Using the Moist Static Energy Budget to Understand Storm-Track Shifts across a Range of Time Scales

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ABSTRACT
Storm tracks shift meridionally in response to forcing across a range of time scales. Here the authors formulate a moist static energy (MSE) framework for storm-track position and use it to understand storm-track shifts in response to seasonal insolation, El Niño minus La Niña conditions, and direct (increased CO₂ over land) and indirect (increased sea surface temperature) effects of increased CO₂. Two methods (linearized Taylor series and imposed MSE flux divergence) are developed to quantify storm-track shifts and decompose them into contributions from net energy (MSE input to the atmosphere minus atmospheric storage) and MSE flux divergence by the mean meridional circulation and stationary eddies. Net energy is not a dominant contribution across the time scales considered. The stationary eddy contribution dominates the storm-track shift in response to seasonal insolation, El Niño minus La Niña conditions, and CO₂ direct effect in the Northern Hemisphere, whereas the mean meridional circulation contribution dominates the shift in response to CO₂ indirect effect during northern winter and in the Southern Hemisphere during May and October. Overall, the MSE framework shows the seasonal storm-track shift in the Northern Hemisphere is connected to the stationary eddy MSE flux evolution. Furthermore, the equatorward storm-track shift during northern winter in response to El Niño minus La Niña conditions involves a different regime than the poleward shift in response to increased CO₂ even though the tropical upper troposphere warms in both cases.

1. Introduction
Storm tracks dominate the extratropical circulation. They play a fundamental role in Earth’s energy budget through their poleward energy flux, which alleviates the energy imbalance between the equator and the pole (Trenberth and Stepaniak 2003a; Shaw et al. 2016). In energy budget decompositions, storm-track energy flux is isolated as transient eddy meridional moist static energy (MSE) flux with eddies defined as deviations from a monthly average (Peixoto and Oort 1992; Trenberth and Stepaniak 2003a). While there exist many climate-based definitions of storm tracks, including regions of maximum transient eddy surface pressure variance and transient eddy kinetic energy (Chang et al. 2002), here we focus on transient eddy MSE flux and define storm-track position as the latitude of zero transient eddy MSE flux divergence.

Storm tracks shift meridionally in response to forcing across a range of time scales. Seasonally the storm-track shifts meridionally in the Northern Hemisphere (NH) but very little in the Southern Hemisphere (SH) [see Fig. 6 in Trenberth and Stepaniak (2003a)]. Interannually, storm tracks shift equatorward in response to El Niño minus La Niña conditions (Seager et al. 2003; Lu et al. 2008). On decadal time scales, ozone depletion shifts the SH storm track poleward (McLandress et al. 2011; Polvani et al. 2011; Thompson et al. 2011; Lee and Feldstein 2013; Grise et al. 2014) whereas ozone recovery is projected to shift it equatorward (Perlwitz et al. 2008; Son et al. 2008). Anthropogenic aerosols shift the NH wintertime storm track equatorward (Ming et al. 2011). On centennial time scales anthropogenic climate change is projected to shift storm tracks poleward (Yin 2005; Shaw et al. 2016). Finally, on millennial time scales, the NH wintertime storm track was shifted equatorward relative to today during the mid-Holocene and Last Glacial Maximum (Brayshaw et al. 2010; Li and Battisti 2008). Storm-track intensity also changes in response to forcing (e.g., Chang 2001; O’Gorman 2010); however, here we focus on storm-track shifts.
What drives storm-track shifts? Previous work focused on momentum budget, potential vorticity, or eddy kinetic energy arguments. Examples include shifts due to changes in 1) Eady growth rate (Brayshaw et al. 2008), 2) the subtropical jet (Son and Lee 2005), 3) stratification (Lorenz and DeWeaver 2007; Gerber and Son 2014), 4) critical or reflection latitudes (Seager et al. 2003; Chen and Held 2007; Kidston and Vallis 2012; Lorenz 2014), 5) eddy diffusivity (Lu et al. 2014), and 6) available potential energy (Mbengue and Schneider 2013, 2017). These previous results represent important steps forward in our understanding of storm-track shifts.

All of the shifts mentioned above are driven by energetic perturbations, for example, seasonal insolation, changes in surface fluxes, or top-of-atmosphere (TOA) radiation. An energetic framework is attractive for understanding storm-track shifts because it connects energetic perturbations to a measure of storm-track position (latitude of zero transient eddy MSE flux divergence). In the tropics, an MSE framework has been used to understand ITCZ shifts via its connection to the energy flux equator (EFE; latitude where MSE flux is zero in the tropics; Schneider et al. 2014). Bischoff and Schneider (2014) derived an MSE framework for EFE shifts based on a Taylor series linearization of MSE flux about the equator. The framework has been applied to ITCZ shifts across time scales (Adam et al. 2016a,b) as well as to aquaplanet models with idealized perturbations (Bischoff and Schneider 2014; Shaw et al. 2015; Bischoff and Schneider 2016).

