



WORLD  
METEOROLOGICAL  
ORGANIZATION



# Impact of Climate Change and Variability on Aviation: Review of Latest Findings

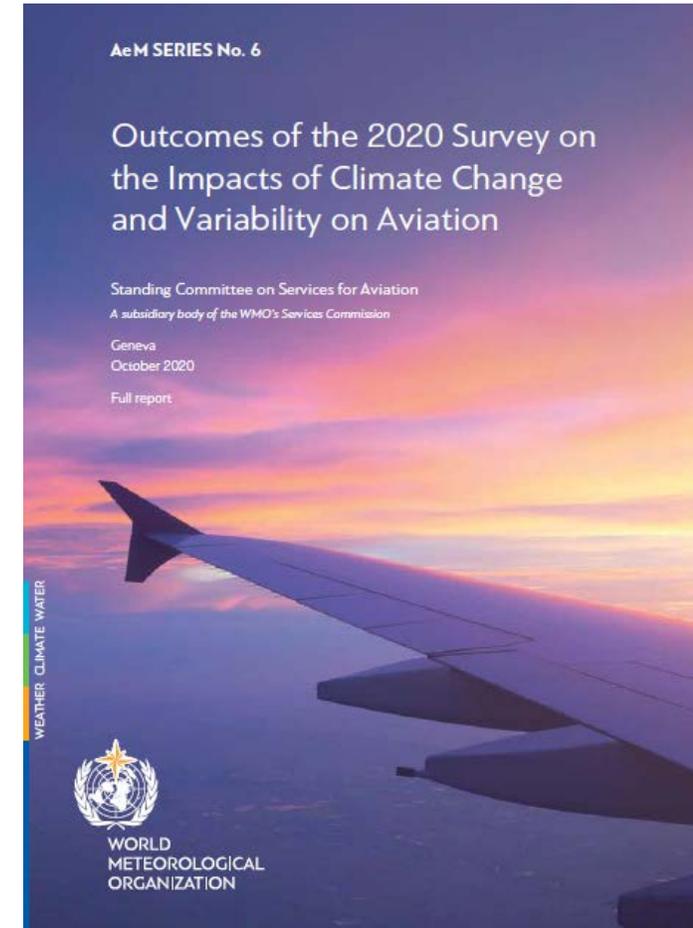
Andrea Henderson  
Chair, SC-AVI

# Content

- Background
- Hazards and Impacts
  - Air Temperature
  - En-Route Turbulence
  - Convection
  - Jet Streams
  - Sea Level Rise
- Key Outcomes

# Background

- In 2020, the WMO SERCOM Standing Committee on Services for Aviation (SC-AVI) conducted a global survey on the impacts of climate change and variability on aviation.
- Final report published by WMO, publicly available:  
<https://library.wmo.int/idurl/4/57199>



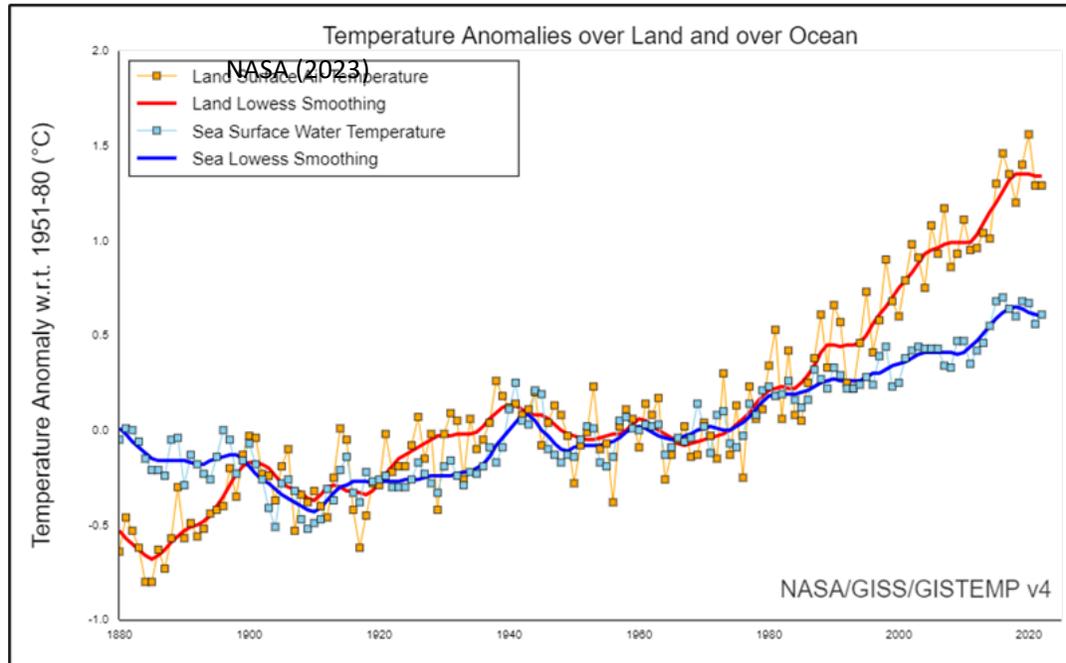
# Hazards and Impacts

Meteorological Hazard	Impact				
	Safety	Infrastructure	Operational	Performance	Environmental
En-Route Turbulence	✓				
En-Route Icing	✓			✓	
Convection	✓	✓	✓		
Jet Streams/Tropopause			✓		✓
Air Temperature	✓	✓	✓	✓	✓
Tropical Storms	✓	✓	✓		
Low-Level Wind	✓	✓		✓	✓
Sandstorm/Dust Storm	✓	✓	✓		
Fog and Visibility	✓		✓		
Precipitation	✓	✓	✓		✓
Sea-Level Rise		✓	✓		✓

