ISA Workshop#7 on Air Transport Vulnerability to Weather & Climate Change
Meteo-France, 23rd June 2026

Impact of Climate Change on Aircraft Take-off Performance
Quantifying future performance degradation for adaptation planning

Suzanne Salles(1,2)

Journal Article:

Salles, S., Ricci, S., Gourdain, N., & Druot, T. (2025). *Multidisciplinary assessment of the impact of temperature rise and headwind on aircraft take-off performance.* Climatic Change, 178(11), 200. https://doi.org/10.1007/s10584-025-04016-0

PhD Thesis:

Suzanne Salles (2025). *Impact of Climate Change on Aircraft Take-off Performance: Quantifying Future Performance Degradation Through Climate Projections for Adaptation Planning.* Available at: https://theses.fr/2025ESAE0062

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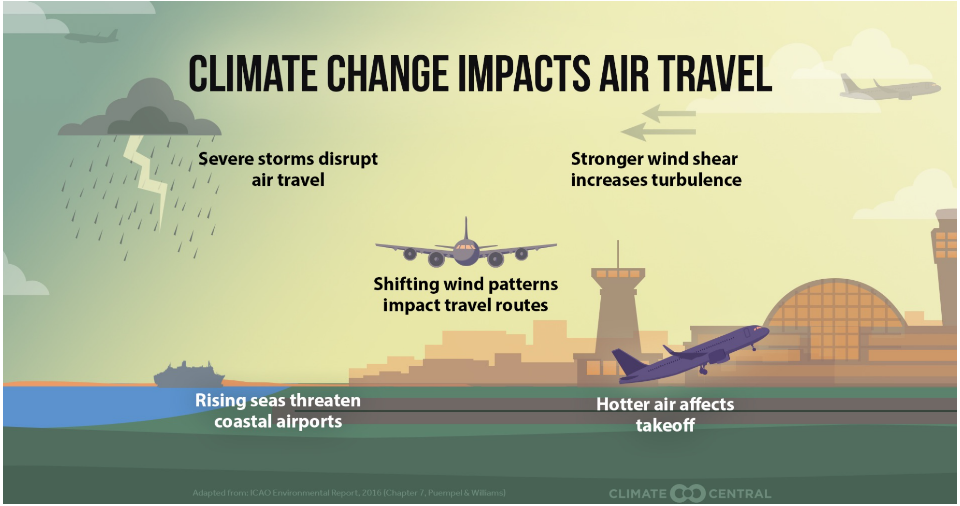
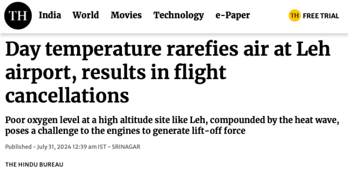
A Multi-Hazard Problem



Adapted from: ICAO Environmental Report, 2016 (Chapter 7, Puempel & Williams)

Extreme Heat is Already Disrupting Operations

Leh, India, 2024



Day temperature rarefies air at Leh airport, results in flight cancellations

Poor oxygen level at a high altitude site like Leh, compounded by the heat wave, poses a challenge to the engines to generate lift-off force

Published - July 31, 2024 12:39 am IST - SRINAGAR

THE HINDU BUREAU

Source: thehindu.com

Phoenix, USA, 2017

Phoenix flights cancelled because it's too hot for planes

20 June 2017

Planes grounded at "too hot" Phoenix airport

As temperatures climb in Phoenix, Arizona, more than 40 flights have been cancelled - because it is too hot for the planes to fly.

Source: bbc.com

London, UK, 2022

LONDON AIRPORT GROUNDS FLIGHTS AFTER RUNWAY BUCKLES FROM HEAT

Source: cnbc.com

Debrecen, Hungary, 2024

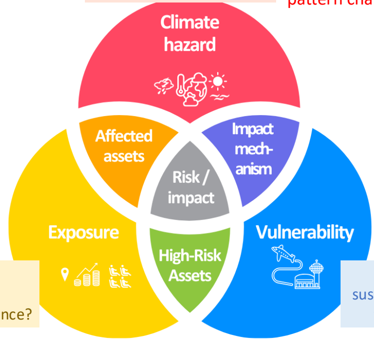
Runway melts at Hungary's number two airport hub due to scorching heat

Source: intellinews.com

A Vulnerability Problem: the IPCC Risk Framing

What is the threat?
Intensity?
Probability of occurrence?

→ Temperature rise and wind pattern changes



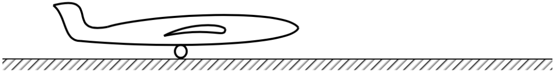
Where?
When?
What consequence?

How susceptible/sensitive to the hazard?

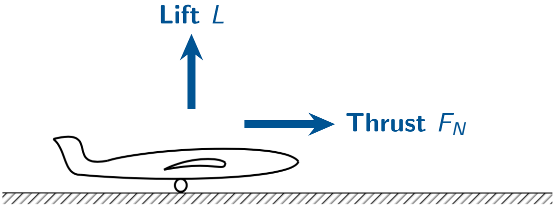
→ Global Airports, in future decades, according to different socio-economic scenarios

→ Aircraft performance response at take-off

Why Atmospheric Conditions Affect Take-off



Why Atmospheric Conditions Affect Take-off

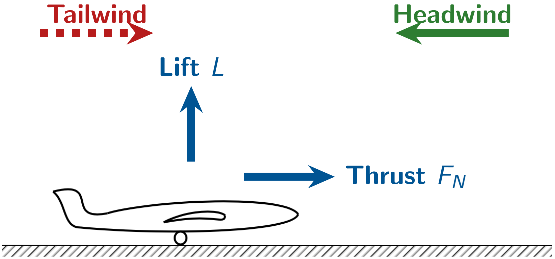


Temperature Effect

$T\uparrow\Rightarrow\ \rho\downarrow\Rightarrow\ L\downarrow,\ F_N\downarrow$

= longer runway needed

Why Atmospheric Conditions Affect Take-off



Temperature Effect

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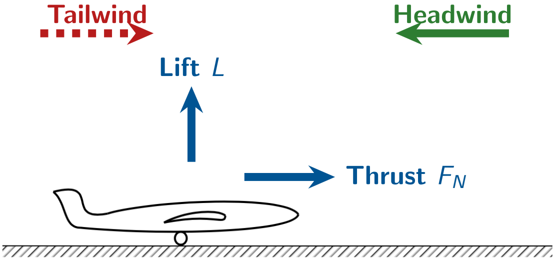
= longer runway needed

