Extratropical Storm Tracks

Allison Wing

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1 Introduction

The extratropical storm tracks are an important part of our climate system. The cyclones that make up the storm tracks are the systems that control the day to day weather in many parts of the mid latitudes. It is thus important to understand the characteristics of the storm tracks and how they may change under global warming scenarios. In this paper, the current climatology of the extratropical storm tracks is reviewed in terms of their geographical location and extent, genesis regions, and intensity. The variation in the storm tracks over the course of the seasonal cycle as well as on interannual and interdecadal time scales is discussed. As a precursor to how the storm tracks may change in a warmer climate, the current trends in the position and intensity of the storm tracks are noted. The relevant theoretical considerations, particularly baroclinicity, are explored, as well as their application to the climate change question. Finally, projections for changes in the extratropical storm tracks in model simulations forced by emissions scenarios are discussed.

2 Current Climatology, Variability, and Trends

2.1 Current Climatology

The current climatology of extratropical storm tracks is a topic that has been studied a great deal. Before reviewing the storm track climatology, it is important to understand how these climatologies are determined. There are various ways of identifying storm tracks, and different studies use different methods. One common method of determining storm tracks is to use feature tracking. The feature tracking methods consists of identifying weather systems using a certain variable (mean sea level pressure, for instance), tracking their positions with time, and producing statistics for their distribution. A second common method of determining storm tracks is to use bandpass filtered variance statistics. This method involves determining the variance of a certain variable at a set of grid points after using a bandpass filter to isolate a frequency band associated with synoptic time scales. As in the feature tracking method, there are different variables one can use to identify a storm. Common fields used include mean sea level pressure, lower and upper

tropospheric height, lower and upper tropospheric meridional wind, lower and upper tropospheric vorticity, lower and upper tropospheric temperature, potential vorticity on the 330K potential temperature surface, and potential temperature on the 2PVU potential vorticity surface (Hoskins and Hodges, 2002). Relative vorticity at 850mb and mean sea level pressure are traditionally used to identify the lower tropospheric storm track activity, while potential temperature on the 2PVU potential vorticity surface (the dynamic tropopause) is often used for the upper tropospheric storm track activity. Although these different variables give the same broad picture of the storm tracks, there are some differences. 850mb relative vorticity identifies smaller scale features compared to mean sea level pressure, for instance. Figure 1 illustrates the scales that different variables emphasize. In addition, most variables indicate that the Atlantic storm track is stronger than

$$MSLP \atop Z_{850}, Z_{250} \Bigg\} \to \begin{matrix} V_{850}, V_{250} \\ T_{850}, T_{250} \\ \theta_{PV=2} \\ \omega_{500} \end{matrix} \Bigg\} \to \begin{matrix} \xi_{850}, \xi_{250} \\ PV_{\theta=330K} \end{matrix}$$

$$> \cdots\cdots\cdots\cdots\cdots\cdots > \cdots\cdots\cdots\cdots >$$

Large Scale   Small Scale
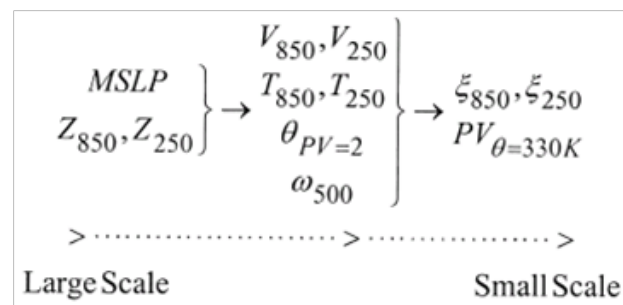
Figure 1: Scales emphasized when using different analysis fields [from Hoskins and Hodges (2002)]

the Pacific storm track, but 850mb height, meridional velocity, and vorticity indicate that they are of equal strength, while potential temperature at 2PVU indicates the Pacific is stronger (Hoskins and Hodges, 2002).A third approach to identifying storm tracks is to look at the eddy kinetic energy and the eddy energy budget. The eddy kinetic energy depends on static stability and meridional temperature gradients via the growth rate of linear baroclinic instability and is therefore an appropriate quantity to use to diagnose storm tracks.

Using the methods described above, many studies have used either NCEP/NCAR or ERA-40 reanalysis data to identify and describe the current locations and features of the extratropical storm tracks. In the Northern Hemisphere, the eddy amplitudes are a maximum in the winter over a band running across the mid latitudes from the western North Pacific across North America and the North Atlantic into Europe, with peaks in variance in both the East Pacific and the North Atlantic (Chang et al., 2002). The storm tracks extend thousands of kilometers downstream from

their genesis regions, which are more pronounced in specific regions due to orographic forcing and local ocean heat fluxes. The main cyclogenesis regions in the Northern Hemisphere are on the eastern side of the Rockies, the eastern slopes of Tibet, east of Japan, the east coast of the United States, and the western Mediterranean Sea (Bengtsson et al., 2006). Cyclolysis occurs throughout the storm track but is strongest in the Gulf of Alaska, northeast Canada, central Russia, and the eastern Mediterranean Sea. Figure 2 shows an example of the storm tracks for a specific winter, while the Figure 3 shows the winter Northern Hemisphere storm track as identified by relative vorticity at 850mb.
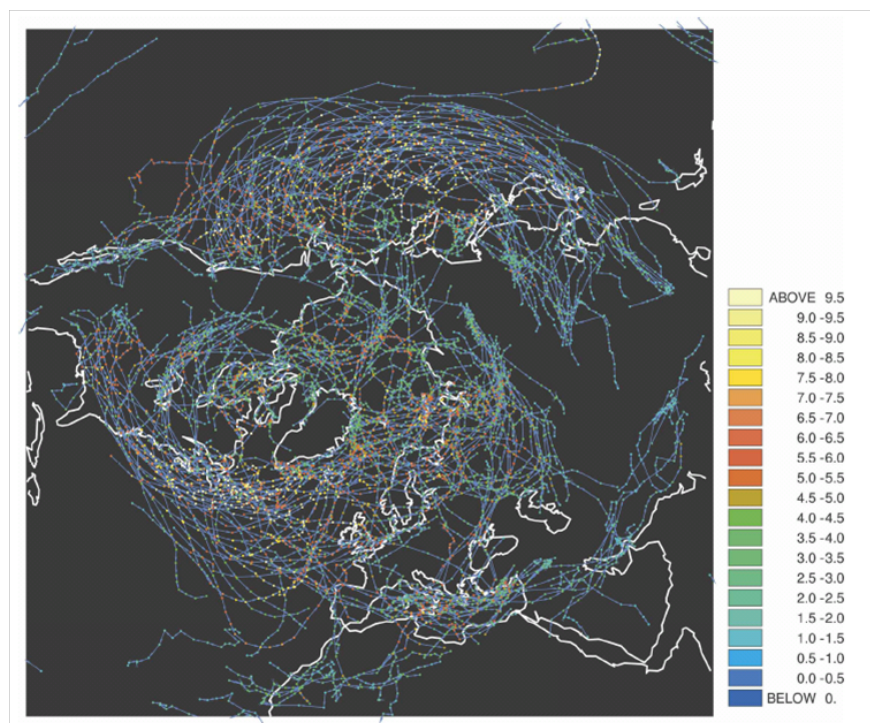

