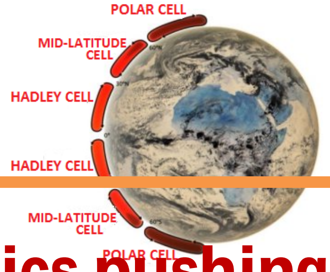

Expanding tropics pushing high altitude clouds towards poles

A new NASA analysis of 30-years of satellite data suggests that a previously observed trend of high altitude clouds in the mid-latitudes shifting toward the poles is caused primarily by the expansion of the tropics.

Clouds are among the most important mediators of heat reaching Earth's surface. Where clouds are absent, darker surfaces like the ocean or vegetated land absorb heat, but where clouds occur their white tops reflect incoming sunlight away, which can cause a cooling effect on Earth's surface. Where and how the distribution of cloud patterns change, strongly affects Earth's climate. Understanding the underlying causes of cloud migration will allow researchers to better predict how they may affect Earth's climate in the future.

George Tselioudis, a climate scientist at NASA's Goddard Institute for Space Studies and Columbia University, was interested in which air currents were shifting clouds at high altitude -- between about three and a half and six miles high -- toward the poles.

The previous suggested reason was that climate change was shifting storms and the powerful air currents known as the jet streams – including the one that traverses the United States – toward the poles, which in turn were driving the movement of the clouds.

To see if that was the case, Tselioudis and his colleagues analyzed the International Satellite Cloud Climatology Project data set, which combines cloud data from operational weather satellites, including those run by the NOAA, to provide a 30-year record of detailed cloud observations. They combined the cloud data with a computer re-creation of Earth's air currents for the same period driven by multiple surface observations and satellite data sets.

What they discovered was that the poleward shift of the clouds, which occurs in both the Northern and Southern Hemispheres, connected more strongly with the expansion of the tropics, defined by the general circulation Hadley cell, than with the movement of the jets.

The Hadley cell is one of the major conduit by which air is moved around the planet. Existing in both hemispheres, it starts when air in the tropics, which is heated at the surface by intense sunlight, warms and rises. At high altitudes it is pushed away from the equator towards the mid-latitudes to the north and south, then it begins to sink back to Earth's surface, closing the loop.

What the team observed, and other people have found it as well, is that the sinking branch of the Hadley cell, as the climate warms, tends to be moving poleward. It's making the tropical region bigger. And that expansion causes the tropical air currents to blow into the high altitude clouds, pushing them toward the poles. The results are published in *Geophysical Research Letters*.

Scientists are working to understand exactly why the tropics are expanding, which they believe is related to a warming climate.

The poleward shift of high altitude clouds affects how much sunlight reaches Earth's surface because when they move, they reveal what's below.

It's like pulling a curtain, said Tselioudis. And what tends to be revealed depends on location -- which in turn affects whether the surface below warms or not. Sometimes when that curtain is pulled, as in the case over the North Atlantic ocean in the winter months, this reduces the overall cloud cover in the lower mid-latitudes, the temperate regions outside of the tropics, Tselioudis said. The high altitude clouds clear to reveal dark ocean below which absorbs incoming sunlight and causes a warming effect.

However, in the Southern Ocean around Antarctica, the high altitude clouds usually clear out of the way to reveal lower altitude clouds below -- which continue to reflect sunlight from their white tops, causing little effect on the solar radiation reaching the surface.

When the results are taken together, the bottom line is that the cloud interactions with atmospheric circulation and solar radiation are complicated, and the tropical circulation appears to play a dominant role.

That information is a new insight that will likely be used by the climate modeling community, including the scientists who contribute modeling expertise to the Intergovernmental Panel on Climate Change. Climate modelers aim for their computer simulations to correspond as closely to reality as possible in order to reliably predict Earth's future climate.

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Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL068242

Key Points:
- The Hadley cell rather than the midlatitude jet is the main contributor of poleward cloud shifts
- The radiative effect of poleward cloud shift changes sign depending on the background cloud field
- The poleward cloud shift of the last 30 years is due to tropical expansion than storm track shift

Supporting Information:
- Supporting Information S1

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Midlatitude cloud shifts, their primary link to the Hadley cell, and their diverse radiative effects

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Abstract We investigate the interannual relationship among clouds, their radiative effects, and two key indices of the atmospheric circulation: the latitudinal positions of the Hadley cell edge and the midlatitude jet. From reanalysis data and satellite observations, we find a clear and consistent relationship between the width of the Hadley cell and the high cloud field, statistically significant in nearly all regions and seasons. In contrast, shifts of the midlatitude jet correlate significantly with high cloud shifts only in the North Atlantic region during the winter season. While in that region and season poleward high cloud shifts are associated with shortwave radiative warming, over the Southern Oceans during all seasons they are associated with shortwave radiative cooling. Finally, a trend analysis reveals that poleward high cloud shifts observed over the 1983–2009 period are more likely related to Hadley cell expansion, rather than poleward shifts of the midlatitude jets.

