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MID-LATITUDE PROCESSES AND CLIMATE CHANGE (I SIMPSON, SECTION EDITOR)

The Future of Midlatitude Cyclones

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Abstract

Purpose of Review This review brings together recent research on the structure, characteristics, dynamics, and impacts of extratropical cyclones in the future. It draws on research using idealized models and complex climate simulations, to evaluate what is known and unknown about these future changes.

Recent Findings There are interacting processes that contribute to the uncertainties in future extratropical cyclone changes, e.g., changes in the horizontal and vertical structure of the atmosphere and increasing moisture content due to rising temperatures.

Summary While precipitation intensity will most likely increase, along with associated increased latent heating, it is unclear to what extent and for which particular climate conditions this will feedback to increase the intensity of the cyclones. Future research could focus on bridging the gap between idealized models and complex climate models, as well as better understanding of the regional impacts of future changes in extratropical cyclones.

Keywords Extratropical cyclones · Climate change · Windstorms · Idealized model · CMIP models

Introduction

The way in which most people will experience climate change is via changes to the weather where they live. In the midlatitudes, this weather is primarily controlled by the passage of extratropical cyclones (ETCs) and their associated fronts. These features are a vital part of the global circulation and bring a large proportion of precipitation to the midlatitudes, including very heavy precipitation events [1–5], which can contribute to flooding. ETCs are also important for bringing strong surface winds and wind gusts [6, 7] and contribute to monetary losses in many regions [8–10]. How these cyclones will change in a future warmer climate is of both socioeconomic and scientific importance, but also presents a very complex challenge.

There are multiple properties of the global climate system that influence the frequency, location, and intensity of ETCs. We have high confidence in the future changes of three of these properties: (1) the atmospheric moisture content will increase due to rising temperatures; (2) the lower-tropospheric meridional temperature gradient will decrease due to polar amplification in the Northern Hemisphere (NH) in the winter in particular, as has already been seen in observations [11]; and (3) enhanced warming in the tropical upper troposphere and cooling in the high latitude stratosphere [12] will lead to an increased meridional temperature gradient in the vicinity of the tropopause slope at around 30–40° north and south. What we have less confidence in is exactly how these three factors will interact and contribute to future changes in ETCs and the aggregated storm tracks.

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The upper and lower level temperature gradients can have compensating effects through changes to the baroclinicity and vertical stratification [13], and the increased atmospheric moisture can also contribute to the ETC changes through latent heating (LH) and impacts on the vertical stratification [13].

The latest Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5 [12]) indicated large uncertainty in projected frequencies and preferred locations of ETCs. Nevertheless, slight decreases in the frequency of ETCs are projected in both hemispheres (in association with the changes in baroclinicity), with significant regional variability [12]. The processes behind the storm track uncertainties have been covered in detail in a previous review paper [13]. Future changes in cyclone impacts in terms of wind speed and precipitation may also depend on more detailed and specific changes in cyclone dynamics, intensity, and structure. The IPCC AR5 and the IPCC Special Report on Extremes (SREX [14]) mostly considered changes to the ETCs, and precipitation and winds separately. Nevertheless, two studies [15–17] cited in the AR5 regional projections chapter [18] showed cyclone-related precipitation increases with generally no increase in wind speed strength. It was also noted that due to many different ways of defining storm intensity, there is “little consensus” on how this might change.

The goal of this review is to summarize recent findings related to possible future changes in ETCs. It will focus on the dynamical mechanisms and future projection of anticipated changes to the structure, intensity, characteristics, and impacts of midlatitude cyclones. The review will draw on studies that make use of a hierarchy of models, from idealized models to complex coupled general circulation models (GCMs). By bringing together the most recent findings, we hope to clarify some of the uncertainties and highlight aspects for which there is a consensus on the future of ETCs.

First, the theoretical mechanisms and results from idealized modeling simulations will be addressed in “Theoretical Mechanisms for Future Changes in ETCs” and “Changes in Extratropical Cyclones from Idealized Models” sections. Projections from more complex models will be described in “Future Changes in Extratropical Cyclone Characteristics from Climate Models” section along with details of the ability of these models to capture the processes of interest. The importance of different cyclone “types” as well as the temporal clustering of cyclones in climate projections is addressed in “Cyclone Temporal Clustering” and “Other Types of Cyclones Affecting the Midlatitudes” sections. A discussion of impacts and their relation to the work described in the preceeding sections is given in “Cyclone Impacts and Their Future Changes” section. Remaining questions will be discussed throughout and presented in terms of future opportunities in “Discussion” section, with a summary provided in the final section.

Theoretical Mechanisms for Future Changes in ETCs

The meridional temperature gradient generated by the differential solar heating between the equator and the poles produces a situation in the midlatitudes where small perturbations (or waves) grow through baroclinic instability [19, 20]. These perturbations develop into ETCs, with finite life cycles. The preferred locations for cyclogenesis are mainly within regions of highest baroclinicity (as determined via the maximum Eady growth rate parameter [21]), or in the lee of significant mountain ranges. Future changes in the horizontal (potential) temperature gradients in both the upper and lower troposphere, as well as changes to the vertical temperature profile (i.e., static stability), are the primary drivers of changes in baroclinicity and therefore the locations of the storm tracks. It is worth noting that observations of the seasonal cycle of the storm tracks in the NH reveal a suppression in the upper level storm track strength in the Pacific at the time of the season when the baroclinicity is largest [22]. This is associated with a larger number of surface cyclones with shorter lifetimes [23] and indicates that the relationship between baroclinicity and the storm tracks is not a simple one.

