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Influence of global warming on extratropical storms

Climate change facts compiled by ProClim

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Executive Summary

Overall, observations show a tendency towards intensification of extratropical cyclones. Climate models show consistent trends that project an increase in the number of severe storms, a decrease in overall storm number, and a poleward shift of storm tracks.

There is a large scatter in the modeled magnitude of these changes. On average, the climate models considered by the Intergovernmental Panel on Climate Change (IPCC) show an increase over the 21st century in the number of intense cyclones by 10–20%, depending on the emission scenario. As the average of the model results is consistent with obser-vations, this could represent a reasonable basis for projection. The trends are projected to be stronger in the Southern Hemisphere.

There are still important uncertainties concerning regional variations. Changes in extra-tropical storm activity are influenced by large-scale atmospheric circulation patterns which are projected differently in various climate models. As these large-scale patterns are not fully understood, the exact geographical distribution of any changes is unclear. The most credible information on future regional changes currently comes from the IPCC model ensemble, which shows an increase of storm activity, representing a mixture of intensity and number, in the eastern North Atlantic and the northern North Pacific.

These results stand under the reservation that climate models still struggle to adequately represent extratropical storms. The analysis of historical storm occurrence is distorted by changes in observation systems, their accuracy over time and the fact that observational trends are derived using specific data sets and depend on the specific definition of a cyclone. These uncertainties are more pronounced for frequency changes and less for intensity changes.

Introduction

Extratropical or mid-latitude storms are low-pressure systems with frontal zones separating cold and warm air masses. The high temperature and pressure gradients in the frontal zone often lead to high wind speed. Both their development and dynamical processes differ from tropical cyclones, though the latter may transform into extratropical storms when leaving the tropical or subtropical ocean. Most extratropical storms are embedded in the so-called "westerlies", the zone of westerly winds separating the cold air masses in the north and the warm air in the south (also called the 'polar front' – see Figure 1). They mainly occur during the winter season in the mid-latitudes. Regions most vulnerable to extratropical storms are highly populated areas in the western part of the continents in the mid-latitudes.

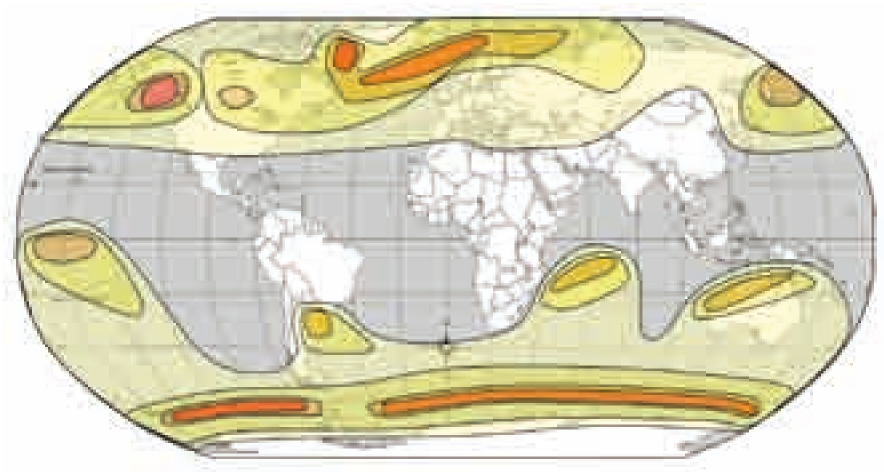


Figure 1
Schematic view of the regions which are frequently touched by extratropical cyclone tracks. Regions with highest frequencies are indicated as red, while orange and yellow respectively indicate lower frequencies of cyclone tracks.

Possible influences of climate change on extratropical storms

The two most important potential influences relate to differences in spatial warming, ie, higher latitudes warm more than the tropics and the increase in atmospheric water vapour content as warmer air can contain more water vapour.

The spatial occurrence of extratropical storms is mainly determined by the atmospheric circulation, which follows the large scale pressure patterns. The intensity of storms and maximum wind speed are determined by regional pressure gradients, dependent on horizontal temperature gradients and the available latent energy. Latent energy can be transformed into kinetic energy when it is retrieved through the condensation of water vapour, after it was initially used to evaporate water. This kinetic energy leads to higher wind speed within developing low pressure systems and is a key factor for the development of extreme cyclones (Wernli et al. 2002).