1. Introduction

Changes in midlatitude clouds with changing atmospheric circulation have been considered a potential source of strong radiative feedbacks on climate change [*Boucher et al.*, 2013]. Since climate models tend to simulate poleward shifts of the midlatitude baroclinic jets with climate warming [e.g., *Yin*, 2005; *Yu et al.*, 2010; *Barnes and Polvani*, 2013], emphasis has been placed on cloud radiative feedbacks resulting from such poleward jet shifts. The majority of climate model simulations included in the Intergovernmental Panel on Climate Change Fifth Assessment Report produce a positive midlatitude cloud radiative feedback, interpreted as the result of a poleward shift of the midlatitude clouds to higher latitudes where they experience smaller solar insolation [*Boucher et al.*, 2013]. This shift allows comparatively more sunlight to reach the lower midlatitude regions producing surface radiative warming. However, more recent modeling studies reveal diverse model behavior with respect to cloud and radiation changes with Southern Hemisphere jet shifts [*Kay et al.*, 2014; *Grise and Polvani*, 2014].

Observational studies have examined cloud type and cloud radiative effect (CRE) shifts with dynamical indices of the position of the midlatitude jet, such as the Southern Annular Mode (SAM) [*Grise et al.*, 2013; *Grise and Polvani*, 2014] and the Northern Annular Mode (NAM) [*Li et al.*, 2014]. Those studies found that in the December, January, and February (DJF) season high clouds shift consistently with the sign of the annular modes in all basins. They also found that longwave (LW) CRE changes are consistent with high cloud shifts in both hemispheres producing poleward warming and equatorward cooling, but shortwave (SW) CRE changes are small in the NH and inconsistent in the SH. Those studies examined jet/annular mode shifts only in the DJF season; as in the NH this is the season when the jet is stronger and in the SH it is the season when ozone depletion effects are more strongly manifested on the circulation changes. In addition, a recent analysis of satellite observations found poleward midlatitude cloud shifts in the last 30 years in all basins and seasons [*Bender et al.*, 2012] and attributed those shifts to potential poleward jet movements, even though the role of a Hadley cell poleward expansion was also discussed. Similar poleward cloud shifts were found in the surface-based cloud observations analysis of *Eastman and Warren* [2013]. Analyses of weather data for the same time period find consistent poleward shifts in the baroclinic jets or storm tracks mostly in the SH summer and fall seasons [e.g., *Wang et al.*, 2006; *Fyfe*, 2003], while analyses of the tropical circulation find consistent signs of poleward expansion of the SH Hadley cell [e.g., *Seidel et al.*, 2008; *Johanson and Fu*, 2009].

In the current study, using reanalysis data and satellite observations, we perform an extensive analysis of the interannual relationships between midlatitude clouds and atmospheric dynamics, examining the correlation of multiple dynamical indices with a suite of cloud and radiation properties. We expand on the previous analyses by adding the Hadley circulation to the list of dynamical indicators and by exploring the relationships in all ocean basins and seasons. Finally, we consider cloud property shifts of the last 30 years in the context of the derived relationships between clouds and atmospheric dynamics.

2. Data Sets and Methods

Two key metrics of the atmospheric circulation are used: the first is the latitudinal position of the midlatitude, eddy driven jet, and the second is the width of the Hadley cell. For the midlatitude jet, we compute the center of mass of the zonal mean westerlies around the 850 hPa maximum and poleward of 20° latitude, from the ERA-Interim reanalysis [*Dee et al*., 2011] following *Ceppi et al*. [2014]. We have also considered the central latitude of the midlatitude storm track density, derived through the use of a storm tracking algorithm [*Bauer and DelGenio*, 2006], and found all the key results to be the same as those for the westerlies. For the Hadley cell, we compute its edge by finding the first latitude poleward of the equator where the atmospheric mean meridional mass streamfunction at 500 hPa changes sign. We have also considered the first latitude poleward of the subtropical minimum where precipitation minus evaporation ($P-E$) becomes zero and, again, found all the key results to be unchanged.

These dynamical parameters are correlated, interannually, with the central latitude of the low, middle, high, and total cloud field (defined with lids at 680 mbar, 440mbar, and 50mbar) from the International Satellite Cloud Climatology Project (ISCCP) data set [*Rossow and Schiffer*, 1999] as well as with the mean value of the SW and LW CRE for the midlatitude region (30–60°N/S) from the ISCCP FD dataset [*Zhang et al*., 2004]. The central latitude of the cloud fields is derived for the 25–65°N/S regions to include the totality of the midlatitude high cloud field and at the same time minimize “contamination” from tropical cloud field changes. The derivation follows the formulation in *Bender et al.* [2012], who calculate the latitude of the weighted center of mass of the cloud field. The cloud and radiation analysis is performed for the 1984–2009 period. Note that correlations were also derived after detrending the relevant data sets, and the results were the same qualitatively and similar quantitatively. Also, in order to address issues related to potential ISCCP biases related to satellite zenith angle regional variability, our analysis was repeated using the *Norris and Evan* [2015]-revised ISCCP data set that aims to remove such biases. The results of that analysis were almost identical to the ones presented here.