LH due to the formation of clouds and precipitation can increase ETC intensity (if all other factors affecting cyclone dynamics are unchanged) through its effect on buoyancy, vertical motion, and thus also sea-level pressure and vorticity [24–26]. The relative contribution of diabatic processes to ETC intensification can be quantified via the pressure tendency equation [27], the omega equation [28, 29], or the Zwack-Okossi equation [30]. Another perspective on the influence of LH on cyclones can be obtained from the potential vorticity (PV) framework [31]: diabatic PV generation associated with LH in clouds leads to the formation of a cyclonic PV anomaly in the lower troposphere that contributes to the cyclonic circulation [25, 26, 32–34]. More recent climatological studies have used this lower-tropospheric PV anomaly as a measure of the relevance of diabatic processes for ETCs in different regions [35] and of different intensities [36, 37], indicating that such lower-tropospheric PV anomalies are dominant factors in the development of many intense ETCs [37]. Similar to the sea-level pressure tendency equation, the PV tendency equation can provide a quantitative estimate of the effects of LH on this PV anomaly [38].

The expected future increase of LH due to larger atmospheric moisture content (in line with higher ETC precipitation, see “Future Changes in Extratropical Cyclone Characteristics from Climate Models” section) may therefore lead to a future strengthening of ETCs. However, changes in other factors driving ETC intensification, such as horizontal and vertical temperature gradients, partly counteract this direct influence of LH. In particular, mid-to-upper-level LH in the extratropical atmosphere is expected to increase the mean static stability [39], which counteracts ETC intensification. The net effect of these processes is difficult to determine and might be small (see “Future Changes in Extratropical Cyclone Characteristics from Climate Models” section).

Changes in Extratropical Cyclones from Idealized Models

Attempts to isolate the effect of changes in atmospheric moisture and LH on ETC dynamics have been made with the help of idealized model simulations. For example, baroclinic life cycle experiments have been undertaken in which the atmospheric moisture content is increased (either directly or by increasing temperature and keeping relative humidity constant). Such experiments indicate that changes in ETC intensity depend on the background state and the complex interactions between LH and dry baroclinic processes [40–42].

One such study showed how increased moisture amounts similar to those in GCM projections could increase the strength of ETCs in terms of the surface winds and vertically integrated eddy kinetic energy (EKE, which reflects wind changes also at upper levels [37]). Studies using ensembles of idealized simulations have shown that the impact of moisture on ETC strength (defined as both EKE and minimum mean sea-level pressure (MSLP)) is small relative to changes in the initial meridional temperature gradient and that ETC strength does not monotonically increase with increased baroclinicity and moisture [41, 43]. These analyses revealed that the ETC response to increasing moisture changes depending on the initial temperature of the background state. Furthermore, the EKE does not increase at higher temperatures due to shifts in the location of the upper level ridge and the diabatic heating, which reduces the positive interaction between upper and lower levels [42, 43]. Increasing upper-level baroclinicity can increase the EKE, which is also related to the role of moisture in the interaction between upper-level and near-surface instabilities [42]. In an idealized GCM simulation, it was found that ETC strength is more sensitive to changes in upper-tropospheric baroclinicity than to changes in the lower troposphere [44].

Finally, other work (using idealized baroclinic life cycle simulations) has shown that higher moisture content will lead to an increased asymmetry between strong, narrow ascent, and broad, slow descent in the midlatitudes [45]. This signal has also been found in GCMs [46]. Corresponding structural changes to the precipitation distribution have also been identified using cyclone-centric compositing techniques, with the heaviest precipitation concentrated near the center of the ETCs in a warmer climate [41, 47]. The footprints of extreme precipitation in an idealized ETC (defined as 99.9th percentile) have been found to increase in size, including the size of coherent regions of extreme precipitation [48]. A broadening of the strong wind footprint in idealized ETCs has also been identified with cyclone-centric compositing [49]. Changes in the size of ETCs in idealized warming simulations appear to be sensitive to the method used to define size, with hardly any change seen in one study [47], and a large decrease in size in another [41].

Most of these idealized studies suggest that if the background state is unchanged, adding moisture leads to stronger ETC circulation; however, such studies cannot address the issue of the impact of moisture on the background state. Moisture is expected to have an impact because moisture transport and LH effectively transport energy towards higher latitudes and altitudes and thus affect horizontal and vertical temperature gradients. The presence of moisture in a quasigeostrophic model [50] or warming in an idealized GCM [47, 51] may actually decrease storm track EKE, which is consistent with a thermodynamic heat engine model [52]. Nevertheless, in the same idealized GCM simulations increased LH led to a robust enhancement of lower-tropospheric PV anomalies [47, 53], and a concomitant intensification (measured in terms of near-surface relative vorticity) of the strongest storms over a wide range of climates.

