GLOBAL TEMPERATURE REDISTRIBUTION BY RECURVING TROPICAL CYCLONES: A WILDCARD IN SUBSEQUENT MIDLATITUDE WINTER SEASONAL FORECASTING

Robert E. Hart
Department of Meteorology, Florida State University, Tallahassee, FL
rhart@met.fsu.edu

1. INTRODUCTION

It has long been taught in atmospheric science that tropical cyclones (TCs) play a role in the transport of heat and moisture poleward. Along with the oceanic currents, the Hadley circulation, latent heat release, and baroclinic eddies, TCs contribute toward preventing the tropics from continuously heating and the poles from continuously cooling from net radiation surplus and deficit, respectively. Early results (Figure 1 from Newton 1972) suggested the various roles of the ocean, atmosphere, and latent heating were fairly evenly spread, although the latitudinal distribution was far from uniform.

Despite this long-lived understanding, the role of TCs in primarily the atmospheric and latent heat transport has remained unquantified. With few exceptions, the pole to equator temperature gradient does not directly produce TCs. However, their very formation necessarily weakens this gradient if they leave the Hadley cell. Thus, recurving TCs are largely a wildcard when it comes to the energy budget of the atmosphere, since their formation does not reduce the baroclinic instability source, but can reduce it if moved far enough poleward of the Hadley cell. If the role of recurving TCs can be quantified, the response of the subsequent winter climate may have increased predictability since the long-term zonal-mean pole to equator temperature gradient is a relatively stable quantity. If one component of the transport in Figure 1 is weakened, the others may adjust to take up the slack since the resulting potential energy of the atmosphere might be higher than normal.

2. DATA AND METHOD

Only the northern hemisphere (NH) is considered in this study, as the historical record of TC frequency is more accurate there, as are the historical atmospheric fields (e.g. reanalysis) since land and oceanic observations are most frequent there. A TC is termed "recurving" and deemed as relevant for this study if it formed at a latitude no more than 30°N and reached a latitude of at least 40°N before dissipation (e.g. Figure 2a,b). Such TCs are argued to have contributed most significantly to the meridional transport of heat, as they generally have moved poleward of the Hadley cell and beyond the trades that would carry their energy back into the tropics after dissipation. TCs that dissipate before reaching 40°N (Figure 2c) or do not form until after 30°N (Figure 2d) are argued to not have contributed significantly to the poleward transport of heat out of the Hadley cell, and thus are not considered here. An active (inactive) recurving season is defined as more than one standard deviation above (below) the 50-year recurving climatological mean (1955-2004).

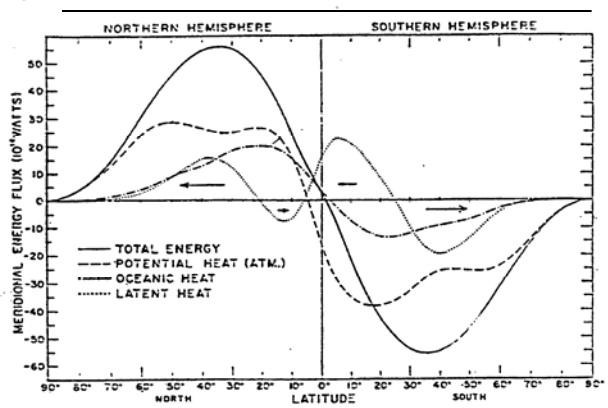

Figure 1: Zonal and annual mean heat flux. The thicker solid line indicates total heat flux. Also shown are contributions to the total by two atmospheric components and the ocean. The atmospheric transport can be in latent (dotted line) or sensible (dashed line) forms. The oceanic transport (dot-dashed) is calculated as a residual from the other three curves. Figure and caption from Newton (1972).

