

1%

of global warming

...comes from aviation,

...is not CO₂ dependent,

...and can easily be removed, **today!**

3%

of CO₂

5%

of net warming

Contrails!



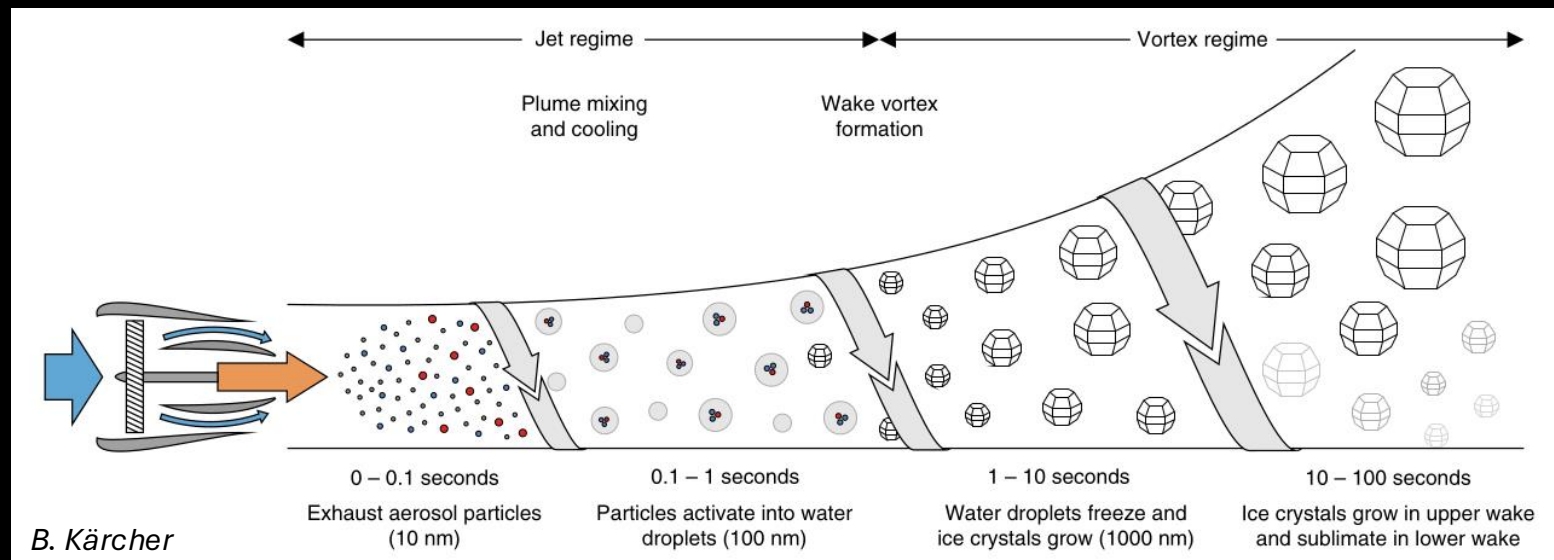
Contrail Avoidance

Decision making under uncertainty

Filip Herbertsson

Contrails

- Just water!
- Forms when exhaust air mixes with ambient air
- Lasting up to ~2 days
- Can have both a warming and a cooling effect