Future Changes in Extratropical Cyclone Characteristics from Climate Models

GCMs are commonly used to determine future changes in climate and meteorological events. The Fifth Coupled Model Intercomparison Project (CMIP5 [54]) provides an archive of data from state-of-the-art models, with the most recent archive (CMIP6) becoming available now (although there are no relevant published studies making use of these brand new data at the time of writing). There are a number of recent studies making use of the CMIP5 archive and similar simulations to try to determine how ETCs might change in the future, particularly with respect to their characteristics such as intensity, winds, and precipitation. There are also methods that can be used to investigate potential future changes in extratropical cyclones that lie in between idealized modeling and full GCM climate simulations. These are known as “analogue” methods, where examples of warmer conditions from the historical record are used as examples of potential future conditions; and “pseudo-climate change” experiments, where high-resolution simulations of case studies are performed with the boundary conditions representative of a warmer climate. Such studies are included in this section.

Model Evaluation

On the whole, GCMs are able to simulate the midlatitude storm tracks over the Atlantic Ocean, Pacific Ocean, Mediterranean, and throughout the Southern Ocean [55–58];

however, there are known systematic biases. Within GCMs, there is a tendency for the North Atlantic storm track to be too zonally orientated [17], the North Pacific storm track to be displaced equatorward [59], and the Mediterranean storm track to be too weak and displaced poleward [60]. In the SH, there is a tendency for the storm track (and also the jet) to be too weak and displaced equatorward relative to reanalysis data [56]. The models that show the largest bias in the storm track position actually project the largest meridional shift in the storm tracks in the future [56]. The representation of the storms themselves also shows biases. While the general dynamical features of ETCs are represented in climate models [61], there are problems representing the moist processes [62–66], with too frequent, low-intensity precipitation, and incorrect LH profiles due to clouds occurring at the wrong heights [62]. There are also biases in cloud fraction that have been attributed to parameterized convection schemes [67]. Given the importance of the LH for determining the poleward propagation of the storms [68], these biases may be related to the storm track biases mentioned above. Furthermore, given the importance of LH in cyclone structure and development (see "Theoretical Mechanisms for Future Changes in ETCs" section), reducing the errors in cloud processes will be instrumental in improving projections of cyclone-related properties.

While the studies highlighted above do provide an overview of the main storm track location and strength, there are still many potential areas of further work that could be undertaken. First, there is very little assessment of the seasonal characteristics of the storm tracks as the studies above are primarily focused on the winter and/or summer. Recent work has shown that there are considerable differences in the seasonal characteristics of the NH storm tracks, which should also be investigated in GCMs [69, 70]. Furthermore, strong storms are known to develop and have a large socioeconomic impact not only in winter but also in the spring/autumn (e.g., the Great Storm of 1987 over the southern UK [71]). Second, regional-scale assessments of the storm tracks need to look beyond the ocean basins; for example, there are important systems that develop in the lee of the Rockies [72], the Andes [73] and the Altai/Sayan/Tibetan Plateau highlands in East Asia [74], or over the Western Mediterranean [75], which propagate over the populated land masses. Such lee cyclones develop as a result of complex topographical/low-level flow interaction [76] and the presence of an upper-level shortwave trough that enables their propagation away from the mountain range [74]. Representing such cyclones in GCMs would present a challenge as they require good resolution/parametrization of topographical interaction with the background flow; however, their representation in, e.g., CMIP5 has received very little attention. Third (and finally), there is evidence that increasing model resolution acts to improve the simulated storm tracks [77], and the simulations performed as part of HighResMIP [78] should provide an opportunity to investigate this further and in much more detail. It is clear that more systematic evaluations of the storm tracks, seasonally, regionally, and in both hemispheres are required to get a true indication of how well the storm tracks are simulated in CMIP6.

ETC Intensity

There are different ways to define ETC intensity, such as the strength of the wind, the cyclonic vorticity, the deepening rates, or the central MSLP. CMIP5 models generally simulate a reduction in ETC intensity (according to both winds and deepening rates) in the NH in response to increasing future atmospheric greenhouse gas concentrations [17, 58, 79, 80]. Using the 90th percentile of 850-hPa wind speed during the historic period as a threshold value for defining extreme ETCs, there is a projected decrease in extreme ETC frequency by 8% in DJF and by 6% in JJA on average in the North Atlantic from the CMIP5 models under RCP8.5 [17]. Similar values apply to the NH as a whole, where there is a projected multi CMIP5 model mean decrease in projected intense ETC frequency by 5% under RCP8.5 [80]. Using recent warm and cold periods as analogues for global warming, no increase in maximum wind speeds associated with ETCs was seen during warm periods [81]. However, an increase in wind associated with ETCs is identified for some regions, notably the British Isles and the North Sea [17]. For example, a case study for storm Xynthia has provided evidence that the very anomalous sea surface temperature (SST) strongly contributed to the extreme impacts [82]. Also, pseudo-climate change experiments of individual cyclones with spatially homogeneous warming mostly indicate an increase in near surface wind gusts, which can largely be explained by the increase in LH [53]. Moreover, there are indications of an increase in the occurrence of ETCs featuring sting jets [83] within storms over the UK for a single climate model [84]. These numbers may increase further as the model resolution gets higher.

