

The seasonal cycle of midlatitude static stability over land and ocean in global reanalyses

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[1] Using a new reanalysis data set, the seasonal cycle of the midlatitude tropospheric static stability is examined. Dry and moist static stability measures are analyzed as a function of latitude, longitude, and season. It is shown that in both the Northern (NH) and Southern Hemispheres (SH), dry and moist static stability averaged over the midlatitudes maximizes in December–February. Examining the spatial structure of the stability changes indicates that the difference in the seasonal cycle between hemispheres is due to the behavior over land, which maximizes its stability in winter. Ocean surfaces have qualitatively similar cycles in both hemispheres. It is clear that moist processes are important in determining the static stability in both hemispheres. Although a previously derived moist scaling theory works fairly well to explain the seasonal changes in both hemispheres, it is argued that the large differences in seasonal cycles between land and ocean may indicate different mechanisms at play between the largely ocean-covered SH and the land-dominated NH. **Citation:** Frierson, D. M. W., and N. A. Davis (2011), The seasonal cycle of midlatitude static stability over land and ocean in global reanalyses, *Geophys. Res. Lett.*, 38, L13803, doi:10.1029/2011GL047747.

1. Introduction

[2] Static stability is a fundamental quantity in the midlatitude atmosphere, influencing phenomena such as moist convection, gravity wave speeds, baroclinic growth rates, and the tropopause height. Increases in the static stability in warmer climates have recently been suggested as a mechanism for poleward expansions of the dry zones in warmer climates [Frierson *et al.*, 2007; Lu *et al.*, 2010]. Such increases in static stability are seen in simulations of global warming throughout the midlatitudes [Frierson, 2006].

[3] In 2000, Martin Jukes published a pioneering paper which suggested that latent heating within baroclinic waves is the most important physical process for determining the static stability of midlatitudes [Jukes, 2000]. Most previous work on the midlatitude tropospheric temperature structure [e.g., Stone, 1978; Held, 1982] relied on purely dry dynamics, although previous observations of Emanuel [1988] and the related theoretical work of Emanuel *et al.* [1987] showed the importance of slantwise moist convection. The notion that latent heating can set the vertical profile of temperature of midlatitudes makes intuitive sense given the importance of moisture on the horizontal temperature structure on Earth. In their Figure 2a, Trenberth and Stepaniak [2003] show that

latent energy dominates the atmospheric energy divergence in the subtropics in both hemispheres, and is the largest component of the energy convergence up to 60 degrees in the Northern Hemisphere (NH) and to 70 degrees in the Southern Hemisphere (SH).

[4] Jukes' specific theory suggested that moist neutrality occurs in cyclones, setting a lower bound for stability. Variance of static stability is produced from meridional advection within synoptic waves, creating a temperature structure that is stable to moist convection in the mean. A mixing length closure is then used to relate variance generation to meridional gradients and results in Jukes' scaling for moist static stability:

$$\frac{\partial \theta_e}{\partial z} \sim \frac{\partial \theta_e}{\partial y}. \quad (1)$$

Jukes [2000] showed that the scaling works well to explain the NH static stability but fails in the SH.

[5] Recent observational studies have provided support for the Jukes [2000] theory. Korty and Schneider [2007] found that continents in the midlatitudes in summer and storm tracks over ocean in winter feature frequent slantwise convective neutrality. Pauluis *et al.* [2008, 2009] show that the global isentropic circulation in midlatitudes is significantly stronger on moist isentropes than on dry isentropes due to the large amount of diabatic ascent within the midlatitude storm tracks, which doubles the moist circulation. The thermodynamic character of the midlatitude ascent shows the characteristics of moist convection, with nearly the same equivalent potential temperature at the surface and at the tropopause.

[6] A number of modeling studies have also provided support for the Jukes [2000] scaling. In a simplified physics aquaplanet general circulation model (GCM), Frierson *et al.* [2006] found that higher moisture content climates have significantly higher static stabilities than dry climates, the driest of which approach nearly dry neutral static stability out to approximately 50 degrees. A follow-up study to this was performed by Frierson [2008], who studied midlatitude static stability in the same simplified physics GCM as in the above study and also in a comprehensive physics GCM, both over aquaplanet boundary conditions. Both models show excellent agreement with the Jukes [2000] scaling; one can predict the midlatitude static stability given only information about the sea surface temperatures (SSTs) using equation (1) evaluated at the surface.