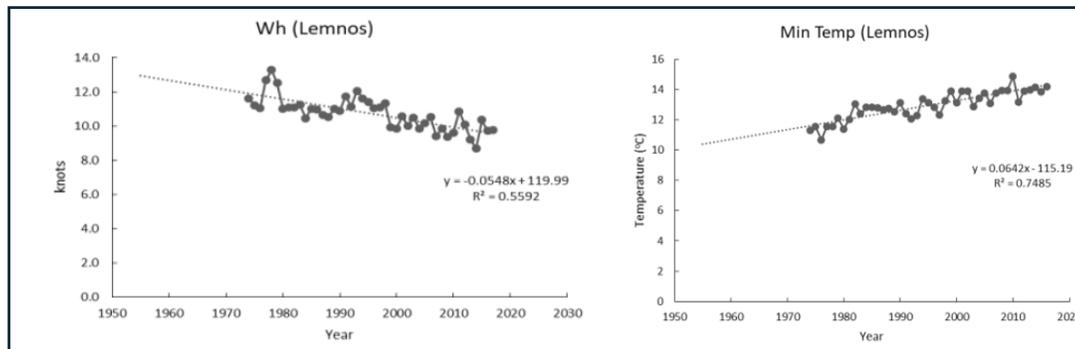
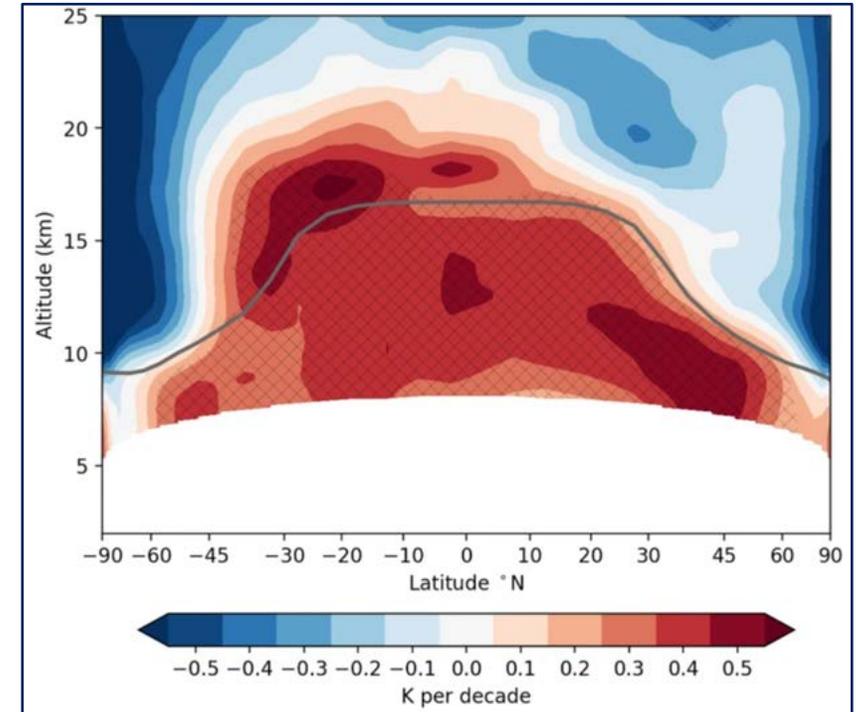


# Air Temperature

## Historical Trends



Ladstadter et al. (2023)



### Results for airports where available payload changes

Airport	Years considered	MTOM at start (kg)	MTOM at end (kg)	Difference (kg)	Mean change per year (kg.pa)
Chios	1974-2017	74,850	69,177	5,673	-132
Skiathos	1987-2015	74,189	73,086	1,103	-39

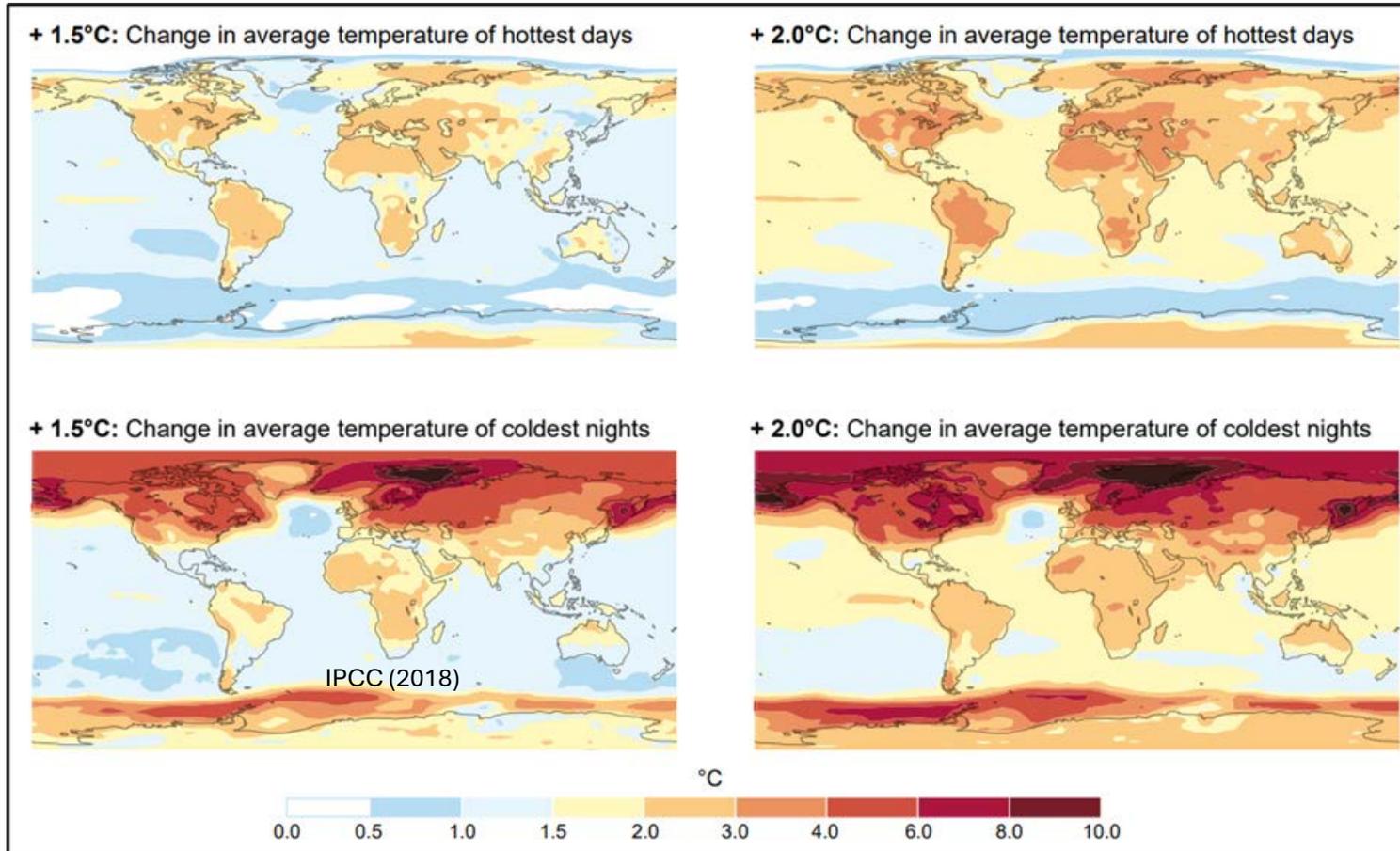
Gratton et al. (2020)

# Air Temperature

OFFICIAL



## Projected Trends



- Number of weight-restriction days during the summer at four major US airports, may increase between 50% and 200% by 2050–2070 under RCP8.5.

