THÈSE

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Impacts de l'augmentation des extrêmes de hautes températures sur la performance du décollage des avions dans la région Euro-Méditerranéenne

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Abstract

The increase in the magnitude and in the frequency of high-temperature extreme events as a result of climate change will impact the aviation operations, with socio-economic, environmental and even health consequences. The main goal of this thesis is to assess the potential impact of increasing high-temperature extremes on aircraft takeoff performance, focusing on the Euro-Mediterranean climate-change "hotspot" region. First, the future evolution of high-temperature extremes is studied. Second, the potential impact is assessed in terms of the engine performance and pollutant emissions, in particular of nitrogen oxides (NO_x), and in terms of the aircraft's Maximum TakeOff Weight (MTOW). Simulations performed with Regional and Global Climate Models (RCMs and GCMs) are considered in a multi-ensemblist approach. The bias-corrected future climate projections are used as input to an engineering software for analysing the engine's behavior, and an empirical law is applied to the climate data to estimate the MTOW. A robust positive trend is found for the levels of NO_x emissions and the MTOW limitations. Nonetheless, there are large uncertainties in the magnitude of the impacts, arising mainly from uncertainties in future climate projections. They would need to be narrowed for the design of adaptation and/or mitigation strategies in the future.

Résumé

L'augmentation de la magnitude et de la fréquence des événements extrêmes de hautes températures à cause du changement climatique impactera les opérations aériennes, avec des conséquences socio-économiques, environnementales et même sanitaires. L'objectif principal de cette thèse est d'évaluer l'impact potentiel de l'augmentation des extrêmes de hautes températures sur la performance du décollage des avions, en particulier dans la région Euro-Méditerranéenne, qui est spécialement sensible au changement climatique. L'évolution future des extrêmes de hautes températures est étudiée d'abord. Ensuite, l'impact potentiel est évalué en termes de la performance du moteur et des émissions de polluants, en particulier d'oxydes d'azote (NO_x), et en termes de la masse maximale décollable (MTOW) de l'avion. Des simulations effectuées avec des modèles climatiques régionaux et globaux sont prises en compte dans une approche ensembliste multi-modèle. Les projections climatiques futures sont utilisées, après la correction des biais des modèles, comme données d'entrée pour un outil type métier utilisé par les motoristes pour analyser le comportement du moteur. Une loi empirique est appliquée aux données climatiques afin d'estimer la MTOW. Une tendance positive robuste est trouvée pour les niveaux d'émissions de NO_x et les limitations de la MTOW. Néanmoins, il y a des grandes incertitudes dans la magnitude des impacts, provenant principalement des incertitudes dans les projections climatiques. Elles devront être réduites pour la conception de stratégies d'adaptation et/ou d'atténuation à l'avenir.

Extended abstract

Extreme heat conditions negatively affect aircraft performances and airport's capacity and efficiency. An increase in the magnitude and in the frequency of high-temperature extremes due to climate change would impact aviation operations, with further socio-economic, environmental and even health consequences. The Mediterranean region is a major climate change "hotspot", specially concerned by the increase in high temperatures. This thesis assess the future impacts of rising high-temperature extremes on aircraft takeoff performance in the Euro-Mediterranean region. The problem is addressed as follows: 1) the future evolution of high-temperature extremes is studied from climate model simulations, and 2) the potential induced impacts are assessed in terms of the levels of pollutant emissions, in particular, of nitrogen oxides (NO_x), and engine performance, and in terms of the aircraft's maximum carrying capacity at takeoff.

Before evaluating the potential impacts of future changes in high-temperature extreme events, the past and future evolution of these events over a list of major and regional airports is analysed from observations and climate model simulations and projections. The daily maximum near-surface air temperature (TX) in summer is used. First, the magnitude of extreme values observed in recent decades is characterized, and trends in summer TX percentiles are computed as well. The quantile regression method allows us to obtain the evolution of the shape of the Probability Distribution Function, in particular, the trends of the median and the extremes, and not only the mean trends like the most-commonly used Ordinary Least Squares regression method. A robust increase is generally found over the airports for all percentiles. Some airports experienced a stronger increase in the

upper percentiles than in the median or in the lower percentiles, which may be particularly problematic for aviation, and other sectors as well. Second, climate models are evaluated in present climate in these terms over the airports. This is a crucial step for the further assessment of future climate projections and related impacts. Simulations performed with Regional and Global Climate Models (RCMs and GCMs) are considered in a multi-model ensemble approach. In particular, the state-of-the-art Euro-CORDEX multi-RCM ensemble and the ensemble of driving GCMs from CMIP5 are used. The two ensembles are compared to each other. Results show that there is no generally prevailing added value in RCMs for the study of the magnitude of high-temperature extremes nor for their temporal trends at the airport scale, despite their higher spatial resolution. Third, the future evolution of summer TX extremes is assessed for different time horizons and different climate change scenarios. A robust increase of the order of few degrees Celsius is found in summer TX extremes in the future for all the airports (up to +3.2°C in the near term and up to +8.5°C in the long term, under the severe scenario), with larger changes projected by the GCMs over the same locations. Forth, biases in future climate projections are corrected before the evaluation of the impact on the aircraft takeoff. Both RCMs and GCMs ensembles are considered here, in order not to underestimate climate modelling uncertainties.

In the second part of the thesis, the potential future increase in the levels of NO_x emissions is assessed using an industrial tool for analysing the engine performance and pollutant emissions. The input value for the ambient temperature is declared as the future magnitude of summer TX extremes over the airports, which was estimated from the climate projections. To the best of our knowledge, this is the first time that data from climate models are used as input to an engine emulator. A general increase is found in the levels of NO_x emissions over the selected airports. It could lead to an increase in absolute NO_x emissions at takeoff of the order of a few percentage points in future extreme events: up to nearly +4% and +6% by the near and medium term, respectively. The potential future decrease in aircraft's maximum carrying capacity induced by the future increase in summer TX is assessed for each airport, following an empirical law for degrading the Maximum TakeOff Weight (MTOW) curves in *Aircraft Characteristics for Airport Planning*. This empirical law was provided by AIRBUS for three different aircrafts representing long-, medium- and short-range couriers. The future reductions in MTOW are generally of the order of tones for the long- and medium-range aircrafts, which could result in weight restrictions corresponding to tens of passengers and/or in delays or cancellations. The short-range aircrafts would experience little to no impact on the MTOW.

Despite the robust positive trend found for the levels of NO_x emissions and the MTOW limitations, there are large uncertainties in the magnitude of the impacts analysed here. They mainly arise from uncertainties in climate projections that would need to be narrowed for the design of adaptation and/or mitigation strategies in the future. Also,

This thesis assess some of the maximum potential impacts that climate change may have on general aviation operations in the coming decades. It illustrates the magnitude of the negative effects that the increase in high-temperature extremes would have on aircraft takeoff performance in terms of pollutant emissions, engine performance and MTOW limitations. All this focused on one of the world's most sensitive areas to climate change: the Euro-Mediterranean region. Moreover, it highlights the positive feedback loop between the rising temperatures and the rising NO_x emissions from aviation. In addition, this thesis provides new methodologies to assess the impacts of climate change on aircraft takeoff at any airport in the world.

Aviation operations at Euro-Mediterranean airports will be likely impacted by the increase in high-temperature extremes in the future. Adaptation and resilience strategies should be designed and deployed. This would require collaboration with airlines, aircraft and engine manufacturers and other stakeholders.

Résumé étendu

Les conditions de chaleur extrême affectent négativement les performances des avions et la capacité et le rendement opérationnels des aéroports. L'augmentation de l'intensité et de la fréquence des extrêmes de hautes températures due au changement climatique pourrait impacter les opérations aériennes, avec des conséquences socio-économiques, environnementales et même sanitaires. La région Euro-Méditerranéenne est specialement sensible au changement climatique; elle est particulièrement concernée par l'augmentation de hautes températures. Dans cette thèse, les impacts potentiels futurs de l'augmentation des extrêmes de hautes températures sur la performance du décollage des avions ont été évalués dans la région Euro-Méditerranéenne. Le problème a été abordé de la façon suivante: 1) l'évolution future des extrêmes de hautes températures a été étudiée à partir de simulations de modèles climatiques, et 2) les impacts potentiels induits ont été évalués en termes des niveaux des émissions de polluants, en particulier d'oxydes d'azote (NO_x), et de la performance du moteur, et aussi en termes de la capacité maximale de l'avion pour soulever du poids au décollage.

Avant d'évaluer les impacts potentiels des changements futurs des événements extrêmes de hautes températures, l'évolution passée et future de ces événements a été analysée sur une liste d'aéroports principaux et secondaires à partir d'observations et de simulations et projections de modèles climatiques. Nous nous sommes focalisés sur la température maximale journalière (TX) en été. Tout d'abord, la magnitude des valeurs extrêmes observées au cours des dernières décennies a été caractérisée, et les tendances des percentiles de la TX estivale ont été également calculées. La méthode de régression par quantiles nous a permis d'obtenir l'évolution de la forme

de la fonction de distribution de probabilité, en particulier, les tendances de la médiane et des extrêmes, et pas seulement les tendances de la moyenne comme la méthode ordinaire de régression des moindres carrés, la plus couramment utilisée dans la littérature. Une augmentation robuste et généralisée a été trouvée aux aéroports pour tous les percentiles. Certains aéroports ont connu une augmentation plus forte des percentiles supérieurs que de la médiane ou des percentiles inférieurs, ce qui pourrait être particulièrement problématique pour l'aviation, et pour d'autres secteurs également. Dans un deuxième temps, les modèles climatiques ont été évalués dans le climat présent sur les aéroports. Il s'agit d'une étape cruciale pour l'évaluation ultérieure des projections climatiques et des impacts futurs. Les simulations réalisées à l'aide de Modèles Climatiques Régionaux et Globaux (RCMs et GCMs) ont été prises en compte dans une approche ensembliste multi-modèle. En particulier, l'ensemble multi-RCM Euro-CORDEX et l'ensemble des GCMs forceurs de CMIP5 ont été utilisés. Les deux ensembles ont été comparés entre eux. Les résultats montrent qu'il n'y a pas de valeur ajoutée généralement dominante des RCMs pour l'étude des valeurs extrêmes de hautes températures ni de leurs tendances à l'échelle de l'aéroport, malgré leur résolution spatiale plus élevée. Troisièmement, l'évolution future des extrêmes estivaux de la TX a été évaluée pour différents horizons temporels et différents scénarios de changement climatique. Une augmentation robuste a été trouvée, de l'ordre de quelques degrés Celsius pour tous les aéroports (jusqu'à +3.2°C à court terme et jusqu'à +8.5°C à long terme, sous le scénario sévère), avec des changements plus importants projetés par les GCMs sur les mêmes emplacements. Enfin, les biais des modèles ont été corrigés dans les projections climatiques futures avant d'évaluer l'impact sur le décollage des avions. L'ensemble des simulations des RCMs et celui des GCMs ont été considérés ici, afin de ne pas sous-estimer les incertitudes de la modélisation climatique.

Dans la deuxième partie de la thèse, l'augmentation potentielle future des niveaux d'émissions de NO_x a été évaluée à l'aide d'un outil type métier qui émule le comportement du moteur de l'avion. La valeur en entrée du logiciel pour la température ambiante a été déclarée comme la magnitude future des extrêmes estivaux de la TX sur les aéroports, qui a été estimée auparavant à partir des projections climatiques. À notre connaissance, il s'agit de la première fois que des données provenantes de modèles climatiques ont été utilisées en entrée d'un émulateur de moteur. Une augmentation générale des niveaux d'émissions de NO_x au décollage a été trouvée sur les aéroports sélectionnés. Elle pourrait conduire à une augmentation des émissions absolues de NO_x au décollage de l'ordre de quelques points de pourcentage lors des futurs événements extrêmes: jusqu'à près de +4% et +6% à court et moyen terme, respectivement. La diminution potentielle de la masse maximale au décollage de l'avion (MTOW) induite par l'augmentation future de TX est évaluée pour chaque aéroport, à partir d'une loi empirique qui consiste à dégrader les courbes MTOW se trouvant dans les manuels *Aircraft Characteristics for Airport Planning*. Cette loi empirique a été fournie par AIRBUS pour trois modèles d'avion différents représentant les longs, moyens et courts courriers. Les réductions futures sur la MTOW trouvées sont généralement de l'ordre de plusieurs tonnes pour les longs et moyens courriers, ce qui pourrait entraîner des restrictions de poids correspondantes à des dizaines de passagers et/ou des retards, voire des annulations. Pour les courts courriers, l'impact sur la MTOW serait faible ou nul.

Malgré la tendance positive robuste trouvée pour les niveaux d'émissions de NO_x et les limitations de la MTOW, il existe des grandes incertitudes quant à la magnitude des impacts analysés ici. Elles proviennent principalement des incertitudes dans les projections climatiques, qui devraient être réduites pour la conception de stratégies d'adaptation et/ou d'atténuation dans le futur.

Cette thèse a évalué certains des impacts potentiels maximums que le changement climatique pourrait avoir sur les opérations de l'aviation générale dans les décennies à venir. Elle a illustré la magnitude des effets négatifs que l'augmentation des extrêmes de hautes températures aurait sur la performance du décollage des avions en termes d'émissions polluantes, de la performance du moteur et des limitations de la MTOW. Tout cela sur l'une des zones les plus sensibles au changement climatique:

la région Euro-Méditerranéenne. En plus, elle a mis en évidence la boucle de rétroaction positive entre l'augmentation des températures et l'augmentation des émissions de NO_x provenant de l'aviation. En outre, cette thèse a fourni de nouvelles méthodologies pour évaluer les impacts du changement climatique sur le décollage des avions dans n'importe quel aéroport du monde.

Les opérations aériennes dans les aéroports Euro-Méditerranéens seront probablement affectées par l'augmentation des températures extrêmes à l'avenir. Des stratégies d'adaptation et de résilience devraient être conçues et déployées. Cela nécessiterait de la collaboration avec les compagnies aériennes, les fabricants d'avions et de moteurs et d'autres parties concernées.

List of Abbreviations

CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM	French National Centre for Meteorological Research
	(Centre National de Recherches Météorologiques)
CO_2	Carbon Dioxyde
CORDEX	Coordinated Regional Climate Downscaling Experiment
EASA	European Union Aviation Safety Agency
EEA	European Environment Agency
Euro-CORDEX	CORDEX simulations for the European domain
FAA	The U.S. Federal Aviation Administration
GCM	Global Climate Model
GHG	Greenhouse Gases
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
ISA	International Standard Atmosphere

JJA	June, July and August
MTOW	Maxmimum Take-Off Weight
$\mathbf{MTOW_0}$	Maxmimum-certificated Take-Off Weight
NOAA	The U.S. National Oceanic and Atmospheric Administration
$\mathbf{NO}_x$	Nitrogen oxydes
PDF	Probability Distribution Function
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RCP8.5	RCP with radiative forcing of 8.5 W/m^2 by 2100 with respect to the pre-industrial era
TOW	Take-Off Weight
TX	Daily maximum near-surface air temperature
TX50p	the median of the TX
TX95p	95^{th} percentile of the TX

Introduction (FR)

L'impact de l'aviation sur le climat a été largement étudié, et aujourd'hui sa contribution au réchauffément global en raison des émissions de dioxyde de carbone est bien connue. Les émissions des oxydes d'azote (NO_x) issues de la combustion et les traînées de condensation des avions ont également joué un rôle important. Le changement climatique pourrait à son tour impacter les operations aériennes. En effet, l'aviation pourrait être à la fois victime et bourreau de ce phenomène. L'impact du changement climatique sur l'aviation reste peu étudié. Il s'agit d'un sujet de recherche émergent, qui est accompagné d'une préoccupation incipiente parmi les services aéronautiques et l'industrie de l'aviation, qui sont concernés par la performance et la sécurité des opérations aériennes face aux enjeux climatiques.

Cette thèse répond à l'intérêt émergent des constructeurs aéronautiques, des organisations nationales et internationales de l'aviation et des compagnies aériennes pour l'évaluation de l'impact potentiel futur du changement climatique sur les opérations de l'aviation générale. La thèse s'inscrit dans le cadre du projet consortium Impact du Changement Climatique sur l'Aviation (ICCA), qui est le résultat d'un Réseau Thématique de Recherche Avancée (RTRA) au niveau local de Toulouse, piloté par le CERFACS en partenariat avec MÉTÉO-FRANCE, ISAE-SUPAERO, ENAC, ONERA et AIRBUS. Le but principal de ce projet est d'améliorer la compréhension du vaste sujet des impacts du changement climatique sur l'aviation, ainsi que de développer et mettre en place des nouvelles méthodologies multi-disciplinaires visant à évaluer quantitativement les impacts potentiels. Il encadre plusieurs actions dans ce sens, tel que l'étude des changements de la turbulence en ciel clair, des conditions de givrage et même des aspects sociologiques de voyager en avion. Cette thèse, en particulier, se focalise sur les effets de l'augmentation des extrêmes de hautes températures sur la performance du décollage des avions, en se concentrant sur les aéroports de la région Euro-Méditerranéenne, l'une des plus sensibles au changement climatique.

Une augmentation de la température ambiante entraîne une diminution de la portance de l'avion en raison de la baisse de la densité de l'air, et elle peut conduire aussi à une diminution de la poussée du moteur. Cela a un impact négatif sur la capacité de l'avion à soulever du poids. Dans le future, il pourrait devenir nécessaire de modifier les horaires des vols, voire d'appliquer des restrictions de poids lors des événements extrêmes de hautes températures, ce qui entraînerait un impact socio-économique.

En outre, des températures ambiantes plus élevées entraînent une augmentation des émissions polluantes du moteur de l'avion. D'une part, cela est dû à la réduction de la performance du décollage dans des conditions ambiantes plus chaudes et à l'intensification de la consommation de carburant qui en résulte. D'autre part, cela est dû à une température de la flamme plus élevée à l'intérieur du moteur, ce qui implique une production plus importante d'oxydes d'azote (NO_x) lors du processus de combustion pour la même quantité de carburant brûlé. L'augmentation du carburant nécessaire pour éffectuer les mêmes opérations dans des conditions plus chaudes pourrait avoir un impact socio-économique ainsi qu'environnemental et sanitaire. La montée des émissions des NO_x pourrait également avoir un impact environnemental et sanitaire. De plus, les émissions de NO_x de l'aviation contribuent au réchauffement de la planète. L'accroissement des émissions de NO_x due à la hausse des températures pourrait se traduire par un réchauffement additionnel.

Les aéroports de la région Euro-Méditerranéenne pourraient être particulièrement impactés par l'intensification et la multiplication des extrêmes de hautes températures, du fait qu'il s'agit d'une région spécialement sensible au changement climatique, notamment à la hausse des températures, et qui se caractérise déjà par des températures estivales élevées dans la période présente.

L'objectif principal de cette thèse est d'évaluer l'impact de l'augmentation des extrêmes de hautes températures sur les performances des avions au décollage dans la région Euro-Méditerranéenne. Il s'agit d'un sujet pluri-disciplinaire impliquant les sciences du climat, de l'aéronautique, la turbomachine et la combustion. L'information climatique issue des projections réalisées avec des modèles climatiques doit d'abord être distillée à l'échelle des aéroports du domaine d'étude. Une approche multi-disciplinaire est ensuite nécessaire pour traduire les changements futurs des températures projetés par les modèles climatiques sur les aéroports en termes des changements des performances de l'avion au décollage. En particulier, cette thèse adresse les changements des niveaux d'émissions de NO_x et de la performance du moteur, ainsi que de la capacité maximale de l'avion à soulever du poids. Les deux premiers sont estimés à l'aide d'un logiciel industriel qui émule le comportement du moteur, et le dernier est dérivé à partir d'une loi empirique suggerée par AIRBUS. Pour la première fois les données des modèles climatiques sont utilisées en entrée d'un émulateur de moteur. Il s'agit aussi de la première fois que l'impact de l'augmentation des températures sur la masse maximale au décollage de l'avion est estimée avec cette loi empirique. Pour cela une collaboration avec les acteurs principaux de l'industrie aéronautique à été nécessaire.

CHAPTER 1

Introduction

1.1 CLIMATE CHANGE

Climate change is one of main challenges of our era. Since 1900, the global mean surface temperature has increased by more than 1°C as a result of the increase in greenhouse gas (GHG) emissions and concentrations from the Industrial Revolution [IPCC 21]. Anthropogenic GHG emissions primarily consist of carbon dioxide (CO_2) from fossil fuel combustion in human activities such as energy production and transportation. Indeed, changes in atmospheric CO_2 concentrations due to fossil fuel burning can be traced, since their emissions alter the isotopic fingerprint of the carbon in the atmosphere, diminishing the relative amount of contemporary $^{14}CO_2$ [Zhang 21]. Changes in land use also contribute to variations in GHG concentrations. These GHG emissions of anthropic origin are considered as an external forcing on the climate system. They alter the Earth's energy imbalance between the incoming energy from the Sun and the returning energy back to space, allowing the atmosphere to retain more energy, increasing the surface temperature. Therefore, anthropogenic GHG emissions are an external radiative forcing of the climate system causing warming on a global scale [IPCC 13, IPCC 21].

The warming of climate has not been homogeneous over time, but has accelerated over the last decades, with two thirds of this warming having taken place since the 1970s [IPCC 13]. Figure 1.1(a) shows the observed change in surface temperature between 1901 and 2012. Most of the globe has warmed, with the greatest increases in temperatures experienced over land as compared to oceans. Therefore, the warming has not been homogeneous in space either.

As a consequence of this warming, the sea level has risen by about 1.8 cm/decade over the period 1950-2000 [Church 04]. This is mainly explained by the thermal expansion of warmer oceans and to glaciers melting. The depth and extent of snow and ice covers have remarkably decreased in recent decades [IPCC 21]. In particular, according to satellite data, Arctic ice sheet extent has decreased by about 2.7% per decade in the cold season over the period 1978-2018 with respect to 1981-2010, and by 12.8% per decade in the warm season [Meredith 19]. Precipitation patterns have also changed across the globe, with increased precipitations over land at the global scale since 1950 [IPCC 21]. The Mediterranean region is affected by both more frequent droughts and intense precipitation events [IPCC 21].

Not only the average temperature has increased, but also the hot extremes, both in frequency and in magnitude [IPCC 13, IPCC 21], as shown in Figure 1.1(b) and Figure 1.1(c). Some regions are more concerned than others. In particular, the Mediterranean region is considered as a major climate-change hotspot, specially sensitive to global warming [Giorgi 06, Diffenbaugh 07, Lionello 18]. As shown in Figure 1.1(b), it has experienced a large increase in temperature extremes, ranging between 1.5 and 3 °C over the period 1951-2010. In addition, Figure 1.1(b) shows that the Mediterranean basin is particularly affected by the rise in the frequency of heat events, which have increased by between 4 and 8 days per decade in the period 1951-2010.

In the absence of mitigation policies, climate change is expected to continue during the 21st century. Moreover, even if mitigation policies were implemented, climate change would continue evolving through 2050 [IPCC 21]. High-temperature

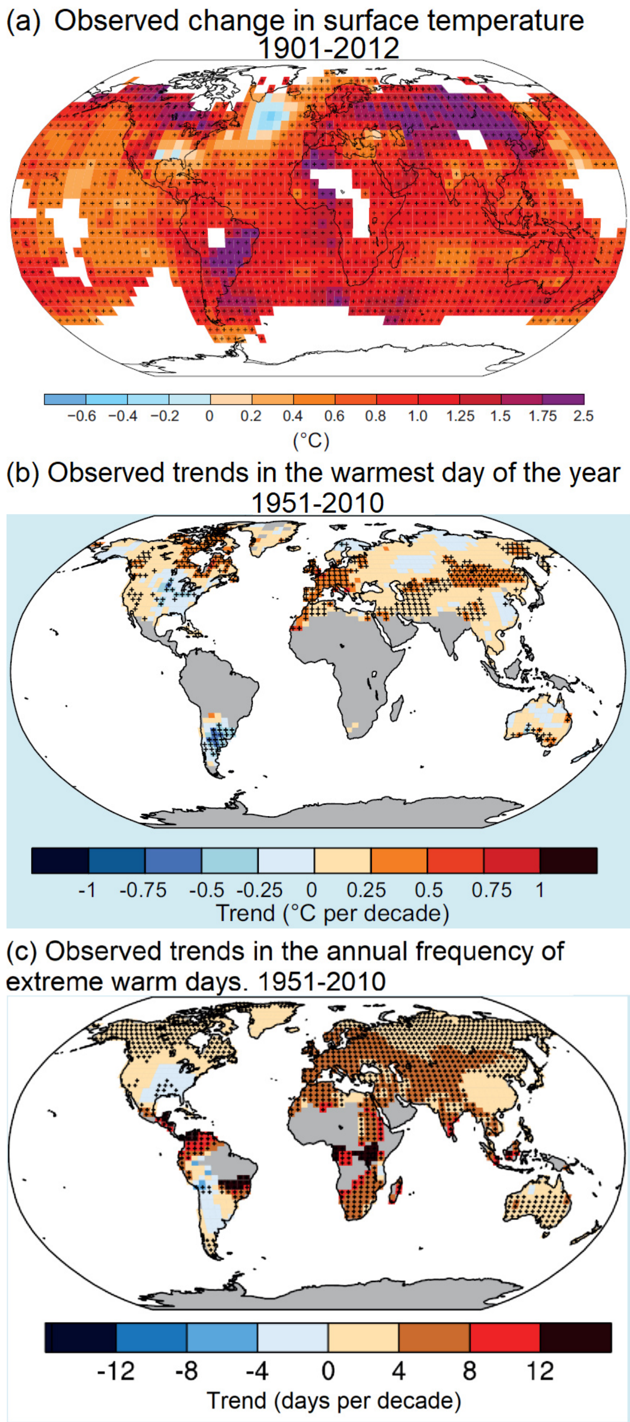

Figure 1.1: (a) Observed change in mean surface temperature for the period 1901-2012. (b) Observed trends in the warmest day of the year between 1951 and 2010. (c) Observed trends in the annual frequency of extreme warm days for the period 1951-2010. Dots indicate where the estimates for the change and trends are significant. Source: [IPCC 13].

extreme events are expected to become more intense and frequent, and to last longer in the future, while cold extremes are projected to be less likely [IPCC 21]. This intensification and multiplication of high-temperature extremes may impact wildlife and ecosystems, human health and human socio-economic activities, including the airline industry. Regions which are already characterized by warm temperatures in summer, as the Euro-Mediterranean region, will be particularly affected by the rise in heat events [IPCC 13, IPCC 21].

1.1.1 Aviation's contribution to climate change

One of the main contributors to climate change is the transport sector [IPCC 13], as mentioned in the previous section. It accounted for 28.5% of total GHG emissions by the European Union in 2019, according to the European Environment Agency (EEA)[1], being the emissions from aviation alone of almost 4%.

Commercial aviation depends on fossil fuels. Aircrafts are powered by the combustion of liquid hydrocarbon fuels derived from petroleum, such as kerosene. In the combustion process, water vapor and carbon dioxide are always generated. Nitrogen oxides are produced as well, mainly nitrogen monoxide and nitrogen dioxide (NO and NO_2, also referred to as NO_x). In addition, carbon monoxide (CO), unburned hydrocarbons and smoke or soot particles (black carbon and organic carbon) [Ruijgrok 05] are produced as a result of incomplete combustion. Most of these combustion products have a radiative effect which alters the Earth's energy budget, impacting climate. Besides the impacts that the aircraft exhaust products have on climate, some of them are also toxic and threaten human health [Cohen 11]. In particular, NO_x irritate the lungs and reduce the body's ability to fight respiratory infections [Chen 07, Andersen 11], and have also been related to lung cancer [Hamra 15].

Water vapor and carbon dioxide are known to be major GHG. NO_x emissions

[1] https://www.europarl.europa.eu/news/en/headlines/priorities/climate-change/20191129STO67756/emissions-from-planes-and-ships-facts-and-figures-infographic

have both a warming and a cooling effect. On the one hand, NO_x are a precursor of ozone (O_3) via photo-chemical reaction with organic compounds in the atmosphere, which generates O atoms that combine with O_2 to form O_3 [Brasseur 98]. The radiative forcing of the tropospheric ozone is known to be positive. On the other hand, NO_x contributes to reducing methane lifetime [Freeman 18]. As methane is another important GHG, this has a negative radiative forcing associated. The net effect of NO_x is estimated to be positive (warming) [Lee 21a]. Soot particles also have a warming effect on climate, since they absorb the incoming short wave radiation from the Sun and they re-emit it as long wave (or thermal) radiation. In addition, the aircraft particulate and water vapor emissions may generate condensation trails, depending on the state of the background atmosphere [Irvine 14]. These condensation trails (contrails) may further enhance cirrus clouds development in ice supersaturated ambient conditions, whose effective radiative forcing is estimated to be positive, although there is a large uncertainty in the estimates [Lee 21a]. Figure 1.2 illustrates the main impacts of aviation emissions on climate.

The CO_2 is a long-lived GHG, remaining in the atmosphere for hundred years or longer. Meanwhile, the lifetime of NO_x is of the order of hours to a day [Jaeglé 98]. The perturbation in the tropospheric ozone caused by the NO_x emissions lasts from weeks to months [Hoor 09], and the induced changes in the methane concentration may remain for a decade [Stevenson 04, Stevenson 09]. The lifetime of contrails is of the order of hours [Bock 16]. Soot particles also have much shorter lifetimes than CO_2. The overall contribution of the aviation to the effective radiative forcing on the climate system is the result of the cumulative CO_2 emissions and the short-lived radiative forcings [Dessens 14]. In [Lee 21a], the total contribution of aviation to anthropogenic climate forcing for the period 2000-2018 is estimated to be 3.5%. Figure 1.3 summarizes the estimates of the effective radiative forcing arising from aviation emissions and induced cirrus clouds formation. The three most important contributions to the resulting net warming effect correspond to contrail cirrus formation, CO_2 emissions and NO_x emissions, in this order. The non-CO_2

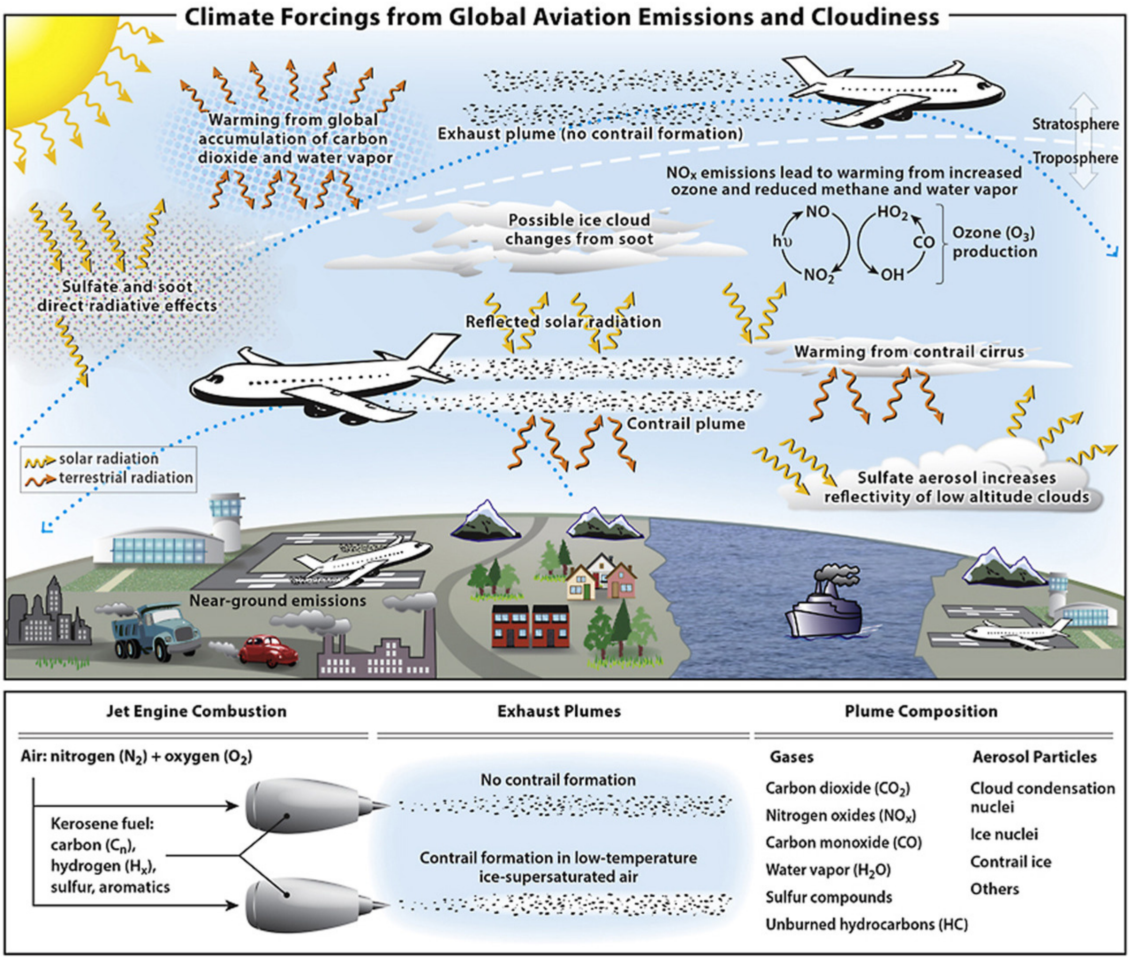

Figure 1.2: Schematic overview of the processes by which aviation emissions and increased cirrus cloudiness affect the climate system [Lee 21a].

terms would account for 2/3 of the net warming, while the cumulative CO_2 emissions would be responsible for 1/3.

Progressive improvements in the aircraft technology, particularly in fuel efficiency, achieved the reduction of pollutant emissions by the aircraft engine. However, the absolute emissions depend on the amount of fuel burnt. Revenue passenger kilometers had a positive trend in the last decades, and air traffic is projected to keep rising [Fleming 19]. Therefore, aviation emissions and their impact on climate are expected to increase along this century [Gossling 20, Terrenoire 19].

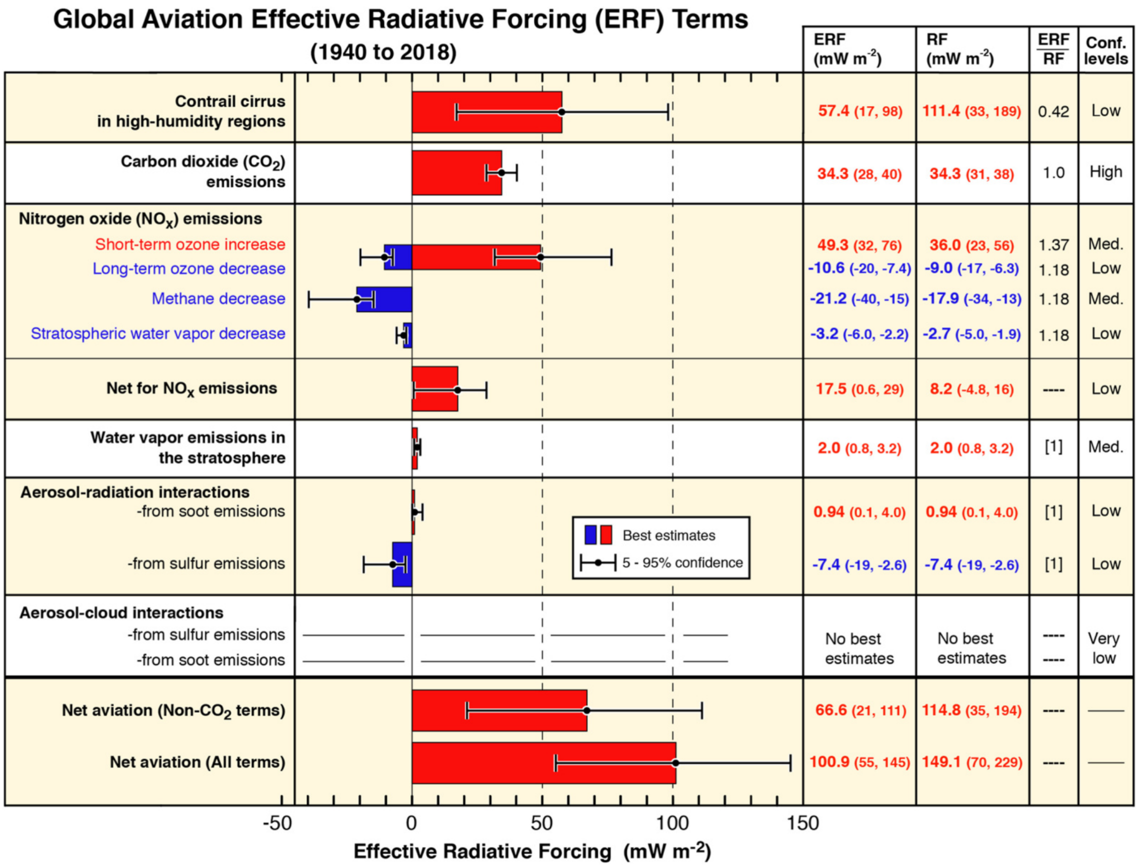

Figure 1.3: Best-estimates for climate forcing terms from global aviation from 1940 to 2018 [Lee 21a]. Radiative Forcing (RF) term is used to describe changes in the imbalance between the Earth's incoming energy from the Sun and the returning energy back to space, considering fixed surface and tropospheric conditions [IPCC 13]. The Effective Radiative Forcing (ERF) does consider adjustments in surface and troposheric conditions (water vapor content, cloudiness, atmospheric thermal structure...) to the forcing agent [IPCC 21].

The positive trend in revenue passenger kilometers in the last decades, and the projected rise in air traffic along this century are expected to increase the aviation emissions and its impact on climate [Gossling 20, Terrenoire 19].

1.2 IMPACTS OF CLIMATE CHANGE ON AVIATION

The impacts of aviation on climate and its contribution to climate change have been largely studied. However, the impacts of climate change on aviation remain mostly unassessed. Indeed, aviation is both a perpetrator and a victim of climate change. Aircraft performances and airports operational efficiency depend on weather conditions [Balicki 14, Schultz 18, Gultepe 19]. In addition, airport infrastructures and aircraft operations are designed to be adapted to the mean local climate in each case, optimizing airport operational efficiency under local meteorological situations. This is the reason why runway lengths of Madrid-Barajas airport are longer than those of London-Heathrow airport, for instance, and the bitumen road layer is thicker for Madrid runways than for London runways, as the first are more frequently and severely subjected to high temperatures. This is also why the Dubai airport schedules long-courrier flights at nighttime, avoiding the hottest hours of the day for the heaviest mission operations. Climate change and the induced changes in adverse weather conditions can thus impact the aviation sector in numerous and diverse aspects. A major concern on this subject began to emerge after the publication of [IPCC 07]. The main impacts of climate change on aviation are presented in this section, according to the reviews done in [ICAO 16b], [EUROCONTROL 18] and [EASA 22a].

The increase in mean summer temperatures may have an impact integrated over time on the energy consumption, if more air conditioning is needed in the hangars, and on infrastructural thermal stress. The extra-energy consumption in summer could be counteracted by the lower need for heating in the cold season under warmer mean winter temperatures. In addition, the warming of temperatures at the airport, specially in winter, would decrease the frequency of ice formation, whether on the airframe or on the runway. This would have a potential positive effect of airport operations. Nonetheless, for some regions with permafrost, this warming would cause its melting, potentially damaging infrastructures. Concerning temperature extremes, extreme cold events are expected to become less likely, while extreme heat events are projected to become more intense and more frequent [IPCC 21]. Therefore, the upper extremes of winter temperatures in both hemispheres should not be problematic since the airports are prepared to operate in a wide range of meteorological conditions: if airports operate under local mean summer temperatures, they are also able to operate under the upper extremes of winter temperatures. Conversely, the impacts that the increase in heat events may have on aviation are various and numerous, deserving a separated section. They are detailed in Section 1.2.1.

Changes in temperature at en-route flight altitudes, in addition to changes in ambient humidity, may affect the icing conditions, impacting the safety of the aircraft or forcing the airplane to fly at a different height, which would change fuel consumption. They can also indirectly impact aviation through changes in the atmospheric jet streams [Williams 16]. This may affect flight routes and flight times, with consequences on fuel consumption too, and thus on emissions and contrails formation.

Moreover, an increase in wind shear can promote clear air turbulence, with significant consequences for passenger safety, and even fatal consequences [Williams 13, Storer 19].

Additionally, the rise in sea level may threaten coastal airports. This, along with the increase in heavy precipitation episodes may increase the risk for submersion in these areas [Yesudian 21].

Changes in wind regimes may affect desert dust episodes, during which the visibility at the airport is reduced, limiting operations. Droughts, desertification and changes in wind conditions may also lead to more frequent dust storms. In addition to hamper operations at the airport, sand and dust entering the engine can also damage it [FAA 17].

Furthermore, a more accentuated difference in temperature between the surface and the atmosphere and a water-richer atmosphere can lead to the more frequent development of unstable situations associated with convective and thunderstorm systems, which are a threat to aviation safety.

Moreover, changes in humidity at both the ground level and at cruising altitudes may impact the operations [Leung 20]. Changes in fog and cloud cover affect the visibility. In addition, a greater content of water in the atmosphere at cruising altitudes may lead to more favorable conditions for icing, negatively impacting the aircraft performances and threatening the aircraft safety [FAA 17]. Also, higher water vapor content in the atmosphere may cause unwanted engine shutdown.

A summary of the main risks of climate change for aviation is included in Figure 1.4.

Although many reports documented the potential impacts of climate change on the air transport sector over the past 15 years, they only begun to be assessed in recent years. Further information on the state of the art concerning the assessment of the observed and the future impacts of these changes can be found in [Thompson 16], [Ryley 20] and [Gratton 22].

Amongst all of the potential changes in climate, there is more confidence about the magnitude of the projected future increase in temperatures [IPCC 21].

1.2.1 Impacts of increasing high-temperature extremes

Extreme hot weather conditions have negative effects on aircraft performances and airport's operational efficiency. An increase in the magnitude and in the frequency of high-temperature extremes due to climate change would impact the aircraft operations, with further consequences at the socio-economic, environmental and even health levels.

Higher temperatures are linked to lower aircraft lift and engine thrust. An increase in temperature results in a decrease in air density, negatively impacting the

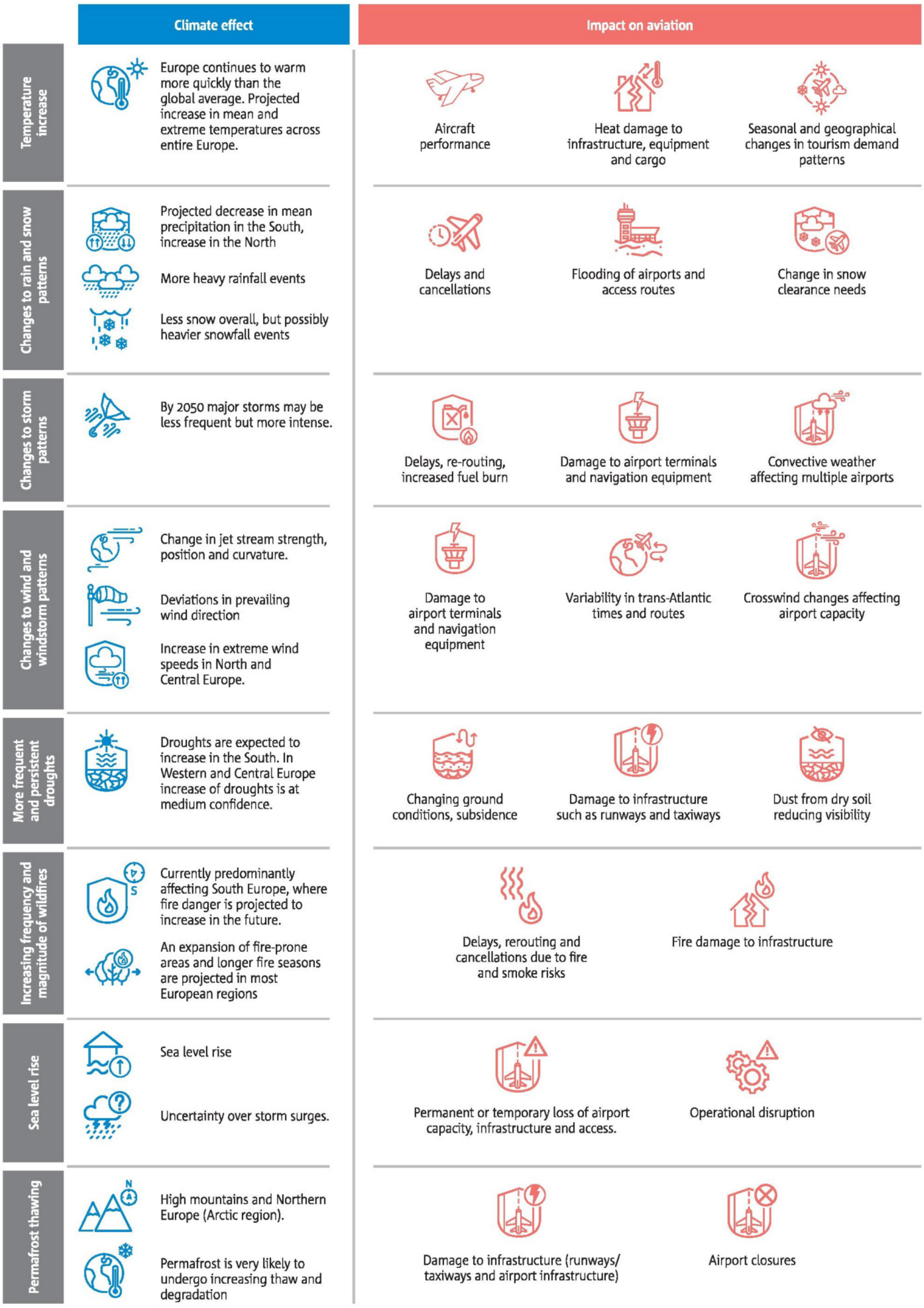

Figure 1.4: Climate change risks for European Aviation [EASA 22a].

lift of the aircraft. This would force the plane to reach a faster speed through thinner air to generate lift at takeoff [Anderson 05]. Considering the aircraft acceleration as a constant, takeoff distances would be lengthened in the process [Zhou 18b, Gratton 20]. Sometimes this speed would be unreachable, depending on the aircraft technical characteristics (e.g. maximum rotational speed of the tire) and/or on runway length limitations, leading to weight restrictions to lighten the aircraft or to flight delays until the temperature decreases enough to takeoff or, in the worst case, to cancellations [Coffel 15, Coffel 17, Gratton 20]. In addition, engine thrust decreases with temperature [Airbus 02, Walsh 04]. It is usually manually restrained to be constant below a certain temperature for fuel economy reasons and also for environmental reasons. Temperatures above this threshold will have a negative effect on thrust. The temperature threshold is typically chosen to be the temperature at International Standard Atmospheric conditions (ISA) +15 °C [Airbus 02]. Figure 1.5 shows the vertical profile of the air temperature and pressure up to 32 km above sea level at ISA conditions. Temperature decreases linearly with height within the first 10 km of the atmosphere at a rate of 6.5 °C/1000 m, that is, the pseudo-adiabatic lapse rate for humid air. The temperature threshold set at ISA+15 corresponds then to 30 °C at sea level, 26 °C at 610 meters or 2000 feet of elevation, 22.1 °C at 1220 meters or 4000 feet and so on. For temperatures above this threshold value, the higher the temperature, the lower the thrust, as illustrated in Figure 1.6, which reduces the capacity of the aircraft to lift weight. Extra fuel consumption would be needed then to generate the thrust required. Accounting for the weight of the extra fuel would be necessary, and it could imply replacing cargo or passengers for fuel.

Moreover, the lower aircraft lift and engine thrust due to higher temperatures also imply lower climb rates [Administration 08]. This may be problematic in the presence of obstacles, such as mountains, that the aircraft needs to overfly, as illustrated in Figure 1.7. The safety margin is reduced, and weight restrictions may become necessary in order to attain the required height with the available resources.

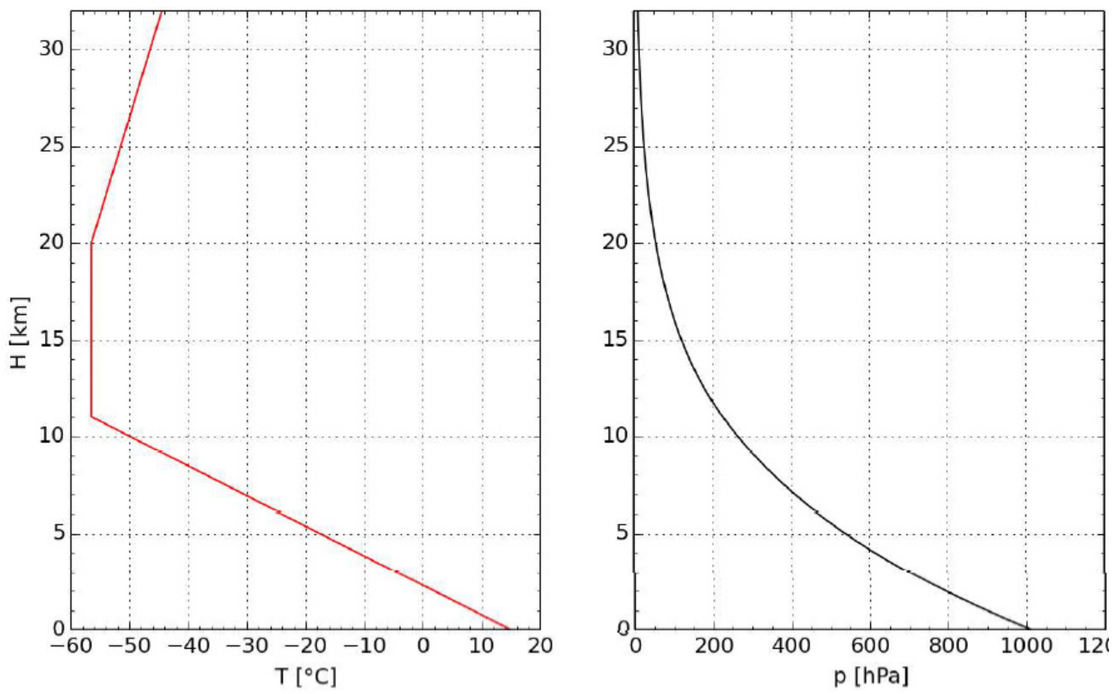

Figure 1.5: Vertical profiles of atmospheric temperature and pressure at ISA conditions established by the International Civil Aviation Organization. Figure abstracted from https://www.foehnwall.at/meteo/isa.html.