[7] A moist control of static stability would suggest that midlatitude dry static stability would increase with global warming, unless there is a large compensating decrease of meridional gradients. Such a robust increase in static stability has been identified by Frierson [2006], with static

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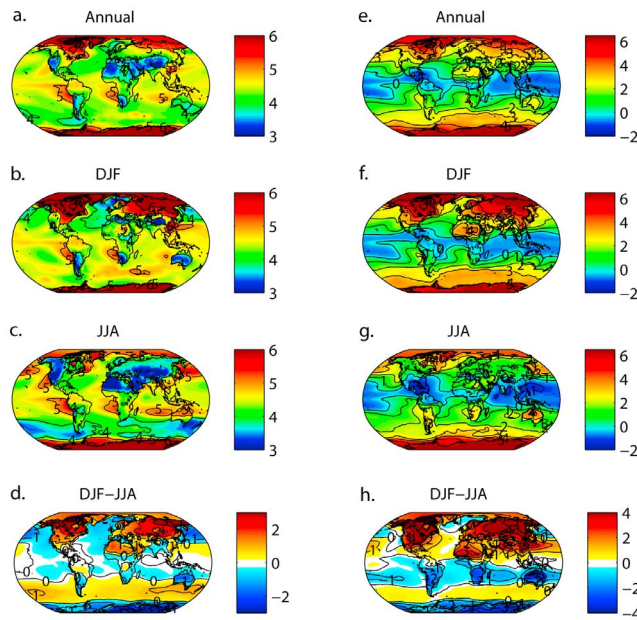


Figure 1. The vertical average of $\frac{d\theta}{dz}$ from the surface to 400 hPa (K/km) for (a) the annual mean, (b) DJF, (c) JJA, and (d) DJF-JJA, and the vertical average of $\frac{d\theta_e}{dz}$ from the surface to 400 hPa for (e) the annual mean, (f) DJF, (g) JJA, and (h) DJF-JJA.

stability increasing in all model-season-hemispheres except for a two models with very large polar amplification over NH land in winter. Increases in dry static stability occur especially in summer, and in the SH. In the work of Frierson [2006], however, the Jukes [2000] scaling is best applicable in the SH, which is attributed to differing responses over land and ocean in the NH with global warming. The fact that the aquaplanet experiments and the SH in global warming experiments support the Jukes [2000] scaling, yet the original Jukes [2000] paper finds a lack of agreement in the more ocean-covered SH is a theoretical dilemma. In this paper we examine more recent reanalysis products and find better agreement of moist scalings in the SH than the NH, in contrast to the original Jukes [2000] study, and point out significant differences in the static stability seasonal cycle over ocean versus land.

2. Results

[8] We use the Modern Era Retrospective-Analysis for Research and Applications (MERRA) data set from NASA [Bosilovich et al., 2008; Rienecker et al., 2011], a new high-resolution reanalysis which took particular care to represent the hydrologic cycle and humidity distribution correctly. The MERRA data set has resolution of $\frac{1}{2}^\circ$ latitude $\times$ $\frac{1}{3}^\circ$ longitude resolution and 42 pressure levels. We utilize monthly averaged data from 1979 to 2009. Stability measures are constructed using surface (10 m) variables and pressure level data aloft. We calculate tropopause heights using the method of Reichler et al. [2003] using the WMO tropopause definition of 2 K/km lapse rate.

[9] We first examine annual and seasonal mean dry static stability as a function of latitude and longitude, starting with the average $\frac{d\theta}{dz}$ between the surface and 400 hPa. We will

consider stability measures which average from the surface to the tropopause as well; the primary reason we consider the 400 hPa definition first is that it does not have jumps caused by discontinuities in the tropopause height at the subtropical jet, and allows one to focus clearly on differences in static stability between land and ocean. Average dry static stability in the annual mean, DJF, JJA, and DJF-JJA are plotted in Figures 1a–1d. Several features stand out in the annual mean dry static stability plot. There are very high stabilities near the poles, with values exceeding 5 K/km over all of Antarctica and much of the Arctic. Local minima of dry stability occur over subtropical continents, with values below 3.5 K/km. Local maxima of stability occur near stratocumulus regions and in the equatorial east Pacific, although these two features are significantly less prominent if static stabilities above the boundary layer only are averaged (not shown).