Here we derive an MSE framework for storm-track position and use it to understand storm-track shifts across a range of time scales. We apply the framework to storm-track shifts in response to seasonal insolation, El Niño minus La Niña conditions, and increased CO2. The response to increased CO2 is decomposed into direct [increased CO2 with fixed sea surface temperature (SST)] and indirect (increased SST with fixed CO2) contributions using an atmospheric general circulation model (AGCM). Our goal is to understand 1) why seasonal storm-track shifts are larger in the NH than in the SH and 2) why storm tracks shift equatorward in response to El Niño minus La Niña conditions but poleward in response to increased CO2 even though the tropical upper troposphere warms in both cases. The paper is organized as follows. We derive the MSE framework and describe the datasets in section 2. Our results for seasonal, interannual, and centennial storm-track shifts are presented in section 3. The conclusions and discussion are summarized in section 4.

2. Energetic framework and datasets

a. Energetic framework

We investigate storm-track shifts using the atmospheric MSE budget. The time, zonally averaged, and vertically integrated atmospheric MSE budget is

$$\partial_t \langle [\bar{H}] \rangle + \partial_y \langle [\bar{m}] \rangle = \text{EIA} \quad (1)$$

(Neelin and Held 1987), where \(t\) is time; \(h\) is the thermal energy \((h = c_p T + Lq, \text{where} c_p \text{is the specific heat at constant pressure,} T\) is the temperature, \(L\) is the latent heat of vaporization and \(q\) is the specific humidity); \(m\) is the MSE \((m = c_p T + Lq + \Phi, \text{where} \Phi\) is the geopotential); \(v\) is the meridional wind; the overbar and the square brackets denote monthly and zonal averages, respectively; angle brackets denote a mass-weighted vertical integration; and \(\partial_i (\cdot) = \partial \phi (\cos \phi (\cdot)) / (a \cos \phi)\) is the meridional divergence in spherical coordinates where \(\phi\) is latitude and \(a\) is the radius of Earth. The MSE input to the atmosphere (EIA) is the difference between TOA and surface fluxes.

The MSE flux is decomposed into three contributions: that is, \(\langle [\bar{m}] \rangle = \langle [\bar{v} \bar{m}] \rangle + \langle [\bar{v}^* \bar{m}^*] \rangle + \langle [\bar{v}^T \bar{m}^T] \rangle\), where the prime and the asterisk denote deviations from the monthly and zonal average, respectively; \(\langle[\bar{v}\bar{m}]\rangle\) are the MSE flux divergence by the different contributions. The MM divergences dominate—whereas for eddies (Rossby waves) thermal energy flux dominates—that is, \(c_p \langle [\bar{v}^T \bar{m}^T] \rangle + L \langle [\bar{v}^* \bar{q}^*] \rangle > \langle [\bar{v}^T \bar{F}] \rangle + L \langle [\bar{v}^* \bar{q}^*] \rangle > \langle [\bar{v}^T \bar{F}] \rangle\)—because they are mostly geostrophic (Figs. A1 and A2). According to the MSE flux decomposition the atmospheric MSE budget (1) can be written as

\[ F_{\text{MM}} + F_{\text{SE}} + F_{\text{TE}} = (\text{EIA} - \partial_y \langle [\bar{H}] \rangle) = F_{\text{NE}}, \]

where \(F_{\text{MM}} = \partial_y \langle [\bar{v} \bar{m}] \rangle, F_{\text{SE}} = \partial_y \langle [\bar{v}^* \bar{m}^*] \rangle, \text{and} F_{\text{TE}} = \partial_y \langle [\bar{v}^T \bar{m}^T] \rangle\) are the MSE flux divergence by the different circulation components and \(F_{\text{NE}}\) is the net energy (difference between MSE input to the atmosphere and atmospheric storage).

We define storm-track position as the latitude of zero transient eddy MSE flux divergence—that is, the latitude \(\phi_0\) where \(F_{\text{TE}}|_{\phi_0} = 0\)—and consider two methods for quantifying storm-track shifts. The first method is motivated by previous work that derived an MSE framework for EFE shifts based on a Taylor series
linearization of MSE flux about the equator (Bischoff and Schneider 2014). Here we consider a Taylor series linearization of the transient eddy MSE flux divergence about a reference latitude near the storm-track position. The second method does not involve a Taylor series or reference latitude; instead, the change in MSE flux divergence at all latitudes is added to the climatological transient eddy MSE flux divergence.

1) METHOD 1

Linearizing $F_{TE}$ about a reference latitude $\phi_r$, we have

$$0 = F_{TE|\phi_r} \approx F_{TE|\phi_r} + a \partial_{\phi} F_{TE|\phi_r} \delta_1,$$

where $\delta_1 = \phi_o - \phi_r$ such that

$$\delta_1 = \frac{-1}{a a \partial_{\phi} F_{TE|\phi_r}},$$

where the subscript indicates method 1. Hence, the position of storm track relative to the reference latitude is determined by the ratio of transient eddy MSE flux divergence and its slope at the reference latitude. The denominator is negative definite in the NH and positive definite in the SH because the storm track represents a local maximum and minimum of area-weighted transient eddy MSE flux, respectively. The reference latitude is chosen to ensure the accuracy of the linearized Taylor series for the climatology (see appendix C). Since the linearization is accurate for latitudes near the climatological storm-track position we consider reference latitudes equal to the storm-track position $\pm 1^\circ$ in $0.5^\circ$ increments and show the mean and standard deviation across that range.