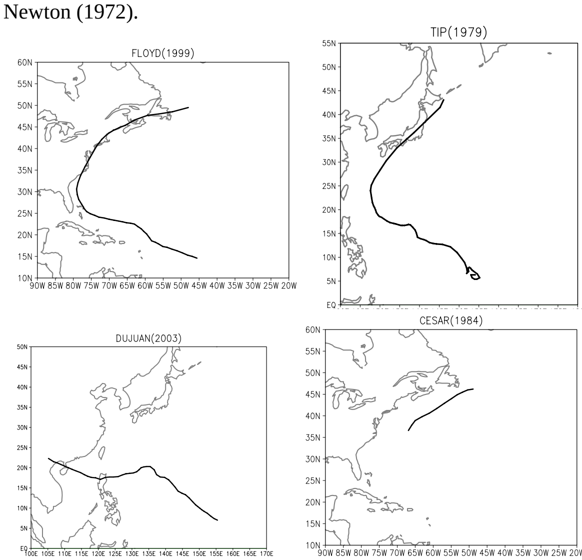

Figure 2: Examples of storms that qualify for analysis in this study (Super Typhoon Tip, 1979; Hurricane Floyd, 1999) and those that do not (Typhoon Dujuan, 2003; Tropical storm Cesar, 1984).

3. RESULTS

a. RECURVING TC CLIMATOLOGY

The historical archive of TC tracks is provided by the best-track post-analysis for each of the basins (Jarvinen et al. 1984; Neumann et al. 1993). The distribution of recurving TCs for each relevant NH basin from 1955-2004 is shown in Figure 3a, with approximately 46% contribution from the Atlantic basin, 53% from the western Pacific, and around 1% from the eastern Pacific. There is on average 9 recurving NH TCs each year, with a standard deviation of 3.9. Thus, an inactive recurving season is defined as 5 storms or less with an active as 12 storms or more. The distribution of these active and inactive years is shown in Figure 3b. In each subset (active recurving and inactive recurving), there is each at least one strong El Niño and strong La Niña, with several cases of near-normal conditions, suggesting that ENSO is not a driving factor in distinguishing either the frequency of NH recurving TCs, nor the subsequent winter climate. The mean year of each subset is approximately the same (1980 vs. 1981), arguing that superficially there is no long-term trend evident in hemispheric-total recurving TCs. Further, all decades from 1950s through 2000s are represented in both inactive and active recurvature sets.

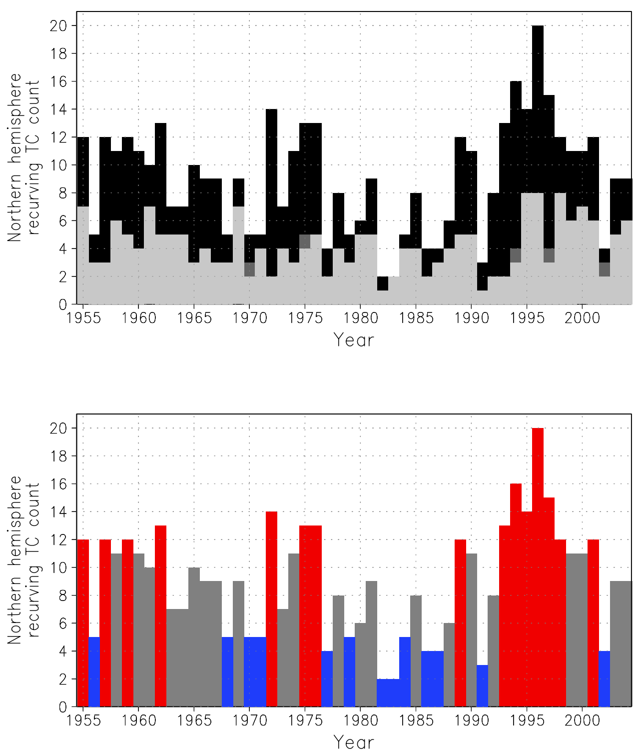

Figure 3: top) The basin-specific contribution to the northern hemispheric recurving total. Black represents the western Pacific contribution, dark gray the eastern Pacific and light gray the north Atlantic. bottom) Frequency of northern hemispheric recurving TCs. Red (blue) years are years in which the frequency was at least one standard deviation above (below) normal of 9.

