospheric energy budget in mid-latitudes must be radiative cooling and convective heating.

There remains an acute need for basic understanding of land climate, particularly in mid-latitudes, where most land lies (Byrne et al., 2024; McColl et al., 2022). We have shown that bulk RCE is common in mid-latitudes, meaning this major simplification of the atmospheric energy budget can be used to develop basic understanding of land climate in these regions. Recent examples of advances that invoke RCE or bulk RCE over land include a theory for near-surface relative humidity over land (McColl & Tang, 2024), a resolution to the “aridity paradox” (Tang & McColl, 2025), mechanisms by which dry soils modulate rainfall (Cheng et al., 2021; Hohenegger & Stevens, 2018), and basic understanding of land planets (Becker & Stevens, 2014; Rochetin et al., 2014). Despite the idealizations invoked in bulk RCE, our work suggests that insights gained from these studies should be

expected to translate, to a first approximation, to annually-averaged mid-latitude land on Earth, even at relatively small spatial scales.

It would also be useful to move beyond column-integrated quantities to understand the extent to which RCE holds in the traditional sense (at each height in the atmosphere, rather than just the column average). In addition, while bulk RCE is a good model of annually-averaged mid-latitude land surfaces, it is not a good model of summertime mid-latitude land surfaces, even though convective fluxes are typically largest in summer. Nor is it a good model of tropical land surfaces, either in the annual mean or for any particular month or season. Rather, in these cases, MSE flux divergence and radiative cooling similarly contribute to balance out convective heating, rather than radiative cooling alone. This regime has been termed “radiative-convective-dynamical equilibrium” (Warren et al., 2020) or “radiative-convective-advective equilibrium” (Miyawaki et al., 2022; Romps, 2021). While this regime has received some recent attention over ocean (Romps, 2021; Warren et al., 2020), it has received relatively little attention over land (with Zeng and Neelin [1999] a notable exception), and should be investigated further in future work.

### Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

### Data Availability Statement

All data used in this study are publicly-available. The monthly averaged ERA5 data set on single-levels is downloadable from the European Union's Copernicus Climate Data Store at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=overview>. The MERRA-2 datasets are available from NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC) at <https://doi.org/10.5067/OJRLVL8YV2Y4> and <https://doi.org/10.5067/OU3HJDS973O0> for surfaces fluxes and radiation data respectively. All data analysis and figure creation was performed using python. The code, including instructions to download the data, is publicly available and archived on Open Science Framework repository (Matthews, 2025).

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# Supporting Information for “Bulk radiative-convective equilibrium is common over mid-latitude land”

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## Contents of this file

1. Text: Reanalyses
2. Text: Alternative definitions in prior studies
3. Text: Sensitivity to using definitions from prior studies
4. Figures S1 through S5

**Introduction:** This document contains supplementary text and five supplementary figures (S1 through S5). Figure S1 compares the analysis performed with the ERA5 dataset in the main text to the same analysis performed with the MERRA-2 dataset (Hersbach et al., 2020; Gelaro et al., 2017). Figure S2 shows a map of where the loose, preferred, and strict definitions defined in SI: Sensitivity to using definitions from prior studies apply. Figure S3 shows the sensitivity of the results in Figure 1 plots (e) and (f) to changing  $\varepsilon$ .

Figure S4 shows global maps of the flux divergences of moist static energy, dry static energy, and water vapor times the latent heat of vaporization. Figure S5 shows the annual, June-July-August, and December-January-February averaged plots of top of atmosphere radiation balance ( $Q_t$ ).