Figure 2: Example of extratropical cyclone tracks for the DJF winter of 2002-2003 from ERA-40 based on the relative vorticity at 850hPa. Only systems that last longer than 2 days and travel farther than 1000 km are included. Tracks are the blue lines and the colored dots indicate the intensity along the track in units of $10^{-5}\ s^{-1}$. [from Bengtsson et al. (2006)]

The characteristics of the storm tracks indicate that their source is the baroclinic conversion of available potential energy from the mean flow to the transients. Chang et al. (2002) note that the baroclinic growth peaks where baroclinicity is the greatest, which is at the core of the tropospheric jets just off the east coasts of Asia and North America. The storm tracks also have a vertical structure. Hoskins and Hodges (2002) describe a band starting in the subtropical
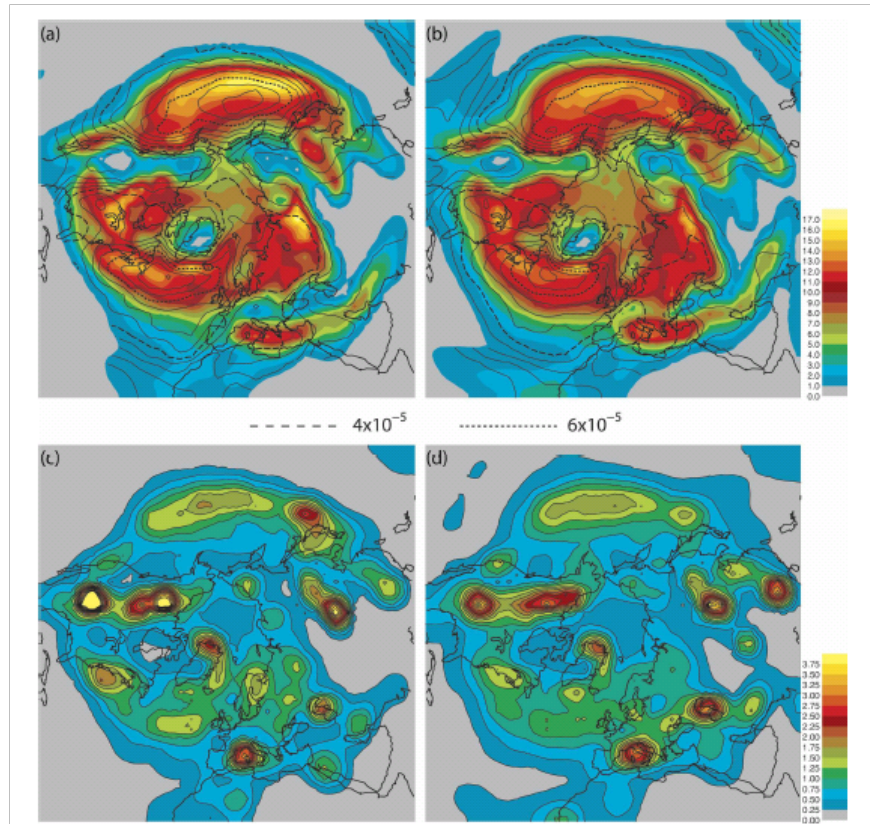
Figure 3: NH DJF cyclonic storm track statistics using relative vorticity at 850hPa for ERA-40 (1979-2002) and ECHAM5(AMIP, averaged over three realizations): (a) ERA-40 track density (color) and mean intensity (line), (b) ECHAM5 track density (color) and mean intensity (line), (c) ERA-40 cyclogenesis density, and (d) ECHAM5 cyclogenesis density. [from Bengtsson et al. (2006)]

eastern North Atlantic that spirals around the hemisphere in the upper troposphere. This band could provide a source of perturbations that amplify through the depth of the troposphere when the lower tropospheric conditions are favorable. Figure 4 shows the principal tracks for lower and upper tropospheric storm track activity.
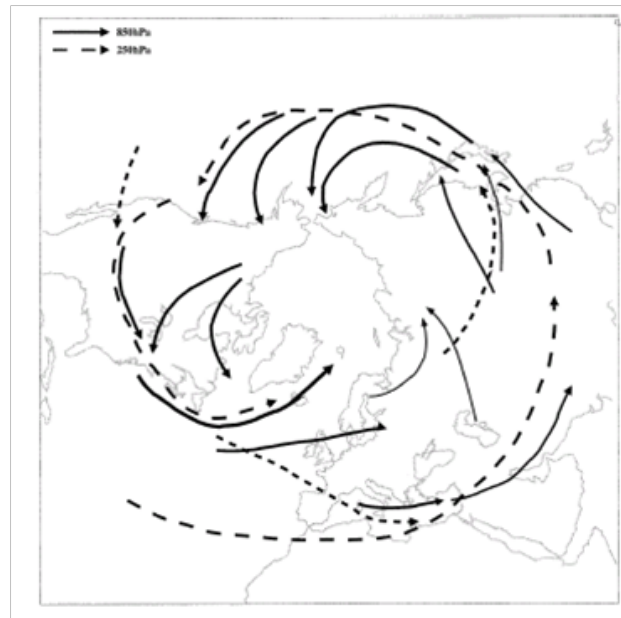