Finally, as the storm tracks are highly nonzonal in the Northern Hemisphere, we have decided to compute the correlations between clouds and circulation for three different regions separately: the North Atlantic (280°E–360°E), the North Pacific (120°E–240°E), and the entire Southern Ocean. We also compute the correlations separately for all four seasons, as the cloud radiative effects are sensitive to the magnitude of the incoming solar radiation. Linear correlations are derived when relating different fields, and their statistical significance is determined using a student’s *t* test.

3. Results

We start by presenting maps of the interannual relationships between the clouds, and their radiative effects, and the two key metrics of the atmospheric circulation. In Figure 1 we show changes in high cloud amount (left column), LW CRE (middle column), and SW CRE (right column) associated with a 1° poleward shift of the midlatitude jet (top row) and the Hadley cell edge (bottom row). Figure 1a is for the North Atlantic and Figure 1b is for the Southern Ocean. For both regions we show the December–February (DJF) months, as these illustrate the most interesting results of our study. For the North Pacific, and for the June–August, (JJA) season, the results will be presented below (in Table 1).

In North Atlantic DJF (Figure 1a) high clouds shift consistently with the Hadley cell and the storm track but the shifts show quantitative differences. Hadley poleward shifts show more pronounced high cloud decreases in lower midlatitudes, while midlatitude jet poleward shifts show more moderate high cloud increases in higher midlatitudes and decreases in lower midlatitudes. In LW CRE, Hadley shifts show stronger and more extensive lower midlatitude cooling, while jet shifts show warming and cooling of similar magnitudes but a more extensive cooling area concentrated in the eastern part of the basin. SW CRE does not change much in the higher latitudes with either jet or Hadley shifts because of the small solar insolation there in the DJF season. In lower midlatitudes there is significant SW warming with Hadley shifts and smaller, but still measurable, SW warming with jet shifts. The high cloud and LW CRE changes presented here are consistent with the results of *Li et al.* [2014], who use CloudSat/CALIPSO high cloud retrievals and Clouds and the Earth’s Radiant Energy