Increasing water vapour content has two effects. First, increasing latent heat energy enhances the maximum potential intensity and wind speed that a storm can attain. This means, more water vapour in a warmer climate in general favors more intense storms. Second, it enhances the latent heat transport between the equator and the pole, thus decreasing the transport of sensible heat. The same amount of air moving from equator to the pole therefore contains more energy as well as a higher temperature. This means less air has to be transported to compensate for the stronger heating of the equator compared to the pole, reducing the meridional (North-South) airflow and average wind speed.

The above-average heating of the higher latitudes has various possible effects. Some of these have converse impacts on storm activity:

a) storm intensity:

- In general there is a decrease of the large-scale temperature difference and thus the average pressure gradients. So, horizontal temperature and pressure gradients along the polar front, which influence both the wind speed and dynamics of storms in the frontal region, could in future decrease.

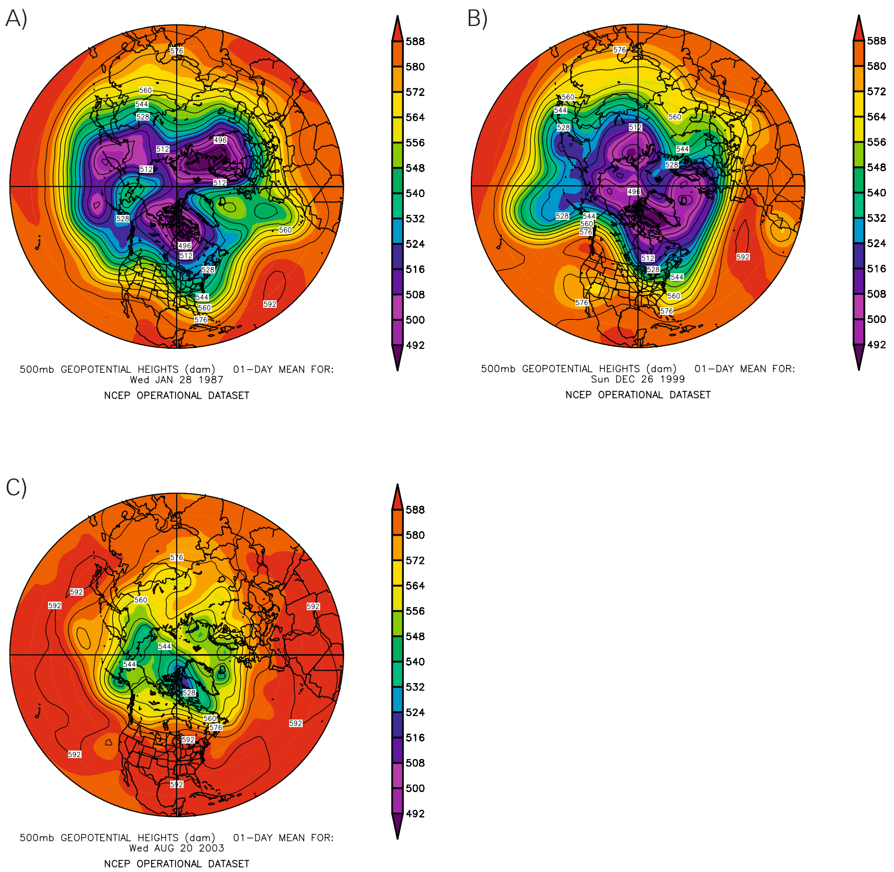


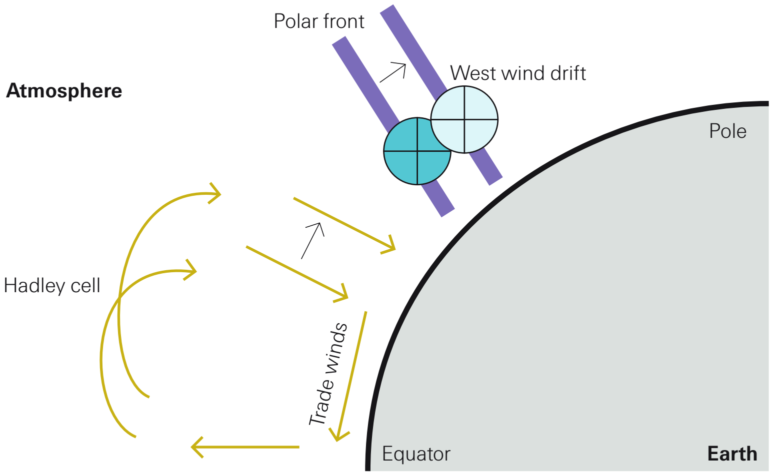
Figure 2
Pressure patterns (geopotential height at 500hPa) over the Northern hemisphere on 20 Jan 1987 (A; during severe cold period in central Europe), 26 Dec 1999 (B; day of Lothar storm), and 20 Aug 2003 (C; during heat wave in Europe). Pressure gradients (corresponding to the distance of black lines) are highest in winter with zonal flow (A,B), medium in winter with meridional flow (A,B) and lowest in summer (C).
Images provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.cdc.noaa.gov/. Data is from NCEP/NCAR Reanalysis (Kalnay et al. 1996)