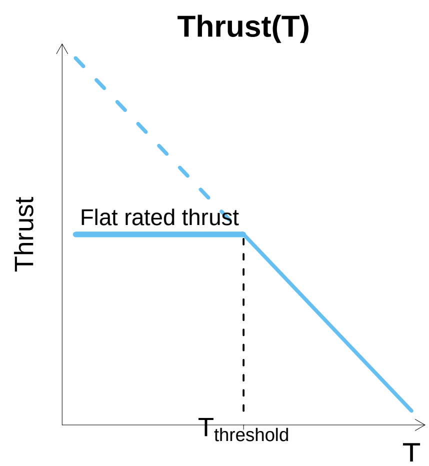

Figure 1.6: Illustration of the inverse relationship between the engine thrust and the outside ambient temperature T. Thrust is usually manually flat rated below a certain temperature $T_{\text{threshold}}$, as explained in the text. Figure adapted from [Airbus 02].

Aircraft engines intake ambient air, which is why they are also called breathing engines. The overall engine efficiency is the resulting product of its thermal and mechanical efficiencies [Kershner 70]. An increase in the intake air temperature has a negative effect on the thermal efficiency, since the temperature difference between the incoming air and the exhaust gases is smaller. Also, the mechanical efficiency of the components of the engine might be negatively affected under warmer ambient temperatures. In particular, the compressor would need to do more work in order to compress the equivalent mass of air under warmer conditions. This decrease in engine efficiency will be maximum under extremely high temperature events.

Although aircraft engines are prepared to operate in a wide range of ambient conditions, working under extreme heat conditions deteriorates the engine, causing premature wear, consequenlty worsening its performance.

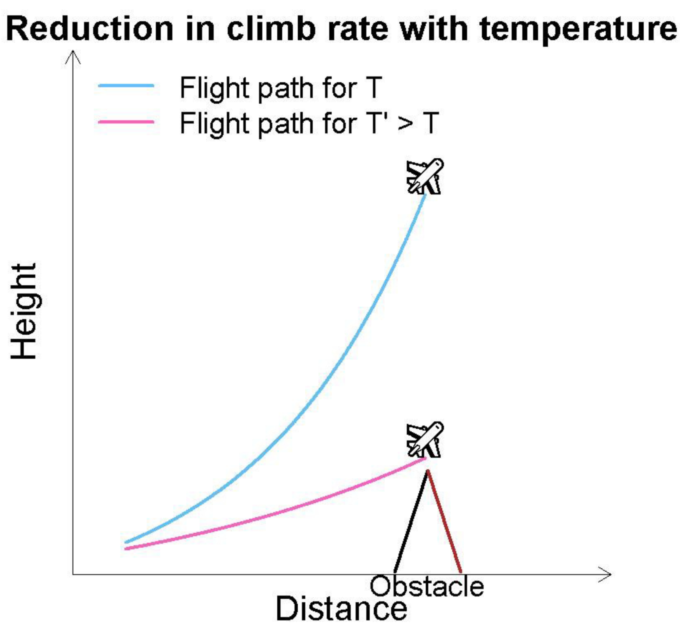

Figure 1.7: Illustration of the reduced climb rate due to higher temperatures.

Concerning the pollutant emissions, the amount of NO_x produced in the combustion process depends, among other factors, on the maximum temperature of the flame in the combustion chamber, which in turn depends on the ambient intake air temperature (among other chemical considerations) [Gokulakrishnan 13]. Figure 1.8 illustrates the increase in NO_x emissions with the increase in the temperature of the flame above a certain threshold. The hotter the near-surface air temperature, the higher the temperature inside the engine, and the more NO_x are produced and emitted into the atmosphere. High-temperature extremes are of particular interest since NO_x emissions will be maximum regarding temperature effects during the course of these events. The negative impact on the airport's air quality and that of its surroundings could also be greater [Masiol 14].

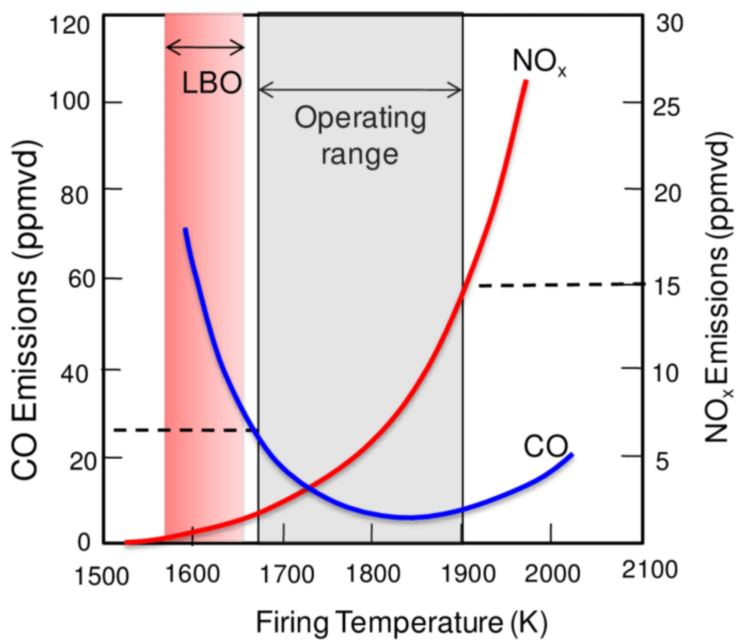

Figure 1.8: Illustration of the NO_x and CO emissions dependence on the flame temperature in the combustion chamber of a turbofan aero-engine (abstracted from [Bompelly 12]). The shading zone corresponds to the operating range for minimizing the NO_x and CO pollutant emissions.

Figure 1.8 also includes the CO emissions as a function of the firing temperature. While the NO_x emissions always increase with temperature above a certain threshold, there is a temperature range for which CO emissions decrease with increasing temperature. There must be a trade-off between the NO_x and CO emissions in order to minimize the pollutant emissions. The engine's operating range of temperatures is established in order to meet the pollutant emission limits. In the context of global warming, the implementation of new emission regulations could become necessary for the engine certification.

Additionally, the heat accumulated in the brakes during landing must be dissipated before the plane can takeoff again. Very hot conditions at the airport may result in longer than anticipated ground stays to cool the brakes, or require the use of external fans. This could also have a negative impact on the life of carbon discs.

Fire risk also increases under extreme hot conditions [Thompson 16]. Special care should be taken at the airport under high ambient temperatures with regards to jet fuel stock, manipulation and use, whose flammability limits range between 38 °C and 70 °C, depending on the specific fuel type [Edwards 17]. It is not only the fire risk at the airport that is important to consider. The safety at the airport could also be threatened by a fire originated in the nearby. The visibility could be reduced due to the smoke column, preventing aircraft operations.

As mentioned previously (see Section 1.2 above), an increase in the exposure to hot conditions might amplify the need for air conditioning and it might damage the infrastructures as well due to thermal stress [Thompson 16]. During extreme events, energy supply could be compromised by the demand, and infrastructures would be more likely to suffer sudden punctual damages.

Human heat stress in another important factor to take into account, especially for the outdoor workers at the airport. In order to ensure their thermal comfort and avoid preventable accidents at work, changes in flight schedules or cancellations could eventually become necessary.

To the best of our knowledge, flight disruptions related to high temperatures have only been reported during extreme heat events or record-shattering heat episodes so far. The most iconic episode is that of the 2017-heatwave at Phoenix airport, when thermometers reached 49 °C, and flights were grounded for several days[2]. Temperature conditions exceeded the maximum temperature for which regional, small aircrafts that operate in this airport were certified. Also, in the summer of 2018, temperatures rose up to 35 °C at the London City airport, which is limited by its short runway (1500 meters), and several passengers were not allowed to board the plane in some flights in order to lighten the aircraft for takeoff[3]. Most recently, the heatwave that has shaken Europe in early July 2022 has risen temperatures up to 40 °C in the UK. This has damaged the runway bitumen at London-Luton airport, which is adapted to rainfall-related wear but not to temperatures that high, causing delays and cancellations[4]. Also, the Royal Air Force reported the runway melting at its largest air base of Brize Norton during this extreme heat event, and air traffic had to be diverted to the airports nearby. Nonetheless, let us recall that even if aircrafs are able to operate in high or extremely high temperatures, these conditions might damage the engine.

There is an emergent concern about the impacts of the warming high-temperatures on the air transport amongst the national and international aviation-related organisms. The Transportation Research Board and National Research Council of the U.S. emitted a report in 2009 on the plausible impacts of climate change on the U.S. transportation [Board 08], after the release of the [IPCC 07]. One of the main threats for air transport is considered to be the increase in very hot days and heat waves. The International Civil Aviation Organisation (ICAO) reported its concern about the impacts of rising temperature maxima at the airport level because of climate change in [ICAO 16b]. Also, EUROCONTROL considered increasing temperatures and extreme weather events as main challenges for

[2]https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/06/20/its-so-hot-in-phoenix-that-airplanes-cant-fly/

[3]https://www.thesun.co.uk/travel/6884106/ba-kicks-20-passengers-off-holiday-flight-to-ibiza-because-the-35c-heatwave-made-the-plane-too-heavy/

[4]https://edition.cnn.com/travel/article/uk-airport-suspends-flights-amid-melting-runway-reports/index.html

European aviation in the report *European Aviation in 2040 - Adapting Adaptation to a Changing Climate* [EUROCONTROL 18]. Furthermore, the *European Aviation Environmental Report* emitted in 2019 by the European Union Aviation Safety Agency (EASA), the European Environment Agency (EEA) and EUROCONTROL also includes the warming of Southern Europe in summer as a problematic issue for "aircraft performance, heat damage to infrastructure and seasonal and geographical changes in tourism demand patterns" [EASA 19].

The national and international aviation-related agencies are not the only ones interested in this problematic. Since the impacts of the increase in high-temperature extremes on aviation have a social component, this subject burst into the media in 2017 with the Phoenix episode, and has been recurrent since then, especially in summer, when extreme heat disrupts aviation operations and passenger holidays.

Moreover, an indirect effect of the increase in heat stress would be the change in flight patterns, as reported in [EASA 19]. Cooler climate regions could become more popular summer vacation destinations, like Northern Europe, to the detriment of traditional touristic zones, like Euro-Mediterranean countries [Barrios 15]. Social movements in response to climate change seeking out to mitigate it could also negatively affect the airline industry in an indirect manner. This is the case for the *Flygskam* movement, whose name is the Swedish word for "flight shame". This anti-flying movement was born recently in Sweden and became popular in the media by 2019 [1][2][3][4].

For all of the above reasons, the study of the impacts of the increasing intensity and magnitude of high-temperature extreme events is crucial for the aviation sector.

[1]https://www.bbc.com/worklife/article/20190718-flygskam

[2]https://www.bbc.com/future/article/20190909-why-flight-shame-is-making-people-swap-planes-for-trains

[3]https://www.nytimes.com/2019/12/18/travel/Sweden-flight-shaming.html

[4]https://www.washingtonpost.com/travel/2019/07/09/europes-flight-shame-movement-doesnt-stand-chance-us/

1.3 STATE OF THE ART AND LIMITATIONS

The impacts of increasing temperatures due to climate change on aircraft performances started being assessed only few years ago.

In [Coffel 15], the future potential impact of increasing extreme temperatures on aircraft takeoff performances is firstly assessed in terms of maximum weight limitations. Climate data are originally combined with aircraft technical data in order to quantify this impact. The study is focused on four airports in the United States. The future changes in the mean summer daily maximum temperature and in the annual maximum temperature over the airports are assessed from climate projections. These future climate projections were performed in the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5) [Taylor 12] using Global Climate Models (GCMs). The takeoff of a mid-sized Boeing 737-800 aircraft from the longest runway of each airport under the future projected extreme temperatures is considered. The dependence between the Maximum allowable TakeOff Weight (MTOW) and the air temperature at the runway level, is obtained from the takeoff performance curves in the Boeing 737-800 *Airplane Characteristics for Airports Planning* (ACAP) manual [Airplanes 13].

An increase in the number of days where it would not be possible to takeoff the Boeing 737-800 Maximum-certificated Take-Off Weight ($MTOW_0$) during the hottest hour of the day in summertime is found, which may have negative effects on the airline industry. These days are considered by the authors as *weight restricted days*. Figure 1.9 illustrates the positive trend in the number of 10000 lbs-weight restricted days for the airport of Denver: from around 60 days in 1980-1990 to more than 110 by 2060-2070. However, as highlighted in [Hane 16], the TOW limitations with respect to the $MTOW_0$ do not systematically imply weight restrictions, since flight operations rarely imply 100% of the $MTOW_0$ of the aircraft. Thus, the future number of weight-restricted days estimated in [Coffel 15] would be most likely overestimated. More accurate results could be obtained by taking into account real scheduled flights data from airlines, such as the scheduled time and the TOW of the flights. Also, the function of the MTOW with temperature is estimated by fitting only four points of weight-temperature pairs, which is scarce. Therefore, the method for deriving the impact could be improved by using more accurate data from aircraft manufacturers or pilot operational tools. Moreover, the study could be limited by the use of climate simulations from GCMs whose horizontal spatial resolution is about 200 km, on average, for addressing the climatic changes at the airport scale. The use of finer resolution climate models, such as Regional Climate Models (RCMs) with a horizontal spatial resolution of about 12 km, could be more suitable, as it has already been shown for precipitation extremes in [Torma 15], [Prein 16], [Fantini 18], [Solman 19], [Di Virgilio 20] and [Vichot-Llano 21], among many others.

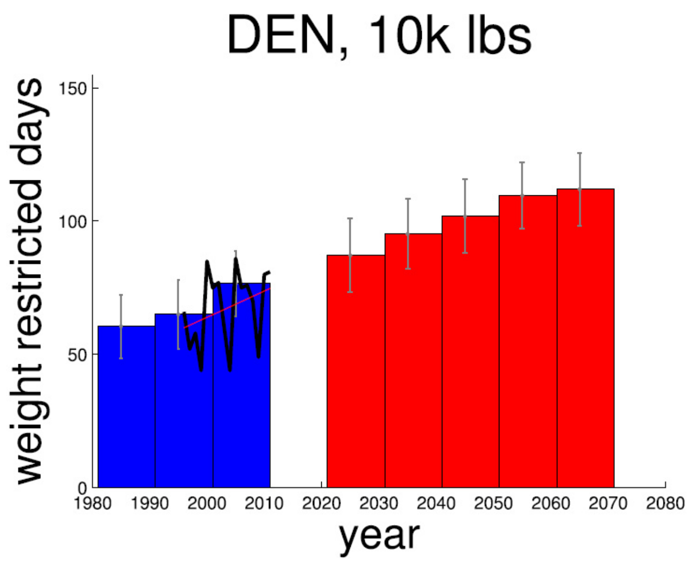

Figure 1.9: Evolution in the number of weight-restricted days for a Boeing 737-800 by at least 10000 lbs at the airport of Denver. Source: [Coffel 15].

The above study is further extended in [Coffel 17] to a list of major airports distributed worldwide, and several models of aircrafts representing mid-size and large-size current fleets are considered too. Long couriers are found to be subjected to greater weight limitations because of higher temperatures than medium-range aircrafts. Airports at high elevations or with short runways would be the most affected, such as Denver (DEN) and New York-La Guardia (LGA) in the U.S., for instance. Nonetheless, the study presents the same limitations as the former.

In [Zhou 18a], the impact of rising temperatures on maximum payloads is also assessed, focusing on the Chinese aviation sector. Seven Chinese airports are selected as case studies because of their high elevation or their logistical importance. Future changes in the mean summer daily maximum temperature at the airports are assessed using climate simulations performed with the GCM MPI-M/ECHAM6.3-LR [Stevens 13]. In particular, two large ensembles of 10-year time slice simulations are considered for the future period 2106-2116, under two different global warming scenarios from the Half a degree Additional warming, Prognosis and Projects Impacts (HAPPI project, [Mitchell 17]): +1.5 °C and +2.0 °C by the end of the 21st century with respect to pre-industrial conditions (1861-1880). A third large ensemble for the recent period 2006-2015 is used for assessing the changes between future and present climate. The change in the maximum potential number of weight-restricted days is obtained following the methodology presented in [Coffel 15], also for a Boeing 737-800. Not all of the airports would be impacted, and some of them would only be affected under the +2.0 °C scenario. Nevertheless, most of them would experience significant increases in the number of days where such a mid-size aircraft would not be able to takeoff with its maximum payload. As this study followed the methodology proposed in [Coffel 15], it presents the same limitations concerning the derivation method for the dependence between the MTOW and temperature, as well as the overestimation of the real magnitude of the future impact. Also, this study is based on climate simulations performed with a GCM whose horizontal spatial resolution is about 200 km, same as for the CMIP5 GCMs used in [Coffel 15] and in [Coffel 17]. In addition, results solely rely on one climate model simulations, instead of on a Multi-Model Ensemble (MME) of simulations such as the CMIP5 ensemble. The use of MMEs for impact studies is crucial for estimating the modelling uncertainties. Moreover, the length of the periods of study (10 years) may not be long enough for computing the climatologies; the recommendation of the World Meteorological Organisation (WMO) is a period of 30 years.

In [Carpenter 18], the June 2017 heat wave event that affected operations at Phoenix airport is analysed in detail. Hourly temperature data recorded during that event are considered along with data on the operating aircrafts for the scheduled flights. This information is combined with the weight limitations on the MTOW_0 tabulated for a Boeing 737-800 aircraft departing Phoenix airport under different temperature thresholds provided in [Coffel 17]. This allowed for the estimation of the maximum potential impact on takeoff weights for missions operated with that aircraft model during that heat event. Nonetheless, the author is aware that the departures scheduled that day could not have been affected if the TOWs were lower than the Boeing 737-800 MTOW_0. No data from airlines was available to check if the impact quantification was right in this regard.

The future impacts of higher temperatures on maximum payloads because of lift reduction are indirectly assessed from the evolution of the near-surface air density in [Ren 19a]. The MTOW is directly proportional to the air density. In this study, the air density is considered as the sole atmospheric variable having an effect on the maximum aircraft carrying capacity. Monthly data of air temperature, pressure and humidity are used for computing the near-surface air density at global level from CMIP5 GCMs simulations. The changes in maximum payloads by the end of the century with respect to present climate conditions are deduced from the changes in air density, circumventing the inaccessibility of aircraft manufacturer specifications. A global decrease in maximum payloads is found. The air temperature is identified as the main driver for changes in air density, although changes in humidity would also play a role in some regions. This study illustrates the effects of a warmer, lighter atmosphere on MTOWs. However, higher temperatures may also have a negative effect on the engine thrust, implying additional limitations for the aircraft payload capacity. This is not taken into account. In addition, the impacts will be local and need to be quantified at the airport scale.

In [Zhou 18b], the future impact of climate change on takeoff performances is assessed in terms of the takeoff distance and the climb rate. Thirty major international airports around the world are selected as case studies. First, the future projected changes in the daily air temperature and air pressure in summer are studied over these airports. Then, Koch charts are used to deduce the takeoff distance and climb rate correction factors with respect to ISA conditions for the future temperature and pressure conditions (see Figure 1.10). In addition, the impact on takeoff distances is quantified for a Boeing 737-800. In the future, longer takeoff distances would be needed and climb rates would be smaller over these airports. In particular, the widely and commonly used mid-size aircraft Boeing 737-800 would need between 3.5 and 69.5 meters more, depending on the airport, to takeoff 70000 kg in next decades, and between 6.7 and 168.7 additional meters from the mid- to late-century. Figure 1.11 illustrates the lengthening of takeoff distances for the airport of Dubai: from 2050 m, in average, in 1966-2005 to 2050 m by 2021-2050 and to 2160 m by 2071-2100. Another important finding is that the negative impact of the increase in temperature on takeoff performances is projected to be greater than the positive effect that could have the increase in air pressure found in some regions. As the previous works [Coffel 15, Coffel 17, Ren 19a], this study is based on the CMIP5 ensemble of future climate projections performed with GCMs, whose representation of temperatures at the airport scale may be hampered by their coarse spatial resolution. Furthermore, the Koch charts are a good alternative in the absence of the specific aircraft flight manual, but the use the aircraft manufacturer companies data is always preferable.

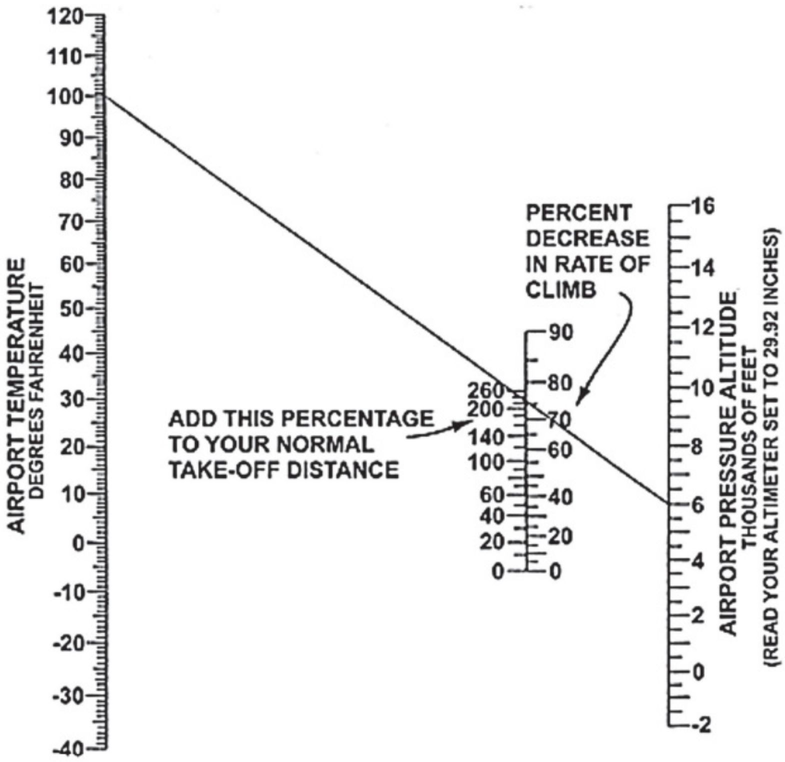

Figure 1.10: Koch chart used in [Zhou 18b] to estimate the takeoff distance and climb rate correction factors with respect to ISA conditions for the future temperature and pressure conditions. Source: [Administration 08].

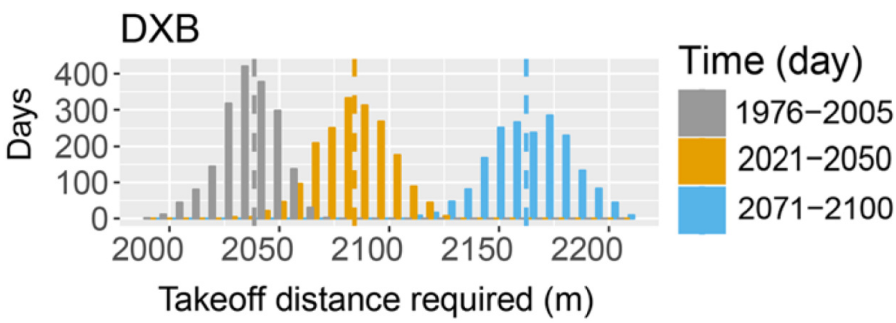

Figure 1.11: Probability distribution functions of required takeoff distance for a Boeing 737-800 in 1976–2005 (gray), 2021–2025 (yellow), and 2071–2100 (blue) at the Dubai airport. Source: [Zhou 18b].

The impact of warming mean minimum temperatures on takeoff performances in recent decades is also studied in [Gratton 20], along with changes in wind conditions. The study is focused on ten Greek airports, and two aircraft models representing short- and medium-range aircrafts are considered. At the airports with shorter runways, the increase in temperature resulted in a decrease in the MTOW. At the airports where takeoff is not limited by the runway length, greater takeoff distances would have been required to takeoff the $MTOW_0$. The effect of warming temperatures is found to be more important than the changes in wind conditions. The impacts in future climate remain unassessed.

The future evolution in the number of days where the MTOW is limited by the increase in temperatures is also assessed over Canada in [Zhao 20]. The study is focused on 13 major Canadian airports. The weight limitations are analysed for three aircraft categories: short-, medium- and long-range courriers. Changes in the daily maximum temperature in summer over the airports are analysed from future climate projections performed using the CanESM2 RCM at 0.5 ° ($\sim$ 55.5 km) of horizontal spatial resolution, driven by its "big brother", the GEM GCM [Côté 98]. A general future increase in the number of weight-limited days is found, as a consequence of the projected increase in temperatures. The magnitude of the impact depends on the aircraft type and on the airfield considered. Although the CanESM2 RCM is evaluated before assessing the impacts, its added value with respect to the GEM GCM is not assessed. In addition, the study is based on simulations performed with a single climate model. The consideration of a multi-model ensemble of simulations is needed in order to account for modelling uncertainties, as aforementioned. Moreover, the size of the grid cells ($\sim$ 3080 km^2) is far greater the size of the airports, which is of the order of tens of km^2. The use of a multi-RCM ensemble with even higher resolution could be more suitable.

Moreover, in [Mcrae 21], the impact of warmer temperatures on aircraft performances is indirectly assessed from changes in density altitude. The density altitude is the "pressure altitude corrected for nonstandard temperature variations"

[Administration 08]. Warmer temperatures result in higher density altitudes, which negatively impact aircraft performances. The General Aviation “rules of thumb” are applied in order to deduce the changes in takeoff and landing distances and in maximum payloads from the changes in density altitude at the Little Rock airport, in the United States. The study corroborates previous work on decreased aircraft performances in the future due to climate change. Nonetheless, more accurate results could be obtained by using aircraft manufacturers data instead of the General Aviation “rules of thumb”.

Furthermore, in [Lee 21b], the future costs of higher temperatures to airlines from delays, re-accommodations, cancellations and weight restrictions are assessed. An operational model is developed to this end. The application is made using data from a real airline on its operating airports. Future temperatures over the airports by 2030 and 2050 are analysed from CMIP5 global climate projections, and compared to temperatures in 2014. Weight restrictions are deduced from charts in the aircraft manufacturers manuals, following the method first used in [Coffel 15]. The results suggest that the daily extra-costs for airlines could substantially increase under the severe scenario of climate change, being the re-accommodation of passengers on other flights the main cause. However, both the climate data used and the method for deriving the weight limitations as a function of temperature could be improved, as already discussed for other research using the same data and methodology.

The study of the impacts on the Chinese aviation sector carried out in [Zhou 18a] is further extended in [Yuan 21]. A list of 53 additional airports is considered. The future climate projections used in this case were performed with the most up-to-date CMIP6 GCMs, as compared to the CMIP5 simulations used in [Zhou 18a]. In addition, the impacts on the maximum aircraft carrying capacity are estimated using an operational software for pilots, which relies on aircraft manufacturers data. Thus, the method for obtaining the weight limitations with temperature increases is improved with respect to the former study. Nonetheless, the horizontal spatial resolution of CMIP6 GCMs is comparable to that of the CMIP5 GCMs, which might be too coarse for assessing the impacts at the airports scale, as already stated.

In [Imanov 22], the impact of ambient temperature, at ground level and at en-route altitude, on the engine performance at takeoff and during the cruise phase is analysed. In particular, the fuel flow and the exhaust gas temperature parameters are focused, as indicators for the degradation of the engine. Increasing the fuel supply in order to produce the required thrust in warmer, thinner air results in higher values of the exhaust gas temperature, which deteriorates the rear components of the engine (the turbine), decreasing the efficiency of the other engine's primary components, particularly the compressor. Data recovered from 20 flights departing from the Baku airport (Azerbaijan) with a Boeing 787-800 aircraft are analysed. The values of the parameters of interest for five summer days in 2021 are compared with those measured in five winter days selected from that same year. Higher fuel flow is found in summer, along with larger exhaust gas temperatures, as compared to winter conditions. Therefore, the aircraft engine deteriorates faster in the summer the due to higher temperatures. Although the authors claim to have addressed the impact of climate change on engine performances, neither the time scale nor the sample size they analysed are suitable for a climate-change scale study. A larger observational data collection is needed to estimate the observed impact of climate change in these terms, of the order of decades. Moreover, the use of future climate projections is required to assess the potential future impact.

Finally, in [Haji 22], the trends in the MTOW and in the takeoff distances in the recent period 1990-2020 over the international airport of Zanzibar are analysed. The observed annual series for the mean maximum temperature at the airport are analysed. An operational tool for flight management is used in this study for computing the maximum payloads and distances at takeoff associated to these temperatures. A general negative trend in the maximum carrying capacities and a positive trend in distances are found, which are in line with previous studies carried out at other airports. The magnitudes of the trends depend on the type of aircraft considered. The future potential impact still needs to be assessed.

It is worth highlighting that the findings in the literature suggest that the projected increase in temperatures would induce greater impacts on aircraft and engine takeoff performances than the changes in pressure, humidity or wind conditions [Guinn 16, Zhou 18b, Ren 19a, Gratton 20].

The main limitations of the literature concerning the impact assessment of increasing temperatures on aircraft takeoff performances can be summarised as follows:

a) Although many studies evaluated the impacts of warmer temperatures, only a few focused on high-temperature extremes, which are of particular interest as explained in Section 1.2.1.

b) Most of the previous works assessed the impacts in terms of the maximum payload limitations, and some of them in terms of the lengthening of takeoff distances. However the future impacts on aircraft engine performances and on pollutant emissions have not been studied yet.

c) The focus has not yet been placed on the Euro-Mediterranean region at its entirety, although it is a major climate-change hotspot specially concerned by the increase in high temperatures, as presented in Section 1.1.

d) The use of a multi-model ensemble of future climate projections performed with RCMs has not been yet considered, although the higher resolution of RCMs over that of the GCMs could be more suitable for assessing the impacts at the airport scale. The added value of RCMs over GCMs in these terms still needs to be assessed.

e) The inaccessibility of data or of accurate data from aircraft manufacturers and airlines.

1.4 OBJECTIVES

The mail goal of this thesis is to assess the future impacts of rising high-temperature extremes on aircraft takeoff performances in the Euro-Mediterranean region in terms of a) the pollutant emissions, in particular, of NO_x, and of b) the aircrafts maximum carrying capacity at takeoff. The focus on the Euro-Mediterranean region is partly motivated by the special sensitivity of this area to climate change, as presented in Section 1.1. This, together with the warm temperatures that characterize the summer in this region, makes it one of the most affected areas of the globe by the increase in the exposure to extremely high temperatures. The increase in the risk of impact on aircraft takeoff performances resulting from the increase in the exposure to extreme hot conditions could also be greater for the Euro-Mediterranean airports than for the others, depending on their respective vulnerabilities (high elevation, short runway length, obstacles nearby...). If so, the impacts of high-temperature extreme episodes would be more and greater for Euro-Mediterranean aerodromes. Despite the described particular interest of this region with regards to the impacts of increasing high-temperature extremes on aircraft takeoff performances, to the best of our knowledge, they have not been addressed so far in the literature. This is the second reason for choosing the Euro-Mediterranean region as our region of interest. The original objective is divided into two sub-objectives:

1. To study the evolution of high-temperature extreme events over the airports in the Euro-Mediterranean region.
2. To assess the potential induced impacts on pollutant emissions and aircraft's maximum carrying capacity at takeoff.

Additionally, each sub-objective is broken down into smaller tasks, as described bellow:

1. To study the evolution of high-temperature extremes over the Euro-Mediterranean airports, it is essential:

    (a) To characterize the magnitude and the frequency of these events in past and future climate, as well as to evaluate their trends and changes, using observations and climate model projections.

    (b) To assess the confidence in future climate projections by evaluating climate models in present climate against observations.

    (c) To determine whether the use of RCM projections, rather than GCM projections, would be more suitable for the study of high-temperature extremes at the airport scale, and their evolution in a changing climate.

    (d) To quantify the uncertainty in future climate projections, by considering a multi-model ensemble of simulations under different climate change scenarios, and comparing the RCM projections with those of the GCMs.

    (e) To correct climate model systematic errors or biases[5] concerning the simulation of high-temperature extremes in future projections.

2. To assess the potential impact on pollutant emissions and on maximum carrying capacity at takeoff, it is necessary:

    (a) To find the future changes in the levels of NO_x emissions deduced from the changes in high-temperature extreme events, with respect to the recent decades.

    (b) To estimate the dependence relationship between the MTOW of the aircraft and the near-surface air temperature, given the airport elevation and the runway length.

[5] Separation from the observations in present climate

(c) To find the future changes in the maximum aircraft carrying capacity associated to the changes in high-temperature extremes, with respect to the last decades, at each airport.

(d) To quantify the differences in the magnitude of the impact across the airports and between civil aircraft types.

1.5 SCOPE AND STRUCTURE

This thesis aims at assessing the future impacts of rising high-temperature extremes on aircraft takeoff performances in the Euro-Mediterranean region. Focusing on the Euro-Mediterranean airports will provide further knowledge of the local impacts of climate change on aviation in one of the world's most threatened areas, filling this gap in the literature. Focusing on high-temperature extreme events will allow for assessing the maximum potential impacts that the increase in temperatures may have on airport operations and aircraft performances. This will provide better understanding of the negative effects of climate change on aviation. In addition, the study of the future potential impacts on the engine performances at takeoff, including the emission of pollutants, will help complete the picture of the multiple impacts that climate change may have on aviation.

This research could be helpful for the design of adaptation or mitigation strategies in the aviation sector at the Euro-Mediterranean scale.

In Chapter 1, the general context of the thesis and the problematic were presented. The review of the existing literature on the topic was done, exposing its limitations and the need for further work and improvements. Based on the limitations identified in previous studies, the main goal of the thesis was set.

In Chapter 2, the past and future evolution of high-temperature extreme events over a list of Euro-Mediterranean airports is analysed from observations and climate model projections. Climate models are evaluated in present climate and the added value of RCMs over GCMs is assessed. The future projections of RCMs are compared to those of the GCMs. The magnitude of high-temperature extreme events in future climate is assessed by applying a bias correction to the future climate projections.

In Chapter 3, the potential increase in NO_x emissions induced by the projected growth in high-temperature extremes is assessed over major Euro-Mediterranean airports using an industrial engineering software. The potential decrease in aircraft's maximum carrying capacity at takeoff is assessed over major, regional and small airports in the region of study using an empirical law provided by AIRBUS.

Finally, the general conclusions and perspectives are drawn in Chapter 4.

CHAPTER 2

Evolution of high-temperature extremes over the Euro-Mediterranean airports

This chapter presents the results concerning the first sub-objective of the thesis: the study of the evolution of high-temperature extreme events over the airports in the Euro-Mediterranean region. This work has been the subject of a scientific publication entitled *Evolution of high-temperature extremes over the main Euro-Mediterranean airports* in the international journal Climate Dynamics [Gallardo 23]. It is included here in Section 2.2, preceded by a brief summary in French in Section 2.1. The supplementary material is also included in Appendix A.

The second part of the chapter concerns the additional analyses carried out in order 1) to identify the best-performing RCM for the representation of high temperatures at the airport scale and 2) to estimate the magnitude of future high-temperature extremes over the airports. The results are presented in Section 2.3.

2.1 RÉSUMÉ

L'analyse de l'évolution passée et future des extrêmes de hautes températures sur des aéroports majeurs du domaine Europe-Méditerranée est abordée ici. On s'est focalisés en particulier sur les extrêmes supérieurs de la température maximale journalière en été comme représentatifs des extrêmes de hautes températures.

La magnitude des extrêmes de hautes températures a d'abord été caractérisée au niveau des aéroports à partir des observations et des réanalyses. Les tendances subies au cours des dernières décennies ont été également estimées. Les résultats montrent l'accentuation des extrêmes de hautes températures pour tous les cas d'étude. La concordance entre les différents jeux de données analysés a permis de baser l'ultérieure évaluation des modèles de climat sur une seule référence observationnelle.

La représentation des extrêmes de hautes températures et de leurs tendances passées a été évaluée pour l'ensemble des modèles climatiques régionaux Euro-CORDEX. Les résultats montrent que lorsque les RCMs sont forcés par des données quasi-observationnelles, ils surestiment la magnitude des extrêmes supérieurs. Ensuite, la performance des RCMs a été comparée à celle des GCMs forceurs de CMIP5. Il n'y a pas de valeur ajoutée systhématique des RCMs sur les GCMs en termes de la représentation de la magnitude des valeurs extrêmes de hautes températures ni de leurs tendances à l'échelle des aéroports.

Finalement, les changements entre le climat futur et le climat présent projettés par les deux ensembles de modèles ont été analysés et comparés entre eux. L'ensemble des GCMs de CMIP5 projette une augmentation plus forte des températures que l'ensemble des RCMs d'Euro-CORDEX. Cette différence est cohérente avec d'autres études et elle est associée dans la litérature avec plusieurs facteurs, tels que la non prise en compte de l'évolution des aérosols dans les RCMs, ni de l'effet de la réponse physiologique des plantes au CO_2, ou avec les différences

entre les changements projetés pour la couverture nuageuse par les deux ensembles. Étant donnée cette différence entre les modèles globaux et régionaux dans le futur, et compte tenu des résultats de l'évaluation, il est conclut que les deux ensembles devraient être considérés pour mener des études d'impact concernant la température ainsi que pour concevoir des mesures d'atténuation ou adaptation au niveau régional et local, pour ne pas sousestimer la magnitude de l'incertitude de la modélisation climatique.

Les deux ensembles projettent en moyenne des changements du $95^{ème}$ quantile de la température maximale journalière d'été compris entre +1.7°C et +3.2°C dans les 30 ans à venir, et entre +4.9°C et +8.5°C vers la moitié du $XXI^{ème}$ siècle, sous le scénario de changement climatique le plus sévère. L'aéroport le plus vulnérable à subir des températures extrêmes chaudes le plus fréquemment et les plus intenses est celui de Madrid-Barajas, étant donnée sa climatologie dans la période présente et l'amplitude des changements projetés dans le futur.

Il a été montré que les modèles climatiques présentent des biais quant à représentation de la magnitude des extrêmes de hautes températures à l'échelle des aéroports. Des études récentes donnent des pistes pour améliorer les modèles régionaux à cet égard. Il a été suggéré que la modélisation plus détaillée des villes (y compris les aéroports), une meilleure prise en compte des aérosols et de leur transport ou la simulation de la convection profonde contriburaient à une meilleure représentation des températures à l'échelle régionale et locale. Des efforts supplémentaires devraient être déployés dans ce sens. C'est pourquoi, la première analyse supplémentaire vise à identifier le RCM le plus performant parmi l'ensemble Euro-CORDEX (Section 2.3.1).

D'autre part, les biais des modèles doivent être corrigés avant d'aborder le deuxième sous-objectif de la thèse dans le chapitre suivant, qui concerne l'étude de l'impact potentiel futur de l'augmentation des extrêmes de hautes températures sur le décollage des avions. La deuxième analyse suppémentaire vise donc à corriger ces biais pour estimer la magnitude des extrêmes de hautes températures dans le climat futur (Section 2.3.2) dans le but de dériver l'impact associé à de telles températures dans le Chapitre 3. Ces données seront utilisées à l'entrée du logiciel industriel Gasturb pour le calcul de la performance du moteur, et une loi empirique sera appliquée aussi à ces données climatiques pour estimer la masse maximale décollable par l'avion.

2.2 ARTICLE

Climate Dynamics
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Evolution of high-temperature extremes over the main Euro-Mediterranean airports

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Abstract

The increasing intensity and frequency of high-temperature events in response to climate change can potentially impact the aviation industry, since aircraft takeoff and landing performances depend on near-surface air temperature. Previous studies have combined climate data with aircraft technical data to estimate the future impact of rising high temperatures on aircraft takeoff. They found a decrease of maximum takeoff weights and the lengthening of takeoff distances. The Mediterranean region is a climate change "hot spot" area, specially concerned by extreme high-temperatures increase. In this study, the magnitude and trends of the daily maximum near-surface temperature extremes in summer were analysed over major airports in Southwestern Europe. Trends in the period 1961–2014 were analysed from observations and reanalysis. Future changes by 2021–2050 and 2071–2100, with respect to 1961–2005, were analysed from simulations performed with Regional and Global Climate Models (RCMs and GCMs). Before assessing future climate projections, climate models were evaluated in present climate, and the RCM and GCM ensembles were compared to each other. No clear added value was found for RCMs over GCMs in present climate at the airport scale in these terms. GCMs project larger temperature changes than RCMs over the same locations. Multi-model ensemble mean projected changes under the RCP8.5 scenario range between + 1.7 and + 3.2 °C by the near term, and between + 4.9 and + 8.5 °C by the long term, across the airports and the RCM and GCM ensembles. This increase of high-temperature extremes would impact airport operations. Adaptation or mitigation policies would become necessary.

Keywords Climate change · Local climate · Airports · Mediterranean Europe · Regional climate model · Euro-CORDEX

1 Introduction

The magnitude and the frequency of high-temperature extreme events have increased remarkably in the recent decades as a result of climate change (IPCC 2013, 2021; Mishra et al. 2015; Manning et al. 2019). In the absence of mitigation policies, global warming is expected to continue during the twenty-first century, and extreme warm temperature events will become more intense and frequent and they will last longer, while extreme cold events are expected to be less likely (IPCC 2013, 2021). Certain regions which are already characterized by warm and hot summer temperatures, like the Mediterranean Europe, are notably concerned (IPCC 2013, 2021; Stegehuis 2016; Manning et al. 2019) and will be impacted by global warming in numerous and diverse fields. The aeronautical sector is among these vulnerable fields. The impacts of climate change on aviation are various and numerous (Thompson 2016; Burbidge 2016; Ryley et al. 2020; Gratton et al. 2022). This study is particularly motivated by those impacts related to the increase in high temperature extremes at the ground level over the airports, directly affecting aircraft performances at takeoff and landing, and airport's operability.

Higher temperatures are linked to lower aircraft lift and engine thrust. An increase in temperature results in a decrease in air density, which would force the plane to reach a faster speed through thinner air to generate lift at takeoff (Anderson 2005). Considering the aircraft acceleration as a constant, takeoff distances would be lengthened in the process (Zhou et al. 2018; Gratton et al. 2020). Sometimes this speed would be unreachable, depending on the aircraft

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technical characteristics and/or on runway length limitations, leading to weight restrictions, flight delays or even cancellations (Coffel and Horton 2015; Coffel et al. 2017; Gratton et al. 2020). In addition, engine thrust decreases with temperature (Airbus 2002). It is usually manually restrained to be constant below a certain temperature for fuel economy and environmental reasons. Temperatures above this threshold will have a negative effect on thrust. The temperature threshold is typically chosen to be International Standard Atmospheric Conditions + 15 °C (ISA + 15), that is 30 °C at sea level (Airbus 2002). Above ISA + 15, the higher the temperature, the lower the thrust, which reduces the capacity of the aircraft to lift weight. Also, warmer ambient temperatures result in higher temperatures of the flame in the combustion chamber, leading to an increase of pollutant emissions into the atmosphere, in particular, of nitrogen oxides (Heywood 2018).

Fire risk also increases under extreme hot conditions (Thompson 2016). Special care should be taken at the airport under high ambient temperatures with regards to jet fuel stock, manipulation and use, whose flammability limits range between 38 and 70 °C, depending on the specific fuel type (Edwards 2017). An increase in the exposure to hot conditions might amplify the need for air conditioning and it might damage the infrastructures as well (Thompson 2016). During extreme events, energy supply could be compromised by the demand, and infrastructures would be more likely to suffer sudden punctual damages.

Finally, airport infrastructures and aircraft operations are designed to be adapted to the mean local climate in each case, optimising airport operational efficiency. Also, the aircrafts are designed to operate in a wide range of ambient conditions. Nonetheless, their operational capabilities and performances might be negatively impacted during extreme or record-shattering episodes, since they lay outside the ranges for which they were conceived. With climate change, these out-of-range high temperatures are expected to be more likely and more intense.

To the best of our knowledge, the impact studies carried out so far addressing the increase in high temperatures at the ground level over the airports are focused on aircraft takeoff performances. Previous studies have already modelled and quantified the increase in disrupted aircraft takeoff performances in terms of takeoff distance and maximum takeoff weight due to more frequent high-temperature extremes. Coffel and Horton (2015) and Coffel et al. (2017) evaluated the increase in the number of weight restricted flights related to the increase in high temperatures. Zhou et al. (2018) assessed the lengthening of takeoff distances with the increase of high temperatures at runway level. Both medium and long range aircrafts would see their maximum takeoff weight limited by the increase in high temperatures, and they would also need longer distances for takeoff. Payload penalty is greater for elevated airports with short runways. Nonetheless, their impact quantification might be overestimated, since missions rarely imply the 100% of fuel capacity nor the maximum takeoff weight of the aircraft (Hane 2016). Coffel et al. (2017) and Zhou et al. (2018) combined future climate projections with aircraft technical data to estimate the future evolution of takeoff distances and weight restricted flights in the twenty-first century. The climate projections that these two studies used were performed with Global Climate Models (GCMs) that participate in the 5th phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012). However, the average horizontal spatial resolution of global climate simulations used is about 150 km, which may hamper their representation of very local phenomena such as high-temperature extreme events at the airport scale, and their changes in a warming climate (Salathe et al. 2008; Dulière et al. 2011). Regional climate simulations with finer spatial resolution might be a better approach to study regional and local phenomena (Feser et al. 2011; Di Luca et al. 2012), in particular, those related to climatological extremes. The added value of regional climate models (RCMs) in the study of regional precipitation extremes has already been shown in Sánchez et al. (2011), Torma et al. (2015), Prein et al. (2016), Fantini et al. (2018), Solman and Blázquez (2019), Di Virgilio et al. (2020) and Vichot-Llano et al. (2021), among others. However, there are few studies addressing the added value of high resolution models, such as RCMs, in representing local temperature extremes.

Vautard et al. (2013) studied the effect of high resolution on the representation of heat waves using RCM simulations performed within the international Euro-Coordinated Regional Climate Downscaling Experiment (Euro-CORDEX; Jacob et al. 2014, 2020). They compared the performances of RCMs at two different spatial resolutions (0.11° versus 0.44°). Although a clear added value of the higher resolution could not be established generally, local improvements were found in some regions, in particular, on the coasts of Spain. In Iles et al. (2020), the added value of high resolution in representing temperature extremes over Europe is studied using RCMs and GCMs. Limited benefits are obtained from higher resolution experiments, except over mountains. A recent study by Squintu et al. (2021) has compared the performance of high versus low spatial resolution global models simulations from the CMIP6 HighResMIP experiment (Haarsma et al. 2016). It concludes that increasing model resolution in GCMs does not substantially improve the representation of extreme summer maximum temperatures, and results in weaker temporal trends in Southern Europe in the observational period.

The aim of this study is two-fold. Firstly, it attempts to evaluate the RCM performances as well as their added value in representing local high-temperatures over the main

Table 1 Observational datasets and reanalysis available at the airports selected for this study

Airport	EOBS 01deg	NOAA GHCN-Daily	SPAIN02	SAFRAN-France
MAD	✓	✓	✓	
TLS	✓	✓		✓
ORY	✓	✓		✓
BCN	✓	✓	✓	
NCE	✓			✓
FCO	✓			
ATH	✓			
LYS	✓	✓		✓
MXP	✓			

Euro-Mediterranean airports. We focus on the magnitude of the extreme events and the temporal trends in the latest decades. Secondly, it aims to assess the future changes in the magnitude of high-temperature extremes by using RCM projections, which will be compared to GCM projected changes over these airports. To our knowledge, this is the first attempt to evaluate the performances of a multi-RCM ensemble and assess the RCMs added value in terms of temperature extremes at the airport scale. It would also be the first attempt to evaluate high temperature changes at the airports using the state-of-the-art Euro-CORDEX RCMs ensemble. To the best of our knowledge, the consideration of future climate projections from both RCM and GCM ensembles for addressing climate change impacts at regional-to-local scales is unconventional, while it may be crucial for designing adaptation and mitigation policies at these scales.

This document is organised as follows: data and methods are described in Sect. 2, results are presented and discussed in Sect. 3, before conclusions and perspectives are presented in Sect. 4.

2 Data and methods

2.1 Observations, reanalysis and climate simulations

Nine of the most frequented airports located over South-western Europe were selected: (1) Adolfo Suárez Madrid-Barajas (MAD), (2) Paris Orly (ORY), (3) Toulouse-Blagnac (TLS), (4) Josep Tarradellas Barcelona-El Prat (BCN), (5) Nice Côte d'Azur (NCE), (6) Leonardo Da Vinci Rome-Fuimicino (FCO), (7) Athens Eleftherios Venizelos (ATH), (8) Milan Malpensa (MXP) and (9) Lyon-Saint Exupery (LYS) (Table 1). A large variety of local topographies are represented within this group of airports: the first three airports are located over flat lands, airports from 4 to 7 are located near the coast and the last two are close to mountain chains (Fig. 1).

The variable considered for this study is the daily maximum near-surface temperature (*TX*) in summer (June, July and August; JJA).

