How Will Climate Change Affect Aviation?

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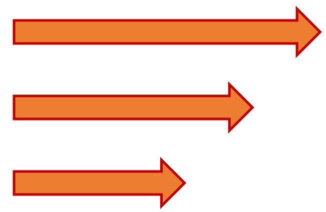
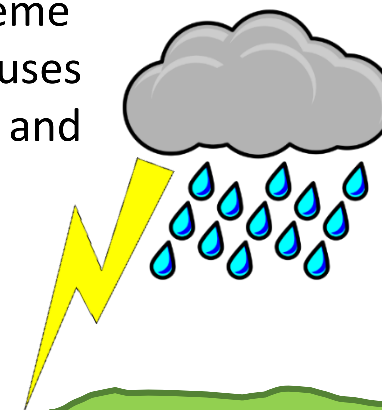
Possible impacts

Shifting wind patterns modify optimal flight routes and fuel consumption



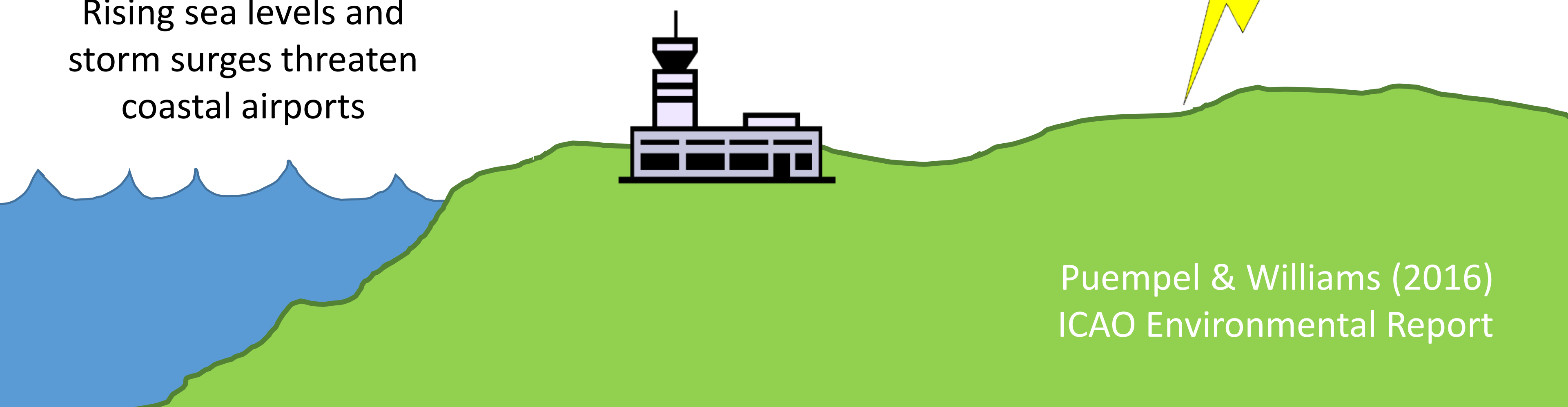
Stronger jet-stream wind shears increase clear-air turbulence