Concerning the Southern Hemisphere (SH), the wind intensity of extreme winter ETCs is projected to increase, ranging from 19 to 52% for different intensity definitions, from the CMIP5 models under RCP8.5 [85]. The opposing response of intense ETC frequency in the NH versus the SH is consistent with the projected changes in the 850-hPa equator-to-pole air temperature gradient (i.e., a decrease in the NH and an increase in the SH [86]). For a more in-depth analysis of the regional climate impacts of changes in ETC winds and their uncertainties, the reader is directed to another review article in this issue [87].

Defining intense ETCs based on their deepening rate rather than wind speed shows that the frequency of explosive cyclones, i.e., ETCs with deepening rates that exceed one Bergeron [88], are projected to decrease in the NH Atlantic by about 17% under RCP 8.5 [79]. This reduction is correlated with a decline in the lower-tropospheric Eady growth rate and is stronger for models with smaller biases in the frequency of explosive cyclones. On the other hand, explosive ETCs are projected to shift northwards in the NH Pacific, with no significant frequency changes when averaged across the Pacific basin. Dynamical downscaling experiments showed that the projected reduction of explosive ETC frequency in the Atlantic is not very sensitive to changes in the horizontal model resolution, possibly due to the lack of impact of resolution on the maximum Eady growth rate in that study [89]. This result is somewhat in contrast with other studies that show increased sensitivity to warming in higher resolution models [90].

ETC Precipitation

Water vapor is expected to increase in a warming climate given the Clausius-Clapeyron relationship, so confidence is relatively high that there will be a future increase in precipitation with ETCs. This is important since ETCs account for 80–90% of the precipitation at mid to high latitudes [2, 5]. CMIP5 models show an increase in precipitation on ETC days of 10–15% along the US East Coast by 2100 [91] and a 15–30% increase in cyclone-related precipitation [92, 93], with the relatively deep cyclones (central MSLP < 990 hPa) having the largest increase [5]. From downscaled regional modeling, the precipitation around ETCs may increase by 30–35% by 2100, which is slightly less than the Clausius-Clapeyron scaling, and the increases seem to be larger in downscaled CMIP5 model data than at the native resolution [94]. ETCs with large rain rates will be more frequent and have greater spatial extent across the North Atlantic storm track [95]. Two atmospheric analogue studies also found an increase in the precipitation intensity associated with ETCs in warmer, moister conditions [81, 82]. Such increases in precipitation intensity associated with midlatitude weather systems (mainly frontal) have been observed in particular regions [96], but a global systematic study of observed trends in ETC precipitation is currently lacking, possibly due to a lack of required observations.

Nevertheless, future changes in cyclone precipitation may deviate from this general intensification tendency in specific regions. For example, the projected future decrease in precipitation in the Mediterranean is related to both a decrease in the number of Mediterranean cyclones and also a decrease in the precipitation amount within cyclones in specific subregions [60]. Uncertainties associated with changes in the storm tracks in the future also lead to uncertainties in how precipitation will change in different regions [97, 98].

ETCs are also highly relevant for snowfall events in higher latitudes [99]. Snowfall is projected (using CMIP5 simulations) to decrease over much of the mid to high latitudes by the end of the twenty-first century under a high emission scenario but increase over much of the very high latitudes [100]. The decreases are mainly associated with a change in the precipitation fraction falling as snow, and the increases are associated with increased total precipitation. The relationship between these changes and ETCs specifically has not yet been addressed.

It has been recognized that a high model resolution (~ 20 km) is required to accurately capture cloud-diabatic processes, which often take place on relatively small spatial scales (mesoscales), e.g., in the region of fronts and their associated conveyor belts [101]. Several studies have thus relied on regional climate models to assess the effect of LH on future cyclone changes in realistic setups [95, 102]. These regional simulations project a robust amplification of lower-tropospheric PV within cyclones (again in line with increased precipitation intensities) and a tendency towards higher near-surface wind velocities, albeit with some spatial variability. Moreover, in areas showing large precipitation increases (such as the East Coast of the USA), the feedback between the LH from heavy precipitation and cyclone deepening will be enhanced [5] with implications for the life cycle characteristics of the cyclones (with slower deepening rates at the start and increased deepening rates later in the life cycle) [94]. Feedbacks may further increase the precipitation by increasing the forcing for ascent [95], although the rising moisture content is likely the dominant factor for the changes in precipitation intensity [92].

Cyclone Life Cycles and Structure

Idealized models have shown changes to the structure of precipitation and winds in warmer climates (see "Changes in Extratropical Cyclones from Idealized Models" section), and an increase in cyclone lifetimes [47]. A single climate model study looking at the 100 most intense cyclones (using either the maximum central vorticity or the precipitation as the intensity measure) indicated that the composite ETC structure does not change by the end of the twenty-first century [15]. Another study compositing a very large number of cyclones from a large ensemble [92] and a regional modeling study [95] were consistent with the idealized picture of the largest precipitation intensification near the cyclone center. There is less consistency in the changes to the structure of the winds [95].