Figure 4: Schematic of principal tracks from lower (solid line) and upper (dashed line) tropospheric storm track activity based on ζ_{850} and θ_{PV2} [from Hoskins and Hodges (2002)]

Figure 5 shows the Southern Hemisphere storm track density (top panel) and cyclogenesis density (bottom panel) from ERA-40 reanalysis in the winter season (Bengtsson et al., 2006). In the Southern Hemisphere, the storm track spirals from Australia to southern South America and then from the genesis regions across the Atlantic and Indian Oceans and around Antarctica in the extreme South Pacific (Hoskins and Hodges, 2005). The genesis regions are over southern South America between $30°S$ and $45°S$ (east of the Andes) and on the Antarctic coast south of Tasmania (Hoskins and Hodges, 2005; Bengtsson et al., 2006). The maximum cyclone activity in the storm track is near 50S year round, strongest in the South Indian Ocean and weakest in the South Pacific ((Trenberth, 1991; Sinclair, 1994). In general, there is growth equatorward of $50°S$ and decay poleward of $60°S$, especially around the Antarctic coast (Hoskins and Hodges, 2005; Bengtsson et al., 2006). The Southern Hemisphere storm tracks are much more zonally symmetric than the Northern Hemisphere storm tracks. As in the Northern Hemisphere, there
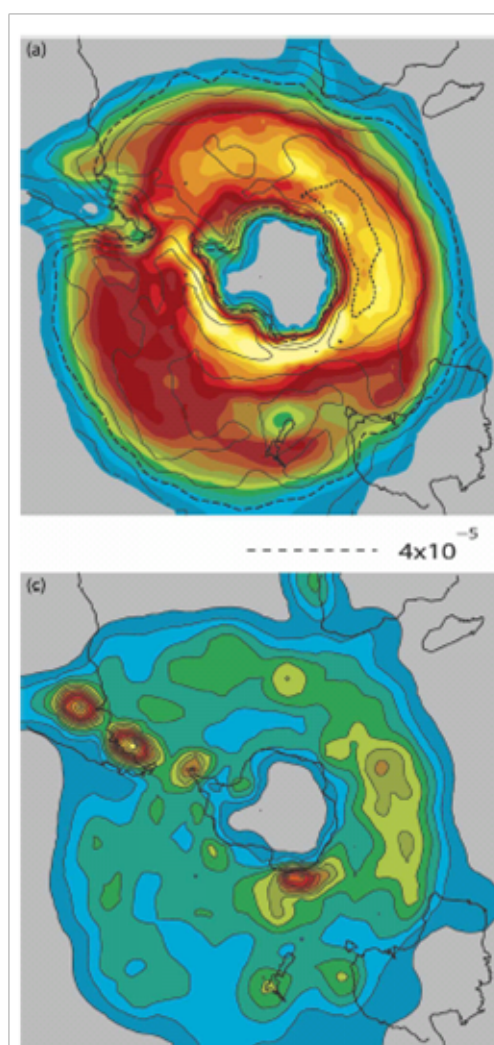
Figure 5: Track density (top) and cyclogenesis (bottom) density for Southern Hemisphere winter (JJA) from ERA-40. Relative vorticity at 850mb is used. [from Bengtsson et al. (2006)]

is evidence of a vertical structure in the Southern Hemisphere in which the upper tropospheric storm track can initiate genesis in the next region via downstream development and growth in favorable regions (Hoskins and Hodges, 2005).

The observed midwinter transient eddy energy budget can provide insights into how the storm tracks are generated, maintained, and dissipated. Figure 6 shows the eddy energy budget for the Northern Hemisphere in January calculated from reanalysis data. There are clearly peaks in transient eddy energy over the two storm track regions. The baroclinic conversion is upstream of the peak eddy energy, again implicating baroclinic conversion as an energy source for the storm tracks. Baroclinic conversion is the conversion of available potential energy from the mean flow to kinetic energy of the transient eddies. Barotropic conversion (encompassing non-baroclinic processes such as deformation) is positive over the storm track entrance regions and negative over the storm track exit regions. The divergence of total energy flux is an energy sink over the entrance regions, while it is an energy source over western North America, the east North Atlantic, Europe, and Asia. This indicates that energy is redistributed from regions where generation occurs into the downstream regions. Dissipation of the storm tracks is via barotropic conversion to the mean flow kinetic energy and surface friction. Although not shown, condensational heating adds 20% to the baroclinic generation rate over the storm track entrance regions (Chang et al., 2002).

2.2 Variability

There is a great deal of natural variability in the extratropical storm tracks. Particularly in the Northern Hemisphere, there is a clear seasonal cycle in the location and intensity of the storm tracks. The North Atlantic and North Pacific storm tracks shift equatorward in the winter and poleward in the summer and are substantially stronger in the winter than in the summer (Chang et al., 2002; Eichler and Higgins, 2006). The most intense storms in the North Atlantic occur in the winter, while in the North Pacific the most intense storms occur in the fall. The Southern Hemisphere displays much less variation between seasons. In the summer, there is a nearly circular high latitude storm track, while in the winter the high latitude storm track is more asymmetric and extends over a broader range of latitudes (Trenberth, 1991; Bengtsson et al.,
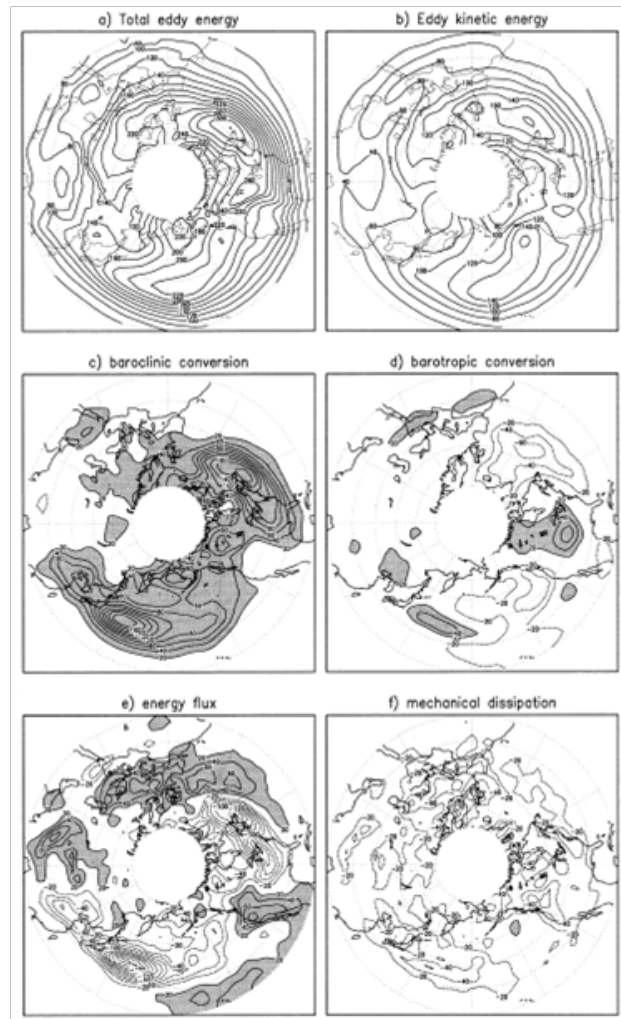
Figure 6: Vertically averaged distribution of (a) EAPE + EKE, (b) EKE, (c) baroclinic conversion, (d) barotropic conversion, (e) convergence of total energy flux, and (f) mechanical dissipation (computed as a residual in the EKE budget) [from Chang et al. (2002)]