More extreme weather causes disruptions and delays



Warmer air imposes take-off weight restrictions

Rising sea levels and storm surges threaten coastal airports



Puempel & Williams (2016)
ICAO Environmental Report

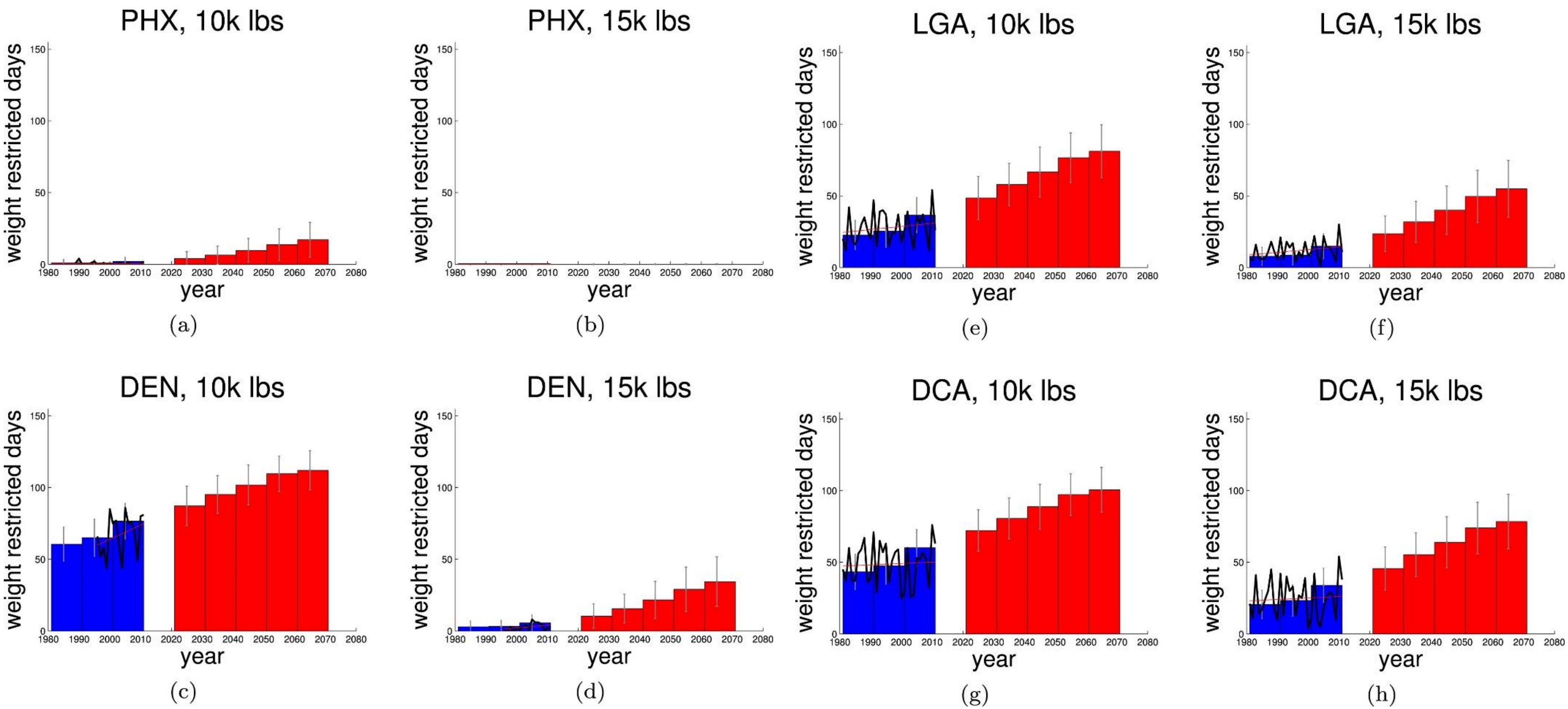
Rising sea levels

- Global sea-level rise is 3.4±0.4 cm per decade and accelerating
- Airport elevations: LGW +62m, LHR +25m, La Guardia +6m, Dundee +5m, San Francisco +4m, JFK +4m, Corfu +2m, Schiphol -3m, Atyrau -22m
- Thirteen of the USA's largest airports have at least one runway within reach of a moderate-to-high storm surge (National Climate Assessment 2014)
- Sea-level rise could threaten runway capacity at more than 30 European airports (Eurocontrol 2014)

Take-off weight restrictions

Phoenix International Airport

New York LaGuardia Airport



Denver International Airport

Washington Reagan National Airport

Coffel and Horton (2015)