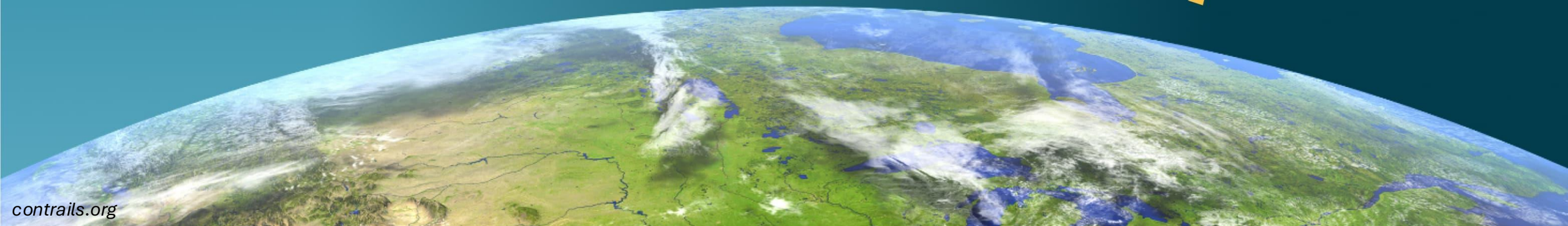


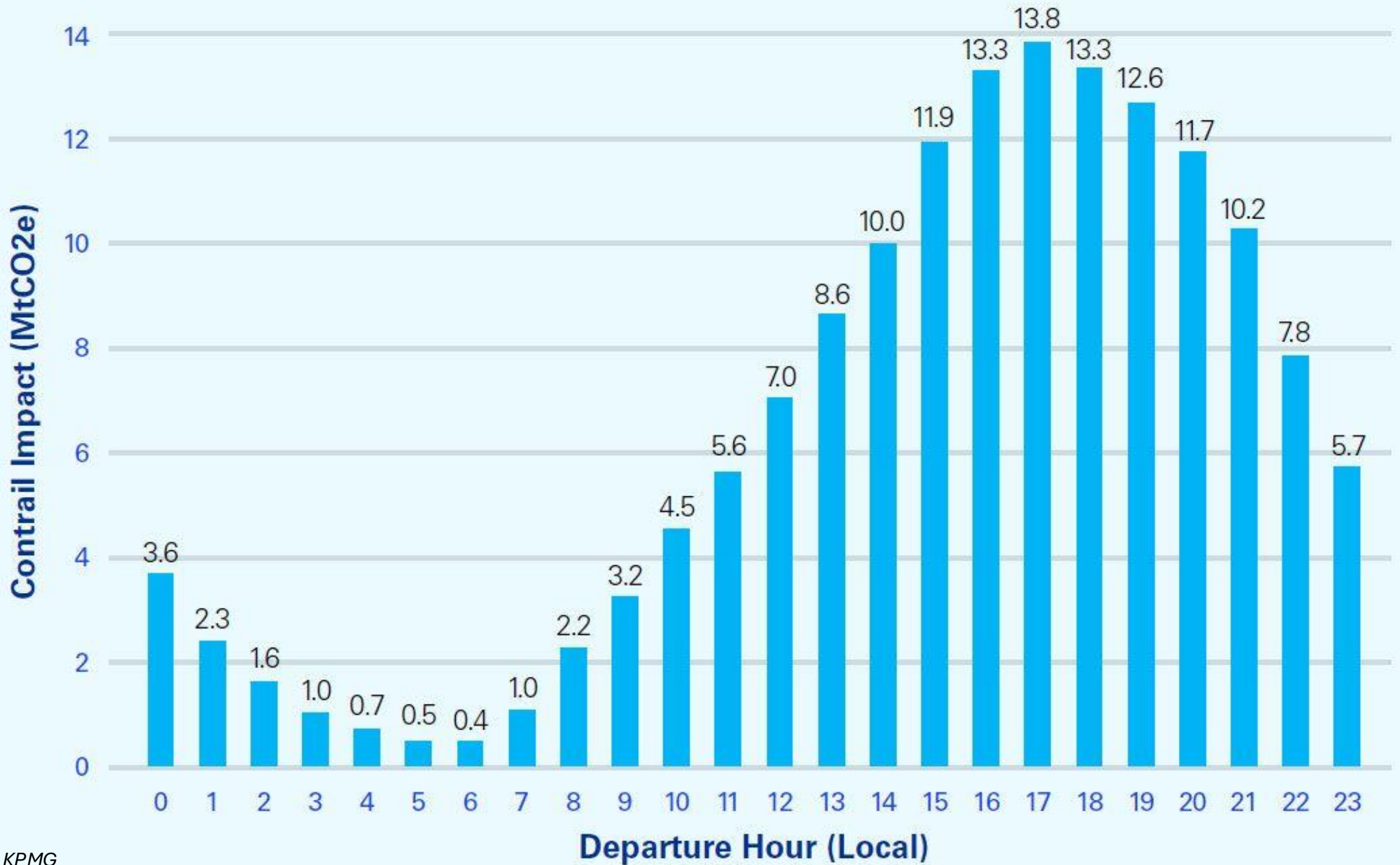
Some of the sun's energy gets reflected away from the earth by contrail-induced cirrus clouds

Earth radiates heat back out into space

...but most of the sun's energy passes through, warming the Earth.