There is also some suggestion that in the 100 most intense ETCs, the low-level winds and the vorticity decay more quickly after the peak intensity, but only for the most strongly precipitating ETCs [15]. The poleward propagation of ETCs is influenced by the latent heating that occurs in the warm conveyor belt region [103] via the low-level PV anomaly. As LH increases in the future, cyclones are expected to move faster and more polewards [68, 104], which may have impacts for future hazard forecasting, and thus also on the quantification of the climate change impacts associated with ETCs.

One important component of the structure of ETCs is the associated fronts. CMIP5 models project decreases in the frequency and strength of fronts over large parts of the NH and a small increase over western Europe [105]. The increase over Europe is consistent with observational studies [106], and may be associated with increased humidity. The decreases are consistent with the decreasing low-level baroclinicity. If the front frequency decreases but ETC precipitation increases, this suggests the potential for an increase in frontal precipitation intensity in the future, or a shift of the precipitation within the cyclones to a more central part of the cyclone consistent with idealized and climate modeling studies [47, 92]. These are aspects of the ETC structure that would benefit from further research.

Cyclone Temporal Clustering

Under particular large-scale atmospheric conditions, several cyclones may traverse a specific region within a short time period. Such a succession of storms is often called a “cyclone cluster” [107] and can be associated with “cyclone families,” often leading to large cumulative impacts (e.g., high precipitation and flooding). This characteristic has been identified in the North Atlantic region, and there are specific dynamical features associated with the occurrence of cyclone clustering [108]. The first is the modulation by large-scale atmospheric patterns (notably the North Atlantic Oscillation), whose phase shifts and persistence are associated with Rossby wave breaking [109], which lead to higher cyclone counts at a certain location via strong steering of the storms. The second factor is the development of secondary cyclones on the trailing fronts of a previous system [110], increasing the number of cyclones in a family. Still, cyclone clusters may also occur purely by chance [111]. In statistical terms, clustering can be quantified using the dispersion statistic [112], which estimates if the rate of occurrence of an event (e.g., cyclone passages in a certain location) corresponds to a homogenous Poisson process (random), to a regular process (underdispersion), or to clustering (overdispersion). Evaluations of different reanalyses [112–114] revealed that the flanks and the exit region of the North Atlantic storm track are preferential areas for clustering, while the storm track core region is underdispersive.

In general, climate models can reproduce the spatial pattern of clustering despite several biases [111, 114]. Regarding future projections, there are generally inconsistent results from different climate models [111, 114], primarily attributed to large sampling uncertainty. Cyclone clustering may decrease over parts of the North Atlantic and Europe, but generally, the changes in the dispersion statistic are small and uncertain [111]. In fact, the impact of climate change on the physical processes associated with cyclone clustering is also uncertain, namely in terms of jet variability and Rossby wave breaking [115]. Thus, the impact of climate change on cyclone clustering is still unclear and needs further evaluation. A recent evaluation of HiGEM simulations revealed that this high-resolution coupled GCM simulates similar cyclone and clustering statistics to reanalyses [116]. This is attributed to the good representation of Rossby wave breaking over the North Atlantic in HiGEM. These results motivate a detailed assessment of the impact of climate change on cyclone clustering based on the new CMIP6 coupled atmosphere-ocean model ensemble in order to better understand how the resultant extreme weather and socioeconomic impacts might change.

Other Types of Cyclones Affecting the Midlatitudes

Extratropical Transition of Tropical Cyclones

Except for the Southern Indian Ocean, the annual frequency of tropical cyclones undergoing extratropical transition (ET [106–108]) does not show any statistically significant trend in the present climate [117]. The investigation of potential changes of tropical cyclones (TCs) undergoing ET in a warmer climate has received relatively little attention. This is partly due to the limitations associated with objective, automated TC detection and tracking methods as well as with the definition of ET itself. In addition, a comparison of high-resolution National Center for Atmospheric Research Community Atmospheric Model hindcasts, reanalysis data, and TC best track data indicated systematic structural errors present during ET in climate models [118].

Notwithstanding these limitations, recent studies have assessed the changes of ET in a warmer climate using the cyclone phase space of Hart [119] as the classification standard of ET [120]. For warmer climate scenarios, it is expected that the number of TCs undergoing ET will increase over the North Atlantic [121–123] partly due to spatial shifts in TC genesis locations [123]. This increased frequency of TCs undergoing ET is projected to lead to an increase of rainfall associated with ET events in the northeastern USA. In addition, the TCs undergoing ET may become more intense as depicted by high-resolution pseudo-climate change simulations of Hurricane Sandy [124]. Further downstream, a warmer Atlantic Ocean may result in an increased frequency of post-ET reintensification, which will likely affect western Europe [122]. Though first approaches towards assessing the changes of ET in a warmer climate have been made, multimodel studies focused on the global climatology of ET are needed to generate a comprehensive picture of ET, particularly in relation to winds and precipitation.