A shift of storm-track position between two climates is given by

$$\Delta \delta = \frac{-1}{a a \partial_{\phi} F_{TE|\phi_r}} F_{TE|\phi_r} + \frac{1}{a} \partial_{\phi} F_{TE|\phi_r} \Delta \delta_1 + \frac{1}{a} \Delta \delta_1,$$

where the terms on the right-hand side represent 1) a change in $F_{TE}$, 2) a change in the slope of $F_{TE}$, and 3) a change in both 1 and 2. Figure 1 illustrates a shift of the NH storm track due to a change in the first two terms. Increased transient eddy MSE flux divergence at the reference latitude (i.e., $\Delta F_{TE|\phi_r} > 0$) shifts the storm track poleward (Fig. 1a). Increased slope at the reference latitude (i.e., $\Delta \partial_{\phi} F_{TE|\phi_r} > 0$) also induces a poleward shift (Fig. 1b).

The MSE budget provides a physical interpretation of storm-track shifts. According to the MSE budget (2) a change in the transient eddy MSE flux divergence or its slope is related to a change in net energy or the flux divergence by other circulation components—that is, $\Delta F_{TE} = \Delta F_{NE} - \Delta F_{MM} - \Delta F_{SE}$ and $\Delta \partial_{\phi} F_{TE} = \Delta \partial_{\phi} F_{NE} - \Delta \partial_{\phi} F_{MM} - \Delta \partial_{\phi} F_{SE}$. Thus, any storm-track shift can be decomposed into contributions from net energy, mean meridional circulation, stationary eddies, and a cross term (CT):

$$\Delta \delta = \Delta \delta_{1,NE} + \Delta \delta_{1,MM} + \Delta \delta_{1,SE} + \Delta \delta_{1,CT},$$

where
The cross term arises from simultaneous MSE flux divergences and slope changes of the different shift contributions. The error for method 1, called the Taylor series linearization error, is quantified as the difference between the actual shift \((\Delta \delta)\) and the shift calculated following method 1 \((\Delta \delta_1)\).

2) METHOD 2

Method 1 is based on a linearized Taylor series and may depend on the choice of reference latitude. To ensure the results are independent of Taylor series linearization error, we consider a second method. Let the climatological storm-track position be \(\phi_0\) (i.e., \(F_{\text{TE}}|_{\phi_0} = 0\)) and let the storm-track position in response to a change of transient eddy MSE flux divergence \(\Delta F_{\text{TE}}\) be \(\phi_{\text{TE}}\); that is, \((F_{\text{TE}} + \Delta F_{\text{TE}})|_{\phi_0} = 0\), such that the storm-track shift is \(\Delta \delta_2 = \phi_{\text{TE}} - \phi_0 = \Delta \delta\), where the subscript indicates method 2. According to the MSE budget (2) any change in transient eddy MSE flux divergence can be expressed as \(\Delta F_{\text{TE}} = -\Delta F_{\text{NE}} - \Delta F_{\text{MM}} - \Delta F_{\text{SE}}\). Hence, the shift can once again be decomposed into contributions from net energy, mean meridional circulation, stationary eddies, and a cross term:

\[
\Delta \delta_2 = \Delta \delta_{2,\text{NE}} + \Delta \delta_{2,\text{MM}} + \Delta \delta_{2,\text{SE}} + \Delta \delta_{2,\text{CT}}
\]  

(11)

and

\[
\Delta \delta_{2,\text{NE}} = \phi_{\text{NE}} - \phi_0, \quad \text{where } (F_{\text{TE}} + \Delta F_{\text{NE}})|_{\phi_0} = 0,
\]

(12)

\[
\Delta \delta_{2,\text{MM}} = \phi_{\text{MM}} - \phi_0, \quad \text{where } (F_{\text{TE}} - \Delta F_{\text{MM}})|_{\phi_0} = 0,
\]

(13)

\[
\Delta \delta_{2,\text{SE}} = \phi_{\text{SE}} - \phi_0, \quad \text{where } (F_{\text{TE}} - \Delta F_{\text{SE}})|_{\phi_0} = 0, \quad \text{and}
\]

\[
\Delta \delta_{2,\text{CT}} = \Delta \delta - (\Delta \delta_{2,\text{NE}} + \Delta \delta_{2,\text{MM}} + \Delta \delta_{2,\text{SE}}).
\]

(14)

(15)

Once again, the cross term arises from simultaneous changes of the different shift contributions.