...but the contrail-induced cirrus clouds absorb some of this heat and act like a blanket around the Earth.





Persistence



Not persistent



Persistent

When do persistent contrails form?

— Liquid saturation line

— Ice saturation line

● Ambient conditions

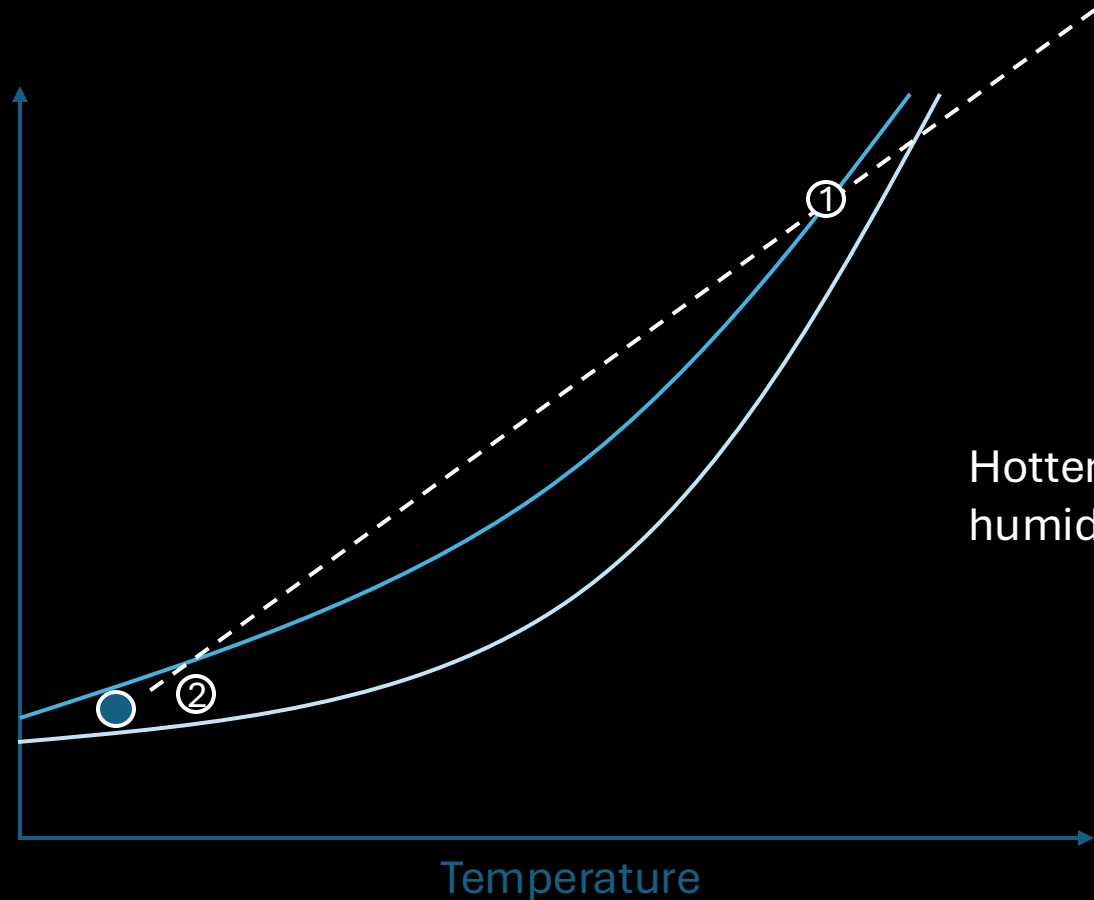
-- Mixing line

① Ice particles form

② Ice particles persist

Water partial
pressure

Less humid
ambient air



Hotter or less
humid exhaust

Temperature

When do persistent contrails form?