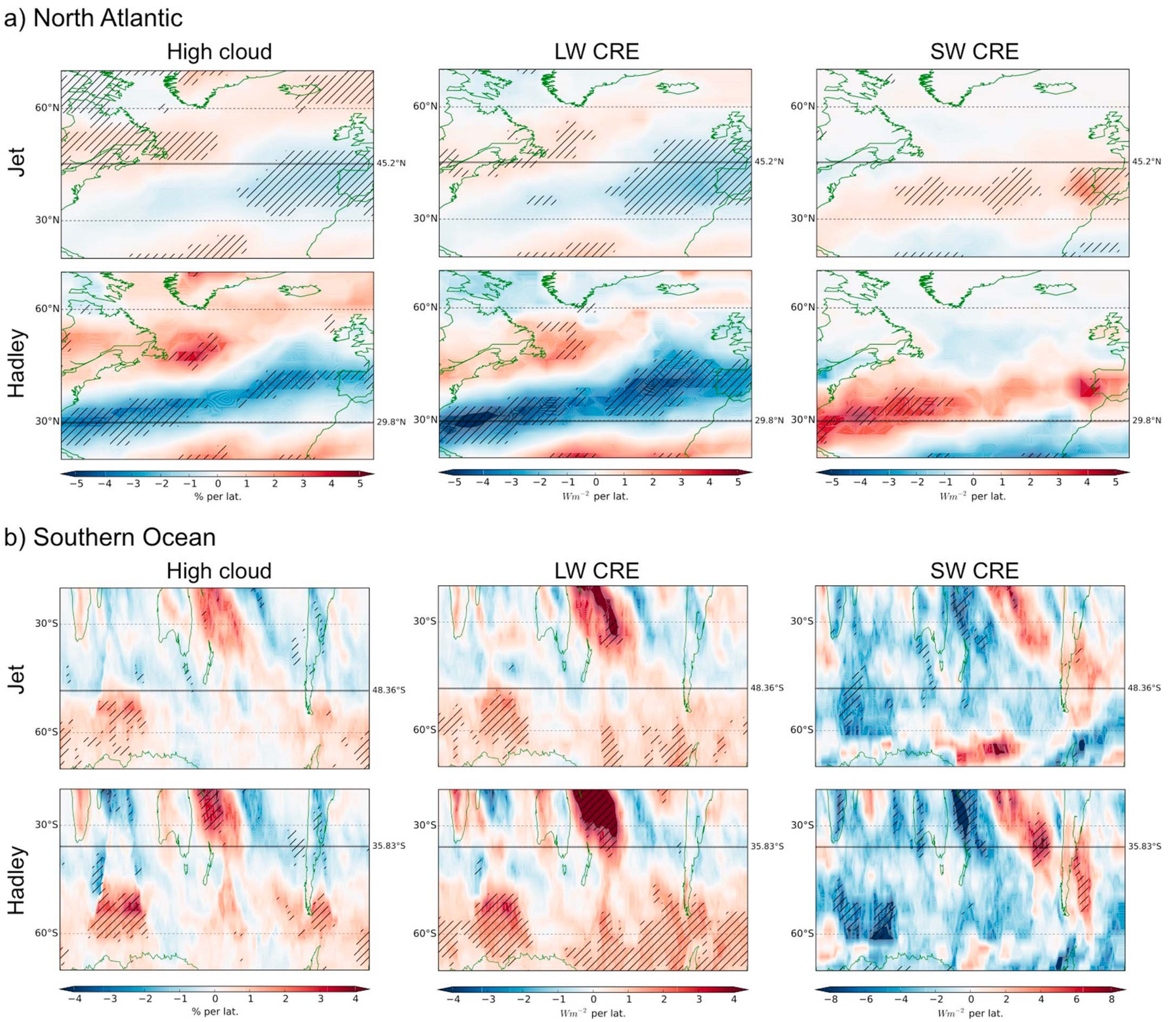

Figure 1. DJF changes in high cloud amount (left column), LW CRE (middle column), and SW CRE (right column) for an 1° poleward shift of the midlatitude jet (top row) and the Hadley cell edge (bottom row) for (a) the North Atlantic and (b) the Southern Ocean. Hatching indicates statistical significance at the 95% level. Note the different color scales between the LW CRE and the SW CRE over the Southern Ocean.

System radiative fluxes for a 5 year period and correlate them with NAM shifts. However, they find that the change in SW CRE is a factor 2–3 smaller than the change in LW CRE everywhere, while our analysis shows this to be true only at the higher latitudes of the basin. This could be due to differences in data sets, the smaller time period that they used, or the fact that they use a water vapor and temperature adjusted CRE. Whatever the cause, we note the overall close agreement between our analysis and theirs: this indicates the robustness of the derived relationships between dynamics, clouds, and radiation shifts.

In the Southern Ocean DJF (Figure 1b), high clouds shift poleward with interannual poleward Hadley cell and jet shifts: however, Hadley cell widening is associated with high cloud increases between 40 and 60°S (and smaller, less consistent decreases between 30 and 40°S), whereas jet shifts are linked to cloud increases concentrated between 50 and 60°S (and smaller decreases between 30 and 50°S). Accordingly, LW CRE shows radiative warming in the poleward belt (40–60°S for Hadley and 50–60°S for the jet) and smaller radiative cooling

Table 1. Slopes (*m*) and Correlation Coefficients (*R*) of the Linear Regressions Between the Hadley Cell Edge and the Baroclinic Jet Latitudes, and the Central Latitudes of Total, High, and Low Cloud and the Mean Midlatitude Values of LW and SW CRE for the Three Basins and the DJF and JJA Seasons[a]

		SH				North Atlantic				North Pacific			
DJF		Hadley (°)		Jet (°)		Hadley (°)		Jet (°)		Hadley (°)		Jet (°)	
		m = 0.54, R = 0.58				**m = 0.15, R = 0.57**				m = 0.10, R = −0.29)			
		m	*R*	*m*	*R*	*m*	*R*	*m*	*R*	*m*	*R*	*m*	*R*
	Total (°)	0.043	0.292	0.008	0.060	0.110	0.367	**0.040**	**0.518**	0.00	0.007	−0.023	−0.346
	High (°)	**0.262**	**0.466**	0.119	0.224	**0.648**	**0.646**	**0.143**	**0.555**	0.084	0.100	−0.025	−0.081
	Low (°)	**−0.147**	**−0.441**	−0.077	−0.245	−0.171	−0.364	−0.038	−0.313	−0.048	−0.116	−0.035	−0.236
	SW CRE (W m^{-2})	**−1.110**	**−0.429**	**−0.984**	**−0.404**	**0.554**	**0.391**	**0.211**	**0.583**	−0.15	−0.104	−0.059	−0.111
	LW CRE (W m^{-2})	0.322	0.359	0.169	0.201	**−0.936**	**−0.536**	**−0.223**	**−0.498**	0.286	0.212	0.02	0.032
JJA		Hadley (°)		Jet (°)		Hadley (°)		Jet (°)		Hadley (°)		Jet (°)	
		m = 0.15, R = 0.17				m = 0.37, R = 0.31				m = 0.33, R = 0.39			
		m	*R*	*m*	*R*	*m*	*R*	*m*	*R*	*m*	*R*	*m*	*R*
	Total (°)	0.066	0.239	−0.017	−0.098	0.046	0.289	−0.014	−0.074	0.030	0.339	0.017	0.224
	High (°)	**0.466**	**0.490**	0.036	0.061	**0.123**	**0.522**	0.036	0.131	**0.092**	**0.395**	0.051	0.254
	Low (°)	**−0.452**	**−0.630**	−0.120	−0.268	−0.024	−0.103	−0.041	−0.149	−0.044	0.283	0.020	0.149
	SW CRE (W m^{-2})	**−0.470**	**−0.405**	−0.164	−0.226	−0.02	−0.021	0.310	0.311	−0.16	−0.117	0.410	0.353
	LW CRE (W m^{-2})	0.280	0.187	0.152	0.162	−0.018	−0.052	−0.133	−0.329	0.063	0.137	0.353	−0.371

