



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.

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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.

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 preceding 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

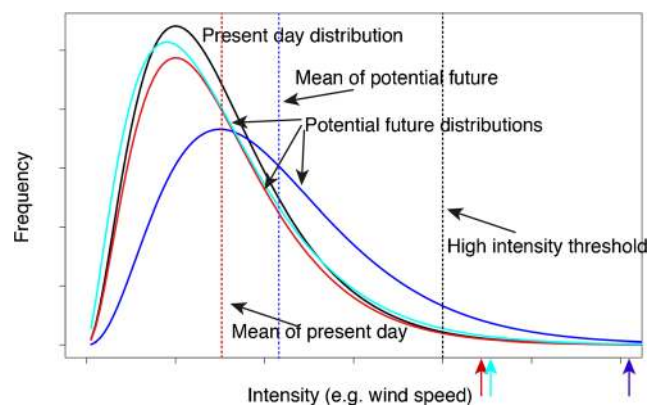


Fig. 1 Schematic of frequency distributions of intensity of ETC using hypothetical gamma distributions. Black = present day; red, cyan, blue = potential future. The black line represents present day distribution; the red line represents the same parameters as present day but 10% fewer storms; cyan and 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.

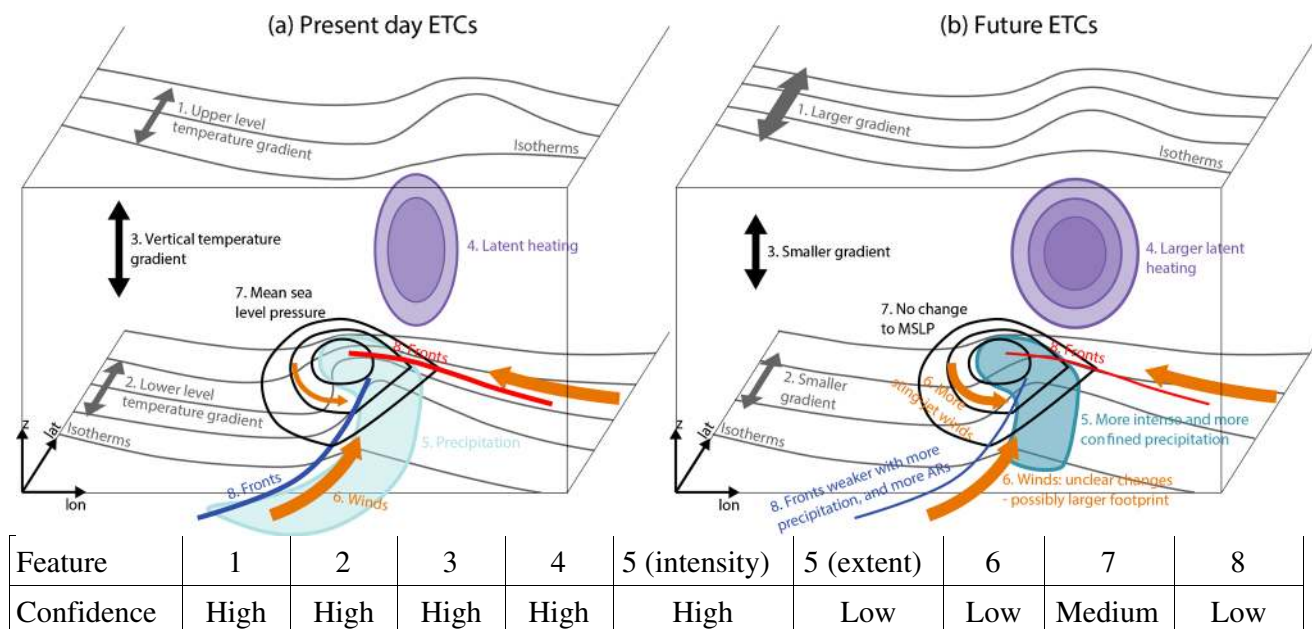


Fig. 2 Schematic diagram summarizing future changes to extratropical cyclones in the NH. The table shows the confidence in the change of each

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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References

- Catto JL, Jakob C, Berry G, Nicholls N. Relating global precipitation to atmospheric fronts. *Geophys Res Lett*. 2012;39.
- Hawcroft MK, Shaffrey LC, Hodges KI, Dacre HF. How much Northern Hemisphere precipitation is associated with extratropical cyclones? *Geophys Res Lett* 2012;39
- Pfahl S, Wernli H. Quantifying the relevance of cyclones for precipitation extremes. *J Clim*. 2012;25:6770–80.
- Catto JL, Pfahl S. The importance of fronts for extreme precipitation. *J Geophys Res*. 2013;118:10,791–801.