Engine

1

Liquid droplets form

Weather

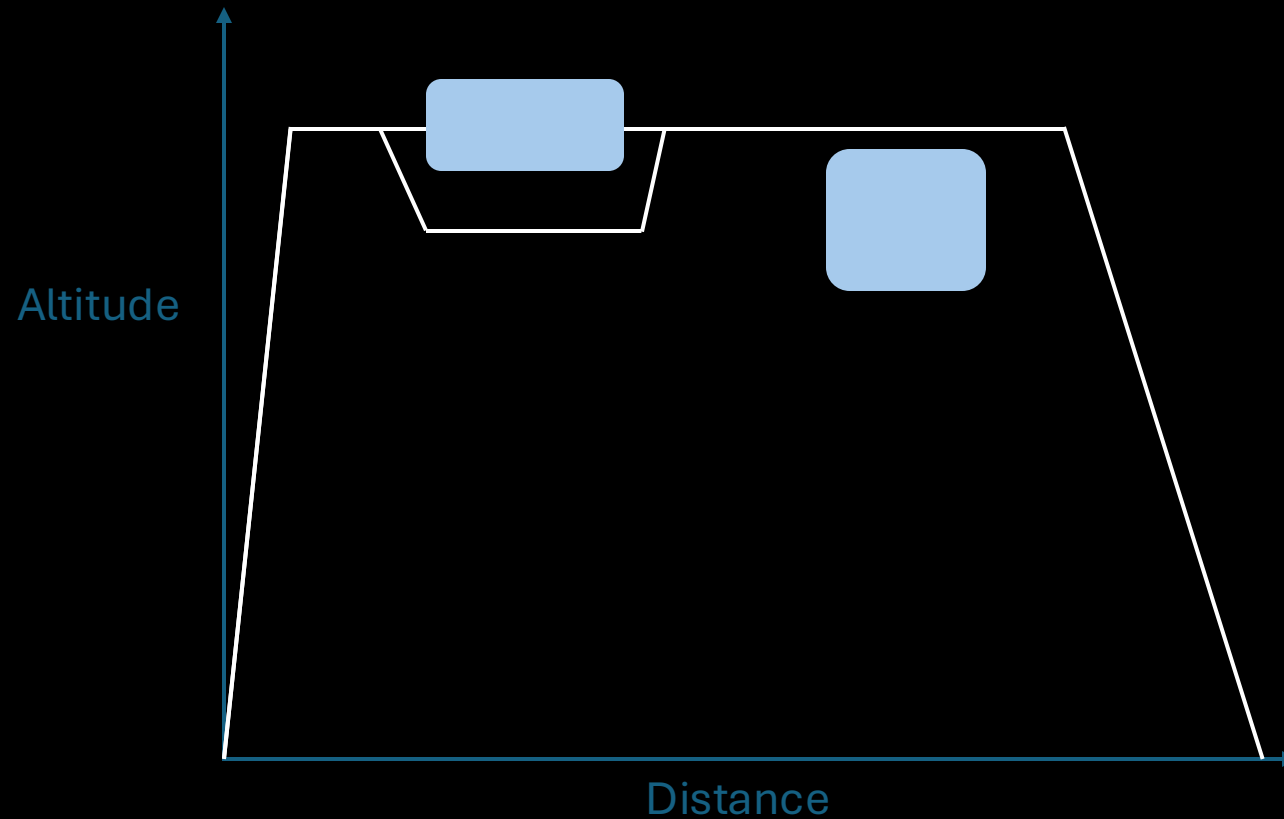
2

Ice-super saturated region (ISSR)