[10] In terms of annual mean dry static stability in the midlatitudes, the Southern Ocean exhibits approximately zonally symmetric stability values of 4.3 K/km, with slightly lower values near the Drake Passage and slightly higher values below South Africa. In the NH midlatitudes, there is significantly more zonal asymmetry. Low values of stability occur over the American Southwest, Southern Europe/North Africa, and the Middle East through the Gobi Desert, while eastern Canada and central Russia have larger stability values. Over ocean, static stability is generally in between the extremes over land, although there are clear variations over ocean as well, with higher static stability over the North Pacific than the North Atlantic by approximately 0.5 K/km.

[11] Examining the DJF and JJA static stability and their difference in Figures 1b–1d, the most striking change with the seasonal cycle is over land, with increased stability in winter and decreased stability in summer, indicated by red colors in the NH and blue colors in the SH in Figure 1d. Ocean surfaces in midlatitudes generally exhibit the opposite seasonality, with increased stability in summer and decreased in winter. The seasonal cycle of midlatitude oceans is similar in the NH and the SH, indicating that significant land-sea contrast is evidently not necessary for increased stability over ocean in summer. Subtropical oceans generally have opposite seasonality to the midlatitude oceans, with slightly increased stability in winter and decreased stability in the summer.

[12] Zonal mean dry static stabilities for the annual mean, DJF, and JJA, plotted out to 60 degrees only to focus on the midlatitudes, is shown in Figure 2a. The seasonal cycle in the SH is as described above, with summer exceeding the annual mean by approximately 0.3 K and winter having approximately 0.4 K lower dry stability than the annual mean. The NH shows opposite behavior in the zonal mean, with winter stability exceeding the annual mean. The seasons start to diverge at approximately 40°N and seasonality increases poleward. The seasonal cycle is skewed as well, with more increase in stability in DJF than decrease in JJA. The difference in NH and SH seasonal cycle is primarily due to the fact that the changes over land dominate in the NH. The large difference in behavior over land versus ocean means that the zonal mean is not truly representative of either surface in the NH.

[13] Zonally averaged dry static stability averaged between the surface and the WMO tropopause is plotted in Figure 2b. We consider this static stability measure as well

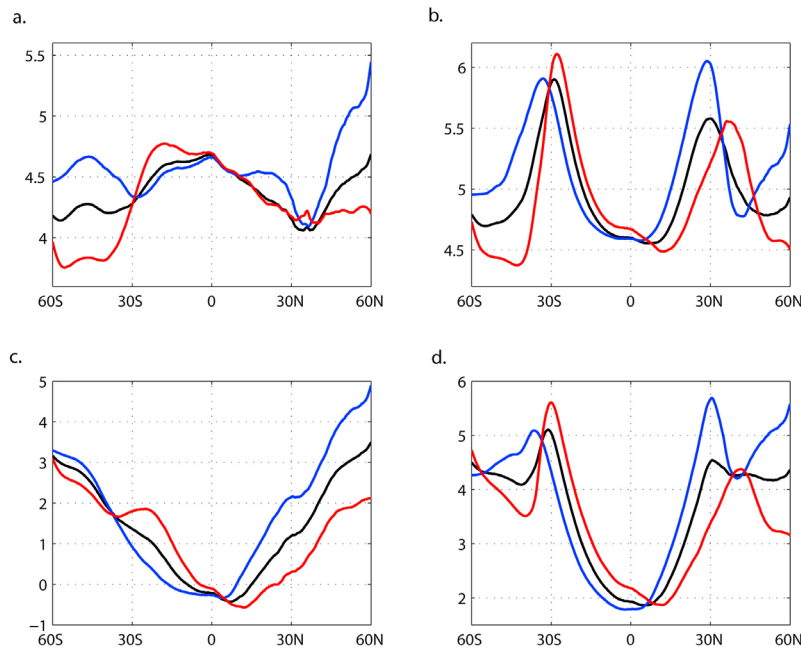


Figure 2. The zonal mean (a) $\frac{d\theta}{dz}$ averaged between the surface and 400 hPa, (b) $\frac{d\theta}{dz}$ averaged between the surface and the tropopause, (c) $\frac{d\theta}{dz}$ averaged between the surface and 400 hPa, (d) $\frac{d\theta}{dz}$ averaged between the surface and the tropopause. In each plot, black is the annual mean, blue is DJF, and red is JJA.

because theoretical studies suggest that averages up to the tropopause must be considered for use in scaling theories [Frierson, 2008]. The structure of tropical static stabilities change significantly, with decreases in dry stability in the deep tropics due to approximately dry neutral conditions in the tropical upper troposphere, and sharp increases in dry stability peaking near 30 degrees in each hemisphere. The increases are associated with higher static stabilities near the tropopause around the subtropical tropopause region. Poleward of the tropopause jump region, the static stabilities and their seasonal cycles behave similarly as in Figure 2a, with slightly reduced magnitude of seasonal changes.