- Zhang Z, Colle BA. Changes in extratropical cyclone precipitation and associated processes during the twenty-first century over eastern North America and the Western Atlantic using a cyclone-relative approach. *J Clim*. 2017;30(21):8633–56.
- Fink AH, Brucher T, Ernert V, Krüger A, Pinto JG. The European storm Kyrill in January 2007: synoptic evolution, meteorological impacts and some considerations with respect to climate change. *Nat Hazards Earth Syst Sci*. 2009;9:405–23.
- Dowdy A, Catto JL. Extreme weather caused by concurrent cyclone, front and thunderstorm occurrences. *Sci Rep*. 2017;7.
- Roberts JF, Champion AJ, Dawkins LC, Hodges KI, Shaffrey LC, Stephenson DB, et al. The XWS open access catalogue of extreme European windstorms from 1979 to 2012. *Nat Hazards Earth Syst Sci*. 2014;14:2487–501.
- MunichRe G. Schadenspiegel special feature issue risk factor of air . 2008. Available from: www.munichre.com
- Shimkus CE, Ting M, Booth JF, Adamo SB, Madajewicz M, Kushnir Y, et al. Winter storm intensity, hazards, and property losses in the New York tristate area. *Ann N Y Acad Sci*. 2017;1400(1):65–80.
- Wang J, Kim H-M, Chang EKM. Changes in northern hemisphere winter storm tracks under the background of Arctic amplification. *J Clim*. 2017;30(10):3705–24.
- Collins M, Knutti R, Arblaster J, Dufresne J-L, Fichet T, Friedlingstein P, et al. Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, editor. *Climate Change 2013: the physical science basis contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge and New York: Cambridge University Press; 2013.
- Shaw TA, Baldwin M, Barnes EA, Caballero R, Garfinkel CI, Hwang YT, et al. Storm track processes and the opposing influences of climate change. *Nat Geosci*. 2016;9(9):656–64.
- IPCC. Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate

- Change. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, et al., editors. . Cambridge, and New York: Cambridge University Press; 2012. p. 582.
15. Bengtsson L, Hodges KI, Keenlyside N. Will extra-tropical storms intensify in a warmer climate? *J Clim*. 2009;22:2276–301.
 16. Zappa G. Regional climate impacts of future changes in the mid-latitude atmospheric circulation: a storyline view. *Curr Clim Change Rep*. 2019. <https://doi.org/10.1007/s40641-019-00146-7>.
 17. Zappa G, Shaffrey LC, Hodges KI, Sansom PG, Stephenson DB. A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. *J Clim*. 2013;26:5846–62.
 18. Christensen JH, Krishna Kumar K, Aldrian E, An S-I, Cavalcanti IFA, Castro M de, et al. Climate phenomena and their relevance for future regional climate change. In: *Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 2013*.
 19. Eady ET. Long waves and cyclone waves. *Tellus*. 1949;1:33–52.
 20. Chamey JG. The dynamics of long waves in a baroclinic westerly current. *J Meteor*. 1947;4:135–63.
 21. Hoskins BJ, Valdes PJ. On the existence of storm tracks. *J Atmos Sci*. 1990;47:1854–64.
 22. Nakamura H. Midwinter suppression of baroclinic wave activity in the Pacific. *J Atmos Sci*. 1992;49:1629–42.
 23. Schemm S, Schneider T. Eddy lifetime, number, and diffusivity and the suppression of eddy kinetic energy in midwinter. *J Clim*. 2018;31(14):5649–65.
 24. Davis CA, Stoelinga MT, Kuo Y-H. The integrated effect of condensation in numerical simulations of extratropical cyclogenesis. *Mon Wea Rev*. 1993;121:2309–30.
 25. Stoelinga MT. A potential vorticity-based study of the role of diabatic heating and friction in a numerically simulated baroclinic cyclone. *Mon Weather Rev*. 1996;124(5):849–74.
 26. Ahmadi-Givi F, Craig GC, Plant RS. The dynamics of a midlatitude cyclone with very strong latent-heat release. *Quart J Roy Meteor Soc*. 2004;130:295–323.
 27. Fink AH, Pohle S, Pinto JG, Knippertz P. Diagnosing the influence of diabatic processes on the explosive deepening of extratropical cyclones. *Geophys Res Lett*. 2012;39.
 28. Gray SL, Dacre HF. Classifying dynamical forcing mechanisms using a climatology of extratropical cyclones. *Quart J Roy Meteor Soc*. 2006;132:1119–37.
 29. Davies HC. The quasigeostrophic omega equation: reappraisal, refinements, and relevance. *Mon Weather Rev*. 2015;143(1):3–25.
 30. Azad R, Sorteberg A. A diagnosis of warm-core and cold-core extratropical cyclone development using the Zwack-Okossi equation. *Atmos Sci Lett*. 2009;10(4):220–5.