Wind Effect

Headwind → reach speed sooner

Tailwind → need more groundspeed

Why Atmospheric Conditions Affect Take-off



Temperature Effect

$T \uparrow \Rightarrow \rho \downarrow \Rightarrow L \downarrow, F_N \downarrow$

= longer runway needed

Wind Effect

Headwind → reach speed sooner

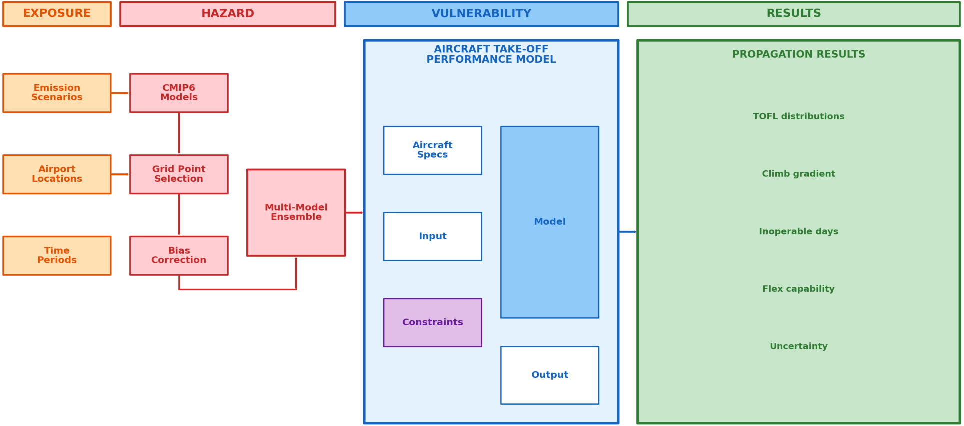
Tailwind → need more groundspeed

This thesis: quantify these effects under climate projections, 2 SSP scenarios, 60 airports, until the end of the century.

METHOD (in brief)

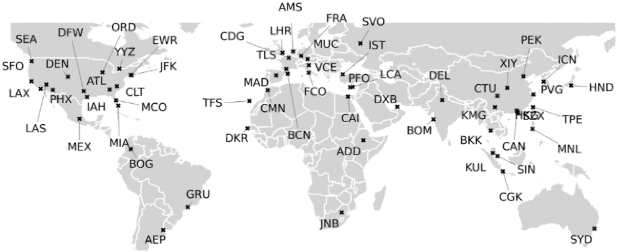
Climate projections → a take-off performance model

One Pipeline: From Climate Models to Take-off



Climate models → bias correction at each airport → daily take-off model → impact metrics

Climate Inputs: an Ensemble, Corrected at Each Airport



60 international airports used in this study

Multi-model ensemble

6 CMIP6 models (5 for wind), spanning the IPCC sensitivity range; “one model, one vote”. Two scenarios: **SSP1-2.6** / **SSP5-8.5**.

Bias-corrected vs ERA5

Climate data at each location is bias corrected against reference historical ERA5 data.

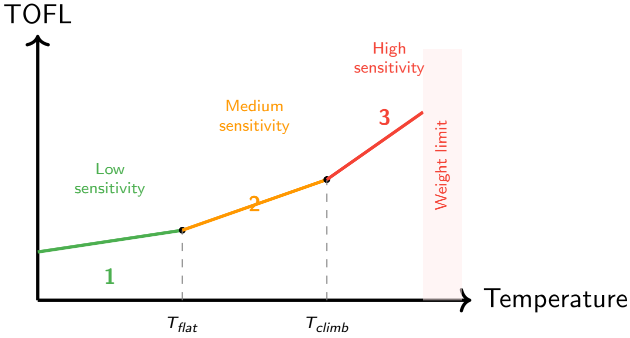
2 possible futures

Future cliate data is taken for two possible socio economic scenarios: **SSP1-2.6** and **SSP5-8.5**.

One thing to keep in mind

The operating temperature limit **decreases with altitude** → high airports start closer to the edge.

The Take-off Model: a Nonlinear, Regulated Response



Warming pushes operations from Regime 1 → 2 → 3 (accelerating)

The main performance indicator

The take-off Field length **TOFL**
Distance needed for a safe take-off.

The aircraft model

A semi-empirical model based on certification limits and simplified integration of dynamic equations during take-off.

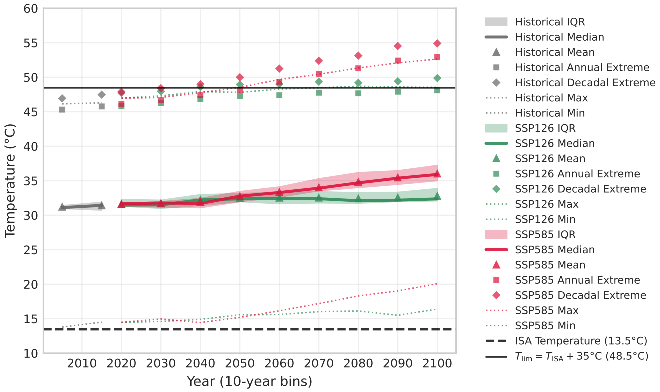
Validation (vs Boeing 737-800)

377 m RMSE, +3.4% bias. The **temperature sensitivity** that drives the climate signal is well captured; a known altitude bias shifts absolute values but **not the rankings or trends**.

RESULTS I

What the climate does

Case Study – Delhi: Extremes, Not Averages



SSP1-2.6: $+1.2°$C, stabilises

SSP5-8.5: $+4.5°$C, still rising

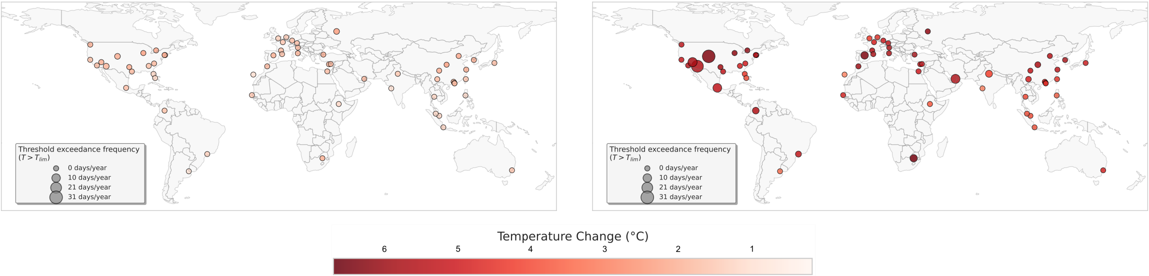
Days/yr above the limit

0 historically → **15.5** (SSP5-8.5) vs 0.3 (SSP1-2.6) by 2090.
Nonlinear after 2050.