*Coffel and Horton (2015)*

- During the warmest part of the day, 10% to 30% of flights may require payload and fuel weight restriction of 0.5% to 4.0% by mid-to-late 21st century.

*Coffel et al. (2017)*

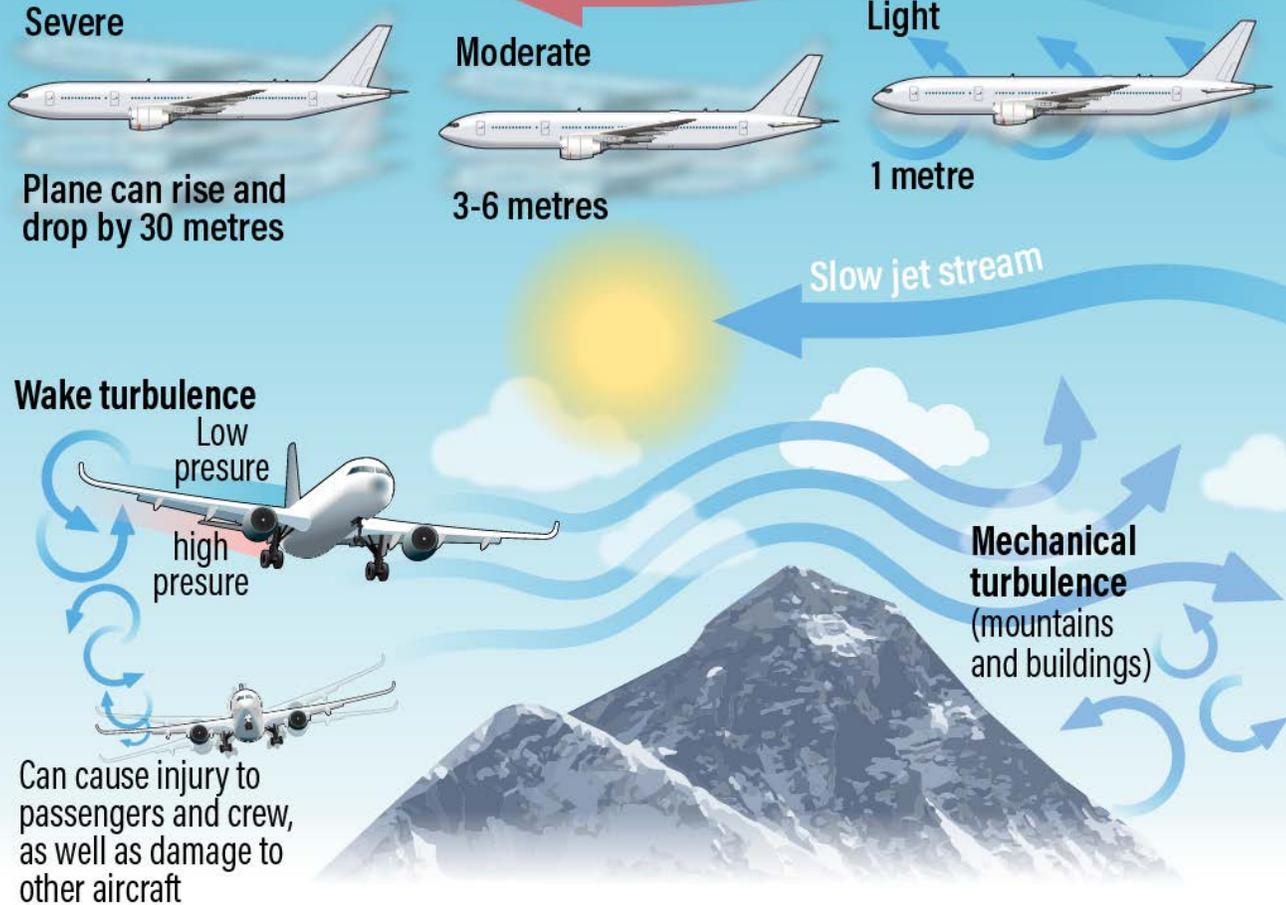
OFFICIAL

# En-Route Turbulence

OFFICIAL



## TURBULENCE EXPLAINED



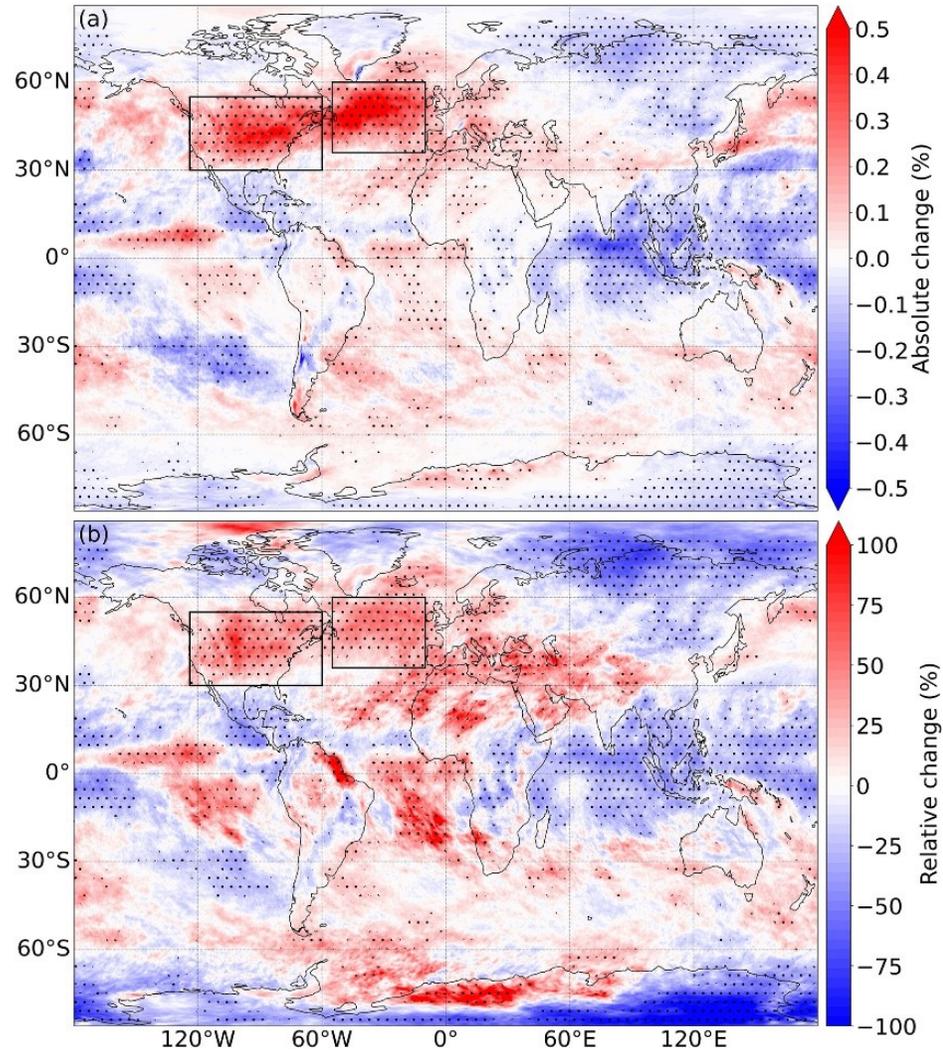
Graphic: Roy Cooper, The National



OFFICIAL

# En-Route Turbulence

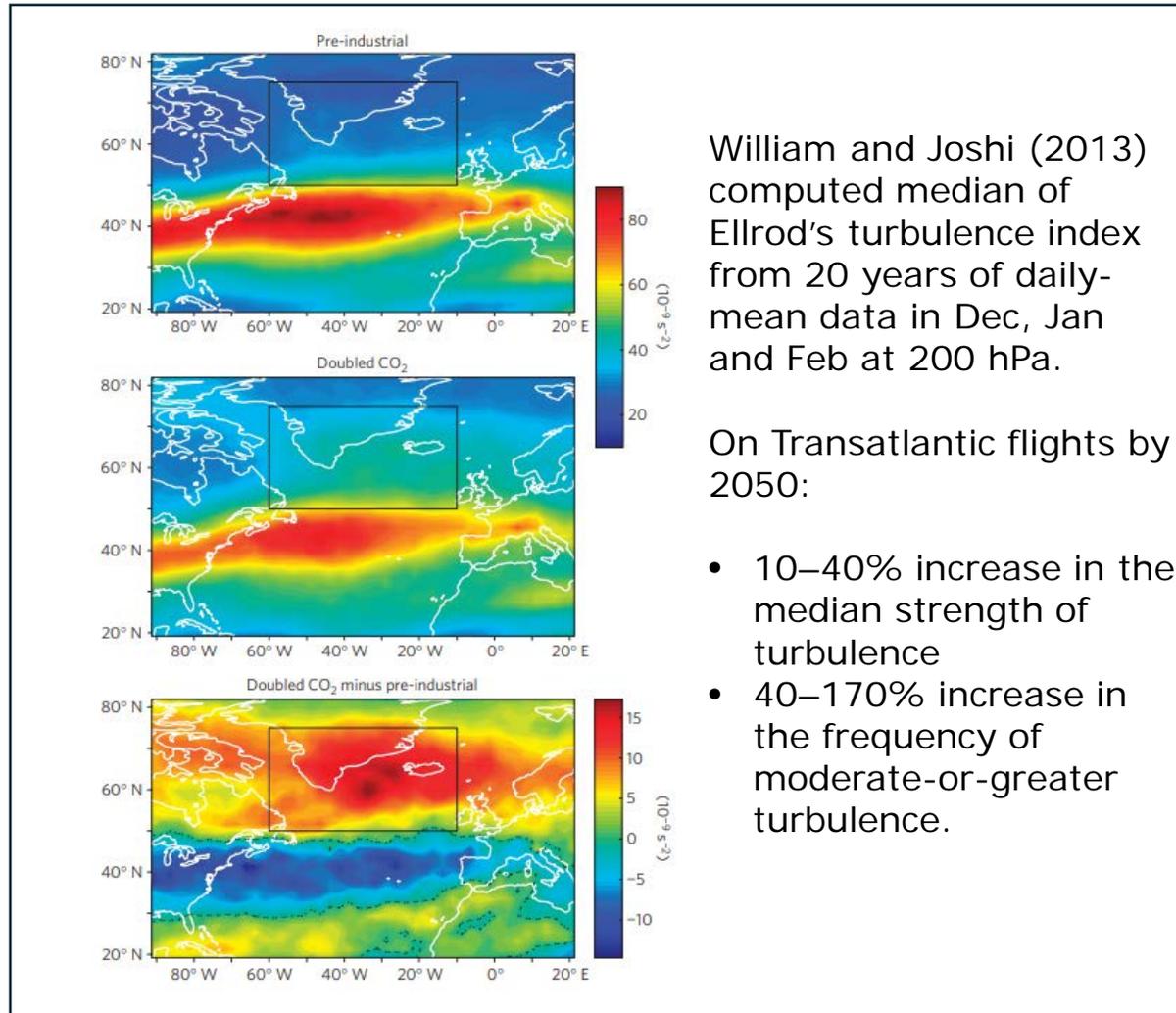
## Historic Analysis



(Prosser et al., 2023)