 31. Hoskins BJ, McIntyre ME, Robertson AW. On the use and significance of isentropic potential vorticity maps. *Quart J Roy Meteor Soc*. 1985;111:877–946.
 32. Eliassen A, Kleinschmidt E. Dynamic meteorology, *Handbuch der Physik (Encyclopedia of Physics)*. Flügge S, editor. Springer-Verlag; 1957. 1–154 p.
 33. Crezee B, Joos H, Wernli H. The microphysical building blocks of low-level potential vorticity anomalies in an idealized extratropical cyclone. *J Atmos Sci*. 2017;74(5):1403–16.
 34. Quinting JF, Reeder MJ, Catto JL. The intensity and motion of hybrid cyclones in the Australian region in a composite potential vorticity framework. *Q J R Meteorol Soc*. 2019;145(718):273–87.
 35. Dacre HF, Gray SL. Quantifying the climatological relationship between extratropical cyclone intensity and atmospheric precursors. *Geophys Res Lett*. 2013;40:2322–7.
 36. Čampa J, Wernli H. A PV perspective on the vertical structure of mature midlatitude cyclones in the northern hemisphere. *J Atmos Sci*. 2012;69(2):725–40.
 37. Seiler C. A climatological assessment of intense extratropical cyclones from the potential vorticity perspective. *J Clim*. 2019. <https://doi.org/10.1175/JCLI-D-18-0461.1>.
 38. Büeler D, Pfahl S. Potential vorticity diagnostics to quantify effects of latent heating in extratropical cyclones. Part I: Methodology *J Atmos Sci*. 2017;74(11):3567–90.
 39. O’Gorman PA. The effective static stability experienced by eddies in a moist atmosphere *Journal of the Atmospheric Sciences*. 2011;68:75–90.
 40. Booth JF, Wang S, Polvani L. Midlatitude storms in a moister world: lessons from idealized baroclinic life cycle experiments. *Clim Dynam*. 2013;41:787–802.
 41. Tierney G, Posselt DJ, Booth JF. An examination of extratropical cyclone response to changes in baroclinicity and temperature in an idealized environment. *Clim Dyn*. 2018;51(9–10):3829–46.
 42. Rantanen M, Räisänen J, Sinclair VA, Järvinen H. Sensitivity of idealised baroclinic waves to mean atmospheric temperature and meridional temperature gradient changes. *Clim Dyn*. 2019;52: 2703–19.
 43. Kirshbaum DJ, Merlis TM, Gyakum JR, McTaggart-Cowan R. Sensitivity of idealized moist baroclinic waves to environmental temperature and moisture content. *J Atmos Sci*. 2018;75:337–60.
 44. Yuval J, Kaspi Y. Eddy activity sensitivity to changes in the vertical structure of baroclinicity. *J Atmos Sci*. 2016;73(4):1709–26.
 45. Booth JF, Polvani L, O’Gorman PA, Wang S. Effective stability in a moist baroclinic wave. *Atmos Sci Lett*. 2015;16(1):56–62.
 46. Tamarin-Brodsky T, Hadas O. The asymmetry of vertical velocity in current and future climate. *Geophys Res Lett*. 2019;46(1):374–82.
 47. Pfahl S, O’Gorman P, Singh MS. Extratropical cyclones in idealized simulations of changed climates. *J Clim*. 2015;28:9373–92.
 48. Phibbs S, Toumi R. The dependence of precipitation and its footprint on atmospheric temperature in idealized extratropical cyclones. *J Geophys Res Atmos*. 2016;121(15):8743–54.
 49. Sinclair VA, Haapanala P, Räisänen J, Rantanen M. The structure of extratropical cyclones in a warmer climate, *Weather Clim. Dynam. Discuss*. In review, 2019. <https://doi.org/10.5194/wcd-2019-2>.
 50. Laine A, Lapeyre G, Riviere G. A quasigeostrophic model for moist storm tracks. *J*. 2011;68:1306–22.
 51. O’Gorman PA, Schneider T. Energy of midlatitude transient eddies in idealized simulations of changed climates. *J Clim*. 2008;21(22):5797–806.
 52. Laliberté F, Zika J, Mudryk L, Kushner PJ, Kjellsson J, Döös K. Atmospheric dynamics. Constrained work output of the moist atmospheric heat engine in a warming climate. *Science*. 2015 Jan 30;347(6221):540–3.
 53. Büeler D, Pfahl S. Potential vorticity diagnostics to quantify effects of latent heating in extratropical cyclones. Part II: application to idealized climate change simulations. *J Atmos Sci*. 2019;76: 1885–1902. <https://doi.org/10.1175/JAS-D-18-0342.1>.