**Reanalyses:** To determine where bulk RCE is a reasonable approximation, we analyze vertically- and temporally- averaged budgets of MSE, DSE and specific humidity ( $q$ ) in two reanalyses. Single-level monthly energy fluxes from the ERA5 reanalysis were used to calculate mean and seasonal  $Q_n$ ,  $H$ ,  $\lambda E$ , and  $P$  (Hersbach et al., 2023). Divergences of  $m$ ,  $s$ , and  $q$  were calculated as the residuals of these fluxes following M22, as available divergence data is less reliable (Miyawaki et al., 2022). The data is taken from the ERA5 monthly averaged single-level reanalysis from 1940-2025 at a  $0.25^\circ$  resolution (Hersbach et al., 2023). Years from 1980-2005 are selected following M22. The analysis was repeated with MERRA-2. The MERRA-2 data is from the monthly mean, time-averaged, single-level, assimilation, surface flux diagnostics dataset (Gelaro et al., 2017; Global Modeling and Assimilation Office (GMAO), 2015a) and radiation diagnostics dataset (Gelaro et al., 2017; Global Modeling and Assimilation Office (GMAO), 2015b).

Using reanalysis data over other observational datasets has several advantages. Reanalysis products assimilate data from satellites, aircraft, weather stations, and other sources into numerical models to produce high temporal and spatial resolution datasets. No spatially continuous global observations exist for surface sensible and latent heat flux. Other observational products of these and related quantities still rely on a high degree



of modeling and calibration and are not direct measurements themselves. State of the art reanalyses, such as the fifth generation of reanalysis from the European Centre for Medium-Range Weather Forecasts (ERA5), have been shown to be comparable to and even outperform other data products. For instance, ERA5 shows greater accuracy than the radiative dataset from Clouds and Earth’s Radiant Energy System (Tang et al., 2021) over land. Compared to other reanalyses, ERA5 has been shown to have the lowest error of relevant fluxes ( $Q_n$ ,  $H$ ,  $\lambda E$ ) over the Indian Ocean (Pokhrel et al., 2020). ERA5 also shows consistent improvements in all areas over previous generations of ERA (e.g. ERA-Interim) from advances in radiation schemes, handling of observations, ocean waves, and land hydrology among other domains (Hersbach et al., 2020). To ensure our results are not dependent on the choice of reanalysis, we repeated our analysis with the MERRA-2 reanalysis (Gelaro et al., 2017). While our analysis is necessarily subject to errors in the reanalyses, our main claim is supported by a simple argument that is independent of the reanalyses used here, as we will show.

**Alternative definitions in prior studies:** The two most similar prior studies (M22 and J19) use different definitions of RCE. Both studies consider the column-integrated energy budget and thus focus on bulk RCE. However, they make several different choices compared to our study. While reasonable in many respects, here we provide justifications for not using them, and examine the sensitivity of our main results to these choices.

M22 define a steady-state region as in RCE when

$$-R \leq \varepsilon_{\text{M22}} Q_n, \tag{S1}$$

where they choose  $\varepsilon_{\text{M22}} = 0.1$ . Note that M22 choose to multiply  $\varepsilon_{\text{M22}}$  by  $Q_n$ , whereas we multiply  $\varepsilon$  by  $F$  (equation 2). As noted in the introduction, this definition is unusual because it includes cases in which cooling is primarily achieved by MSE flux divergence, rather than radiative cooling. This definition is not enforcing a true radiative-convective equilibrium. M22 justify their choice on the basis that “temperature profiles in regions of divergence are set by convective adjustment (Warren et al., 2020)” (p. 1046). However, convective neutrality is neither necessary nor sufficient for bulk RCE to hold. It is not necessary because, for example, the cited study in M22, Warren et al. (2020), find that time- and space-averaged convective available potential energy (CAPE) is largest in simulations in bulk RCE (that is, without any MSE flux divergence), which is inconsistent with convective neutrality. It is not sufficient because, for example, convective neutrality is a reasonable approximation over tropical land surfaces but, as we have shown, bulk RCE is relatively uncommon over tropical land (Fig. 1e).