Extremes, not averages, drive impacts

Temperature change: Global Patterns

SSP1-2.6 **SSP5-8.5**



Average warming

Airports with the highest warming from historical (1980-2015) to end-of-century period (2075-2100):

JNB +6.5, MAD +6.4, DEN +6.3°C

Threshold exceedance

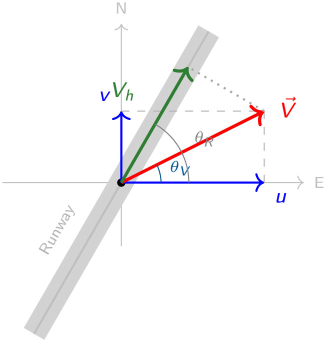
Airports with the most days over the threshold ($T > T_{\text{lim}}$):

DEN 31, PHX 27 d/yr

Takeaway

- Most warming $\neq$ most days over the limit ($T > T_{\text{lim}}$)
- Days over the limit depend on the baseline climate as much as on the warming

Wind: Projecting onto the Runway



Wind: u, v components

u = eastward, v = northward (at 10 m). We project the wind vector onto each runway's axis.

Headwind component

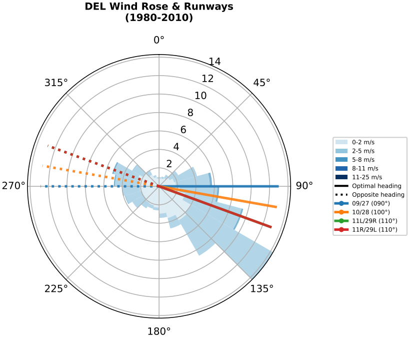
$$V_h = |\vec{V}| \cos(\theta_V - \theta_R)$$

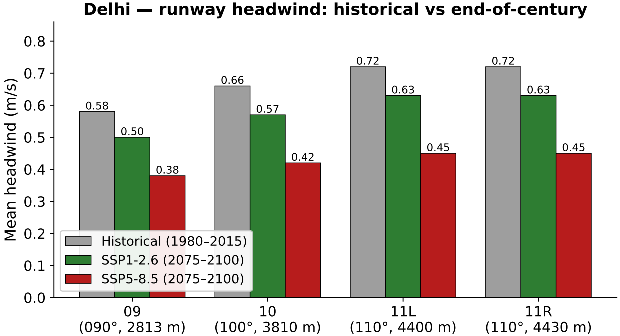
$V_h > 0$: headwind $V_h < 0$: tailwind

Which heading?

Two directions per runway. We fix the **historical-best heading** (1980–2015) and **hold it** So that the change captured is a climate signal, not representative of day to day operations.

Headwind results: Delhi – All Runways, Both Scenarios



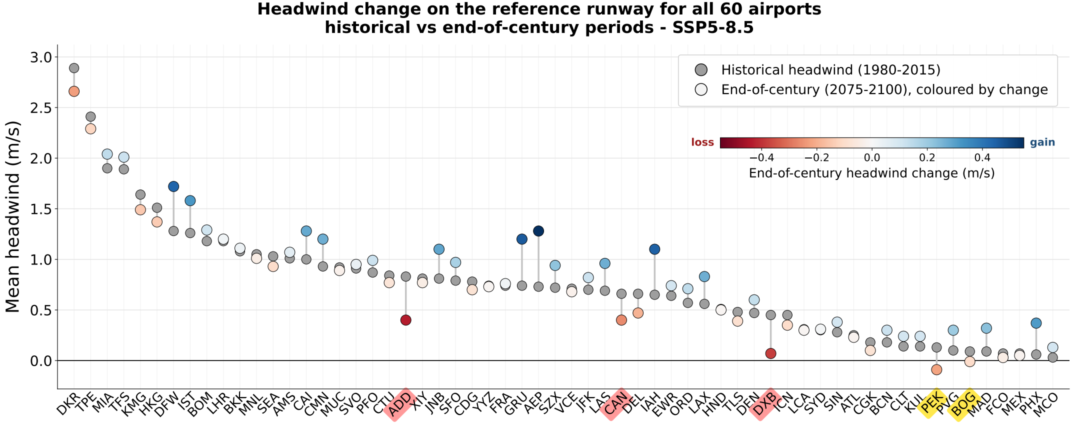


Wind mostly from the ESE (∼110°) → all runways gain headwind

All four runways, both scenarios.

Best: **11R** (longest, 4,430 m)
Worst **09** (shortest, 2,813 m)
Every runway loses headwind; **mitigation roughly halves the loss** (11R: −0.09 vs −0.27 m/s).

Headwind results: All airports – Best Runways, Scenario SSP5-8.5



Headwind change on the reference runway for all 60 airports
historical vs end-of-century periods - SSP5-8.5

Impact is local

It depends on the airport — **not** on how windy it is. Neither the windiest nor the calmest are the most affected.

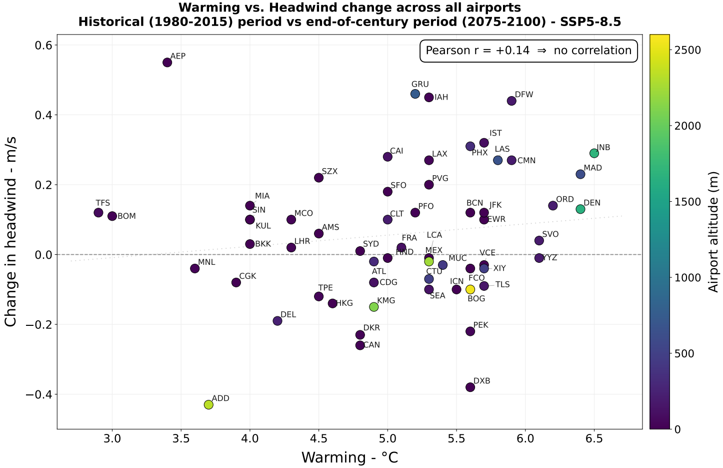
Hardest hit

Addis, Dubai, Guangzhou lose the most headwind; **Beijing** and **Bogotá** reverse to a tailwind.