2006). There is also a subtropical jet-related lower latitude storm track over the South Pacific in the winter (Hoskins and Hodges, 2005). Unlike the Northern Hemisphere, there is little to no drop off in intensity of the Southern Hemisphere storm tracks in the summer. In the Southern Hemisphere, the strongest meridional temperature gradients in the middle latitudes are actually in the summer, supporting the strong summer storm track activity (Trenberth, 1991). There is also interannual variability associated with climate oscillations such as ENSO. There is some evidence that the Northern Hemisphere storm tracks shift equatorward and downstream in El Nino years, with an opposite shift in La Nina years (Chang et al., 2002; Bengtsson et al., 2006; Eichler and Higgins, 2006). This can lead to large regional differences in storm track density and intensity. The amplitude of the storm tracks also vary on interdecadal time scales.

2.3   Trends

In addition to natural variability, the extratropical storm tracks are potentially affected by climate change. Before examining how storm tracks react to anthropogenically forced climate change scenarios, observed data is examined to see if any trends can be recognized. McCabe et al. (2001) examined trends in the frequency and intensity of Northern Hemisphere surface cyclones between 1957 and 1997 from the NCEP/NCAR reanalysis. They found a decrease in cyclone frequency between $30°N$ and $60°N$ and an increase in cyclone frequency poleward of $60°N$, consistent with a poleward shift in the storm tracks. They also detected an increase in cyclone intensity which was particularly strong in the higher latitudes. Using the same data, Geng and Sugi (2001) found an increase in the cyclone density of the northern North Atlantic as well as an intensifying trend of cyclone central pressure gradient, translational speed, and deepening rate. They also noted that both the baroclinicity and jet stream maximums exhibit a northeastward extension similar to that of the cyclone activity. The left panel of Figure 7 shows counts of winter cyclones in the North Atlantic from the ERA-40 reanalysis, clearly indicating the opposing trends in high and middle latitude cyclones. In the Southern Hemisphere, detecting trends is difficult because of abrupt jumps in cyclone frequency due to changes in observing practices. However, after attempting to diminish the effects of abrupt changes in the time series, Wang et al. (2005) found that strong cyclone activity in winter increased over the circumpolar oceanic region but

decreased between $40°S$ and $60°S$ (see right panel of Figure 7).

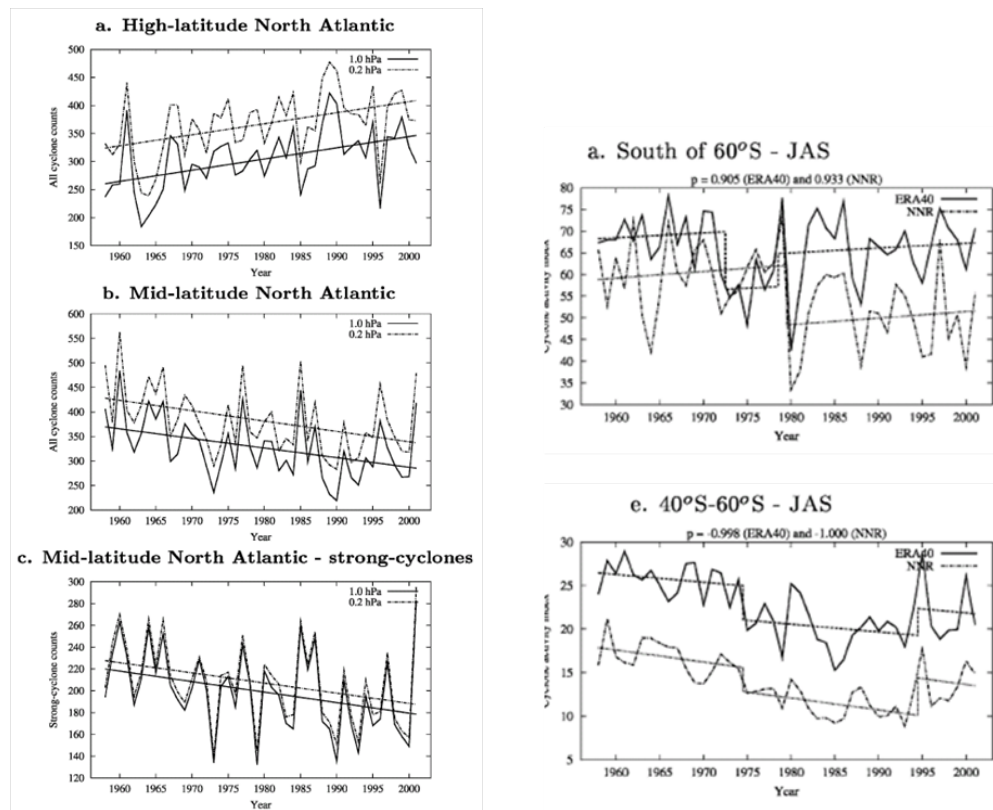Figure 7: Left panels are time series of counts of winter (JFM) cyclones over (top) the high-latitude North Atlantic ($55°N$-$70°N$, $45°W$-$15°E$) and (middle) the mid-latitude North Atlantic ($45°N$-$55°N$, $75°W$-$10°W$), as identified from ERA-40 using detection thresholds of 1.0 and 0.2 hPa (bottom) The same as (middle), but for the counts of winter strong cyclones. Right panels are time series of counts of winter (JAS) cyclones over the Southern Hemisphere over (top) south of $60°S$ and (bottom) $40°S$-$60°S$. [from Wang et al. (2005)]