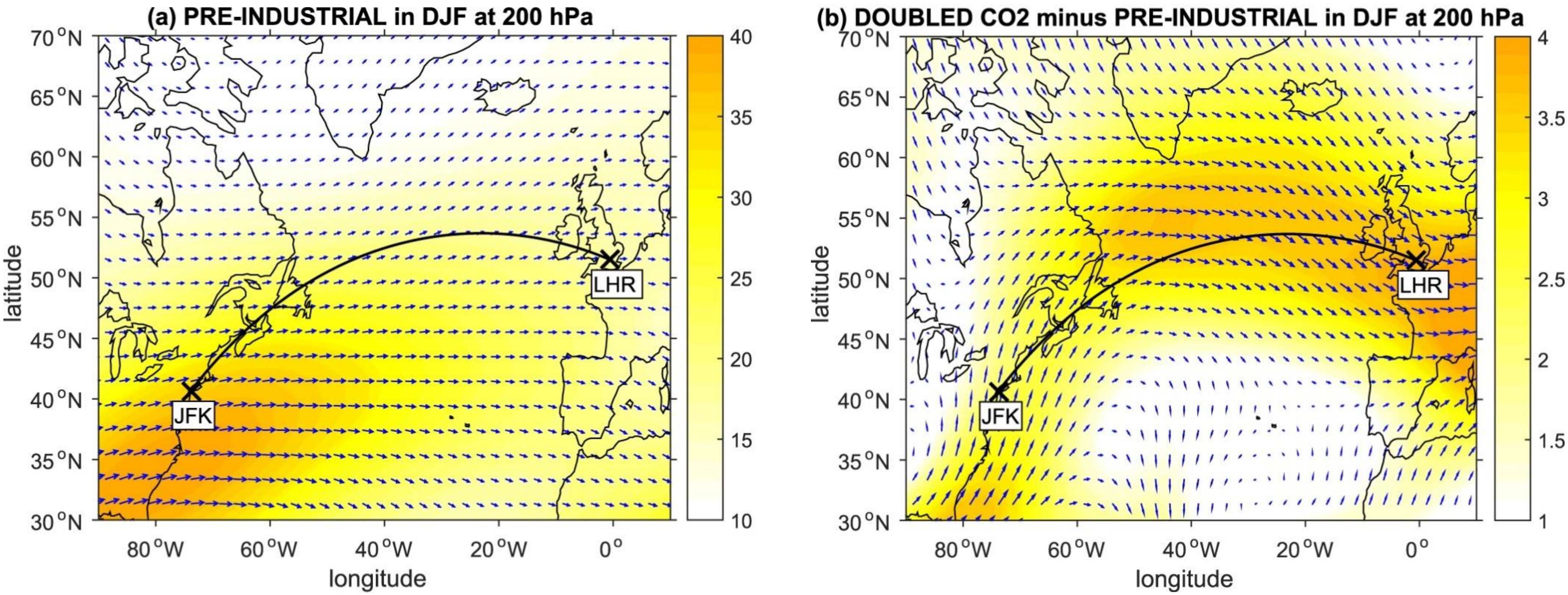
More extreme weather: lightning

Table 1. Future changes predicted by GCMs. Predicted changes in global mean temperature (ΔT) and percent per global mean °C changes in CONUS annual mean CAPE (ΔCAPE), precipitation (ΔPr), and CG lightning flash rate (ΔCG) are shown for 11 CMIP5 GCMs. Changes are calculated for the years 2079–2088 of the RCP8.5 experiment relative to the years 1996–2005 of the historical experiment.

GCM	ΔT (°C)	ΔCAPE (%°C)	ΔPr (%°C)	ΔCG (%°C)
BCC-CSM1.1	3.4	6.4	-0.6	3.4
BCC-CSM1.1(m)	3.1	8.8	-0.2	6.9
CanESM2	4.7	12.9	4.2	17.3
CCSM4	3.9	7.3	2.0	9.1
CNRM-CM5	3.9	9.9	2.6	12.2
FGOALS-g2	3.1	11.5	-1.8	7.0
GFDL-CM3	5.0	16.5	2.6	17.6
GFDL-ESM2M	2.5	13.4	2.7	15.9
MIROC5	3.4	15.1	0.3	16.3
MRI-CGCM3	3.4	12.5	3.0	14.7
NorESM1-M	3.6	8.5	1.4	10.3
Mean:	3.6	11.2	1.5	11.9