- Change in moderate or greater severity of clear air turbulence from 1979 to 2020 using ECMWF's ERA5 reanalysis data at 197hPa pressure level
- Increasing turbulence in the North and South Atlantic region.
- Decreasing turbulence in the Central America, Northern Russia and Indian Ocean.
- Autumn and Winter has more clear air turbulence of all strengths compared to Spring and Summer.
- Some anecdotal experiential evidence from Flight Crew of more frequent turbulence.

## Future Projections



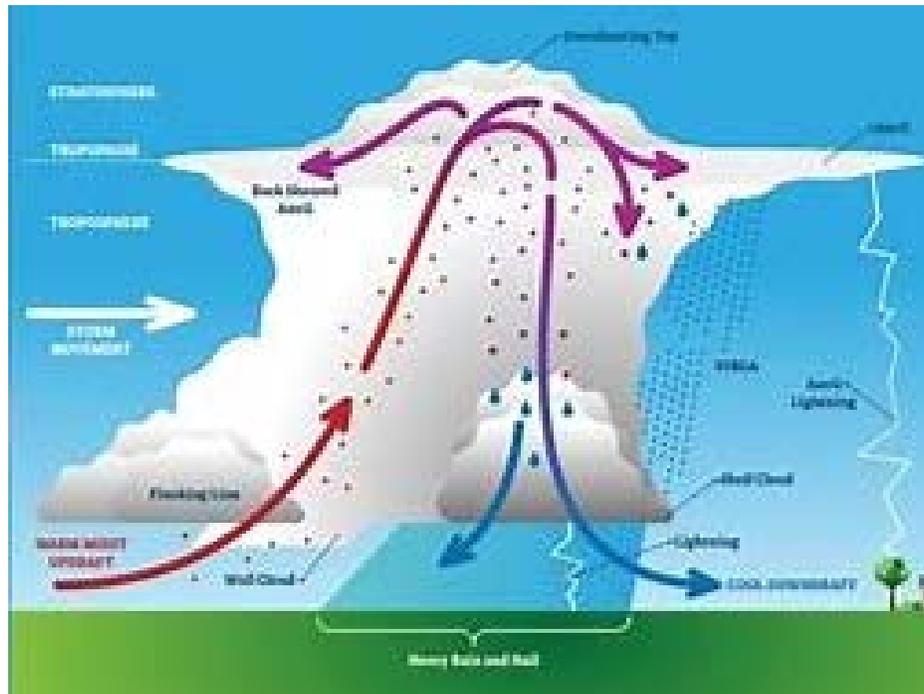
(Period 2056-2100, relative to 1970-2014 average)