A long-term trend

25-year period averages — the trend, **not** day-to-day weather.

Temperature vs. headwind impact



Reading the plot

Each airport: its **warming** (x) against its **headwind change** (y), end-of-century, SSP5-8.5. Colour shows **altitude**.

The two are uncorrelated

The most-warming airports are **not** those losing the most headwind ($r = 0.14$). Addis loses the most headwind at **low** warming; only Dubai is hit by **both**.

Why it matters

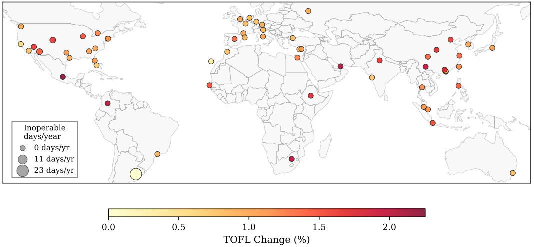
Heat and wind are **independent** hazards — vulnerability is **airport-specific**, with no simple "hottest = worst" rule.

RESULTS II

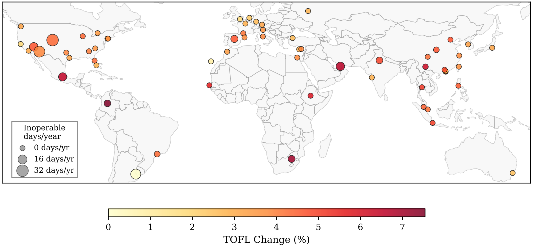
What it does to operations

Take-off Length: the Headline

SSP1-2.6



SSP5-8.5



Setup

2075–2100, 737-800 at **75 t** (below MTOW 79 t), best runway

Means

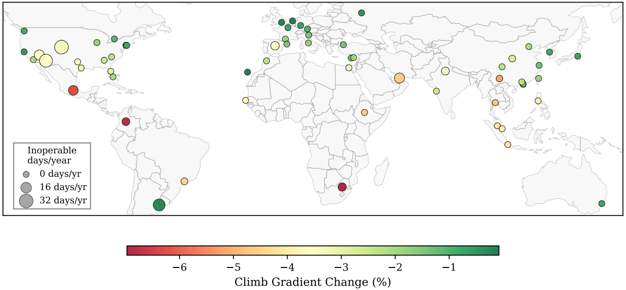
+1.2% / **+3.9%** (up to +7.5%); up to **32 inoperable days/yr**

Two readings

% of TOFL increase = gradual (manageable)
Number of inoperable days = binary (no take-off)

Safety Margins decrease: Climb angle after take-off

Climb-gradient change – SSP5-8.5



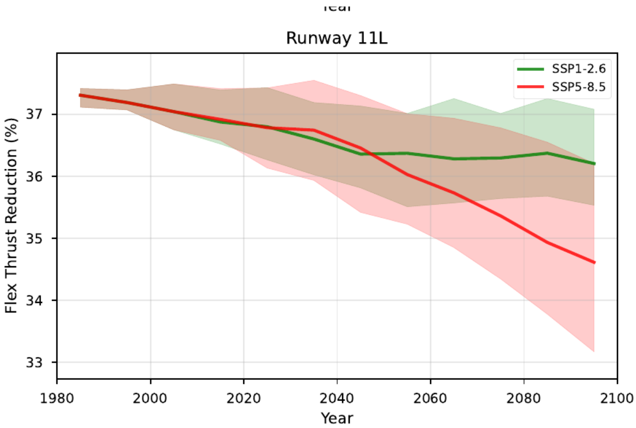
The other casualty: climb margin

The aircraft must still clear obstacles ($\gamma_{S2} \geq 2.4\%$). That margin **erodes with heat**:

SSP5-8.5: **-1 to -6%** (MEX, BOG -6%; PHX, DEN -5%).

Same heat, **two costs**: longer runway *and* thinner margin.

Flex Take-off: Quiet Efficiency, Lost



Delhi (11L): flex capability shrinks as the century warms

Flex = reduced-thrust take-off

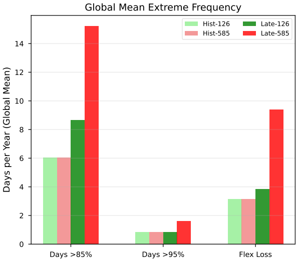
Standard practice on cool days: saves fuel, **spares the engines**.

The cost: full thrust, every day

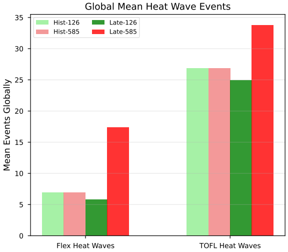
More fuel + thermal stress → **shorter engine life**, higher maintenance. Not a safety number – a **direct operating cost**.

Extreme Events: From Rare to Routine

How often – days over the runway limit



How persistent – multi-day heat waves



Operational heat wave $= \geq$**3 consecutive days** with take-off length over an operational threshold ($>$85% or $>$95% of runway, or flex lost).

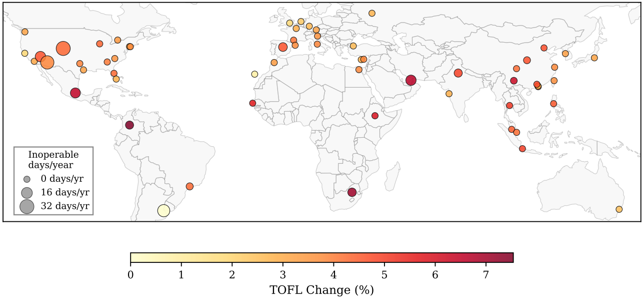
The shift (late century, SSP5-8.5)

Global-mean flex-loss days **3.1→9.4**/yr (**+201%**); flex-loss heat waves **+238%**. SSP1-2.6 stays nearly flat.