[a]Bold type indicates slope regressions significant at the 95% level. The top panels show *m* and *R* values between the Hadley cell edge and the jet latitudes.

between 30–40°S for Hadley and 30–50°S for the jet. The SW CRE, on the other hand, shows radiative *cooling* throughout the middle and high-latitude region, for both the Hadley and jet poleward shifts, with the exception of the region east of South America that shows SW radiative warming. These findings agree with those reported in *Grise et al.* [2013] and *Grise and Polvani* [2014] for SH cloud and radiation changes accompanying poleward jet shifts. This is expected as similar methodologies and the same data sets are used in these two analyses.

The plots in Figure 1 offer only a partial, and qualitative, picture of the relationships between Hadley and jet shifts and the corresponding changes in clouds and radiation. To offer a more complete and quantitative picture of cloud/dynamics interactions and the corresponding radiative changes, linear correlation analysis is performed between all the dynamical indices and the suite of cloud and radiation properties, and the results are summarized in Table 1. The table shows the correlations between the latitudes of the Hadley cell edge and the eddy-driven jet and several clouds variables: the central latitude of the total, high, and low cloud fields, and the midlatitude mean SW and LW CRE. Results are shown for the three midlatitude regions, and the DJF and JJA seasons. The slope (*m*) and correlation coefficient (*R*) values are listed in the table, while on the top of each panel we report the *m* and *R* values for the correlations between the Hadley cell edge and the jet latitude. Positive SW/LW CRE correlations with Hadley and jet latitude signify warming caused by poleward circulation movement, and negative correlations signify cooling caused by poleward circulation movement. Also, correlations significant at the 95% level are shown in bold type, and they are the ones that we concentrate on in this discussion. Finally, we note that for reasons of clarity the results for the March–May (MAM) and September–November (SON) seasons are shown in a supporting information table (Table S1).

We start by considering the correlation of the circulation with the cloud fields. From Table 1 it can be seen that the only consistent interannual correlation between a cloud field property and a dynamical index is the one between the *high* cloud field and the Hadley cell edge: poleward expansion of the Hadley cell is connected with poleward shifts in high cloud central latitude in all seasons and basins, with statistically significant correlations nearly everywhere (the North Pacific winter season is the only exception). The *total* cloud field also shifts poleward with the Hadley cell edge in all basins and seasons, but the correlations are not statistically significant, while the *low* cloud field shifts equatorward almost everywhere with poleward Hadley shifts but the correlations are significant only over the Southern Ocean. Note that over the Southern Ocean the equatoward shift of the low clouds is due to their decrease at the higher midlatitude regions, which shifts the center of mass of the low cloud field to lower latitudes.

Poleward shifts of the midlatitude jet, on the other hand, are associated with significant poleward shifts in the high and total cloud field only in the North Atlantic and only in the winter season. Note how in all other seasons the jet and cloud field correlations are of varying signs and, in general, not statistically significant.

Note also that in the North Atlantic DJF season, the Hadley cell edge and jet latitude are positively and significantly correlated, as they are in the South Ocean DJF season [see also *Kang and Polvani*, 2011]. The results in Table 1 suggest that the correlations between the midlatitude jet latitude and cloud shifts are only robust during seasons when the Hadley cell edge latitude and jet latitude are significantly correlated with one another (Table 1). Hence, if the Hadley cell is the dominant driver of the cloud shifts, the influence of the midlatitude jet could be exaggerated during these seasons due to the high correlation between the jet and Hadley cell metrics.