Kim et al. (2023)

Strength Category	North Atlantic		North America		North Pacific		Europe	
	200 hPa	250 hPa	200 hPa	250 hPa	200 hPa	250 hPa	200 hPa	250 hPa
Light	+75.4	+47.3	+110.1	+71.0	+120.7	+82.0	+90.5	+59.9
Light-to-moderate	+124.1	+80.7	+113.6	+57.5	+106.6	+53.8	+130.7	+75.8
Moderate	+143.3	+74.4	+100.3	+50.2	+90.2	+41.6	+126.8	+60.8
Moderate-to-severe	+148.9	+71.0	+94.3	+47.0	+73.1	+35.3	+142.1	+66.1
Severe	+181.4	+88.0	+112.7	+58.9	+91.6	+40.1	+160.7	+90.6

Strength Category	South America		Africa		Asia		Australia	
	200 hPa	250 hPa	200 hPa	250 hPa	200 hPa	250 hPa	200 hPa	250 hPa
Light	+18.3	+13.4	+24.2	+18.9	+102.5	+65.1	+18.0	+9.5
Light-to-moderate	+27.1	+18.0	+27.9	+23.3	+92.4	+48.7	+23.1	+12.9
Moderate	+34.3	+22.8	+34.3	+26.0	+78.1	+48.7	+29.6	+19.1
Moderate-to-severe	+43.3	+23.8	+36.6	+26.9	+59.2	+47.9	+36.9	+24.8
Severe	+62.0	+31.6	+51.1	+40.2	+64.1	+55.4	+52.5	+35.4

## Convection and Associated Hazards Overview



### Impact / Dangerous for aviation:

Hail, strong downdrafts, squalls, wind shear, gusts, lightning

### Investigated regions as per the Compendium:

- Indian peninsula
- North America
- Europe
- Africa
- Global scale

### Investigations in analysed papers based on:

- Reanalysis data for historical trends
- For climate projections
  - Global climate models: CMIP5, CMIP6
  - Regional climate models

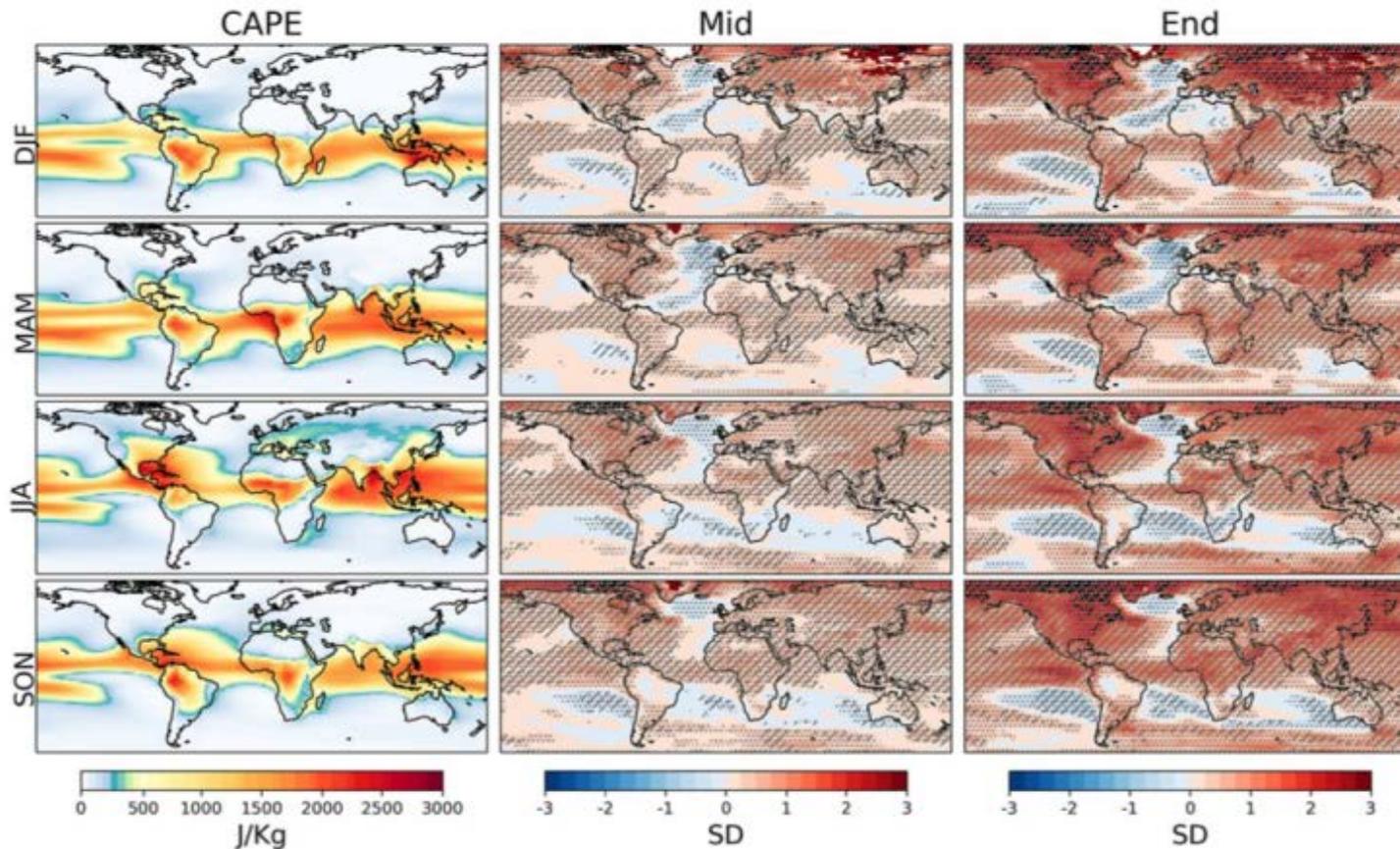
### Proxies for convection, some examples:

- CAPE – Convective available potential energy
- CIN – Convective inhibition
- Wind shear
- Simulated radar reflected thresholds

# Convection

OFFICIAL

## Global climatology and climate projections



### Example: Leopore et al., 2021:

- Investigations on CMIP6
- Seasonal climatology CAPE 1980 – 2010
- 30-year projected changes CAPE on SSP-8.5 scenario:
  - 2030 – 2060
  - 2070 - 2100

Projected changes are expressed in terms of multi-model seasonal interannual standard deviation of the historical period.