Takeaway

The change in the *average* is modest; the change in **frequency and persistence** is not. Today's **rare** disruptions become **routine** at vulnerable airports – and **mitigation keeps them rare**.

Where It Concentrates: High Altitude



SSP5-8.5, late century, best runway, 75 t

Largest increases

AEP +7.5, BOG +7.2, MEX +6.9, DEN +6.3% – all high-altitude

Most inoperable days

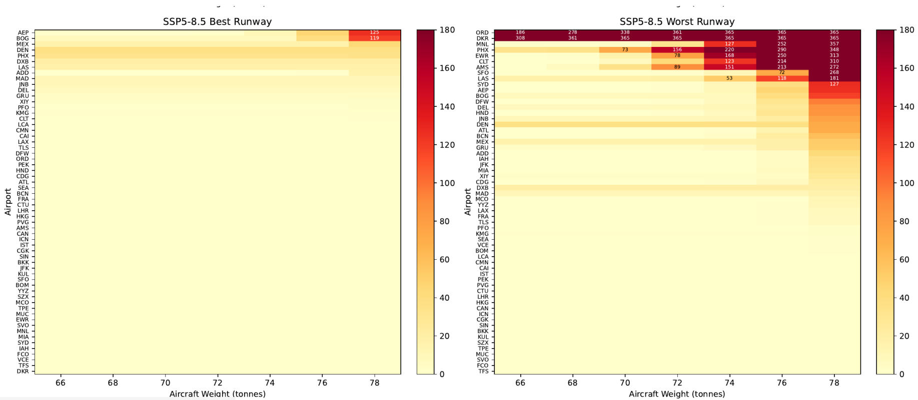
DEN 32, PHX 27, BOG 25 d/yr (75 t)

Shrinking margins

Thin air + low limit → these aircraft already fly near the edge, so the *same* warming tips them over. **Altitude is a multiplier.**

Two Drivers of Operability: Runway Length & Weight

SSP5-8.5, late century – inoperable days vs aircraft weight, best vs worst runway



Read it two ways

Weight sensitivity: weight 66→78 t **down** Best vs worst runway
Both drive operability.

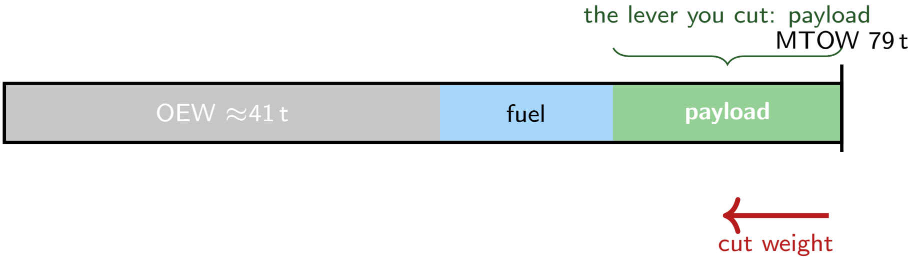
Runway gap (75 t)

Best 0–32 d/yr vs worst up to **253**; gap **221 max / 21 mean**. At **78 t**, ORD & DKR fail **365 d**.

Two levers

Runway ≥**2,800 m** = resilient; or fly **lighter** (next slide). Weight effect is sharply nonlinear.

Weight: a Lever You Can Pull – in Passengers



Weight, in passengers

· · · × 10

1 passenger + bag ≈ 100 kg ⇒ **1 tonne ≈ 10 passengers**

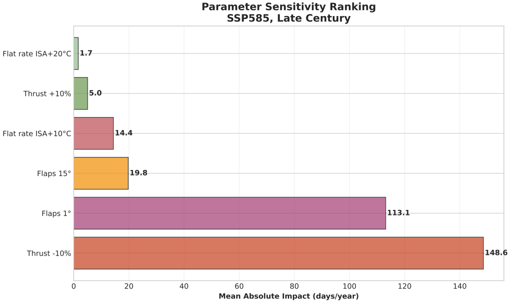
Manila – short runway, at max weight

357 days/yr grounded. Remove **4 t (≈40 passengers)**
→ **127 days = 230 operable days recovered**.

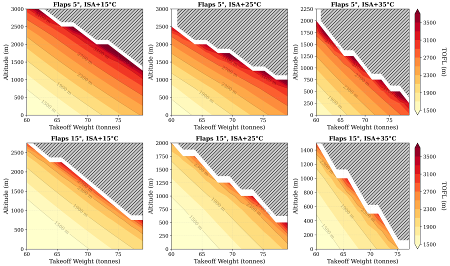
Near the threshold: ∼50 operable days bought *per tonne*.

The fastest lever – but each tonne is ∼10 passengers off the flight. An **emergency** measure, not a fix.

We Also Varied the Aircraft: What Moves the Needle



Mean Δ inoperable days/yr (SSP5-8.5)



Feasible weight × altitude envelope: **Flaps 5°** vs **15°**

Thrust dominates – asymmetric
−10% costs **149** d/yr; +10% buys 5. Protect against *loss* (engines, maintenance).

More flaps backfire
Extra flap shortens the roll but **shrinks the envelope at altitude** – the one-engine-out climb limit hits earlier.

Flat-rating helps
Holding thrust to higher T adds resilience. All effects **5–8**× stronger at altitude.

MAKING SENSE OF IT

Levers, timing, and the mitigation co-benefit

From Results to Levers: an Adaptation Hierarchy

The sensitivity studies (weight, thrust, flaps, flat-rating, runway length) sort into three levers:

1. Infrastructure

Runway ≥2,800 m

2. Technology

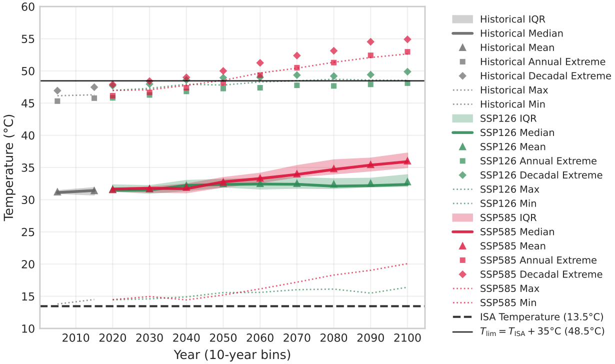
Engines more resilient to hot temperatures

3. Operations

Weight & scheduling

No single lever suffices – and the strongest lever of all is **global emissions mitigation**.