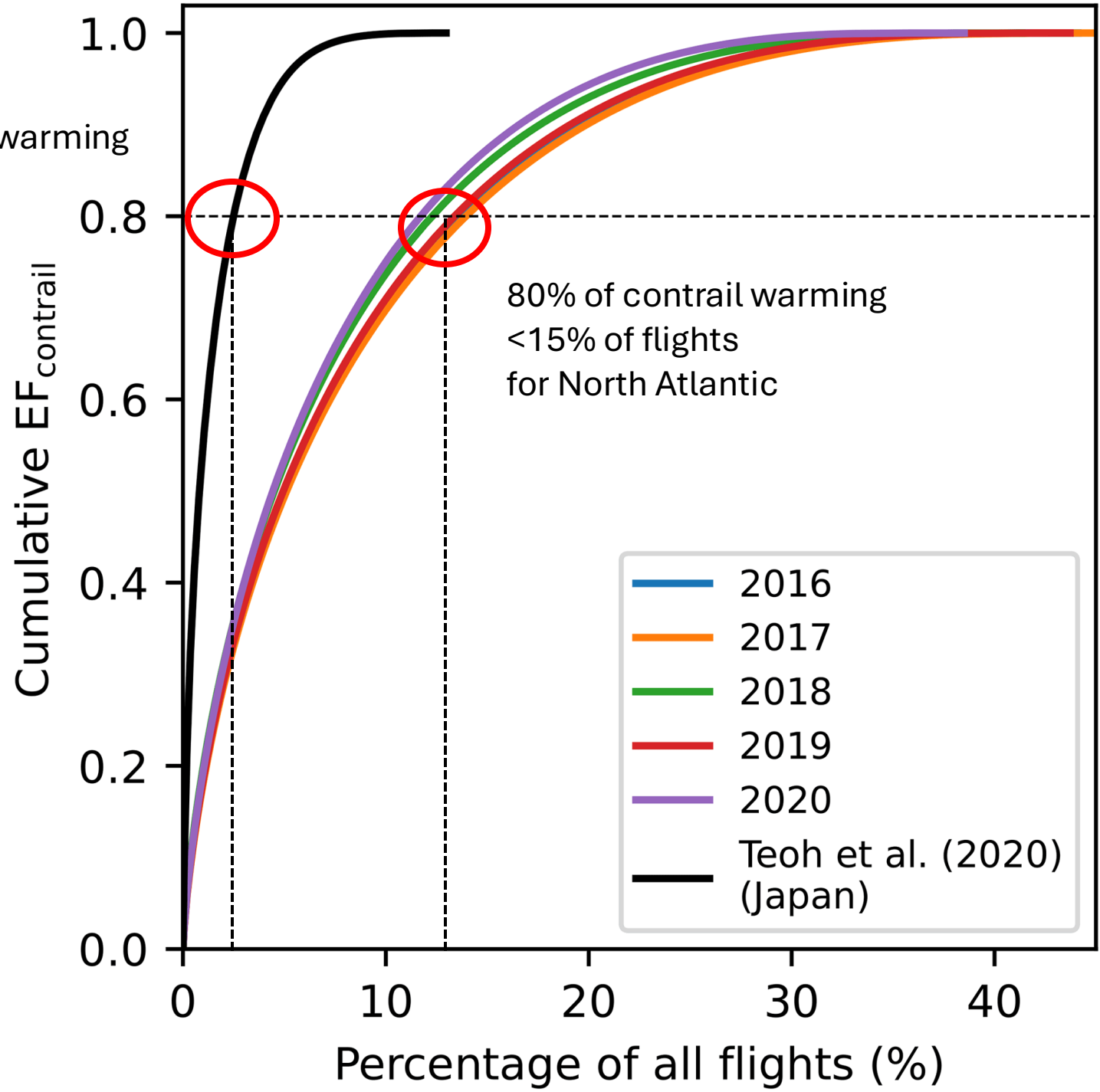
How to avoid persistent contrails

— Flight trajectory

■ ISSR



80% of contrail warming
<5% of flights
for Japan


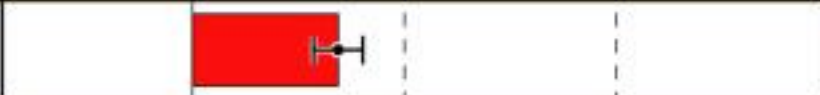


80% of contrail warming
<15% of flights
for North Atlantic

- 2016
- 2017
- 2018
- 2019
- 2020
- Teoh et al. (2020) (Japan)