In summary, method 1 is based on a linearized Taylor series and was motivated by the success of the linearized Taylor series framework for EFE shifts (Bischof and Schneider 2014). The advantage of method 1 is that it quantifies whether linear changes at the reference latitude (change in \(F_{\text{TE}}\) and its slope) accurately capture the storm-track shift. This allows for a clear geometric interpretation of the shift (see Fig. 1). Note this is similar to the linearized EFE framework of Bischof and Schneider (2014), which has a clear geometric interpretation (see their Fig. 1). The disadvantages of method 1 include the use of a linearized Taylor series and reference latitude. Method 2 is more accurate because it effectively includes all orders of the Taylor series and it does not depend on a reference latitude. However, it does not provide a simple geometric interpretation.

b. Datasets

We use monthly atmospheric MSE flux data from the NCEP reanalysis (Kalnay et al. 1996) covering the period 1970–2015. The data were processed and decomposed following Marshall et al. (2014). The annual, zonal-mean total MSE flux and its decomposition into mean meridional circulation, stationary eddy, and transient eddy contributions is shown in Fig. 2a. The seasonal evolution is shown in Figs. 2b–d. There is larger seasonality of transient eddy MSE flux in the NH than in the SH. The NH storm-track position (i.e., the latitude \(\phi_0\), where \(F_{\text{TE}}|_{\phi_0} = 0\)) exhibits a seasonal amplitude of 13.3° about its annual-mean position of 43.3°N, which reflects an equatorward shift in winter and poleward shift in summer (red line; Fig. 3a). In contrast, the seasonal amplitude of SH storm-track position is only 3.6° about its annual-mean position of 43.8°S (blue line; Fig. 3a). In both hemispheres, the seasonal cycle of storm-track position is of similar amplitude for the
latent and sensible heat MSE flux components (Fig. A1).

The mean meridional circulation MSE flux reflects the seasonal evolution of the Hadley circulation in the tropics (Fig. 2c), which coincides with seasonal shifts of the EFE that exhibits a seasonal amplitude of 24.2° (black line; Fig. 3a) about its annual-mean position of 1.9°N. The Ferrel cell dominates the mean meridional circulation MSE flux in the midlatitudes and opposes the transient eddy MSE flux. The seasonal evolution of stationary eddy MSE flux in the NH (Fig. 2d) reflects large amplitude wintertime stationary eddies driven by diabatic heating, topography, and transient eddy vorticity flux [see Fig. 13 in Wang and Ting (1999); Held et al. 2002], whereas summertime stationary eddies are driven by monsoonal diabatic heating [see Fig. 15 in Wang and Ting (1999)]. The SH exhibits a much weaker seasonal evolution of stationary eddy MSE flux (Fig. 2d) consistent with its smaller land area. The seasonal evolution of the MSE flux in the NCEP reanalysis is robust when compared to ERA-Interim (Dee et al. 2011) covering the period 1979–2015 (cf. Figs. 2 and 3 with Figs. B1 and B2).


c. Atmospheric general circulation model experiments

To examine storm-track shifts on longer time scales (i.e., in response to increased CO2), we conduct simulations with the MPI-ESM-LR AGCM, herein referred to as MPI AGCM (Stevens et al. 2013). The AMIP configuration of the MPI AGCM with prescribed historical forcings (i.e., radiative forcing, SST, sea ice, etc.) from 1979 to 2008 (Gates et al. 1999) does a reasonable job of reproducing the seasonal cycle of MSE flux (Fig. 4), EFE, and storm-track position (Fig. 3b).

Following previous work, we quantify the direct and indirect (fast and slow) effect of increased CO2 using AGCMs (He et al. 2014; Shaw and Voigt 2015; He and...
The direct effect involves increasing CO2 by 4 times its climatological value with fixed SST. Shaw and Voigt (2016a) showed that increased CO2 over land dominates the storm-track shift in response to the CO2 direct effect (see their Table 1). Thus, the direct effect will focus on the response to increased CO2 over land. The indirect effect involves increased SST with fixed CO2. The simplest SST warming is uniform warming by 4 K, which we will refer to as increased SST. The MPI AGCM simulations used here are the same as those in Shaw and Voigt (2016a). The data are interpolated onto a 0.1° grid.

3. Results

The MSE framework connects storm-track shifts and energetic perturbations. The importance of this connection can be illustrated by making a falsifiable prediction of month-to-month storm-track shift in response to seasonal insolation. Given the transient eddy MSE flux divergence $F_{\text{TE}}$, storm-track position $f_0$, and TOA albedo $\alpha_{\text{TOA}}$ during month $m$, method 2 predicts the storm-track shift between months $m$ and $m+1$ given the TOA insolation change $\Delta F_{\text{TOA,SW}}^m$; that is, $\Delta \delta z_{\text{TE}} = \Delta \delta z_{\text{NE}} = \phi_{\text{NE}} - \phi_0$, where $(F_{\text{TE}} + \Delta F_{\text{NE}})|_{\phi_{\text{NE}}} = \left\{F_{\text{TE}} + (1 - \alpha_{\text{TOA}}) \Delta F_{\text{TOA,SW}}^m\right\}|_{\phi_{\text{NE}}} = 0$. Figure 5a shows the predicted seasonal storm-track shift. Note for some months there is no latitude where the transient eddy MSE flux divergence equals zero after adding the insolation change—that is, the prediction fails. If insolation dominated storm-track shifts, then there would be a poleward shift between winter and summer and an equatorward shift between summer and winter in both hemispheres. Interestingly, the...
observed NH shift is smaller and out of phase with the predicted shift. In the NH there is a poleward shift from April minus March to August minus July and an equatorward shift from September minus August to December minus November (red line; Fig. 5b). In the SH the observed shift is much weaker and does not exhibit clear seasonality (blue line; Fig. 5b). Clearly, TOA insolation alone does not determine the seasonal storm-track shift.