 54. Taylor KE, Stouffer RJ, Meehl GA. An overview of CMIP5 and the experiment design. *Bull Amer Meteor Soc*. 2012;93:485–98.
 55. Booth JF, Kwon Y-O, Ko S, Small RJ, Msadek R. Spatial patterns and intensity of the surface storm tracks in CMIP5 models. *J Clim*. 2017;30(13):4965–81.
 56. Chang EKM, Guo Y, Xia X, Zheng M. Storm-track activity in IPCC AR4/CMIP3 model simulations. *J Clim*. 2013;26(1):246–60.
 57. Chang EKM. CMIP5 projection of significant reduction in extratropical cyclone activity over North America. *J Clim*. 2013;26:9903–22.
 58. Ulbrich U, Leckebusch GC, Pinto JG. Extra-tropical cyclones in the present and future climate: a review. *Theor Appl Clim*. 2009;96:117–31.

59. Yang M, Li X, Zuo R, Chen X, Wang L. Climatology and inter-annual variability of winter North Pacific Storm Track in CMIP5 models. *Atmosphere* (Basel). 2018;9(3).
60. Zappa G, Hawcroft MK, Shaffrey L, Black E, Brayshaw DJ. Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models. *Clim Dyn*. 2015;45(7–8):1727–38.
61. Catto JL, Shaffrey LC, Hodges KI. Can climate models capture the structure of extratropical cyclones? *J Clim*. 2010;23:1621–35.
62. Govekar P, Jakob C, Catto JL. The relationship between clouds and dynamics in Southern Hemisphere extratropical cyclones in the real world and a climate model. *J Geophys Res*. 2014;119:6609–28.
63. Hawcroft MK, Dacre HF, Forbes R, Hodges KI, Shaffrey LC, Stein T. Using satellite and reanalysis data to evaluate the representation of latent heating in extratropical cyclones in a climate model. *Clim Dyn*. 2017;48:2255–78.
64. Hawcroft MK, Shaffrey LC, Hodges KI, Dacre HF. Can climate models represent the precipitation associated with extratropical cyclones? *Clim Dyn*. 2016;47:679–95.
65. Catto JL, Jakob C, Nicholls N. A global evaluation of fronts and precipitation in the ACCESS model. *Aust Meteorol Ocean Soc J*. 2013;63:191–203.
66. Catto JL, Jakob C, Nicholls N. Can the CMIP5 models represent winter frontal precipitation? *Geophys Res Lett*. 2015;42:8596–604.
67. Naud CM, Booth JF, Del Genio AD. Evaluation of ERA-interim and MERRA cloudiness in the Southern Ocean. *J Clim*. 2014;27(5):2109–24.
68. Tamarin-Brodsky T, Kaspi Y. Enhanced poleward propagation of storms under climate change. *Nat Geosci*. 2017;10(12):908–13.
69. Hoskins BJ, Hodges KI. The annual cycle of northern hemisphere storm tracks. Part II: Regional Detail *J Clim*. 2019;32(6):1761–75.
70. Hoskins BJ, Hodges KI. The annual cycle of northern hemisphere storm tracks. Part I: Seasons *J Clim*. 2019;32(6):1743–60.
71. Prichard B. The great storm of 16 October 1987. *Weather*. 2012;67(10):255–60.
72. Thomas BC, Martin JE. A synoptic climatology and composite analysis of the Alberta clipper. *Weather Forecast*. 2007;22(2):315–33.
73. Hoskins BJ, Hodges KI. A new perspective on southern hemisphere storm tracks. *J Clim*. 2005;18:4108–29.
74. Newton CW. Associations between twice-yearly oscillations of the North Pacific cyclone track and upper-tropospheric circulations over the eastern hemisphere. *Mon Weather Rev*. 2004;132(1):348–67.
75. Trigo IF, Davies TD, Bigg GR. Objective climatology of cyclones in the Mediterranean region. *J Clim*. 1999;12(6):1685–96.
76. Ren X, Yang X, Chu C. Seasonal variations of the synoptic-scale transient Eddy activity and polar front jet over East Asia. *J Clim*. 2010;23(12):3222–33.
77. Colle BA, Zhang Z, Lombardo KA, Chang E, Liu P, Zhang M. Historical evaluation and future prediction of Eastern North American and Western Atlantic extratropical cyclones in the CMIP5 models during the cool season. *J Clim*. 2013;26:6882–903.
78. Haarsma RJ, Roberts MJ, Vidale PL, Senior CA, Bellucci A, Bao Q, et al. High resolution model Intercomparison project (HighResMIP v1.0) for CMIP6. *Geosci Model Dev*. 2016;9(11):4185–208.
79. Seiler C, Zwiers FW. How will climate change affect explosive cyclones in the extratropics of the Northern Hemisphere? *Clim Dyn*. 2016;46:3633–44.