Problem: Uncertainty

Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018)

		ERF (mW m ⁻²)	RF (mW m ⁻²)	$\frac{\text{ERF}}{\text{RF}}$	Conf. levels
Contrail cirrus in high-humidity regions		57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO ₂) emissions		34.3 (28, 40)	34.3 (31, 38)	1.0	High

17 – 98 mW/m²

40 – 350% CO₂e

ISSR prediction

50 % precision

”If we predict an ISSR,
we will find one in half
of the cases”

Unnecessary avoidance...

90 % recall

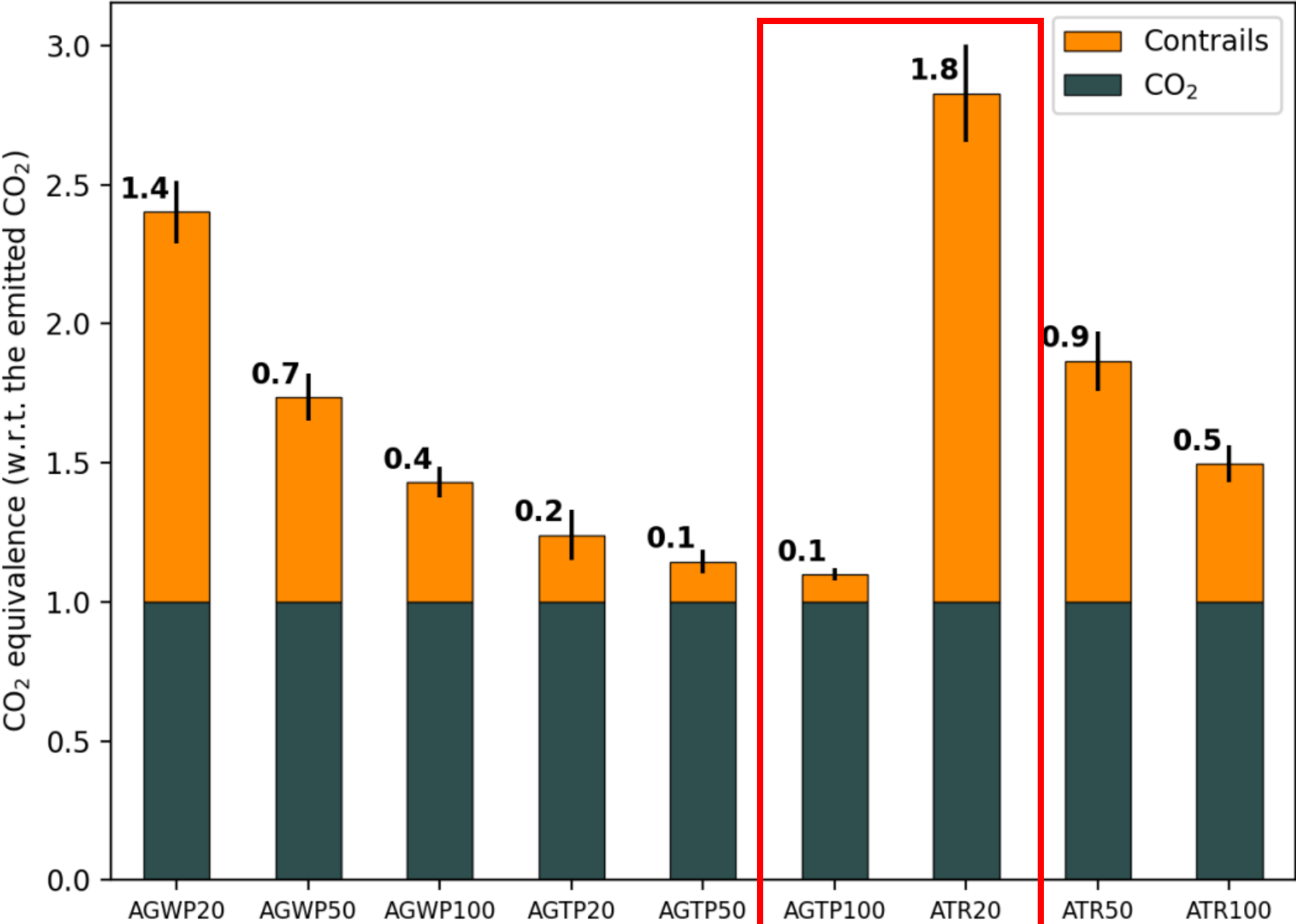
”We catch 90 % of all
ISSRs”