In the following subsections the MSE framework is applied diagnostically across three time scales (seasonal, interannual, and centennial) to determine the dominant contributions in (6). Since the MSE framework is based on the MSE budget, it does not imply causality; however, it can be used to formulate hypotheses to test causality as discussed in section 4. The goal is to find shifts involving one or two dominant contributions. To extract robust behavior we focus on large amplitude shifts—that is, shifts larger than $1^\circ$ latitude (shifts less than $1^\circ$ latitude are indicated by gray shading in all figures).

a. Seasonal shift

On seasonal time scales we focus on month-to-month storm-track shifts. According to method 1 [see (5)], changes in transient eddy MSE flux divergence at the reference latitude dominate the storm-track shift (blue line; Fig. 6). The Taylor series linearization error is small (black line; Fig. 6).

The decomposition of the seasonal storm-track shift in the NH into net energy, mean meridional circulation, stationary eddy, and cross term contributions following method 1 [see (6)] is shown in Fig. 7a. The change of MSE flux divergence at the reference latitude dominates over the slope and cross term contributions [see (7)–(9) and Fig. C2]. According to method 1 the stationary eddy contribution (blue line; Fig. 7a) dominates the seasonal shift. During other times, the shift is less than $\pm 1^\circ$ and all contributions are important. The stationary eddy contribution also dominates according to method 2 (blue line; Fig. 7b). In the SH, the month-to-month shift is less than $\pm 1^\circ$ with the exception of May minus April when there is an equatorward shift; however, no contribution dominates according to both methods (Figs. 7c,d). The cross term is small in both hemispheres for both methods (black line; Fig. 7).

Overall, the MSE framework suggests that the seasonal storm-track shift in the NH is connected to the

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**Figure 5.** Month-to-month storm-track shift (a) predicted using method 2 in response to TOA insolation with fixed TOA albedo and (b) observed in the NCEP reanalysis.

**Figure 6.** Month-to-month storm-track shift according to method 1 [see (5)] in the (a) Northern and (b) Southern Hemispheres in the NCEP reanalysis. The actual storm-track shift $\Delta \delta$ and Taylor series linearization error ($\Delta \delta - \Delta \delta_1$) are shown for comparison.
seasonal evolution of stationary eddy MSE flux divergence. The latitudinal structure of compensation for July minus June, September minus August, and December minus November is shown in Fig. 8. Between July and June, stationary eddies diverge MSE flux in the subtropics and converge it in midlatitudes (blue line; Fig. 8a) whereas transient eddies converge MSE flux in midlatitudes (red line; Fig. 8a) resulting in a poleward shift of the storm track. Between September and August, stationary eddies diverge MSE flux in midlatitudes (blue line; Fig. 8b) whereas transient eddies converge MSE flux in midlatitudes (red line; Fig. 8b) resulting in an equatorward shift of the storm track. Finally, between December and November, stationary eddies diverge MSE flux in midlatitudes (blue line; Fig. 8c) whereas transient eddies converge MSE flux in midlatitudes (red line; Fig. 8c) resulting in an equatorward shift of the storm track. The seasonal shifts in the NCEP reanalysis are in general agreement with those from ERA-Interim (cf. Figs. 7 and 8 to Figs. B3 and B4).

b. Interannual shift

On interannual time scales we consider the storm-track shift due to ENSO, which is the dominant mode of climate variability. The jet stream shifts equatorward in response to El Niño minus La Niña conditions during NH winter (December–February; Seager et al. 2003; Lu et al. 2008). Consistent with the jet shift, the storm-track position defined as the latitude of zero transient eddy MSE flux divergence shifts equatorward by 1.5° and 0.8° in the NH and SH, respectively. Table 1 summarizes the storm-track shifts computed following methods 1 and 2.