Subtropical Cyclones

Subtropical cyclones occur in most ocean basins, and their thermal structure is characterized by a warm core at low levels and a cold core at upper levels (e.g., see [125] for a comprehensive review). While their genesis occurs in the subtropics, the cyclones can propagate into the midlatitudes [126]. Though earlier studies hypothesized that changes in SST or in the midlatitude flow could lead to an increased frequency of subtropical cyclones [127, 128], the systematic investigation of potential changes in a warmer climate has received very little attention until more recently. This may be due to the large computational resources needed to run models at high enough resolution to resolve the mesoscale processes involved in the formation and maintenance of subtropical cyclones [129, 130]. More recently, studies assessed trends of subtropical cyclones over the eastern North Atlantic and in particular over the Mediterranean using ensembles of high-resolution global and regional climate models. A common agreement of these studies is that the frequency of subtropical cyclones will decrease in both regions, though the maximum intensity is expected to increase [131–138] including stronger winds and more rainfall [139]. The projected decrease in the frequency of Mediterranean cyclones coincides with observations for past decades [140].

Arctic Cyclones

Arctic cyclones are another category of baroclinic disturbance that affect the northern high latitudes and have received some recent attention. A review of Arctic cyclones [141] summarized that future projections from GCMs with different warming scenarios show a decrease in the frequency of these cyclones during the winter and an increase during the summer by the end of the twenty-first century. This is despite the observed increase in Arctic cyclone activity over the recent past from ETCs moving into the region (rather than from cyclones generated in the region) [142] and an increase in extreme Arctic cyclones (defined as cyclones with MSLP below the fifth percentile) [143]. The extreme cyclones are influenced both by enhanced surface fluxes due to decreased sea ice and by atmospheric circulation [143]. In the future, changes in the large-scale circulation might play a larger role and be responsible for the decrease projected.

Cyclone Impacts and Their Future Changes

Wind

As discussed in "Changes in Extratropical Cyclones from Idealized Models" section, there is generally a decrease in ETC wind speed projected in the NH. Superficially, this would imply a reduction in wind hazards associated with ETCs; however, they do not account for changes in mesoscale processes within ETCs that can further enhance wind damage. For example, recent work [84] shows a 60% increase in sting jet precursor conditions over the North Atlantic in general and a doubling over the British Isles during September to May for 2100 relative to present day (RCP8.5). More broadly, an increase in damaging windstorms for central and western Europe during the next several decades and smaller changes or a small decrease for northern and southern Europe [144, 145] can be found. Overall, monetary losses from European wind storms (ETCs) are expected to increase by about 8% for every 1 °C increase (mean increase of about 25% for a 2.5 °C temperature increase [146]). This estimate is highly uncertain and will depend on future economic scenarios and adaptation measures.

By comparison, cyclone intensity is expected to increase in the SH [85], which would imply that there should be an increase in wind-related hazards. Nevertheless, most of the SH midlatitudes contain little land, and therefore, the hazards in populated areas may not be affected by these changes in ETCs. Instead, focus should be on specific cyclone categories (e.g., hybrid cyclones [147]), which are known to have large impacts on populated areas. Overall, it is clear that there is a lack of studies that focus on how wind impacts of specific cyclone types or the subsynoptic processes may change into the future in both hemispheres.

Inland Flooding

There is presently a lack of information regarding future changes in flood magnitude or frequency, due to modeling uncertainties (hydrological models and downscaling techniques in particular) and large interannual variability [148]. Furthermore, catchment-specific information is needed to project future flooding [149] as well as better understanding of physical mechanisms that govern flood occurrence, such as precipitation duration, spatial extent, and intensity associated with different weather systems.

Nevertheless, the projected increase in ETC-associated precipitation would be expected to cause increased inland flooding from these storms, which could cause issues in populated regions of the eastern USA and western Europe. One example of widespread inland flooding occurred over the UK in December, January, and February (DJF) 2013–2014 [150], which was caused by cyclone temporal clustering [151]. Storm Desmond, which hit the UK in December 2015, caused widespread flooding and about £0.5 billion of damage [152], due to a large atmospheric river tracking across the Atlantic. As AR intensity is generally expected to increase in a warming climate [153, 154], the impacts of events such as Storm Desmond may also increase. Overall, as precipitation around ETCs is projected to increase by at least 20–35% over the Northeast USA by 2100 [94]; the flooding impacts of such cyclone clustering and AR events are also likely to increase. Further regional and global studies on these projected changes are therefore urgently required.

Coastal Flooding and Wave Damage

Coastal flooding from storm surge is one of the most dangerous and damaging hazards from ETCs, either from winter storms [155] or tropical storms undergoing ET, such as hurricane Sandy (2012) as it approached the US East Coast [156, 157]. Even though the ETC winds are typically weaker than a hurricane, the ETC wind field is larger in spatial extent and can enhance the coastal flooding over several high tide cycles [158]. As a result, for New York City (NYC), 15 of the top 22 known historical storm tide events were caused by ETCs [159]. A multilinear regression method using derived surface wind stress and sea-level pressure from several CMIP5 models under the RCP8.5 scenario found little change in storm surges for the NYC area from present day to 2054–2079 [160]. Moreover, by using a hydrodynamic model forced with six hourly 10-m winds and sea-level pressures, only small increases were found in surge heights for a number of coastal cities along the Northeastern US Coast for the same models, time period, and scenario [161]. Nonetheless, there are relatively large uncertainties, since one climate model predicted a 25–40% increase in surge heights. Furthermore, with rising sea levels during the next several decades, the return periods for coastal flooding with minimal surge increases are expected to decrease significantly. The ~0.5 m of regional sea-level rise in NYC between 1800 and 2000 implies that Sandy's return period decreased by a factor of three [162]. In the future for NYC, a 1-in-100-year flood for NYC is expected to occur every 8–59 years (90th and 10th percentiles) by the 2080s [159].