80. Chang E. Projected change in Northern Hemisphere winter cyclones with associated extreme winds. *J Clim*. 2018;31(16):6527–42.
81. Li M, Woollings T, Hodges K, Masato G. Extratropical cyclones in a warmer, moister climate: a recent Atlantic analogue. *Geophys Res Lett*. 2014;41(23):8594–601.
82. Ludwig P, Pinto JG, Reyers M, Gray SL. The role of anomalous SST and surface fluxes over the southeastern North Atlantic in the explosive development of windstorm Xynthia. *Quart J Roy Meteor Soc*. 2014;140:1729–41.
83. Browning KA. The sting at the end of the tail: damaging winds associated with extratropical cyclones. *Quart J Roy Meteor Soc*. 2004;130:375–99.
84. Martínez-Alvarado O, Gray SL, Hart NCG, Clark PA, Hodges K, Roberts MJ. Increased wind risk from sting-jet windstorms with climate change. *Environ Res Lett*. 2018;13(4):044002.
85. Chang EKM. Projected significant increase in the number of extreme extratropical cyclones in the Southern Hemisphere. *J Clim*. 2017;30(13):4915–35.
86. Harvey BJ, Shaffrey LC, Woollings TJ. Equator-to-pole temperature differences and the extra-tropical storm track responses of the CMIP5 climate models. *Clim Dyn*. 2014;43(5):1171–82.
87. Zappa G. Regional climate impacts of future changes in the mid-latitude circulation: a storylines view. *Curr Clim Chang Reports*. 2019;In press.
88. Sanders F, Gyakum JR. Synoptic-dynamic climatology of the “bomb. *Mon Wea Rev*. 1980;108:1589–606.
89. Seiler C, Zwiers FW, Hodges KI, Scinocca JF. How does dynamical downscaling affect model biases and future projections of explosive extratropical cyclones along North America’s Atlantic coast? *Clim Dyn*. 2018;50:677–92.
90. Willison J, Robinson WA, Lackmann GM. North Atlantic storm-track sensitivity to warming increases with model resolution. *J Clim*. 2015;28(11):4513–24.
91. Lombardo K, Colle BA, Zhang Z. Evaluation of historical and future cool season precipitation over the eastern United States and Western Atlantic storm track using CMIP5 models. *J Clim*. 2015;28(2):451–67.
92. Yettella V, Kay JE. How will precipitation change in extratropical cyclones as the planet warms? Insights from a large initial condition climate model ensemble. *Clim Dyn*. 2017;49(5–6):1765–81.
93. Hawcroft M, Walsh E, Hodges K, Zappa G. Significantly increased extreme precipitation expected in Europe and North America from extratropical cyclones. *Environ Res Lett*. 2018;13(12).
94. Zhang Z, Colle BA. Impact of dynamically downscaling two CMIP5 models on the historical and future changes in winter extratropical cyclones along the East Coast of North America. *J Clim*. 2018;31(20):8499–525.
95. Michaelis AC, Willison J, Lackmann GM, Robinson WA. Changes in winter North Atlantic extratropical cyclones in high-resolution regional pseudo-global warming simulations. *J Clim*. 2017;30(17):6905–25.
96. Bishop DA, Williams AP, Seager R. Increased fall precipitation in the Southeastern United States driven by higher-intensity, frontal precipitation. *Geophys Res Lett*. 2019;46:8300–8309. <https://doi.org/10.1029/2019GL083177>.
97. Chang EKM, Zheng C, Lanigan P, Yau AMW, Neelin JD. Significant modulation of variability and projected change in California winter precipitation by extratropical cyclone activity. *Geophys Res Lett*. 2015;42:5983–91.
98. Osburn L, Keay K, Catto JL. Projected change in wintertime precipitation in California using projected changes in extratropical cyclone activity. *J Clim*. 2018;31:3451–66.
99. Suriano ZJ, Leathers DJ, Hall DK, Frei A. Contribution of snow-fall from diverse synoptic conditions in the Catskill/Delaware watershed of New York state. *Int J Climatol*. 2019;39(8):3608–18.

100. Krasting JP, Broccoli AJ, Dixon KW, Lanzante JR, Krasting JP, Broccoli AJ, et al. Future changes in northern hemisphere snowfall. *J Clim*. 2013;26(20):7813–28.
101. Willison J, Robinson WA, Lackmann GM. The importance of resolving mesoscale latent heating in the North Atlantic storm track. *J Atmos Sci*. 2013;70:2234–50.
102. Marciano CG, Lackmann GM, Robinson WA. Changes in U.S. East Coast cyclone dynamics with climate change. *J Clim*. 2015;28(2):468–84.