Several observations and reanalysis datasets were considered. Time series of in situ measurements at meteorological stations over the airports from the National Oceanic and Atmospheric Administration (NOAA) Global Historical Climatology Network (GHCN)-Daily dataset were used (Menne et al. 2012b). The NOAA GHCN-Daily dataset contains a large collection of meteorological series from land stations worldwide, and it is the result of international agreements to exchange climate data. Concerning Europe, the data available from the European Climate Assessment and Dataset project (ECA&D; Klein Tank et al. 2002) are

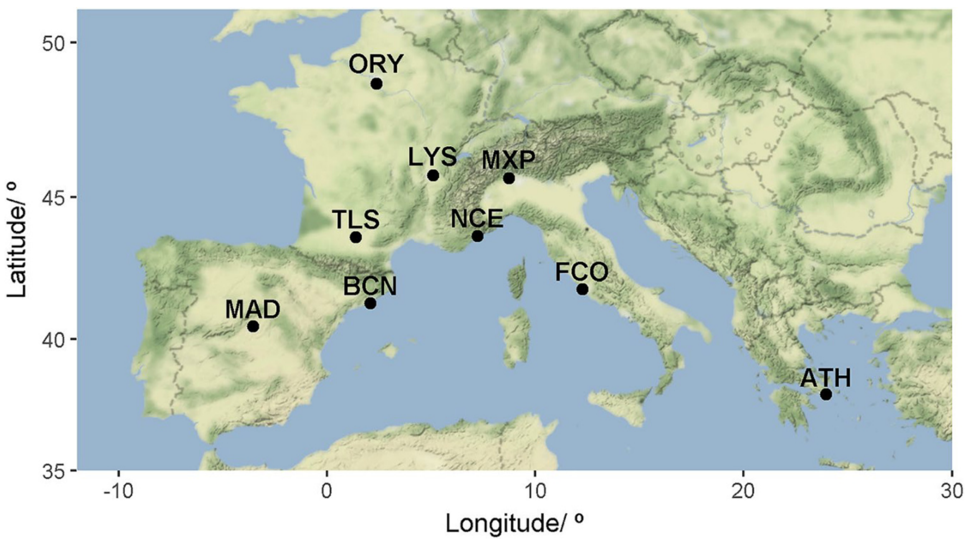


Fig. 1 Airports selected as case studies

Table 2 Principal characteristics for the datasets used in this study: type, spatial domain, resolution and covered period

Dataset	Type	Domain	Resolution	Period
NOAA GHCN-Daily	Observations	Global	In situ stations	1961–2019
EOBS 01deg	Gridded observations	Europe	11 km	1950–2021
SPAIN02	Gridded observations	Spain	10 km	1971–2015
SAFRAN-France	Reanalysis	France	8 km	1961–2014
CORDEX evaluation	Simulations	Europe	12 km	1979–2008
CORDEX historical	Simulations	Europe	12 km	1950–2005
CORDEX RCP2.6	Simulations	Europe	12 km	2006–2100
CORDEX RCP4.5	Simulations	Europe	12 km	2006–2100
CORDEX RCP8.5	Simulations	Europe	12 km	2006–2100
CMIP5 historical	Simulations	Global	150 km	1850–2005
CMIP5 RCP4.5	Simulations	Global	150 km	2006–2100
CMIP5 RCP8.5	Simulations	Global	150 km	2006–2100

considered, with most of the observational records starting in 1961. All the data collected and merged for the NOAA GHCN-Daily dataset undergo a quality-control assessment that is common for all the measurements. This dataset is frequently updated, with at least regular monthly updates for European stations. Here, the latest update of the NOAA GHCN-Daily version 3 was used (Menne et al. 2012a), which was available up to December 2019. The data were accessed via R software using the 'rnoaa' package (Chamberlain 2021).

E-OBS gridded observational dataset was also analysed (Haylock et al. 2008; Cornes et al. 2018). It is a land-only dataset available over Europe, built on series from stations that are considered in the ECA&D project. The version 24.0e of the dataset, which is available on a regular grid of 0.1° × 0.1° (EOBS 01deg) from 1950 to 2021, was used.

The SPAIN02 gridded observational dataset was also considered (Herrera et al. 2012). This is a product provided by the University of Cantabria (Spain) based on meteorological series recorded by the Spanish Meteorological Agency (AEMET) over the peninsular Spain and the Balearic islands. For developping this gridded dataset, a two-step area-averaged interpolation method was applied, where monthly means are interpolated first using thin plate splines, and then daily anomalies are interpolated using ordinary kriging. The fifth and latest version of SPAIN02 dataset (Herrera et al. 2016; Kotlarski et al. 2019) was obtained from the AEMET climate services portal (http://www.aemet.es/es/serviciosclimaticos/cambio_climat/datos_diarios?w=2&w2=1). This covers the period 1971-2015 and is available on a regular 0.1° × 0.1° grid.

Another dataset considered for this study is the *Système d'Analyse Fournissant des Renseignements Atmosphériques à la Neige-France* reanalysis (SAFRAN-France; Quintana-Segui et al. 2008; Vidal et al. 2010). SAFRAN-France is a product of Météo-France, which offers climate data over the Metropolitan France on a 8 km regular grid for the period 1950–2014. An optimal interpolation algorithm is used to spatialize the observations in 300-m vertical layers over climatically homogeneous zones. Preliminary estimates or *first guess* of the air temperature field, calculated from a meteorological model or a reanalysis such as NCEP, are modified to minimize the weighted sum of the differences between the first guess and the observed values at nearby stations for each grid point. A spatial interpolation is then performed to project the variables onto a regular 8 km-square grid.

Although the SPAIN02 and SAFRAN-France national gridded datasets include more stations for temperature than the NOAA GHCN-Daily or the EOBS dataset, they also present some disadvantages. For instance, SPAIN02 covers a shorter period as compared to the NOAA product and EOBS 01deg, and it has been shown that SAFRAN-France must be used with caution for the analysis of temperature trends (Vidal et al. 2010). The analysis of trends using the NOAA GHCN-Daily series should also be done with caution. In the absence of *the best reference*, all of the available datasets were considered and intercompared.

Table 1 summarises the observational datasets and reanalysis that are available for each selected airport. Table 2 synthesizes the main characteristics of the datasets described above.

The RCM simulations analysed in this study belong to the Evaluation, the Historical and the Representative Concentration Pathways (RCPs) Euro-CORDEX-11 ensembles (Jacob et al. 2014, 2020). The horizontal spatial resolution of these simulations is 0.11 ° (~ 12 km). Figure 2 illustrates how the scale of RCMs relates to the scale of the airports. The Evaluation ensemble consists of RCM simulations driven by the ERA-Interim reanalysis (ERAI hereinafter; Berrisford et al. 2011) at their boundaries. Table 3 summarizes the 7 RCMs used in this study from the Evaluation experiment. The Historical experiment consists of climate simulations in which the RCMs are forced by some CMIP5 models. The Historical

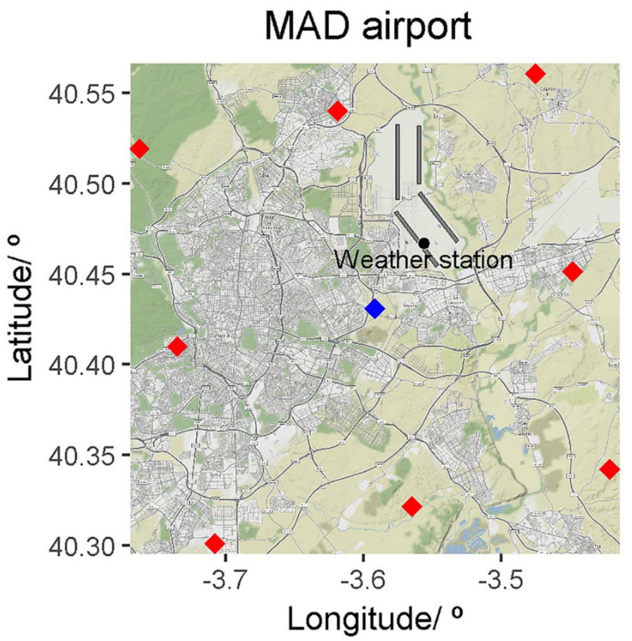


Fig. 2 MAD airport and the grid of the RCM ALADIN63 from Euro-CORDEX-11. The black point corresponds to the meteorological station located at the airport. The diamonds designate the centroids of the model grid cells, with the blue one indicating the selected grid point as the one containing this airport for the analysis

simulations used here correspond to 58 combinations of 8 driving GCMs for 11 RCMs. Table 4 details the RCM × GCM matrix. Also, in the three RCPs scenario experiments (RCP2.6, RCP4.5 and RCP8.5) RCMs are driven by CMIP5 GCMs. Table 5 inventories the GCM-RCM pairs of simulations considered for each of the three RCP scenarios: 11 simulations for RCP2.6, 13 simulations for RCP4.5 and 35 simulations for RCP8.5, resulting from the combination of 7 driving GCMs with 10 RCMs. The CMIP5 ensemble is also used (Taylor et al. 2012), since the driving models for the currently widely available Euro-CORDEX experiments are selected from this data base. Table 6 presents the CMIP5 simulations considered in this study. In total, simulations performed with 34 different GCMs were used.

2.2 Characterisation of *TX* extremes and trends

The magnitude of extreme events was analysed from quantile–quantile (q–q) diagrams, as in Herrera et al. (2010) for precipitation or in Christensen and Boberg (2012) for monthly mean temperatures, for instance. In these q–q plots, the quantiles of the different datasets were compared with those of the observational reference dataset.

Trends were computed by the quantile regression method, which was first introduced in Koenker and Bassett (1978), and further developed in Koenker (2005) and Koenker (2017). This method allows the estimation of the linear temporal trends of the *TX* Probability Distribution Functions (PDFs) by quantiles (or percentiles), thus offering information about the evolution of the PDF shape, and not only about mean changes as the most-commonly used Ordinary Least Squares (OLS) regression method does. It shares the same principle as the OLS regression method for the estimation of the conditional mean. In the OLS regression method, an estimation of the conditional expected value of the response variable is computed by minimizing the sum of squared residuals. This is not the case for conditional quantiles, for which the optimization function is the sum of asymmetrically weighted absolute residuals (Koenker and Hallock 2001), as the number of positive and negative residuals now depends on the quantile range.

Uncertainties were estimated by bootstrapping for both extremes magnitude and quantile trends. In the case of the quantile regression method, the bootstrap sampling was made over 15-consecutive-days clusters to preserve temporal homogeneity. All quantile trends were computed in R using the ‘quantreg’ package (Koenker 2021).

The analysis presented in this study can be organised in five steps.

1. Extreme values and trends of *TX* in the recent period 1961–2014 were characterized from the observational and reanalysis datasets over the nine selected airports (Table 1). To estimate to what extent the observational reference choice may affect the further evaluation of climate models, the results from the different observations and reanalysis were intercompared. In the gridded datasets, the nearest grid point to each airport was selected for the analysis.
2. The Euro-CORDEX Evaluation experiment was evaluated with respect to an observational dataset in terms of extremes magnitude and the quantile trends of *TX* for the period 1979–2008. This analysis allowed us to estimate the errors that are specific to RCMs. The land-sea mask corresponding to each RCM was taken into account to select the nearest grid points to the airport locations. The nearest point with at least 0.6 of land area fraction was selected in each case.
3. The Evaluation and Historical Euro-CORDEX RCM ensembles were compared. This step allowed us to analyse the propagation of GCM errors into RCMs in the Historical experiment. It is crucial to evaluate the Historical experiment before assessing future climate projections from the RCP experiments. For a fairer comparison, each RCM in the Evaluation experiment was counted as many times as there were simulations for that same RCM in the Historical experiment.

Table 3 List of the available RCM simulations from the Euro-CORDEX Evaluation experiment in the period 1979–2008

i	RCM	Reference(s)
1	CLMcom-ETH-COSMO-crCLIM-v1-1	Böhm et al. (2006), Rockel et al. (2008)
		Will et al. (2017)
2	CNRM-ALADIN53	Colin et al. (2010)
3	CNRM-ALADIN63	Colin et al. (2010)
4	GERICS-REMO2015	Jacob et al. (2012, 2014)
5	ICTP-RegCM4-6	Giorgi et al. (2012)
6	KNMI-RACMO22E	van Meijgaard et al. (2012)
7	SMHI-RCA4	Samuelsson et al. (2011)

4. The Historical RCM ensemble was compared to the subset of driving GCMs from the Historical CMIP5 experiment over the airports for the common period 1961–2005: 8 GCMs drove 11 RCMs for a total of 58 GCM-RCM pairs of simulations (see Table 4). The GCM simulations in the driving CMIP5 ensemble were weighted according to the number of RCMs that each GCM forced in the Euro-CORDEX Historical experiment. This step provided an assessment of the added value of increasing the resolution in climate models in representing the magnitude and trends of *TX* extreme events. For this step, RCMs and GCMs were compared over their native horizontal resolution, which allowed the added value of RCMs over the GCMs to be assessed at small scale. Nearest grid points to airports were selected as presented in step 2, for both GCMs and RCMs. The average distance between the airports and the selected grid points within GCMs was 60 km for inland airports, and about 150 km for coastal airports.
5. Future climate projections from the Euro-CORDEX and the CMIP5 RCP ensembles were analysed at their respective native resolution to investigate the changes in *TX* extremes for the periods 2021–2050 (near term) and 2071–2100 (long term), with respect to the historical period 1961–2005. This last step allowed the estimation of the magnitude of projected changes in *TX* extremes, and the comparison of RCM projections to the driving GCM projections, and to the CMIP5 ensemble as a whole, over the airports. One member per model was considered for the whole CMIP5 ensemble. Also, the RCM future projections were compared to those of their driving GCMs in terms of the quantile trends for the median and the upper 90th and 95th percentiles in the same 30-year future periods.

A height correction was applied to all the gridded datasets as in Kotlarski et al. (2019), to offset the temperature differences resulting from the altitude differences between the elevation of the airports and that of the selected grid points. A decrease in temperature with elevation following an adiabatic atmospheric profile was considered, that is, − 6.5 °C every + 1000 m.

3 Results

3.1 Observed extreme values and trends

The main purpose of this section is to characterize the differences between all of the available datasets over the selected airports, in terms of the magnitude of extreme values and trends of the summer *TX*.

Figure 3 shows the 90th, 95th and 99th upper percentiles of summer *TX* for the observations and reanalysis over the airports. All the quantiles are plotted versus those from EOBS 01deg. When both datasets are identical, they overlap on the diagonal line, while points laying above (below) indicate greater values (lower values) compared to the EOBS 01deg quantiles. Warmest temperatures were recorded at MAD airport, with 90th to 99th percentiles ranging from 36.4 to 39.0 °C. Second place in the ranking of the highest observed 99th percentile values is for ATH with 37.4 °C (not shown), and third place is for TLS, with 36.8 °C. On the other hand, the lowest 99th percentile values were observed at NCE and BCN airports, with 33.0 °C and 33.6 °C, respectively. The most moderate temperature extreme is found at ORY airport, with 29.5 °C for the 90th percentile. SAFRAN-France presents lower values than EOBS 01deg for extremely high temperatures at French airports, they are around 0.8 °C smaller. SPAIN02 also presents upper percentile values that are 0.5 °C smaller in average than those of EOBS 01deg at MAD airport, whereas they are 0.2 °C greater in average at BCN airport. Meanwhile, the NOAA GHCN-Daily and the EOBS 01deg datasets show very similar results, even though the NOAA product presents high temperatures that are 0.7 °C smaller than those of EOBS 01deg at BCN airport. The maximum differences between datasets for the *TX* summer upper percentiles range from ± 0.3 °C for ORY to 1.5 °C for TLS.

Observed quantile trends at the nine airports are shown in Fig. 4, as well as the uncertainty associated to the trend estimation for each quantile, as explained in Sect. 2.2. In this study, 19 quantiles from 5th to 95th are considered. All the quantiles of *TX* increased for all the cases. However, the shape of the quantile trends envelope differs amongst the airports considered. ORY and MAD airports exhibit large asymmetries in the distribution of quantile trends. They

Table 4 The RCM × GCM matrix indicating which combinations from the Euro-CORDEX Historical experiment were available for the study in the period 1961-2005

	CNRM-CM5	EC-EARTH	GFDL-ESM2G	HadGEM2-ES
CLMcom-CCLM4-8-17	✓(r1i1p1)	✓(r12i1p1)		✓(r1i1p1)
CLMcom-ETH-COSMO-crCLIM	✓(r1i1p1)	✓(r12i1p1) ✓(r1i1p1) ✓(r3i1p1)		✓(r1i1p1)
CNRM-ALADIN53	✓(r1i1p1)			
CNRM-ALADIN63	✓(r1i1p1)			✓(r1i1p1)
DMI-HIRHAM5	✓(r1i1p1)	✓(r12i1p1) ✓(r1i1p1)		✓(r1i1p1)
GERICS-REMO2015	✓(r1i1p1)		✓(r1i1p1)	
ICTP-RegCM4-6	✓(r1i1p1)	✓(r12i1p1)		✓(r1i1p1)
IPSL-WRF-381P	✓(r1i1p1)	✓(r12i1p1)		✓(r1i1p1)
KNMI-RACMO22E	✓(r1i1p1)	✓(r12i1p1) ✓(r1i1p1) ✓(r3i1p1)		✓(r1i1p1)
SMHI-RCA4	✓(r1i1p1)	✓(r12i1p1) ✓(r1i1p1) ✓(r3i1p1)		✓(r1i1p1)

	IPSL-CM5A-LR	IPSL-CM5A-MR	MPI-ESM-LR	NorESM1-M
CLMcom-CCLM4-8-17			✓(r1i1p1)	
CLMcom-ETH-COSMO-crCLIM			✓(r1i1p1) ✓(r12i1p1) ✓(r3i1p1)	✓(r1i1p1)
CNRM-ALADIN63			✓(r1i1p1)	✓(r1i1p1)
DMI-HIRHAM5		✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)
GERICS-REMO2015	✓(r1i1p1)		✓(r3i1p1)	✓(r1i1p1)
ICTP-RegCM4-6			✓(r1i1p1)	✓(r1i1p1)
IPSL-WRF-381P		✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)
KNMI-RACMO22E		✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)
MPI-CSC-REMO2009			✓(r1i1p1) ✓(r2i1p1)	
SMHI-RCA4		✓(r1i1p1)	✓(r1i1p1) ✓(r2i1p1) ✓(r3i1p1)	✓(r1i1p1)

show contrasted behaviors, with the strongest increase of highest quantiles at ORY airport (0.60 ± 0.15 °C/decade according to EOBS 01deg) and strongest increase of lowest quantiles at MAD airport (0.8 ± 0.2 °C/decade, also for EOBS 01deg). TLS has also experienced slightly stronger trends at higher percentiles. In addition, LYS also presents asymmetries, with trends being larger for the median than for the upper and lower extremes, but only according to the NOAA GHCN-Daily dataset. These uneven distributions of the percentile trends justify the choice of the quantile regression method for the computation of the evolution of high temperatures. For the rest of airports, the PDF shifted towards higher temperatures in an almost homogeneous way, as differences between lowest and highest percentile trends are minimal compared to those obtained at ORY and MAD airports. Trends of the 95th percentile, which is commonly used to characterize extremes, range between 0.25 and 0.75 °C/decade for most of the airports (TLS, BCN, NCE, ATH, LYS and MXP), when considering all of the available datasets. The weakest trends for 95th percentile are observed at FCO airport and they range between 0.13 and 0.27 °C/decade. Positive trends found for all the airports are coherent with the rise in heat events in the Euro-Mediterranean region in recent decades (IPCC 2013, 2021). This study on major Euro-Mediterranean airports expands the list of airports that have been considered so far (Coffel and Horton 2015; Coffel et al. 2017; Zhou et al. 2018), and which have been found

Table 5 The RCM × GCM matrix indicating which combinations from the Euro-CORDEX RCPs scenarios experiment were available for the study between 2021 and 2100

	CNRM-CM5	EC-EARTH	HadGEM2-ES	IPSL-CM5A-LR	MPI-ESM-LR	NorESM1-M
RCP2.6						
CLMcom-CCLM4-8-17		✓(r12i1p1)				
CNRM-ALADIN63	✓(r1i1p1)					
DMI-HIRHAM5		✓(r3i1p1)	✓(r1i1p1)			
GERICS-REMO2015	✓(r1i1p1)			✓(r1i1p1)		
ICTP-RegCM4-6			✓(r1i1p1)		✓(r1i1p1)	✓(r1i1p1)
SMHI-RCA4		✓(r12i1p1)				
KNMI-RACMO22E	✓(r1i1p1)					
RCP4.5						
CLMcom-CCLM4-8-17	✓(r1i1p1)	✓(r12i1p1)	✓(r1i1p1)		✓(r1i1p1)	
CNRM-ALADIN53	✓(r1i1p1)					
CNRM-ALADIN63	✓(r1i1p1)					
DMI-HIRHAM5		✓(r3i1p1)	✓(r1i1p1)			✓(r1i1p1)
IPSL-WRF-381P				✓(r1i1p1)		
SMHI-RCA4	✓(r1i1p1)	✓(r12i1p1)		✓(r1i1p1)		
RCP8.5						
CLMcom-CCLM4-8-17	✓(r1i1p1)	✓(r12i1p1)	✓(r1i1p1)		✓(r1i1p1)	
CLMcom-ETH-COSMO-crCLIM	✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)		✓(r1i1p1)	✓(r1i1p1)
CNRM-ALADIN53	✓(r1i1p1)					
CNRM-ALADIN63	✓(r1i1p1)		✓(r1i1p1)		✓(r1i1p1)	✓(r1i1p1)
DMI-HIRHAM5	✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)
GERICS-REMO2015	✓(r1i1p1)					
ICTP-RegCM4-6	✓(r1i1p1)	✓(r12i1p1)	✓(r1i1p1)		✓(r1i1p1)	✓(r1i1p1)
IPSL-WRF-381P	✓(r1i1p1)	✓(r12i1p1)	✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)	✓(r1i1p1)
SMHI-RCA4	✓(r1i1p1)	✓(r1i1p1)		✓(r1i1p1)		

to be more exposed to extreme heat conditions because of global warming.

The EOBS 01deg dataset shows a very similar behavior to that of the NOAA GHCN-Daily dataset, for both extreme values and trends. This is probably explained by the fact that the nearest in situ stations to the selected airports that the EOBS 01deg dataset integrates are also included in the NOAA GHCN-Daily dataset. SPAIN02 and SAFRAN-France show large discrepancies with respect to the EOBS 01deg and the NOAA GHCN-Daily datasets. In general, SAFRAN-France exhibits larger trends than EOBS 01deg or the NOAA product for the upper quantile, except for the TLS airport. For SPAIN02, the reason of the differences from other datasets can be explained by the sensitivity of trends computation to the period of study (see Table 2). Indeed, if we recompute the quantile trends for a common period (1971–2014) for all the datasets at the Spanish airports, SPAIN02 exhibits more similar trends to the EOBS 01deg and the NOAA GHCN-Daily datasets (Supplement, Fig. 1). Nevertheless, SAFRAN-France reanalysis presents larger trends for the 95th percentile than the EOBS 01deg and the NOAA GHCN-Daily datasets, they are 0.4 °C/decade greater at ORY and NCE, and around 0.15 °C/decade greater at LYS, while it matches both at TLS.

To conclude, differences between datasets for *TX* trends in the observational period can reach up to 0.4 °C/decade (for central estimates), depending on the location and also on the percentile. However, all of the datasets remain mainly coherent at most airports because of the wide amplitude of the confidence intervals from the quantile trends computation. Also, the maximum difference between datasets obtained for the upper percentile magnitudes of *TX* is 1.5 °C for temperatures that exceed 35 °C. According to these results, we consider that the choice of the observational reference among these datasets may not be determinant for the evaluation of the climate models in terms of the local *TX*. We consider hereinafter EOBS 01deg as the observational reference for the evaluation of the climate models at the airport scale, since data are available over all the selected

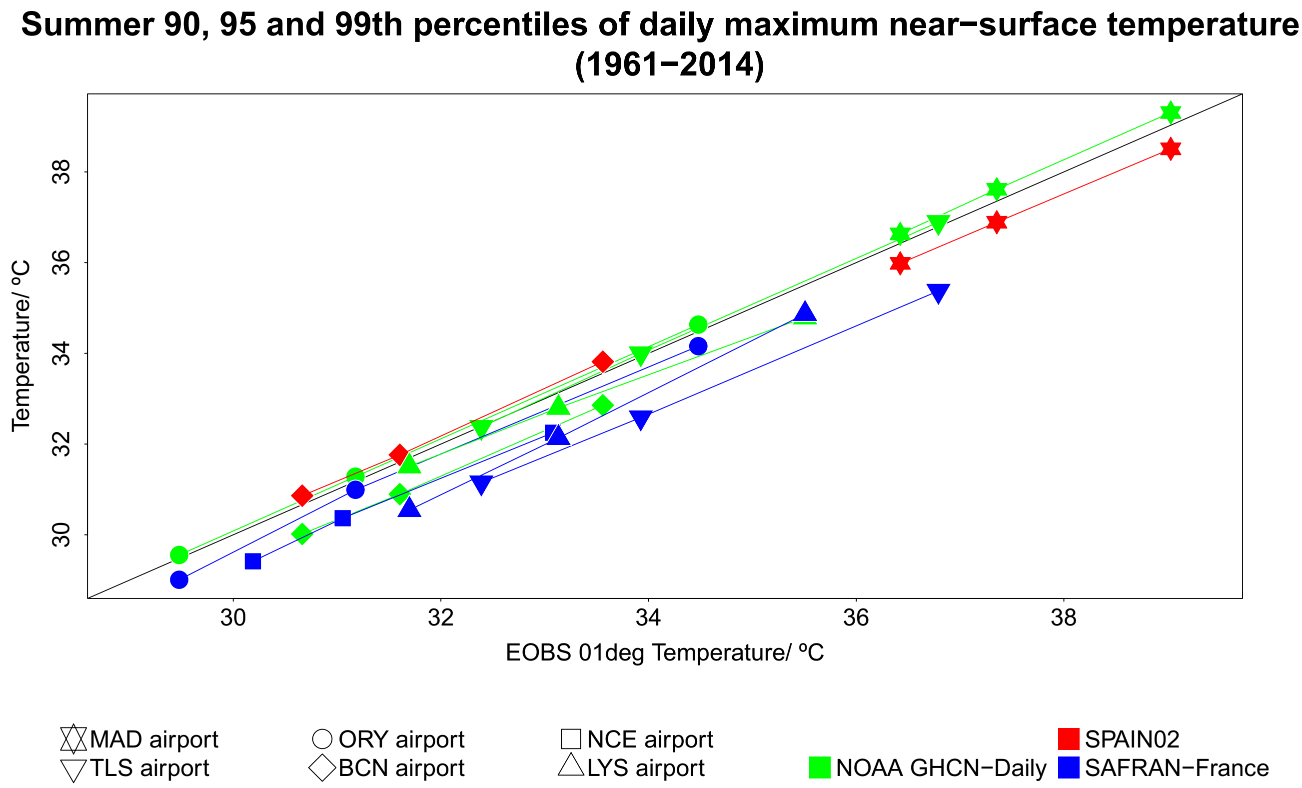


Fig. 3 q–q plot of the *TX* upper percentiles observed in the summer season between 1961 and 2014. NOAA GHCN-Daily (green points), SPAIN02 (red points) and SAFRAN-France (blue points). EOBS 01deg is considered as reference (horizontal axis). The tick marks represent MAD airport (stars), TLS airport (triangles down), ORY airport (circles), BCN airport (diamonds), NCE airport (squares) and LYS airport (triangles up)

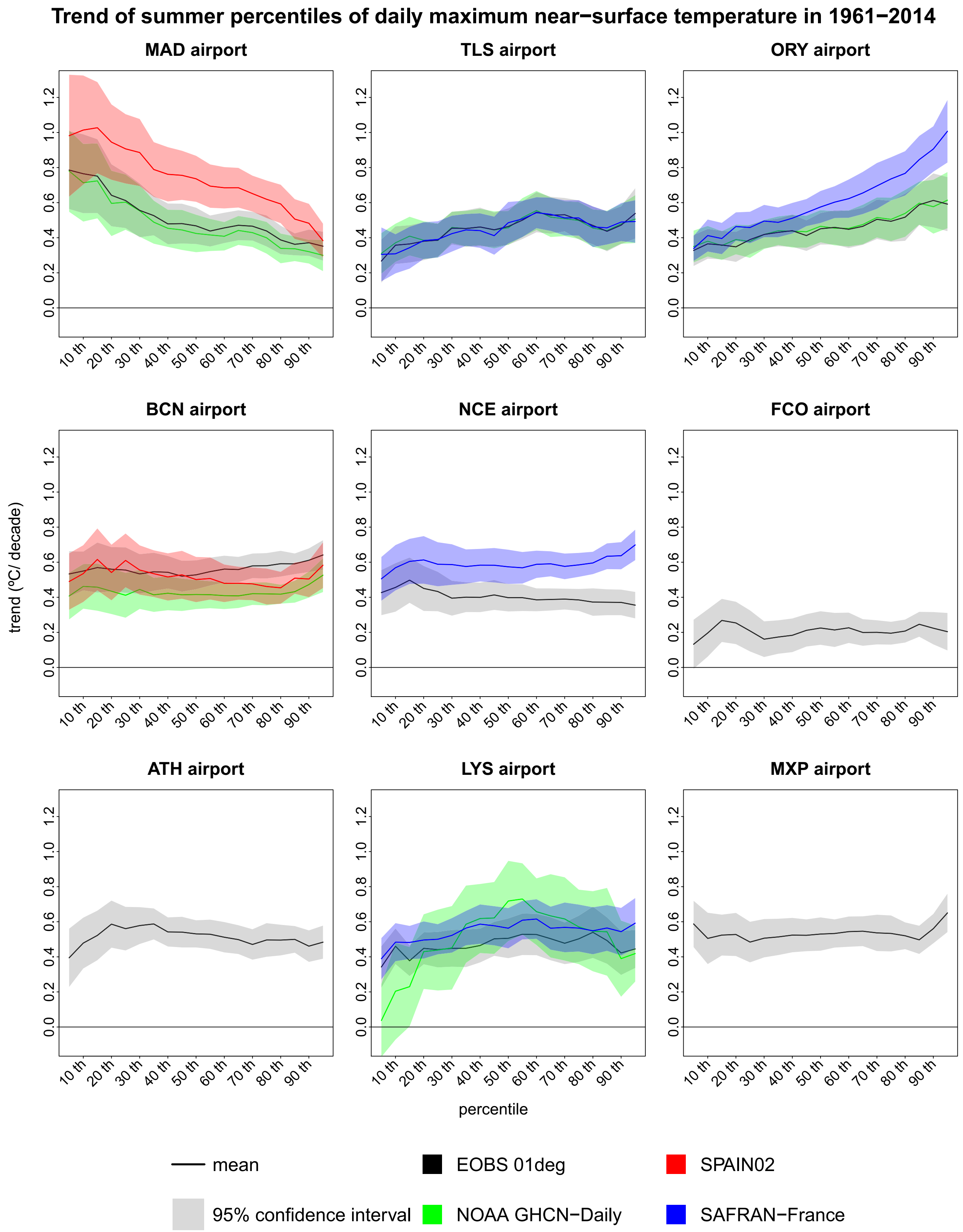
airport locations, and its resolution is nearly the same as that of the RCMs.

3.2 Evaluation of RCMs

The magnitude of *TX* extremes is clearly overestimated by RCMs in the Evaluation experiment (Fig. 5). These biases do not change much with the percentile range, but their amplitudes depend on the airport. The largest biases are found at TLS, NCE and MXP airports, being of + 3.3 °C in average, and reaching up to + 6.0 °C for some models. The lowest biases are found at MAD and ORY airports, being less than + 1.5 °C in average. With SPAIN02 or SAFRAN-France as observational reference, the warm bias of RCMs at MAD, TLS, NCE, and LYS would have been even higher. Conversely, when RCMs are driven by GCMs in the Historical experiment, the MME mean biases change in magnitude and even in sign at most of the airports and decreases. Nonetheless, the amplitude of the MME spread, considered as the difference between the maximum and the miximum from the ensemble simulations, amongst the Historical ensemble is very large, ranging between − 6 and + 6 °C. This change in the behavior of RCMs could be explained by the interaction and/or the superposition of the RCM intrinsic biases with the driving GCM biases, suggesting an error compensation (Colmet-Daage et al. 2018).

Figure 6 shows that, in general, there are no substantial differences between the observed *TX* quantile trends and the simulated trends by the RCMs in the Evaluation and Historical ensembles, since the observational spread generally lays within the envelope spanned by RCMs for most percentiles across the airports. However, MME mean trends are generally lower than the observed trends. Only at ATH airport, the observed trends do lie completely outside of the Evaluation MME spread for almost all of the percentiles, except for the extremes and the median. The inter-model spread of the Evaluation ensemble for the upper percentiles trend is generally very wide, exceeding 0.3 °C/decade in the 30-years period in most of the cases. The Historical experiment depicts a larger inter-model spread concerning all percentile trends. In particular, the inter-model spread amplitude for the highest quantile trends can reach more than 2 °C/decade.

Results from the evaluation of RCMs are consistent with Vautard et al. (2013). They also found that RCMs generally


Trend of summer percentiles of daily maximum near−surface temperature in 1961−2014
MAD airport
TLS airport
ORY airport
BCN airport
NCE airport
FCO airport
ATH airport
LYS airport
MXP airport
trend (ºC/ decade)
percentile
0.0
0.2
0.4
0.6
0.8
1.0
1.2
10 th
20 th
30 th
40 th
50 th
60 th
70 th
80 th
90 th
mean
95% confidence interval
EOBS 01deg
NOAA GHCN−Daily
SPAIN02
SAFRAN−France

◂**Fig. 4** Quantile trends of the *TX* between 1961 and 2014 in JJA, computed for MAD, TLS, ORY, BCN, NCE, FCO, ATH, LYS and MXP airports from EOBS 01deg (black), NOAA GHCN-Daily (green) and SPAIN02 (red) observational datasets, and for SAFRAN-France (blue) reanalysis. Solid lines correspond to the mean of the bootstrap distribution, and shading indicates the 95% confidence interval. For SPAIN02, a lack of 10-year data at the beginning of the period was accepted, which means that trends were actually computed over the period 1971–2014

overestimate summer temperature extremes, in particular, in the Mediterranean region. Moreover, the positive intrinsic bias of the Euro-CORDEX RCMs for summer temperatures in Southern Europe was also highlighted in Kotlarski et al. (2014).

To conclude, the GCM-driven experiment exhibits smaller biases in the MME mean for extreme temperatures than in the ERAI-driven experiment, with − 0.4 versus + 2.3 °C, in average, but a larger MME spread. The amplified spread in extreme temperatures when RCMs are driven by GCMs was also found in Moberg and Jones (2004), Kjellström et al. (2007) and Nikulin et al. (2011). The RCM MME spread main dependence on the driving GCMs was previously pointed out in Déqué et al. (2012) for mean summer temperatures.

3.3 Added value of RCMs over GCMs

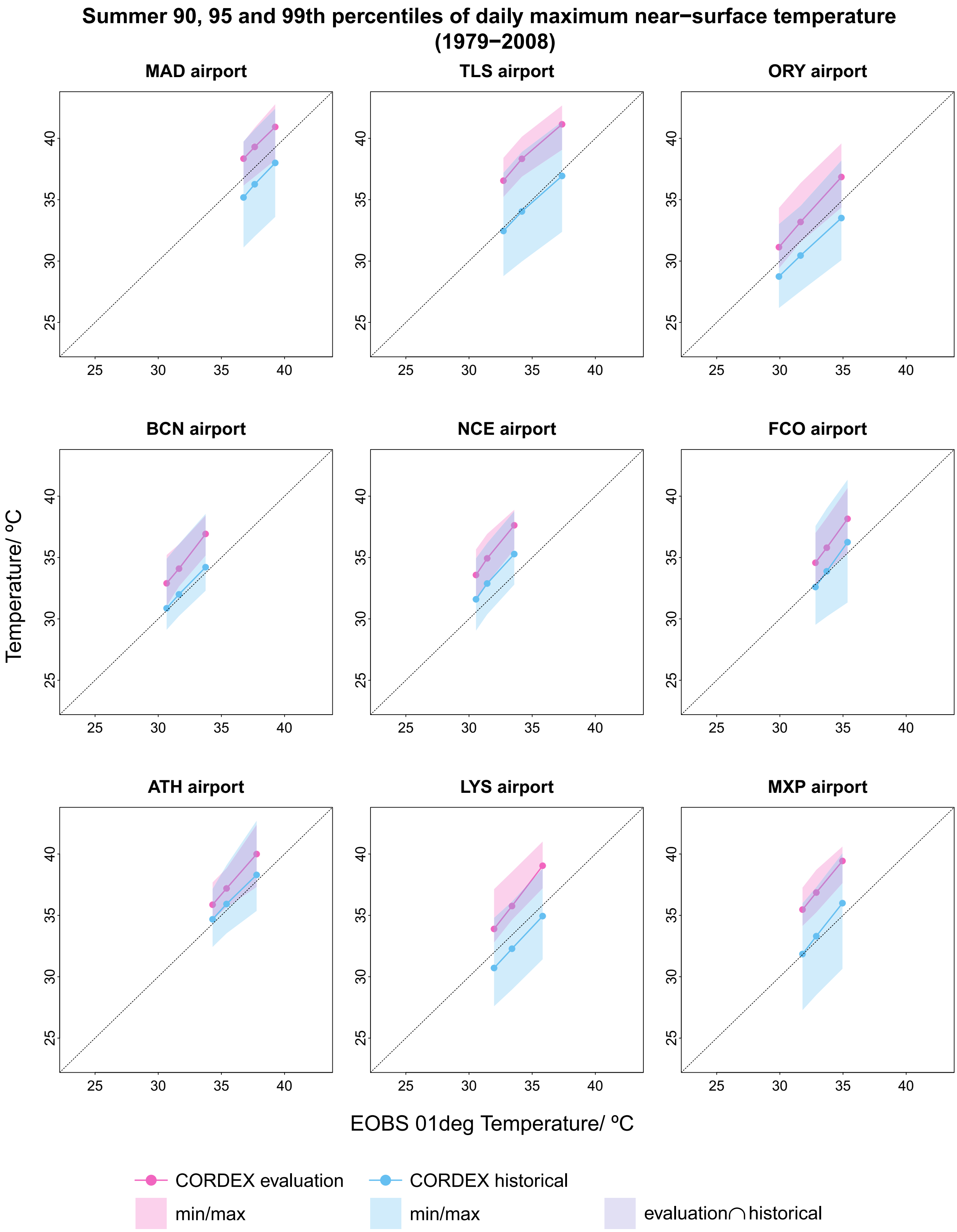
Figure 7 shows that the driving GCM MME mean underestimates the *TX* extremes over the 5 inland airports, while it underestimates them over the 4 coastal airports. This prevailing cold bias of CMIP5 for summer temperatures over Southwestern Europe is consistent with results found by Cattiaux et al. (2013). An advantageous interaction of the RCM inherent positive biases with the GCM biases could explain the apparent better results of the Historical RCM ensemble versus the Evaluation ensemble found in Sect. 3.2. The large GCM ensemble spread entirely envelops the observations. Only at BCN, NCE and MXP airports *TX* extremes are found to be completely underestimated by the whole ensemble of driving GCMs. RCMs show an apparent added value regarding *TX* extremes, as the MME mean is in some cases really close to the observations, and the RCM ensemble seems to be more performant than the driving GCMs, in particular, over BCN, NCE and MXP airports, the first two on the coast, and the third one near to mountain chains. Nonetheless, according to the results in Sect. 3.2, this apparent added value is likely the result of each pair of GCM-RCM errors interaction, as already mentioned. These results are coherent with Vautard et al. (2013), where local improvements were found in the representation of heat waves over Europe

Table 6 List of GCM simulations from the CMIP5 RCP scenarios experiments analysed in this study in the period 1961–2005

i	GCM	Historical	RCP4.5	RCP8.5
1	ACCESS1-0	r1i1p1	r1i1p1	r1i1p1
2	BNU-ESM	r1i1p1	r1i1p1	r1i1p1
3	CCSM4	r1i1p1	r1i1p1	r1i1p1
4	CESM1-BGC	r1i1p1	r1i1p1	r1i1p1
5	CESM1-CAM5	r1i1p1	r1i1p1	r1i1p1
6	CMCC-CESM	r1i1p1		r1i1p1
7	CMCC-CMS	r1i1p1	r1i1p1	r1i1p1
8	CMCC-CM	r1i1p1	r1i1p1	r1i1p1
9	CNRM-CM5*	r1i1p1	r1i1p1	r1i1p1
10	CSIRO-Mk3-6-0	r10i1p1	r10i1p1	r10i1p1
11	CSIRO-Mk3L-1-2	r1i1p1	r1i1p1	
12	CanESM2	r1i1p1	r1i1p1	r1i1p1
13	EC-EARTH*	r1i1p1 r12i1p1	r1i1p1	r1i1p1
14	FGOALS-g2	r1i1p1	r1i1p1	r1i1p1
15	GFDL-CM3	r1i1p1	r1i1p1	r1i1p1
16	GFDL-ESM2G*	r1i1p1	r1i1p1	r1i1p1
17	GFDL-ESM2M	r1i1p1	r1i1p1	r1i1p1
18	GISS-E2-R	r6i1p1	r6i1p1	
19	HadGEM2-AO	r1i1p1	r1i1p1	r1i1p1
20	HadGEM2-CC	r1i1p1	r1i1p1	r1i1p1
21	HadGEM2-ES*	r1i1p1	r1i1p1	r1i1p1
22	IPSL-CM5A-LR*	r1i1p1	r1i1p1	r1i1p1
23	IPSL-CM5A-MR*	r1i1p1	r1i1p1	r1i1p1
24	IPSL-CM5B-LR	r1i1p1	r1i1p1	r1i1p1
25	MIROC-ESM-CHEM	r1i1p1	r1i1p1	r1i1p1
26	MIROC-ESM	r1i1p1	r1i1p1	r1i1p1
27	MIROC5	r1i1p1	r1i1p1	r1i1p1
28	MPI-ESM-LR*	r1i1p1 r2i1p1 r3i1p1	r1i1p1	r1i1p1
29	MPI-ESM-MR	r1i1p1	r1i1p1	r1i1p1
30	MRI-CGCM3	r1i1p1		r1i1p1
31	MRI-ESM1	r1i1p1		r1i1p1
32	NorESM1-M*	r1i1p1	r1i1p1	r1i1p1
33	bcc-csm1-1-m	r1i1p1	r1i1p1	r1i1p1
34	inmcm4	r1i1p1	r1i1p1	r1i1p1

The GCMs used to drive the Euro-CORDEX RCMs are indicated with an asterix

in some coastal emplacements, using higher resolution climate simulations. In Iles et al. (2020), increasing the resolution was also found to be beneficial for the representation of high-temperature events over mountainous regions in Europe, as warm biases were smaller at higher resolution.


Summer 90, 95 and 99th percentiles of daily maximum near−surface temperature (1979−2008)
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TLS airport
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BCN airport
NCE airport
FCO airport
ATH airport
LYS airport
MXP airport
25
30
35
40
Temperature/ ºC
EOBS 01deg Temperature/ ºC
CORDEX evaluation
CORDEX historical
min/max
min/max
evaluation∩historical

◀**Fig. 5** q–q plot of the *TX* upper percentiles between 1979 and 2008 in JJA, for the Euro-CORDEX Evaluation and Historical experiments (pink and blue, respectively). The reference is EOBS 01deg data as explained in the text. Colored solid lines represent the MME mean of each experiment, and shading corresponds to the interval between minimum and maximum values obtained for each model ensemble

Figure 8 highlights that it is generally not possible to exclude the observations, which are a single realisation of the climate system among all the possible ones, from the distribution of realisations simulated by the RCM and GCM Historical ensembles that represent the internal climate variability (as modelled by both Euro-CORDEX and CMIP5 Historical ensembles). The MME mean of the two ensembles present smaller trends and less variation between *TX* percentiles than those observed.

Moreover, the amplitude of the inter-model spread of the RCM Historical ensemble is generally comparable to the one of the driving GCM ensemble for *TX* extremes, as shown in Fig. 7, despite the fewer number of unique GCM simulations integrating the second ensemble (9 GCMs in CMIP5 Historical versus 47 GCM-RCM combinations in Euro-CORDEX Historical). As already mentioned in Sect. 3.2, the driving GCM was highlighted as the main source of uncertainty amongst RCMs in simulating mean summer temperatures in Déqué et al. (2012). The comparison of the MME spread amplitudes of the two ensembles regarding *TX* quantile trends suggests that MME spread amplitude in RCMs is modulated by the MME spread amplitude of the driving GCMs, although larger uncertainties are clearly found in the RCM experiment at TLS, ORY and LYS airports, as shown in Fig. 8.

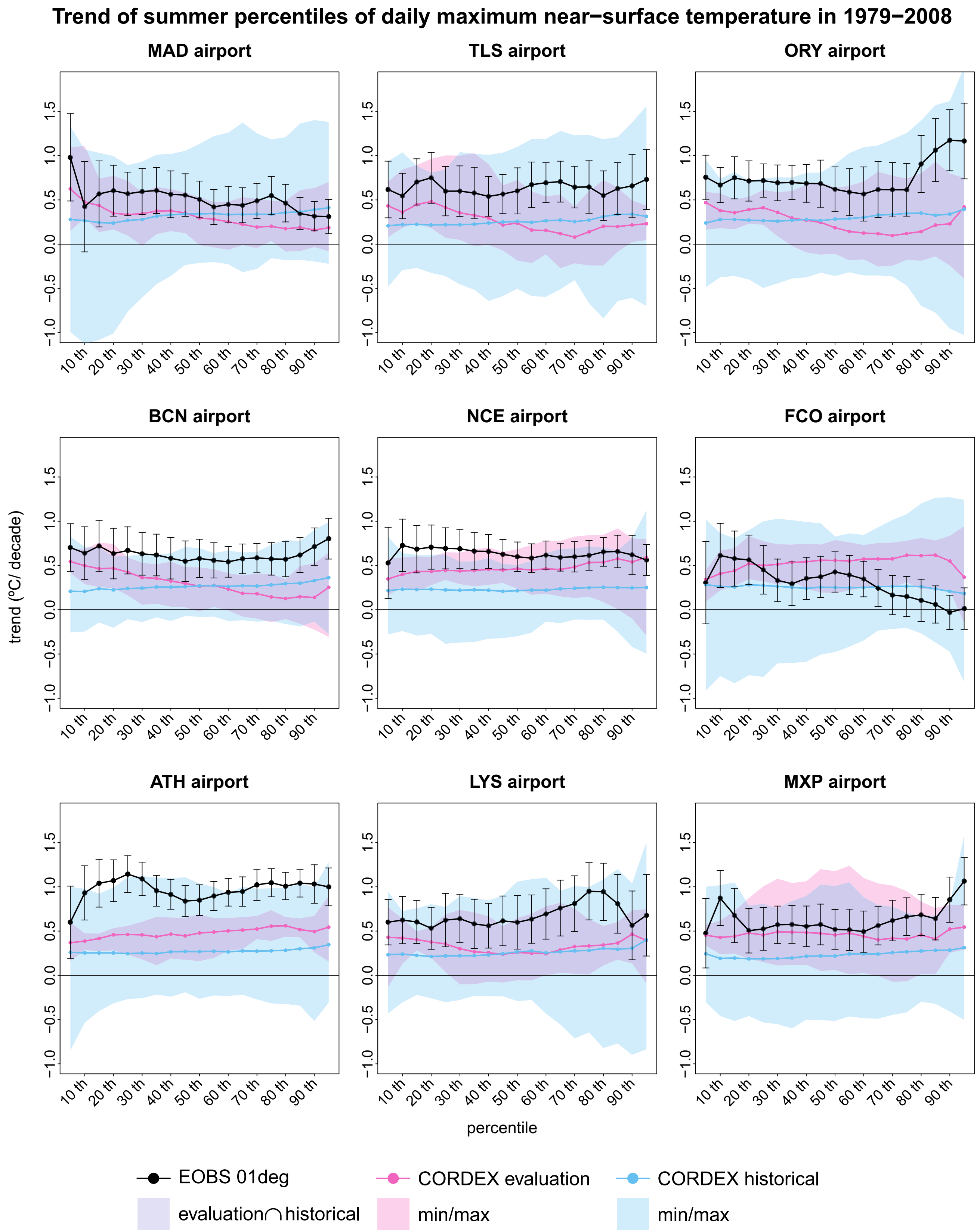
These results indicate that it is difficult to conclude on an added value of higher resolution RCMs with respect to GCMs in representing extreme values and trends of high temperatures at the small scale of the airport. These findings are consistent with those in Vautard et al. (2013) and Squintu et al. (2021). Only increasing model resolution may not be a sufficient condition to improve the representation of local extreme temperature phenomena and their evolution.

3.4 Future climate projections

Figure 9 represents the future changes of the 95th percentile as simulated by the Euro-CORDEX MME mean for the most severe RCP8.5 scenario. The coastal airports show the smallest increase: less than 2 °C by the near term, and around 5 °C by the end of the century. This is in line with the lower warming projected by the Euro-CORDEX ensemble for the Atlantic coast of Portugal, found in Cardoso et al. (2019), as compared to the eastern and more continental part of the country. At ORY airport, the magnitude of the 95th percentile is also projected to increase approximately 1.7 and 5.0 °C by the near and long term, respectively. The other airports experienced stronger changes in the 95th percentile, ranging between 2 °C for the near term and about 6 °C for late twenty-first century. These results are consistent with the increase of *TX* extremes during this century projected by the Euro-CORDEX ensemble over the Mediterranean and Southern Europe found in Zittis et al. (2019) and in Coppola et al. (2021). We have also investigated the projected changes for the median and the quantiles 90 and 99, 99.5 and 99.9th. In general, a stronger increase is projected for the highest quantiles with respect to the median under the severe scenario in the two horizon periods (not shown). In particular, these differences between the 95th percentile and the median can reach up to 0.4 °C by the near term, and up to 1.1 °C by the long term. This is in agreement with Cardoso et al. (2019) for future Euro-CORDEX projections over Portugal. They are also in accordance with the future high-temperature changes projected for a list of airports distributed worldwide analysed in previous studies (Coffel and Horton 2015; Coffel et al. 2017; Zhou et al. 2018).

MME mean projected changes by the near term found for the RCP2.6 and RCP4.5 scenarios lay within the envelope of the RCP8.5 experiment ensemble (Supplement, Fig. 3a). This result suggests that the emission scenario and anthropogenic forcing are not the dominant sources of uncertainty by the near term, which is consistent with Kay et al. (2015). Instead, models and internal variability may be the main sources of uncertainty. Conversely, MME mean changes are well differentiated by the long term for the different scenarios (Supplement, Fig. 3b). In particular, regarding the 95th percentile, differences between the RCP8.5 and RCP2.6 scenarios range between 3.4 and 4.5 °C, and between 2.2 and 2.9 °C for the RCP8.5 and the RCP4.5 scenarios comparison.

The warming projected for the *TX* 95th summer percentile by the CMIP5 MME mean is between 0.8 and 1.2 °C greater than the one simulated by the Euro-CORDEX in the near term, and between 1.8 and 2.7 °C greater in the long term, as shown in Fig. 10. The magnitude of this difference was found to be the same for the median as for the upper extremes (Supplement, Fig. 2). Similar differences were found in average when comparing the RCMs to the subset of driving GCMs, although they are slightly less pronounced by the long term. This suggests that the difference between the changes projected by the whole CMIP5 ensemble and those projected by the Euro-CORDEX ensemble is not due to an under-sampling issue in the selection of the forcing models. The MME spread for CMIP5 as a whole is clearly wider than



Trend of summer percentiles of daily maximum near−surface temperature in 1979−2008
MAD airport
TLS airport
ORY airport
BCN airport
NCE airport
FCO airport
ATH airport
LYS airport
MXP airport
trend (ºC/ decade)
percentile
10 th
20 th
30 th
40 th
50 th
60 th
70 th
80 th
90 th
−1.0
−0.5
0.0
0.5
1.0
1.5
EOBS 01deg
CORDEX evaluation
CORDEX historical
evaluation∩historical
min/max
min/max

◂**Fig. 6** Quantile trends of the *TX* between 1979 and 2008 in JJA for the EOBS 01deg observational dataset (black), the Euro-CORDEX Evaluation and Historical experiments (pink and blue, respectively). Error bars represent the 95% confidence interval for the observed trends. Colored solid lines represent the MME mean of each experiment, and shading corresponds to the interval between minimum and maximum values found for each of the two ensembles

that for the driving GCMs, even though their MME means are not so different from each other.