Waves and associated coastal erosion from ETCs can increase coastal flooding damage. ETCs can have large coastal erosion impacts given the prolonged wave energy over several tidal cycles, but there is a scarcity of observational datasets of extreme beach erosion to adequately resolve the impacts of individual storms [163]. Projections of deep-water wave climatologies by 2100 are highly variable [164–166]. A particular wave model and historical analysis showed that synoptic storms (2–10-day bandpass filtered winds) have the largest impact on the waves from East Coast of North America to western Europe [167]. This study noted a large uncertainty in future wave heights over the North Atlantic given the relatively large variability in storm track intensity and frequency in this region. Future wave increases are most pronounced across the SH and are associated with the strengthening of the Southern Ocean westerlies and southerly shift of the storm track [166, 168]. Wave directionality is also important [163] and modulates the amount of wave exposure along the coast, but there is little understanding of these future changes.

Discussion

The Differing Ways of Defining Changes Associated with ETCs

In "Future Changes in Extratropical Cyclones from Climate Models" section, some different diagnostics that can be used to define cyclone intensity were discussed. One factor that creates difficulty in reaching a consensus on how the intensity of cyclones might change in the future is the way in which the intensity itself is analyzed. If we consider winds as an example, there are different ways of analyzing future changes in cyclone-related winds, some of which can be visualized with the schematic in Fig. 1.

1. Geographically: how does the frequency or intensity of cyclone-related wind change at a given location?
2. Mean intensity change: how does, e.g., the mean or maximum wind around a cyclone change? This is demonstrated by the colored vertical lines in Fig. 1 and may not show any change despite a change in the shape of the distribution. For example, the cyan curve has the same mean as the black and red curves, but clearly different shape distribution. Since the distribution is non-Gaussian (as would be many of the variables associated with ETCs) looking at the median rather than the mean of the distribution might be more informative, although in the case here, the median of the cyan curve would be lower. Looking at the

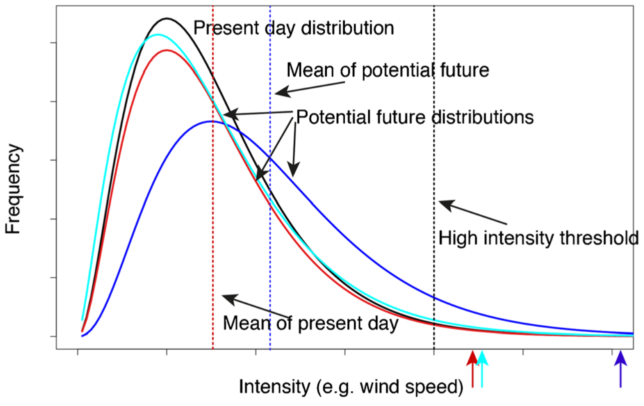


Fig. 1 Schematic of frequency distributions of intensity of ETC using hypothetical gamma distributions. Black = present day; red, cyan, blue = potential future. The black line represents present day distribution; the red line represents the same parameters as present day but 10% fewer storms; cyan and blue represent different possible distributions. The red vertical dashed line is the mean of the black, red, and cyan curves, and the blue dashed line is the mean of the blue curve. The colored arrows represent the 99th percentiles of the black and red, cyan, and blue curves

whole distribution would give the greatest understanding of the changes.

3. Frequency change: how does the frequency of cyclones with high wind speeds change? This would be related to the number of events above the high-intensity threshold. If the number of storms decreases without any change in the distribution, this number would decrease. However, if the shape of the distribution changes (e.g., the cyan or blue distributions in Fig. 1), this could increase.
4. Extreme intensity: how does the intensity of the extreme events change? (i.e., what is the change in the 99th percentile for example). This is illustrated by the colored arrows in Fig. 1 and shows that it is possible to have the same mean but a higher 99th percentile value when the distribution shape changes.
5. Footprint: how does the size of the region affected by high intensity winds change?

Studies that consider all of these together for a single region or one method for the whole globe would be extremely useful towards future synthesis reports in order enable a consistent comparison of different studies. This seems like a good avenue for future research efforts, although comparing the distributions of intensity from models with differing resolutions could be difficult. This would need to be taken into account by using data interpolated to the same grid. Methods 2–4 would likely be more directly applicable to idealized studies, which do not have geographical considerations, thereby helping to bridge the gap between idealized and complex GCM results.

Remaining Questions and Future Directions

There are a number of questions remaining and potential areas of research on the future of ETCs, which are summarized here.