[14] We next study the moist static stability, defined as the average $\frac{\partial\theta_e}{\partial z}$ between the surface (10 m) and 400 hPa. This definition takes into account the effect of both the vertical temperature structure and the moisture content on moist stability. The latitude-longitude plots for the annual mean, DJF, JJA, and DJF-JJA are shown in Figure 1e–1h. The moist static stabilities have a significantly larger range than the dry stabilities. In the tropics the moist stability is negative, reflecting the local minima of θ_e in the midtroposphere. Moist stability measures averaged up to the tropopause exhibit positive static stability everywhere (not shown). Near the poles, the moist stabilities are approximately the same high values as the dry stability, reflecting the low moisture contents of polar regions.

[15] In moist stability in the annual mean (Figure 1e), continents stand out less from surrounding oceans. This is because ocean areas have higher moisture content, which reduces moist stability. Deserts also stand out less from surrounding continental areas when compared with Figure 1a; the Sahara, for instance, changes from a large local minimum in dry stability to a slight local maximum in moist stability. With the exception of just a few regions, moist stability exhibits a rather uniform increase from lowest

values in the deep tropics to highest values at high latitudes at all longitudes. Midlatitudes in the SH exhibit moist stability values ranging from 1 K/km at 30 degrees to 3.5 K/km in the Southern Ocean south of Africa. In the NH midlatitudes, oceanic values range from 0 K/km in the west Atlantic and Pacific at 30 degrees to 3 K/km in the North Pacific. Large zonal contrasts in moist stability exist especially on the east side of continents which exhibit large values as compared with nearby oceans.

[16] The seasonal cycle of moist stability, plotted in Figures 1f–1h, shows a large difference between land and ocean surfaces, with land surfaces clearly more stable in winter everywhere. Differences of 3 K/km between ocean and land are typical at the same latitude in the NH in DJF in Figure 1f, and differences that are nearly as large are seen between SH continents and their surrounding ocean areas in JJA in Figure 1g. In summer the destabilization of land surfaces becomes especially more clear over moist continental regions such as southeast North America and the Asian monsoon regions. The especially high moisture contents of these regions assures that the areas have small (and often negative) moist stability despite their large dry stability in Figures 1b–1c. Over ocean there are significantly smaller seasonal changes of the moist stability, as can be seen in Figure 1h. In the Southern Ocean in midlatitudes, summer moist stability exceeds winter values by approximately 0.5 K/km. At lower latitudes of the SH, the seasonal cycle is reversed, with higher moist stabilities in winter. Similar features can be identified over the NH oceans, although only higher latitude oceans show higher moist stabilities in summer (north of ~50 degrees in the Atlantic and north of ~40 degrees in the Pacific). South of this, ocean surfaces generally show larger moist stability in winter, although with significantly muted amplitude as compared with land surfaces.