As for the projected changes, the projected trends in the future periods 2021–2050 and 2071–2100 are greater amongst the driving GCMs than amongst the RCMs, according to their MME means (Supplement, Fig. 4 and 5). The driving CMIP5 GCMs project in average trends 0.9 °C/decade warmer than the Euro-CORDEX RCMs by the near term. In the further period, driving GCMs do also generally project mean warmer trends than RCMs, but differences between the two MME mean are much smaller as compared to the next decades (0.3 °C/decade in average).

Warmer changes projected by CMIP5 GCMs as compared to Euro-CORDEX RCMs were also found in Boé et al. (2020) for the mean summer temperature, and in Coppola et al. (2021) using extreme temperature indices. The lack of evolving aerosols during the twenty-first century in most of the RCMs is highlighted in Boé et al. (2020) as one explanation for this. In addition, in Coppola et al. (2021) differences between changes for cloud cover projected by the two ensembles (Bartók et al. 2017) is pointed out as another plausible explanation, along with the lack of representation of the effect of the plants physiological response to CO_2 in RCMs (Schwingshackl et al. 2019), also mentioned in Boé et al. (2020).

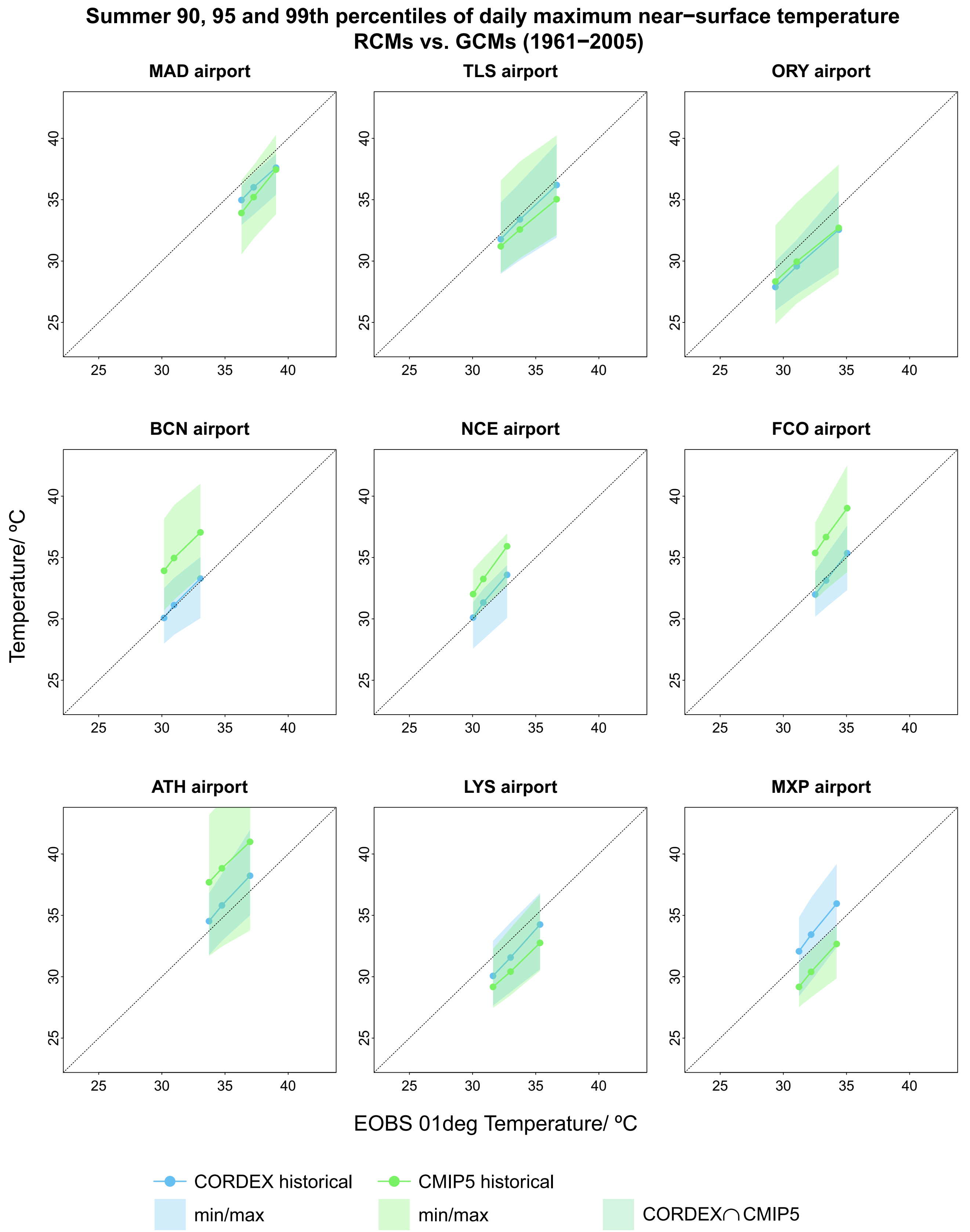
Furthermore, the link between the magnitude of future projected changes for *TX* extremes by the models and their biases in present climate was investigated. An inter-model Pearson correlation test amongst the Euro-CORDEX and the CMIP5 ensembles was performed for each airport, between the projected changes under the RCP8.5 scenario by 2021–2050 and 2071–2100 with respect to 1961–2005, and the model biases in 1961–2005. This analysis revealed that future projected changes in high-temperature extremes are not generally correlated to the model biases in present climate. Only in few cases this correlation was found to be weak but significant (p-value < 0.05), with correlation values ranging from 0.39 to 0.55 (see Supplementary Figs. 6–9). This is in contrast with what was suggested for mean summer temperature in Boberg and Christensen (2012) and for monthly temperatures in Christensen and Boberg (2012).

In summary, mean projected changes by the Euro-CORDEX ensemble (by the CMIP5 ensemble, respectively) for *TX* extremes during the twenty-first century under the RCP8.5 scenario, relative to the historical period, range between + 1.7 and + 2.2 °C (+ 2.7 and + 3.2 °C) by the near term, and between + 4.9 and + 6.2 °C (+ 7.2 and + 8.5 °C) by the long term, over the main Southwestern European airports. MAD would be the airport most exposed to extreme heat, since this location combines one of the largest projected changes amongst all the case studies with the warmest extreme values observed in the present climate. Changes projected by RCMs are much smaller than the ones projected by CMIP5 GCMs.

4 Conclusions

The aeronautics and aviation industries are vulnerable to global warming as aircraft performances and operations depend on air temperature. High-resolution RCMs may be an appropriate tool to address the study of future potential impacts at the airport scale. The prior evaluation of RCMs is crucial before carrying out this impact assessment.

In this study, the performance of RCMs from Euro-CORDEX in the simulation of extreme values and trends of high temperatures at the airport scale was evaluated. The series of the maximum daily 2-m temperature at nine of the major Euro-Mediterranean airports were analysed for the past decades. Most of the airports considered as case studies are original to this study. They have not been considered before, and yet they are major airports located in one of the most important climate change “hot spots”. A set of observations and reanalysis products were first analysed and compared amongst each other in order to estimate how the observational reference choice can influence the evaluation of the climate models. Trends were computed using quantile regression for a list of percentiles sampling the whole summer *TX* PDF for each airport. This method allows us to obtain the evolution of the shape of the PDFs, in particular, the median and extreme trends, and not only the mean trends like the most-commonly used OLS regression method. Positive trends exceeding 0.2 °C/decade in the observational period 1961–2014 were found for all the airports, and regarding all of the *TX* quantiles. This corroborates the existence of a potencial risk for airports over the Euro-Mediterranean region due to global warming. In addition, the median and extreme quantiles showed marked differences in terms of the warming magnitude, in particular, for ORY and MAD airports. While higher quantiles



Summer 90, 95 and 99th percentiles of daily maximum near−surface temperature
RCMs vs. GCMs (1961−2005)
MAD airport
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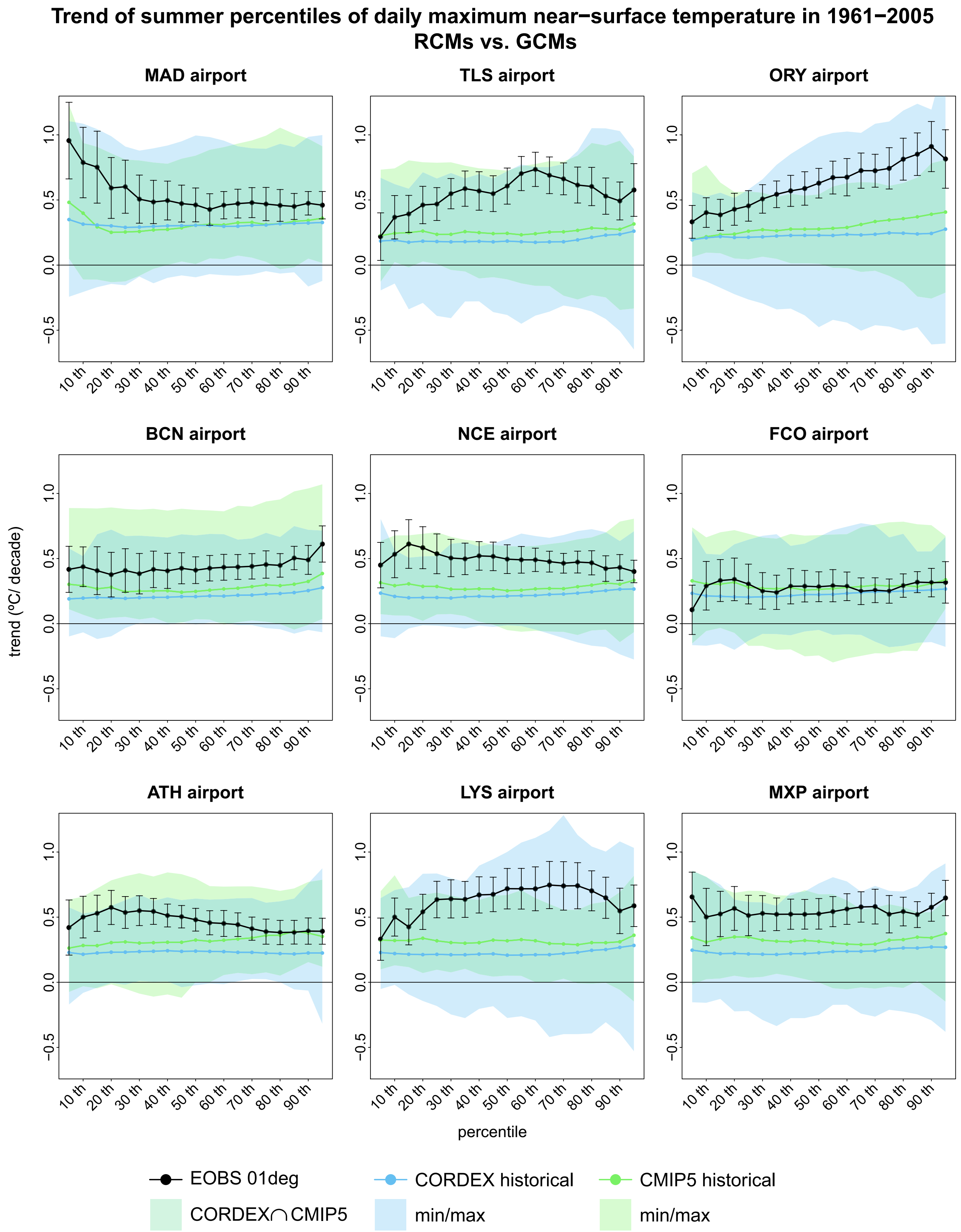
◂**Fig. 7** q–q plot of the *TX* upper percentiles between 1961 and 2005 in JJA, for the Euro-CORDEX Historical ensemble (blue) and the forcing CMIP5 GCM (weighted) sub-ensemble (green). The reference is EOBS 01deg data as explained in the text. Colored solid lines represent the MME mean of each experiment, and shading corresponds to the interval between minimum and maximum values obtained for each model ensemble

experienced larger warming than the lower quantiles and even the median at ORY, a contrasted behavior was found for the MAD airport. This result highlights the need for computing the temperature trends by quantiles, since *TX* extreme events are the most problematic for aviation, yet this method is not broadly used in the literature. Although observational datasets exhibit some differences, the maximum divergence concerning the *TX* upper percentiles is 1.5 °C for temperatures exceeding 35 °C, and *TX* trends are mainly coherent amongst the datasets for most of the airports.

Euro-CORDEX RCMs were evaluated by comparing regional climate simulations with an observational reference. First, RCM performances when driven by the ERAI reanalysis were studied using the Evaluation experiment. A systematic overestimation of *TX* extremes by RCMs was found. As suggested in Vautard et al. (2013), the overestimation of temperatures by Euro-CORDEX RCMs may be linked to the underestimation of the precipitation over these locations. This affects the regional partitioning between sensible and latent heat fluxes, to the detriment of latent heat, since less soil moisture is available for evaporation. This hypothesis was not further investigated in our study. An additional analysis of the RCM Historical experiment reveals that model performances improve when RCMs are driven by GCMs. However, this improvement in RCM performances is likely the result of error interaction for each pair of GCM-RCM combinations, reducing biases but not for good reasons. In addition, the observed trend is included in the distribution of the past trends simulated by the RCMs. Finally, the added value of RCMs with respect to GCMs was explored. The quantile regression method enabled a more detailed evaluation and comparison of RCMs versus GCMs than that seen in the literature in terms of temperature trends. Similar results were found in the two ensembles for the simulated *TX* trends, whose distributions do not differ substantially from the observed trends. Nonetheless, even if similar trends are simulated by RCMs and GCMs in the past period, changes projected by the two ensembles in future climate largely differ from each other, as already highlighted in Boé et al. (2020) and in Coppola et al. (2021). Indeed, we also found that CMIP5 GCMs project warmer changes than the Euro-CORDEX ensemble even if both ensembles project a robust increase for all the airports. This disparity between GCMs and RCMs is ascribed to differences in the representation of aerosols within RCMs versus GCMs in Boé et al. (2020), and to differences in the representation of plant physiological effects (Schwingshackl et al. 2019). In Coppola et al. (2021), different cloud cover future evolution in GCMs and RCMs (Bartók et al. 2017) is also mentioned as another possible reason for this. Contrary to what the RCM and the GCM ensembles simulate in the present climate, the upper extremes are projected to experience larger warming than the median in the future. We consider important to investigate the reason for this in further studies.

The smaller warming in RCMs compared to GCMs is an important issue that should be taken into account for future impact assessment with RCM projections. On the one hand, our results from the evaluation of RCMs and GCMs in the present climate do not allow us to conclude that one ensemble is better than the other. On the other hand, concerning future projections, CMIP5 GCMs consider more realistic changes in forcing factors than Euro-CORDEX RCMs (Schwingshackl et al. 2019; Boé et al. 2020). Thus, considering only regional climate projections would lead to an underestimation of the real uncertainty in future climate projections. The design of adaptation and mitigation policies at regional to local scales should not be based solely on RCM future projections. As long as these large discrepancies are not fully explained, we find that both RCM and GCM future projections should be taken into consideration for impact assessment and the development of climate change policies at the airport scale. The mean increase in *TX* extremes across the airports is projected by RCMs (by GCMs, respectively) to be greater than 1.7 °C (2.7 °C) in the next decades by RCMs and GCMs under the severe RCP8.5 scenario, and it could even reach 2.2 °C (3.2 °C) for some airports. By the end of the twenty-first century high-temperatures are projected by RCMs (by GCMs, respectively) to be more than 4.9 °C (7.2 °C) warmer than in recent decades across all the airports, and up to 6.2 °C (8.5 °C) warmer in some cases. MAD airport would be the the location most exposed to extreme heat conditions, as it combines the highest temperature extremes in the present period with a large projected increase in future climate.

We conclude from this study that there is no generally prevailing added value in the state-of-the-art Euro-CORDEX RCMs in the representation of *TX* extremes and of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min/max

◂**Fig. 8** Quantile trends of the *TX* between 1961 and 2005 in JJA for the EOBS 01deg observational dataset (black) and for the Euro-CORDEX Historical ensemble (blue) and the forcing CMIP5 GCM (weighted) sub-ensemble (green). Error bars represent the 95% confidence interval for the observed trends. Colored solid lines represent the MME mean of each experiment, and shading corresponds to the interval between minimum and maximum values found for each of the two ensembles

their temporal trends at the airport scale, despite their higher spatial resolution. As highlighted in Vautard et al. (2013) and Sørland et al. (2018), physical parametrizations would also play a major role, which encourages the implementation of more realistic parametrizations at the regional scale in RCMs. Urban areas are generally represented in Euro-CORDEX RCMs as rock covers with high roughness length, high albedo and low water storage capacities (Langendijk et al. 2019). Recent studies have achieved better results by implementing more realistic parametrizations and also modelling some mesoscale processes. In Daniel et al. (2019) more accurate results for near-surface temperature are obtained by considering a more detailed description of the materials and of the topography of urban areas for the Parisian region. This leads not only to a better representation of the local temperature in the city, but also of the city interactions with its surroundings, in particular, the Urban Heat Island effect. For the study of local high-temperatures at the airport scale, the characterization of the airport as a city as in Daniel et al. (2019), as well as the nearby cities which can influence the temperature at the airport could play an important role. Also, in Nabat et al. (2020), a better representation of near-surface temperatures in the Euro-Mediterranean region is attained by considering aerosols transport and enlarging the set of aerosol types taken into account. This highlights that improvements can be made in high resolution RCMs, and further effort needs to be done in this direction. Moreover, concerning precipitation extremes, Caillaud et al. (2021) show the added value of finer-resolution RCM in the representation of heavy rainfall events when combined with explicitly resolved deep convection and proper parametrizations of mesoscale processes. This new generation of Convection-Permitting RCMs could also bring a better representation of the 2-m near-surface air temperature (Lucas-Picher et al. 2021).

The impact of climate change on aviation is an emergent field of research. We find that our analysis of climate information presents some improvements with respect to the impact studies carried out so far at the airport scale:

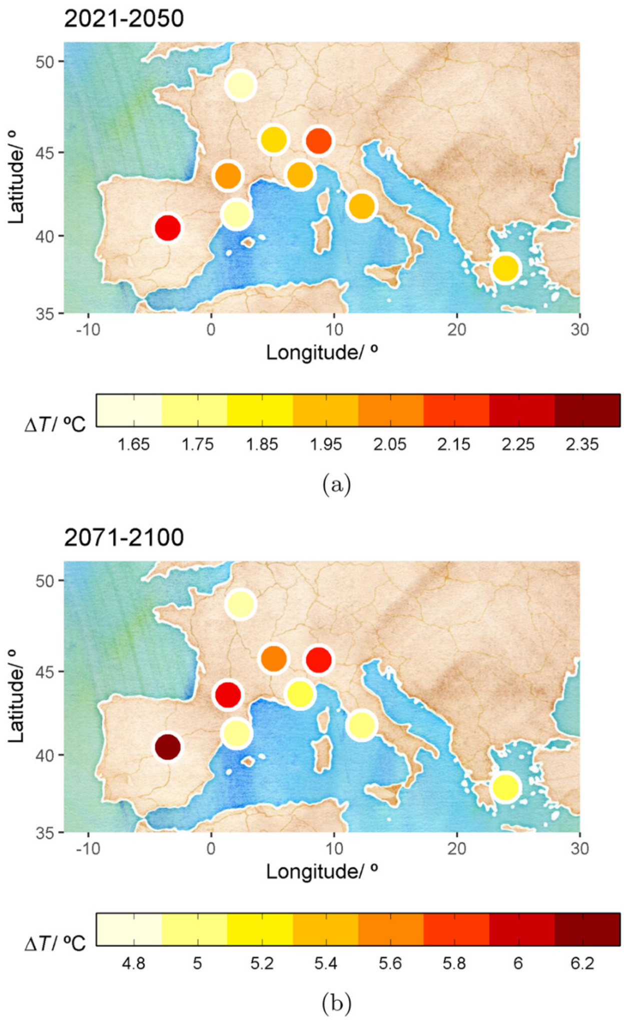

Fig. 9 Projected changes in the 95th percentile of the summer *TX* over MAD, TLS, ORY, BCN, NCE, FCO, ATH, LYS and MXP airports, computed as the difference between the periods 2021–2050 and 1961–2005 (**a**), and between the periods 2071–2100 and 1961–2005 (**b**), simulated by the Euro-CORDEX MME mean for the RCP8.5 scenario

- the intercomparison of different observational datasets before evaluating climate model performances, to further assess future projections,
- the evaluation of trends using quantile regression,
- the consideration of both multi-GCM and multi-RCM ensembles of future climate projections over the airports.

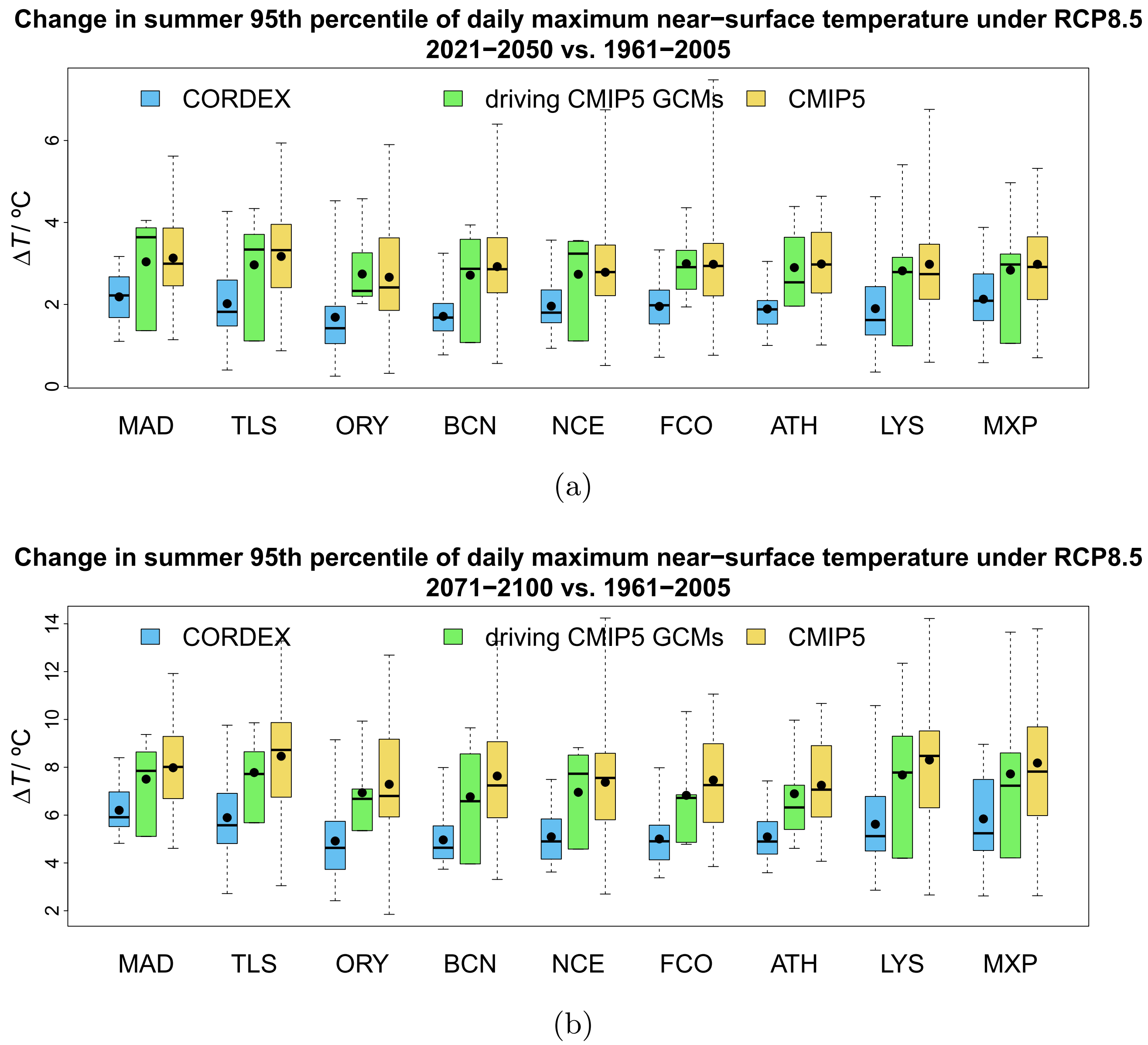

Fig. 10 Projected changes in the 95th percentile of the summer *TX* between 2021–2050 and 1961–2005 (**a**), and between 2071–2100 and 1961–2005 (**b**), over the nine airports simulated by the Euro-CORDEX (blue), the driving GCMs (green) and the CMIP5 (yellow) RCP8.5 experiment ensembles. The boxes are delimited by the first and third quartiles, with the median the segment in between, and points indicating the MME mean. The lower (upper) whiskers correspond to the minimum (maximum) values of the distribution in each case

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Figures were produced using R, in particular, maps were generated with the 'ggmap' package (Kahle and Wickham 2013). Special thanks to S. Somot for constructive discussions on this study, and to J. A. García-Valero and R. Baró for their help in inventorying the state-of-the-art observational datasets. We are also grateful to S. Bonnet for the instructive discussions on aircraft performances. Finally, we would like to thank the reviewers for their constructive comments and suggestions, which have served to improve the manuscript.

Author contributions ES and ER conceptualized the study. VG performed the analyses and prepared the manuscript. All authors participated in the discussion and revised the manuscript.

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Data availability CMIP5 and CORDEX multimodel datasets are publicly available via the website of Earth System Grid Federation (http://pcmdi9.llnl.gov/). E-OBS dataset was accessed from https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php. NOAA Global Historical Climatology Network Daily (GHCN-Daily) data can be downloaded from https://registry.opendata.aws/noaa-ghcn. The Spain02 v5 dataset is available at http://www.meteo.unican.es/datasets/spain02). The SAFRAN-France reanalysis data were provided by Météo-France under request.

Declarations

Conflict of interest We declare that we have no conflict of interest.

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2.3 ADDITIONAL ANALYSES

It has been shown in the previous section that climate models present biases in simulating the magnitude of high-temperature extremes at the airport scale. As discussed in [Gallardo 23], recent studies give hints for improving the representation of temperature extremes in regional models. It has been suggested that a more detailed modelling of cities (including airports), a better consideration of aerosols and their transport, or the simulation of deep convection would contribute to a better representation of climate extremes from the regional to local scales. The analysis in Section 2.3.1 complements the previous section and aims to identify the best-performing RCM amongst the Euro-CORDEX ensemble.

Model biases must be corrected before addressing the second sub-objective of the thesis in the next chapter, which concerns the assessment of the future impact of increasing high-temperature extremes on aircraft takeoff. Section 2.3.2 presents the bias-correction method used to estimate the magnitude of high-temperature extremes in future climate in order to further assess the impacts in Chapter 3. It presents the resulting magnitude for these events over the selected airports as well. These data will be used in the following chapter as input to an engineering software to study the behavior of the engine under such future temperatures, and an empirical law will be applied also to these data to estimate the MTOW of the aircraft.

2.3.1 Simulation of high temperatures at the airport scale: performance skill of climate models

As explained above, the main goal of this section is to identify the best-performing Euro-CORDEX RCMs for the representation of high temperatures and their trends in the observational period. To this end, the RCMs skill is assessed in terms of the magnitude and trends of the TX summer 50^{th} and 95^{th} percentiles ($TX50p$ and $TX95p$ hereinafter) using the Euro-CORDEX Evaluation experiment. The bias is considered as the difference between the model estimates and the observations in each case.

Figure 2.1 and Figure 2.2 show the absolute value of the bias in $TX50p$ and $TX95p$ in summer, and in their quantile trends, respectively. The best-performing RCM in terms of the magnitude of the $TX95p$, regardless of the airport location, is the KNMI-RACMO22E. It is also the best-performing, after the SMHI-RCA4, in terms of the magnitude of $TX50p$. At the same time, the KNMI-RACMO22E is one of the worst-performing models concerning trends, in particular, it is the worst with regards to the trend in $TX95p$ (Figure 2.2). In addition, the worst performing models concerning the magnitude of TX percentiles are not necessarily the worst performing models concerning their trends. The ICTP-RegCM4-6 is the best-performing model for simulating the observed trends. These results show that there is not a link between the skill in simulating the magnitude of high temperatures and the skill in simulating their trends in the observational period. This suggests that the representation of the magnitude of high temperatures could be driven by different features than the modelling of their trends. The characterization of urban areas could be determinant for the representation of the magnitude of extreme values, for instance, as well as including a more complete representation of the aerosol species. As highlighted in [Boé 20], including the evolution of aerosol concentrations plays a major role in trends and changes in surface temperatures. Considering the evolution in land use could be a key feature for improving the representation of trends as well.

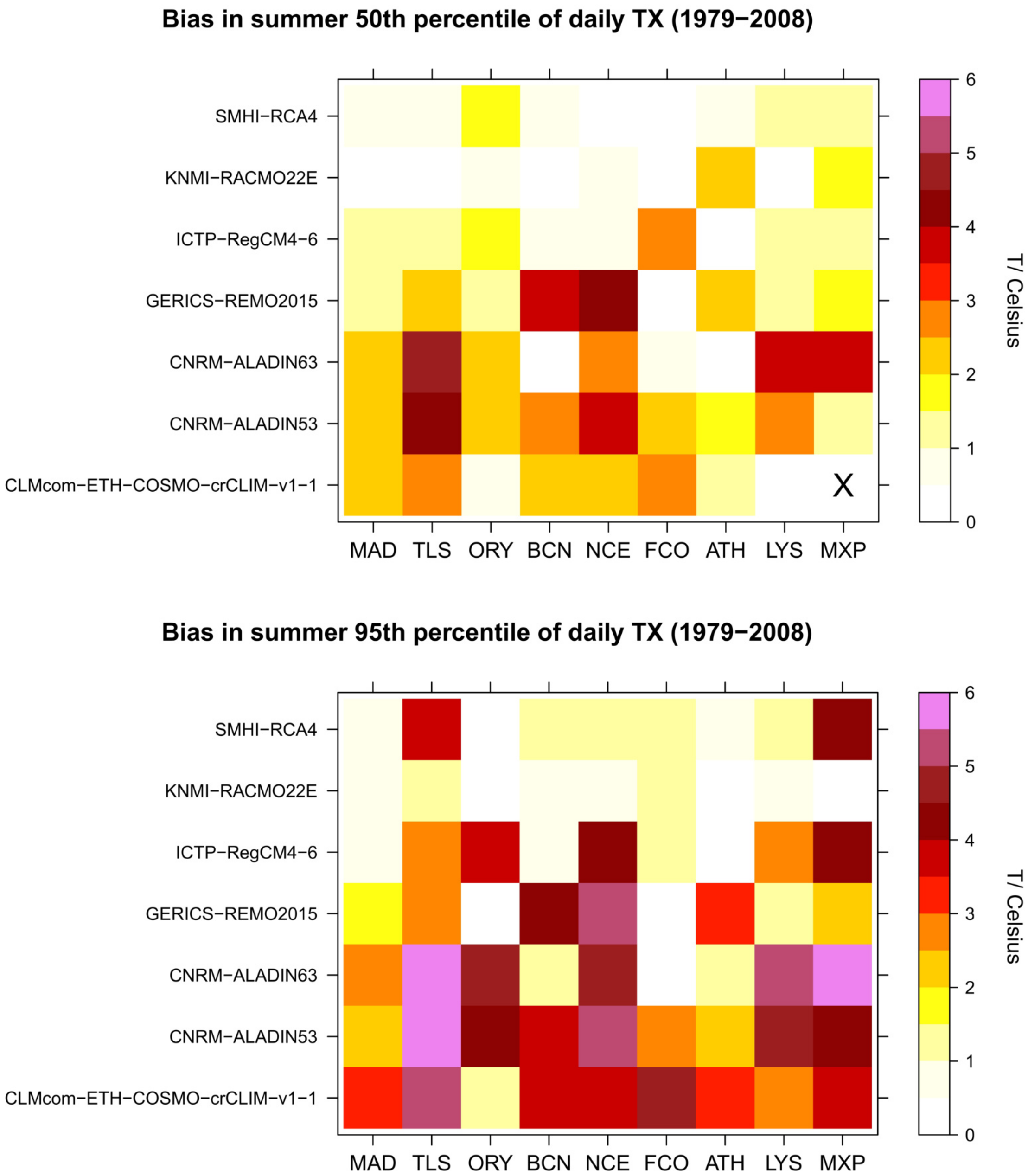

Figure 2.1: Absolute value of the bias in the summer 50^{th} and 95^{th} percentiles of the daily TX (1979-2008) presented by the Euro-CORDEX RCMs in the Evaluation experiment over the airports. EOBS 01deg is the observational reference. Cross marks where the difference between the simulations and the observations is smaller than the 95% confidence interval for the observed value.

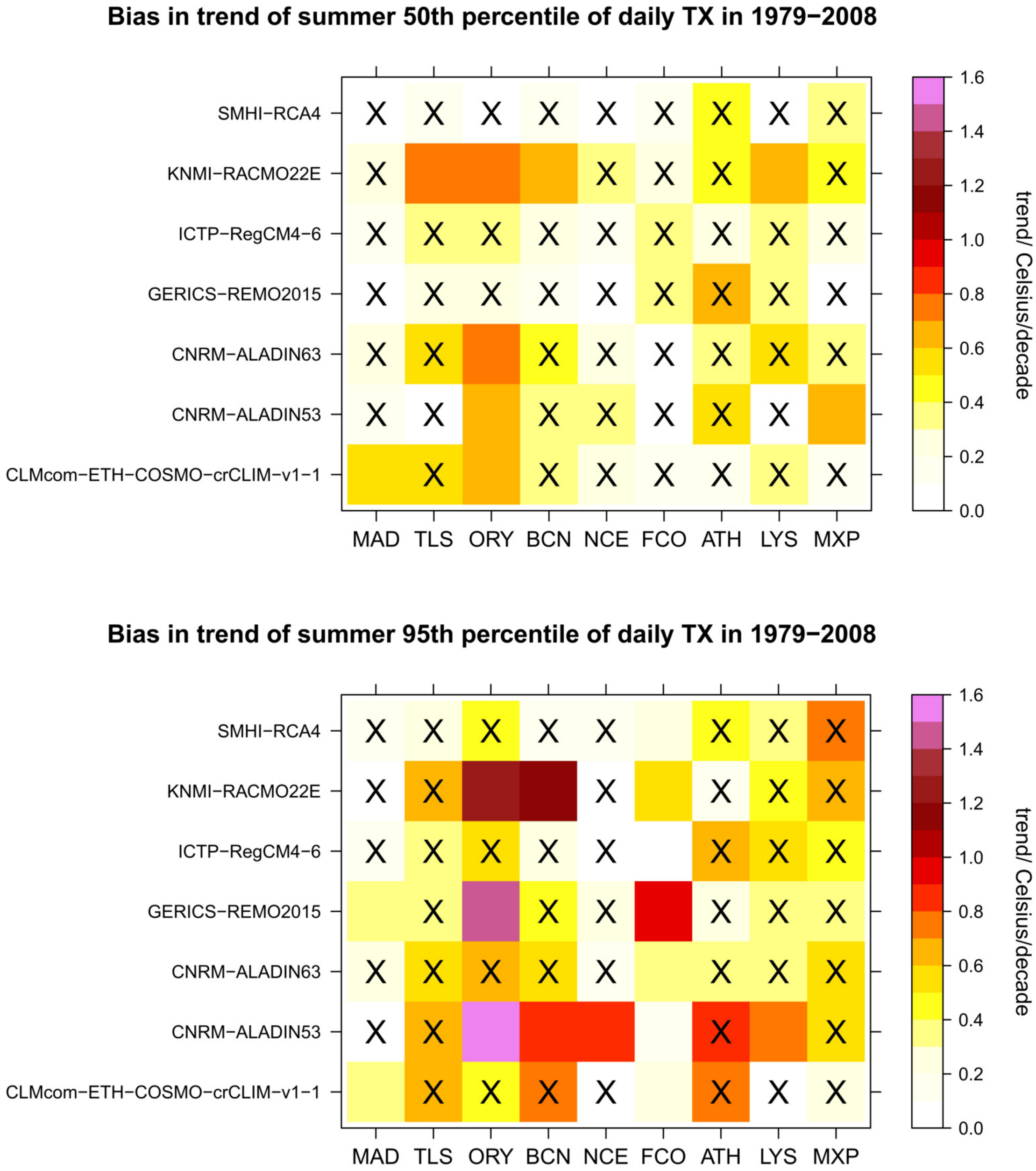

Figure 2.2: Absolute value of the bias in the trend of the summer 50^{th} and 95^{th} percentiles of the daily TX between 1979 and 2008 presented by the Euro-CORDEX RCMs in the Evaluation experiment over the airports. EOBS 01deg is the observational reference. Crosses mark where the difference between the simulations and the observations lays within the 95% Confidence Interval of the observed value.

2.3.2 Extreme events in future climate

Climate models present biases in the simulation of the magnitude of high-temperatures, as shown in [Gallardo 23]. A bias correction is needed before assessing the impacts in future climate in Chapter 3. As the observed trends are within the distribution spanned by the ensemble of simulated trends, we will consider that future climate projections do not need to be bias corrected regarding trends, and therefore regarding changes either. The magnitude of future high-temperatures could thus be simply obtained by adding the observed value estimated in a reference period to the change projected by climate models in a future period with respect to that reference period. This is a variation of the so-called quantile delta mapping (QDM) bias-correction method [Cannon 15], which has been adapted here for correcting the future projected climatology rather than output series from climate models, ignoring the detrending step in the original QDM method. This allows the estimation of the discretized Probability Distribution Function (PDF) for the summer TX in a future 30-year climatological standard period. The main advantage of this method is that it allows us to directly correct the climatology of the summer TX, without assuming its PDF shape, while preserving the projected changes by climate models in all quantiles, as compared to other bias correction methods reviewed in [Casanueva 20]. Figure 2.3 illustrates this method for the case of TLS airport. We apply the bias correction to the discretized PDF of the summer TX (0.1, 0.5, 1.0, 5.0, 10.0, 20.0, 30.0, 40.0, 50.0, 60.0, 70.0, 80.0, 90.0, 95.0, 99.0, 99.5 and 99.9$^{\text{th}}$ percentiles), with a special focus on the 95th percentile, as representative for the upper extremes. These data will be used in the next chapter in order to address the induced impacts. Both Euro-CORDEX and CMIP5 projections are considered in order to better account for climate modelling uncertainty, as explained in [Gallardo 23]. It is worth noting that for the impact evaluation, the whole set of available simulations from the two ensembles are used, while for the added value

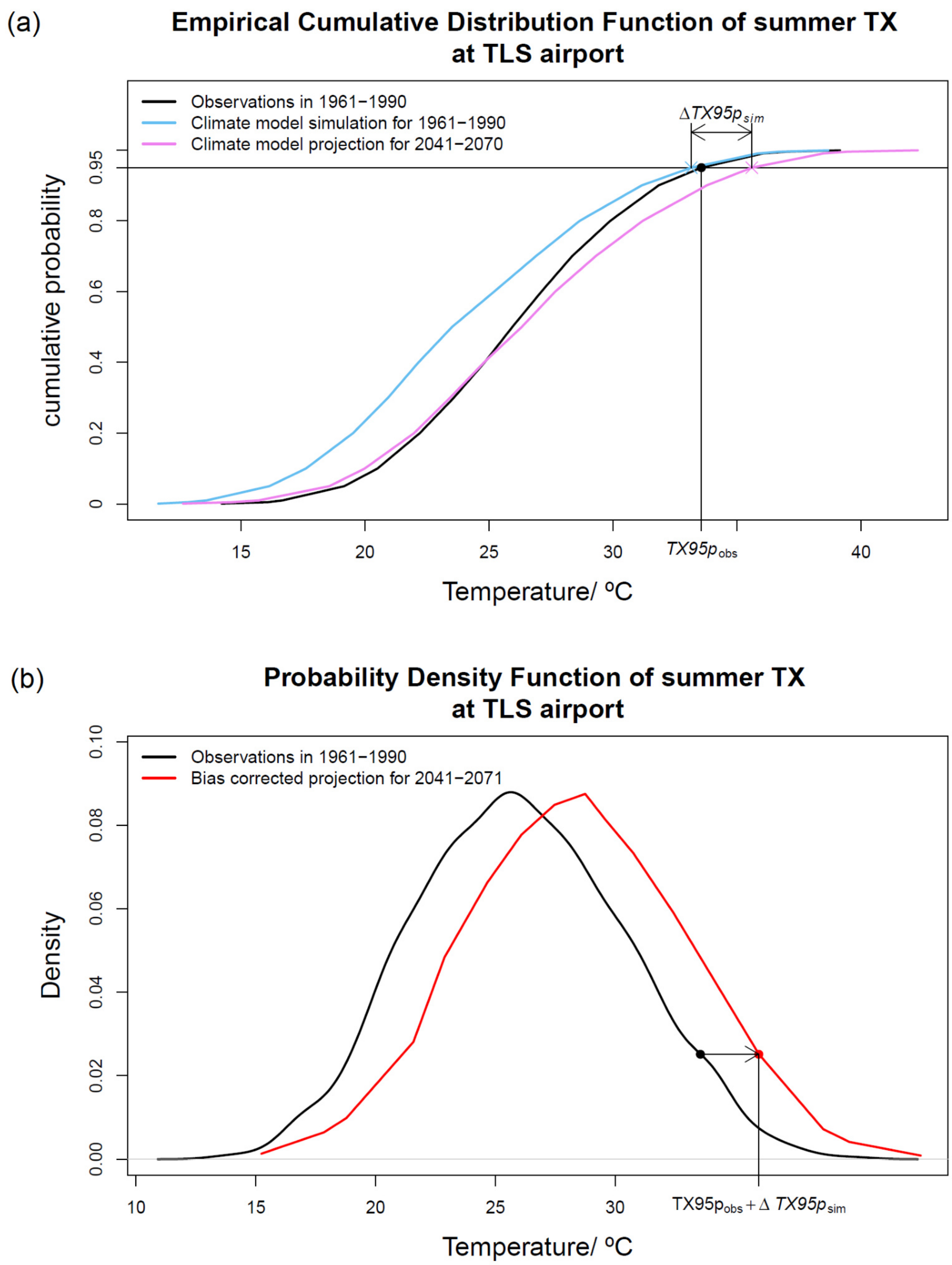

Figure 2.3: (a) Empirical cumulative distribution function of the summer TX at TLS airport. Observations in the reference period 1961-1990 are in black, the historical climate model simulation for 1961-1990 is in blue and the future climate model projection for 2041-2070 is in violet. (b) Bias-corrected projected PDF for 2041-2071 (red), built from the observed PDF in the reference period (black) and the projected future changes simulated by the climate model.

assessment of RCMs over GCMs, only the pairs of driving GCM with the driven RCM simulations were considered.

We have chosen 1961-1990 as the reference period. Both Euro-CORDEX and CMIP5 Historical runs cover this period, and observations are available. We have considered the future periods 2021-2050 (near term) and 2041-2070 (mid-term) for the further evaluation of climate impacts in Chapter 3. By the near term, only the RCP8.5 scenario was explored since the other scenarios project changes that lay within the range of changes projected by the RCP8.5 simulations [Gallardo 23] (Supplementary Fig. 3a). In addition, there are more available simulations for this scenario than for the others. By the long term, the simulations from the Euro-CORDEX RCP2.6, 4.5 and 8.5 experiments were considered, and those available from the CMIP5 RCP4.5 and 8.5 experiments.

Figure 2.4 and Figure 2.5 show the change in the magnitude of the upper TX percentiles observed in recent decades and projected by the near and medium term, respectively, under the severe scenario. Future changes projected by climate models are likely too weak. The mean changes projected by the RCMs ensemble for the near term with respect to 1961-1990, generally equate the changes observed in the last 30 years. This is the case for TLS, ORY, BCN, NCE, LYS and MXP airports. Even in the mid-term, and under the severe scenario, the RCMs ensemble projects changes which compare, on average, to the observed changes in the past 30 years at ORY, BCN and NCE. Only at FCO slight changes are observed, while the climate models do project important variations in the future. The GCMs ensemble also probably underestimates the projected future changes. For this reason, the impact assessment in next chapter will be carried out considering only the most severe climate change scenario RCP8.5.

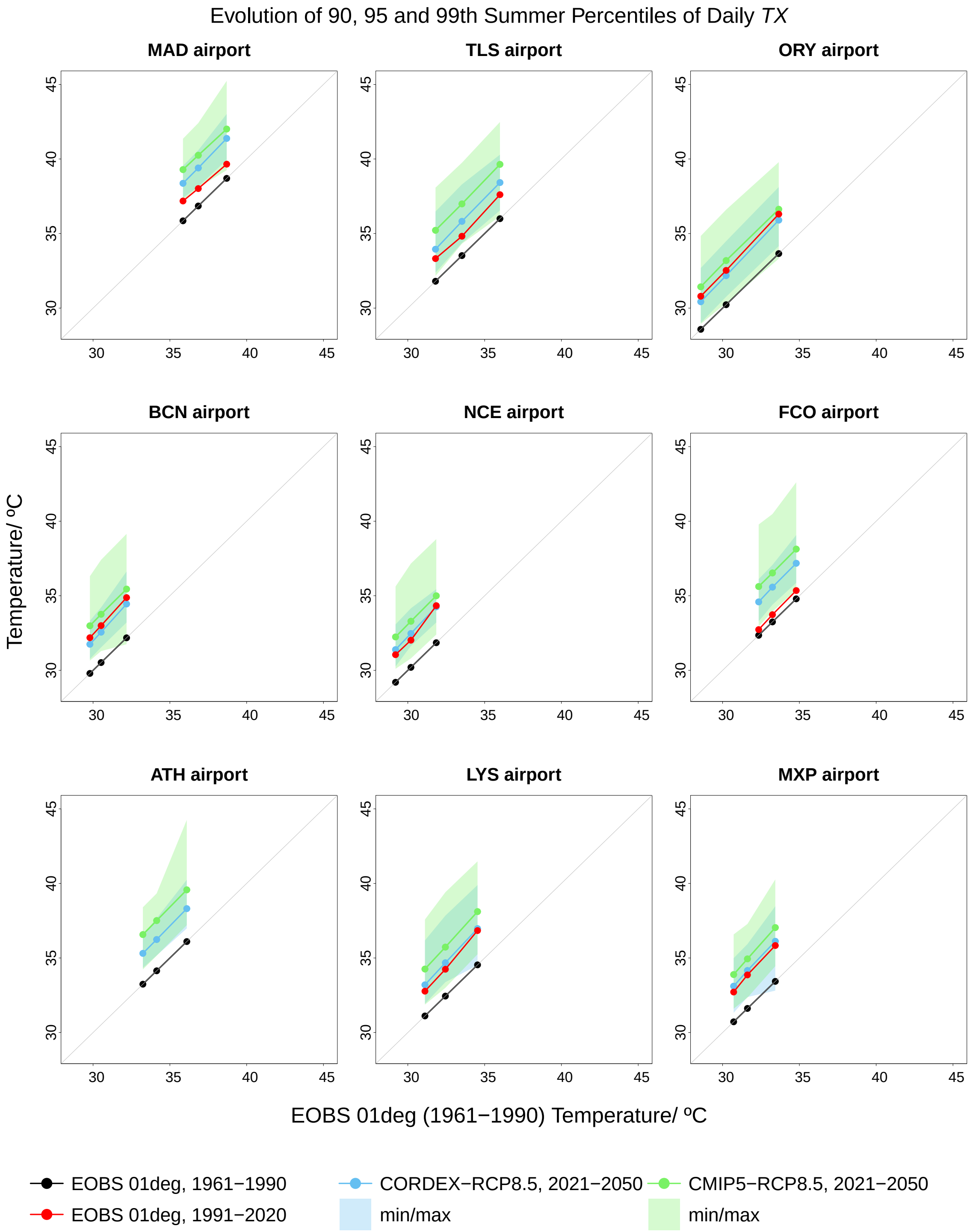

Figure 2.4: Magnitudes of the upper percentiles of the summer TX observed in 1961-1990 (black) and in 1991-2020 (red), and that projected by the Euro-CORDEX (blue) and CMIP5 (green) ensembles under the RCP8.5 scenario by 2021-2050. They are all plotted versus the observed values in the reference period 1961-1990. For ATH there was not enough data available in 1991-2020 for computing the seasonal percentiles. Colored solid lines represent the MME mean of each model experiment, and shading corresponds to the interval between minimum and maximum values found for each of the two ensembles.