Next, we turn to the correlation between the dynamics and the cloud radiative effects. The LW CRE shows significant correlations with both the Hadley edge and the jet latitude only in the North Atlantic winter season. The SW CRE, on the other hand, shows significant correlations with the Hadley cell in all seasons over the Southern Oceans and in the North Atlantic winter season and with the jet in the Southern Ocean summer and the North Atlantic winter. The crucial point here is that in the Southern Oceans, the poleward shift of the Hadley edge is associated with a SW radiative cooling, both in the winter and in the summer seasons, while in the North Atlantic winter season the poleward shift of both the Hadley cell and the baroclinic jet is linked to a SW radiative warming. As illustrated in Figure 1, this warming is found in the lower midlatitudes, with a negligible SW effect in the higher midlatitudes due to the low solar insolation there in the winter season. The results in Table 1 also show that at least in the case of the poleward shift of the North Atlantic jet, the total cloud field also shifts poleward, which would cause decreases in total cloud cover in the lower midlatitude areas. And, surprisingly, no significant poleward shifts appear to exist in the total cloud field over the Southern oceans. Finally, we note that the positive correlations between the Hadley cell edge and the high cloud central latitude are also present in the MAM and SON seasons (Table S1), as are the negative correlations between the Hadley cell edge and the SW CRE.

The question that arises, then, is why do poleward shifts of the Hadley cell and the midlatitude jet produce a warming in the lower midlatitudes of the North Atlantic but an overall cooling at similar latitudes of the Southern Ocean, despite the consistent poleward shift of the high clouds in both regions? This question is explored in Figure 2, which shows the zonal mean regression on the Hadley cell and the jet of the SW CRE (top row), the high cloud cover (middle row), and the total cloud cover (low row), for the DJF season and for (a) the North Atlantic and (b) the Southern Ocean. Statistically significant changes are indicated by a bold line, while the mean positions of the Hadley cell edge and the jet are indicated with vertical lines.

In the North Atlantic, one can see in Figure 2a that a SW warming of approximately 1 and 2 W/m^2 occurs in the lower midlatitudes (30–40°N) with the jet and Hadley poleward shifts, respectively, and that warming corresponds to 0.5% and 2% decreases in both high and total cloud in the region. Poleward of 40°N there is no SW cooling, despite moderate but significant high and total cloud increases with the jet, probably due to the low amounts of solar insolation in this region.

Over the Southern Ocean, in contrast, Figure 2b shows that a SW cooling of about 2 W/m^2, for both Hadley and the jet shifts, occurs poleward of 45°S, corresponding to a 1% increase in both high and total cloud in the region. It must be noted that a SW cooling of 1 W/m^2 with a corresponding 2% high and total cloud increase also occurs in the JJA season, even with the low solar insolation. Equatorward of 45°S, however, there is no SW warming occurring despite small but significant decreases in high cloud with the poleward Hadley shift. This is likely due to the fact that the total cloud field does not show significant changes in that region with either the Hadley or the jet shifts (Figure 2b, bottom row).

A preliminary explanation for this lack of total cloud change may be derived from the climatological structure of the Southern Ocean cloud field. In that region, low- and middle-level clouds dominate the total cloud amount [*Haynes et al*., 2011]. In fact, over the Southern Ocean the sum of low-top and middle-top clouds is greater than 70% for the entire 30–65°S latitude band, as shown in Figure S1. The only exception to this is a small area east of South America. This implies that poleward shifts in high clouds occur in a background of very high coverage of low and middle clouds. At the same time, that background field of low and middle clouds remains unchanged during poleward shifts of the Hadley cell and the jet, as demonstrated in Figure S2. This is why the impact of the high cloud shifts on the total cloud cover, and on the resulting CRE, is very small. Note, in fact, that the region east of South America where the low/middle cloud cover is lowest is also the region where SW warming occurs when high clouds shift poleward (Figure 1b, right column). The dynamical and thermodynamical reasons behind this response of the low and middle cloud fields to Hadley and jet changes must be further explored.