3 Theory

3.1 Baroclinicity

As noted above, baroclinic instability is the mechanism generating the transient eddies that compose the storm tracks via strong baroclinic conversion of the available potential energy of the mean state to the kinetic energy of the transient eddies. Therefore, the dominant theoretical consideration in determining the effect of climate change on storm tracks is the effect of climate

change on baroclinicity. Baroclinic growth peaks where baroclinicity is the largest. The magnitude and dependence of baroclinicity is captured by the Eady parameter (Lindzen and Farrell, 1980):

$$\Gamma = \frac{f}{N}\frac{\partial \bar{u}}{\partial z} = \frac{-g}{N}\frac{1}{\bar{T}}\frac{\partial \bar{T}}{\partial y}$$

As the Eady parameter indicates, baroclinicity depends on both the meridional temperature gradient and static stability. Both of these factors are predicted to change under climate change scenarios. However, before getting to the question of how baroclinicity changes under climate change, it should be understood how baroclinicity, and therefore the storm tracks, is maintained in the present climate. As Chang et al. (2002) note, it is not obvious that the storm tracks should be self-maintaining. The eddies that make up the storm tracks mix temperature, which would act to destroy the meridional temperature gradients that the existence of the storm tracks depend on. This does happen, as extratropical cyclones are a mechanism for poleward heat transfer, but obviously doesn't happen everywhere, since the storm tracks are a continuous feature of the general circulation. Hoskins and Valdes (1990) suggested factors that might allow for the enhanced baroclinicity over storm track entrance regions. First of all, the most intense mixing by eddies is downstream of the regions of peak baroclinicity. In addition, latent heat release can be an additional energy source; condensational heating caused by the eddies themselves over the storm track entrance region may help maintain the enhanced baroclinicity there. They also note that the wind stress induced by the eddies may contribute to driving the warm western boundary currents which establish regions of high baroclinicity due to land-sea temperature contrasts. Finally, enhanced baroclinicity over the storm track entrance regions could also be maintained by stationary waves induced by topography.

Because baroclinicity depends on both the meridional temperature gradient and the static stability, the effect of climate change on baroclinicity (and therefore storm tracks) is complicated. Stronger warming in the high latitude regions (due to effects such as the ice-albedo feedback) means that there may be a reduced meridional temperature gradient. This would reduce baroclinicity and seemingly decrease the number of storms (Yin, 2005; Bengtsson et al., 2006). However, the magnitude of meridional temperature gradient change varies with altitude. It decreases a lot near the surface, but less so at higher altitudes, and even may increase near the tropopause. This

begs the question, at which altitude is the meridional temperature gradient important for storm tracks? O'Gorman and Schneider (2008) found that the eddy kinetic energy scales linearly with the mean available potential energy and that the mean available potential energy depended on the vertically integrated meridional temperature gradient. McCabe et al. (2001) and Yin (2005) also noted that the higher tropopause would mean a deeper baroclinic zone and that some system could utilize this increased supply of available potential energy aloft.

3.2   Diabatic Effects

The climate change predictions are complicated by the fact that baroclinicity is not the only thing that matters for storm tracks. Diabatic effects can also play a strong role. It was already noted that latent heat due to condensation can act as an additional energy source in the development of eddies. Chang et al. (2002) found that the growth rate and amplitude of baroclinic waves were enhanced by condensational heating, but that surface sensible heat fluxes generally act as an energy sink. As for how climate change may impact storm tracks via moisture effects, increased water vapor in a warmer climate would increase latent heat release, which could enhance the intensity and energy of eddies (McCabe et al., 2001; Bengtsson et al., 2006). However, complicating the matter is the fact that in a moister atmosphere, horizontal latent heat transport may increase. This would mean that eddies are more efficient at transporting energy poleward so the same temperature gradient could be maintained by smaller and/or fewer eddies. Therefore, eddy amplitude and frequency may decrease. Clearly there are many factors that affect the storm tracks under climate change scenarios, both through changes in baroclinicity and moisture effects.

3.3   Stationary Waves:Land-Sea and Orography

Aside from baroclinicity and diabatic effects, there are other factors important to the theory of storm tracks. Stationary waves driven by orographic forcing and land-sea contrast are important to determining local regions of strong baroclinicity and the shape of the storm tracks (Trenberth, 1991). Brayshaw et al. (2009) used idealized and semi-realistic boundary conditions in an atmosphere GCM to isolate the importance of land-sea contrast and orography. They found

that extratropical landmasses lead to a suppressed storm track over the continent due to increased surface friction and reduced moisture availability. However, enhanced confluence near the eastern coast of the continent and enhanced baroclinicity extending eastward over the downstream ocean contributed to a locally increased storm track in that region. They noted that North America is the ideal shape and has the ideal orientation of its mountain range for generating the North Atlantic storm track. The Rockies orography generates an anticyclone over the poleward portion and a cyclone over the equatorward portion, which causes a strong southwest to northeast tilt to the jet and storm track on the downstream side. This orientation of flow is favorable to the storm track because it lies along an axis similar to the axis of the east coast of the United States. This, plus enhanced baroclinicity due to cold continental air over the warm ocean, cause the storm track to be enhanced off the east coast. This combined orography and land-sea effect is strongest in winter and highlights the importance of the stationary waves in determining the storm track.