J19 define RCE in terms of the DSE budget of a vertically integrated column of air, instead of the MSE budget. Using this definition, RCE only strictly arises when:

$$Q_n + H + \lambda P = \underbrace{\langle \partial_t \bar{s} \rangle + \langle \bar{\nabla} \cdot (\mathbf{v} \bar{s}) \rangle}_{R_s} = 0, \quad (\text{S2})$$

where  $\lambda P$  is precipitation in  $\text{W m}^{-2}$ . To add flexibility to this definition, for the same reasons as outlined earlier, they define a region as in RCE when

$$|R_s| \leq \varepsilon_{\text{J19}}, \quad (\text{S3})$$

where they choose  $\varepsilon_{\text{J19}} = 50 \text{ W m}^{-2}$ . Combining the DSE budget (first equality in equation S2) with the atmospheric moisture budget ( $E - P = \langle \partial_t \bar{q} \rangle + \langle \bar{\nabla} \cdot (\mathbf{v} \bar{q}) \rangle$ ) yields the MSE budget (equation 1). To understand the relation between our definition and J19’s

definition, the three budgets can be combined to obtain, at steady state,

$$\langle \overline{\nabla \cdot (\mathbf{v}m)} \rangle = \langle \overline{\nabla \cdot (\mathbf{v}s)} \rangle + \lambda \langle \overline{\nabla \cdot (\mathbf{v}q)} \rangle. \quad (\text{S4})$$

This equation shows that J19's definition is qualitatively similar to our definition when the moisture flux divergence is small.

However, our definitions qualitatively differ for the case in which  $\langle \overline{\nabla \cdot (\mathbf{v}s)} \rangle$  and  $\lambda \langle \overline{\nabla \cdot (\mathbf{v}q)} \rangle$  both have large absolute magnitudes but are opposite in sign, and thus cancel out to yield small  $\langle \overline{\nabla \cdot (\mathbf{v}m)} \rangle$ . According to J19's definition, this case is not bulk RCE whereas, according to our definition, it is. As shown in Fig. S4, this case is common, so resolving this disagreement is important. Such cases can arise in the presence of larger-scale atmospheric circulations, which are inconsistent with classical RCE. However, for bulk RCE, the relevant quantity at steady state is the column-integrated flux *divergence*, which can be small even when fluxes are large at specific heights. Put simply, if the flux of energy flowing into the column is the same as the flux flowing out, then there is no energy flux divergence, and the column is in bulk RCE, even if the fluxes are large. This remains true when the flux of energy flowing in is primarily latent heat (that is, in the form of moisture), and the flux of energy flowing out is primarily sensible. This occurs, for example, when a circulation transports moist air into the column at low levels – which rises and condenses, warming the upper troposphere – and transports warmer, drier air out of the column in the upper troposphere. This is one case in which  $\langle \overline{\nabla \cdot (\mathbf{v}s)} \rangle$  and  $\lambda \langle \overline{\nabla \cdot (\mathbf{v}q)} \rangle$  are both large but opposite in sign. More broadly, this corresponds to the case of zero gross moist stability (Beucler & Cronin, 2016), where gross moist stability is the ratio of the moist static energy flux divergence to the convective mass flux per unit

area (Neelin and Held (1987); but see Raymond, Sessions, Sobel, and Fuchs (2009) for a broader review that includes alternative definitions). In our view, there is no good reason to exclude this common case from the definition of bulk RCE, which is why we adopt equation 2 in our definition.

**Sensitivity to using definitions from prior studies:** In this section, we examine the sensitivity of our results to using alternative definitions of bulk RCE used in prior studies (J19 and M22). We refer to equation 3 as the “preferred” definition and a modified version of M22’s definition (in which  $Q_n$  is replaced with  $F$  in equation S1) as the “loose” definition, since it includes cases that we do not believe represent a true radiative-convective equilibrium. For J19’s definition, we modify their definition slightly to use a relative threshold rather than an absolute threshold. The use of an absolute threshold was reasonable in J19 because they focused on the tropics, but we will be applying it at higher latitudes, where energy fluxes are smaller. Using an absolute threshold of  $50 \text{ W m}^{-2}$  would result in almost all regions at high latitudes being classified as in RCE, which does not make sense. We instead use a relative threshold, and apply it to all three quantities discussed above (MSE, DSE and water vapor) such that

$$|\langle \partial_t \bar{x} \rangle + \langle \nabla \cdot (\mathbf{v}x) \rangle| \leq \varepsilon F, \quad \forall x \in \{m, s, q\}. \quad (\text{S5})$$