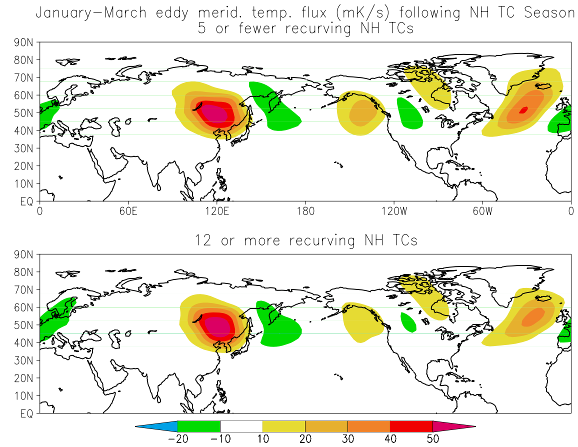

Figure 4: Impact of recurving TCs on the subsequent January-March 500mb meridional heat flux. The magnitude of meridional heat flux in the western hemisphere is significantly increased following less active NH recurving TC seasons. Data source: NCAR/NCEP reanalysis.

b. 500mb EDDY TEMP. FLUX

The hemispheric three-month-mean conditions at 500mb for the January through March following each year in the blue and red subsets of Figure 3b were produced using the NCAR/NCEP reanalysis dataset (Kalnay et al. 1996). The three-month-mean eddy meridional flux of temperature (v'T'), where the prime represents anomaly from the mean along a latitude circle, is shown for the composite-mean inactive recurving season (Figure 4a) and composite-mean active recurving season (Figure 4b). Positive values represent correlation of temperature anomaly with meridional wind anomaly, and the poleward flux of warm air (or equatorward flux of cold air). Following inactive recurving seasons, the regions of climatological strongest eddy forcing in the western hemisphere (north Atlantic and northeast Pacific) both strengthen.

The zonal mean of the eddy flux shown in Figure 4 is presented in Figure 5a. It is here that the impact of recurving TCs on the strength of the subsequent winter climate becomes most apparent. The strength of the zonal mean eddy temperature flux peak is 15% stronger following inactive recurving seasons than following active recurving seasons. When areally-averaged from 40°N to the pole, there is an average 15% difference as well. With an average recurving frequency difference of approximately 10 storms between the two recurving sets (4 vs. 14 for the inactive and active recurving seasons, respectively), this implies that a typical TC reduces the subsequent midlatitude winter baroclinic energy by approximately 1.5%. The average recurving season (9 storms) thus reduces the magnitude of winter midlatitude eddy fluxes by approximately 14%, suggesting that recurving TCs do indeed play a significant role in poleward redistribution of heat.

There are natural uncertainties and biases to reanalysis datasets (Sterl 2004), which raise the question of how well the means shown in Figure 5a represent reality. A significant measure of support of the results can be found in Figure 5b, wherein the mean flux calculations were performed again, except using the ERA40 reanalysis (Uppala et al. 2005). Although the magnitude of the flux difference is approximately 50% less using the ERA40, it should be noted that the period of record for the ERA40 is August 1957- September 2002, such that three years from Figure 3 could not be included. Nevertheless, even in the ERA40, the difference between the two mean flux profiles in Figure 5b is on the order of 7%.