OFFICIAL

# Convection

## Short summary

From literature analysis for investigated regions about climate projections:

### Convection:

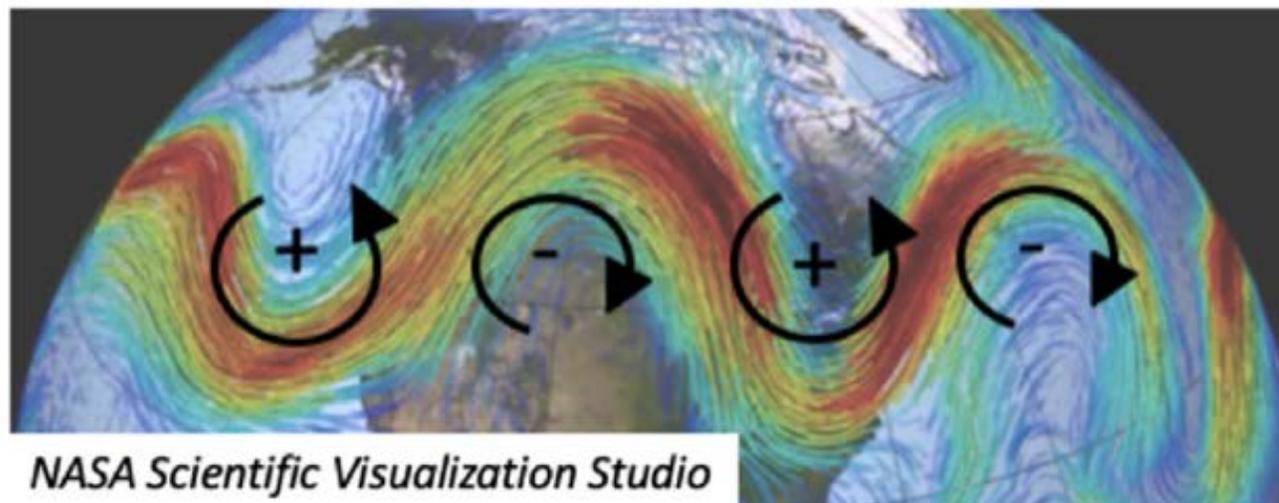
- **USA:** Increasing CAPE / convective activity in east part of USA
- **Europe:** Increasing convective activity in Europe, mostly in eastern part
- **Africa:** Decreasing precipitation intensity in northern part, increasing intensity expected in southern part of Africa.

### Hail:

- Hail frequency decrease in East Asia and North America, slightly increase in Australia and Europe.

# Jet Streams

## Overview



View of subpolar jet stream with Rossby-wave

### Impact on aviation:

- Tailwinds can reduce flight time and fuel consumptions
- Headwinds can increase flight time and fuel consumptions

### Jet stream under climate change condition:

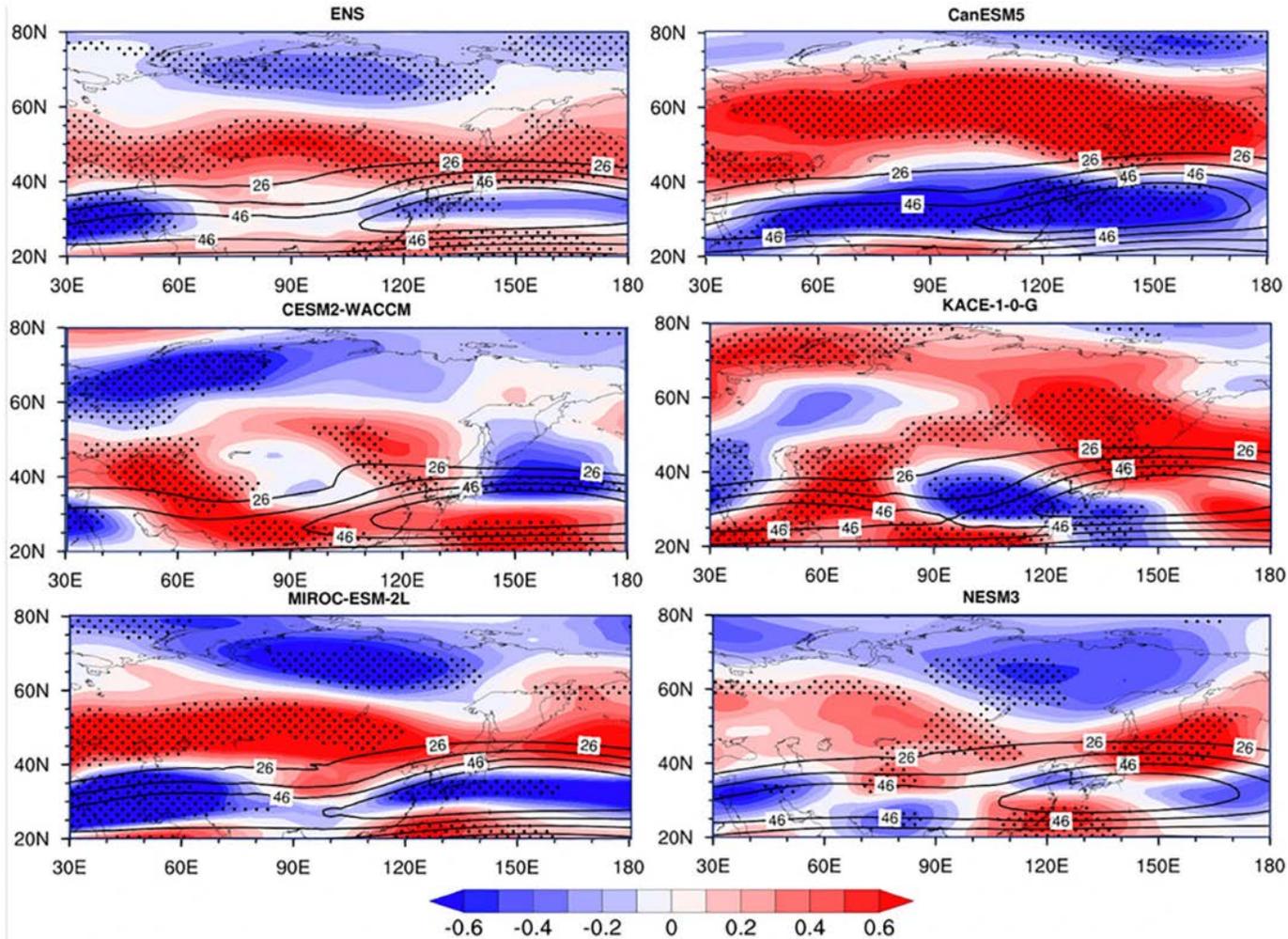
- Poles are warming stronger than the equator
  - weakening temperature gradient
- reverse behavior at altitude:
  - increasing meridional temperature gradient, thus increasing zonal wind speed in jet stream level

# Jet Streams

OFFICIAL



## Wintertime trends of zonal wind speeds



### Example: Lv et al., 2020

- Wintertime trends (m/s/decade) of zonal wind speed in Northern Eurasia at 250 hPa level
  - Period: 2015 – 2100
  - CMIP6, SSP245 and SSP585
- Increasing zonal wind speed between 40°N and 60°N
- Corresponding vertical wind shear tends to increase consequently.