103. Tamarin T, Kaspi Y. The poleward motion of extratropical cyclones from a potential Vorticity tendency analysis. *J Atmos Sci*. 2016;73(4):1687–707.
104. Graff LS, Lacasce JH. Changes in cyclone characteristics in response to modified SSTs. *J Clim*. 2014;27:4273–95.
105. Catto JL, Nicholls N, Jakob C, Shelton KL. Atmospheric fronts in current and future climates. *Geophys Res Lett*. 2014;41:7642–50.
106. Schemm S, Sprenger M, Martius O, Wernli H, Zimmer M. Increase in the number of extremely strong fronts over Europe? A study based on ERA-Interim reanalysis (1979–2014). *Geophys Res Lett*. 2017;44(1):553–61.
107. Bjerknes J, Solberg H. Life cycle of cyclones and the polar front theory of atmospheric circulation. *Geophys Publ*. 1922;3:1–18.
108. Pinto JG, Gómara I, Masato G, Dacre HF, Woollings T, Caballero R. Large-scale dynamics associated with clustering of extratropical cyclones. *J Geophys Res*. 2014;119:13704–19.
109. Benedict JJ, Lee S, Feldstein SB. Synoptic view of the North Atlantic oscillation. *J Atmos Sci*. 2004;61(2):121–44.
110. Parker DJ. Secondary frontal waves in the North Atlantic region: a dynamical perspective of current ideas. *Quart J Roy Meteor Soc*. 1998;124:829–56.
111. Economou T, Stephenson DB, Pinto JG, Shaffrey LC, Zappa G. Serial clustering of extratropical cyclones in a multi-model ensemble of historical and future simulations. *Quart J Roy Meteor Soc*. 2015;141:3076–87.
112. Mailier PJ, Stephenson DB, Ferro CAT, Hodges KI. Serial clustering of extratropical cyclones. *Mon Wea Rev*. 2006;134:2224–40.
113. Vitolo R, Stephenson DB, Cook IM, Mitchell-Wallace K. Serial clustering of intense European storms. *Meteorol Zeitschrift*. 2009;18(4):411–24.
114. Pinto JG, Bellenbaum N, Karremann MK, Della-Marta PM. Serial clustering of extratropical cyclones over the North Atlantic and Europe under recent and future climate conditions. *J Geophys Res*. 2013;118:12,412–476,485.
115. Barnes EA, Hartmann DL. Detection of Rossby wave breaking and its response to shifts of the midlatitude jet with climate change. *J Geophys Res*. 2012;117.
116. Priestley MDK, Dacre HF, Shaffrey LC, Hodges KI, Pinto JG. The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high-resolution global climate model data. *Nat Hazards Earth Syst Sci*. 2018;18(11):2991–3006.
117. Bieli M, Camargo SJ, Sobel AH, Evans JL, Hall T, Bieli M, et al. A global climatology of extratropical transition Part I: characteristics across basins. *J Clim*. 2019;32:3557–3582. <https://doi.org/10.1175/JCLI-D-17-0518.1>.
118. Zarzycki CM, Thatcher DR, Jablonowski C. Objective tropical cyclone extratropical transition detection in high-resolution reanalysis and climate model data. *J Adv Model Earth Syst*. 2017;9(1):130–48.
119. Hart RE. A cyclone phase space derived from thermal wind and thermal asymmetry. *Mon Wea Rev*. 2003;131:585–616.
120. Bieli M, Camargo SJ, Sobel AH, Evans JL, Hall T, Bieli M, et al. A global climatology of extratropical transition Part II: statistical performance of the cyclone phase space. *J Clim*. 2019;32:3583–3597. <https://doi.org/10.1175/JCLI-D-18-0052.1>.
121. Haarsma RJ, Hazeleger W, Severijns C, de Vries H, Sterl A, Bintanja R, et al. More hurricanes to hit western Europe due to global warming. *Geophys Res Lett*. 2013;40(9):1783–8.
122. Baatsen M, Haarsma RJ, Van Delden AJ, de Vries H. Severe autumn storms in future Western Europe with a warmer Atlantic Ocean. *Clim Dyn*. 2015;45(3):949–64.
123. Liu M, Vecchi GA, Smith JA, Murakami H. The present-day simulation and twenty-first-century projection of the climatology of extratropical transition in the North Atlantic. *J Clim*. 2017;30(8):2739–56.
124. Lackmann GM. Hurricane Sandy before 1900 and after 2100. *Bull Am Meteorol Soc*. 2015;96(4):547–60.
125. da Rocha RP, Reboita MS, Gozzo LF, Dutra LMM, de Jesus EM. Subtropical cyclones over the oceanic basins: a review. *Ann N Y Acad Sci*. 2019;1436(1):138–56.