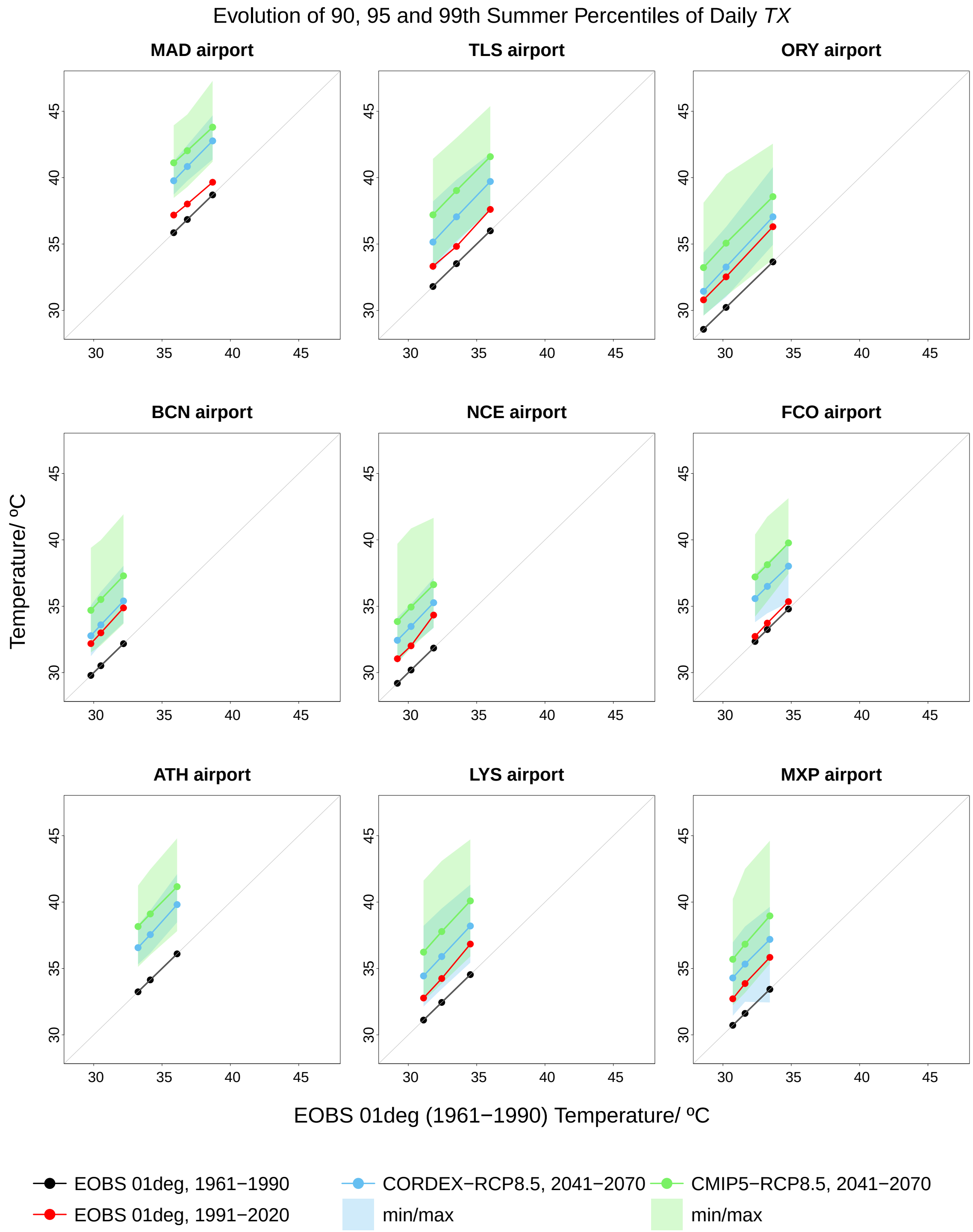

Figure 2.5: Magnitudes of the upper percentiles of the summer TX observed in 1961-1990 (black) and in 1991-2020 (red), and those projected by the Euro-CORDEX (blue) and CMIP5 (green) ensembles under the RCP8.5 scenario by 2041-2070. They are all plotted versus the observed values in the reference period 1961-1990. For ATH there was not enough data available in 1991-2020 for computing the seasonal percentiles. Colored solid lines represent the MME mean of each model experiment, and shading corresponds to the interval between minimum and maximum values found for each of the two ensembles.

It was shown in [Chen 20] that the CMIP5 RCP scenarios generally project lower warming in the temperature extremes than the new CMIP6 SSP experiments. A recent study by [Ribes 22] showed that the CMIP6 simulations project a greater warming in the mean summer temperature over Metropolitan France when constrained to the observations at the regional scale. They also highlighted the unrealistic small warming of mean summer temperatures projected by the Euro-CORDEX ensemble. Although they focused on Metropolitan France, they suggest that their results could be representative for a wider domain, in particular, for Western Europe. All of these findings suggest that the impacts on takeoff performance induced by the future increase in high temperatures as projected by the Euro-CORDEX and CMIP5 ensembles, which will be addressed in the following chapter, could be underestimated.

CHAPTER 3

Impacts on aircraft takeoff performance

In Chapter 2, climate model simulations to study future high-temperature extremes over the selected airports were evaluated, and the magnitude of future high-temperature extremes was characterized. In this chapter, the impact of the future projected high-temperature extremes on aircraft takeoff performance is evaluated, in terms of pollutant emissions by the aircraft engine in Section 3.2 and on the MTOW limitations in Section 3.3. Both sections are presented in draft manuscript form, and each section includes an abstract in French. They are preceded by a brief description of the physical mechanisms explaining how the temperature affects the aircraft and engine performances in Section 3.1.

3.1 THE EFFECTS OF HIGH TEMPERATURES ON AIRCRAFT TAKEOFF PERFORMANCE

The takeoff is one of the most critical phases of the flight, where the aircraft's engine needs to work at nearly its maximum power. High temperatures may impact the takeoff performance in several ways. In this section, the effects on aircraft lift, engine performance and pollutant emissions are described.

The lift is one of the four forces acting on an airplane, along with the weight, the thrust and the drag (see Figure 3.1). The lift force is the result of a difference in the pressure exerted on the aircraft, which is achieved by the airfoil shape of the wings, primarily. The wings speed-up the airflow along the top surface, resulting in lower pressures in this area by conservation of energy (Bernoulli's principle, see Figure 3.2). Lift is also achieved in part by the inclination of the aircraft with respect to the incoming airflow, that is, by the so-called angle of attack (see Figure 3.3). The inclination also changes the local velocity of the airflow, resulting in lower pressures on the top surface of the aircraft, as shown in Figure 3.3.

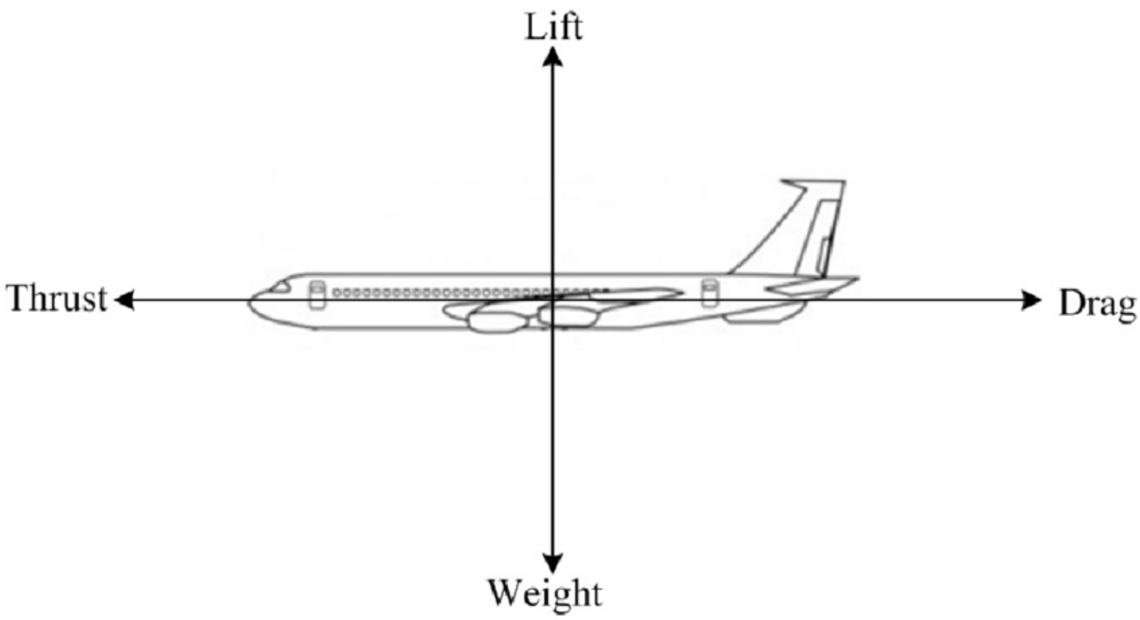

Figure 3.1: The four forces acting on an airplane. From [Murrieta Mendoza 13].

The lift force depends on the mass airflow rate, which depends on the air density, that is inversely proportional to the air temperature. Therefore, the warmer the ambient temperature, the lower the density of the air, resulting in lower lift. This hampers the aircraft's capacity to lift weight. Higher speeds would be required under warmer conditions at the airport in order to takeoff the same weight. As a consequence, longer takeoff distances would be covered. Depending on the technical or safety operating limits of the aircraft, and/or on the runway length, the takeoff could not be performed, and it would be then necessary to lighten the aircraft or change of runway, re-schedule the flight or cancel it.

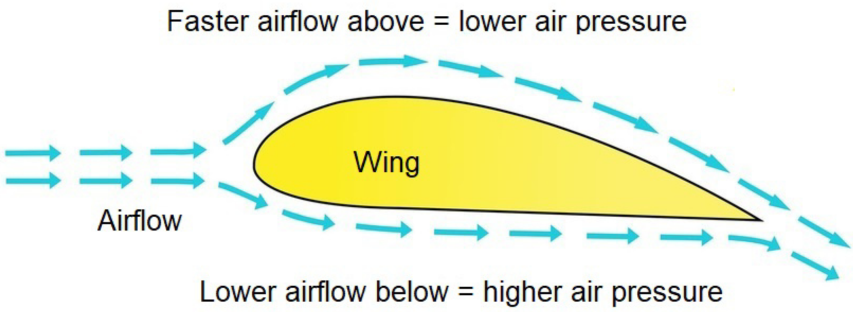

Figure 3.2: Diagram of the lift generation by the aircraft wings. Rights: The University of Waikato Te Whare Wānanga o Waikato.

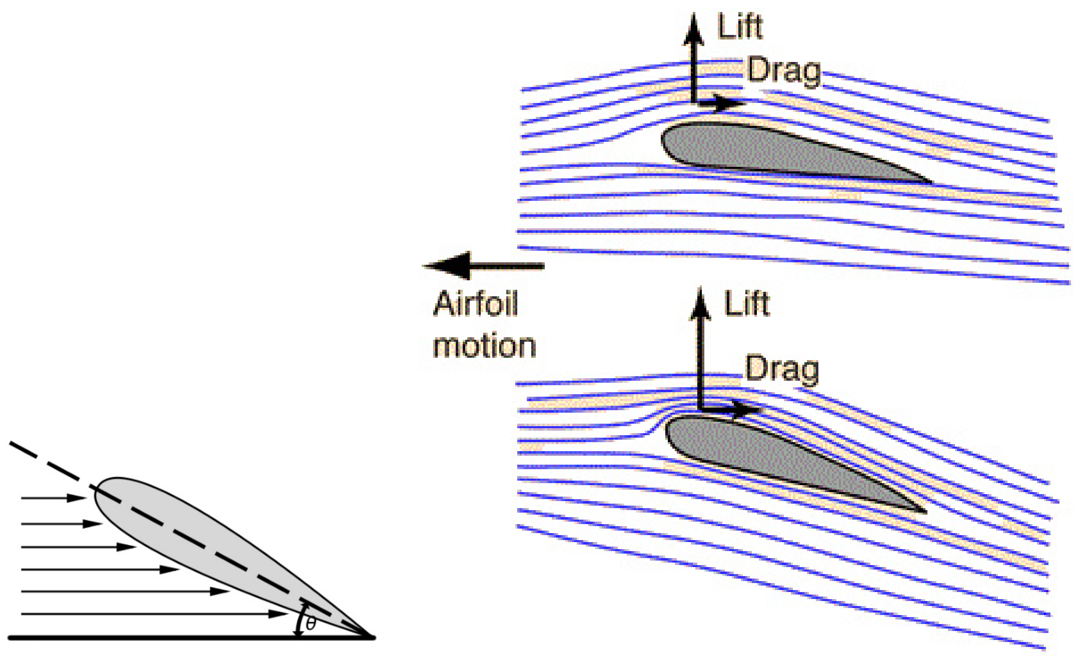

Figure 3.3: Angle of attack (left) and illustration of the lift generation by the inclination of the aircraft (right). Sources: Christopher S. Baird; http://hyperphysics.phy-astr.gsu.edu/hbase/pber.html.

The thrust force that pushes the airplane forward is also negatively affected by high temperatures. Thrust is the reaction force to the acceleration of a mass of a working fluid in the opposite direction by a propulsion system. The greater the mass of the incoming flow, the larger the thrust generated. In an airplane, the engine intakes ambient air and accelerates it backwards by combining a fan and a jet propulsion principle. A significant part of the incoming air is accelerated by the engine's front fan and passes around the engine core (compressor-combustor-turbine), or bypasses it, leaving the engine through a slightly greater section than the entrance, which contributes to further accelerating the air (by conservation of momentum). The other part of the intake air passes through the core and is first compressed, then heated from fuel combustion at nearly constant pressure, and finally expanded and exhausted through the turbine and the nozzle, respectively. This thermodynamical cycle is called the Brayton cycle, and it extracts the energy from the fuel to produce mechanical work that is used to generate thrust, as well as to drive the compressor through the axial rotor. A diagram of an aeronautical engine is presented in Figure 3.4, as well as the temperature and pressure stages along the engine's cycle.

The magnitude of the thrust depends on the incoming mass airflow rate as for the lift, with higher ambient temperatures resulting in lower thrust too. Therefore, a further limitation on the aircraft's maximum carrying capacity from reduced thrust is expected in addition to that from decreased lifting capacity. The lower lift and engine thrust also result in lower climb rates at takeoff, that is, the height gained by horizontal distance traveled. This may be problematic for obstacle clearance, specially concerning large size aircrafts.

Moreover, lower engine efficiency is expected under hotter ambient conditions, since more work needs to be done by the engine to compress the sparser molecules of warmer air, in addition to the lower thermal efficiency of the thermodynamic cycle. All of this would result in lower fuel efficiency and increased fuel consumption, with a consequent increase of the absolute pollutant emissions by the engine.

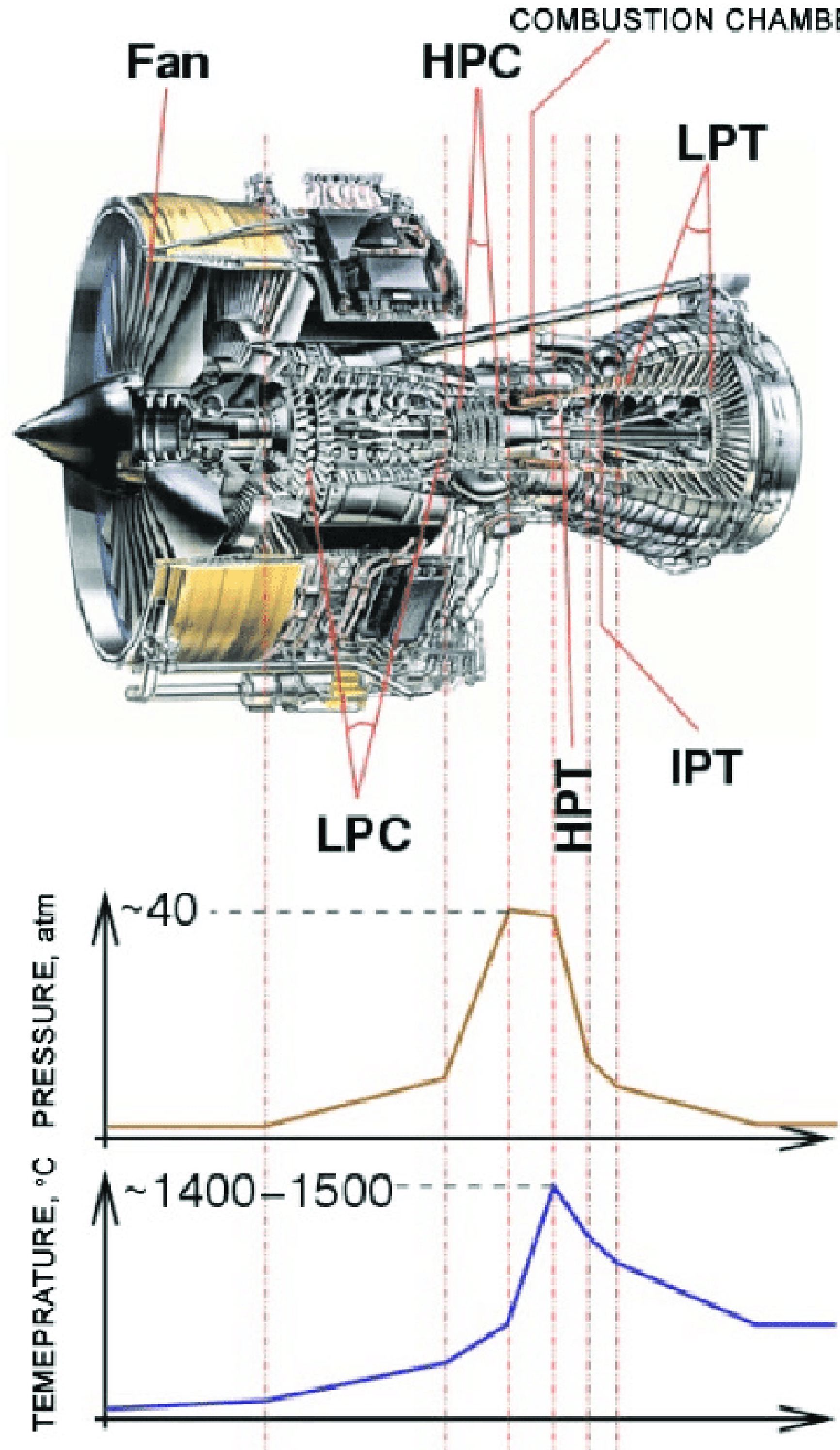

Figure 3.4: Aeronautical engine and its components: the fan, the Low and High Pressure Compressors (LPC and HPC), the combustor and the High and the Low Pressure Turbines (HPT and LPT). From: [Sińczak 10].

As aforementioned, the energy to accelerate the incoming airflow comes in part from the energy of the fuel (liquid hydrocarbons such as kerosene) released by combustion in the engine's combustion chamber, also called the combustor. A part of the incoming ambient air enters the combustor, where the fuel is injected and the combustion process takes place. When the fuel's chemical energy is released, the temperature of the mixture increases at nearly constant pressure, with the extinction of the reactants and the production of new chemical species (burnt gases), such as the NO_x. Figure 3.5 presents a simplified scheme of a combustion chamber in a typical turbofan aeronautical engine.

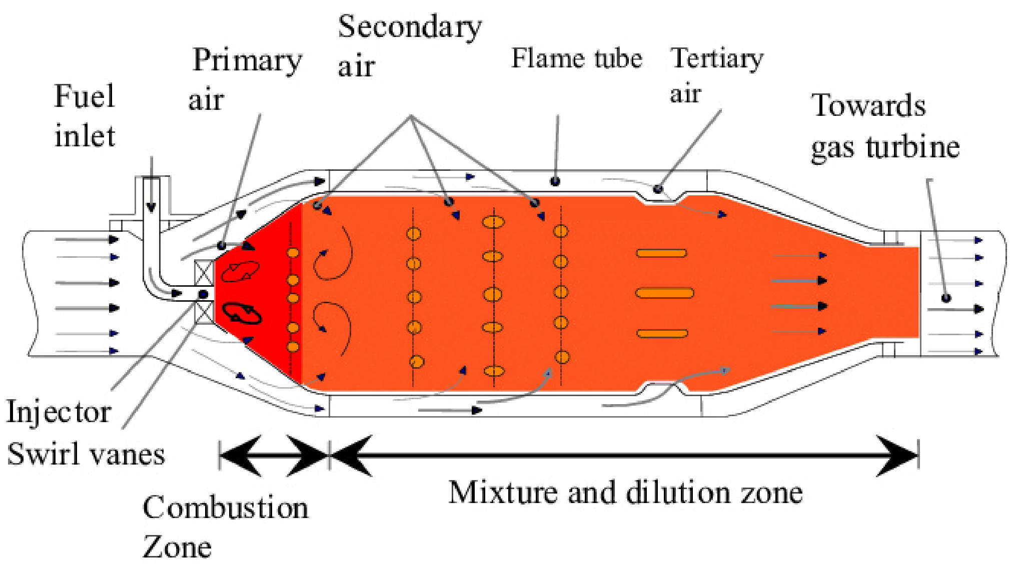

Figure 3.5: Scheme of a combustion chamber inside an aeronautical engine. Source: [Martínez 11].

Above a sufficiently high temperature, NO_x are produced by the thermal mechanism, that is highly dependent on the flame temperature, which in turn depends on the ambient intake air temperature. During extreme heat events, the levels of NO_x emissions will be maximum, regarding the effect of temperature, and as well as the impact on lift, thrust and engine performance.

The temperature of the flame is not the only responsible for NO_x formation.

The structure of the flame and the air-fuel mixture composition plays also a role. There are two main canonical flame configurations to apprehend the very complex structure that the flame exhibits in practice: the premixed flame and the diffusion flame. They are both illustrated in Figure 3. In the first case, the fuel is already mixed with the oxidizer (the air) before the entering the chamber. On the other hand, the diffusion flame corresponds to a situation where the oxidizer and the fuel are injected separately into the combustion chamber, and they progressively mix together. In this configuration, the mixture fraction depends on the zone of the domain.

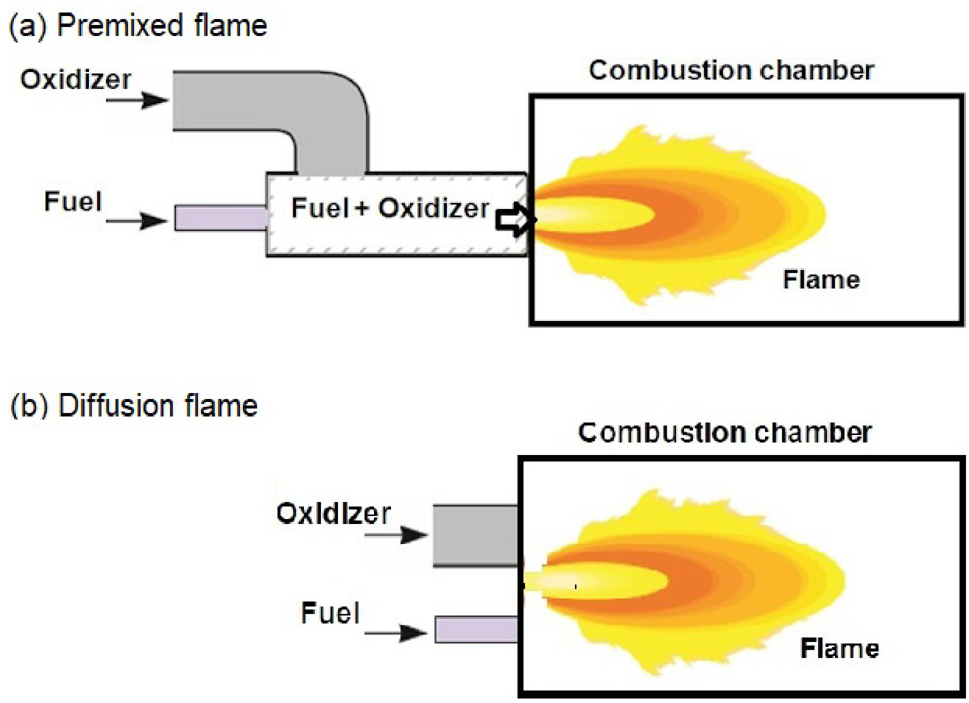

Figure 3.6: Configuration of premixed flames (a) and diffusion flames (b). https://cfdflowengineering.com/cfd-modeling-of-turbulent-combustion/.

Combustion is a complex process involving chemical kinetics, thermodynamics, energy transfer and mass transport. In addition, turbulence is present is most cases. It is possible to solve numerically what happens inside the combustion chamber using 3D Computational Fluid Dynamics methods. There also exist models for solving the chemical kinetics. However, the computational cost of these methods is high. A more global approach to the system of the engine, less costly is needed. The so-called 0D/1D system simulations fulfill this function. They are based on phenomenological models parametrized using experimental data, and they have a low computational cost associated.

3.2 IMPACT OF CLIMATE CHANGE ON AVIATION POLLUTANT EMISSIONS

3.2.1 Résumé

Les émissions de l'aviation ont un impact sur le système climatique, avec un effet radiatif positif net (réchauffement), et contribuent au changement climatique. L'objectif ici est d'évaluer, en retour, l'impact du changement climatique sur les émissions de l'aviation. En effet, la quantité de NO_x émise par kg de carburant consommé par le moteur de l'avion, qui peut être caractérisée par l'indice des émissions de NO_x (EI_{NO_x}), est connue pour augmenter lorsque la température de l'air est plus élevée. Dans cette étude, l'impact sur les émissions de NO_x des changements dans la magnitude des extrêmes de haute températures dans la saison estivale est évalué pour une liste d'aéroports principaux sélectionnés dans la région Euro-Méditerranéenne. Des observations et des projections climatiques futures issues des RCMs et GCMs sont utilisées pour analyser le changement de la magnitude de ces événements au cours des périodes 1961-1990, 1991-2020, 2021-2050 et 2041-2070 sous le scénario le plus sévère de changement climatique RCP8.5 de CMIP5. Les données climatiques sont utilisées comme conditions d'entrée pour un outil type métier de la turbomachinerie pour le calcul des paramètres qui caractérisent la performance des moteurs (Gasturb). Cet outil permet d'estimer entre autres les émissions de NO_x pendant les événements extrêmes. Pour la période récente 1991-

2020, les résultats montrent une augmentation des niveaux d'émissions de NO_x comprise entre +0.5 % et +2.7 % par rapport à la période de référence 1961-1990. D'ici 2021-2050, une augmentation relative comprise entre +2.2 % et +3.9 % est trouvée sur les aéroports, d'après les moyennes multi-modèles des RCMs et des GCMs, et entre +3.3 % et +5.9 % d'ici 2041-2070. La banque de données de l'ICAO inventorie les émissions de gaz d'échappement des moteurs d'avion, fournies par les fabricants. D'après cette base de données, l'EI_{NO_x} au décollage pour le modèle de moteur CFM56-5B3/3 équipant les avions de taille moyenne comme l'Airbus A320, est de 30.9 g/kg, et le débit de carburant au décollage est de 1.462 kg/s. Par conséquent, une augmentation relative de l'EI_{NO_x} comprise entre 2.2% et 5.9% entraînerait une augmentation des émissions de NO_x comprise entre 34 g et 93 g au décollage par vol, en considérant que la performance du décollage dure environ 35 secondes. Par exemple, si l'aéroport effectue environ 20 départs de vol par heure, cela pourrait conduire à une augmentation de +0.7 kg à presque +2 kg lors des épisodes extrêmes de hautes températures en été. Cela pourrait conduire à une augmentation des émissions absolues de NO_x provenantes de l'aviation, ce qui forcerait d'avantage le système climatique et pourrait détériorer la qualité de l'air à l'aéroports et aux alentours.

3.2.2 Manuscript (draft)

Abstract. Aviation emissions, both gaseous and particulate, impact the climate system, with a net positive radiative effect (warming), and contribute to climate change. The objective is to evaluate, in turn, the impact of climate change on aviation emissions. In particular, the amount of NO_x emitted per kg of fuel burnt by the aircraft engine, which can be characterized by the NO_x Emission Index (EI_{NO_x}) is expected to increase under warmer ambient temperatures. In this study, the change in NO_x emissions induced by changes in high-temperature extremes is assessed over a list of major airports selected in the Euro-Mediterranean region. The daily maximum near-surface air temperature (TX) extremes in summer is considered. Observations and future climate projections performed with both Regional and Global Climate Models (RCMs and GCMs) are used to estimate the change in the magnitude of these events through the periods 1961-1990, 1991-2020, 2021-2050 and 2041-2070 under the most severe scenario of climate change RCP8.5, from the previous CMIP Phase 5. Climate data are used as input conditions to the software engineering tool Gasturb for engine performances computation. Gasturb allows the estimation of the NO_x emissions during TX extreme events. Results show an increase in the levels of NO_x emissions of between +0.5% and +2.7% by 1991-2020, relative to the reference period 1961-1990. By 2021-2050, a relative increase of between +2.2% and +3.9% is found at the airports, across the RCM and GCM Multi-Model Ensemble means, and of between +3.3% and +5.9% by 2041-2070. These relative increases may lead to a substantial growth in absolute NO_x emissions from aviation, which would further force the climate system and potentially worsen the air quality at the airports and their surroundings.

Keywords : high temperatures, extreme events, airports, aircraft engine, nitrogen oxides emissions.

3.2.2.1 Introduction

The impacts of aviation on climate and its contribution to climate change have been widely studied. The carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions from fossil fuel combustion in the aircraft engine have a net postive radiative effect on the climate system [Lee 21a]. The CO_2 and NO_x emissions from aviation, together with the condensation trails that form downstream the aircrafts at en-cruise altitudes [Irvine 14], are estimated to have contributed to the anthropogenic climate forcing by 3.5% for the period 2000-2018, with the CO_2 and the non-CO_2 terms accounting for 1/3 and 2/3, respectively, of that contribution [Lee 21a]. Conversely, the impacts of climate change on aviation emissions have been little addressed. The warming of high temperatures at the airports due to climate change [IPCC 13, IPCC 21, Gallardo 23] will negatively impact the aircraft lift at takeoff due to reduced air density, and also the engine thrust [Anderson 05, Coffel 15, Airbus 02]. Higher fuel consumption will be necessary in order to meet the operational requirements, which will result in an increase in the absolute emissions. In addition, the thermal engine efficiency decreases with the outside temperature, resulting in decreased overall engine efficiency, and consequently in increased fuel consumption [Ren 19b, Ren 20]. Besides the increase in the aircraft absolute emissions due to higher fuel consumption under warmer ambient conditions, the amount of pollutants emitted per kg of fuel burnt could also increase, in particular, of NO_x emissions. The amount of NO_x produced per kg of fuel burnt in the combustion process depends on the maximum temperature of the flame inside the combustion chamber of the engine, which in turn depends on the ambient intake-air temperature [Gokulakrishnan 13]. The higher the temperature at the airport, the more NO_x are produced and emitted per kg of fuel burnt by the aircraft engine. During high-temperature extreme events at the airport this emission rate will be maximum. In the context of climate change, these episodes are expected to become more intense [IPCC 13, IPCC 21], leading to more NO_x emitted per kg of fuel, and potentially to increased NO_x absolute emissions during such events. To the best of our knowledge, the impact of climate change on aviation pollutant emissions has not been assessed in these terms yet.

The main goal of this study is to assess the impact of the increase in high-temperature extremes at the airports, on the NO_x emitted by the aircraft engine. To this end, we use climate data as input ambient conditions to the engineering software Gasturb for the computation of engine performances. We consider a list of major airports in the Euro-Mediterranean region, which is an area specially sensitive to climate change, and is particularly affected by the increase in the exposure to extremely high temperatures [IPCC 13, IPCC 21]. The temperature data are issued from climate model experiments performed by Global and Regional Climate Models (GCMs and RCMs) from the CMIP5 [Taylor 12] and Euro-CORDEX [Jacob 14, Jacob 20] international initiatives, respectively. In a previous study, the skill of these models in representing high-temperature extremes was evaluated over the selected airports [Gallardo 23]. Once the climate models have been evaluated, the future changes in the upper extremes of high-temperatures were assessed in [Gallardo 23], as well as their associated uncertainties. We focus on the NO_x emissions per kg of fuel burnt, also referred to as the NO_x Emission Index (EI_{NO_x}). The changes in the EI_{NO_x} relative to a reference period in recent decades are analysed from the changes in the NO_x severity index (sNO_x index), to which the EI_{NO_x} is considered to be directly proportional [GmbH 22]. The changes in the sNO_x index in recent decades are assessed then from climate observations, and future changes in next decades and by mid-century are assessed from climate model projections for the high temperature extremes. To the est of our knowledge, this is the first time that climate model data are used input ambient conditions to an engine emulator to study the impact of global warming on the engine behavior.

The data and methods are presented in Section 3.2.2.2. Results are shown and discussed in Section 3.2.2.3. Finally, conclusions are drawn in Section 3.2.2.4.

3.2.2.2 Data and Methods

Climate data

Nine major airports in the Euro-Mediterranean region are selected as case studies. In particular, we select the same airports considered in [Gallardo 23] for the study of the evolution of high-temperature extremes at the airports scale over this region. They are listed in Table 3.1.

The climate variable we consider is the daily maximum near-surface air temperature (TX) in summer (June, July, August), also as in [Gallardo 23], with a special focus on its 95^{th} percentile ($TX95p$).

Table 3.1: List of airports selected as case studies.

Airport	Name	Country	Elevation/ m
MAD	Madrid-Barajas Adolfo Suárez	Spain	610
TLS	Toulouse-Blagnac	France	152
ORY	Paris-Orly	France	89
BCN	Barcelona-El Prat Josep Tarradellas	Spain	4
NCE	Nice-Côte d'Azur	France	4
FCO	Rome-Fiumicino Leonardo da Vinci	Italy	5
ATH	Athens-Eleftherios Venizelos	Greece	94
LYS	Lyon-Saint Exupéry	France	250
MXP	Milan-Malpensa	Italy	305

The EOBS observational gridded product at 0.1° ($\sim$ 10 km) of horizontal spatial resolution is used as reference dataset (EOBS 01deg) [Haylock 08,Cornes 18]. EOBS 01deg presents the advantage of including data for all the selected locations over other observational datasets [Gallardo 23].

Additionally, future climate projections performed with both Regional and Global Climate Models (RCMs and GCMs) are considered. In particular, the simulations from the multi-RCM Euro-CORDEX-11 ensemble [Jacob 14, Jacob 20] and those from the multi-GCM CMIP5 ensemble [Taylor 12]. The use of the two Multi-Model Ensembles (MMEs) is shown to be necessary in order not to underestimate climate modelling uncertainties in [Gallardo 23]. The simulations from the CORDEX and CMIP5 Historical and RCP8.5 scenario experiments are used (Table 3.2 and Table 3.3, Appendix 1).

Also, [Gallardo 23] show that climate models present biases in the summer $TX95p$ at the airports scale that need to be corrected before the impact assessment. Here, they are corrected using a variation of the quantile delta mapping method [Cannon 15]. The future magnitude of the summer TX percentiles is obtained by adding the changes projected by climate models to the observed values in the reference period 1961-1990, for each model. Figure 3.7 presents the resulting

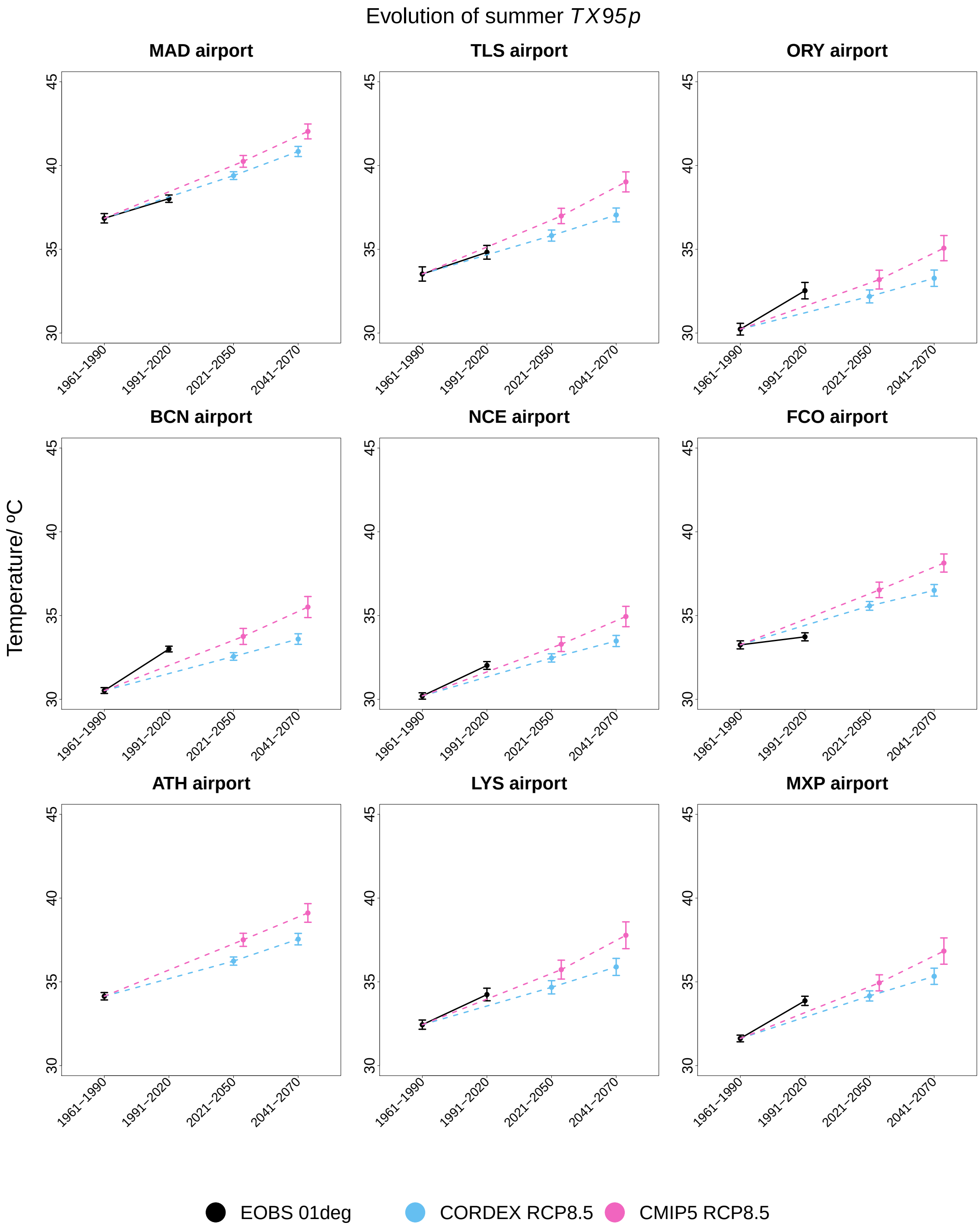

Figure 3.7: Evolution of the summer $TX95p$ through the observational periods 1961-1990 and 1991-2020 according to the EOBS 01deg data set (black), and up to 2021-2050 and 2041-2070, under the severe scenario of climate change RCP8.5, as projected by the bias-corrected CORDEX and CMIP5 ensembles (blue and pink, respectively). Time periods are indicated on the horizontal axis. Error bars indicate the 95% confidence interval in each case.

magnitude for the summer $TX95p$ over the airports in the future periods 2021-2050 and 2041-2050, as projected by the MMEs after the bias correction. It also includes the observed magnitude in 1961-1990 and in 1991-2020. These values will be used as input quantities in the software engineering tool for engine performances computation, as described further below.

As shown in Figure 3.7, the path projected from the future estimates backward to the observational reference period lays below the observed magnitude in 1991-2020 in most cases. Thus, climate models likely underestimate the changes in summer $TX95p$, which would result in the underestimation of the future potential impact. This is in line with previous findings in [Chen 20] and [Ribes 22] showing that CMIP5 scenario experiments project lower warming in temperature extremes than the new CMIP6 scenarios experiments, and suggesting that the latter are likely too conservative regarding the warming of mean summer temperatures, respectively. [Ribes 22] also highlights the unrealistic small warming of mean summer temperatures projected by the Euro-CORDEX ensemble.

Moreover, Figure 3.7 shows the difference between the future magnitudes projected by the RCMs and by the GCMs, with warmer temperatures projected by the latter, which is one of the reasons why the two ensembles should be considered for impact assessment, as discussed in [Gallardo 23].

Engine performances computation

Climate data are used as input to a software engineering tool for engine performances computation. The tool used is Gasturb [Kurzke 07], in particular, its version 14 [GmbH 22]. This is an industrial tool used by turbomachinery engineers and made available to students under license (see Figure 3.8).

Gasturb allows the selection of the engine type and its configuration setting. An engine type consistent with those of the long- and medium-range commercial aircrafts is chosen: the Geared Unmixed Flow Turbofan. A suitable configuration to describe the turbofan engines powering medium-range aircrafts is set. In particular, the parameter values for the CFM56-5B engine configuration within Gasturb presented in [Costa Baptista 17] are used for this study. This engine model is manufactured by CFM International (Safran Aircraft Engines & GE Aviation Partnership), and it is used to power mid-size aircrafts such as the A320.

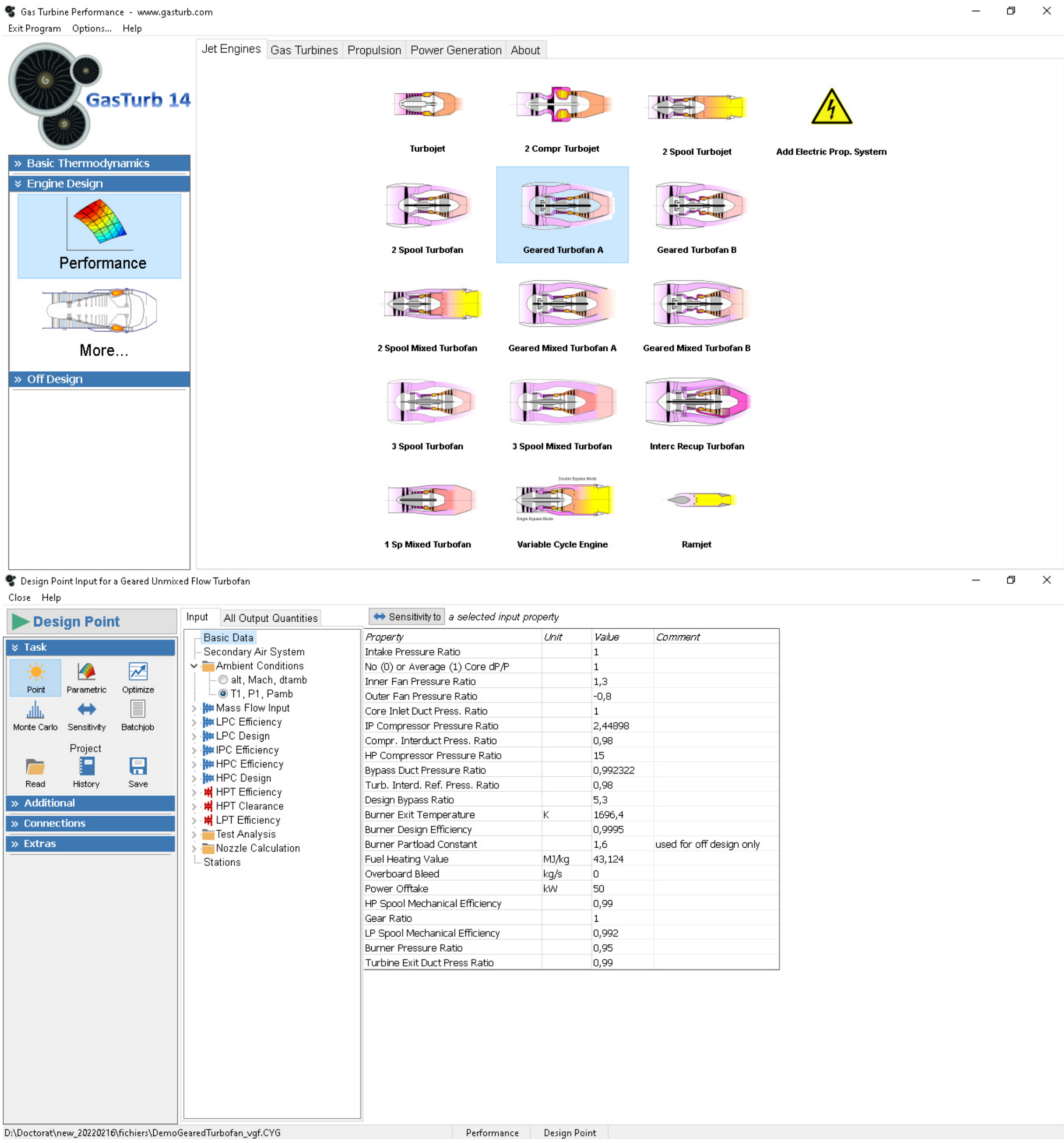

Figure 3.8: Exemple of Gasturb 14 interface.

The ambient conditions (air temperature, atmospheric pressure and relative humidity) are imposed in Gasturb for the performance analysis. We declare the ambient temperature as the observed summer $TX95p$ in the periods of study 1961-1990 and 1991-2020, and the future summer $TX95p$ projected by the climate models by 2021-2050 and 2041-2070, under the severe scenario of climate change RCP8.5 (see Figure 3.7).

The atmospheric pressure and relative humidity are set to be constant throughout the periods. The ambient pressure at the airports is set as the pressure corresponding to the elevation of each airport in an adiabatic atmosphere (Appendix 2, Table 3.4). The ambient relative humidity is set to be a value consistent with the ambient relative humidity in $TX95p$ events. It is declared as the average of the observed[1] mean daily relative humidity of the summer days where the TX is equal to the local summer $TX95p$ in the reference period 1961-1990 at each airport (Appendix 2, Table 3.4).

Once the configuration of the engine is set and the input ambient atmospheric conditions are imposed, the engine performances are computed with Gasturb. This computation within the software relies on semi-empirical approaches, which are based on phenomenological models parametrized using experimental data, used for simulating the engine's global behavior and the pollutant emissions. Although there exist other models that simulate better the complexity of the combustion process inside the engine, such as Large Eddy Simulations (LES) or the Reynolds-Averaged Navier-Stokes (RANS), as compared to the simplified engine system equations, the latter allows us to make the application to the climatic part in an easy, quick and numerically cheap way. For the first approach ever to address this problem, we considered the system equations approach enough.

We focus on the sNO_x index output variable from the Gasturb performance analysis. This indicator of NO_x production is estimated by Gasturb using the following empirical equation provided by the U.S. National Aeronautics and Space

[1] According to EOBS 01deg dataset.

Administration (NASA) [Council 92]:

$$sNO_x = \left(\frac{P_3}{2965\text{kPa}}\right)^{0.4} \cdot e^{\left(\frac{T_3 - 826\text{K}}{194\text{K}} + \frac{6.29 - 100 \cdot q}{53.2}\right)}$$

with P_3 and T_3 the pressure and temperature at the exit of the high-pressure compressor of the engine, and q the specific humidity (water-air ratio). The sNO_x index represents the scaled amount of NO_x emitted by the engine, regardless of the flight phase (takeoff, cruise, landing...), dependent on ambient conditions. The amount of NO_x emitted by the aircraft engine per kg of fuel burnt (NO_x Emission Index; EI_{NO_x}) at takeoff can be estimated from the sNO_x index considering a linear relationship between these two variables [Council 92]. In particular, it is indicated in the Gasturb manual that for conventional single annular combustors, as it is the case for the selected engine, the proportionality constant is 32 g NO_x/kg fuel. However, this value does not represent all engine models with conventional combustors, as found in [Chandrasekaran 12], but the proportionality constant between the EI_{NO_x} and the sNO_x index varies with the engine model. Considering the relative changes in the EI_{NO_x} with respect to a reference value would circumvent the lack of accuracy on the proportionality constant value for the selected engine model.

The evolution of the sNO_x index due to the increase in the magnitude of the summer $TX95p$ at the airports is analysed over the periods 1961-1990, 1991-2020, 2021-2050 and 2041-2070, from the observations and the future climate projections. The changes in the sNO_x index relative to the observational reference period 1961-1990 are assessed. The relative changes in the EI_{NO_x} can be considered of the same magnitude, as aforementioned. The NO_x absolute emissions from the aircraft engine increases with the EI_{NO_x}, along with the amount of fuel burnt.

3.2.2.3 Results and Discussion

Figure 3.9 shows the positive trend in the aircraft engine sNO_x index due to the increase in the magnitude of the summer $TX95p$ at the airports. The sNO_x index ranges from 2.9 at ORY, BCN, NCE and MXP to ~ 3.2 at MAD, in the observational reference period 1961-1990. In the following 30-year period, it would have increased to be between 3.0 and 3.3. The aircraft engine would have experienced a relative increase in the sNO_x index of +1.9% by 1991-2020 with respect to 1961-1990, on average at the airports. This means that the amount of NO_x emitted by the aircraft engine per kg of fuel burnt would have increased by the same relative amount between 1961-1990 and 1991-2020 due to the increased intensity of TX extremes. BCN is the most affected airport by this relative increase by 1991-2020, with +2.7%, while FCO is the least impacted airport in these terms, with only +0.5%.

By the near term, the aircraft engine is projected to experience an increase in the sNO_x index of +2.5% relative to 1961-1990, according to the CORDEX Multi-Model Ensemble mean (MME mean), and of +3.6% according to the CMIP5 MME mean, on average at the airports. MAD is the most affected airport by this relative increase projected by the MME mean of both CORDEX and CMIP5: +2.9% (2.7, 3.2) and +3.9% (3.5, 4.3), respectively. Also, ATH is projected by the CMIP5 MME mean to experience the same relative change in the sNO_x index as MAD. ORY and BCN would be the least affected airports in next decades as estimated from the CORDEX MME mean, with +2.2% [(1.8, 2.7), (2.0, 2.4)], while the CMIP5 MME mean projects that it will be FCO, with +3.3% (2.9, 3.7).

By the mid-term (2041-2070), the sNO_x index is projected to increase by +3.7%, relative to 1961-1990, on average at the airports, according to the CORDEX MME mean, and by +5.5% with regards to the CMIP5 MME mean. As for the near term, MAD is also projected to be the most affected airport by this relative increase in sNO_x by mid-century, according to both CORDEX and CMIP5 MME means: +4.6% (4.2, 4.9) and +5.9% (5.4, 6.4), respectively. FCO and BCN are projected to be the airports with the smallest relative increase by the CORDEX MME mean, with +3.3% [(2.9, 3.6), (3.0, 3.6)]. Amongst the CMIP5 ensemble, FCO is also projected to experience the smallest MME mean relative increase, with +4.8% (4.3, 5.3).