OFFICIAL

## Short summary

- Climate change is projected to accelerate the average upper-level jet stream winds following an increase in the meridional temperature gradient aloft in both hemispheres (Shaw and Miyawaki, 2024).
- However, in the Northern Hemisphere it is weaker due to an opposing influence of Arctic amplification of surface temperature during wintertime.
- Various studies on changes in jet stream wind speed on flight duration have been carried out, including by EUROCONTROL.

### **Changes in flow behavior:**

- Due to decreasing meridional temperature gradients at low elevations:
  - weakening of the zonal wind and meandering of the wind band
  - increasing likelihood of forming blocks (Stendel et al., 2021)
  - persistent weather situations, e.g. heat waves, extreme precipitation events, extreme winter weather events.

# Sea Level Rise

OFFICIAL



- **Historical trend:** The rate of global mean sea level (GMSL) rise has varied since 1900, with increasing and decreasing periods. However, the GMSL rise in the twentieth century was faster than in any prior century over the last three millennia and has noticeably accelerated in the recent decade.
- **Projected future GMSL rise** varies with different climate scenarios but is always positive (higher mean sea level). Consequently, the land areas inundated globally are also projected to increase.
  - Up to 2050, IPCC AR6 projects that GMSL rise will vary according to different scenarios. Between the baseline period (1995–2014) and 2050, GMSL is projected to rise by 19 cm under SSP1-2.6 and by 23 cm under SSP5-8.5, which is consistent with AR5 estimates (Fox-Kemper et al., 2021).
  - Globally, the area inundated is projected to increase by 14% (15%) under RCP4.5 (RCP8.5) in 2050, compared to the present day, with an additional 16% (17%) of the population affected (Kirezci et al., 2020).

OFFICIAL

# Sea Level Rise

OFFICIAL



- Higher storm surges and more coastal floodings are expected, with **serious potential consequences to coastal aerodromes and impacts on aviation safety and infrastructure.**

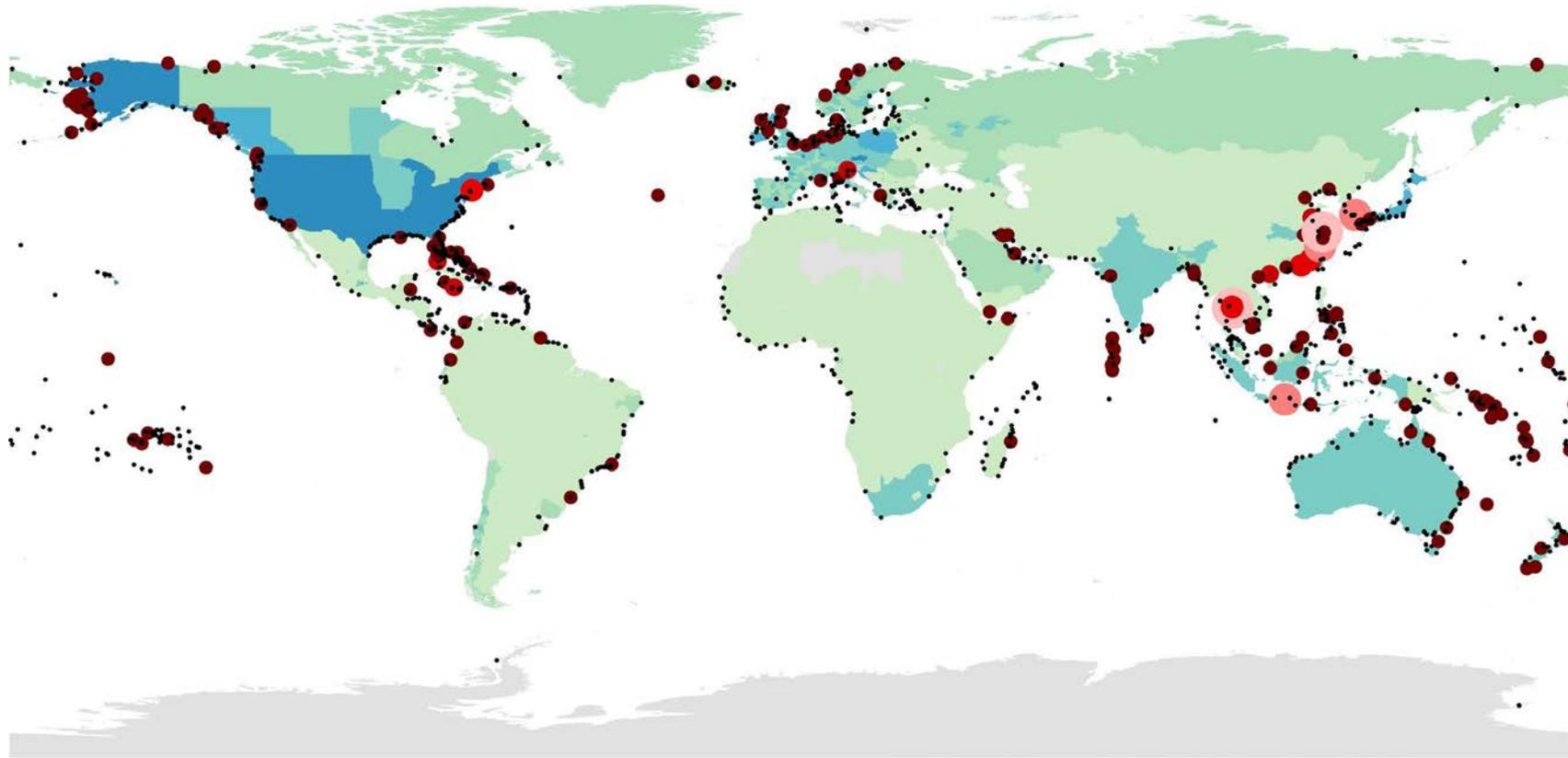


Kansai airport, sept 2018  
@airplusnews

OFFICIAL

# Sea Level Rise

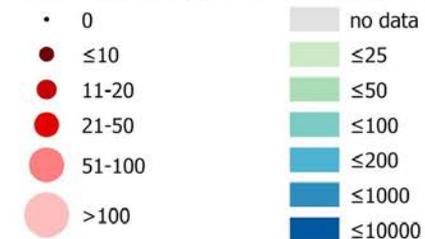
OFFICIAL



*Yesudian and Dawson (2021)*



Risk - RCP8.5 scenario    Standard of Flood Protection



*Note: the Compendium also considers Tropical cyclone, Sandstorm/Dust storm, Low-level wind and wind shear, Freezing precipitation and Fog.*