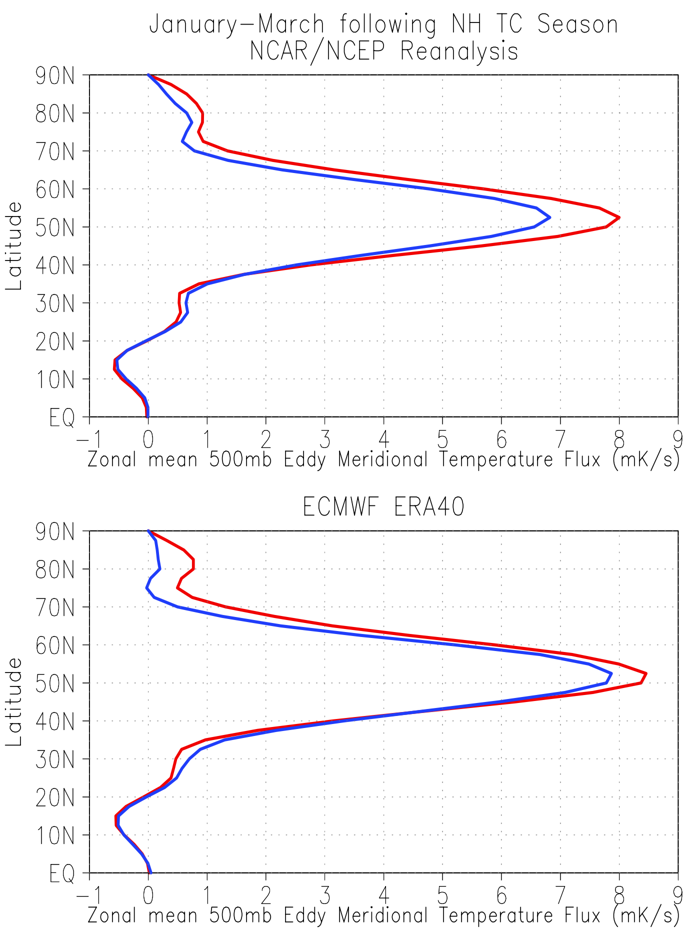

Figure 5: Top panel: Zonal mean of Fig. 4. During years of substantially decreased recurving NH TC activity (red) the subsequent NH midlatitude baroclinic activity peak is considerably more active than during years of substantially increased recurving NH TC activity (blue). The bottom panel is the same calculation, except using ERA40 Reanalysis for the period 1957-2001, illustrating that the relationship extends across other datasets although the magnitude varies.

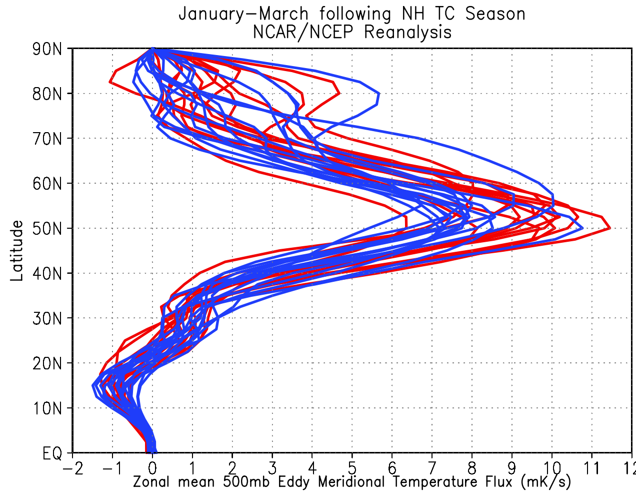

Figure 6: As in Figure 5a, except for each of the years contributing to the two means in that figure. Although there are a few outliers, it is clear that there is a clustering of the profiles and the means in Figure 5a represent well the two clusters shown here.

c. ROBUSTNESS

One must ask whether the mean profiles shown in Figure 5 are the result of a few extreme years overwhelming many near-normal years. As shown in Figure 6, this is clearly not the case. With the exception of a few outliers, the 15 active recurving profiles (blue) and 13 inactive profiles (red) cluster well into two disparate groups, each well-represented by the means in Figure 5a. When the flux is averaged from 40°N to 70°N (90°N), the difference between the two groups shown in Figure 6 is statistically significant to 98% (97%) confidence by a student's t-test. The substantial impact of recurving TCs on subsequent winter climate is shown to be a repeatable phenomenon over the past 50 years, and not the rare occurrence.

d. THICKNESS, TEMP, and PRECIP.

Ultimately, the weakening (enhancement) of the mid latitude eddy forcing shown in Figs. 4 and 5 argues that polar air would cease moving equatorward at a higher (lower) latitude, on average. Such changes would lead to warmer or colder midlatitude winter climate. Indeed, as shown in Fig. 7, during winters following inactive recurving seasons, the midlatitude lower tropospheric thickness is substantially cooler nearly across the full range of longitudes. It is evident that the baroclinic mean response is not linear: a greatly decreased recurving season does not simply result in the inverse temperature anomaly pattern of a greatly increased recurving season.

The thickness anomalies shown in Figure 7, while revealing, do not explicitly illustrate the surface impact. To elucidate that impact, the record of monthly mean temperature from the GHCN was examined and partitioned into active and inactive recurving seasons (Figure 8). Only stations with the full period of record matching the reanalysis (1955-2004) were used, eliminating most of the world unfortunately. However, for those stations with complete records in the United States (Figure 8a), it is evident that an active recurving season leads to a substantially warmer than normal winter (1°C or more for a three-month mean) in the northeast United States and a cooler than normal winter for the western United States.

Active recurving seasons also produce wetter than normal winters (Figure 8b) for the northeast United States, with a drier than normal winter for the Gulf and southeast United States coasts. Whether these precipitation anomalies result simply from the response of saturation vapor pressure to increased temperatures, or from a changed storm track, remains to be determined.