3.4   Other Factors

Another important effect on the storm tracks is downstream development. Chang et al. (2002) found that coherent wave packets make several circuits around the globe with individual eddies amplifying as they propagate over regions of high baroclinicity. Eddies undergo growth and decay throughout the storm track, recycling their energy towards downstream eddies. This is able to extend the storm track from the genesis regions into regions unfavorable for baroclinic conversion. Barotropic effects can also play an important role, particularly in the decay phase. Barotropic effects, such as horizontal shearing deformation, can limit the growth rate. Chang et al. (2002) found, using a highly idealized barotropic model, that zonal variations of the zonal wind alone are capable of modulating the storm track eddies, resulting in zonally localized storm tracks (as are observed).

4   Climate Change Simulations

Since, as described above, the theory on storm tracks is rather complex and encompasses many different processes and factors, it is difficult to make a prediction on how the extratropical storm tracks may change under global warming scenarios. This is evident when comparing model global warming simulations of storm tracks; there are few robust changes. Idealized models can help simplify the situation and put the results of complex simulations in context. O'Gorman and Schneider (2008), used an idealized model to examine how eddy kinetic energy changed when different radiative parameters were changed. They varied the long wave optical thickness of the atmosphere, as a proxy for changing greenhouse gas concentrations. They found that the eddy kinetic energy was a maximum in a climate close to the reference state (which approximates our current climate) and that it was less for both warmer and cooler climates (see Figure 8). They hypothesized that the insensitivity of eddy kinetic energy (and mean available potential
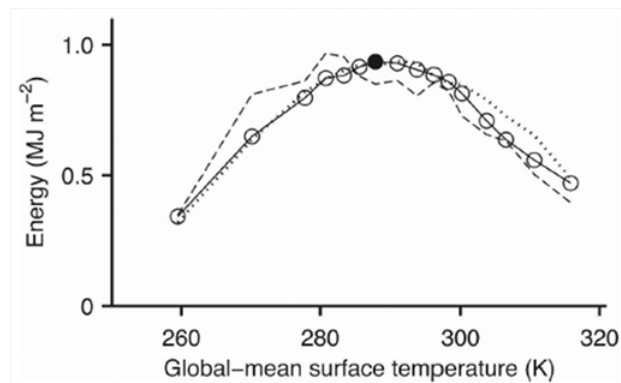

Figure 8: Total EKE (solid line with circles), rescaled near-surface EKE (dotted line) , and rescaled MAPE (dahsed line) vs global mean surface air temperature. [from O'Gorman and Schneider (2008)]

energy) to long wave optical thickness near the reference simulation was because of opposing changes in tropopause height, meridional temperature gradient at different levels, and static stability. The vertically integrated meridional temperature gradient decreased with increasing surface temperature in their simulations, although the surface meridional temperature gradient decreased more strongly. These results would suggest that the eddy kinetic energy might decrease in a warmer climate, but may not be terribly sensitive to changes if the magnitude of the warming keeps the climate relatively close to the current climate.

In addition to examining how climate change affects extratropical storm tracks in idealized scenarios, modeling studies have been done using full coupled climate models at both moderate and high resolution. Different models yield different results, perhaps reflecting the complexity of the problem and its dependence on a great many factors. However, most models do seem to predict a decrease in the number of storms (and cyclone density), large regional changes in cyclone frequency and intensity, and some show a poleward translation of the storm tracks (Sinclair and Watterson, 1999; Geng and Sugi, 2003; Bengtsson et al., 2006, 2009). Results from one particular study (Bengtsson et al., 2006) are shown below. They used the ECHAM5 coupled model to run three 20th century simulations for the time period 1860 to 2000 in which greenhouse gases were prescribed as annual global means according to observations. The three 20th century simulations were extended into the 21st century (2001-2100) using the IPCC emissions scenario A1B. They used thirty year periods of 1961-1990 and 2071-2100 as the 20th century and 21st century scenarios, respectively, and averaged over the three ensemble members before differencing. Their results are shown in Figure 9 and Figure 10.