126. Guishard MP, Evans JL, Hart RE. Atlantic subtropical storms. Part II: Climatology *J Clim*. 2009;22:3574–94.
127. Pezza AB, Simmonds I. The first South Atlantic hurricane: unprecedented blocking, low shear and climate change. *Geophys Res Lett*. 2005;32(15).
128. Evans JL, Braun A. A climatology of subtropical cyclones in the South Atlantic. *J Clim*. 2012;25(21):7328–40.
129. Evans JL, Guishard MP. Atlantic subtropical storms. Part I: diagnostic criteria and composite analysis. *Mon Wea Rev*. 2009;137:2065–80.
130. Bentley AM, Keyser D, Bosart LF. A dynamically based climatology of subtropical cyclones that undergo tropical transition in the North Atlantic Basin. *Mon Weather Rev*. 2016;144(5):2049–68.
131. Gaertner MA, Jacob D, Gil V, Domínguez M, Padorno E, Sánchez E, et al. Tropical cyclones over the Mediterranean Sea in climate change simulations. *Geophys Res Lett*. 2007;34(14).
132. Romero R, Emanuel K. Medicanes risk in a changing climate. *J Geophys Res Atmos*. 2013;118(12):5992–6001.
133. Cavicchia L, von Storch H, Gualdi S. Mediterranean tropical-like cyclones in present and future climate. *J Clim*. 2014;27(19):7493–501.
134. Walsh K, Giorgi F, Coppola E. Mediterranean warm-core cyclones in a warmer world. *Clim Dyn*. 2014 Feb;42(3):1053–66.
135. Romera R, Gaertner MÁ, Sánchez E, Domínguez M, González-Alemán JJ, Miglietta MM. Climate change projections of medicanes with a large multi-model ensemble of regional climate models. *Glob Planet Change*. 2017;151:134–43.
136. Tous M, Zappa G, Romero R, Shaffrey L, Vidale PL. Projected changes in medicanes in the HadGEM3 N512 high-resolution global climate model. *Clim Dyn*. 2016 Sep;47(5):1913–24.
137. Gaertner MÁ, González-Alemán JJ, Romera R, Domínguez M, Gil V, Sánchez E, et al. Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution. *Clim Dyn*. 2018 Aug;51(3):1041–57.
138. Nissen KM, Leckebusch GC, Pinto JG, Ulbrich U. Mediterranean cyclones and windstorms in a changing climate. *Reg Environ Chang*. 2014;14(5):1873–90.
139. González-Alemán JJ, Pascale S, Gutierrez-Fernandez J, Murakami H, Gaertner MA, Vecchi GA. Potential increase in hazard from Mediterranean hurricane activity with global warming. *Geophys Res Lett*. 2019;46(3):1754–64.
140. Maheras P, Flocas HA, Patrikas I, Anagnostopoulou C. A 40 year objective climatology of surface cyclones in the Mediterranean region: spatial and temporal distribution. *Int J Climatol*. 2001;21(1):109–30.
141. Screen JA, Bracegirdle TJ, Simmonds I. Polar climate change as manifest in atmospheric circulation. *Curr Clim Chang Reports*. 2018;4(4):383–95.
142. Sepp M, Jaagus J. Changes in the activity and tracks of Arctic cyclones. *Clim Chang*. 2011;105(3–4):577–95.

143. Rinke A, Maturilli M, Graham RM, Matthes H, Handorf D, Cohen L, et al. Extreme cyclone events in the Arctic: wintertime variability and trends. *Environ Res Lett*. 2017;12(9):094006.
144. Karremann MK, Pinto JG, Reyers M, Klawns M. Return periods of losses associated with European windstorm series in a changing climate. *Environ Res Lett*. 2014;9(12):124016.
145. Mölter T, Schindler D, Albrecht A, Kohnle U, Mölter T, Schindler D, et al. Review on the projections of future storminess over the North Atlantic European region. *Atmosphere* (Basel). 2016;7(4):60.
146. Ranson M, Kousky C, Ruth M, Jantarasami L, Crimmins A, Tarquinio L. Tropical and extratropical cyclone damages under climate change. *Clim Chang*. 2014;127:227–41.
147. Quinting JF, Catto JL, Reeder MJ. Synoptic climatology of hybrid cyclones in the Australian region. *Q J R Meteorol Soc*. 2019;145(718):288–302.
148. Kundzewicz ZW, Kanae S, Seneviratne SI, Handmer J, Nicholls N, Peduzzi P, et al. Flood risk and climate change: global and regional perspectives. *Hydrol Sci J*. 2014;59(1):1–28.
149. Watts G, Battarbee RW, Bloomfield JP, Crossman J, Daccache A, Durance I, et al. Climate change and water in the UK – past changes and future prospects. *Prog Phys Geogr Earth Environ*. 2015;39(1):6–28.