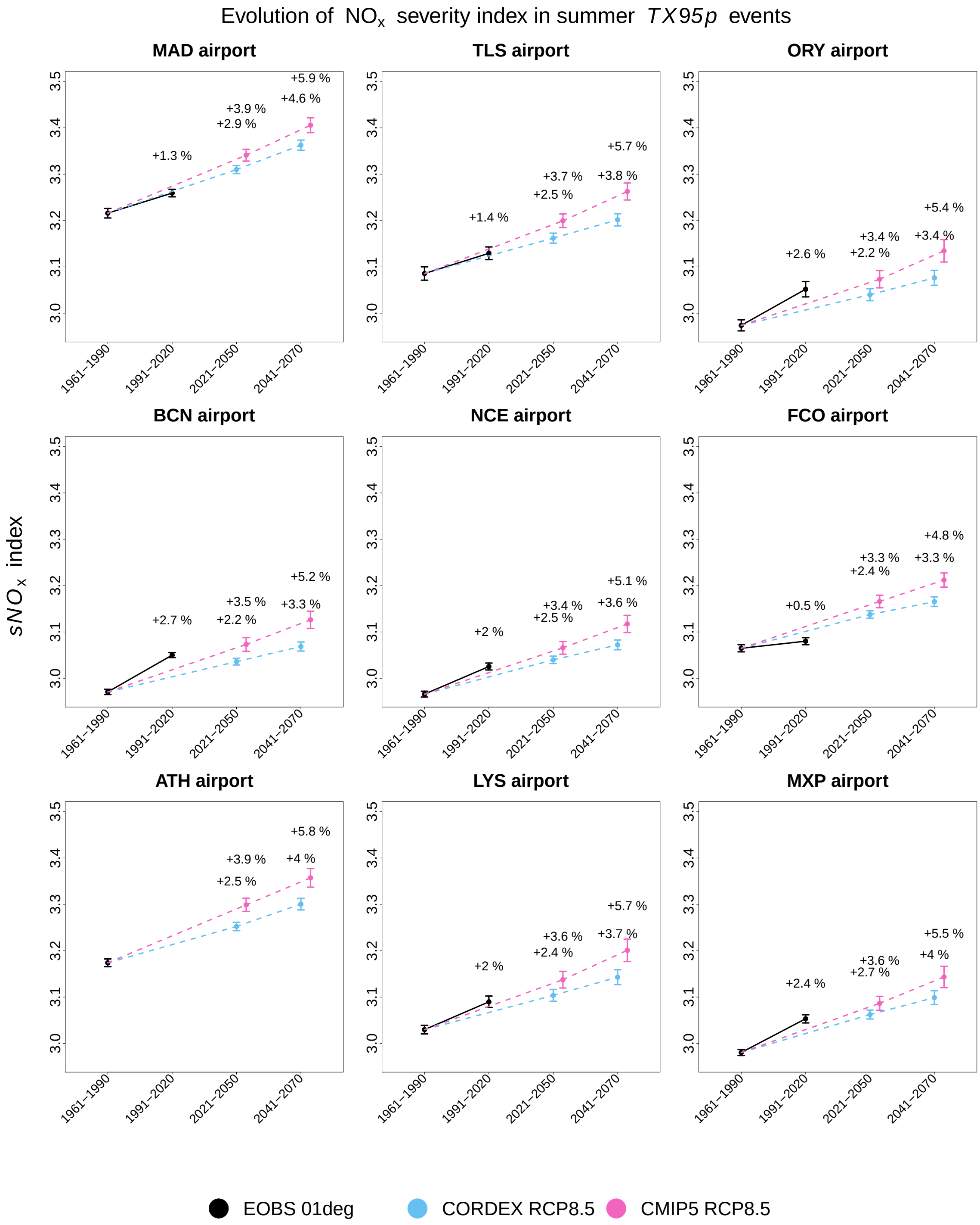

Figure 3.9: Evolution of the aircraft engine NO_x emission severity index during a summer $TX95p$ event through the observational periods 1961-1990 and 1991-2020 according to the EOBS 01deg data set (black), and up to 2021-2050 and 2041-2070, under the severe scenario of climate change RCP8.5, as projected by the bias-corrected CORDEX and CMIP5 ensembles (blue and pink, respectively). Time periods are indicated on the horizontal axis. Error bars indicate the 95% confidence interval in each case.

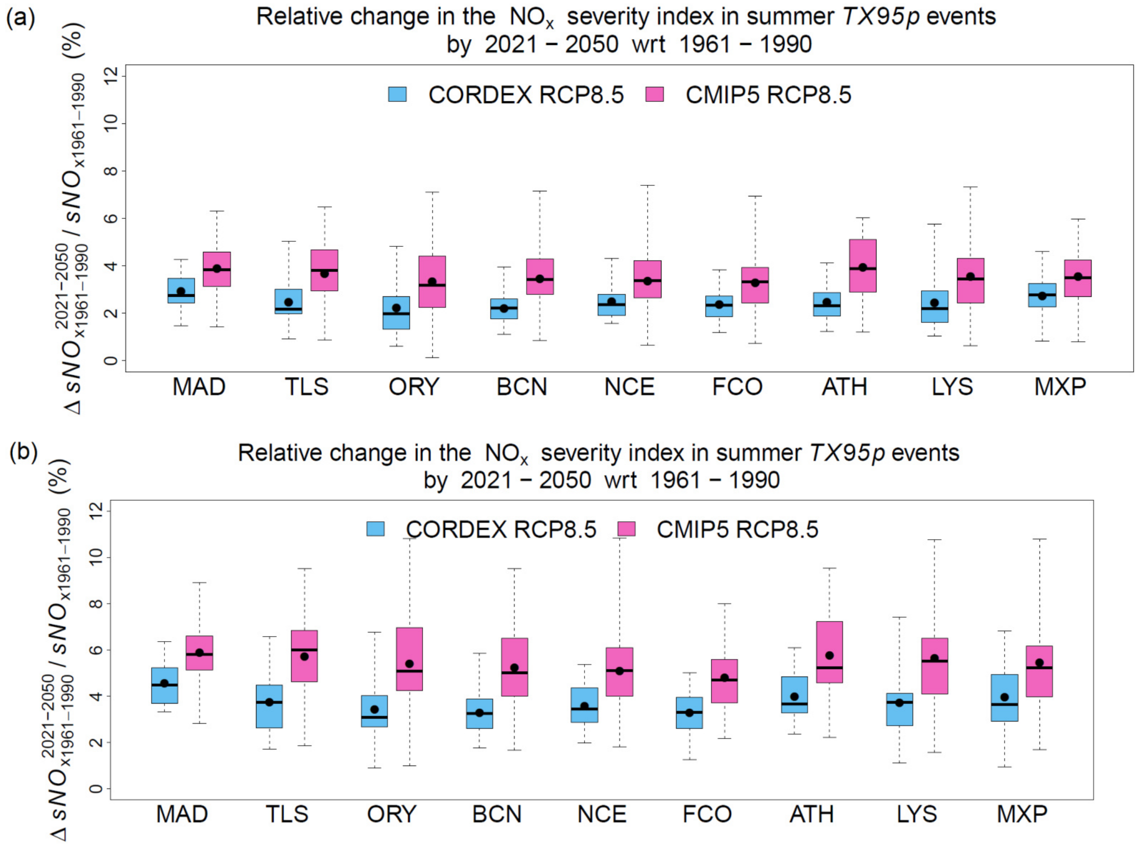

Figure 3.10: Boxplot of the changes in the NO_x severity index in summer $TX95p$ events by 2021-2050 (a) and by 2041-2070 (b) relative to 1961-1990, under the RCP8.5 scenario, as projected by the bias-corrected CORDEX and CMIP5 ensembles (blue and pink, respectively). The boxes are delimited by the first and third quartiles, with the median the segment in between, and points indicating the MME mean. The lower (upper) whiskers correspond to the minimum (maximum) values of the ensemble in each case.

Figure 3.10 shows the boxplot for the projected future changes in the sNO_x index in summer $TX95p$ episodes relative to 1961-1990. In the worst case, that is, according to the CMIP5 MME maximum, a maximum relative increase of +7.4% is projected for NCE by the near term, and of +10.8 % for ORY, NCE, LYS and MXP by the mid-term. The smallest estimate for the relative change in the sNO_x index by 2021-2050 is projected by the CMIP5 MME minimum at ORY, and it is of +0.1%, and by 2041-2070 it is projected by the CORDEX MME minimum to be of +0.9%, also at ORY. Therefore, the relative increase in the sNO_x index of the aircraft engine, due to the increase in the summer $TX95p$ projected by the climate models at the airports, ranges between +0.1% and +7.4% by 2021-2050, and between +0.9% for and +10.8 % by 2041-2070.

The EOBS 01deg dataset is used as observational reference, as it presents data for all selected locations, and in the absence of a better observational dataset. However, more accurate results could have been obtained from the homogenized climate data series from the national meteorological services from *in situ* stations at the airports. Unfortunately, this kind of data are not easily available and special access needs to be requested to the local meteorological services. The use of *in situ* data would have likely conduced to more intense summer $TX95p$ extremes at the airports compared to the spatially gridded EOBS 01deg dataset over a 10 km × 10 km grid, leading to higher sNO_x index and EI_{NO_x} values.

Climate model projections used for the analysis do likely underestimate the increase in the summer $TX95p$, even for the RCP8.5 scenario experiment, as already discussed in Section 3.2.2.2. At ORY, BCN, NCE, LYS and MXP, the future sNO_x index projected over the period 2021-2050 by the CORDEX and CMIP5 MME means is very close to the sNO_x index found in the previous period 1991-2020. The minimum and mean estimates across the two MME for the relative change in sNO_x index discussed above could be too conservative as well. That is, the future increase in the EI_{NO_x} by the aircraft engine will likely be greater.

Furthermore, considering the changes in the ambient relative humidity in addition to the changes in the summer TX extremes could lead to greater changes in the EI_{NO_x}. Higher amounts of NO_x are emitted by the engine under lower relative humidity conditions [Asad 12]. Therefore, a decrease in relative humidity would result in larger NO_x emissions. A preliminary analysis of the changes in the daily mean relative humidity in summer $TX95p$ events shows a decrease between the observational periods 1961-1990 and 1991-2020. The assessment of the future impact on NO_x emissions due to changes in high-temperature extremes along with changes in ambient humidity could be the subject of future work.

In addition to the increase in the amount of NO_x emitted by the aircraft engine due to higher temperature extremes, a decrease in the engine core (compressor-combustor-turbine) efficiency is found (up to -1.8% by the near term and up to -3.4% by the mid-term; not shown), and also a decrease in net thrust (up to -3.9% by the near term and up to -5.7% by the mid-term; not shown), which is consistent with [Ren 19b] and [Imanov 22], and with [Airbus 02], respectively. Therefore, it would be necessary to burn more fuel to achieve the aircraft operational requirements, as also highlighted in [Ren 19b], consequently increasing the pollutant emissions. Moreover, under higher temperature conditions, higher speed is needed at takeoff because of lift reduction [Anderson 05], which implies further fuel consumption with additional emissions. Furthermore, the air traffic demand and the revenue passenger-km is expected to continue rising in the next decades [ICAO 16a]. For all this, the relative increase found for the EI_{NO_x} could lead to a substantial increase of the NO_x absolute emissions from aviation in the future.

This increase in the NO_x emissions due to more intense TX extreme events will have a positive net radiative effect on the climate system [Lee 21a], due to its dominating role in favoring the ozone formation in the troposhere. This could imply further warming of TX extremes in the future, enclosing a positive feedback loop. Besides, increased NO_x emissions at the airports could also worsen the local air quality in such events in the future, with a potentially negative impact on human health [Masiol 14], in particular on the respiratory system. This may be particularly problematic, since higher emissions of NO_x may superpose with higher concentrations of other pollutants also due to climate change. For instance, fine particulate matter of less than 10 microm, also referred to as PM_{10}, and ozone are projected to increase over Southern Europe during the summer [Jiménez-Guerrero 13], mainly due to higher temperatures, precipitation changes and more frequent stagnant conditions [Jimenez-Guerrero 11, Jiménez-Guerrero 13].

As a result of the increase in the ambient air temperature entering the aircraft engine during a summer $TX95p$ event in the future, the exhaust gas temperature is also found to be hotter (up to +2 °C in the near term and up to +3 °C by the mid-term; not shown). The higher temperature of the exhaust gases under warmer ambient conditions is consistent with [Imanov 22], and according to it, this would deteriorate faster the rear components of the engine, in particular, the turbine. The lifetime of commercial aircraft engines could be reduced in the future due to the increase in the magnitude and in the frequency of high-temperature extremes.

Moreover, the decrease in net thrust hampers the aircraft's maximum carrying capacity, potentially leading to weight restrictions, flight delays or cancellations during high temperature events [Coffel 15, Coffel 15, Zhou 18b].

3.2.2.4 Conclusion

The effect of the increase in high-temperature extremes due to climate change on the amount of NO_x emitted by the aircraft engine at the airport was assessed over a list of major Euro-Mediterranean airports, using data from climate models and the Gasturb software. We focused in summer $TX95p$ events. The magnitude of these events in the periods 1961-1990 and 1991-2020 was analysed from observations using the EOBS 01deg gridded dataset. The future magnitude of summer $TX95p$ events by 2021-2050 and 2041-2070 was analysed from climate projections, preformed with both RCMs and GCMs. The projections from the multi-RCM CORDEX ensemble and the multi-GCM CMIP5 ensemble for the RCP8.5 scenario experiment previously analysed in [Gallardo 23] were used. Climate model biases were corrected using a quantile delta mapping approach. The observed and future projected magnitudes for the summer $TX95p$ were used as input ambient conditions in the Gasturb 14 engineering software. This allowed the estimation of the sNO_x index, to which the EI_{NO_x} index is considered to be directly proportional. A positive trend in the amount of NO_x emitted by the aircraft engine per kg of fuel burnt was found at all airports. An increase of between +0.5% and +2.7% (+1.9% on average) is found by 1991-2020, relative to the reference period 1961-1990.

By 2021-2050, under the severe scenario of climate change, the NO_x emitted per kg of fuel could increase at the airports from +2.2% to +2.9% (+2.5% on average) relative to 1961-1990, according to the CORDEX MME mean, and from +3.3% to +3.9% (+3.6% on average), according to the CMIP5 MME mean. There are models that project a maximum relative increase of up to +7.4% over the airports in the next 30 years, and a minimum of +0.6%. By 2041-2070, the CORDEX MME mean projects a relative increase of between +3.3% and +4.6% at the airports (+3.8% on average). Meanwhile, the relative increase projected by the CMIP5 MME mean by the mid-term ranges between +4.8% and +5.9% (+5.5% on average). MAD would experience the greatest relative increase in the two future periods based on the sNO_x index estimates from the CORDEX and CMIP5 MME means. Some models project a maximum relative increase of up to +10.8% over the airports by the mid-century, and a minimum of +0.9%.

The emissions databank[2] of the International Civil Aviation Organization (ICAO) inventories the exhaust emissions of aircraft engines, which are provided by the manufacturers. According to this database, the EI_{NO_x} at takeoff for the CFM56-5B3/3 engine model is 30.9 g/kg and the fuel flow at takeoff is 1.462 kg/s. Therefore, a relative increase in the EI_{NO_x} of between 2.2% and 5.9% would result in a increase in the NO_x emissions of between 34 g and 93 g at takeoff per flight, considering that the takeoff performance lasts about 35 seconds. For instance, if the airport operates about 20 flight departures per hour, this could lead to an increase of between +0.7 kg and almost +2 kg in summer $TX95p$ episodes. The increased levels of NO_x emissions under warmer ambient temperatures concern the liquid fossil fuels currently used in aviation, such as kerosene, and it will concern as well the Sustainable Aviation Fuels (SAF) and the Hydrogen aviation in the future.

The absolute amount of NO_x emissions from aviation could be substantially magnified during high-temperature extreme events in the future from these relative

[2] https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank

increases found for the EI_{NO_x}, in addition to higher fuel consumption arising from the lower engine core efficiency, the lower engine thrust and aircraft lift at takeoff and the projected growth in air traffic. This would cause additional radiative forcing on the climate system, and the deterioration of air quality at the airport and in the vicinities. The global increase in aviation emissions due to increasing high-temperature extremes in order to achieve the operational requirements at takeoff still needs to be assessed.

Moreover, considering the potential increase in aviation absolute emissions from reduced operations performance and engine's efficiency in the context of climate change could be significant when developing future aviation emissions scenarios. To the best of our knowledge, these scenarios only contemplate so far the plausible growth in air traffic and in the revenue passenger-km and the improvements in aircraft and engine technologies.

This problem does not only concern the airports and the aircraft engines. The increase in high-temperature extremes in the cities, which are considered as climate change hotspots too [IPCC 21], could also negatively affect the engines of the urban transport fleet. This will potentially lead to increased NO_x emissions in populated urban areas, which may already suffer from air pollution in the present. This could be an important health issue, and deserves further interdisciplinary research work.

To the best of our knowledge, this is the first time that the impact of climate change on the levels of aviation pollutant emissions is assessed. Also, it would be the first time that data issued from climate model projections are used as input to an engineering software for analysing the engine's behavior. More accurate results could be obtained in the future in collaboration with aircraft engine manufacturers, and also with airline companies.

Acknowledgements. We gratefully thank the CERFACS for supporting this work. We also acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We thank the climate modelling groups (listed in Table 3.2 and Table 3.3, Appendix 1) for producing and making available their model output. We also acknowledge the Earth System Grid Federation infrastructure an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP). We acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the Copernicus Climate Change Service, and the data providers in the ECA&D project (https://www.ecad.eu). The analyses were performed using R Statistical Software (v3.6.2; R Core Team 2021) and the NCAR Command Language (Version 6.6.2) [Software]. (2019). Boulder, Colorado: UCAR/NCAR/CISL/TDD. http://dx.doi.org/10.5065/D6WD3XH5. Figures were produced using R, in particular, maps were generated with the 'ggmap' package [Kahle 13]. Also, thanks to Gasturb 14 the engine pollutant emissions and performances were obtained.

Many thanks to Julien Boé, for the productive discussions on the method of bias correction for climate model data and also on which relative humidity values to set in Gasturb for a more realistic approach.

Appendix 1 Climate simulations

Table 3.2: The RCM × GCM matrix indicating which combinations from the Euro-CORDEX Historical and RCP8.5 scenario experiments were available for the study.

	CNRM-CM5	EC-EARTH	HadGEM2-ES
CLMcom-CCLM4-8-17	r1i1p1	r12i1p1	r1i1p1
CLMcom-ETH-COSMO-crCLIM	r1i1p1	r1i1p1	r1i1p1
CNRM-ALADIN53	r1i1p1		
CNRM-ALADIN63	r1i1p1		r1i1p1
DMI-HIRHAM5	r1i1p1	r1i1p1	r1i1p1
GERICS-REMO2015	r1i1p1		
ICTP-RegCM4-6			r1i1p1
IPSL-WRF-381P	r1i1p1	r12i1p1	r1i1p1
SMHI-RCA4			

	IPSL-CM5A-MR	MPI-ESM-LR	NorESM1-M
CLMcom-CCLM4-8-17		r1i1p1	
CLMcom-ETH-COSMO-crCLIM		r1i1p1	r1i1p1
CNRM-ALADIN53			
CNRM-ALADIN63		r1i1p1	r1i1p1
DMI-HIRHAM5	r1i1p1	r1i1p1	r1i1p1
GERICS-REMO2015			
ICTP-RegCM4-6		r1i1p1	
IPSL-WRF-381P	r1i1p1	r1i1p1	r1i1p1

Table 3.3: List of GCM simulations from the CMIP5 Historical and RCP8.5 scenario experiments analysed in this study.

GCM	realisation
ACCESS1-0	r1i1p1
BNU-ESM	r1i1p1
CCSM4	r1i1p1
CESM1-BGC	r1i1p1
CESM1-CAM5	r1i1p1
CMCC-CESM	r1i1p1
CMCC-CMS	r1i1p1
CMCC-CM	r1i1p1
CNRM-CM5	r1i1p1
CSIRO-Mk3-6-0	r10i1p1
CanESM2	r1i1p1
EC-EARTH	r1i1p1
FGOALS-g2	r1i1p1
GFDL-CM3	r1i1p1
GFDL-ESM2G	r1i1p1
GFDL-ESM2M	r1i1p1
HadGEM2-AO	r1i1p1
HadGEM2-CC	r1i1p1
HadGEM2-ES	r1i1p1
IPSL-CM5A-LR	r1i1p1
IPSL-CM5A-MR	r1i1p1
IPSL-CM5B-LR	r1i1p1
MIROC-ESM-CHEM	r1i1p1
MIROC-ESM	r1i1p1
MIROC5	r1i1p1
MPI-ESM-LR	r1i1p1
MPI-ESM-MR	r1i1p1
MRI-CGCM3	r1i1p1
MRI-ESM1	r1i1p1
NorESM1-M	r1i1p1
bcc-csm1-1-m	r1i1p1
inmcm4	r1i1p1

Appendix 2 Input atmospheric pressure and relative humidity conditions

Table 3.4: Ambient pressure and relative humidity used as input conditions in Gasturb 14 at each airport

Airport	Ambient pressure (hPa)	Ambient relative humidity (%)
MAD	945.51	38
TLS	996.01	59
ORY	1003.10	62
BCN	1012.80	71
NCE	1012.80	69
FCO	1012.70	69
ATH	1002.60	44
LYS	985.03	60
MXP	978.90	64

3.3 DECREASING AIRCRAFTS MAXIMUM TAKEOFF WEIGHT IN THE EURO-MEDITERRANEAN REGION

Decreasing aircrafts MTOW in the EUR-MED region

3.3.1 Résumé

L'augmentation de l'intensité et la fréquence des événements extrêmes de hautes températures a un impact négatif sur la performance du décollage des avions. Des températures ambiantes plus elevées entraînent une diminution de la portance de l'avion et de la poussée du moteur, ce qui réduit la capacité de l'avion à soulever du poids. Cette étude évalue la diminution de la masse maximale de l'avion au décollage ($MTOW$, pour *Maximum TakeOff Weight* en anglais) sur les aéroports Euro-Méditerranéens, en raison de l'augmentation des extrêmes de hautes températures, pour les long-courriers, les moyen-courriers et les court-courriers. Des données climatiques observationnelles dans la période 1961-1990 sont utilisées, ainsi que des projections climatiques futures sous le scénario sévère de changement climatique RCP8.5 pour les périodes 2021-2050 et 2041-2070, pour analyser l'évolution des extrêmes de hautes températures sur les aéroports. Des projections effectuées avec des RCMs et des GCMs sont prises en compte. La $MTOW$ est obtenue en combinant les données climatiques avec des données techniques d'avions, et en appliquant une loi empirique, fournie par AIRBUS, qui relie la $MTOW$ à la température ambiante au décollage.

Les résultats montrent que les aéroports étudiés pourraient être concernés par une diminution de la $MTOW$ de l'ordre de plusieurs tonnes pour les long- et moyen-courriers (jusqu'à 7 tonnes et jusqu'à plus de 11 tonnes à court et moyen terme, respectivement), et de l'ordre de centaines de kgs pour les court-courriers. Cependant, la grande dispersion des modèles climatiques entraîne de grandes

incertitudes dans les projections de la $MTOW$, allant dès changements minimes ou nuls à des changements de l'ordre de plusieurs tonnes. Néanmoins, selon la moyenne multi-modèle de l'ensemble de RCMs et de celle des GCMs, en général, une tendance positive des limitations de la $MTOW$ est trouvée pour la plupart des aéroports étudiés, au moins concernant un type d'avion, ce qui est cohérent avec les études précédentes. Cette diminution de la $MTOW$ est généralement de l'ordre de plusieurs tonnes. Cela pourrait avoir un impact socio-économique, soit du fait d'éventuelles restrictions de poids, de retards ou d'annulations, soit du fait de l'usure du moteur.

Les résultats montrent qu'à l'échelle régionale les projections issues des modèles climatiques présentent des fortes incertitudes, ce qui rend très difficile l'évaluation du changement climatique en ces termes et l'impact potentiel. Ce constat est connu par la communauté scientifique et des nombreaux efforts sont déployés pour réduire l'incertitude dans les projections climatiques, comme les études sur les paramétrisations des modèles, les constraintes émergentes ou des critères de selection de modèles.

3.3.2 Manuscript (draft)

Abstract. The increasing intensity and frequency of high-temperature extreme events negatively impacts the aircraft takeoff performances. Warmer surface air temperatures result in lower aircraft lift and engine thrust, reducing the aircraft's capacity to lift weight. This study evaluates the future evolution in the aircraft's Maximum TakeOff Weight (MTOW) over the Euro-Mediterranean airports due to the increase in high-temperature extremes due to global warming. The MTOW changes are estimated for long-, medium- and short-range aircrafts. Observational climate data for the period 1961-1990, and future climate projections under the severe scenario RCP8.5 for the periods 2021-2050 and 2041-2070 are used to analyze the evolution of high-temperature extremes over the airports. Simulations performed with both Regional and Global Climate Models (RCMs and GCMs) from CMIP5 and

Euro-CORDEX, respectively, are considered. The $MTOW$ is obtained by combining the climate data with aircraft technical data and applying an empirical law provided by AIRBUS which relates the $MTOW$ to the ambient tempeature. Results show that most of the airports could be concerned by a decrease in $MTOW$ of the order of tons and tens of tons for the long- and medium-range aircrafts (up to 7 tons and up to more than 11 tons, by the near and by the mid-term, respectively), and of the order of hundreds of kgs for short-range aircrafts. However, the wide spread amongst climate model simulations results in large uncertainties in the estimates of the evolution of the $MTOW$. Indeed, climate models project from little or no change in $MTOW$ to changes of the order of tons in some cases. The large uncertainties in climate model projections at the airport scale make it difficult to assess climate change in these terms and its potential impact. Nonetheless, according to the multi-model ensemble mean of the RCMs and the GCMs, a general positive trend in $MTOW$ limitations is found for most of the airports for at least one aircraft type, which is consistent with previous studies, and they are usually of the order of tons. This could have a socio-economic impact, either from possible weight restrictions, delays or cancellations, or an economic impact from the wear of the engine.

3.3.2.1 Introduction

Aircrafts are conceived to operate in a wide range of ambient conditions. Nonetheless, even if they are capable to fly under extreme weather conditions, such as extreme heat, their performances might be negatively affected, and their components can be subjected to wear. In particular, high temperatures negatively impact the aircraft lift and the engine thrust. Since the lift of the aircraft is linearly dependent on air density, and air density decreases with temperature at constant pressure, the takeoff performance under higher temperatures requires higher speeds and, consequently, longer distances if acceleration is constant [Anderson 05]. The engine thrust also decreases with the ambient temperature of the intake air [Airbus 22]. For fuel economy and environmental purposes, thrust is usually set to be constant below a certain temperature $T_{\mathrm{threshold}}$ [Airbus 22]. For instance, for twin-engined turbofan aircrafts, thrust is usually flat-rated below the temperature at International Standard Atmospheric conditions (ISA) +15 °C ($T_{\mathrm{ISA+15}}$), that is 30 °C at sea level. This is the case for the commonly used long- and medium-range aircrafts, such as the Airbus A350 and the A320. The lower lift and thrust under warmer conditions hamper the aircraft capacity lo lift weight, potentially leading to weight restrictions, changes in schedules or cancellations [Coffel 15]. In the context of climate change, the magnitude of high-temperature extremes is expected to become more intense and frequent in the future, in particular over the Euro-Mediterranean region [IPCC 13, IPCC 21, Gallardo 23]. This will likely impact the aircraft takeoff performances and the maximum carrying capacity of the aircraft at takeoff over the airports.

Many studies have assessed the impacts of warming temperatures due to climate change on the Maximum TakeOff Weight (MTOW) of the aircrafts [Coffel 15, Coffel 17, Zhou 18a, Carpenter 18, Zhou 18b, Gratton 20, Zhao 20]. They all find a generalized decreasing trend in the $MTOW$ over a list of airports distributed worldwide. The future magnitude of the $MTOW$ limitation varies across the airports depending on its vulnerabilities, such as high elevation or short runways, and also varies across the aircraft types, with the greatest penalties applied to the largest aircrafts. Nonetheless, the Euro-Mediterranean climate change hotspot region has not been focused on yet, at least not to its full extent, but only on Greek airports [Gratton 20], nor the future projected changes in high-temperature extreme events. Moreover, the use of a Multi-Model Ensemble (MME) of Regional Climate Models (RCMs) has not been considered yet, the most part of the literature uses a MME of Global Climate Models (GCMs) with a coarse horizontal spatial resolution of about 200 km in average [Coffel 15, Coffel 17, Zhou 18a, Carpenter 18, Zhou 18b, Gratton 20], and only one study is based on a single RCM simulations [Zhao 20]. Both a multi-RCM and a multi-GCM should be considered for the impact assessment in these terms at the airport scale, according to [Gallardo 23].

In addition, the method used in the cited studies for deriving the $MTOW$ relationship with temperature relies on a 4-point fit only [Coffel 15, Zhou 18a], or in Koch charts [Zhou 18b]. The derivation method of the $MTOW$ as a function of temperature could be however improved.

The main goal of this study is to assess the impact of increasing high-temperature extremes due to climate change on aviation, in terms of aircraft maximum takeoff weight, over the airports in the Euro-Mediterranean region. Both major and regional and small airports are considered. Three aircraft models are selected as representative for long-, medium- and short-range aircrafts. We focus on the extremes of the daily maximum near-surface air temperature in summer at the airport scale. Climate projections performed with both RCMs and GCMs are used to assess the future magnitude of high-temperature extremes over the airports under the severe scenario of climate change. In [Gallardo 23], the RCMs and GCMs from the Euro-CORDEX [Jacob 12, Jacob 14] and CMIP5 [Taylor 12] experiments are evaluated in these terms at the airport scale, and validated for the study of the evolution of high-temperature extremes. The evolution of the $MTOW$ is analysed from the recent decades to the mid-century, combining climate data with aircraft technical data applying an empirical law provided by the aircraft manufacturer company AIRBUS. To the best of our knowledge, this is the best attempt to evaluate the decrease in $MTOW$ with increasing temperatures using this empirical method.

Data and methods are described in Section 3.3.2.2 and Section 3.3.2.3, respectively. Results are presented in Section 3.3.2.4 and discussed in Section 3.3.2.5. Finally, the conclusions are drawn in Section Section 3.3.2.6.

3.3.2.2 Data

Climate observations and future climate projections

A list of airports distributed over Mediterranean countries, mainly in Europe, are selected as case studies. Major airports are considered, as well as regional and small airports (see Figure 3.11). They are presented in Table 3.5 and Table 3.6, respectively, along with their elevation and the length of their longest runway (TakeOff Field Length; TOFL).

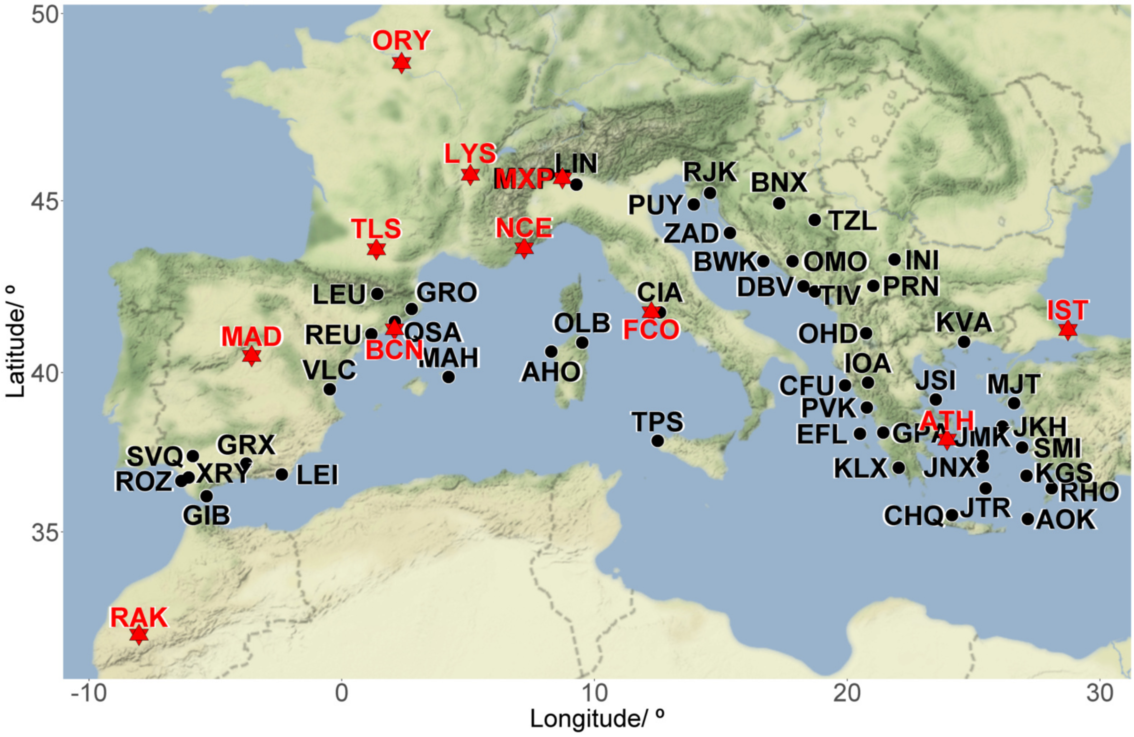

Figure 3.11: Major airports (red stars) and regional and small airports (black dots) selected as case studies

Table 3.5: List of major airports selected as case studies and their main characteristics: the elevation and the longest TOFL in each case

	Name	Country	Elevation/ m	TOFL/ m
MAD	Madrid-Barajas Adolfo Suárez	Spain	610	4350
TLS	Toulouse-Blagnac	France	152	3500
ORY	Paris-Orly	France	89	3650
BCN	Barcelona-El Prat Josep Tarradellas	Spain	4	3350
NCE	Nice-Côte d'Azur	France	4	2960
FCO	Rome-Fiumicino Leonardo da Vinci	Italy	5	3900
ATH	Athens-Eleftherios Venizelos	Greece	94	4000
LYS	Lyon-Saint Exupéry	France	250	4000
MXP	Milan-Malpensa	Italy	305	3915
RAK	Marrakesh-Menara	Morocco	417	3100
IST	Istanbul	Turkey	99	4100

Table 3.6: List of regional and small airports selected as case studies and their main characteristics: the elevation and the longest TOFL in each case

	Name	Country	Elevation/ m	TOFL/ m
GRO	Girona Costa Brava	Spain	143	2400
VLC	Valencia-Manises	Spain	73	2900
SVQ	Sevilla-San Pablo	Spain	34	3360
MAH	Menorca-Mahón	Spain	92	2550
GIB	Gibraltar-North Front	UK	5	1775
XRY	Jerez-La Parra	Spain	28	2300
REU	Reus	Spain	71	2460
LEI	Almería-Antonio de Torres	Spain	21	3200
GRX	Granada-Federico Garcá Lorca	Spain	567	2900
QSA	Sabadell	Spain	148	1050
ROZ	Rota Naval Station	Spain	26	3690
LEU	Andorra-La Seu d'Urgell	Spain	802	1265
LIN	Milan-Linate	Italy	107	2440
CIA	Rome-Ciampino	Italy	130	2205
OLB	Olbia-Costa Smeralda	Italy	11	2745
AHO	Alghero–Fertilia	Italy	27	3000

Table 3.6 Continued.

	Name	Country	Elevation/ m	TOFL/ m
TPS	Trapani-Birgi Vincenzo Florio	Italy	8	2695
DBV	Dubrovnik	Croatia	161	3300
ZAD	Zadar	Croatia	88	2500
PUY	Pula	Croatia	84	2950
RJK	Rijek	Croatia	85	2500
BWK	Brac	Croatia	543	1760
TIV	Tivat	Montenegro	6	2500
PRN	Prishtina-Adem Jashari	Kosovo	545	3000
BNX	Bania Luka	Bosnia and Herzegovina	122	2500
OMO	Mostar	Bosnia and Herzegovina	48	2400
TZL	Tuzla	Bosnia and Herzegovina	233	2500
INI	Nis-Constantine the Great	Serbia	198	2500
OHD	Ohrid-St. Paul the Apostle	N. Macedonia	705	2550
JKH	Chios-Omiros	Greece	5	1510
CFU	Corfu-Ioannis Kapodistrias	Greece	2	2375
RHO	Rhodes-Diagoras	Greece	6	3305
KGS	Kos-Hippocrates	Greece	126	2400
JTR	Santorini	Greece	39	2195
SMI	Samos-Aristarchos	Greece	6	2100
CHQ	Chania-Ioannis Daskalogiannis	Greece	149	3345
JMK	Mykonos-Manto Mavrogenous	Greece	123	1905
JSI	Skiathos-Alexandros Papadiamantis Papadiamantis	Greece	16	1630
PVK	Preveza-Aktion	Greece	3	2870
EFL	Kefalonia-Anna Pollatou	Greece	18	2435
AOK	Karpathos	Greece	20	2400
IOA	Ioannina	Greece	275	2400
KLX	Kalamata-Captain Vassilis Konstantakopoulos	Greece	8	2705
KVA	Kavala-Alexander the Great	Greece	5	3000
MJT	Mitilini-Odysseas Elytis	Greece	18	2405
GPA	Araxos	Greece	14	3350
JNX	Naxos	Greece	3	900

Both observations and future climate projections are used to obtain the evolution of high-temperature extremes over the airports, from the present climate to the near future climate and also in the mid-term. We follow the same methodology as in [Gallardo 23] for the extraction of climate data at the airport scale. We focus on the daily maximum near-surface air temperature (TX) in summer, in particular, on 95^{th} percentile, usually used as representative for the upper extremes of the Probability Distribution Function (PDF). The observational period 1961-1990 is considered, and the future periods 2021-2050 (near term) and 2041-2070 (mid-term). The E-OBS gridded observational dataset [Haylock 08, Cornes 18] is used, specifically the version 24.0e at 0.1° ($\sim$ 11 km) of horizontal spatial resolution (EOBS 01deg hereinafter). We choose EOBS 01deg as observational reference dataset since it contains data over all of the selected airports, as compared to other observational datasets available for the Euro-Mediterranean domain [Gallardo 23]. Future climate simulations considered belong to the severe climate change scenario experiment RCP8.5 from the CORDEX EUR-11 [Jacob 14, Jacob 20] and CMIP5 [Taylor 12] Multi-Model Ensembles (MME). According to [Gallardo 23], both ensembles should be considered for this impact study in order to better account for the modelling uncertainties. Also according to [Gallardo 23], for instance, the CORDEX and CMIP5 MME need to be bias corrected with regards to the future climate projections in terms of the magnitude of TX extremes. Therefore, a quantile bias correction is applied here before assessing the future potential impact. In particular, a variation of the delta quantile mapping method is applied [Cannon 15] (without detrending the climate series), using the EOBS 01deg as observational reference and 1961-1990 (see Figure 3.12(a) as the reference period. Figure 3.12(b) shows the magnitude for the future $TX95p$ as projected by the CMIP5 MME mean by the near term after the bias correction, for which the future $MTOW$ limitations will be computed.

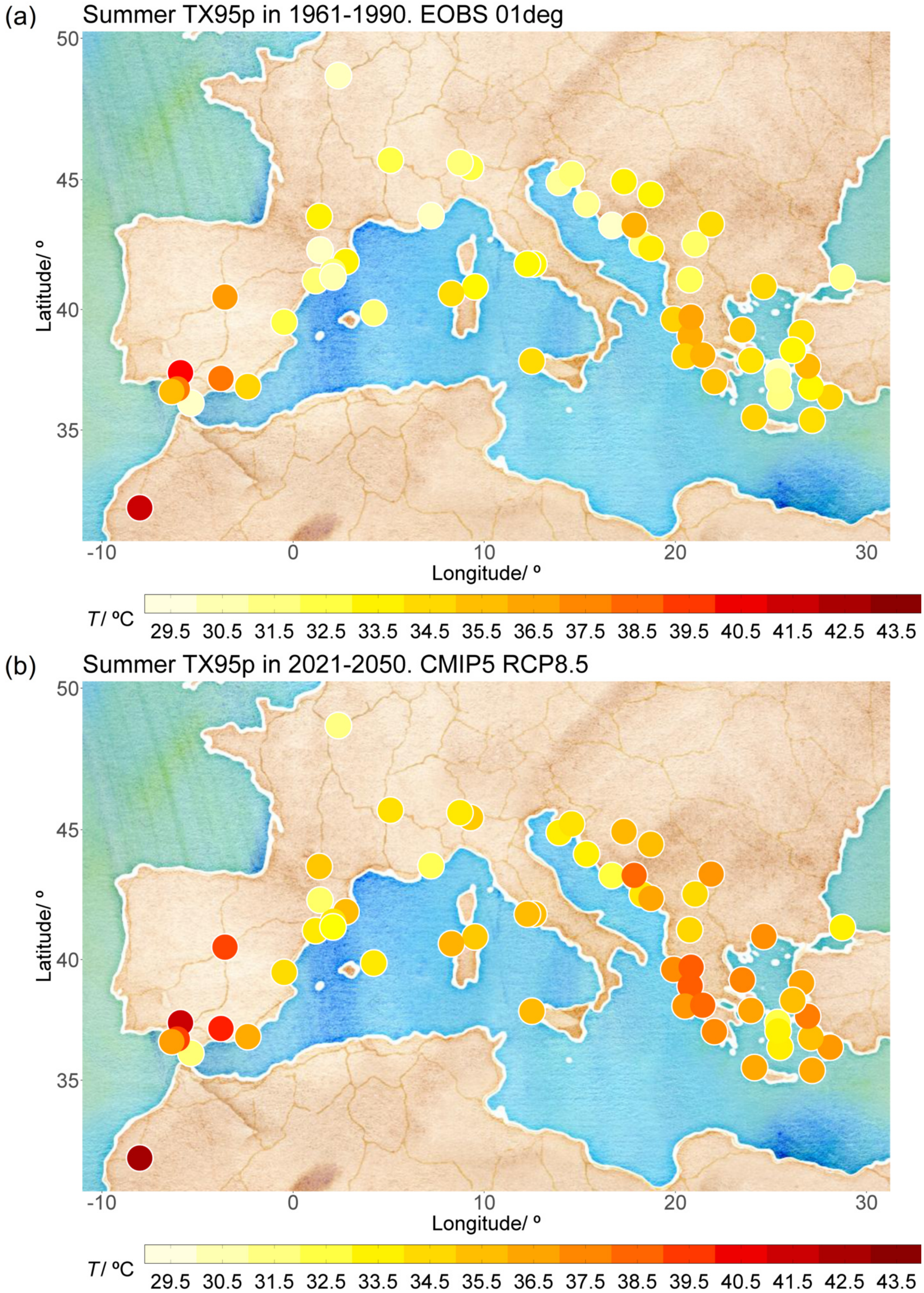

Figure 3.12: (a) Observed temperatures corresponding to the 95$^{\mathrm{th}}$ summer percentile of the daily TX over the airports for the period 1961-1990, according to the EOBS 01deg dataset. (b) Future temperatures corresponding to the 95$^{\mathrm{th}}$ summer percentile of the daily TX over the airports for the period 2021-2050, projected by the (bias-corrected) CMIP5 MME mean under the severe scenario RCP8.5 of climate change.

Aircraft characteristics

Three aircraft models representative of wide-body, narrow-body and regional aircrafts, used for long-, medium- and short-haul flights, respectively, are considered: the A350-1000, the A320-200 and the ATR72-212A. The takeoff of long- and medium-range aircrafts from the major airports is studied, as well as the takeoff of medium- and short-range aircrafts from the regional and small airports.

Aircraft manufacturer specifications are consulted: the certificated MTOW (MTOW_0) for each aircraft model and the MTOW curves from the *Aircraft Characteristics for Airports Planning* (ACAP) manuals. The manufacturer-certificated MTOW ($MTOW_0$) considered for each aircraft model are shown in Table 3.7. The $MTOW$ curves exhibit the $MTOW$ as a function of the TOFL, for different airport elevations, and for different ambient temperature conditions. Figure 3.13 illustrates the $MTOW$ curves which can be found in the ACAP manuals. For a given aircraft model, they describe the relationship between the $MTOW$ and the TOFL, given the ambient temperature conditions, and for different airport elevations. The longer the runway, the more weight the aircraft can takeoff (within its technical capabilities), as longer distances can be travelled to reach the higher speeds required by larger takeoff weights. Also, the higher the airport, the lighter the air, resulting in lower $MTOW$ because of the negative effect of lower air density on aircraft performances, in particular, on lift generation. Temperature also hampers the capability of the aircraft to lift weight, as explained in Section 3.3.2.1. However, only four charts corresponding to four different temperature conditions are usually included in the ACAP manuals. As we need the function that relates the $MTOW$ with temperature to assess the impact on aircraft takeoff performance, we will derive this relationship using an empirical formula, which will be explained in Section 3.3.2.3.

Table 3.7: Manufacturer-certificated MTOW ($MTOW_0$) for the aircraft models selected for the study.

Aircraft model	$MTOW_0$/ kg	Reference
A350-1000	316000	[Airbus 22]
A320-200	78000	https://modernairliners.com/airbus-a320-introduction/airbus-a320-specs/
ATR72-212A	22500	[EASA 22c]

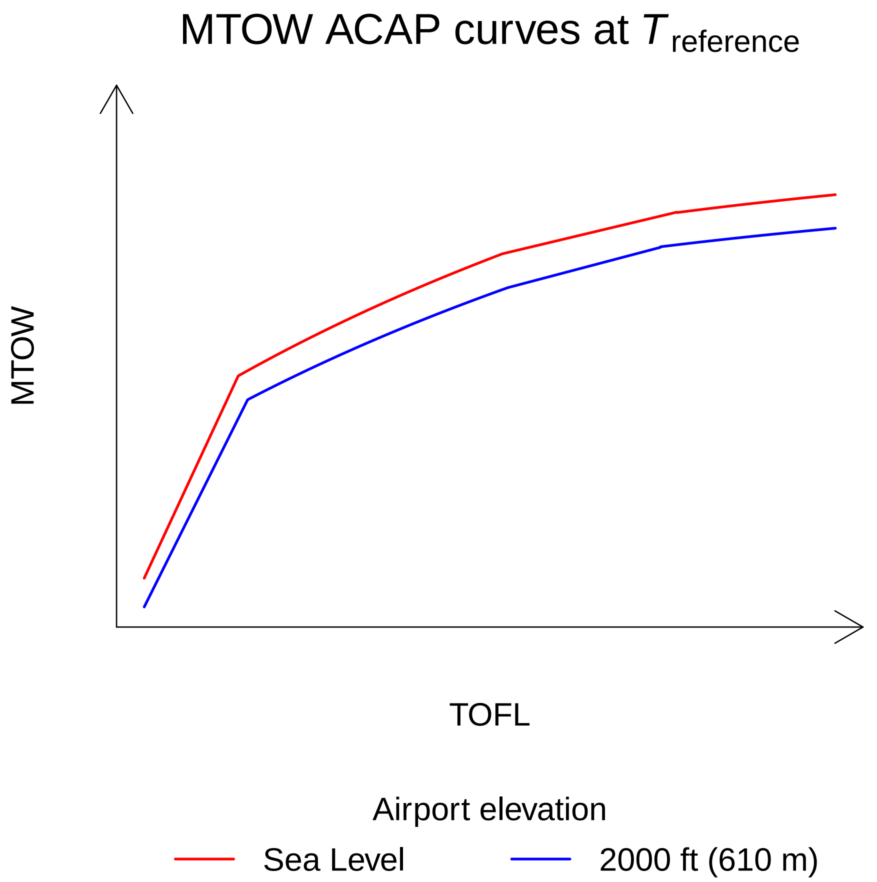

Figure 3.13: Illustration of $MTOW$ curves as a function of the $TOFL$ for a given ambient temperature $T_{\text{reference}}$, and for different airport elevations, which can be found in ACAP manuals (see [Airbus 22], for instance).

3.3.2.3 Method for degrading MTOW with temperature increase

An empirical method is applied to derive the $MTOW$ as a function of air temperature T at the runway level. This method consists in degrading the $MTOW$ curves in the ACAP manuals for the reference temperature values in the charts ($T_{\text{reference}}$), following an empirical law, which was provided by the aircraft manufacturer AIRBUS.

The aircraft's $MTOW$ depends on lift and thrust. The lift is directly proportional to the air density, which in turn is inversely proportional to the air temperature. Thrust also decreases with temperature, but only above a certain temperature threshold, $T_{\text{threshold}}$, as explained in Section 3.3.2.1. Therefore, for temperatures lower than $T_{\text{threshold}}$, the $MTOW$ is affected by the temperature only through the effect of density on lift. Above $T_{\text{threshold}}$, the density effect will act in addition to the negative effect of temperature on thrust. Thus, the penalty on $MTOW$ will be grater above $T_{\text{threshold}}$ because of the superposition of the two temperature effects. The empirical law provided by AIRBUS accounts for this. Moreover, it accounts for the larger impact that high temperatures have on $MTOW$ for airports with short runways limiting the first segment of takeoff, or lift segment.

For a given airport elevation and runway length, the $MTOW$ can be estimated using the following empirical equation:

$$MTOW(T) = \left(\frac{T_{\text{threshold}}}{T}\right)^k \cdot MTOW(T_{\text{reference}}),$$

where $T_{\text{reference}}$ and $T_{\text{threshold}}$ are chosen differently amongst aircraft types. For the A350-1000 and the A320-200, $T_{\text{reference}} = T_{\text{threshold}} = T_{ISA+15}$, whereas for the ATR72-212A, $T_{\text{reference}} = T_{ISA}$ and $T_{\text{threshold}} = T_{ISA+24}$.

The coefficient k differs between the aircraft models depending on whether it is driven by a turbofan engine, as it is the case for the A350-1000 and the A320-200, or a turboprop engine, as the ATR72-212A. The coefficient k also varies for the same aircraft model depending on whether $T > T_{\text{threshold}}$ or $T < T_{\text{threshold}}$. In addition, k

adopts two different values in each case depending on whether the length of the first (or lift) segment of takeoff is longer or shorter than the runway length (see Appendix 2 for further details).

Figure 3.14 illustrates the $MTOW(T)$ function derived using the empirical method enunciated above for two airports with different elevations h_1 and h_2, and with different runway lengths $TOFL_1$ and $TOFL_2$, with $h_1 < h_2$ and $TOFL_1 > TOFL_2$. The second airport will experience larger penalties on the $MTOW$ with temperature increases because of its shorter runway length, which limits the lift segment of takeoff, in addition to its higher elevation, as compared to the first airport.