- In winter, a smaller overall temperature gradient might also favour zonal west-east flow patterns which produce higher local pressure gradients and wind speed than undulating north-south (meridional) flow patterns (see Figure 2). The strong cooling of the high latitudes in winter leads to an increase of the temperature and pressure gradient along the polar front, producing strong westerly winds, as over the Atlantic in Figure 1B. Since a west-east air flow does not favour the mixing of polar cold air and tropical warm air, the gradients increase. If the gradients are strong enough, horizontal waves occur in the flow enhancing the north-south mixing (Figure 1A). If the mixing has reduced the gradients, the flow switches back to east-west again. If global warming reduces polar cooling in the winter, then the temperature gradient will grow more slowly and the zonal east-west flow will last longer. In summer, the temperature difference between pole and equator is too low to produce high regional gradients at all (Figure 1C). The expectation of an enhanced zonal flow in a warming climate is corroborated by the fact that, in comparison with today, proxy-based reconstructions of past atmospheric circulation in the Mediterranean, suggest stronger meridonal circulation during the Little Ice Age (300 years ago; Luterbacher et al. 2006) and an even stronger meridonal circulation during the Last Glacial Maximum (20 000 years ago; Kuhlemann et al. 2008).
- A lower temperature gradient might decrease the dynamics of the circulation pattern, which are driven by the physical push to balance pressure and temperature differences. This decrease might lead to a higher persistence of weather types and to more weather extremes (Kysely and Domonkos 2006). Extreme storms occur in situations of persistent, elongated strong west wind, as eg the storms Vivian or Lothar (Figure 1B). Other weather extremes related to persistent cirulation patterns are heavy snow falls, floods or droughts.
- There is also an increase in the temperature gradient between the upper troposphere and lower stratosphere due to tropospheric warming and stratospheric cooling. This influences the winds on these height levels, and these wind changes can propagate downwards through vertical turbulence to the surface. The cooling of the polar stratosphere due to ozone depletion seems to induce higher polar stratospheric winds influencing the tropospheric jet stream and, at least in the long-term, leading to an increase of wind speed at the surface (e.g. Gillet and Thompson 2003, Kushner and Polvani 2006).

b) geographical distribution:

- the northward extension of the Hadley cell (ie, the circulation encompassing rising air in the tropics, descending air in the subtropics and the trade winds; see Figure 3) has been observed over the last decades (Hu and Fu, 2007, Archer and Caldeira 2008) and is projected for the future (Lu et al., 2008, Seidel et al. 2007). This leads to a general northward shift of the polar front and a corresponding regional shift of the related storm tracks.
- Global warming might alter atmospheric circulation patterns and its oscillations, eg the North Atlantic, Arctic or Antarctic Oscillation (NAO, AO and AAO, respectively). These changes alter the regional distribution of storm frequency and intensity.
- The different warming rates over land and ocean and due to melting sea ice also influence regional temperature and pressure patterns and gradients and therefore influence storm tracks.

Figure 3
Vertical schematic view of the major circulation systems of the Earth's atmosphere and its changes due to global warming. The Hadley cell, including rising air in tropical thunderstorms, descending air in subtropical high pressure systems (e.g. Azores high) and the trade winds, is expected to extend northwards. The West wind drift or polar front, which separates the cold air in the North from the warm air in the South, is expected to shift northwards, too.



In summary, there are many different processes which might change and influence storm tracks and storm intensity. It is quite difficult to estimate, based on current knowledge, which of these factors will be most important.

In the following section, observed trends of extratropical storm activity in the 20th century and model projections for the next century will be discussed.

