

Assessing Climate Change Impacts on Aircraft TakeOff Performance: Potential Consequences of Increasing High-Temperature Extremes at Euro-Mediterranean Airports

Supplementary material

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1 MTOW curves in ACAP manuals

The Maximum TakeOff Weight (MTOW) curves which can be found in the Aircraft Characteristics for Airport Planning (ACAP) manuals exhibit the MTOW as a function of the TakeOff Field Length (TOFL), for different given airport elevations, and for different given ambient temperature conditions. Figure 1 illustrates these MTOW curves.

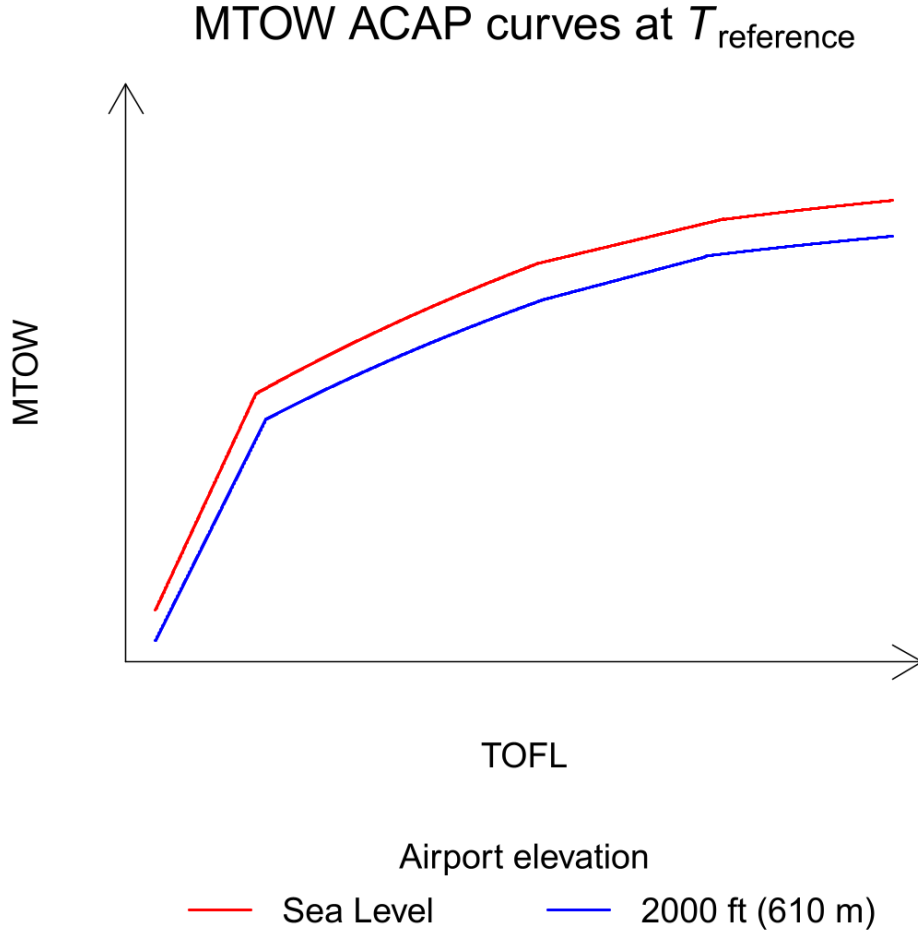


Figure 1: An exemple of the MTOW curves as a function of the TOFL for a given ambient temperature $T_{\text{reference}}$, and for two different airport elevations, which can be found in ACAP manuals (see for instance *Airbus A320 Aircraft Characteristics Airport and maintenance Planning* (2022) <https://www.airbus.com/en/airport-operations-and-technical-data/aircraft-characteristics>)

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 and thrust generation.

2 Empirical equations by AIRBUS for degrading MTOW with temperature

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

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

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

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:

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

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

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.

3 RCP4.5 scenario vs. RCP8.5 scenario

To illustrate the magnitude of the uncertainty in future climate projections arising from the climate change scenario, the analysis is additionally conducted for the medium-emissions scenario RCP4.5 (see Tables 1 and 2). We consider the takeoff of the wide and narrow-body aircraft models from the major airports in the list -which constitute a wide variety of local topographies. Regional aircrafts showed to be less sensitive to warm ambient temperatures. We focus on the midterm horizon (2041-2070).