According to both methods the stationary eddy contribution dominates the equatorward shift of the NH storm track in response to El Niño minus La Niña conditions. Stationary eddies diverge MSE flux in midlatitudes (blue line; Fig. 9a) whereas transient eddies converge MSE flux (red line; Fig. 9a) resulting in an equatorward shift of the storm track. In the SH, the mean meridional circulation and stationary eddies diverge MSE flux in midlatitudes (blue and green line; Fig. 9b) whereas transient eddies converge MSE flux (red line; Fig. 9b). Once again, the ENSO shift in the NCEP reanalysis is in general agreement with that from ERA-Interim (cf. Fig. 9 to Fig. B5).

c. Centennial shift

On centennial time scales we consider the response to increased CO₂. As discussed in section 2b, we...
separate the direct (increased CO$_2$ over land) and indirect (increased SST with fixed CO$_2$) effects of CO$_2$ on the storm track. The direct effect produces a poleward storm-track shift during NH summer but does not significantly impact the SH storm track (Figs. 10a,b). The indirect effect produces an equatorward shift during June in the NH, a poleward shift during January in the NH, and a poleward shift during May and October in the SH (Figs. 10c,d). Consistent with the seasonal shifts, changes in transient eddy MSE flux divergence at the reference latitude dominate the shift according to method 1 (blue line; Fig. 10) and the Taylor series linearization error (black line; Fig. 10) is small.

The decomposition of storm-track shifts in response to increased CO$_2$ into net energy, mean meridional circulation, stationary eddy, and cross term contributions following method 1 [see (6)] is shown in Figs. 11 and 12. According to both methods the stationary eddy contribution dominates the poleward shift during NH summer in response to increased CO$_2$ over land (blue line; Figs. 11a,b). In response to increased CO$_2$ over land, stationary eddies diverge MSE flux in the subtropics and converge it in midlatitudes (blue line; Fig. 13a) whereas transient eddies converge MSE flux in midlatitudes (red line; Fig. 13a) resulting in a poleward shift of the storm track. Overall, the response to increased CO$_2$ over land is similar to the seasonal response between July and June (see Fig. 8a).

According to both methods, the stationary eddy contribution also dominates the equatorward shift of the NH storm track during June in response to increased SST (blue line; Figs. 12a,b). Stationary eddies converge MSE flux in midlatitudes (blue line; Fig. 13b) whereas transient eddies converge MSE flux in midlatitudes (red line; Fig. 13b) resulting in an equatorward shift of the storm track. The response to increased SST during June is opposite of the response to increased CO$_2$ over land during July, suggesting increased CO$_2$ over land and increased SST exert a tug of war on storm-track position (Shaw et al. 2016). According to both methods the mean meridional circulation contribution dominates the poleward shift of the NH storm track in response to increased SST during January (Figs. 12a,b). The mean meridional circulation converges MSE flux in midlatitudes (green line;
Fig. 13c) whereas transient eddies diverge MSE flux in midlatitudes (red line; Fig. 13c) resulting in a poleward shift of the storm track in response to increased SST.

The mean meridional circulation is also the dominant contribution to the poleward shift of the SH storm track in response to increased SST during October (Figs. 12c,d). Once again, the mean meridional circulation converges MSE flux in midlatitudes during October (green line; Fig. 13d) whereas transient eddies diverge MSE flux in midlatitudes (red line; Fig. 13d) resulting in a poleward shift of the storm track.

4. Conclusions and discussion

We developed a framework for understanding shifts of the zonal-mean storm track using the atmospheric MSE budget. The results build upon an MSE framework for EFE shifts (Schneider et al. 2014; Bischoff and Schneider 2014). Storm-track position is defined as the latitude of zero transient eddy MSE flux divergence. Two methods were developed to understand storm-track shifts. The first method is based on a Taylor series linearization of transient eddy MSE flux divergence about a reference latitude near the storm-track position. According to this method, storm-track shifts are driven by changes in transient eddy MSE flux divergence and its slope at the reference latitude. Across the time scales considered, changes in transient eddy MSE flux divergence at the reference latitude dominate storm-track shifts. Thus, a poleward shift of the storm track occurs as a result of a transient eddy MSE flux divergence response at the reference latitude, whereas...
an equatorward shift occurs as a result of a flux convergence. The Taylor series linearization error is small across the time scales considered.

The second method for quantifying storm-track shifts did not involve a Taylor series or a reference latitude. It imposes a change in transient eddy MSE flux divergence at all latitudes to the climatological transient eddy MSE flux. According to the MSE budget, any change in transient eddy MSE flux divergence is balanced by the sum of changes in net energy (MSE input to the atmosphere minus atmospheric storage) and MSE flux divergence by longitudinally symmetric mean meridional circulation and longitudinally asymmetric stationary eddies. Thus, both methods decompose storm-track shifts into contributions from net energy, mean meridional circulation, stationary eddies, and a cross term. The cross term involves changes in multiple contributions and was small across the time scales considered.

Fig. 11. As in Fig. 7, but for the response to increased CO₂ over land in the MPI AGCM.

Fig. 12. As in Fig. 7, but for the response to increased SST in the MPI AGCM.
The MSE framework was applied to storm-track shifts across time scales, including seasonal (month to month) shifts, interannual shifts in response to ENSO, and centennial shifts in response to increased CO2. The response to increased CO2 was decomposed into direct (increased CO2 over land with fixed SST) and indirect (increased SST with fixed CO2) contributions. Seasonal and ENSO shifts were quantified using NCEP reanalysis and ERA-Interim data whereas shifts in response to increased CO2 were quantified using the MPI AGCM. Changes in net energy are a small contribution across the time scales considered. Stationary eddies are the dominant contribution to storm-track shifts in response to seasonal insolation in the NH, El Niño minus La Niña conditions during NH winter, and direct and indirect effects of increased CO2 during NH summer. The mean meridional circulation is the dominant contribution to storm-track shifts in response to the CO2 indirect effect during NH winter and during May and October in the SH.