At steady state, in the case where any two of the flux divergences of  $m$ ,  $s$ , and  $q$  are zero, the third will also be zero by equation S4. We refer to this as the “strict” definition since, as we will show, even much of the tropics fails to meet this definition of RCE. We use the same value of  $\varepsilon = \varepsilon_{\text{M22}} = 0.2$  for all three definitions. This means that the definitions are

nested so that all areas that satisfy the strict definition satisfy the preferred definition, and all areas that satisfy the preferred definition satisfy the loose definition.

We investigated the sensitivity of our findings to the choice of definition used for bulk RCE. We repeated our analyses using the “strict” and “loose” definitions, which we briefly summarize here. Under the strict definition, 30.2% of mid-latitude land (30°-60°) is in bulk RCE, but a mere 4.0% of tropical ocean is in bulk RCE. Under the loose definition, 44% of mid-latitude land is in bulk RCE, with an even greater fraction of mid-latitude ocean in bulk RCE (51.3%), and very high fractions of tropical land and ocean (91.2% and 95.2%). For reasons presented earlier, we view the results using our preferred definition as most reasonable. However, it is worth noting that none of these definitions support an interpretation in which bulk RCE is both a reasonable model of the tropics (as assumed in a wealth of prior literature), but not of mid-latitude land.

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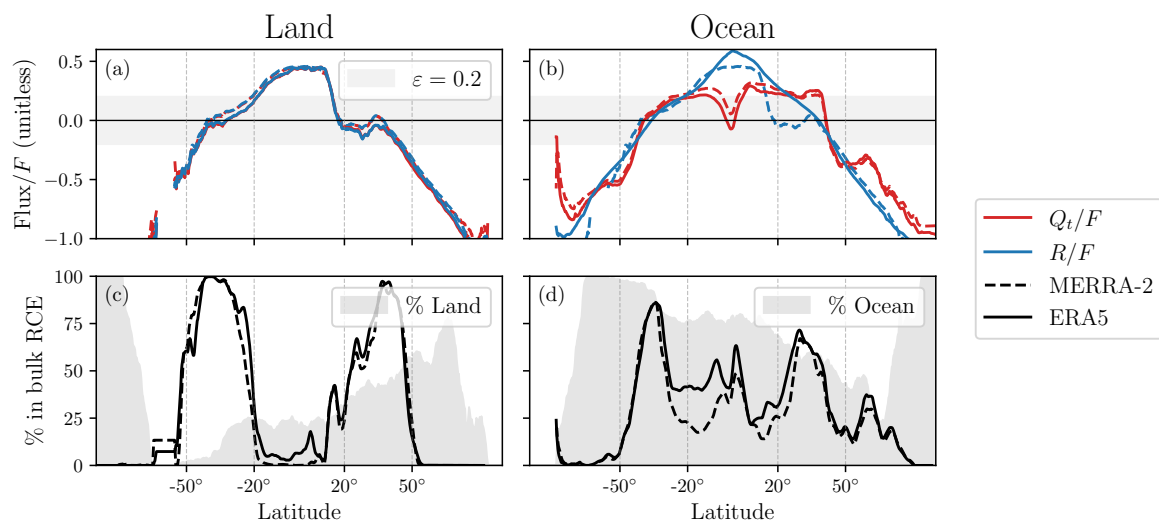
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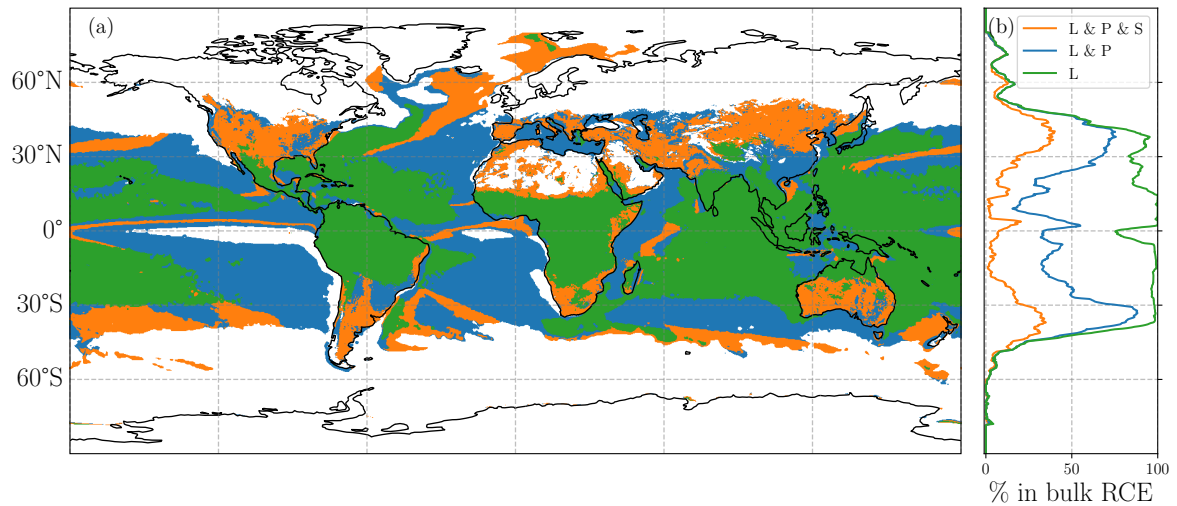
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**Figure S1.**