Timing: a No-Regrets Window, 2025–2040



Delhi temperature: the two scenarios are identical until ∼2040

Scenarios diverge after 2050s

Nearly identical to ∼**2040** (committed warming); separate only after mid-century.

So:

Decisions made now pay off under **both** futures – **no-regrets**. And infrastructure takes 10–15 yr, so the window is **2025–2040**.

The Mitigation Co-Benefit

Metric	**SSP1-2.6**	**SSP5-8.5**
TOFL increase (mean)	∼1%	∼4% (up to 7.5%)
Inoperable days (75 t, best rwy)	<2/yr	10–32/yr
Climb-limited regime	rare	up to 15% of days
Flex capability	preserved	40–60% reduced
Assessment	**Manageable**	**Adaptation required**

Mitigation cuts the worst impacts sharply – >**80%** of temperature-threshold exceedances and ∼**60%** of headwind change. It doesn't only reduce aviation's emissions – it protects aviation's **ability to operate**.

Conclusion

Conclusion

The hazard

Temperature dominates (+2–6°C); wind is secondary but compounds.

The impact

Longer take-off (+4–7.5%), up to 32 inoperable days/yr, thinner safety margins, lost flex.

The vulnerability

Concentrated at high-altitude & short-runway airports; runway length modulates it.

The response

Mitigate, build, adapt operations – and act in the 2025–2040 window.

Climate change creates structural operational constraints – neither uniform nor inevitable.

Thank you – questions welcome

Perspectives: Where This Goes Next

The framework – bias-corrected climate → take-off model → operational metrics – carries naturally beyond this thesis, and several projects are already taking it further:

Already underway

Maxime Bertrand (intern, ISAE-SUPAERO)
Extending the impact analysis to **several aircraft and engine types**.

Gokulnath Ramachandran (PhD, CERFACS)
Carrying it to an **entire aircraft mission**, across different aircraft, in partnership with Airbus.

Further open directions

- Landing performance under the same projections
- Economic cost of inoperable days & lost flex
- Refined high-altitude model corrections

References & Resources

Journal article:

Salles, S., Ricci, S., Gourdain, N., & Druot, T. (2025). *Multidisciplinary assessment of the impact of temperature rise and headwind on aircraft take-off performance.* Climatic Change, 178(11), 200. https://doi.org/10.1007/s10584-025-04016-0

PhD thesis:

Suzanne Salles (2025). *Impact of Climate Change on Aircraft Take-off Performance: Quantifying Future Performance Degradation Through Climate Projections for Adaptation Planning.* https://theses.fr/2025ESAE0062

Short MOOC – open access (ISAE-SUPAERO)

A short introduction to this work, open access to all:

"Impacts of Climate Change on Aviation Take-off & Runway Length"

microlearning.groupe-isae.fr (scan to open →)

Thank you – questions welcome

APPENDICES

Background, methodology & extra detail – for questions

Outline

Methodology

I. Climate Hazard

- CMIP6 multi-model ensemble
- Bias correction (CDFt)

II. Vulnerability & Exposure

- Aircraft performance model
- Multi-runway framework
- 60 global airports

Results & Conclusions

I. Climate Projections

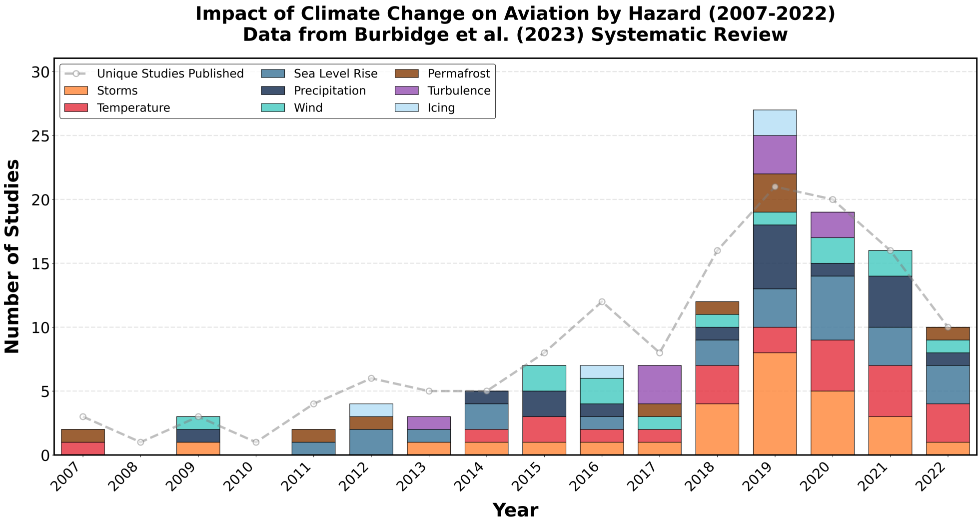
- Temperature & wind trends
- Geographic patterns

II. Operational Impacts

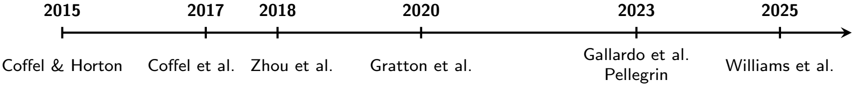
- Performance degradation
- Adaptation strategies

Conclusions & Perspectives

Literature Context: A Growing Research Field



Literature: Key Contributions & Gaps



2015 Coffel & Horton

2017 Coffel et al.

2018 Zhou et al.

2020 Gratton et al.

2023 Gallardo et al.
Pellegrin

2025 Williams et al.

Refs: Coffel & Horton, 2015; Coffel et al., 2017; Zhou et al., 2018; Gratton et al., 2020; Gallardo et al., 2023; Pellegrin, 2023; Williams et al., 2025

Literature: Key Contributions & Gaps

2015	2017	2018	2020	2023	2025
Coffel & Horton	Coffel et al.	Zhou et al.	Gratton et al.	Gallardo et al. Pellegrin	Williams et al.