150. Muchan K, Lewis M, Hannaford J, Parry S. The winter storms of 2013/2014 in the UK: hydrological responses and impacts. *Weather*. 2015;70(2):55–61.
151. Priestley MDK, Pinto JG, Dacre HF, Shaffrey LC. The role of cyclone clustering during the stormy winter of 2013/2014. *Weather*. 2017;72(7):187–92.
152. PWC. PWC 2015 PWC http://pwc.blogs.com/press_room/2015/12/updated-estimates-on-cost-of-storm-desmond-pwc.html (Accessed: 18 April 2019). 2015.
153. Lavers DA, Allan RP, Villarini G, Lloyd-Hughes B, Brayshaw DJ, Wade AJ. Future changes in atmospheric rivers and their implications for winter flooding in Britain. *Environ Res Lett*. 2013;8(3):034010.
154. Espinoza V, Waliser DE, Guan B, Lavers DA, Ralph FM. Global analysis of climate change projection effects on atmospheric rivers. *Geophys Res Lett*. 2018;45(9):4299–308.
155. Colle BA, Buonaiuto F, Bowman MJ, Wilson RE, Flood R, Hunter R, et al. New York City's vulnerability to coastal flooding. *Bull Am Meteorol Soc*. 2008;89(6):829–42.
156. Smith AB, Katz RW. US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Nat Hazards*. 2013;67(2):387–410.
157. Colle BA, Booth JF, Chang EKM. A review of historical and future changes of extratropical cyclones and associated impacts along the US East Coast. *Curr Clim Chang Rep*. 2015;1:125–43.
158. Colle BA, Rojowsky K, Buonaiuto F. New York City storm surges: climatology and an analysis of the wind and cyclone evolution. *J Appl Meteorol Climatol*. 2010;49(1):85–100.
159. Orton P, Lin N, Gornitz V, Colle B, Booth J, Feng K, et al. New York City panel on climate change 2019 report chapter 4: coastal flooding. *Ann N Y Acad Sci*. 2019;1439(1):95–114.
160. Roberts KJ, Colle BA, Korfe N. Impact of simulated twenty-first-century changes in extratropical cyclones on coastal flooding at the battery, New York City. *J Appl Meteorol Climatol*. 2017;56(2):415–32.
161. Lin N, Marsooli R, Colle BA. Storm surge return levels induced by mid-to-late-twenty-first-century extratropical cyclones in the northeastern United States. *Clim Chang*. 2019;2:1–16.
162. Lin N, Kopp RE, Horton BP, Donnelly JP. Hurricane Sandy's flood frequency increasing from year 1800 to 2100. *Proc Natl Acad Sci U S A*. 2016;113(43):12071–5.
163. Harley MD, Turner IL, Kinsela MA, Middleton JH, Mumford PJ, Splinter KD, et al. Extreme coastal erosion enhanced by anomalous extratropical storm wave direction. *Sci Rep*. 2017;7(1):6033.
164. Shimura T, Mori N, Hemer MA. Variability and future decreases in winter wave heights in the Western North Pacific. *Geophys Res Lett*. 2016;43(6):2716–22.
165. Wang XL, Feng Y, Swail VR. Changes in global ocean wave heights as projected using multimodel CMIP5 simulations. *Geophys Res Lett*. 2014;41(3):1026–34.
166. Mentaschi L, Vourdoukas MI, Voukouvalas E, Dosio A, Feyen L. Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophys Res Lett*. 2017;44(5):2416–26.
167. Markina MY, Studholme JHP, Gulev SK. Ocean wind wave climate responses to wintertime North Atlantic atmospheric transient eddies and low-frequency flow. *J Clim*. 2019;32:5619–5638.
168. Semedo A, Weisse R, Behrens A, Sterl A, Bengtsson L, Günther H, et al. Projection of global wave climate change toward the end of the twenty-first century. *J Clim*. 2013;26(21):8269–88.
169. Catto JL. Extratropical cyclone classification and its use in climate studies. *Rev Geophys*. 2016;54.
170. Catto JL. A new method to objectively classify extratropical cyclones for climate studies: testing in the Southwest Pacific region. *J Clim*. 2018;31:4683–704.
171. Maher P, Gerber EP, Medeiros B, Merlis TM, Sherwood S, Sheshadri A, et al. Model hierarchies for understanding atmospheric circulation. *Rev Geophys*. 2019;57(2). <https://doi.org/10.1029/2018RG000607>.
172. Charlton-Perez AJ, Vukadinovic Greetham D, Hemingway R. Storm naming and forecast communication: a case study of Storm Doris. *Meteorol Appl*. 2019;26:682–697. <https://doi.org/10.1002/met.1794>.

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