**Figure S1.** Same as Fig. 1 panels (c), (d), (e) and (f) but including the results from the MERRA-2 reanalysis. Dashed lines represent MERRA-2 results, solid lines show the ERA5 results.

**Figure S2.**

**Figure S2.** Plot (a) shows where the time averaged (1980-2005) energy and moisture budgets meet the three definitions of bulk RCE (loose, preferred, and strict) with  $\varepsilon = 0.2$ . Plot (b) shows the fraction of area by latitude in bulk RCE according to the definitions. L (green) represents the regions where just the loose definition applies. L & P (blue) represents the regions where just the loose and preferred definitions apply. L & P & S (orange) represents the regions where the loose, preferred, and strict definitions apply. See SI: Sensitivity to using definitions from prior studies.

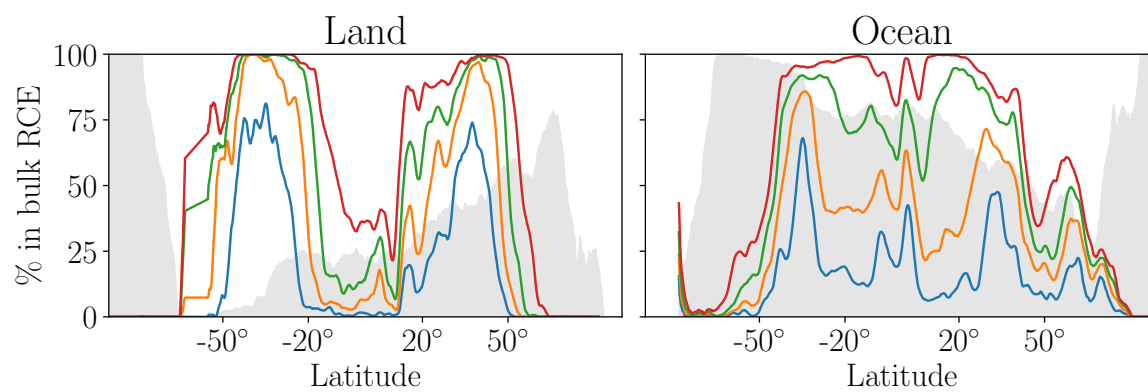
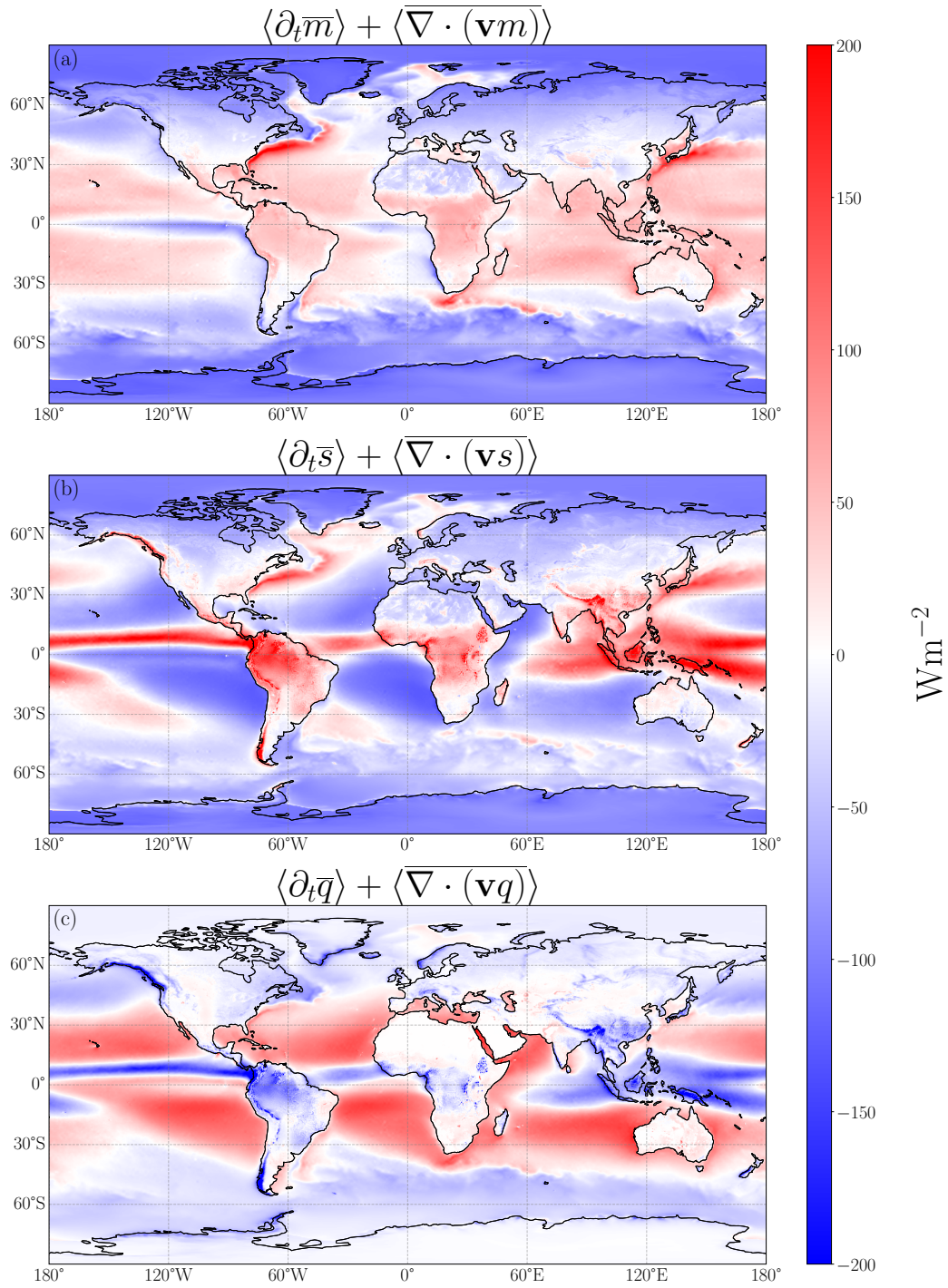
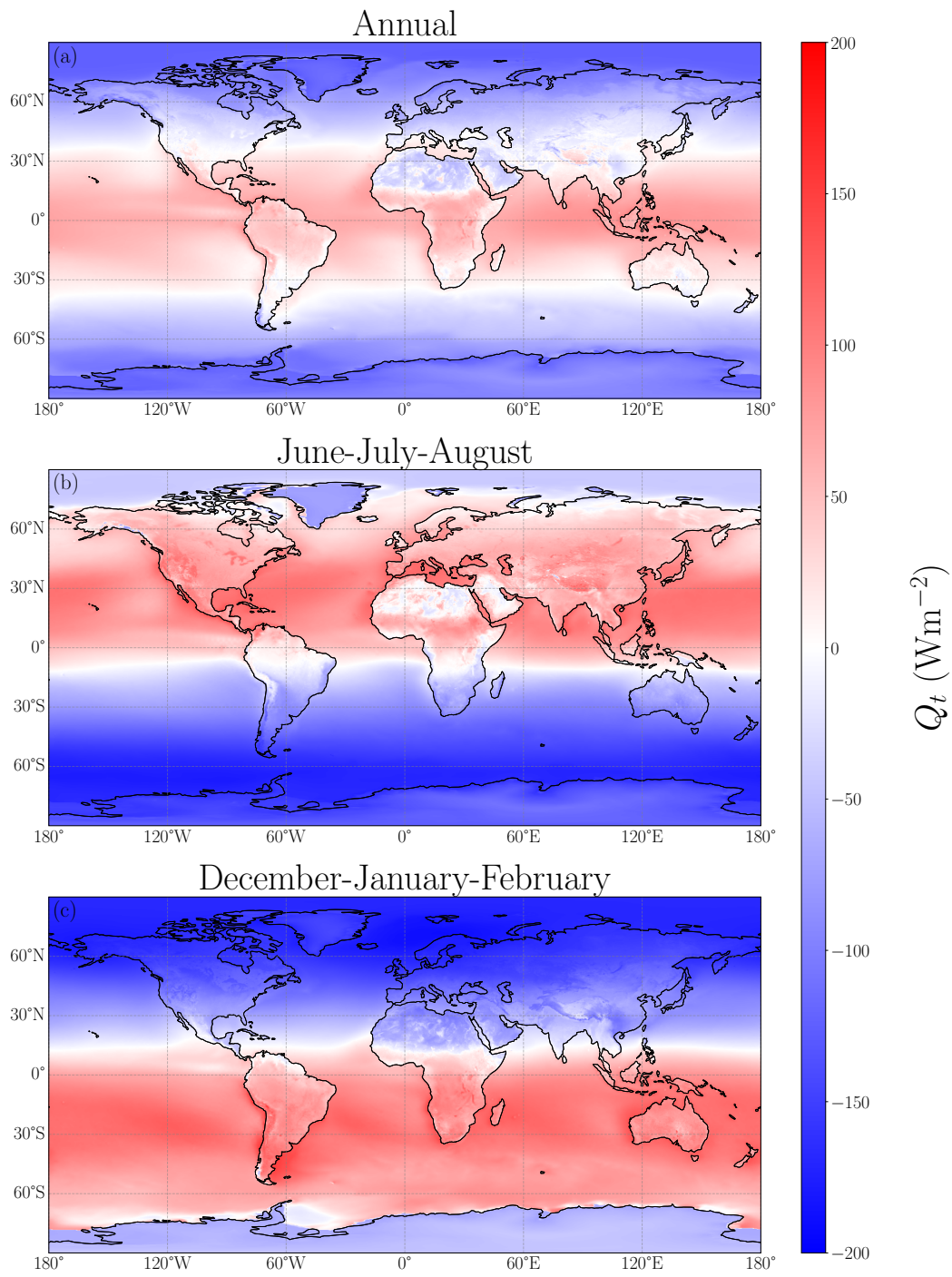
**Figure S3.****Figure S3.** Same as Figs. 1e, f except showing % bulk RCE for different values of  $\varepsilon$ .

Figure S4.



**Figure S4.** Vertically averaged sum of change in storage and flux divergences of (a) MSE, (b) DSE, and (c)  $\lambda q$  averaged from 1980-2005.

**Figure S5.**

**Figure S5.**  $Q_t$  averaged over 1980-2005. The plots show (a) Annual mean, (b) June-July-August mean, and (c) December-January-February mean.