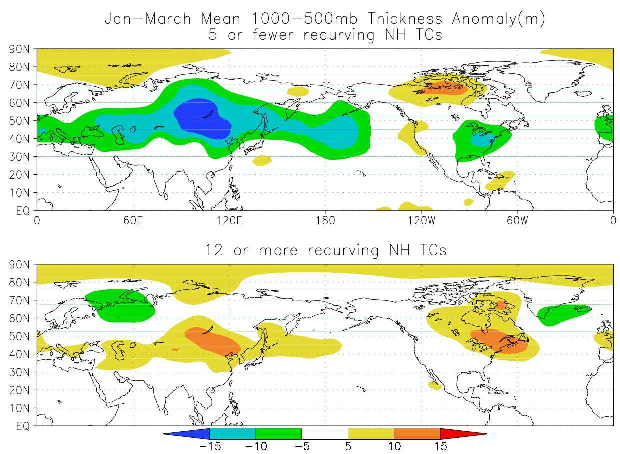

Figure 7: 1000-500mb JFM composite average thickness anomaly (from 1955-2004 mean) corresponding to Fig. 4. The amplification (weakening) of the meridional temperature gradient implied in Figs. 4,5a is well illustrated in the top (bottom) panel.

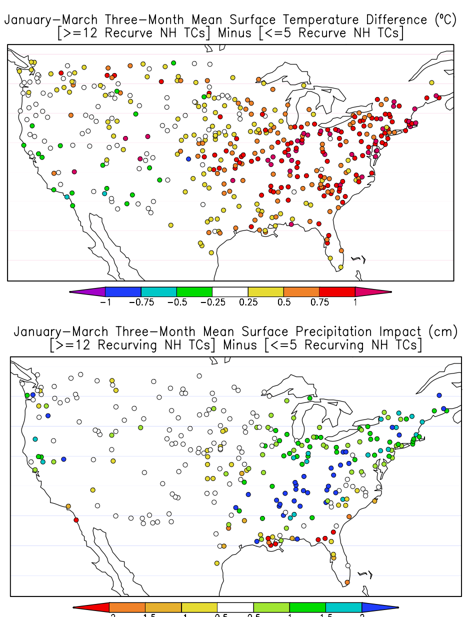

Figure 8: Top) Difference in mean JFM surface temp. between large recurving seasons and small recurving seasons (°C). Red implies a greatly enhanced recurving TC season leads to a warmer than normal winter. Bottom) As in top, except for precip. (cm). Blue implies an enhanced recurving TC season leads to a wetter winter. Source: GHCN.

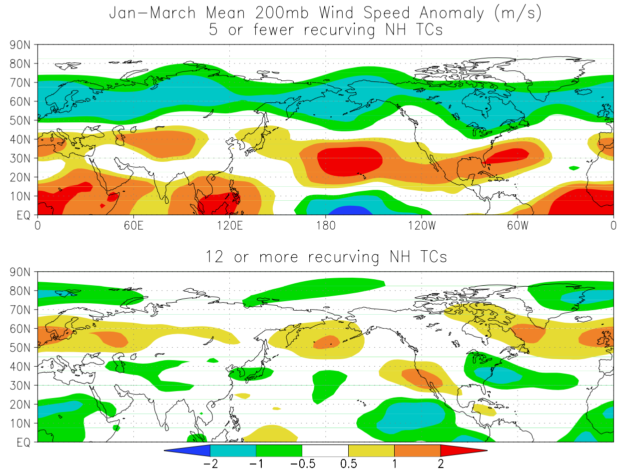

Figure 9: As in Figure 7, except for 200mb zonal wind (m/s).

e. HADLEY, POLAR, FERRELL CELL AND JET MODULATION

The changes shown in Figure 7 imply a possible change to the strength or size of the individual three-cell circulations (Hadley, Polar, Ferrell). As shown in Figure 9, especially for the winters following inactive recurving seasons, there is a very notable change in the mean meridional circulations and the jet streams that lie between each. Following inactive recurving TC seasons, the winter subtropical jetstream accelerates, the polar jet stream decelerates, both of which are consistent with an active baroclinic eddy waveguide. This result also further supports existing research that the subtropical jet stream is significantly modulated by midlatitude eddies (Feldstein and Lee 1998). The anomalous strength of the two jet streams implies a modulation of the three cells of the mean circulation. Lastly, there is some evidence of a modulation of the winter Walker Circulation following anomalous TC recurving activity. The obvious lack of symmetry between the two panels in Figure 9 suggests that response of the winter climate to an anomalous recurving TC season is not linear.