The insignificance of net energy changes is consistent with previous work that highlighted the buffering of seasonal insolation by ocean surface energy storage (Fasullo and Trenberth 2008; Donohoe and Battisti 2013). The dominance of circulation contributions to storm-track shifts suggests that compensation between different circulation components is important for shifts across the time scales considered. Understanding the importance of net energy changes and compensation in response to forcings on different time scales (decadal and millennial)—for example, ozone depletion, anthropogenic aerosol, and paleoclimate changes—is a work in progress.

Since compensation does not imply causality, one cannot draw causal conclusions. However, the results can be used to formulate hypotheses regarding causality. For example, the results show the seasonal storm-track shift in the NH is connected to the stationary eddy MSE flux evolution. Thus, one could hypothesize that in the absence of significant seasonal net energy and stationary eddy changes there is a small seasonal shift (as in the SH). Furthermore, if net energy changes are small but there is a significant stationary eddy signal that is not driven by transient eddies then stationary eddies may cause a seasonal shift. Current research is focused on this interpretation for the NH where summertime stationary eddies reflect monsoonal diabatic heating and not transient eddy vorticity sources according to stationary wave models [see Fig. 15 of Wang and Ting (1999)]. Consistently, when the summertime monsoon circulation and its stationary eddy MSE flux are amplified in response to the CO2 direct effect, the storm

![Graph](Image)
track shifts poleward (Shaw and Voigt 2015, 2016b). Idealized simulations also show that increasing the amplitude of imposed subtropical zonally asymmetric perturbations shifts the storm track poleward (Shaw and Voigt 2014; Shaw and Voigt 2015, 2016b).

Along similar lines, the equatorward shift in response to El Niño minus La Niña conditions during NH winter involves changes in stationary eddies. If the stationary eddy changes are driven directly by the weakening of the Walker circulation (and not by transient eddies), then they may cause the shift. ENSO related variability in the Hadley cell has also been connected to stationary eddy momentum flux changes (Caballero 2007). However, the mean meridional circulation MSE flux in response to El Niño minus La Niña conditions may drive a storm-track shift independent of stationary eddies (Tandon et al. 2013; Lu et al. 2014).

The compensation between the mean meridional circulation and transient eddies in response to the CO₂ indirect effect suggests transient eddy momentum fluxes, which drive the Ferrel circulation (Schneider 2006), may cause the storm-track shift. However, that regime requires a better understanding of the connection between storm-track and eddy-driven jet shifts, which is an active area of research (Lu et al. 2010; Donohoe et al. 2014; Yamada and Pauluis 2016; Dwyer and O’Gorman 2017). Alternatively, changes in the Hadley circulation in response to the CO₂ indirect effect (e.g., Hadley cell expansion) may directly impact the storm track (Butler et al. 2010; Lu et al. 2014; Tandon et al. 2013; Mbengue and Schneider 2017). Assessing the causality of compensation using idealized model simulations is work in progress.

Circulation compensation has a long history in the literature going back at least to Manabe and Terpstra (1974), who noted compensation between stationary and transient eddy MSE flux in response to flattening the continents in an AGCM. More recent examples of stationary-transient eddy compensation include compensation on climatological and interannual time scales in reanalysis data (Trenberth and Stepaniak 2003a,b), wintertime compensation in response to zonally localized surface heat flux perturbations in aquaplanet simulations (Kaspi and Schneider 2013), wintertime compensation due to flattening Tibet (Park et al. 2013), and summertime compensation in response to climate change over land versus ocean across the model hierarchy (Shaw and Voigt 2015, 2016a,b). Mechanistically, compensation can occur via increased stationary eddy MSE flux that reduces baroclinicity and transient eddy MSE flux (Kaspi and Schneider 2013) or it can occur through opposing diffusivity responses [see Figs. 8 and 10 of Shaw and Voigt (2016b)]. While compensation does not occur at each longitude, it does occur in longitudinal sectors.

The MSE framework is based on the MSE budget and is therefore diagnostic. Using the framework to predict shifts of the storm track requires 1) a better understanding of circulation compensation using idealized models and 2) closures for the net energy, mean meridional circulation, and stationary eddy contributions. Our results suggest zonal-mean net energy is not a useful closure; however, previous work suggests MSE input to the atmosphere over land may be a useful closure for stationary eddy MSE flux during NH summer (Shaw and Voigt 2016a,b). While the energetic perspective of storm-track shifts is attractive because it connects storm-track position and energetic perturbations, a complete understanding of shifts must include the momentum budget. Our results also do not account for shifts of zonally localized storm tracks, which are known to occur in response to ENSO, anthropogenic aerosol, and CO₂ changes. The MSE framework is currently being extended to address localized shifts. Overall, the MSE framework represents a step toward a complete understanding of storm-track shifts across a range of time scales.