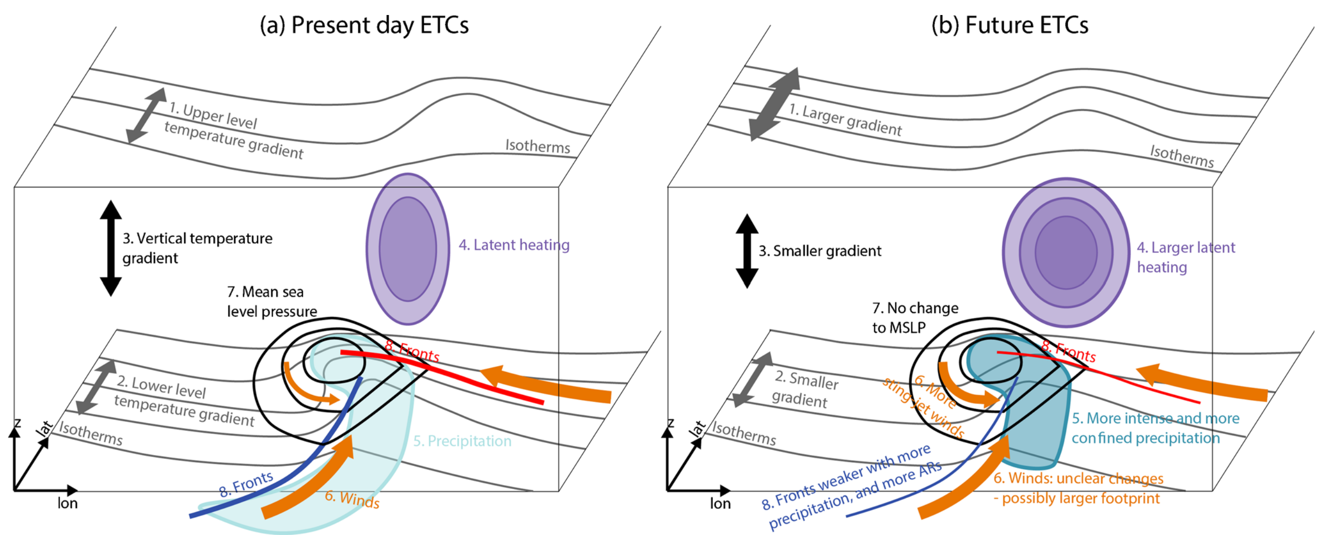
- Currently, there is still a lot of uncertainty and disagreement about the opposing influences of surface and upper-tropospheric warming and LH. How will these shift the storms and affect their frequency and intensity? Higher resolution models may better represent the impact of latent heating on extratropical cyclone intensity, so it will be of great interest to investigate how a suite of high-resolution models [78] will project the future of ETCs. Will these give dramatically different projections?
- A focus on the different types of cyclones that impact the midlatitudes and how they change, for example by using cyclone classification techniques [169, 170], can help better understand changes in cyclones and the aggregated storm tracks.
- Current results from idealized simulations are not easily comparable with the output from complex climate simulations. A recent review paper [171] has analyzed in depth what we can learn from using models of different complexity. In the specific context of ETCs, the consideration of the "hierarchy of processes" seems to be the most relevant. The consideration of models of intermediate process complexity will be instrumental to better link the results from idealized modeling with GCM projections. One of the challenges associated with this is the data required to be output from climate models to diagnose these dynamical processes (e.g., diabatic temperature tendencies).
- There are many studies focusing on small regions or particular sets of statistics. Studies also considering the intensity of cyclones in all of the different ways discussed above for particular regions would also be a valuable addition.
- In terms of developing the communication of future storm risk to the public, making use of the naming of particular storms might be useful [172], where future changes could be described in terms of present day analogues.

Summary

ETCs are expected to change in frequency, preferred location, characteristics, and impacts in the future. The main features of ETCs that have been discussed in this review and how they are expected to change in the future are represented schematically in Fig. 2 and synthesized here with reference to the features in Fig. 2.

1. Baroclinicity and thereby storm development will be impacted by the increased upper tropospheric temperature gradient (feature 1), decreased lower-tropospheric temperature gradient (feature 2) (in the NH only), and increased static stability (feature 3), as well as increased LH release (feature 4). These factors do not change monotonically with warming, and so there are still uncertainties around the precise impact.
2. Precipitation within ETCs is expected to increase in intensity (feature 5), but there are mixed results in terms of how this feeds back onto the intensity of the winds (feature 6) or the central pressure (feature 7).
3. Inland flooding is projected to increase due to precipitation and moisture transport increases (feature 8), but catchment-specific information is lacking. Coastal flooding from storm surges is likely to increase in the future, mainly associated with rising sea levels.
4. While wind strength projections are uncertain (feature 6), there are expected future increases in storm-related costs.

There are clearly still many avenues of research that would yield valuable information to guide adaptation measures for future climate change in the midlatitudes.



Feature	1	2	3	4	5 (intensity)	5 (extent)	6	7	8
Confidence	High	High	High	High	High	Low	Low	Medium	Low

Fig. 2 Schematic diagram summarizing future changes to extratropical cyclones in the NH. The table shows the confidence in the change of each of the features listed in the diagram, based on the assessment of the literature carried out here

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Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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