f. ELIMINATING AUTUMN FORCING

There remains the possibility that the climate difference found in Figure 5 is simply a response to inversely anomalous baroclinic activity during the prior autumn. In such a case, the recurving TCs could be simply tracers of the autumnal baroclinic activity, and thus not a true active forcing mechanism. However, as shown in Figure 10, there is no significant difference in the mean flux during the hurricane season. The anomalous winter activity (Fig. 5) is not simply the response to inversely anomalous autumn baroclinic activity, adding credence to the recurving TCs as a forcing mechanism rather than a tracer.

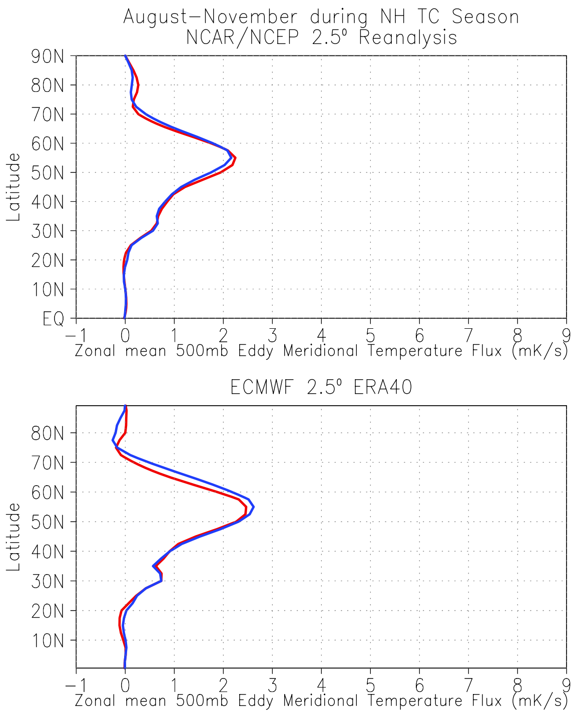

Figure 10: As in Figure 5, except for the months of August-November during the tropical season.

4. CONCLUDING SUMMARY

The results presented here quantify the role of recurving TCs in the meridional redistribution of heat. It is rather revealing that although no attempt was made to account for the varying Hadley cell location or strength, the intensity of recurving TCs, the latitude to which the TC reached, the time of year the TC occurred, or whether the TC track was truncated in the historical record, the impact of recurving TCs on subsequent winter climate was quite evident.

An average recurving TC season weakens the winter eddy flux magnitude by approximately 7-14%, depending on the historical dataset used. If a sufficient number of TCs recurve, the midlatitude baroclinic eddies will necessarily be weaker come winter since there is less potential energy to utilize for baroclinic development. In such a situation, midlatitude winter climate will be warmer, on average. If a small number of TCs recurve, the midlatitude baroclinic eddies will necessarily be stronger come winter since there is more potential energy to utilize for baroclinic development. These conclusions all argue that the consequence of poleward moving TCs is surprisingly long-lived.

With TC recurving frequency seemingly unpredictable from a hemispheric perspective, it follows that some component signal of winter climate is unpredictable until the tropical season has nearly ended. This would appear to impose some predictability bounds on winter climate using statistical or numerical climate models, unless the anomalous probability of TC recurvature frequency can be accurately estimated a-priori.

Regardless, this study suggests a unique view wherein TCs are integral to the variability and forcing of global climate, rather than incidental and solely responsive to other forcings (e.g., ENSO). This more active role of TC recurvature frequency may explain, in part, the great challenge of seasonal midlatitude winter forecasts of temperature and precipitation more than a few months in advance.

5. ACKNOWLEDGMENTS

The manuscript benefited from discussions with R. Maue, H. Winterbottom, C. Evans, J.M. Fritsch, and P. Reasor. The author appreciates early correspondence with K. Emanuel, C. Hosler, and W. Frank.

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