There are several main features of the difference between the storm tracks in the 20th century simulation and the 21st century simulation. In the Northern Hemisphere in DJF, there is a general poleward translation of the storm tracks. This shows up as a reduction in the cyclone density in the southern parts of the storm tracks and an increase in the northern parts of the storm tracks. The intensity changes are less uniform, but broadly indicate an increase in intensity where the cyclone density increases, and vice versa. It is also notable that there are large regions where the difference is very small or zero. In the Southern Hemisphere, the differences are more apparent and more uniform across seasons. There is a poleward translation of the storm tracks and a decrease in the number of weak storms in both winter and summer. There is an increase in the number of strong storms in the winter and a general weakening of intensities in the summer. Finally, as in the Northern Hemisphere, there is a general increase in intensities in the regions where there is an increase in storm track activity. In most model simulations, the general decrease in the number of storms is caused by a decrease in baroclinicity; for example, Sinclair and Watterson (1999) found a decrease in cyclone activity of 10-15% due to weakened baroclinicity. Geng and Sugi (2003) showed, using a high resolution model, that the decrease in baroclinicity in the Northern Hemisphere is mainly caused by a decrease in the meridional
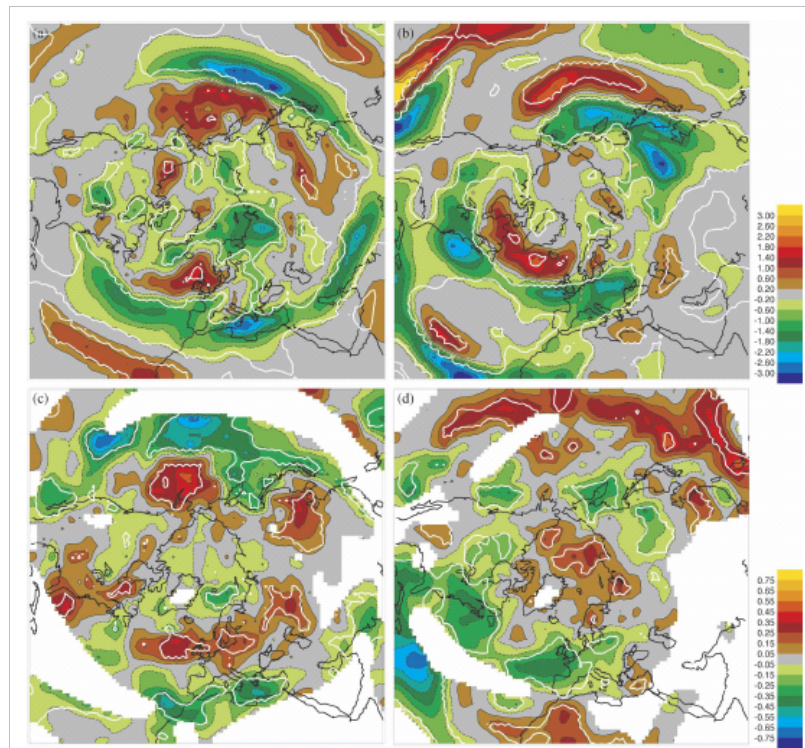
Figure 9: Difference in NH cyclone track statistics for ζ_{850} between the 21st century and 20th century periods (21C-20C) avearged over the three ensemble members before differencing:(a) DJF track density, (b) JJA track density, (c) DJF mean intensity, (d) JJA mean intensity.[from Bengtsson et al. (2006)]
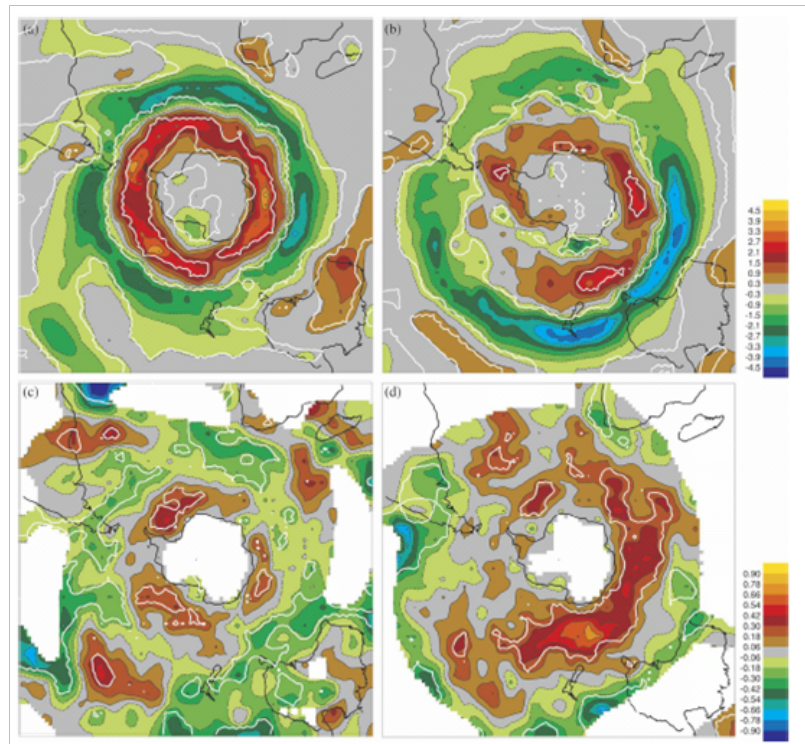
Figure 10: As in Figure 9, but for SH. [from Bengtsson et al. (2006)]

temperature gradient. However, they found that the decrease in baroclinicity in the Southern Hemisphere was mainly caused by an increase in static stability. Like Bengtsson et al. they found the total cyclone density decreased in the winter and the density of the strong cyclones increased in the Southern Hemisphere. However, Geng and Sugi also found that the strong cyclone shifted northward in the northern North Pacific, but shifted southwestward in the northern North Atlantic, which Bengtsson et al. did not find.

As indicated above, examining individual models for the impact of climate change on storm tracks has its limitations because each model produces somewhat different results. It can therefore be advantageous to look at an ensemble mean of a large number of models, in an effort to pick out the most robust features. Various studies have been done in which the ensemble mean of all the models used in the IPCC report is analyzed. Yin (2005) looked at changes in the filtered eddy kinetic energy in the IPCC ensemble of models. He found a clear poleward and upward shift in the storm tracks in the Southern Hemisphere year round and in the Northern Hemisphere winter. The poleward shift in the storm tracks was accompanied by a poleward shift in the vertically integrated momentum flux convergence, which drove a similar shift in the mid

latitude jets and surface zonal wind stress. Yin also found that the eddy kinetic energy of the storm tracks increased in magnitude in the Southern Hemisphere year round and in the Northern Hemisphere winter (but less so than in the Southern Hemisphere) and decreased in magnitude in the Northern Hemisphere summer. He suggested that the smaller increase in eddy kinetic energy in the Northern Hemisphere winter was related to the fact that the poleward shift in baroclinicity was partially offset by a decrease in the high latitude baroclinicity near the surface. However, other studies using the same set of models found different results using different analysis techniques. Lambert and Fyfe (2006) identified storms by the occurrence of a mean sea level pressure value that was lower than each of the four surrounding grid points, unlike Yin, who looked at eddy kinetic energy. In contrast to Yin (and the studies of individual models discussed above), Lambert and Fyfe found no apparent changes in the geographical distribution of storms. As seen in Figure 11, they did find a decrease in the total number of storms and an increase in the intense storms. In addition to using the A1B emissions scenario, they examined the results under other emissions scenarios and found, unsurprisingly, that the magnitude of the changes increases with increased greenhouse gas forcing. Ulbrich et al. (2008) noted that it is somewhat expected that different
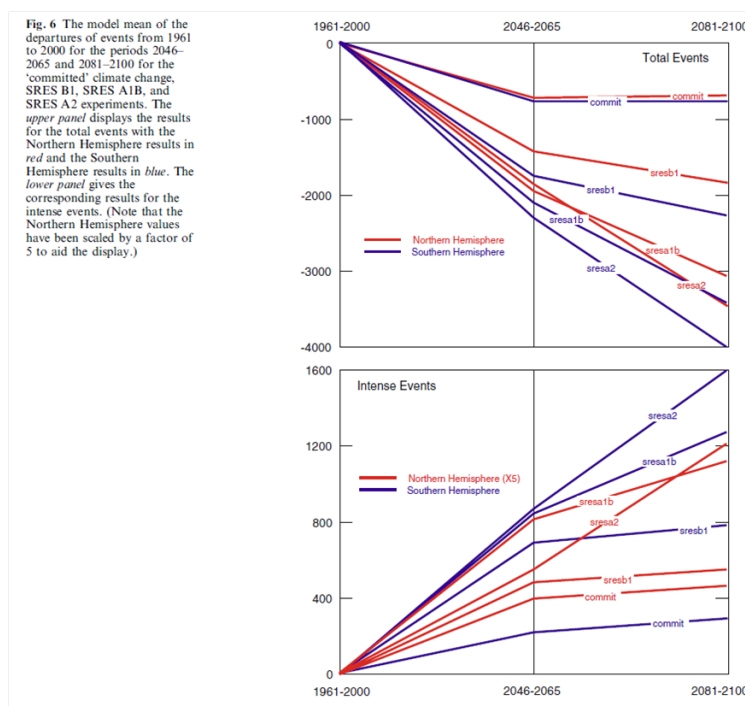