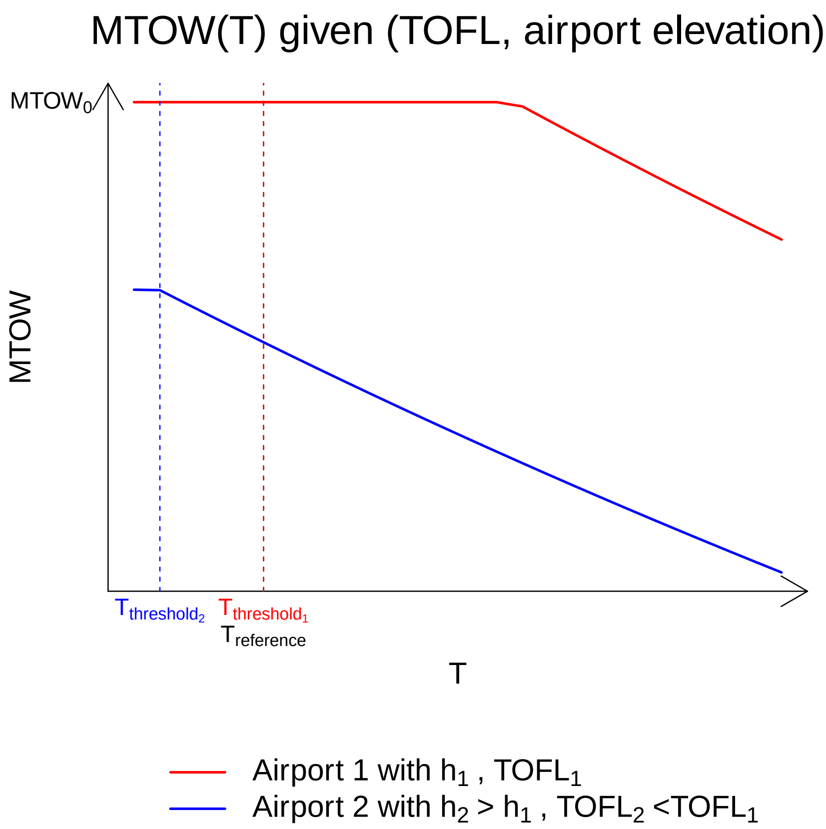

Figure 3.14: Illustration of the $MTOW$ curves derived as a function of the temperature T for a given the TOFL, using the AIRBUS empirical law, for two airports with different elevations and runway lengths.

In this study, we consider that the takeoff is performed using the longest runway of each airport, as is usually the case, the shorter runways are typically used for landing. The $MTOW$ limitations are then estimated at the airports for the summer $TX95p$ observed in the reference period 1961-1990, and in the future periods 2021-2050 and 2041-2070, as projected by the CORDEX and CMIP5 MME under the RCP8.5 scenario. If the $MTOW$ results to be greater than the $MTOW_0$, then we consider that there is no weight limitation.

3.3.2.4 Results

CMIP5 projections by 2021-2050 with respect to 1961-1990

According to Figure 3.15, by 2021-2050, under the RCP8.5 scenario, the $MTOW$ for the A350-1000 in summer $TX95p$ events is projected to be reduced by up to more than 7 tons at MXP and MAD, with respect to 1961-1990, according to the CMIP5 Multi-Model Ensemble (MME) mean. NCE, RAK and TLS are impacted by a decrease of more than 6.2 tons, about 4.4 tons and about 2.4 tons, respectively. The least affected airport is BCN, with a $MTOW$ reduction of 1.1 tons, approximately. ORY, FCO, ATH, LYS and IST are not concerned by any decrease in the $MTOW$ by the near term.

The A320-200 is projected to experience a decrease in its $MTOW$ of up to more than 2 tons at the airports for the next decades with respect to 1961-1990, as shown in Figure 3.16. Only MAD and RAK are affected among the major airports. They present a reduction in $MTOW$ of about 1.8 and 1.3 tons, respectively. Several regional and small airports are concerned: 37 out of 47 airports, which represents more than 78% of the airports. PRN, INI, TLZ and TIV are the most impacted, with a $MTOW$ reduction of between 1.9 tons and 2 tons. On the other hand, MAH, TPS and KVA are the least affected airports, with $MTOW$ reductions ranging from 0.2 to 0.4 tons only. The regional and small airports of VLC, LEI, ROZ, DBV, PUY, RHO, CHQ and GPA are not impacted. AHO, GPA and OLB also present reductions in $MTOW$ but they are of the same magnitude as the confidence interval. The average reduction in $MTOW$ for the affected regional and small airports is 1.1 tons.

Finally, Figure 3.17 shows that the $MTOW$ for the ATR72-212A is projected to be concerned by additional limitations by the near term with respect to the historical reference period only at three airports: QSA, LEU and JNX. The reductions in $MTOW$ found for the short-range aircraft are much smaller than those found for the large- and mid-sized aircrafts, ranging from 150 kg at JNX to 170 kg at LEU, as projected by the CMIP5 MME mean.

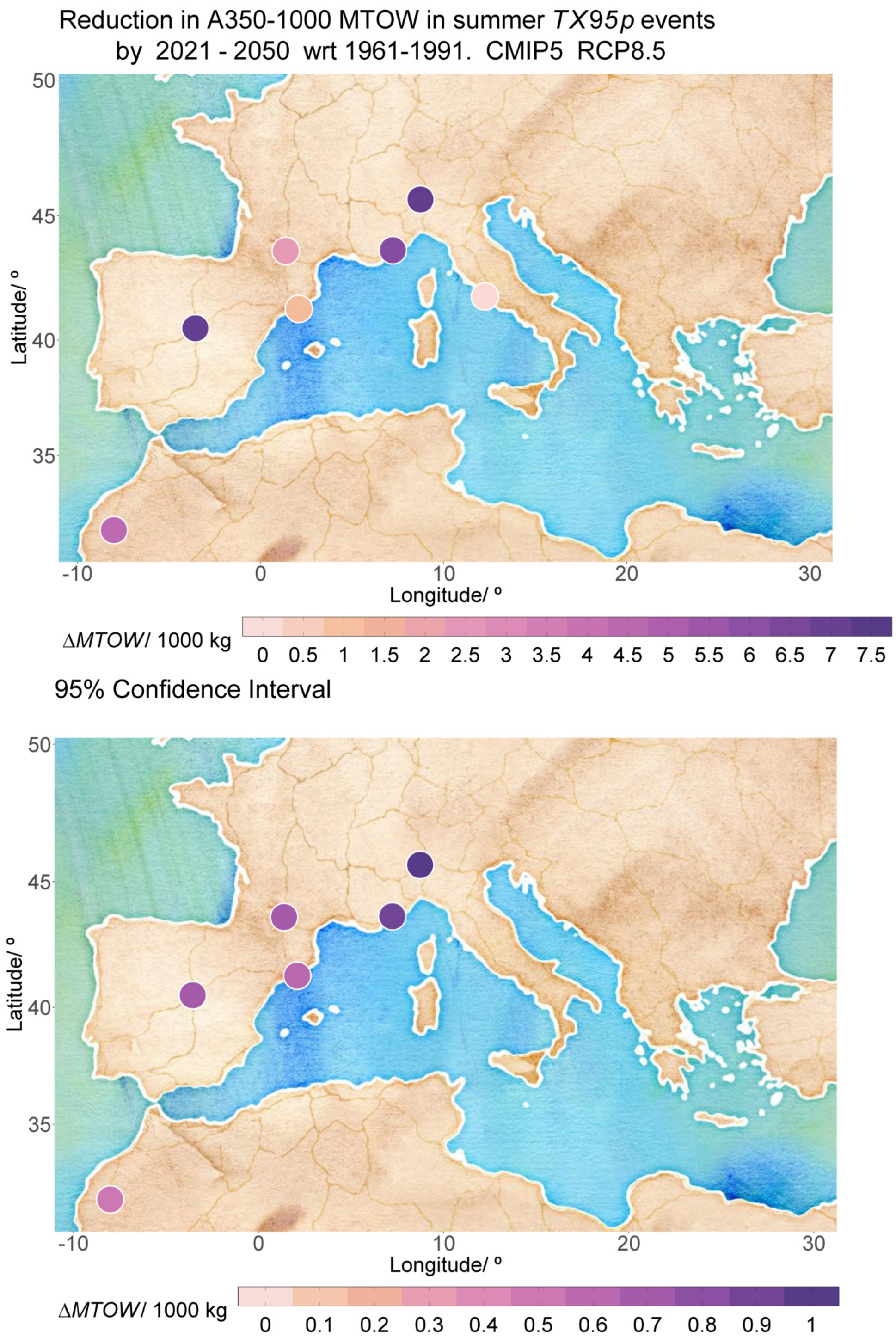

Figure 3.15: MTOW reduction in summer $TX95p$ events by 2021-2050 under the RCP8.5 scenario as projected by the CMIP5 MME mean (top), with respect to the reference period 1961-1990 over the airports, for the A350-1000 aircraft, and the 95% confidence interval (bottom). When the decrease in the MTOW is zero, the airport value is not shown.

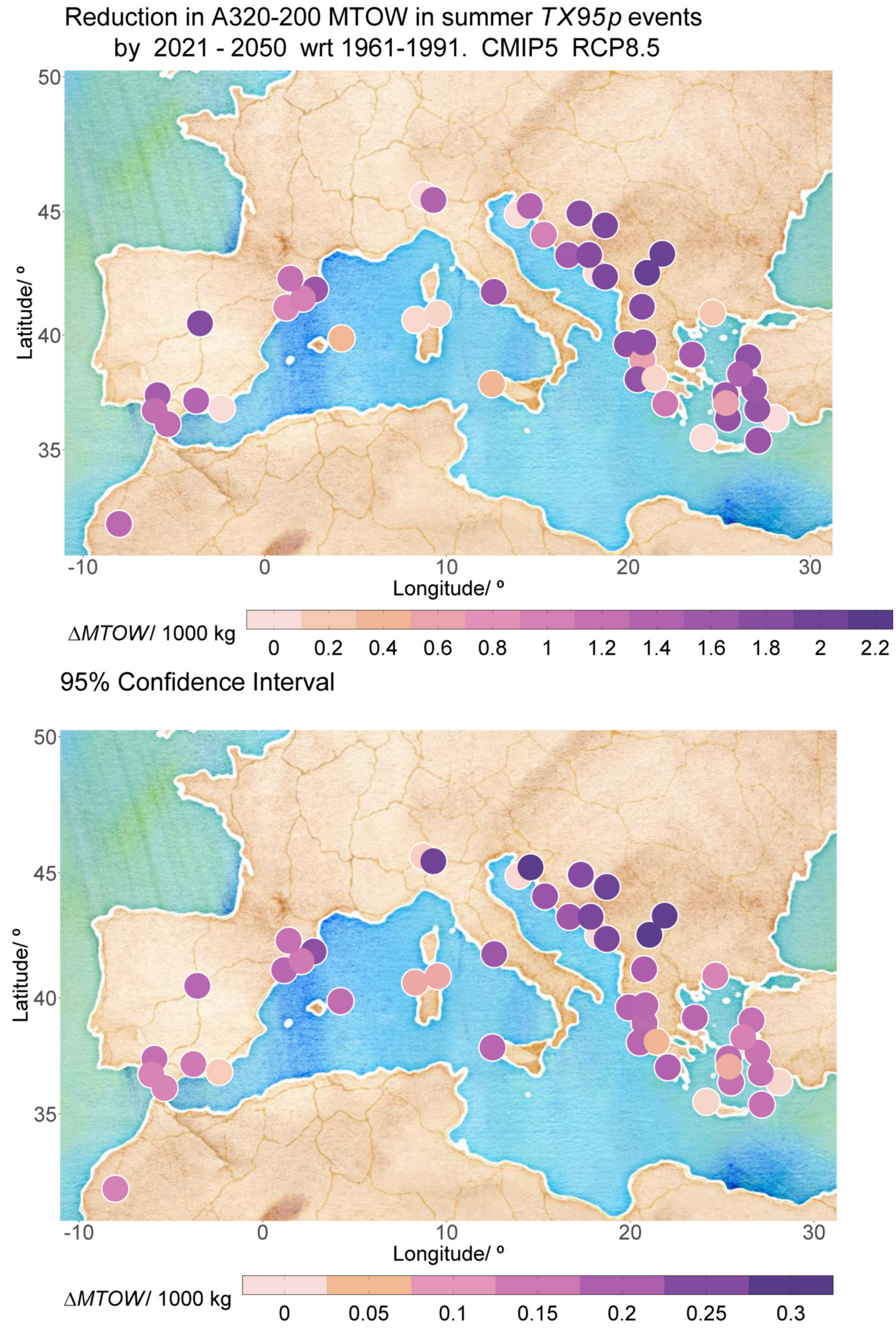

Figure 3.16: MTOW reduction in summer $TX95p$ events by 2021-2050 under the RCP8.5 scenario as projected by the CMIP5 MME mean (top), with respect to the reference period 1961-1990 over the airports, for the A320-200 aircraft, and the 95% confidence interval (bottom). When the decrease in the MTOW is zero, the airport value is not shown.

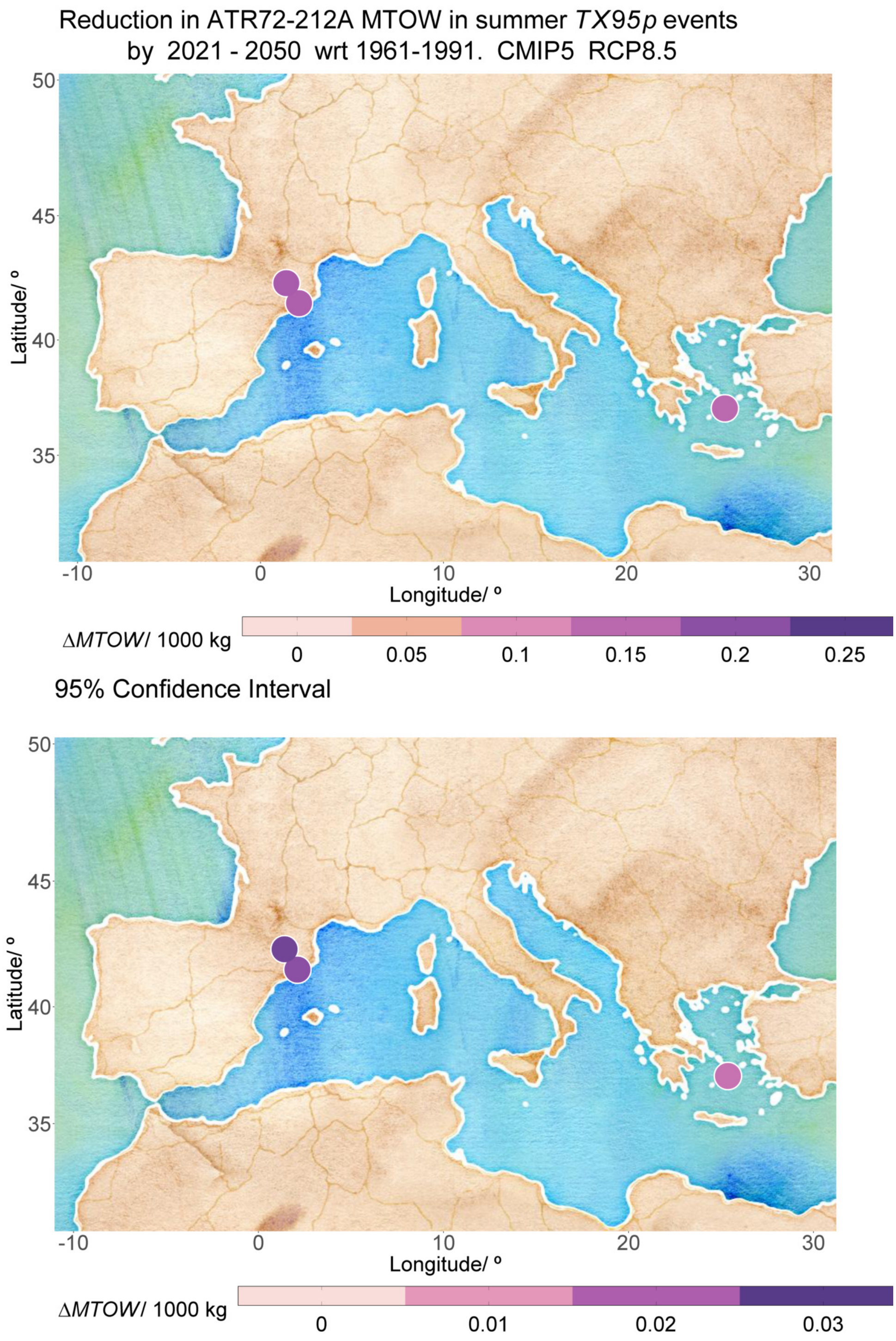

Figure 3.17: MTOW reduction in summer $TX95p$ events by 2021-2050 under the RCP8.5 scenario as projected by the CMIP5 MME mean (top), with respect to the reference period 1961-1990 over the airports, for the ATR72-212A aircraft, and the 95% confidence interval (bottom). When the decrease in the MTOW is zero, the airport value is not shown.

CORDEX vs. CMIP5 projections

Smaller reductions in the $MTOW$ are found according to the CORDEX MME mean than to the CMIP5 MME mean, as the CORDEX ensemble projects smaller changes than CMIP5 in the magnitude of the summer $TX95p$ over the airports [Gallardo 23]. By the near term, this difference is of around 0.7 tons for the A350-1000, of about 0.4 tons for the A320-200 and of around 50 kg only for the ATR72-212A, on average at the affected airports, as shown in Figure 3.18(a). By the mid-term, the differences are approximately of 0.4 tons, 0.7 tons and of 85 kg for the long-, medium- and short-range aircrafts, respectively.

Projections by 2041-2070 with respect to 1961-1990

By 2041-2070, additional constraints to $MTOW$ may arise, according to both CORDEX and CMIP5 MME means, as shown in Figure 3.18(b). The decrease in the A350-1000 $MTOW$ with respect to 1961-1990 could reach up to 11.2 tons at MXP (up to 10.8 tons at MAD), with 4.9 tons (5.0 tons) on average at the airports, as projected by the CMIP5 MME mean (by the CORDEX MME mean, respectively).

The decrease in the A320-200 $MTOW$ at the major airports of MAD and RAK could reach almost 2.8 and 2.0 tons (around 2.1 and 1.8 tons), respectively, relative to 1961-1990, regarding the CMIP5 MME mean (regarding the CORDEX MME mean). At the regional and small airports, the decrease could reach up to 2.1 tons (up to 1.4 tons) at PRN, with 1.1 tons (0.9 tons) less on average at the airports, as estimated from the CMIP5 MME mean (from the CORDEX MME mean, respectively). In addition, new airports that are not affected in the near term would be affected in the mid-term: OLB, KVA and GPA, as projected by the CORDEX MME mean.

The ATR72-212A could reach a reduction in $MTOW$ by the mid-century with respect to 1961-1990 of 330 kg (200 kg), 265 kg (165 kg) and 215 kg (150 kg) at LEU, QSA, and JNX, respectively, as shown by the CMIP5 MME mean (by the

CORDEX MME mean, respectively).

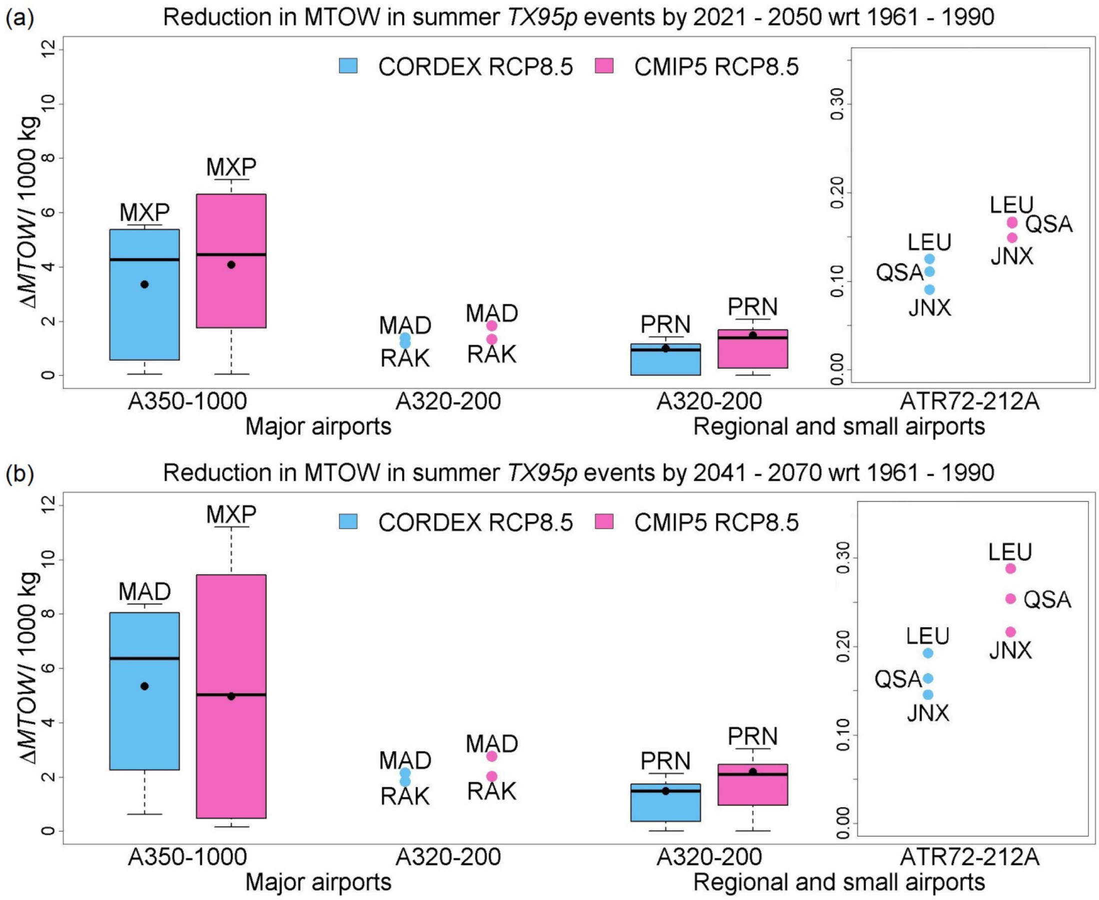

Figure 3.18: Reduction in the MTOW by 2021-2050 (a) and by 2041-2070 (b) with respect to 1961-1990, according to the increase in the magnitude of the summer 95th percentile of the daily TX as projected by the CORDEX and CMIP5 MME means (in blue and pink, respectively), under the RCP8.5 scenario. The boxes are delimited by the first and third quartiles, with the median indicated by the segment in between, and black points indicating the mean across the airports. The lower (upper) whiskers correspond to the minimum (maximum) values of the distribution in each case. When the decrease in the $MTOW$ is zero, the airport value is not considered.

The magnitude of the impact on the $MTOW$ is projected to be greater for the A350-1000 than for the A320-200 and the ATR72-212A, as shown in Figure 3.18. This is in alignment with the previous findings in [Coffel 17], about the larger impact on the $MTOW$ for long-couriers than for mid-sized aircrafts. Nonetheless, the relative impact with respect to the $MTOW_0$ of each aircraft model is projected to be greater for the A320-212A than for the A350-1000 and the ATR72-212A. By the near term, for instance, the average reduction in $MTOW$ at the airports with respect to 1961-1990 corresponds to 1.9% of the $MTOW_0$ for the A320-200, as estimated from the CMIP5 MME mean, as compared to 1.3% for the A350-1000 and to 0.5% for the ATR72-212A. By the mid-term, this relative reduction will be of about 2.8% for the A320-200, as projected by CMIP5 MME mean, as compared to 1.6% for the A350-1000 and to 0.8% for the ATR72-212A.

In addition to the study on the summer $TX95p$, other percentiles have been investigated: 0.1, 0.5, 1.0, 5.0, 10.0, 20.0, 30.0, 40.0, 50.0, 60.0, 70.0, 80.0, 90.0, 95.0, 99.9, 99.5 and 99.9$^{\mathrm{th}}$. The resulting discrete cumulative distribution function of the summer TX for each period of study is considered along with the $MTOW$ estimates for each summer TX percentile in that period, in order to obtain the number of summer days on which different $MTOW$ constraints arise during the TX hour. This allows the analysis of the evolution of the number of summer days potentially restricted by different weights.

Figure 3.19 and Figure 3.20 show the increasing trend in the number of $MTOW$-limited days by different weights for MXP and MAD airports concerning the A350-1000 aircraft, and for MAD, RAK and PRN concerning the A320-200, respectively. These airports were previously identified as the most affected by the future decrease in $MTOW$ with respect to 1961-1990 in summer $TX95p$ events. At MXP, $MTOW$ limitations of 3 tons for the A350-1000 could become necessary on 60% of summer days in next decades, while they were present only on 30% in 1961-1990, and they could affect 70% of summer days by the mid-century, and up to nearly 100%, according to some climate models (see Figure 3.19(a). $MTOW$ limitations of 12, 15 and 20 tons were not present in 1961-1990, but climate models project they could be on about 20%, 10% and 3% of summer days by the near term, and on about 35%, 20% and 10% by the mid-term, respectively. Also, at MAD, $MTOW$ limitations of 20 tons could arise on about 10% and 25% of days in summer by 2021-2050 and 2041-2070, respectively, in contrast to 0 days in 1961-1990 (see Figure 3.19(b). Weight constraints of 3 and 5 tons, which characterized 50% and 40% of summer days in the latest decades, respectively, could become present on up to 100% in the near future as projected by some climate models. These mass values correspond to nearly 2% and more than 3% of the maximum variable TOW of the aircraft.

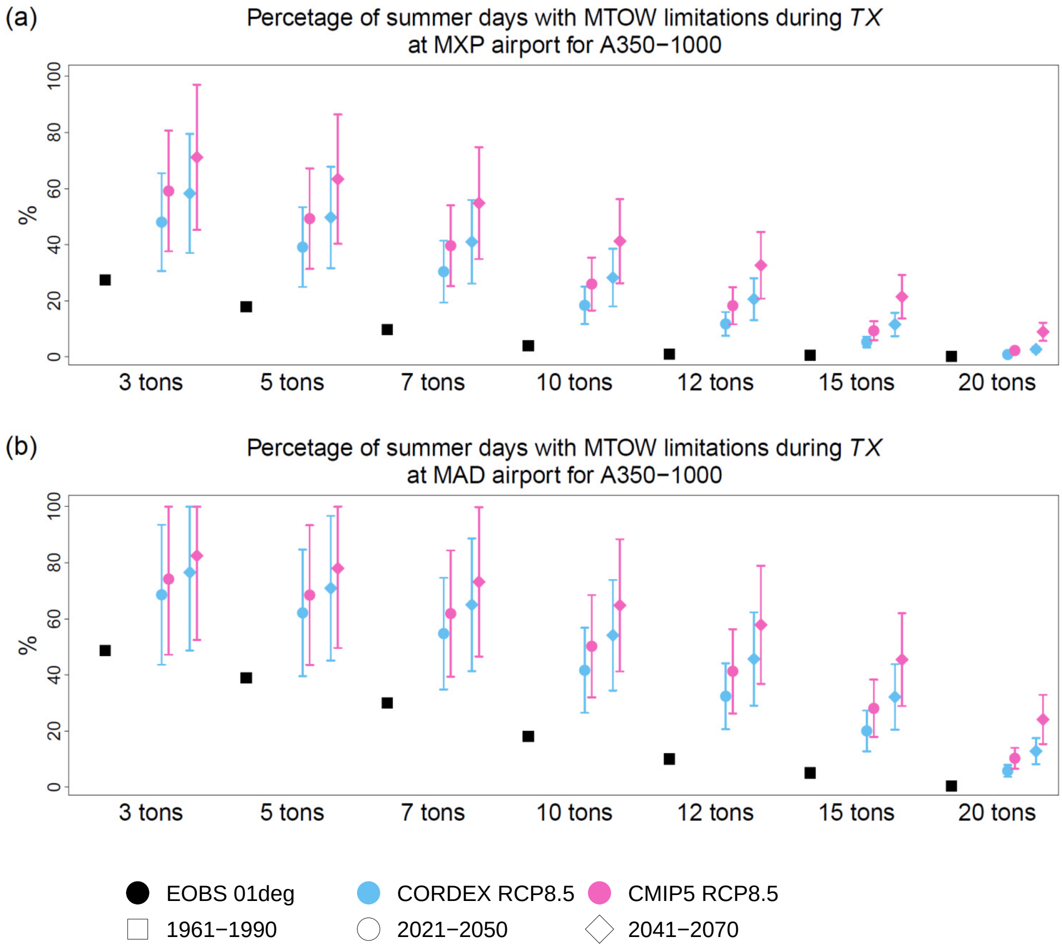

Figure 3.19: Evolution of summer days percentage with different MTOW limitations during TX for the period 1961-1990 (squares) according to the EOBS 01deg dataset (black), and as projected by the bias-corrected CORDEX (blue) and CMIP5 ensembles (pink) by 2021-2050 (circles) and by 2041-2070 (diamonds), under the RCP8.5 scenario: (a) at MXP for the A350-1000, (b) at MAD for the A350-1000. Error bars correspond to the 95% confidence interval (in the observational period they are smaller than the dots size).

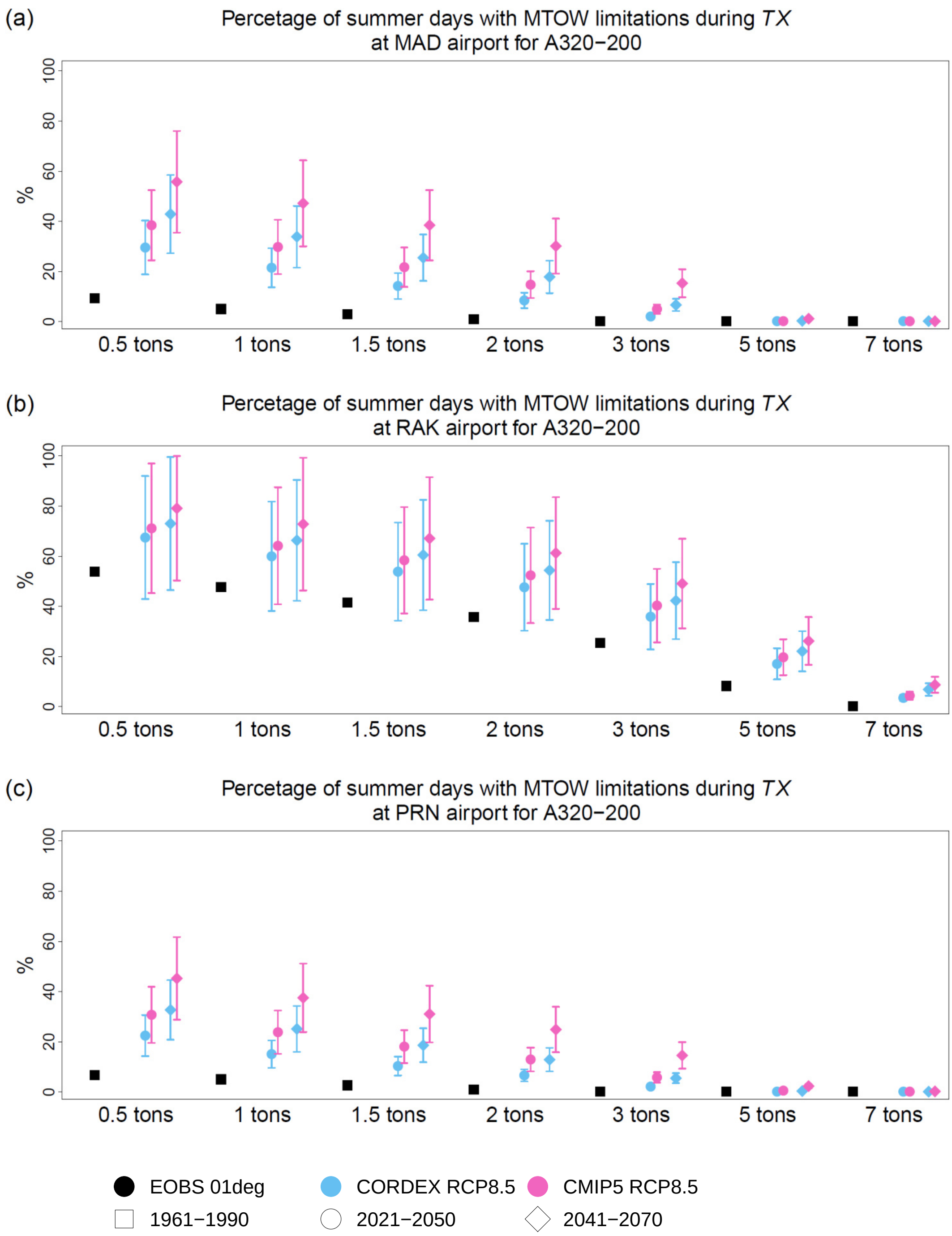

Figure 3.20: Evolution in the percentage of summer days with different MTOW limitations during the daily TX hour for the observational period 1961-1990 (squares) according to the EOBS 01deg dataset (black), and as projected by the bias-corrected CORDEX and CMIP5 ensembles (blue and pink, respectively) by 2021-2050 (circles) and by 2041-2070 (diamonds), under the RCP8.5 scenario: (a) at RAK for the A320-200, (b) at MAD for the A320-200 and (c) at PRN for the A320-200. Error bars correspond to the 95% confidence interval (in the observational periods they are smaller than the dots size).

For the A320-200, the $MTOW$ may become constrained in some summer days by 3 tons from the next decades at MAD and PRN, while they were not present at all on the past reference period (see Figure 3.20(a) and Figure 3.20(c). At RAK, the mid-sized aircrafts could start being limited by about 7 tons in $MTOW$ on 5% of summer days in the next thirty years (see Figure 3.20(b). It is worth noting that 3 and 7 tons represent about 8.5% and nearly 20% of the maximum variable TOW of this aircraft model, respectively.

3.3.2.5 Discussion

As highlighted in [Hane 16], even if the aircraft is not capable of taking off with 100% of its manufacturer-certificated $MTOW_0$, weight restrictions may not be necessary, as commercial flight missions rarely involve this quantity. Therefore, the $MTOW$ limitations as a result of global warming found in this study for commercial aircrafts could have no impact at all on the weight of future flight missions. The large constraints found here, specially those of the order or tens of tons, could however result in actual restrictions. The percentage of summer days where these limitations are projected to be present is substantial. The airline schedules would be necessary to conduct the impact study on that term, as also pointed out in previous studies [Coffel 17, Zhou 18b, Carpenter 18]. In any case, this future reduction in $MTOW$ is symptomatic of decreased aircraft and engine performances at takeoff. Thus, the magnitude of this reduction is linked with the magnitude of the impact of higher temperature extremes on aircraft takeoff performances over the airports studied. In absolute terms, the long-courrier aircraft model is affected by greater $MTOW$ limitations, on average, than the medium- and short-courrier aircraft models considered, which is consistent with previous studies [Coffel 17,Zhao 20,Gratton 20]. However, in relative terms to their respective $MTOW_0$, the narrowbody jet A320-200 results to be the most affected in the Euro-Mediterranean region. According to https://www.statista.com/, the narrowbody jets would have represented 60% of the worldwide commercial aircraft fleet in 2022.

Therefore, the commercial aviation could be notably affected. Even if the aircraft is able to take off with its $MTOW_0$, weight restrictions to passengers and cargo may become necessary if extra fuel is required due to reduced performances. The aircraft weight distribution between fuel, cargo, passengers and crew depends on the mission and on airlines policies, and data from the involved companies would be necessary in order to find more accurate results.

Additional weight limitations may become necessary if the aircraft needs to attain a certain climb rate to clear obstacles at takeoff, specially for large size aircrafts. This is not taken into account in the method for the $MTOW$ derivation used here. Moreover, the climate model projections used are likely too conservative [Chen 14, Ribes 22]. The limitations on $MTOW$ could be then greater than those obtained in this study, potentially involving weight restrictions.

Furthermore, we show that the uncertainty in the future projected $MTOW$ limitations is too wide, given the large MME spread of both CORDEX and CMIP5 at the airport scale. Other data sets should be explored to see whether it is possible to reduce this uncertainty, such as an ensemble of future climate projections observationally constrained [Ribes 22]. Sub-selecting the climate models that best fit to the purpose of the study amongst the ensembles, or weighting the climate model projections according to the model performances are other options which may be used to reduce the uncertainty in climate projections [IPCC 21]. Also, the use of climate model emulators, with reduced complexity, could help reduce climate modelling uncertainties and produce more adapted information at regional to local scales [IPCC 21]. Large efforts are being made by the scientific community to reduce uncertainty in climate projections and to adapt climate information for impact assessment and the design of adaptation and mitigation strategies at regional and local scales. For instance, this is one of the main objectives of the ambitious French initiative TRACCS[1].

[1] https://climeri-france.fr/traccs-objectifs/

3.3.2.6 Conclusion

In this study the impact of the increasing magnitude of high-temperature extremes on aircraft takeoff performances over the Euro-Mediterranean region is assessed. Three aircraft models representing the most part current fleet are selected: the A350-1000 for the long-range aircrafts, the A320-200 for the medium-range aircrafts and the ATR72-212A for the short-range aircrafts. Major and regional and small airports are considered. Climate data are used along with aircraft technical data, and an empirical law is applied, in order to obtain the $MTOW$ limitations for each aircraft type at the airports by 2021-2050, and by 2041-2070, under the RCP8.5 scenario, with respect to 1961-1990. Not all of the selected airports are impacted, but most of them are, at least concerning one of the aircraft types. In general, the $MTOW$ limitations are of the order of thousands of kg, except for the short-range aircraft ATR72-212A, for which they are one order of magnitude smaller ($\sim$ 100 kg). The average weight per passenger plus the carry-on weight plus the carry-on luggage is of about 100 kg per passenger, according to [EASA 22b]. Therefore, the $MTOW$ limitations found at the Euro-Mediterranean airports may potentially lead to weight restrictions of the order of tens of passengers for the long- and medium-range aircrafts, while of few passengers only for the short-range aircrafts. However, there is a large uncertainty in future climate projections that needs to be narrowed, and the use of airlines schedules data is also suitable for accurate results. Nevertheless, the study illustrates the magnitude of the impact of aircraft takeoff performances in the Euro-Mediterranean region based on $MTOW$ limitations, which account for lift and thrust reduction under higher temperature extremes. In addition, the use of both a multi-RCM and a multi-GCM ensemble for assessing future climate projections over the airports allows for better accounting for climate modelling uncertainties. The method to derive the $MTOW$ limitations with the temperature used here is also new with respect to the previous climate impact assessments conducted in this regard. The empirical law suggested by the aircraft manufacturer company could be more suitable than the 4-point fit used in [Coffel 15], [Coffel 17] and [Zhou 18a], for instance, or the Koch charts used in [Zhou 18b], leading to more accurate results.

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Special thanks to Serge Bonnet (Airbus) for the instructive lessons on aircraft performances and all of the interesting discussions on the analyses and results. We are also grateful to him for his key role in providing us with the aircraft technical data and the empirical law for the MTOW, as well as to Julien Jaskulski and Julien Decronsonnière (Airbus).

Appendix 1 Climate simulations

Table 3.8: The RCM × GCM matrix indicating which combinations from the Euro-CORDEX Historical and RCP8.5 scenario experiments were available for the study.

	CNRM-CM5	EC-EARTH	HadGEM2-ES
CLMcom-CCLM4-8-17	r1i1p1	r12i1p1	r1i1p1
CLMcom-ETH-COSMO-crCLIM	r1i1p1	r1i1p1	r1i1p1
CNRM-ALADIN53	r1i1p1		
CNRM-ALADIN63	r1i1p1		r1i1p1
DMI-HIRHAM5	r1i1p1	r1i1p1	r1i1p1
GERICS-REMO2015	r1i1p1		
ICTP-RegCM4-6			r1i1p1
IPSL-WRF-381P	r1i1p1	r12i1p1	r1i1p1
SMHI-RCA4			

	IPSL-CM5A-MR	MPI-ESM-LR	NorESM1-M
CLMcom-CCLM4-8-17		r1i1p1	
CLMcom-ETH-COSMO-crCLIM		r1i1p1	r1i1p1
CNRM-ALADIN53			
CNRM-ALADIN63		r1i1p1	r1i1p1
DMI-HIRHAM5	r1i1p1	r1i1p1	r1i1p1
GERICS-REMO2015			
ICTP-RegCM4-6		r1i1p1	
IPSL-WRF-381P	r1i1p1	r1i1p1	r1i1p1

Table 3.9: List of GCM simulations from the CMIP5 Historical and RCP8.5 scenario experiments analysed in this study.

GCM	realisation
ACCESS1-0	r1i1p1
BNU-ESM	r1i1p1
CCSM4	r1i1p1
CESM1-BGC	r1i1p1
CESM1-CAM5	r1i1p1
CMCC-CESM	r1i1p1
CMCC-CMS	r1i1p1
CMCC-CM	r1i1p1
CNRM-CM5	r1i1p1
CSIRO-Mk3-6-0	r10i1p1
CanESM2	r1i1p1
EC-EARTH	r1i1p1
FGOALS-g2	r1i1p1
GFDL-CM3	r1i1p1
GFDL-ESM2G	r1i1p1
GFDL-ESM2M	r1i1p1
HadGEM2-AO	r1i1p1
HadGEM2-CC	r1i1p1
HadGEM2-ES	r1i1p1
IPSL-CM5A-LR	r1i1p1
IPSL-CM5A-MR	r1i1p1
IPSL-CM5B-LR	r1i1p1
MIROC-ESM-CHEM	r1i1p1
MIROC-ESM	r1i1p1
MIROC5	r1i1p1
MPI-ESM-LR	r1i1p1
MPI-ESM-MR	r1i1p1
MRI-CGCM3	r1i1p1
MRI-ESM1	r1i1p1
NorESM1-M	r1i1p1
bcc-csm1-1-m	r1i1p1
inmcm4	r1i1p1

Appendix 2 Degrading MTOW with temperature

For turbofan-engine aircrafts A350-1000 and A320-200:

$$MTOW(T < T_{\text{ISA}} + 15°\text{C}) = \begin{cases} MTOW(T_{\text{ISA}} + 15°\text{C}) \times \left(\dfrac{T_{\text{ISA}} + 15°\text{C}}{T}\right)^{0.5}, \text{ if } TOFL < L_0 \\ \\ MTOW(T_{\text{ISA}} + 15°\text{C}) \times \left(\dfrac{T_{\text{ISA}} + 15°\text{C}}{T}\right)^{0.08}, \text{ if } TOFL > L_0 \end{cases}$$

$$MTOW(T > T_{\text{ISA}} + 15°\text{C}) = \begin{cases} MTOW(T_{\text{ISA}} + 15°\text{C}) \times \left(\dfrac{T_{\text{ISA}} + 15°\text{C}}{T}\right)^{2.0}, \text{ if } TOFL < L_0 \\ \\ MTOW(T_{\text{ISA}} + 15°\text{C}) \times \left(\dfrac{T_{\text{ISA}} + 15°\text{C}}{T}\right)^{2.2}, \text{ if } TOFL > L_0 \end{cases}$$

with $L_{0,\text{A350-1000}} \simeq 3665$ m and $L_{0,\text{A320-200}} \simeq 2980$ m the corresponding values of the length of the lift segment, obtained graphically from the ACAP curves.

For turboprop-engine aircraft ATR72-212A:

$$MTOW(T < T_{\text{ISA}} + 24°\text{C}) = \begin{cases} MTOW(T_{\text{ISA}}) \times \left(\dfrac{T_{\text{ISA}}}{T}\right)^{0.75}, \text{ if } TOFL < L_0 \\ \\ MTOW(T_{\text{ISA}}) \times \left(\dfrac{T_{\text{ISA}}}{T}\right)^{0.43}, \text{ if } TOFL > L_0 \end{cases}$$

$$MTOW(T > T_{\text{ISA}} + 24°\text{C}) = \begin{cases} MTOW(T_{\text{ISA}}) \times \left(\dfrac{T_{\text{ISA}}}{T}\right)^{2.0}, \text{ if } TOFL < L_0 \\ \\ MTOW(T_{\text{ISA}}) \times \left(\dfrac{T_{\text{ISA}}}{T}\right)^{2.2}, \text{ if } TOFL > L_0 \end{cases}$$

with $L_{0,\text{ATR72-212A}}$ the length of the lift segment, obtained graphically from the ACAP curves provided by AIRBUS (not specified due to confidentiality issues).

The values for k and for $T_{\text{threshold}}$ and $T_{\text{reference}}$ were provided by Airbus.

In some cases, it was necessary to extrapolate the ACAP curves for runways out of the chart range, usually for longer runways, specially for the ATR72-212A, and for shorter runways in a few cases too.

CHAPTER 4

Conclusions

4.1 SYNTHESIS

The changes in mean and extreme weather conditions as a result of climate change affect the aviation operations. This thesis responded to the emerging interest of aircraft manufacturers (AIRBUS), national and international aviation-related organizations (the French Civil Aviation Authority, EASA, EUROCONTROL) and airlines (AirFrance), in assessing the potential impact of climate change on General Aviation operations. In particular, this thesis addressed the effects of increasing high-temperature extremes at the airports on aircraft takeoff performance, focusing on the Euro-Mediterranean region, one of the most affected by climate change. The impact was assessed in terms of increased levels of NO_x emissions and reduced engine performance, and in terms of decreased maximum takeoff load capacity of the aircraft.

In Chapter 2, the past and future evolution of high-temperature extreme events over a list of Euro-Mediterranean airports was analysed from observations and climate model simulations and projections. Climate models were evaluated in present climate and the added value of RCMs was assessed with respect to the

GCMs in terms of their ability to simulate extreme events and their past trends at the airport scale. In a second stage, the future projections of RCMs were compared to those of the GCMs. Before the impact assessment, the magnitude of high-temperature extreme events in future climate was estimated by applying a bias correction to the future climate projections. The main conclusions from this chapter are the following:

- Euro-Mediterranean airports have experienced an increase in high-temperature extremes in the recent decades, and they will be concerned by a future further increase along the 21st century. This could have negative consequences on the airline industry, making adaptation or mitigation policies necessary.

- There is no generally prevailing added value of the state-of-the-art multi-RCM ensemble Euro-CORDEX over the driving multi-GCM ensemble CMIP5 for the representation of high-temperature extremes and their trends over the airports, both ensembles remaining compatible with observations.

- GCMs project a larger future warming than RCMs over the same locations.

- Given the last two points, both RCMs and GCMs ensembles should be considered for impact studies and the design of adaptation and mitigation policies at regional and local scales, in order not to underestimate climate modelling uncertainties.

- The future magnitude of high-temperature extremes as projected by the bias-corrected climate models is most likely to be underestimated, and so would be the inferred magnitude of the potential impact.

In Chapter 3, the future potential impact on aircraft takeoff performance induced by the projected increase in high-temperature extremes was assessed. In sub-Chapter 3.2, the changes in the levels of NO_x emissions and in engine performance over major Euro-Mediterranean airports were analysed using the Gasturb engineering software. In sub-Chapter 3.3, the evolution of the aircraft's maximum carrying capacity over major, regional and small airports in the region of study was analysed using an empirical law suggested by AIRBUS combined with aircraft manufacturers data. The A350-1000, A320-200 and ATR72-212A models were considered to be representative for the long-, medium- and short-range aircrafts, respectively. The key findings of this chapter are the following:

- As a result of the rise in temperatures, Euro-Mediterranean airports will be concerned by an increase in the levels of NO_x emissions by the aircraft engine, as well as by the decrease in engine performance at takeoff.

- The increase in the levels of NO_x emissions by the aircraft engine could lead to the increase in the NO_x absolute emissions at takeoff of the order of a few percentage points in future extreme events: up to nearly +4% and +6% by the near and medium term, respectively. This, together with the increased fuel consumption resulting from the decreased aircraft and engine performances plus the projected growth in air traffic could result in a substantial increase of the NO_x absolute emissions from aviation in the future. As a consequence, the climate system would be subjected to additional radiative forcing, which could further enhance the warming of high-temperature extremes, thus closing a positive feedback loop. In addition, higher NO_x emissions could deteriorate the air quality at the airport and the vicinities, with potentially negative consequences for human health.

- The decreased aircraft engine performance will result in higher fuel consumption in order to achieve the same operational requirements under higher temperature extremes in the future. This will consequently lead to greater absolute emissions from aviation, both gaseous and particulate, not only of NO_x, which could negatively affect the environment and biodiversity, socio-economics and human health.

- Euro-Mediterranean airports will be concerned by the decrease in the aircraft's maximum carrying capacity at takeoff as a result of lower engine performance and aircraft lift under higher temperature extremes in future climate. Major, regional and small airports will be affected, at least for one aircraft type amongst the long-, medium- and short-range courriers.

- The future reductions in MTOW are generally of the order of tons for the long- and medium-range aircrafts, which could result in weight restrictions corresponding to tens of passengers and/or in delays or cancellations. This would cause an important socio-economic impact for airlines and customers, most of the current fleet being composed of mid-sized aircrafts. The short-range aircrafts would not be concerned by reductions in MTOW over the vast majority of the airports considered in the domain, and where they are, the reductions in MTOW are of the order of 100 kg as compared to the 1000 kg found for the other two aircraft types.

Despite the robust positive trend found for the levels of NO_x emissions and the MTOW limitations, there are large uncertainties in the magnitude of the impacts. They mainly arise from uncertainties in climate projections that would need to be narrowed for the design of adaptation and/or mitigation strategies in the future. The system approaches developed and used by aircraft engine manufacturers to simulate the behavior of the whole engine, could have led to more realistic results of the engine performance and pollutant emissions. Also, more accurate results could have been obtained by using an aviation operational software for pilots for the MTOW computation, instead of an empirical law. Moreover, the use of operational data from flight companies and Air Traffic Management (ATM) systems would have allowed a better estimation of the potential impact on the airline industry.

This thesis assessed some of the maximum potential impacts that climate change may have on General Aviation operations in the coming decades. It showed the magnitude of the negative effects that the increase in high-temperature extremes would have on aircraft takeoff performance in terms of pollutant emissions, engine performance and MTOW limitations. All this focused on one of the world's most sensitive areas to climate change: the Euro-Mediterranean region. Moreover, it highlighted the positive feedback loop between the rising temperatures and the rising NO_x emissions from aviation. In addition, this thesis provided new methodologies to estimate the impacts of climate change on aircraft takeoff at any airport in the world.

We expect that this work will attract the attention of airlines, engine and aircraft manufacturers as well as other stakeholders, in the hope that they will be interested in collaborating with us to refine the impact assessment.

4.2 PERSPECTIVES

To improve the simulation of high-temperature extremes at the airports scale within RCMs

We have shown that climate models present biases in the simulation of high-temperature extremes at the airports scale. RCMs overestimate their magnitudes, on average, contrary to GCMs, which underestimate them, while the trends simulated by the two ensembles are generally coherent with observations. The improvement of the simulation of high-temperature extremes in this regard could lead to more accurate results of the magnitude of the future impacts of climate change on aviation. Recent studies give hints for improving the representation of high-temperature extremes by RCMs in particular. It has been suggested that a more detailed modelling of cities [Daniel 19] (including airports), a better consideration of aerosols and their transport [Nabat 20] or the simulation of deep atmospheric convection [Lucas-Picher 21] would contribute to a better representation of surface temperatures at regional and local scales. In particular, it is possible to couple the

RCM ALADIN-Climat developed by the French National Centre for Meteorological Research (CNRM) [Spiridonov 05] with the Town Energy Balance model (TEB; [Masson 00]) for urban canopy, as in [Daniel 19]. This could lead to a better simulation of extreme local phenomena such as the high-temperature extremes over the airports, potentially leading to more accurate results from the impact study. Moreover, the use of the Convection-Permitting RCM CNRM-AROME [Seity 11, Termonia 18, Caillaud 21] at 2.5 km of horizontal spatial resolution coupled with TEB, as in [Michau 23], could also be a more suitable tool for the study of weather phenomena at local scale of urban areas. These possibilities could be explored in future work.