OFFICIAL

# Key Outcomes

OFFICIAL



- **Almost all meteorological hazards are expected to have a **greater** impact on aviation operations in the short-to-medium term.**
- **Current research is mostly focused on North American and European regions due to the concentration of air traffic. Research needs to be expanded to all regions of the world.**
- **Research gaps:**
  - **En-route icing** hazard, both historic and future projections
  - **Tropopause height and temperature** trends is under-studied and future projections are not clear.
  - Threshold **temperatures** for airport surface damage and aircraft structure and systems reliability needs to be quantified.
  - En-route cruise **temperature** trends for all geographical regions required.
  - Low-level and near-surface **wind speed** projections not yet estimated.
  - **Fog and visibility** has significant operational impact, but projections are unclear.
  - Research on **economic and social climate impact** on aviation has received little attention so far.

OFFICIAL

# Key Messages

OFFICIAL



Climate change may increase turbulence frequency and severity due to stronger jet streams. Better global forecasting is essential, especially in areas with high-density air traffic.



Climate projections suggest fewer tropical cyclones overall, but these cyclones are expected to be more intense, with higher peak wind speeds and heavier precipitation due to global warming.



Historical and future trends in icing are unclear although limited research suggests rising icing altitudes. Dedicated research on all icing indicators, including temperature, humidity and cloud water, is needed for a more accurate assessment.



Low-level wind shear studies are scarce. Near-surface wind speeds are projected to decrease in the northern hemisphere and increase in the southern hemisphere, though these projections carry significant uncertainty. More research is needed to understand the effects of climate change.



Rising global temperatures are projected to increase severe convection and hailstorm frequency, particularly at higher latitudes, impacting aviation operations on the ground and in the air.



Research on the impact of climate change on sandstorms and dust storms is limited. More robust studies are needed to understand future trends and the associated impacts on aviation.



Climate change is expected to strengthen jet streams, affecting wind speeds, clear air turbulence and flight times, but with regional variations. The effects in the northern hemisphere are expected to be weaker due to Arctic amplification.



Fog frequency varies regionally, influenced by temperature, humidity, wind and local topography. Climate change affects fog patterns; however, for an improved understanding of fog trends, aerosol concentration projections are also needed.



Climate projections indicate a rising tropopause height globally, but trends vary. More research is needed on the effect of climate change on the tropopause.



Freezing precipitation, mostly in the northern hemisphere, is shifting poleward and inland. However, more research is needed to improve future projections of freezing precipitation in a changing climate and to better understand the associated impacts on aviation.



Warmer near-surface temperatures impact aircraft take-off performance, fuel efficiency and runway conditions. Increased weight restrictions and potential surface damage are concerns, but more research is needed to assess the critical threshold meteorological conditions.



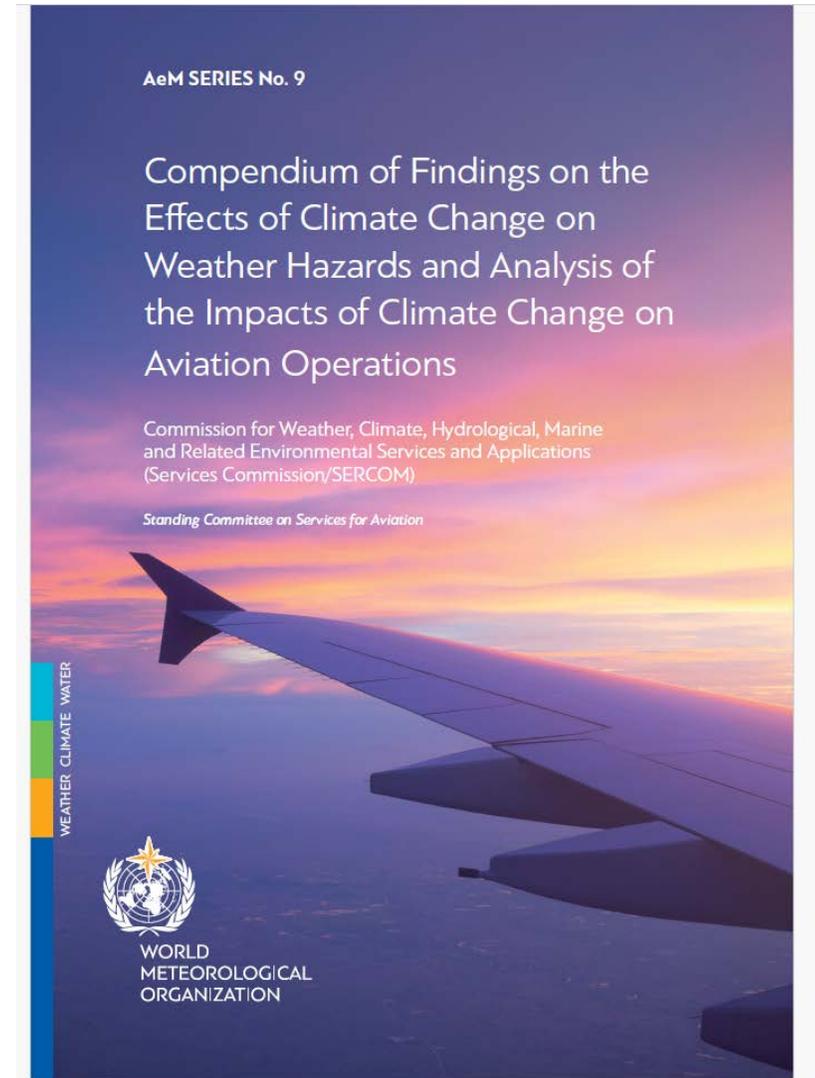
Global mean sea level rose more rapidly in the twentieth century than in any prior century in the last three millennia and continues to accelerate. If this trend continues, coastal and low-lying airports will be particularly vulnerable to increased flooding and storm surges.

OFFICIAL

# On the WMO e-Library

- Published by WMO in March 2025
- Freely available on the WMO e-Library

<https://library.wmo.int/idurl/4/69458>



Thank you !    Merci !



aviation@wmo.int



<https://community.wmo.int/en/activity-areas/aviation>



WMO OMM

World Meteorological Organization  
Organisation météorologique mondiale