...but low risk of
accidental contrails

Metrics

- Radiative Forcing (RF)
 - Effective Radiative Forcing (ERF)
 - Energy Forcing (EF)
 - Global Warming Potential (GWP)
 - Global Temperature change Potential (GTP)
 - Average Temperature Response (ATR)
 - Short-lived effects weighted GWP (GWP*)
 - Efficacy weighted GWP (EGWP)
-
- Different time horizons (20, 50, 100 years)

Cumulated climate impact (relatively to CO₂)



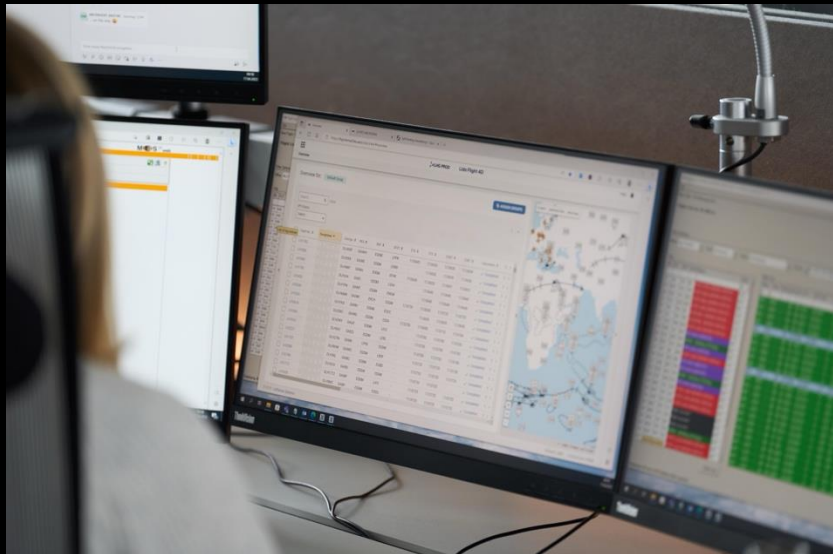
A. Borella et al.