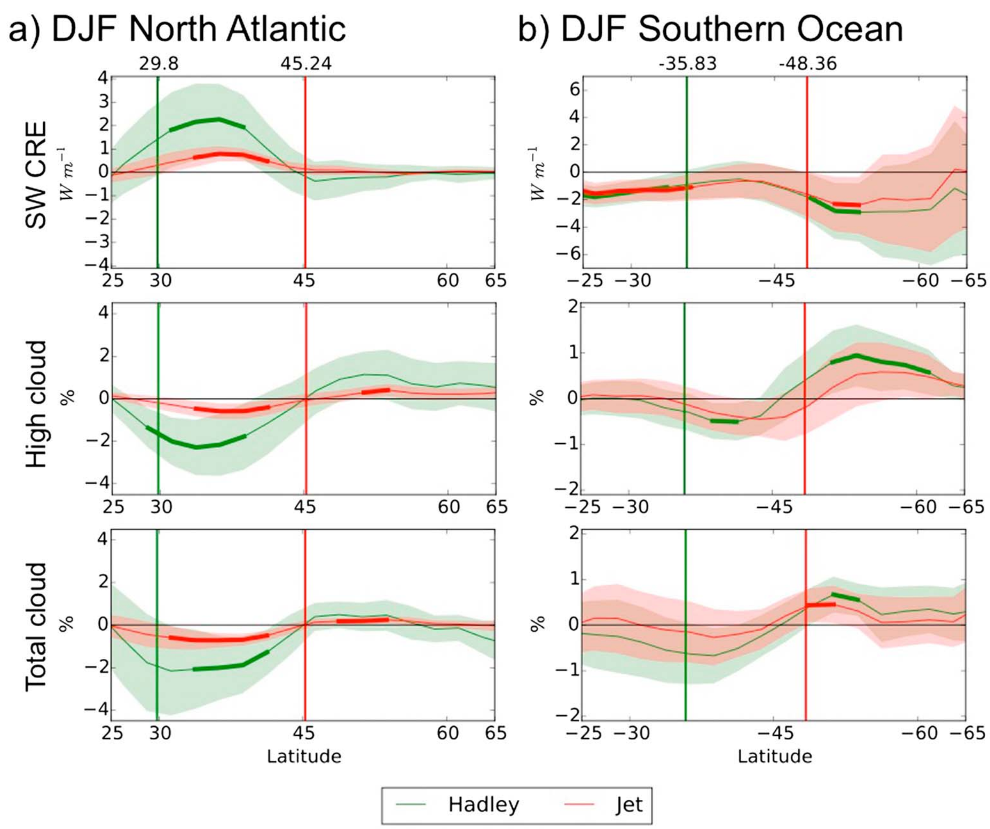

Figure 2. The regression on the Hadley cell edge (green) and jet latitude (red) of the SW CRE (top row), the high cloud cover (middle row), and the total cloud cover (bottom row), for the DJF season and for (a) the North Atlantic and (b) the Southern Ocean. Bold line sections indicate statistically significant changes, shading the 95% confidence interval, and the vertical lines indicate the climatological position of the Hadley cell edge and the jet.

4. Discussion

The results presented in this study show that Hadley cell edge poleward shifts correlate significantly with high cloud central latitude shifts in almost all basins and seasons. Baroclinic jet poleward shifts, on the other hand, correlate significantly with high cloud central latitude shifts only in the winter season of the North Atlantic storm track. This is because while in most basins and seasons, both Hadley and jet poleward shifts increase high cloud amounts at the higher midlatitude regions, Hadley cell poleward shifts also reduce high cloud amounts in the lower midlatitude regions (see Figure 2), and the combined change produces consistently significant correlations between Hadley cell edge and high cloud central latitude shifts. In the North Atlantic winter season, poleward high cloud shifts caused by either Hadley or jet shifts produce net shortwave warming, as cloud cover increases in a region of low solar insolation, while it decreases in a region of much higher incoming solar energy. Over the Southern Oceans and in all seasons, however, poleward shifts of high clouds caused by Hadley edge shifts are associated with high-latitude shortwave cooling and no lower latitude shortwave warming. This is due to the fact that in the lower midlatitude regions, where low and middle clouds show amounts of 70% or greater, the high cloud shift produces negligible radiative signatures.

The relationships between the dynamical circulations and the cloud type central latitudes derived in this study can be used to interpret the results of the recent study of *Bender et al.* [2012], who reported the existence of multidecadal poleward shifts in the midlatitude cloud field. In Figure 3 we plot the 1984–2009 time series of the Hadley cell edge latitude, the midlatitude jet latitude, and the high cloud central latitude, for DJF (top row) and JJA (bottom row), and for the three ocean basins. For the Southern Ocean, both the Hadley cell edge and the high cloud central latitude have been shifting consistently poleward, in all seasons, with comparable rates of 0.3–0.5°/decade or about 0.8–1.3° in the last 26 years. The Southern Ocean jet has shifted poleward at a similar rate only in DJF, but even then the shift is not statistically significant for that specific