Figure 2 allows for the comparison of the changes in the 95th percentile of the daily maximum near-surface air temperature ($TX95p$) in summer, as projected by the two Multi-Model Ensembles (MMEs) of climate models, Euro-CORDEX and CMIP5, under the RCP4.5 and RCP8.5 scenarios. The most part of the distributions of the projected changes under the RCP4.5 generally falls within the range spanned by the RCP8.5 projections, separately for each MME, and also when considering jointly the two MME (CORDEX $\cup$ CMIP5). Moreover, the differences between scenarios within the same MME are generally smaller than the differences between the two MME under the same scenario RCP. This suggests that, even by mid-century, the main source of uncertainty in future climate projections stems from climate models, not from the climate change scenario, for the case of changes in high-temperature extremes at regional to local scale in the Euro-Mediterranean region.

Under the RCP4.5 scenario, the smaller projected changes in high-temperature extremes may result in smaller reductions in MTOW than under the RCP8.5; however, given the large uncertainties from climate models (considering both MMEs) these reductions remain broadly consistent with those projected under the high-emissions scenario (see Figures 3 and 4).

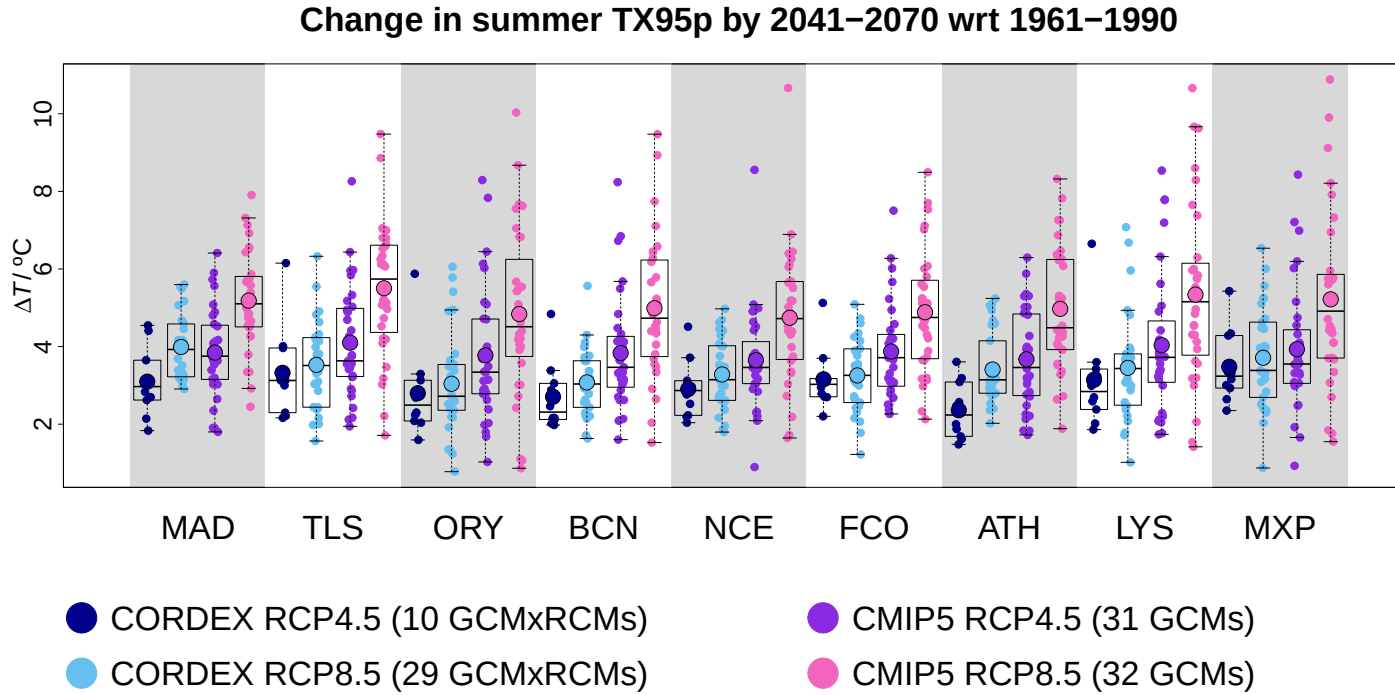


Figure 2: Change in the magnitude of summer 95th percentile of daily maximum near-surface air temperature ($TX95p$) at the airports by 2041-2070 with respect to 1961-1990, as projected by the CORDEX and CMIP5 ensembles under the RCP8.5 scenario (in light blue and pink, respectively), and under the RCP4.5 scenario (in dark blue and purple, respectively). The boxes are delimited by the first and third quartiles, with the median indicated by the segment in between, and larger points indicating the multi-model ensemble mean in each case, while smaller points indicate estimates from individual models. The lower (upper) whiskers correspond to the minimum (maximum) values of the distribution in each case