Problem: Operation

Types of avoidance

Strategic

- Happens before the flight
- Done by flight planner
- Uses weather prediction



Tactical

- Happens during flight
- Done by pilot
- Uses real-time weather



Problem during tactical stage

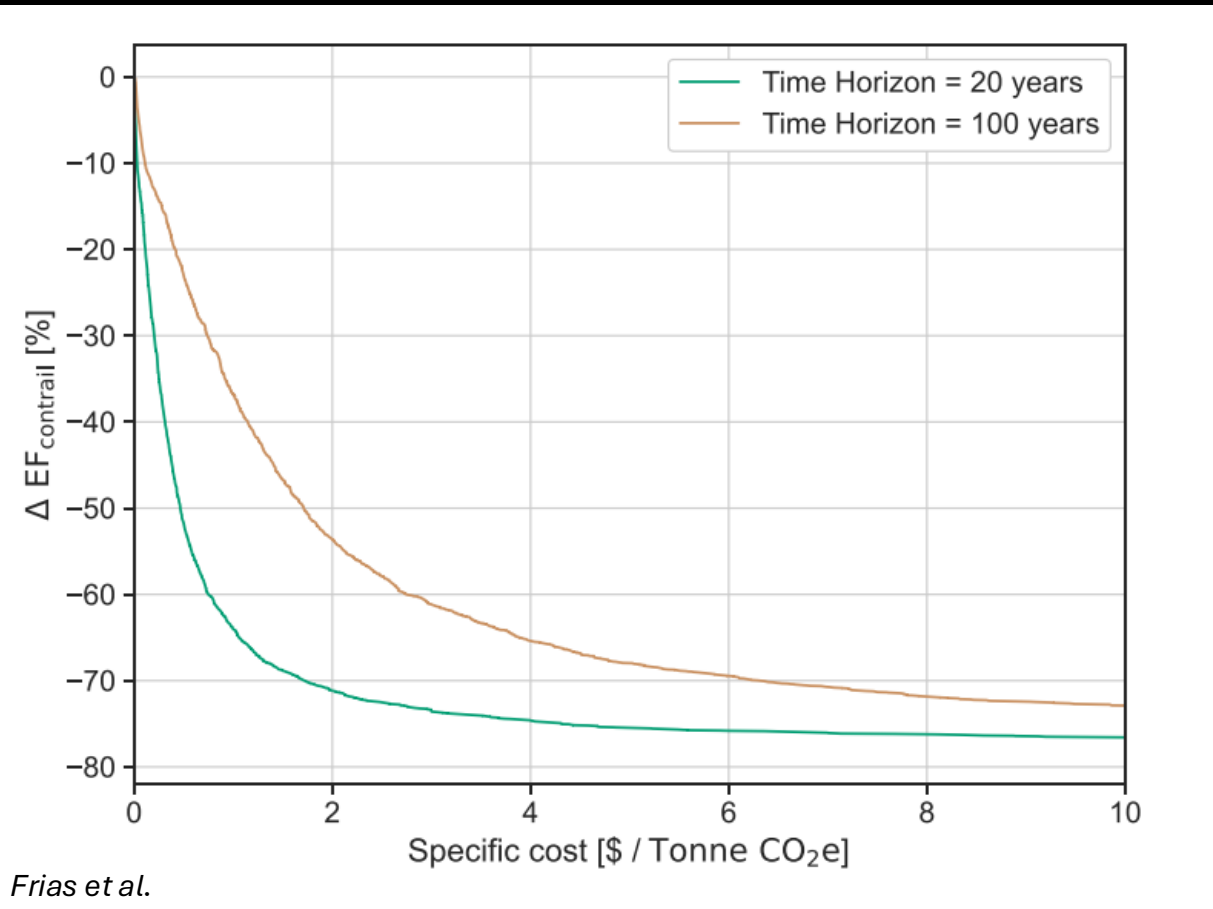
- ATC may give "better route"
- ATC may not allow route change
- Fractured airspace
- Too little space available
- Uninformed pilots
- Delays and available fuel



Problem: Incentives

Wrong incentives for airlines

- Increases complexity and workload
- Increases fuel costs
- No "correct" way of performing avoidance
- Risk of "green washing"

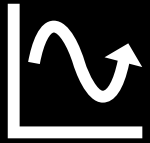


Challenging implementation of incentives

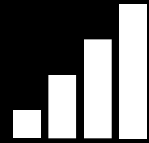
- Should you limit...
 - Flight distance (bad incentives)
 - Contrail distance (bad proxy)
 - Warming effect (difficult to estimate)
 - Limiting airspace (causes blockage)
- International issue
- Airlines not always capable of acting → Unfairness

Solution

Solution



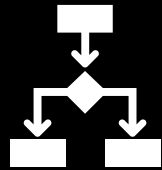
Ways to mitigate
effects of uncertainty



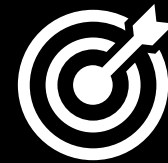
Unified way to compare
climate forcings



Better informed
colleagues



Structured way to
perform mitigation



Well-targeted incentives