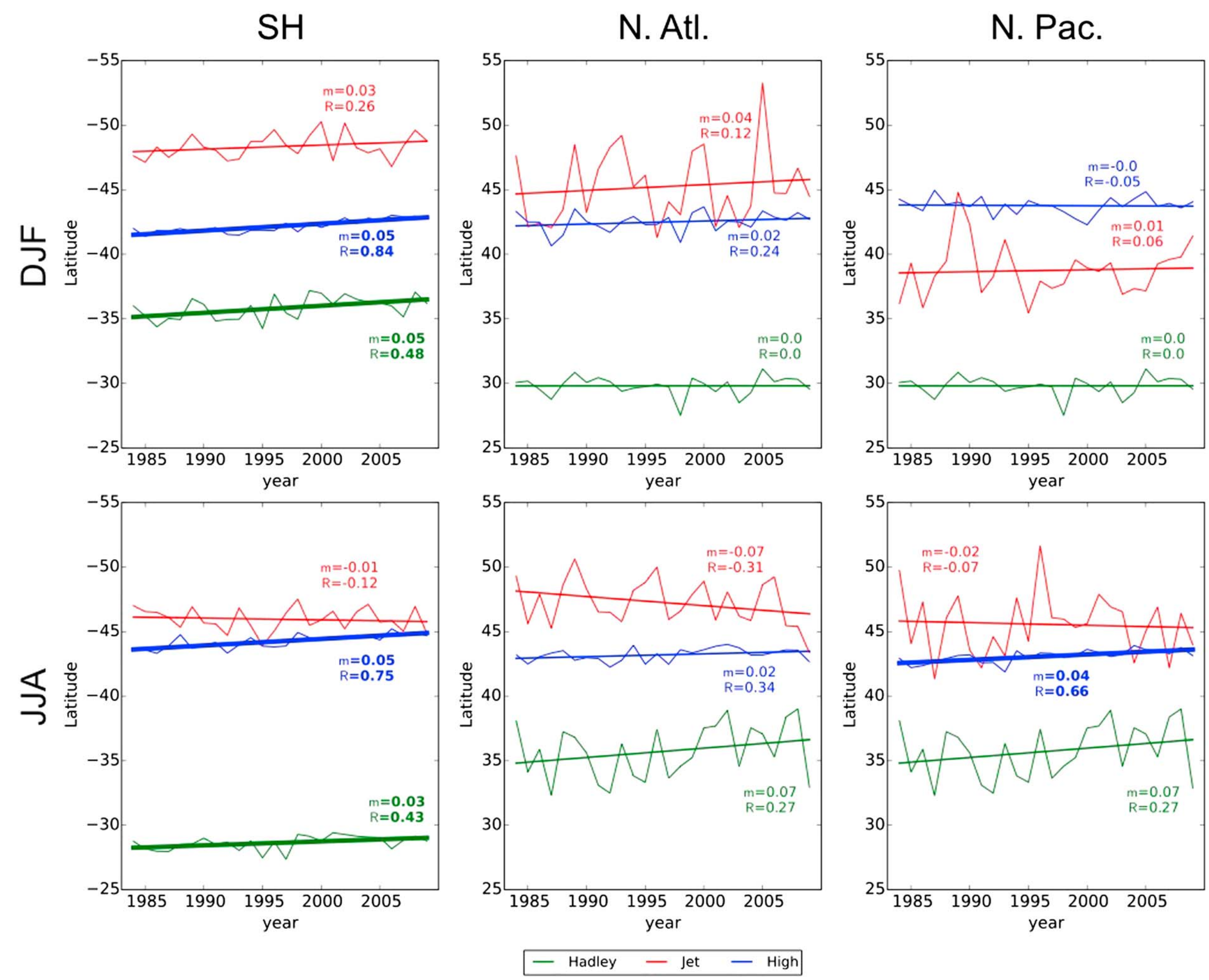

Figure 3. Time series over the 1984–2009 period of the Hadley cell edge, the baroclinic jet latitude, and the high cloud central latitude in (top row) DJF and (bottom row) JJA over the (left column) Southern oceans and the (middle column) North Atlantic and (right column) North Pacific basins. Poleward shifts are represented by positive slopes in all basins. The solid line is a linear regression of the points, the slope (*m*, in degrees per year) and correlation coefficient (*R*) values of the regressions are listed, and bold lines/numbers represent regressions significant at the 95% level.

time period. In the Northern Hemisphere regions, the poleward shifts of the high cloud field are significant only for the North Pacific summer season, and are not accompanied by corresponding significant shifts in the dynamical circulations, even though the Hadley cell edge does show a shift poleward in the Northern Hemisphere summer.

This study concentrates on the cloud and radiation response to dynamical shifts that may be caused by natural variability patterns, such as El Niño–Southern Oscillation or Pacific Decadal Oscillation, or anthropogenic influences such as ozone depletion and greenhouse warming. The analysis results suggest that the observed multidecadal Southern Hemisphere cloud field shifts are more likely related to tropical expansion than to a poleward shift in the storm tracks. This result, along with the strong correlations of the Hadley cell edge with the midlatitude high cloud field, highlights a prominent role of the Hadley circulation in affecting midlatitude cloud shifts and indicates that tropical expansion, rather than baroclinic jet shifts, might be the more important driver of midlatitude radiative feedbacks resulting from cloud-dynamics interactions. It is important to note, however, that the dynamical interactions between the Hadley cell and the midlatitude jets are complex and not yet fully understood. Our analysis also shows that the high cloud amount is the cloud property that more strongly responds to circulation changes and that the radiative effect of poleward high cloud shifts can differ significantly, even in sign, depending in part on the properties of the background cloud field in which the high clouds are embedded.

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