Vulnerability

Performance response

- Manufacturer charts (temp only)
- → **Gratton 2020:** Physics-based model + wind

Refs: Coffel & Horton, 2015; Coffel et al., 2017; Zhou et al., 2018; Gratton et al., 2020; Gallardo et al., 2023; Pellegrin, 2023; Williams et al., 2025

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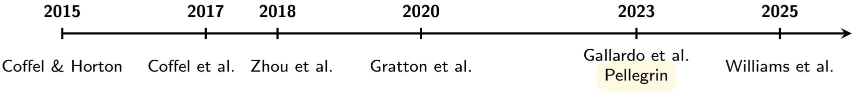

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Vulnerability

Performance response

- Manufacturer charts (temp only)
- → **Gratton 2020:** Physics-based model + wind

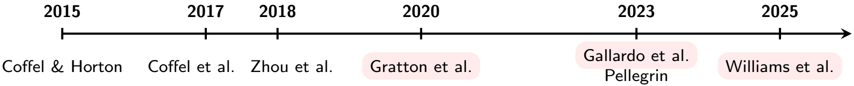
Exposure

Geographic scope

- Limited airports in specific regions
- → **Pellegrin 2023:** 881 airports globally + air traffic

Refs: Coffel & Horton, 2015; Coffel et al., 2017; Zhou et al., 2018; Gratton et al., 2020; Gallardo et al., 2023; Pellegrin, 2023; Williams et al., 2025

Literature: Key Contributions & Gaps



2015 Coffel & Horton

2017 Coffel et al.

2018 Zhou et al.

2020 Gratton et al.

2023 Gallardo et al.
Pellegrin

2025 Williams et al.

Vulnerability

Performance response

- Manufacturer charts (temp only)
- → **Gratton 2020:** Physics-based model + wind

Exposure

Geographic scope

- Limited airports in specific regions
- → **Pellegrin 2023:** 881 airports globally + air traffic

Climate Hazard

Projection methods

- CMIP5 global model
- → **Gallardo 2023:** Regional vs GCM
- → **Williams 2025:** CMIP6

Variables considered

- Only Temperature
- → **Gratton 2020:** Added wind

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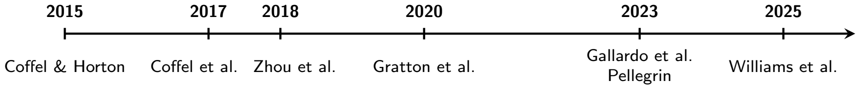

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This thesis: Integrated Framework

Climate: CMIP6 multi-model + bias corr., T & Wind **Vulnerability:** New model + multi-runway **Exposure:** 60 airports + 2 scenarios

Refs: Coffel & Horton, 2015; Coffel et al., 2017; Zhou et al., 2018; Gratton et al., 2020; Gallardo et al., 2023; Pellegrin, 2023; Williams et al., 2025

Context: ICCA Project

ICCA: Impact of Climate Change on Aviation

French ecosystem (Toulouse) + European network (EN-ICCA)
Coordinated by EASA ● Part of EU Adaptation Strategy

This Thesis

Temperature & Wind impacts

- CMIP6 multi-model ensemble
- Take-off performance model
- 60 airports globally
- SSP1-2.6 & SSP5-8.5

ISA labeled

ISAE-SUPAERO & CERFACS

Related CERFACS Work

Mediterranean warming

Gallardo, Sanchez et al., 2023
Regional temperature impacts on take-off performance

Clear-air turbulence

Foudad et al., 2023
CAT changes under climate warming

Ongoing ICCA Work

Icing hazards

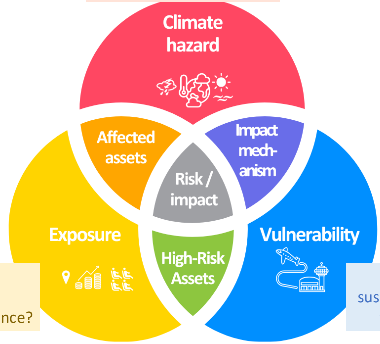
Perrini, Page (CERFACS)
Ice accretion projections under climate change

Multi-hazard assessment

ICCA collaborative network
Comprehensive risk framework

Refs: Gallardo et al., 2023, *Clim. Dyn.*; Foudad et al., 2023, *JGR: Atmos.*

Defining Impact: Key Questions



What is the threat?
Intensity?
Probability of occurrence?

Where?
When?
What consequence?

How
susceptible/sensitive
to the hazard?

Choice of Climate Variables

Temperature: T_{max} (Daily Maximum)

- Performance worst at hottest time of day
- Conservative for safety assessment

Temperature Limit

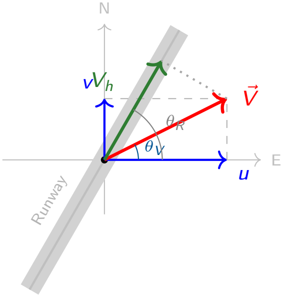
$$T_{lim} = T_{ISA} + 35C$$

- T_{ISA} = standard atmosphere temperature
- Decreases with altitude (6.5°C per km)
- $\rightarrow$ Higher airports have lower T_{lim}