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APPENDIX A

Decomposition of Eddy MSE Flux

The transient and stationary eddy MSE flux is decomposed into latent heat, sensible heat, and potential energy flux components in Figs. A1 and A2. The results show thermal energy flux dominates for eddies (Rossby waves)—that is, \( c_p \left( \overline{\theta v} \right) + L \left( \overline{\theta q} \right) \) and \( c_p \left( \nabla \cdot q \right) \). Because they are mostly geostrophic.
In addition to the NCEP reanalysis we also used monthly atmospheric MSE flux data from ERA-Interim covering the period 1979–2015. The data were processed and decomposed following Marshall et al. (2014) and interpolated onto a 0.1° grid. The annually averaged and seasonal evolution of the MSE flux for ERA-Interim compares well with the NCEP reanalysis (cf. Fig. B1 and Fig. 2). Consistently, there

APPENDIX B

ERA-Interim

In addition to the NCEP reanalysis we also used monthly atmospheric MSE flux data from ERA-Interim covering the period 1979–2015. The data were processed and decomposed following Marshall et al. (2014) and interpolated onto a 0.1° grid. The annually averaged and seasonal evolution of the MSE flux for ERA-Interim compares well with the NCEP reanalysis (cf. Fig. B1 and Fig. 2). Consistently, there

FIG. A1. Seasonal evolution of vertically integrated and zonal-mean transient eddy (a) MSE flux (PW) in the NCEP reanalysis decomposed into (b) latent heat, (c) sensible heat, and (d) potential energy flux. Note that the potential energy flux has been multiplied by 25 and all flux components have been multiplied by $2\pi a \cos\phi$.

FIG. A2. As in Fig. A1, but for the seasonal evolution of vertically integrated and zonal-mean stationary eddy flux.
FIG. B1. As in Fig. 2, but for ERA-Interim.

FIG. B2. As in Fig. 3, but for ERA-Interim.

FIG. B3. As in Fig. 7, but for ERA-Interim.
is also good agreement between the seasonal positions of the EFE and storm-track position in the two reanalysis datasets (cf. Fig. B2 and Fig. 3a).

According to the ERA-Interim dataset, stationary eddy MSE flux divergence dominates the seasonal shift of the NH storm track consistent with the NCEP reanalysis (cf. Fig. B3 and Fig. 7). However, the largest month-to-month poleward shift occurs for June minus May in the ERA-Interim data instead of for July minus June as in the NCEP data.

Figures B4 and B5 should be compared with Figs. 8 and 9, respectively; see the discussion in the main text.

APPENDIX C

Method 1 Reference Latitude

Method 1 is based on a Taylor series linearization of $F_{\text{TE}}$ about a reference latitude $\phi_r$. The reference latitude is a mathematical concept that has no physical significance. It is chosen to minimize the Taylor series

![Figure B4](image-url)

**Fig. B4.** As in Fig. 8, but for ERA-Interim.

![Figure B5](image-url)

**Fig. B5.** As in Fig. 9, but for ERA-Interim.
The Taylor series linearization error as a function of the reference latitude during August is shown in Fig. C1. The linearization is only accurate in the vicinity of the climatological storm-track position (51.3°N). A similar linear regime exists for other months. To capture the range of latitudes representative of the linear regime, method 1 uses a reference latitude defined as the climatological storm-track position in 0.5° increments (see gray shading in Fig. C1). The results for method 1 are summarized by the mean (circle) and plus and minus one standard deviation (vertical bar) across the range of reference latitudes in Figs. 6, 7, 10–12, B3, and C2–C4.

A reference latitude corresponding to the annual-mean storm-track position and Hadley cell edge (latitude where the 10-m zonal-mean zonal wind is zero) were considered but not used because the associated Taylor series linearization error is very large at those latitudes during some months (e.g., August). While the Taylor series could be extended to include higher-order terms, we do not think it is necessary because method 2 effectively includes all orders of the Taylor series. Furthermore, the Hadley cell edge does not exhibit a clear connection to the storm-track position interannually in the NH or during winter in the SH (Kang and Polvani 2011).
Method 1 decomposes storm-track shifts into contributions from net energy, mean meridional circulation, stationary eddies, and a cross term [see (7)–(9)]. In all decompositions, the MSE flux divergence change (blue line; Figs. C2–C4) dominates the total shift (red line; Figs. C2–C4) and the difference between methods 1 and 2 is small (black line; Figs. C2–C4).

![Diagram](image)

**Fig. C4.** As in Fig. C2, but for the response to increased SST in MPI AGCM.

Method 1 decomposes storm-track shifts into contributions from net energy, mean meridional circulation, stationary eddies, and a cross term [see (7)–(9)]. In all decompositions, the MSE flux divergence change (blue line; Figs. C2–C4) dominates the total shift (red line; Figs. C2–C4) and the difference between methods 1 and 2 is small (black line; Figs. C2–C4).

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