Observations:
The analysis of the historical development of storm activity has to deal with changes of observation systems and accuracy over time. Moreover, Raible et al. (2008) detected that resulting trends might depend on how cyclones are physically defined, for example by minimum pressure, wind speed or both. They compared the two re-analysis data sets from the U.S. National Centers for Environmental Prediction (NCEP) and the European Center for Medium Range Weather Forecasts (ERA40) and found differences in sign for the frequency trend in the North Atlantic and no consistent frequency trends between different methods to define a cyclone in the climatological data sets. The trends in intensity, however, are consistent for different data sets in the North Atlantic and the Pacific. The comparison for different definitions is still missing. In addition, different tracking schemes used to identify storm tracks and the life-time of storms might also influence trends (Ulbrich et al. 2008b).

Analysis of observations shows, that at least since the late 1970s (Gillett et al. 2003), there seems to have been a general increase of mid-latitude mean sea level pressure gradients in winter, exceeding expected internal variability and anthropogenic forced signals in climate models. Such an increase would favor storms in general.

Existing storm analysis examines the evolution of annual average activity. Some studies differentiate between seasons. The studies differ in analysis methods and regions examined. Bärring and von Storch (2004) and Alexandersson et al. (2000) show a decrease of storm activity from the end of the 19th century until about 1960 and an increase afterwards in north western Europe. There is also a positive correlation between storm activity and the North Atlantic Oscillation (NAO) pattern. Alexander et al. (2005) found an increase in number and intensity of severe storms over the south of UK since 1950 and a decrease over Iceland. A number of studies find an increase of storm activity during the second half of the 20th century over the North Atlantic (Geng and Sugi 2001, Simmonds and Keay 2002) and the North Pacific (Graham and Diaz 2001, Wang et al. 2006), especially in winter. Other studies show an increase of intense extratropical cyclone systems, but a decrease in total storm number (e.g. Gustafsson 1997, McCabe et al. 2001). Favre and Gershunov (2006) found an intensification of cyclones over the North-Eastern Pacific and further southerly trajectories since the mid-1970s.

Several studies find a poleward shift of the storm tracks over the past five decades (eg Simmonds and Keay 2002, Wang et al. 2006), with a mean northward shift over the past half century amounting to 180km over the North Atlantic (Wang et al. 2006).

In summary, there is a general tendency towards a poleward shift of storm tracks and more intense extratropical cyclones. Whilst there is no clear long-term trend in frequency more studies show a decrease in frequency.

Projections:
There are numerous climate model studies investigating projections of the evolution of extratropical storms in the 21st century. Lambert and Fyfe (2006) compared 15 models which have been examined in the Fourth Assessment Report 2007 of the IPCC and found that on average the models reproduced the observed 1961–2000 mean annual number of intense cyclones as well as the mean annual total number of cyclones. However, there is a considerable spread between the models, especially concerning intense cyclones.

Over the 20th century, all models consistently show a negative trend of the total number of cyclones and an increase in the number of intense cyclones. Over the average of the models, however, the decrease of the total number is higher than the observed trend. The models, then, are able to reproduce the sign of observed trends well, but differ in the magnitude of the trends.

These models on average project a global decrease of the total number of cyclones between about 2.5 to 5% and an increase in the number of intense cyclones between about 10% and 20% respectively, dependent on the underlying emission scenario[1] (see table 1). Lambert and Fyfe (2006) show a similar result with the increase of intense cyclones being more pronounced in the southern hemisphere. Other overviews of general circulation model results also show a tendency towards more intense storms, which is more pronounced in scenarios with higher greenhouse gas emissions (Leckebusch and Ulbrich 2004), and an increase in the frequency of strong cyclones combined with a decrease of weak or medium cyclones, respectively (Geng and Sugi 2003, Leckebusch et al. 2007).

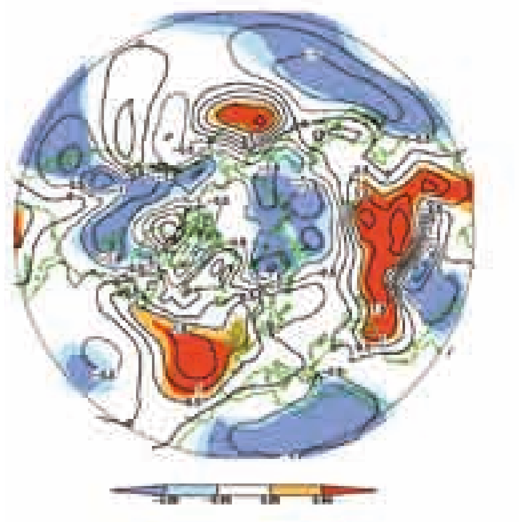
Consistent with recent observations, there are a number of studies which find a poleward shift of mid-latitude storm tracks (Geng and Sugi 2003, Fischer-Bruns et al., 2005, Yin 2005, Bengtsson et al. 2006).