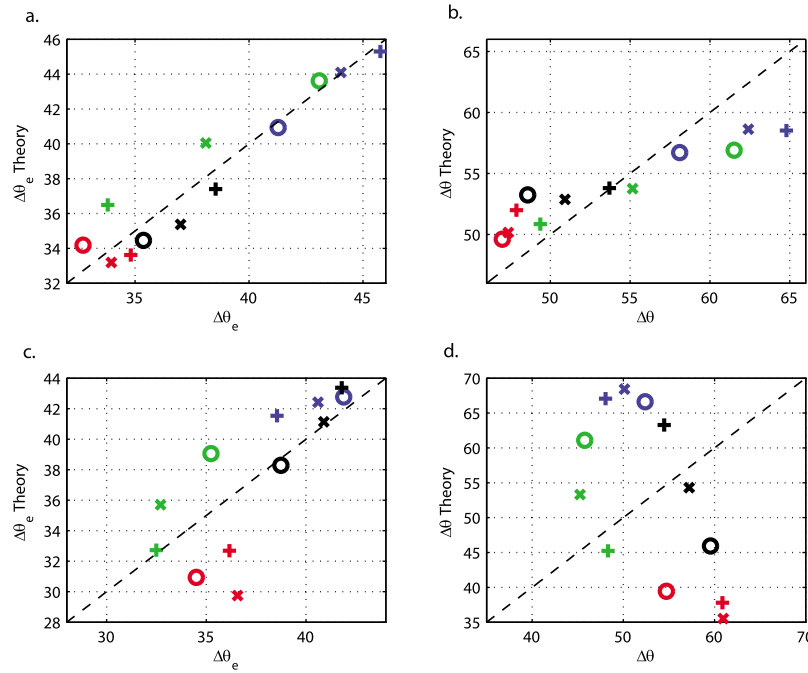


Figure 3. Scaling theories versus observed midlatitude static stabilities. (a) The moist scaling theory versus observed moist static stability for the SH. (b) The dry scaling theory versus observed dry static stability for the SH. (c) The moist scaling theory versus observed moist static stability for the NH. (d) The dry scaling theory versus observed dry static stability for the NH. In each plot, blue colors indicate DJF, green is MAM, red is JJA, and black is SON, with circle, cross, and plus as the three consecutive months in each sequence. See text for full definitions of the theoretical prediction and average stability definitions.

[17] We next examine zonal mean moist stabilities in Figure 2c. In the tropics the winter moist stability exceeds the corresponding summer value by up to 2 K/km in the NH and slightly less in the SH. The seasonality generally increases with latitude within the tropics. In the extratropics, however, the hemispheres are starkly different, with DJF moist stabilities exceeding the JJA and annual mean values in both hemispheres. This is more pronounced and more latitudinally uniform in the NH, while in the SH the behavior starts at approximately 40 degrees and increases slightly polewards. In the NH midlatitudes, DJF moist stability exceeds JJA values by between 2–3 K/km, while in the SH, DJF moist stability values are up to 0.5 K/km larger than JJA. It is clear from inspection of Figures 1e–1f that the seasonal cycle of the SH reflects the behavior of the ocean, while in the NH the seasonal cycle is reflective of land surfaces. As stated before, the seasonalities over both ocean and land individually are qualitatively similar in the two hemispheres. It is primarily the land fraction difference in the two hemispheres that leads to the different behaviors in Figure 2c.

[18] As a final characterization of the moist static stability, we plot the zonally averaged moist stability averaged up to the tropopause in Figure 2d. In this diagnostic, the tropics now exhibit positive moist stability at all latitudes, so there is less variation of this diagnostic as compared to the moist stability averaged only up to 400 hPa. As in the dry stability averaged up to the tropopause, there is a local minimum of this field near the equator, with increasing values out to the subtropical jet and tropopause break region at 30 degrees. Despite the additional complexity associated with the tropopause break, midlatitude moist stabilities exhibit qualita-

tively similar seasonal variations in this diagnostic. In the SH, DJF moist stability exceeds JJA values by up to 0.8 K/km, while in the NH DJF values exceed JJA by up to 2 K/km. Again, the difference between hemispheres in whether the winter or summer moist stability is larger is due to the land fraction differences in the NH and SH.

3. Comparison With Scaling Theories

[19] In section 2 we have shown that midlatitude dry and moist static stability exhibit rather different seasonalities as a function of location, and that these differences are primarily due to the presence of continents. Midlatitude ocean surfaces show increases of stability in the summer season, while midlatitude land is more stable in winter. These results imply that any kind of zonal or midlatitude average will not be completely representative of all of the areas averaged over, especially in the NH, where differences of 3 K/km between adjacent areas are typical. Keeping this limitation in mind, we evaluate the efficacy of scaling theories to explain the midlatitude averaged static stability as has been studied in previous works [Stone, 1978; Jukes, 2000].

[20] In Figure 3, we compare the average stability between 30 and 60 degrees latitude for each month of the year (i.e., the average of all available Januaries, etc.) with predictions from different scaling theories based on meridional gradients averaged between 30 and 60 degrees. As in the work of Frierson [2008], we use the θ and θ_e difference between the surface and the tropopause as dry and moist static stability measures, respectively. Dry and moist theoretical predictions are calculated as the surface meridional gradient of θ and θ_e , respectively, area-weighted and multiplied by a

length scale constant empirically calculated using a best-fit procedure. We report the best-fit length scale for the cases where the theoretical prediction is successful.