Moreover, the recent configuration for the CNRM-ALADIN released by the CNRM has been found to achieve a better representation of high-temperature extreme values and trends over the airports selected in the study, with respect to the previous Euro-CORDEX versions. In particular, this configuration includes the following improvements:

- a tuning for the hydrological and radiative balances (radiative properties of clouds, cloud scheme, convection scheme, soil depth...),
- an interactive aerosol scheme,
- an more realistic climatology for ozone,
- the use of the spectral nudging technique [von Storch 00] to correct the divergent behavior of the atmosphere at the boundaries of the domain of the experiment.

Since all of these elements were considered altogether in the tunning process of the model, more research efforts should be made in order to identify the key features among the list above which have led to a better simulation of high temperature extreme values and trends in a changing climate at the local scale.

In addition to the need for improving climate models, there is the need for narrowing climate model uncertainties. In this thesis, the uncertainties in climate projections are estimated using multi-model ensembles, considering one realisation or member per model only, without model discrimination, and characterized by the 95% confidence interval of the ensemble, as in [IPCC 13, IPCC 21], or by the MME spread (min/max) in [Gallardo 23]. Nonetheless, it would be possible to reduce these uncertainties by considering only the projections of climate models whose performances best fit the purpose of the study, or by weighting climate model projections according to model performances, as discussed in [IPCC 21]. Climate model emulators could help reducing climate modelling uncertainties too, and produce more adapted information at regional to local scales [IPCC 21].

Future work could also be based on the use of observationally constrained future climate projections for the analysis of the evolution of high-temperature extremes over the airports [IPCC 21, Ribes 22]. The emergent constraints are based on identifying the relationship between two variables simulated by climate models, one in future climate, Y, and the other in present climate, X [Hall 19]. Once this relationship is identified, the range of observed values of X in present climate can be used to narrow or constrain the range of plausible future values of Y as projected by the climate models. This constitutes another technique for reducing uncertainties in future climate projections [IPCC 21].

To consider the diurnal cycle

In this thesis, only the daily maximum near-surface air temperature in summer is considered to assess the induced impacts by the rising high-temperature extremes at the airports. Taking into account the diurnal cycle of the near-surface air temperature in the warm season, as in [Coffel 17], could lead to a more precise evaluation of the impact on aircraft operations. In particular, it would allow for determining at what time of the day the impacts will be more relevant and whether, for example, aircrafts should takeoff at earlier/later times on extremely hot days.

Other fact to consider is that temperatures that characterized the summer season in latest decades will also characterize the preceding and later months to the summer in the future, as a consequence of global warming. The months of May and September should also be considered for future impact assessment in these terms. This would help get further knowledge about the potential impacts.

Additionally, the consideration of the changes in other weather variables, along with the changes in temperature, could lead to more accurate results on the magnitude of future potential impacts. In particular, the changes in relative humidity could be considered within Gasturb for the evaluation of the changes in NO_x emissions. However, data for this variable at the suitable hourly temporal resolution are rarely available, and the data from the local meteorological services are not easily accessible. The Integrated Surface Database (ISD) of the U.S. National Oceanic and Atmospheric Administration (NOAA) could be an option in this regard. It includes data from meteorological *in situ* stations worldwide at hourly resolution. Airports often have their own automated weather station recording meteorological data at least each hour, and sometimes even more frequently. The meteorological variables recorded include the near-surface air temperature, the dewpoint temperature (for humidity computation) and the atmospheric pressure. The ISD database includes data from these automated stations for many airports in the world. Nonetheless, these data must undergo a quality control before being used. Efforts should be deployed in this direction, given the great potential of this database, not only for improving impact assessment, but also for improving the understanding of extreme heat events at the local scale and for the evaluation and improvement of climate models in this regard.

To expand the study to airports in other regions

The main advantage of the methodology followed to assess the impacts is that it can be applied to any other airport. The CORDEX initiative covers the globe with regional domains, and regional future climate projections are available for any other region of the world, not just the Euro-Mediterranean. Also, the simulations from the CMIP successive initiatives span the globe.

Even if the results are not shown in this thesis, some major international airports have already been included in the analysis: Dubai (United Arab Emirates), Nairobi (Kenia), Hong Kong (China), Phoenix (U.S.), Mexico, Saint Martin (France/ the Netherlands), Quito (Ecuador), Bogotá (Colombia), Santiago de Chile and Juan Santamaría (Costa Rica). They were suggested by AirFrance and they are considered as potentially vulnerable to the increase in high-temperature in terms of aircraft performances because they are already limited by short runways, by high elevation and/or by extremely high temperatures already in present climate.

Furthermore, an action-oriented gridded dataset could be developed for air traffic and airport adaptation, following this methodology and using the climate data considered here, combined with all airport locations in the domain and their characteristics (elevation, runway length).

To assess the impact on global aviation emissions

In this thesis, the potential increase in the NO_x emissions by the aircraft engine was assessed as a function of the projected rise in high-temperature extremes at the airports. The future increase in global emissions from aviation, including NO_x, due to decreased aircraft and engine performances under warmer ambient temperatures still needs to be assessed. This would require operational data from airlines. This would also require the consideration of climate data of the diurnal temperature (and humidity) cycle(s) to estimate the integrated change in emissions over time.

In addition, the projected growth in air traffic should be considered.

To assess the impact on the local air quality

The rise in aircraft's emissions at the airport due to increased fuel consumption and to increased levels of NO_x produced under warmer ambient high temperatures may negatively impact the air quality at the airport and the surroundings. This can potentially threaten human health. An event-based approach could be applied to compare the air quality at the airport in a high-temperature extreme episode in future climate with respect to recent climate, for a case study. To this end, the projected future climate conditions and the future estimates for aircraft emissions should be considered along with a pollutant dispersion model and a method for deriving the air quality at the airport. This work could be done in collaboration with the French Aerospace Lab-ONERA, as they have already developed an approach to determine the impact of aircraft's pollutant emissions on the airport's air quality [Sarrat 17].

To assess other impacts induced by the increase in high-temperature extremes at the airports

The future magnitude of high-temperature extremes projected over the Euro-Mediterranean airports selected as case studies could be used to assess other induced impacts of rising high temperatures on aviation. For instance, they could be used to assess the impact on landing performances, on the aircraft tire-pavement adhesion, on the melting of the runway asphalt, on human and infrastructural heat stress, on fire risk, on the energy consumption, etc.

All of this further research could be developed in the framework of the new EASA's European Network on Impact of Climate Change on Aviation. This initiative seeks to comply with the objectives of the *European Climate Law* for "enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change" of the aviation sector. Indeed, managing the impacts of climate change on aviation safety appears amongst the strategic objectives in the *European Plan for Aviation Safety 2023-2025* [EASA 23].

Conclusions (FR)

Le changement des conditions climatologiques moyennes et extrêmes résultant du changement climatique affectent les opérations aériennes. Cette thèse répond à l'intérêt émergent des constructeurs aéronautiques (AIRBUS), des organisations nationales et internationales de l'aviation (la Direction Générale de l'Aviation Civile, l'EASA, EUROCONTROL) ainsi que des compagnies aériennes (AirFrance), pour évaluer l'impact potentiel du changement climatique sur les opérations de l'Aviation Générale. En particulier, cette thèse s'est focalisée sur les effets de l'augmentation des extrêmes de hautes températures sur la performance du décollage des avions, en ciblant les aéroports de la région Euro-Méditerranéenne, l'une des plus concernées par le changement climatique. L'impact a été évalué en termes de l'augmentation des niveaux d'émissions de NO_x et de la réduction de la performance du moteur, et en termes de la diminution de la masse maximale décollable de l'avion.

Dans le Chapitre 2, l'évolution passée et future des événements extrêmes de hautes températures a été analysée sur une liste d'aéroports Euro-Méditerranéens à partir d'observations et de simulations et projections de modèles climatiques. Les modèles climatiques ont été évalués dans le climat présent, et la valeur ajoutée des RCMs sur les GCMs a été étudiée en termes de leur capacité à simuler les événements extrêmes et leurs tendances passées à l'échelle des aéroports. Dans un deuxième temps, les projections futures des RCMs ont été comparées à celles des GCMs. Avant de mener l'étude d'impact, la magnitude future des événements extrêmes de hautes températures a été estimée en appliquant une méthode de correction de biais aux projections climatiques. Les principales conclusions de ce chapitre sont les suivantes:

- Les aéroports Euro-Méditerranéens ont connu une augmentation des extrêmes de hautes températures au cours des dernières décennies, et ils seront concernés par une augmentation additionnelle au cours du 21$^{\text{ème}}$ siècle. Cela pourrait avoir des répercussions négatives sur le secteur du transport aérien, rendant nécessaires des politiques d'adaptation ou d'atténuation.

- Il n'y a pas de valeur ajoutée généralisée de l'ensemble multi-RCM Euro-CORDEX par rapport à l'ensemble multi-GCM forceur CMIP5 pour l'étude des extrêmes de hautes températures ni de leurs tendances sur les aéroports, les deux ensembles restant compatibles avec les observations.

- Les GCMs projettent un réchauffémment futur plus important que les RCMs sur les mêmes aéroports.

- Compte tenu des deux derniers points, l'ensemble des RCMs et celui des GCMs devraient être pris en compte tous les deux pour les études d'impact et la conception de politiques d'adaptaition et d'atténuation à l'échelle régionale et locale, afin de ne pas sous-estimer les incertitudes de la modélisation climatique.

- La magnitude future des extrêmes de hautes températures telle que projetée par les modèles climatiques est très probablement sous-estimée, de même que la magnitude de l'impact potentiel induit estimée.

Dans le Chapitre 3, l'impact potentiel futur sur les performances des avions au décollage induit par l'augmentation projetée des extrêmes de hautes températures a été évalué. Dans le sous-Chapitre 3.1, les changements des niveaux d'émissions de NO_x et de la performance du moteur ont été analysés sur les aéroports Euro-Méditerranéens principaux à l'aide d'un outil type métier de la turbomachinérie (Gasturb). Dans le sous-Chapitre 3.2, l'évolution de la masse maximale de l'avion au décollage a été analysée sur des aéroports majeurs, régionaux et petits de la région d'étude, ceci en utilisant une loi empirique fournie par AIRBUS combinée aux données techniques des constructeurs aéronautiques. Les modèles A350-1000, A320-200 et ATR72-212A ont été considérés comme représentatifs des avions longs, moyens et courts courriers, respectivement. Les principales conclusions de ce chapitre sont les suivantes :

- Comme conséquence de la hausse des températures, les aéroports Euro-Méditerranéens seront concernés par une augmentation des niveaux d'émissions de NO_x par le moteur de l'avion, ainsi que par la diminution de la performance du moteur au décollage.

- L'augmentation des niveaux d'émissions de NO_x par le moteur de l'avion pourrait entraîner une augmentation des émissions absolues de NO_x au décollage de l'ordre de quelques points de pourcentage lors des futurs événements extrêmes : jusqu'à près de +4% et +6% à court et moyen terme, respectivement. Ce phénomène, ajouté à l'augmentation de la consommation de carburant résultante de la diminution de la performance de l'avion et du moteur et à la croissance projetée du trafic aérien, pourrait entraîner une augmentation substantielle des émissions absolues de NO_x de l'aviation à l'avenir. En conséquence, le système climatique serait soumis à un forçage radiatif supplémentaire, qui pourrait accentuer le réchauffement des températures extrêmes, fermant ainsi une boucle de rétroaction positive. En outre, l'augmentation des émissions de NO_x pourrait détériorer la qualité de l'air à l'aéroport et aux alentours, avec des conséquences potentiellement négatives pour la santé humaine.

- La diminution de la performance du moteur d'avion entraînera une augmentation de la consommation de carburant pour répondre aux mêmes exigences opérationnelles dans des conditions de température extrêmes plus sévères à l'avenir. Cela entraînera par conséquent une augmentation des émissions absolues de l'aviation, tant gazeuses que de particules, et pas seulement de NO_x, ce qui pourrait avoir des répercussions négatives sur l'environnement et la biodiversité, la socio-économie et la santé humaine.

- Les aéroports Euro-Méditerranéens seront concernés par la diminution de la capacité de l'avion à décoller du poids, en raison de la baisse de la performance du moteur et de la portance de l'avion dans des conditions extrêmes plus chaudes dans le futur. Les aéroports principaux, régionaux et petits seront affectés, au moins pour un type d'avion parmi les longs, moyens et courts courriers.

- Les futures réductions de la MTOW sont généralement de l'ordre de plusieurs tonnes pour les avions longs et moyens courriers, ce qui pourrait entraîner des restrictions de poids correspondant à des dizaines de passagers et/ou des retards ou des annulations. Cela aurait un impact socio-économique important pour les compagnies aériennes et les usagers, la majorité de la flotte actuelle étant composée d'avions de taille moyenne. Les avions courts courriers ne seraient pas concernés par des réductions de la MTOW sur la grande majorité des aéroports considérés dans le domaine, et là où ils le sont, les réductions de la MTOW sont de l'ordre de 100 kg contre celles de 1000 kg trouvées pour les deux autres types d'avions.

Malgré la tendance positive robuste trouvée pour les niveaux d'émissions de NO_x et les limitations de la MTOW, il existe de grandes incertitudes quant à la magnitude des impacts. Elles proviennent principalement des incertitudes dans les projections climatiques, lesquelles devraient être réduites pour la conception de stratégies d'adaptation et/ou d'atténuation à l'avenir. Les approches système développées et utilisées par les motoristes aéronautiques pour simuler le comportement de l'ensemble du moteur aurait pu conduire à des résultats plus réalistes de la performance du moteur et des émissions polluantes. Par ailleurs, des résultats plus précis auraient pu être obtenus en utilisant un logiciel opérationnel pour le calcul de la MTOW comme ceux utilisés par les pilotes, au lieu d'une loi empirique.

L'utilisation des données opérationnelles des compagnies aériennes et des systèmes de gestion du trafic aérien (ATM) aurait permis également de mieux estimer l'impact potentiel sur l'industrie du transport aérien.

Cette thèse a évalué certains des impacts potentiels maximums que le changement climatique pourrait avoir sur les opérations de l'aviation générale dans les décennies à venir. Elle a illustré la magnitude des effets négatifs que l'augmentation des extrêmes de hautes températures aurait sur la performance du décollage des avions en termes d'émissions polluantes, de la performance du moteur et des limitations de la MTOW. Tout cela sur l'une des zones les plus sensibles au changement climatique: la région Euro-Méditerranéenne. En plus, elle a mis en évidence la boucle de rétroaction positive entre l'augmentation des températures et l'augmentation des émissions de NO_x provenant de l'aviation. En outre, cette thèse a fourni des nouvelles méthodologies pour évaluer les impacts du changement climatique sur le décollage des avions dans n'importe quel aéroport du monde. Nous espérons que cette thèse attirera l'attention des compagnies aériennes, des motoristes et d'autres acteurs, dans l'espoir qu'ils seront intéressés à collaborer avec nous pour affiner l'évaluation des impacts.

A P P E N D I X A

Supplementary material of Evolution of high-temperature extremes over the main Euro-Mediterranean airports

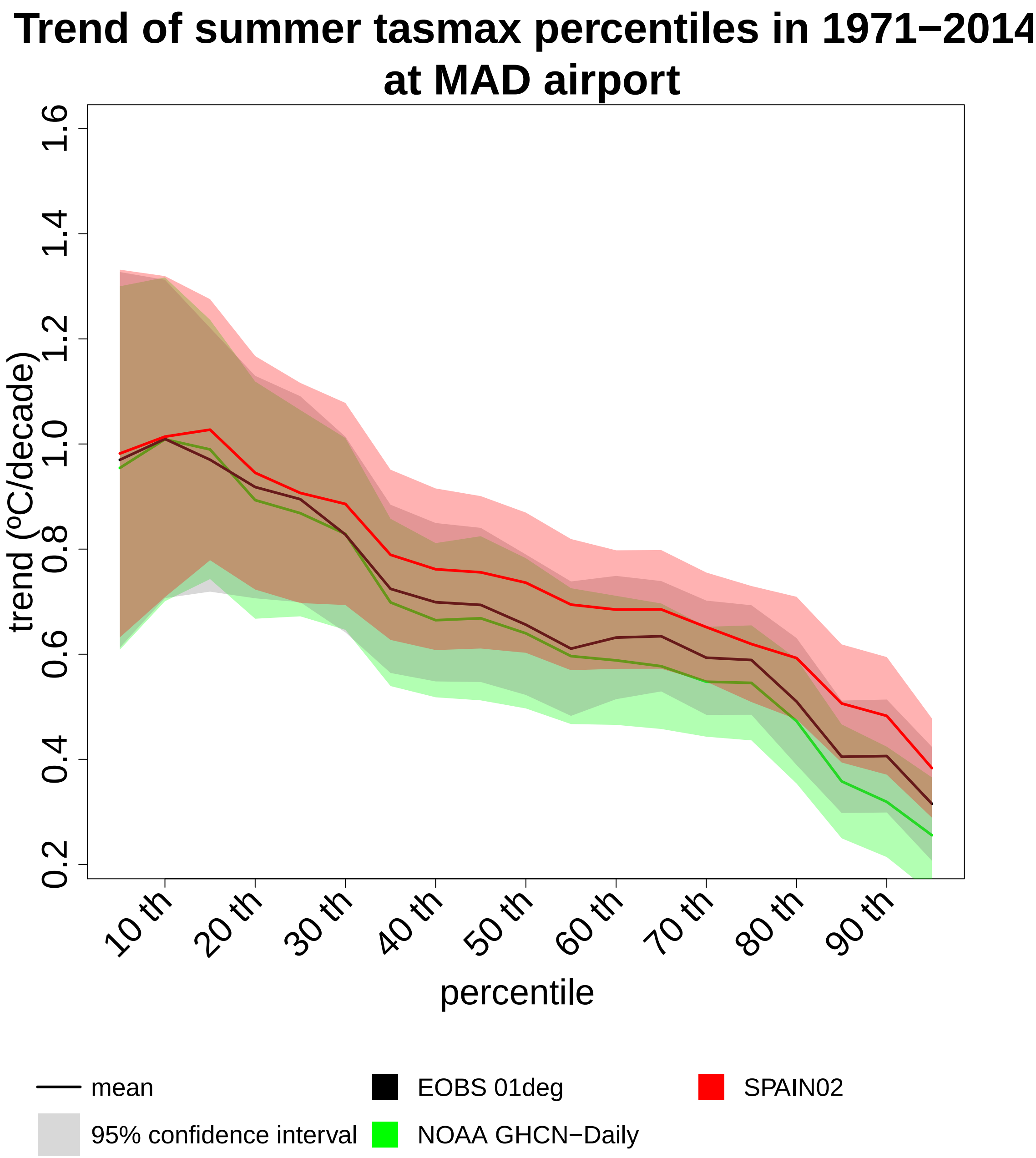
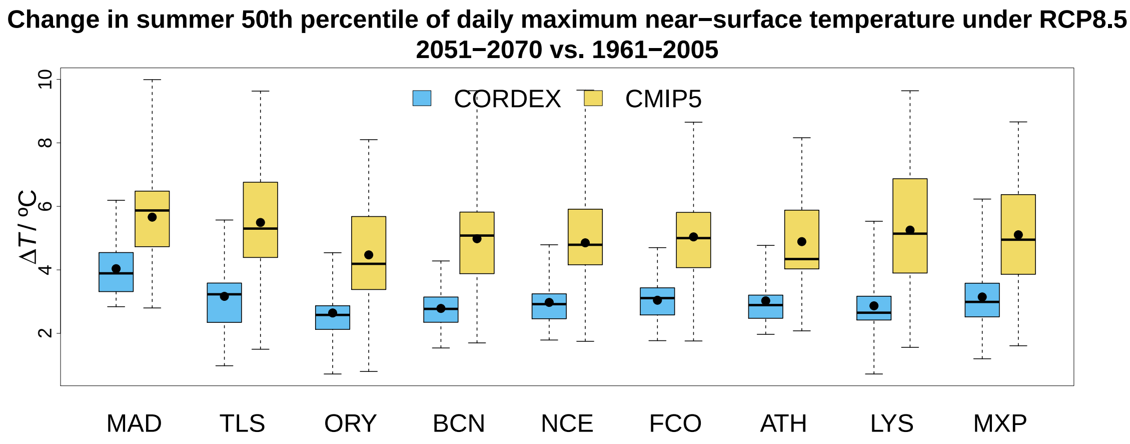
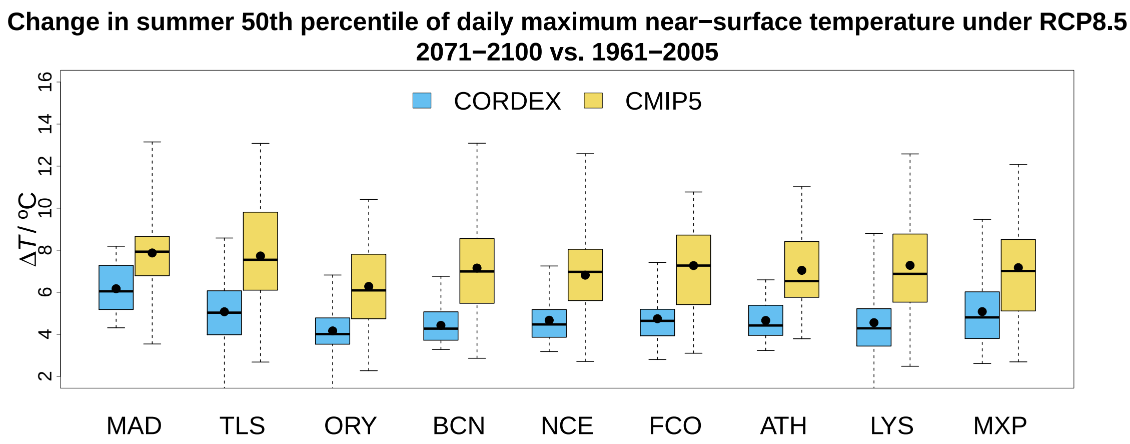


Figure A.1: Quantile trends of the TX between 1971 and 2014 in JJA, computed for MAD airport from EOBS 01deg (black), and NOAA GHCN-Daily (green) observational datasets and for SPAIN02 (red). Solid lines correspond to the mean of the bootstrap distribution, and shading indicates the 95% confidence interval.

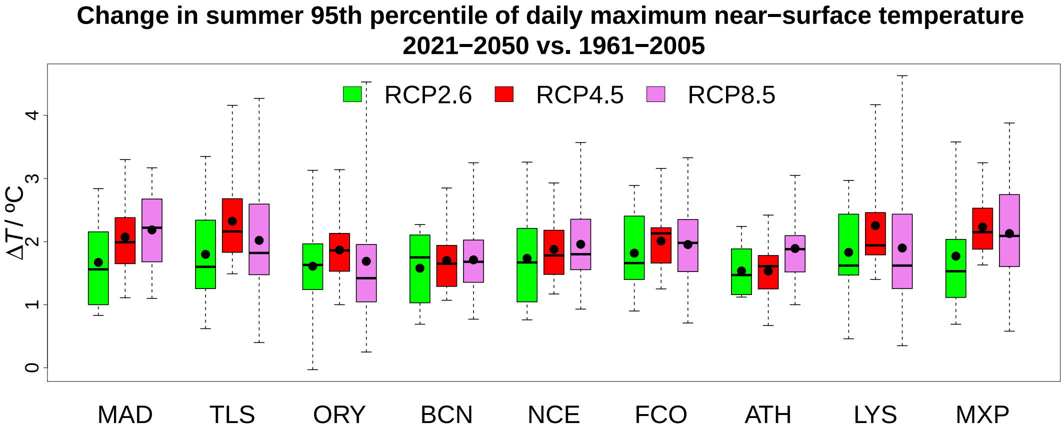


(a)

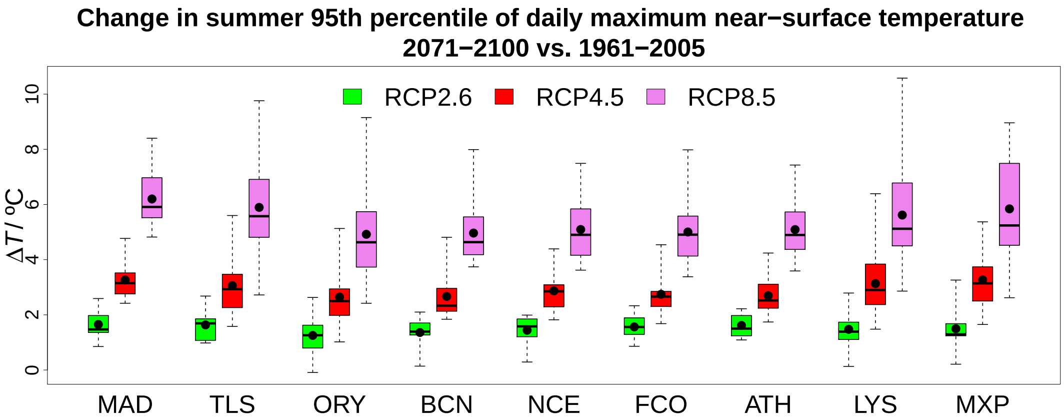


(b)

Figure A.2: Projected changes in the median of the summer TX between 2021-2050 and 1961-2005 (a), and between 2071-2100 and 1961-2005 (b), over the nine airports simulated by the Euro-CORDEX (blue) and the CMIP5 (yellow) RCP8.5 experiment ensembles. The boxes are delimited by the first and third quartiles, with the median the segment in between, and points indicating the MME mean. The lower (upper) whiskers correspond to the minimum (maximum) values of the distribution in each case.



(a)



(b)

Figure A.3: Projected changes in the 95$^{\text{th}}$ percentile of the summer TX between 2021-2050 and 1961-2005 (a), and between 2071-2100 and 1961-2005 (b), over the nine airports simulated by the Euro-CORDEX under the RCP2.6 (green), RCP4.5 (red) and RCP8.5 (viol) experiment ensembles. The boxes are delimited by the first and third quartiles, with the median the segment in between, and points indicating the MME mean. The lower (upper) whiskers correspond to the minimum (maximum) values of the distribution in each case.

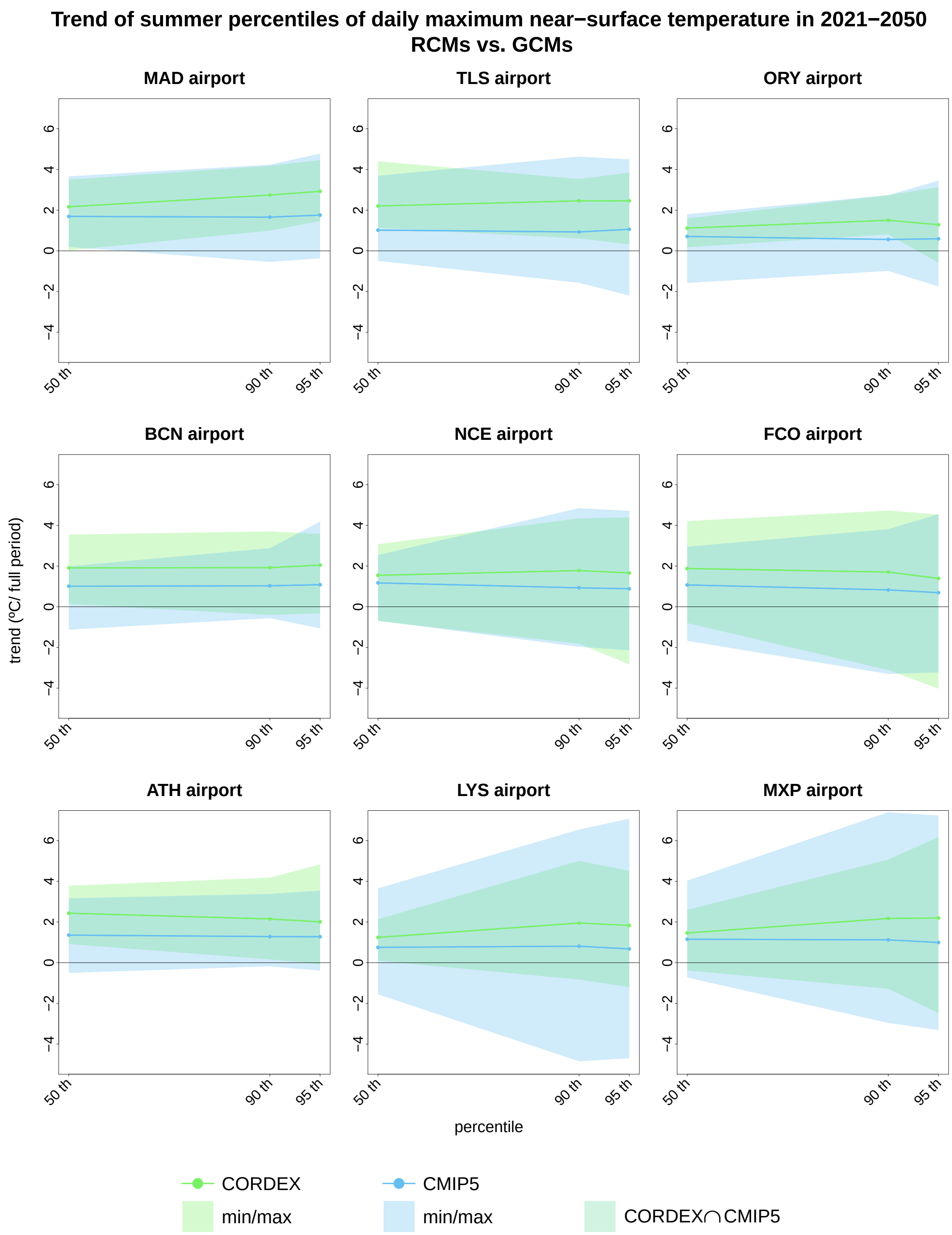


Figure A.4: Quantile trends of the TX between 2021 and 2050 in JJA for the Euro-CORDEX ensemble (blue) and the driving CMIP5 GCM (weighted) sub-ensemble (green), under the RCP8.5 scenario. Colored solid lines represent the MME mean of each experiment, and shading corresponds to the interval between minimum and maximum values found for each of the two ensembles.

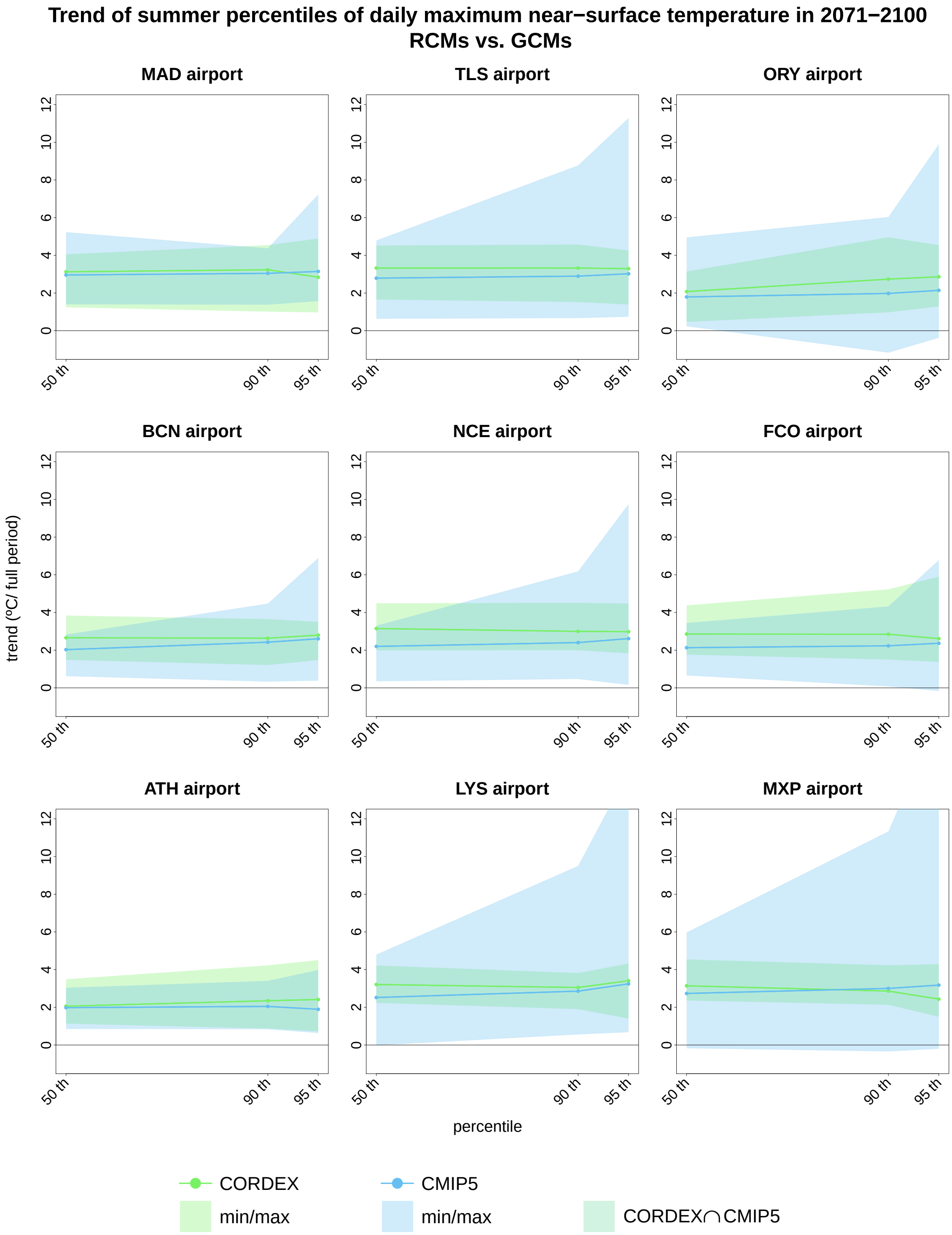


Figure A.5: Quantile trends of the TX between 2071 and 2100 in JJA for the Euro-CORDEX ensemble (blue) and the driving CMIP5 GCM (weighted) sub-ensemble (green), under the RCP8.5 scenario. Colored solid lines represent the MME mean of each experiment, and shading corresponds to the interval between minimum and maximum values found for each of the two ensembles.

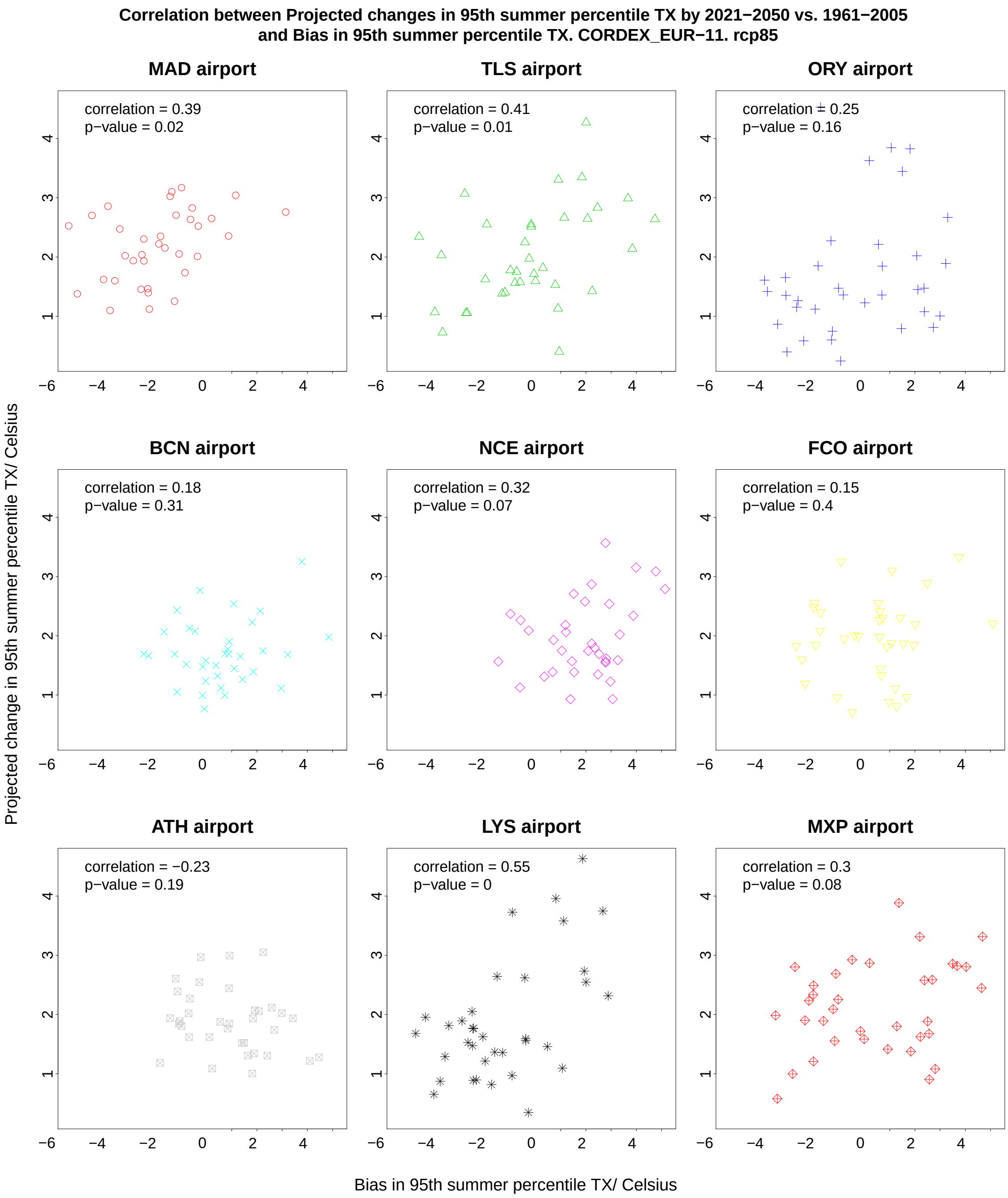


Figure A.6: Inter-model correlation between the projected changes under the RCP8.5 scenario by 2021-2050 with respect to 1961-2005 and the model biases in the historical period, for the Euro-CORDEX ensemble at the selected airports.

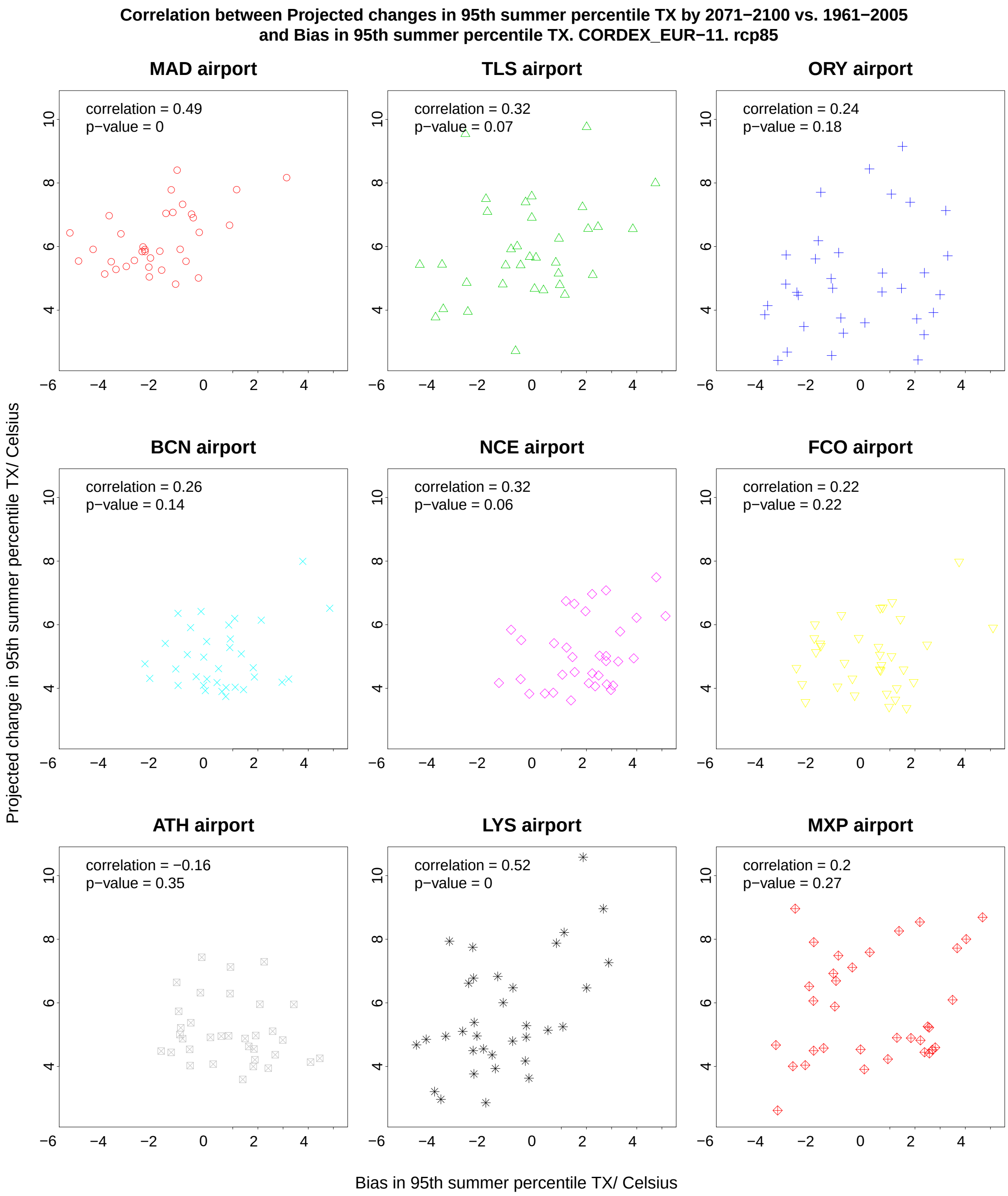


Figure A.7: Inter-model correlation between the projected changes under the RCP8.5 scenario by 2071-2050 with respect to 1961-2005 and the model biases in the historical period, for the Euro-CORDEX ensemble at the selected airports.

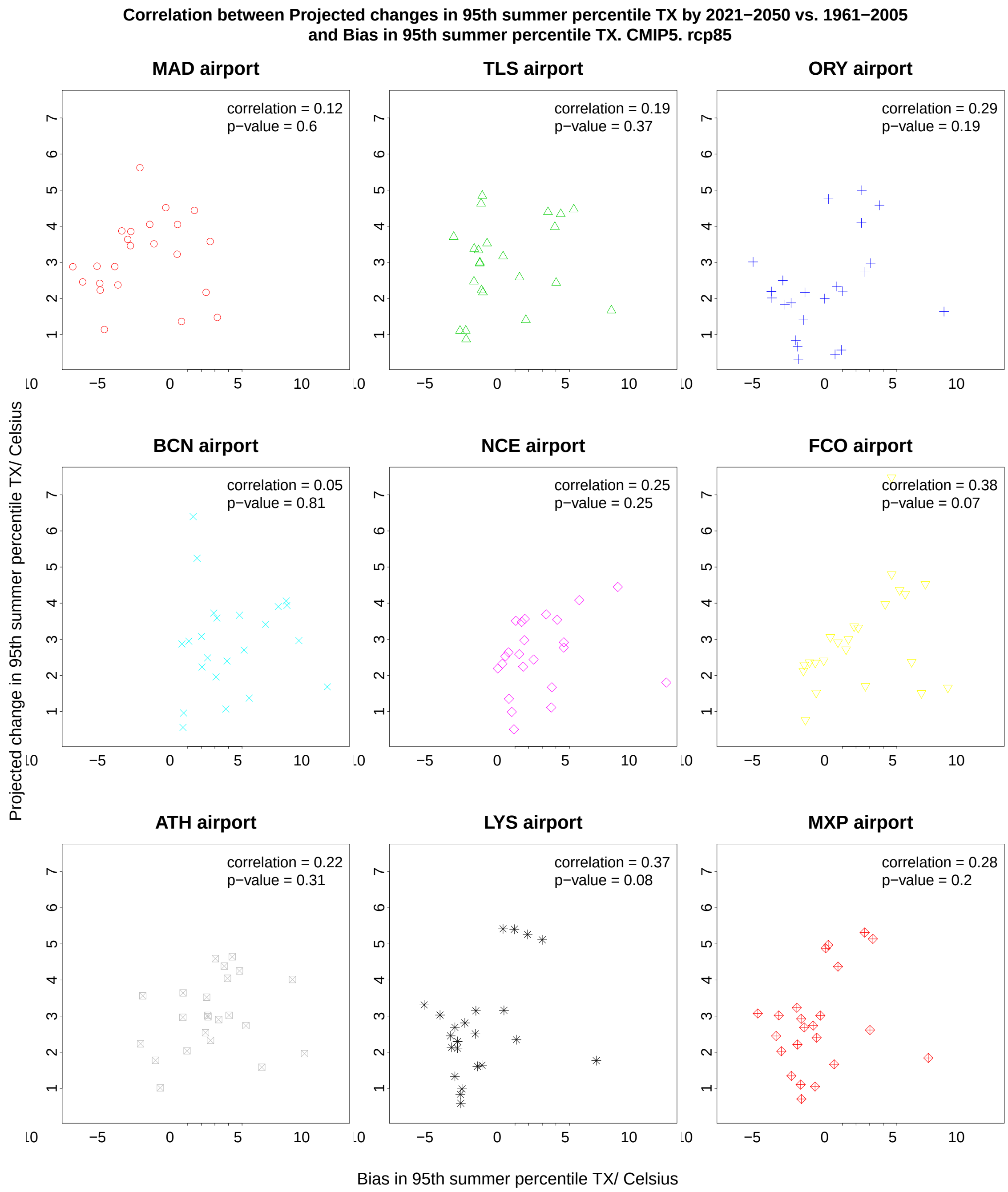


Figure A.8: Inter-model correlation between the projected changes under the RCP8.5 scenario by 2021-2050 with respect to 1961-2005 and the model biases in the historical period, for the whole CMIP5 ensemble (one member per model) at the selected airports.

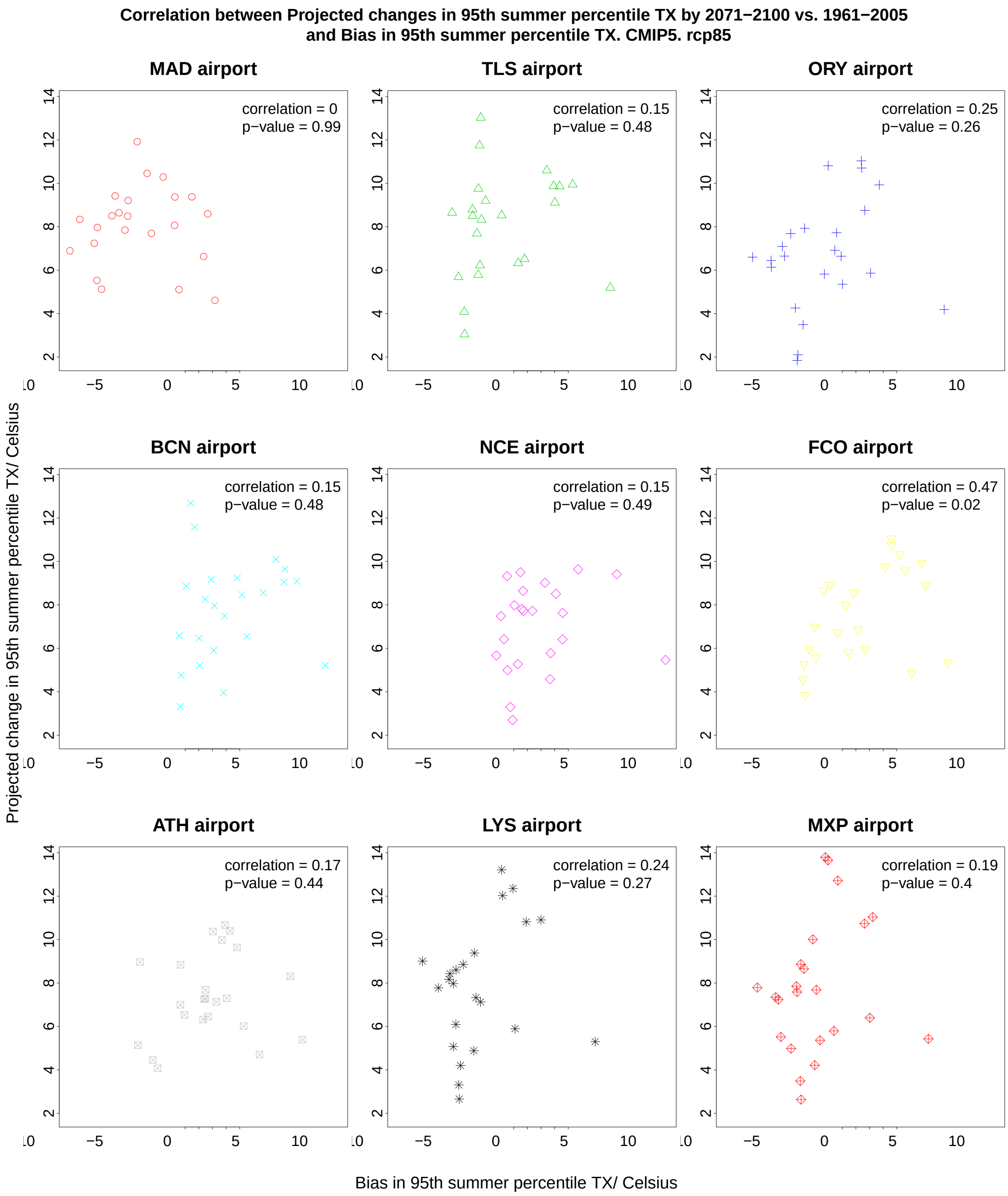


Figure A.9: Inter-model correlation between the projected changes under the RCP8.5 scenario by 2071-2100 with respect to 1961-2005 and the model biases in the historical period, for the whole CMIP5 ensemble (one member per model) at the selected airports.

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