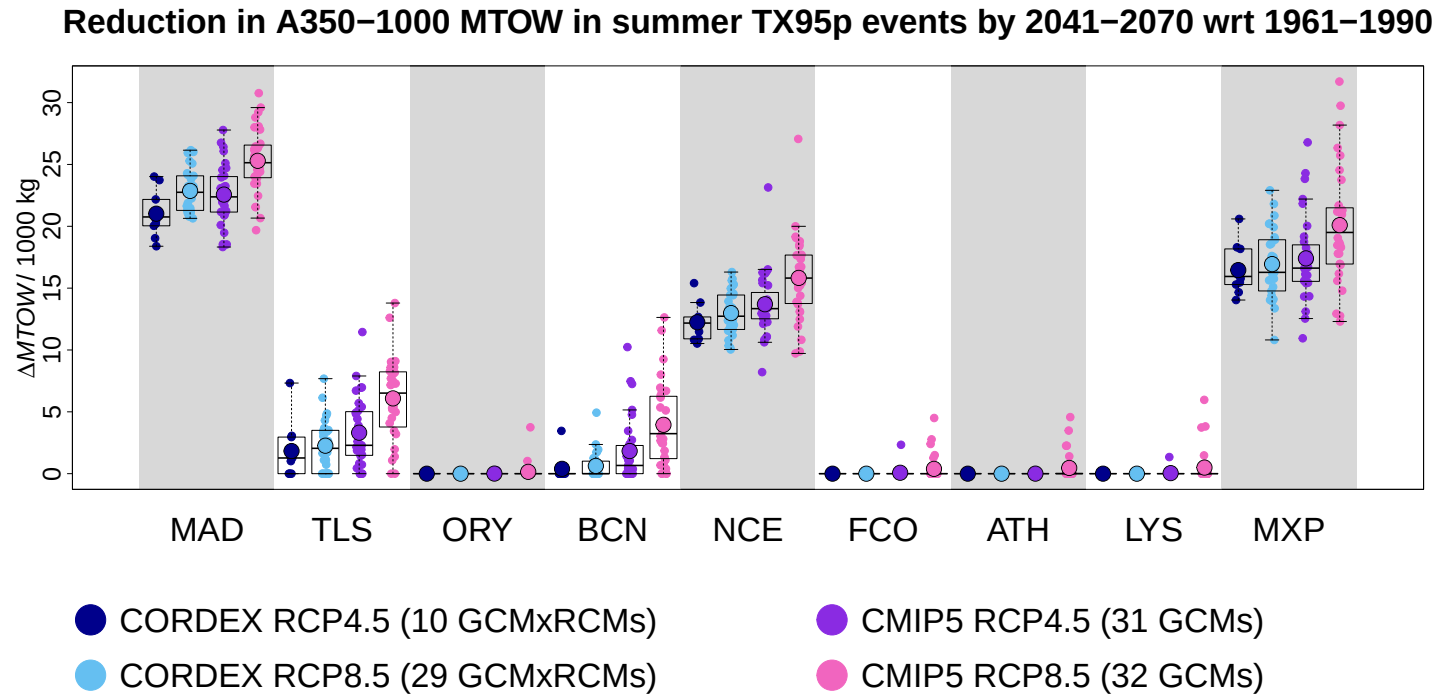


Figure 3: Reduction in the MTOW of an A350-1000 wide-body aircraft at the airports by 2041-2070 with respect to 1961-1990, according to the increase in the magnitude of the summer 95th percentile of the daily maximum near-surface air temperature (TX_{95p}), as projected by the CORDEX and CMIP5 ensembles under the RCP8.5 scenario (in light blue and pink, respectively), and under the RCP4.5 scenario (in dark blue and purple, respectively). The boxes are delimited by the first and third quartiles, with the median indicated by the segment in between, and larger points indicating the multi-model ensemble mean in each case, while smaller points indicate estimates from individual models. The lower (upper) whiskers correspond to the minimum (maximum) values of the distribution in each case