[21] We begin with the moist scaling theory for the SH in Figure 3a. In contrast to the results reported by *Juckes* [2000], the moist scaling works rather well to explain the SH seasonal cycle. Larger gradients in moist stability in summer, caused primarily by higher moisture contents especially at low latitudes, accompany the higher moist static stability during these months. The correlation coefficient for this scaling is 0.87 and the best-fit length scale is 3300 km. This scaling would suggest that the larger dry static stability seen in SH summer is due in part to increased moisture content in that season, and in part due to the increased gradients of θ_e .

[22] In Figure 3b, we plot the dry scaling relation for the SH. The scaling does not perform as well as the moist scaling, but there is still some agreement. Meridional gradients in potential temperature increase during winter at high latitudes, but there is a compensating decrease in the lower midlatitudes due to the large land fraction near the edge of the midlatitudes. The increase in temperature gradient at the edge of these continents during winter is not large enough for the scaling to have as good fidelity. Dry scalings perform significantly worse than moist scalings if other latitude bands are considered (such as 40–60 degrees, not shown).

[23] In Figure 3c, we plot the moist scaling relation in the NH. While there is some correlation ($R = 0.70$), the scaling performs less well than in the SH. Meridional gradients maximize in winter and fall due to the large temperature gradients in this season, but have minimum values in spring rather than summer as required for the scaling to have complete fidelity. We suggest that part of the reason for the poorer performance of the scaling as compared with the SH is the large variation in moist stability and meridional gradient of equivalent potential temperature with location.

[24] We show that dry scalings perform even worse than moist scalings in the NH in Figure 3d. This relation shows the incorrect sign of the behavior, with dry meridional gradients maximizing in winter and minimizing in summer, opposite to the zonally averaged behavior. One might notice that in Figure 3d, the observed dry stability is largest in July and August, and is smallest in May and April. The apparent difference from Figure 2b is that the tropopause height increases in summer (due primarily to higher temperatures), resulting in increased stability in those months. Both dry and moist scaling relations that use bulk static stability averaged up to a fixed level only (e.g., 400 hPa) rather than up to the tropopause work similarly poorly in the NH (not shown).

4. Conclusions

[25] We have shown that in contrast to results given in the original study of *Juckes* [2000], moist scaling theories work remarkably well in the SH, and somewhat less well in the NH. Dry scaling theories perform poorly in both hemispheres. This helps to reconcile results from aquaplanet simulations of *Frierson* [2008], in which ocean-covered surfaces also show fidelity with the scalings of *Juckes* [2000]. It additionally fits with the changes with global warming classified by *Frierson* [2006], in which the SH increases its dry static stability in a manner that approximately fits with the *Juckes* scaling. While most models

show increases in dry stability in the NH with global warming in all seasons, the moist scaling theory works poorly to explain the spread of results in the NH in the *Frierson* [2006] study.

[26] The observed seasonal cycle of the midlatitude dry stability in the SH shows a pronounced maximum in DJF, and the moist static stability additionally maximizes in this season (although to a lesser amount). From the perspective of the moist scaling theory, the dry static stability increases in SH summer due to the higher surface moisture content in that season. The moist static stability increases as well in this season due to the fact that moisture content increases primarily on the equatorward side of midlatitudes, due to the nonlinearity of Clausius-Clapeyron, causing meridional moist gradients to increase in DJF.

[27] The large difference in the seasonal cycle over land and over ocean in the NH suggests several additional follow-up studies. We have shown that the ocean surface in the NH behaves similarly to that in the SH, with increases in summer and decreases in winter. Over land, the static stability becomes significantly larger in winter, and since there is more land than ocean in the NH, the zonally averaged behavior is dominated by this surface. It is unclear how much of the observed seasonal cycle in the NH ocean is due to interactions with the neighboring continents, and how much can be explained by zonally symmetric arguments as in the SH and in the original *Juckes* [2000] study. We hope that if GCMs can replicate this observed seasonal cycle, some idealized modeling experiments may be able to answer these questions. Such studies are in progress by the authors. The large variation of static stability between ocean and land in the NH likely strongly influences the character of baroclinic eddies in this hemisphere. One such influence of the high static stability over land in the winter appears to be the midwinter suppression of eddy activity in the North Pacific [*Penny et al.*, 2010].

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