Figure 11: Storms identified by occurrence of an MSLP value which is lower than each of the four surrounding grid points.[from Lambert and Fyfe (2006)]

approaches in different studies would lead to different results because the different approaches highlight different aspects of the storm tracks. Their own analysis of the ensemble mean of the IPCC models found that storm track activity shifted in some areas, but didn't resemble the clear poleward shift of zonal mean eddy activity found in other studies. They did note that increased storm track activity was expected in the eastern North Atlantic, Western Europe, the North Pacific, and parts of Asia (see Figure 12). The variation in the results of different models and

Fig. 2. Greenhouse gas signal for MSLP storm track in 1/10 hPa, computed as the difference between the forcing period of SRES A1B (2080–2100) and the present-day forcing (1960–2000). Values over high ground (>1000 m MSL) are omitted. Significant differences at 95% (and 99%) confidence levels are in color, with a *t* test on the winter basis.
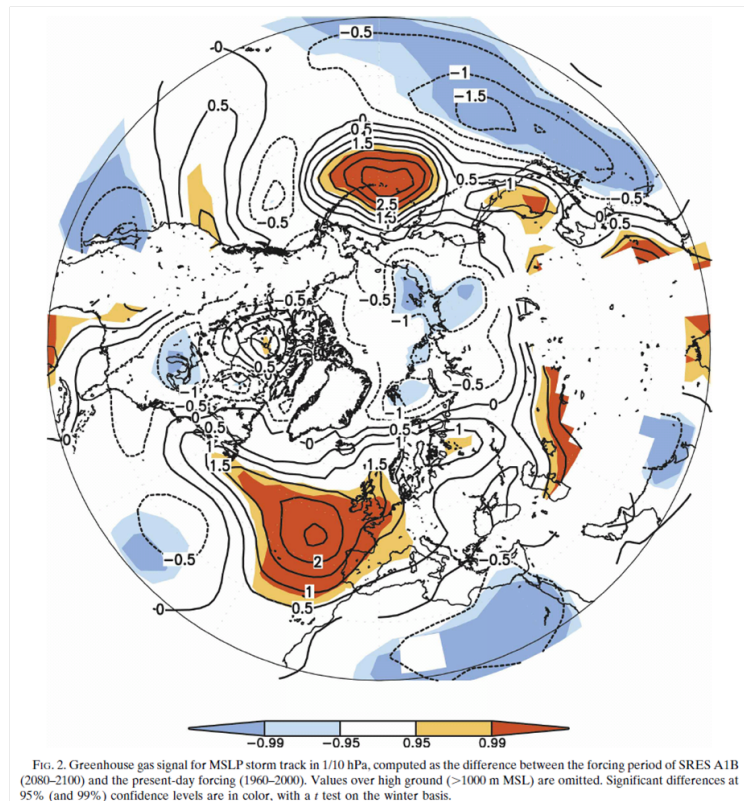
Figure 12: from Ulbrich et al. (2008)

in the results of different types of analysis does not give much confidence to the predictions on how storm tracks may change under global warming scenarios. As discussed previously, there are many competing factors that influence the storm tracks, and changes in these factors may produce opposing effects on the storm tracks. This could contribute (as it does in O'Gorman and Schneider (2008)) to a relative insensitivity of the storm tracks to changes in greenhouse gases near the reference climate. Presuming that global warming doesn't cause the climate to move very far from the current climate, the storm track characteristics in simulations may just not be very different from what they are in the current climate. Identifying small differences from

the current state in climate models is difficult, and may contribute the contrasting results from different models and different analysis methods.

5   Summary

In summary, the current climatology of the extratropical storm tracks has been reviewed in terms of their location and intensity. In comparing the seasonal cycle of the Northern Hemisphere and the Southern Hemisphere, the Northern Hemisphere experiences much more variation. The Northern Hemisphere track shift equatorward in the winter and poleward in the summer. The most intense extratropical storms in the Northern Hemisphere are in the winter, while the summer storm tracks are much weaker. Using reanalysis data, trends have also been detected over the past half century. In both hemispheres, there has been a decrease in cyclone frequency in the mid latitudes and an increase in higher latitudes, consistent with a poleward shift in the storm tracks. There is also evidence that cyclone intensity has been increasing, especially in the high latitudes. In terms of the theory for storm tracks, because of their complexity and the variety of factors that influence them, there is no unified theory. Baroclinic instability is the mechanism generating the transient eddies that compose the storm tracks. The process of baroclinic conversion from the available potential energy of the mean flow to the kinetic energy of the transients is main source of energy. Changes in baroclinicity are caused by changes in the meridional temperature gradient and/or changes in the static stability, both of which are expected to change under global warming scenarios. Diabatic effects due to changes in moisture under global warming scenarios complicate efforts at predicting how the storm tracks will change. Model simulations of storm tracks under global warming scenarios reflect their complex nature and the many factors that influence them. Idealized models indicate that the eddy kinetic energy is insensitive to changes in greenhouse gas forcing near the reference climate. This is probably due to the myriad of factors that influence the storm tracks and compensate each other. This may contribute to the fact that full coupled models don't show large changes in the storm tracks and disagree with each other a great deal in the specifics of how the storm tracks change. In comparing different full coupled GCM's and the ensemble mean of the IPCC suite of models, there are only a few robust results. In future global warming scenarios, the number of extratropical cyclones is reduced in winter, but the number

of intense cyclones increases in some regions. There is also some evidence for a poleward shift in storm tracks. Overall, the extratropical storm tracks are an important feature of the general circulation but their complexity prevents us from having a clear idea of how they may change in the future.

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