Example: Delhi (237m): $T_{lim} = 48.5C$

Wind: u, v components

- u = eastward, v = northward (10m)
- Project onto runway axis

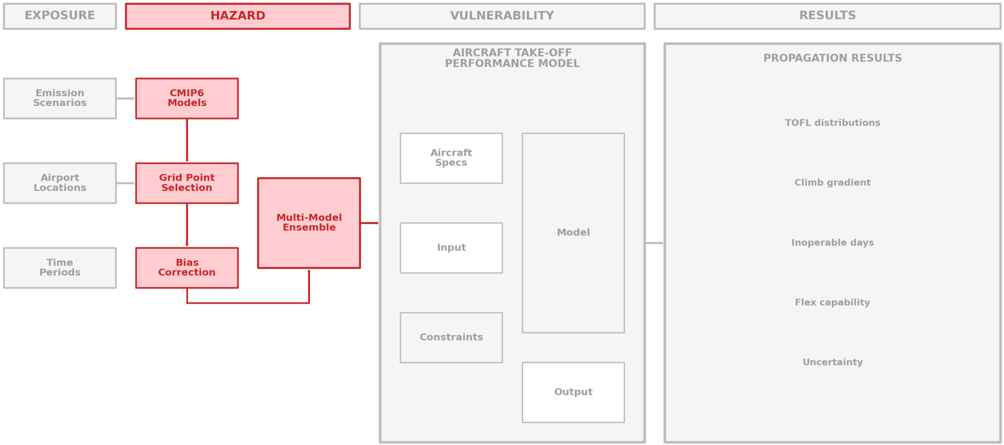


Headwind Component

$$V_h = |\vec{V}| \cdot \cos(\theta_V - \theta_R)$$

$V_h > 0$: headwind ✓ $V_h < 0$: tailwind

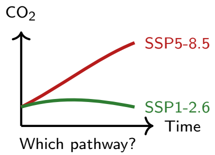
Workflow: Climate Data Processing



Three Sources of Uncertainty

1. Scenario Uncertainty

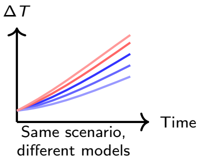
We don't know future emissions



Solution: Compare 2 scenarios
SSP1-2.6 vs SSP5-8.5

2. Model Uncertainty

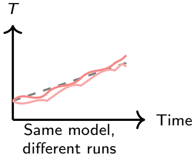
Models differ in climate sensitivity



Solution: 5-model ensemble
ECS from 2.5°C to 5.6°C

3. Internal Variability

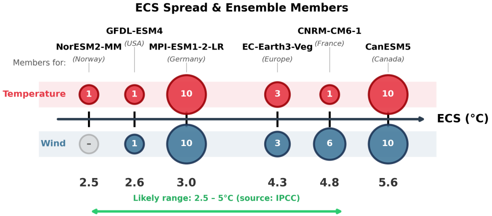
Natural climate fluctuations

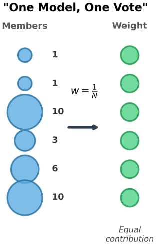


Solution: Multiple members
per model (26 total)

Multi-model ensemble addresses all three → Robust uncertainty quantification

Multi-Model Ensemble (ECS spread)





Model selection

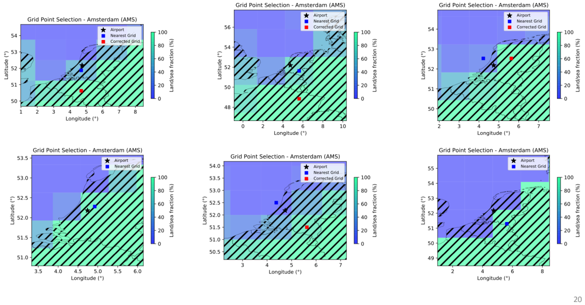
6 models chosen to span equilibrium climate sensitivity (ECS 2.5–5.6° C).

"One model, one vote"

Equal weighting – avoids over-confidence from performance metrics that may not hold in the future.

Grid Selection & Land–Sea Mask

Grid point selection per airport



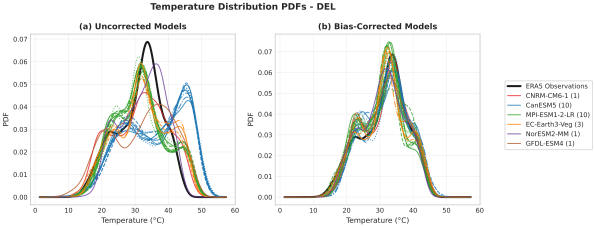
Spatial discretisation

Models resolve ∼100–200 km cells; we pick the cell at each airport.

Land–sea mask

Coastal airports: ensure the cell is **land**, not sea – avoids a systematic temperature bias.

Bias Correction (CDFt)



Delhi – validation 2000–2015

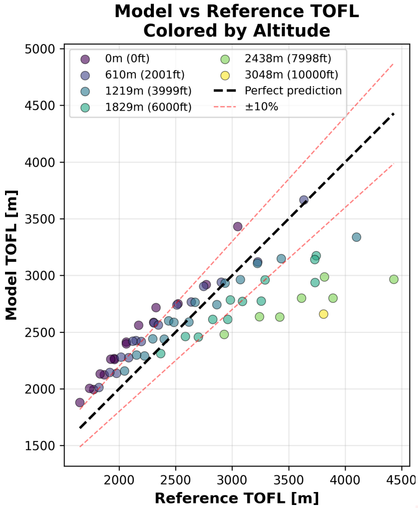
CDFt method

Maps the model's cumulative distribution onto the reference – corrects the **whole distribution**, preserves the change signal.

Result

Bias $+1.34^\circ$C $\rightarrow$ -0.01°C; RMSE -21%. Wind validated similarly (wind roses).

Model Validation Detail



Dataset

Boeing 737-800 planning data; multiple altitudes, ISA to ISA+35 °C, 66–78 t.

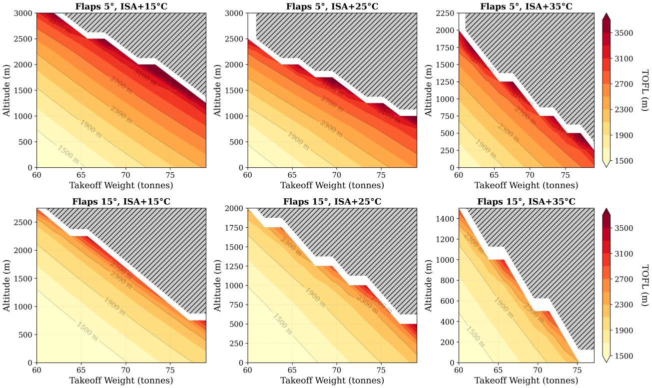
Accuracy (methodology chapter)

377 m RMSE (∼11%), **+3.4% bias** across ISA to ISA+35 °C; temperature slope error ±16% below 1,800 m (95% of operations).

Limitation

Altitude bias ∼ −1.5%/1000 m, **independent of temperature** → trends & rankings robust.

Configuration Envelope



Weight × altitude × temperature

Hatched = take-off length exceeds runway (infeasible).

At ISA+35°C

Flaps 5°: max alt ≈2000 m; Flaps 15°: ≈1400 m. High airports lose operability first.

Composite Impact Score

$$\textbf{Composite} = 0.7\times\ \text{Availability Loss} + 0.3\times\ \text{Capability Loss}$$

$$\textbf{Economic} = \text{Days Lost} + 0.5\times\ \text{Capability Degradation}$$

Terms

Availability = % of days flex is possible; Capability = thrust reduction still achievable.

Why 70/30?

Outright loss of flex is costlier than gradual reduction – it forces full thrust and prevents any optimisation.