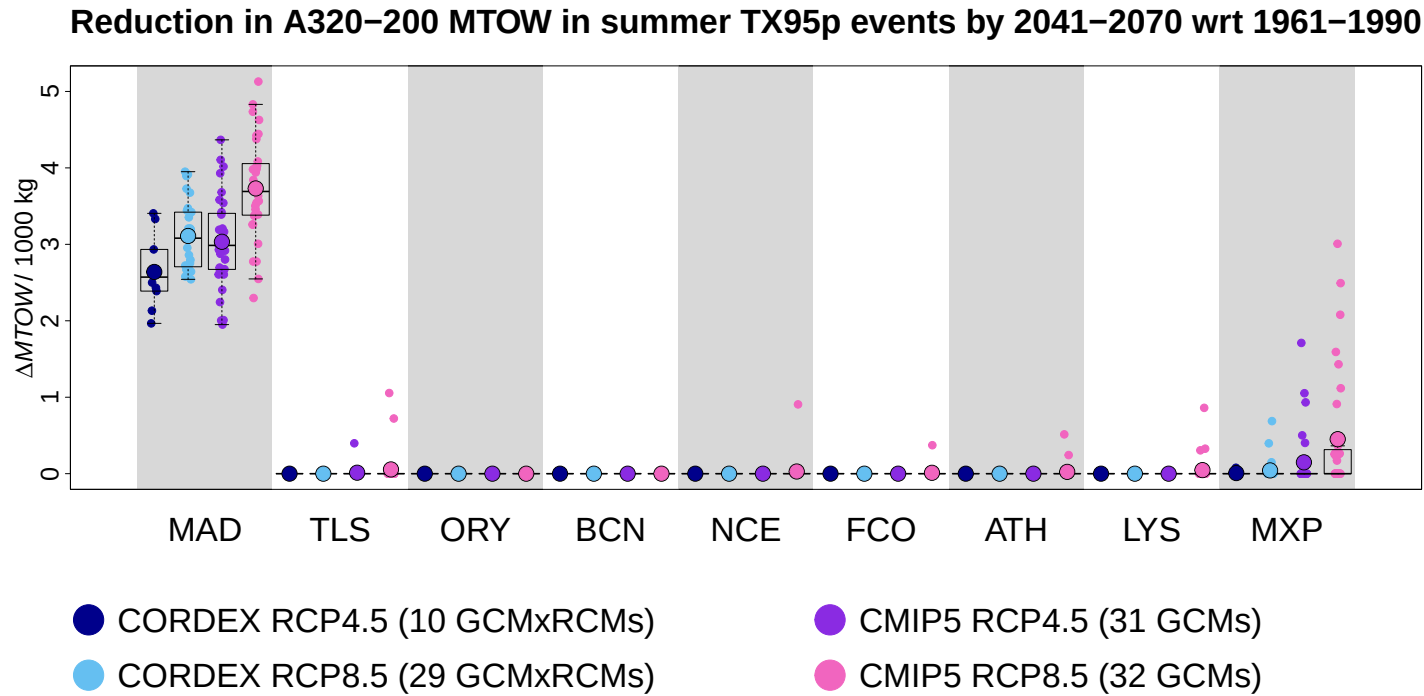


Figure 4: Reduction in the MTOW of an A320-200 narrow-body aircraft at the airports by 2041-2070 with respect to 1961-1990, according to the increase in the magnitude of the summer 95th percentile of the daily maximum near-surface air temperature (TX_{95p}), as projected by the CORDEX and CMIP5 ensembles under the RCP8.5 scenario (in light blue and pink, respectively), and under the RCP4.5 scenario (in dark blue and purple, respectively). The boxes are delimited by the first and third quartiles, with the median indicated by the segment in between, and larger points indicating the multi-model ensemble mean in each case, while smaller points indicate estimates from individual models. The lower (upper) whiskers correspond to the minimum (maximum) values of the distribution in each case

Table 1: The RCM $\times$ GCM matrix indicating which combinations from the Euro-CORDEX Historical and RCP4.5 scenario experiments were available for the analysis

	CNRM-CM5	EC-EARTH	HadGEM2-ES
CLMcom-CCLM4-8-17	r1i1p1	r12i1p1	r1i1p1
CNRM-ALADIN53	r1i1p1		
CNRM-ALADIN63	r1i1p1		
DMI-HIRHAM5		r3i1p1	r1i1p1
	IPSL-CM5A-MR	MPI-ESM-LR	NorESM1-M
CLMcom-CCLM4-8-17		r1i1p1	
DMI-HIRHAM5			r1i1p1
IPSL-WRF-381P	r1i1p1		

Table 2: List of GCM simulations from the CMIP5 Historical and RCP4.5 scenario experiments considered in the analysis

GCM	realisation
ACCESS1-0	r1i1p1
BNU-ESM	r1i1p1
CCSM4	r1i1p1
CESM1-BGC	r1i1p1
CESM1-CAM5	r1i1p1
CMCC-CMS	r1i1p1
CMCC-CM	r1i1p1
CNRM-CM5	r1i1p1
CSIRO-Mk3-6-0	r10i1p1
CSIRO-Mk3L-1-2	r1i2p1
CanESM2	r1i1p1
EC-EARTH	r1i1p1
FGOALS-g2	r1i1p1
GFDL-CM3	r1i1p1
GFDL-ESM2G	r1i1p1
GFDL-ESM2M	r1i1p1
GISS-E2-R	r6i1p1
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
NorESM1-M	r1i1p1
bcc-csm1-1-m	r1i1p1
inmcm4	r1i1p1