The model projections concerning the regional development of extratropical cyclones show one consistent result: regional changes might be very different compared with the global mean and even differ in sign. Caires and Sterl (2005) have shown that the shifts of storm tracks are related to changes in atmospheric circulation patterns, especially the North Atlantic Oscillation. Thus the changes of the circulation patterns play an important role for the characteristics of regional changes.

The projections of regional storm patterns, especially concerning frequency and intensity, are quite different because individual climate models project different circulation changes including future North Atlantic Oscillation patterns. As the IPCC model ensemble shows a reasonable representation of the observed regional patterns (1961-2000), the model ensemble might be the best basis for regional projections. The ensemble of 16 GCMs shows regions with significant increase or decrease of storm activity (Ulbrich et al. 2008a; see Figure 4). A recent review of storm analyses (Ulbrich et al. 2008b) concludes that under climate change conditions there will be a decrease of storm number in winter, but that in most models there will be an increase of intense cyclones in specific regions (NE Atlantic and British Isles, and over the North Pacific). The trend in extreme cyclones over the Northern hemisphere depends on how "extreme" is defined: an increasing trend in extreme cyclone number occurs when they are defined by extremely low pressure values, while a decreasing trend occurs when they are defined by an integrated pressure value.. For the Southern Hemisphere, Ulbrich et al. (2008b) find the most robust result to be a general southward shift of storm tracks, leading to less cyclone activity around 50°S and increased activity around 60°S.

[1] Emission scenarios have been calculated for the Third Assessment Report 2001 of the IPCC and were published in the IPCC Special Report on Emission Scenarios (SRES). These scenarios calculate the development of greenhouse gas emissions in the 21st century, based on different assumptions concerning the socio-economic evolution over that time (e.g. population growth, technological development, etc.). The A2 scenario shows emission amounts at the higher end of the scenario range, the B2 scenario emission amounts rather at the lower end of the range.

Figure 4
Impact of greenhouse gas warming on mean sea level pressure storm track (difference between the periods 2080–2100 (medium emission scenario) and 1960–2000; in 0.1 hPa). Significant differences at 95% (and 99%) confidence levels are in color (Source: U.Ulbrich (Free University of Berlin), J. Pinto, and M. Reyers (University of Köln); adapted from Fig. 2 in Ulbrich et al. (2008a))



While some studies compare different models, Pinto et al. (2007b) focused on one model, which is very close to the IPCC[2] model average and the observations (the German ECHAM5 climate model). In the following, some important regional results are listed:

Hemispheric:
- Pinto et al. (2007b) find an intensification of storms over most of the Northern hemisphere, more pronounced over the North Atlantic and Europe and less pronounced over Asia, the far-east and the North Pacific. The number of storms decreases in general.
- Geng and Sugi (2003) find an increase of storm frequency in the Northern Hemisphere in summer, especially on the eastern coasts of Asia and North America.
- Land and Feichter (2003) find an increase in cyclone activity in the mid-latitudes of the Southern Hemisphere.

Europe:
- Reduced number of storm systems over central Europe, but an increased activity of extreme cyclones (i.e. the strongest 5%) for the western parts of central Europe (overview of global and regional atmospheric circulation models by Leckebusch et al. 2006).
- An increase in the intensity of extreme storms over a band in central Europe (southern UK, northern France, Denmark, northern Germany, part of Eastern Europe), consistent in regional climate models (Schwierz et al. 2007). This pattern is most pronounced and the increase is strongest for rare events.
- An intensification of storms, but a decrease of storm number, except in the west of UK, due to a shift of the North Atlantic Oscillation towards the positive phase in that model (Pinto et al. 2007b).
- An increase of storm track activity west of central Europe between the Azores and the British Isles by 5-8% (2081-2100 compared to 1961-2000 for high emission scenario) (Ulbrich et al. 2008)
- An increase in extreme winds in the middle and Northern Europe (Pinto et al. 2007b)

[2] Intergovernmental Panel on Climate Change

Northern Pacific and North America:

- Ulbrich et al. (2008) find an increase of storm activity over the northern North Pacific and a decrease over the southwestern North Pacific and west of Baja, California.
- Salathé (2006) finds a northward shift and intensification of the storms and the Aleutian low pressure system over the North Pacific.
- An increase of storm frequency in summer on the eastern coasts of North America. (Geng and Sugi 2003)

Asia:

- An increase in extreme winds in China (Pinto et al. 2007b)
- An increase of storm frequency in summer on the eastern coasts (Geng and Sugi 2003)

Table 1

Average projections of 15 climate models of the 4th Assessment Report of the IPCC (IPCC 2007) of trends in storm numbers over the 21st century, dependent on the emission scenarios (commitment means a hypothetical scenario with CO_2 concentrations held constant at year 2000 levels, SRES scenarios are from the IPCC special report on emission scenarios (2002). Note that for intense cyclones the trends are more pronounced in the Southern hemisphere (about +30% compared to about +10% in the Northern hemisphere for the A2 scenario)
Source: Lambert and Fyfe (2006)

Emission scenario	**commitment**	**B1**	**A1B**	**A2**
Total number	–1.3%	–2.6%	–4.2%	–4.8%
Intense cyclones	+4.5%	+8.8%	+15.4%	+18.4%

Storm losses:

A number of GCM studies have addressed the possible increase of storm-related loss potential over Europe. Since extreme storms are the dominant factor determining losses the simulated increase of extreme mid-latitude storms leads to a corresponding increase of loss potential in the model studies. The variability of the results, however, is large. In a statistical loss model Pinto et al. (2007a) e.g. find a range of –4% to +43% in mean annual loss for Germany in the 21st century for individual model runs (also depending on the emission scenario1). They also find a substantial increase in inter-annual variability of loss amount. Projected loss increase is most pronounced in Western and Central Europe, with loss increases of up to about 40% in Germany, France and the United Kingdom (Pinto et al. 2007a, Leckebusch et al. 2007).

A combination of regional climate model scenarios with an insurance loss model, ie an operational loss model, showed an increase of European-wide losses from 1961–1990 to 2071–2100 of up to 44% for annual losses and of about 25%, 50%, and 100% for a 10-year, 30-year, and 100 year loss event respectively. There is considerable variability of the expected losses for individual countries, with Denmark and Germany experiencing the largest loss increases (116% and 114%, respectively). For all European countries except for Ireland (–22%) a loss increase is expected. Besides Ireland, a loss decrease is also projected for parts of Scandinavia and parts of the Mediterranean. (Schwierz et al. 2007).

Conclusions

Both observational trends and recent climate model studies support indications of an increase in the number of intense storms. Some results point to a decrease of general storm frequency, but there is no consistent pattern. A further consistent result is a poleward shift of cyclone activity. The large variability in the model results concerning regional changes underlines that there might be local and regional changes of storm frequency and intensity in the future. These may be substantially different from the global mean, but such local changes are still uncertain and reflect different model behaviours.

The different regional patterns from the models are probably due to different projected changes in circulation patterns, like the NAO. In some climate models, greenhouse warming shifts the NAO to a more positive state, which would lead to an indirect influence on storm tracks, because these are different for the positive and the negative phase of the NAO. However, since the average of the models (model ensemble) represents the observations, i.e the global average in number, intensity and regional pattern, reasonably well, the model ensemble projection should give useful information on probable changes of regional patterns.

The long-term influence of anthropogenic global warming on changes in storm activity is difficult to detect, because it might be masked by simultaneous decadal or multi-decadal variability due to atmospheric oscillations (Arctic Oscillation, Antarctic Oscillation, see FactSheet "Indices") which influence storm tracks. Furthermore, observational trends are uncertain due to possible biases in the re-analysis datasets and depend on how cyclones or storms are physically defined.

Climate models still have difficulties to represent extratropical storms adequately, and several key characteristics depend on the model's horizontal resolution, at least in most regions (Jung et al. 2006, Wernli and Schwierz 2006). This problem might be at least in part because the representation of fronts of smaller but sometimes strong cyclones (as eg the storm "Lothar" in 1999) improves considerably with higher resolution.

In summary, the currently most robust model results are a general shift of storm tracks towards the poles, which is more pronounced in the Southern hemisphere (IPCC 2007) and an increase in extreme storms (Leckebusch et al. 2007). There is a tendency towards a decrease in numbers of storms, but corresponding results are less consistent.

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