- The annual number of lightning strikes in the USA is predicted to increase by an average of 11.9% per °C of global warming (Romps et al. 2014)
- This figure equates to an increase of about 50% over this century

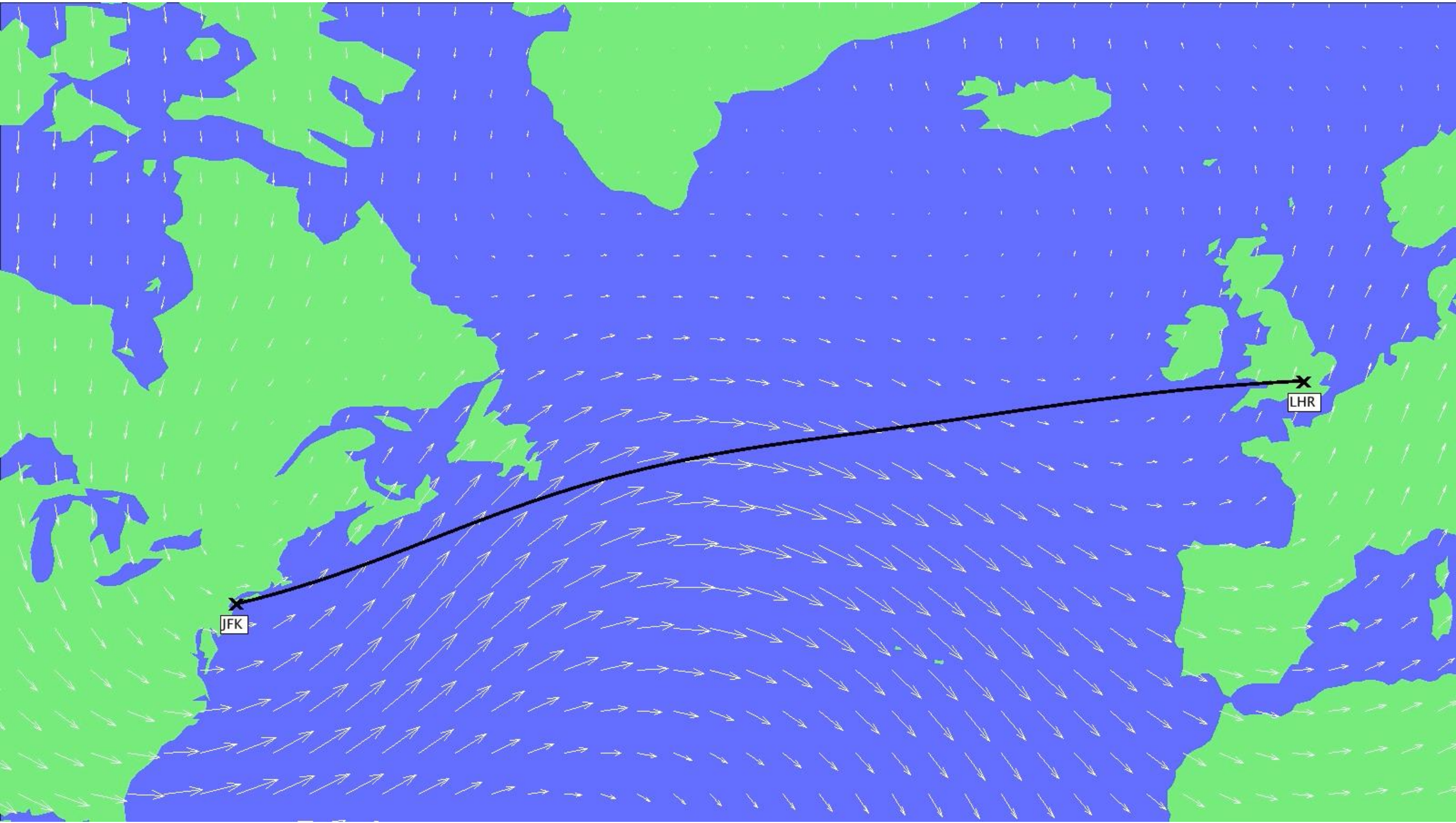
Shifting wind patterns



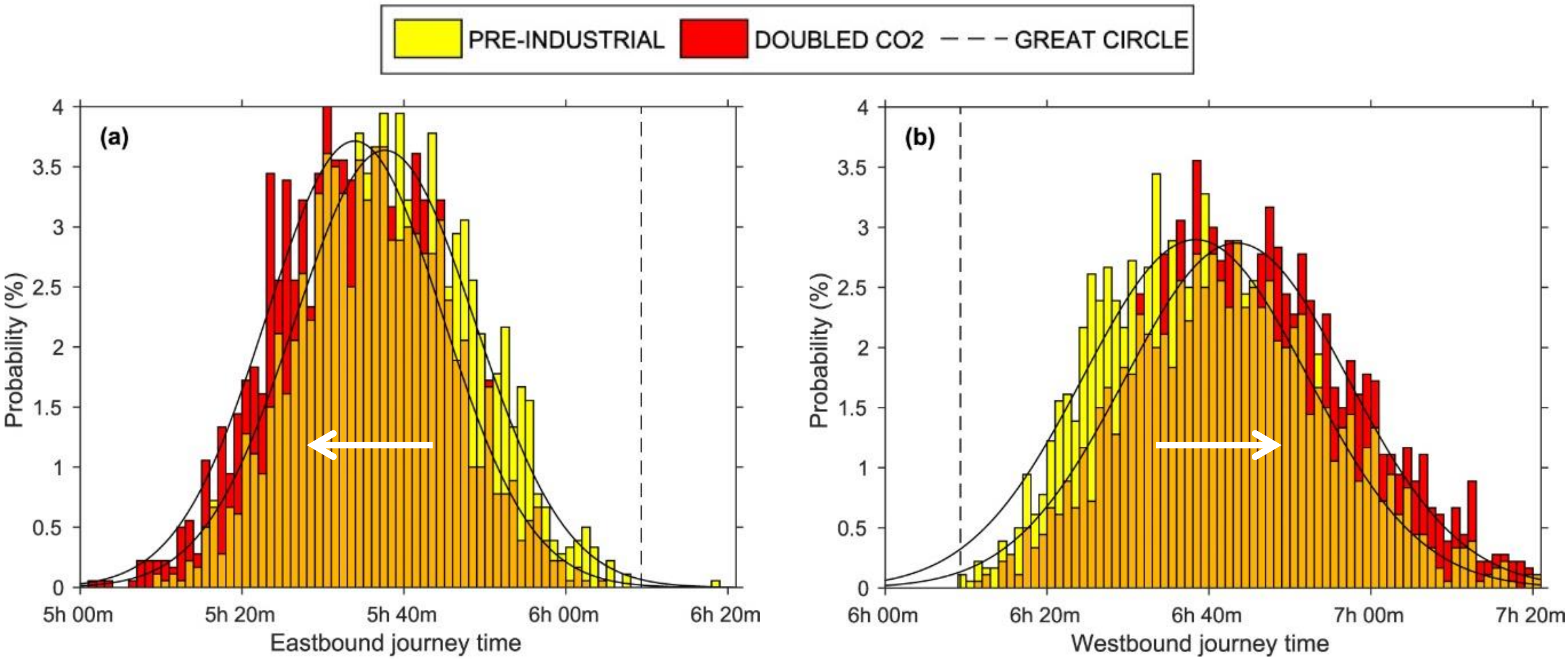
Average tailwind / headwind increases by 14.8% from 21.4 to 24.6 m s^{-1}

Williams (2016)

Climate model winds fed into flight routing algorithm



Modified flight time distributions



Likelihood of taking under 5 h 20 min more than doubles from 3.5% to 8.1%

Likelihood of taking over 7 h 00 min nearly doubles from 8.6% to 15.3%

Williams (2016), see also Irvine et al. (2016)

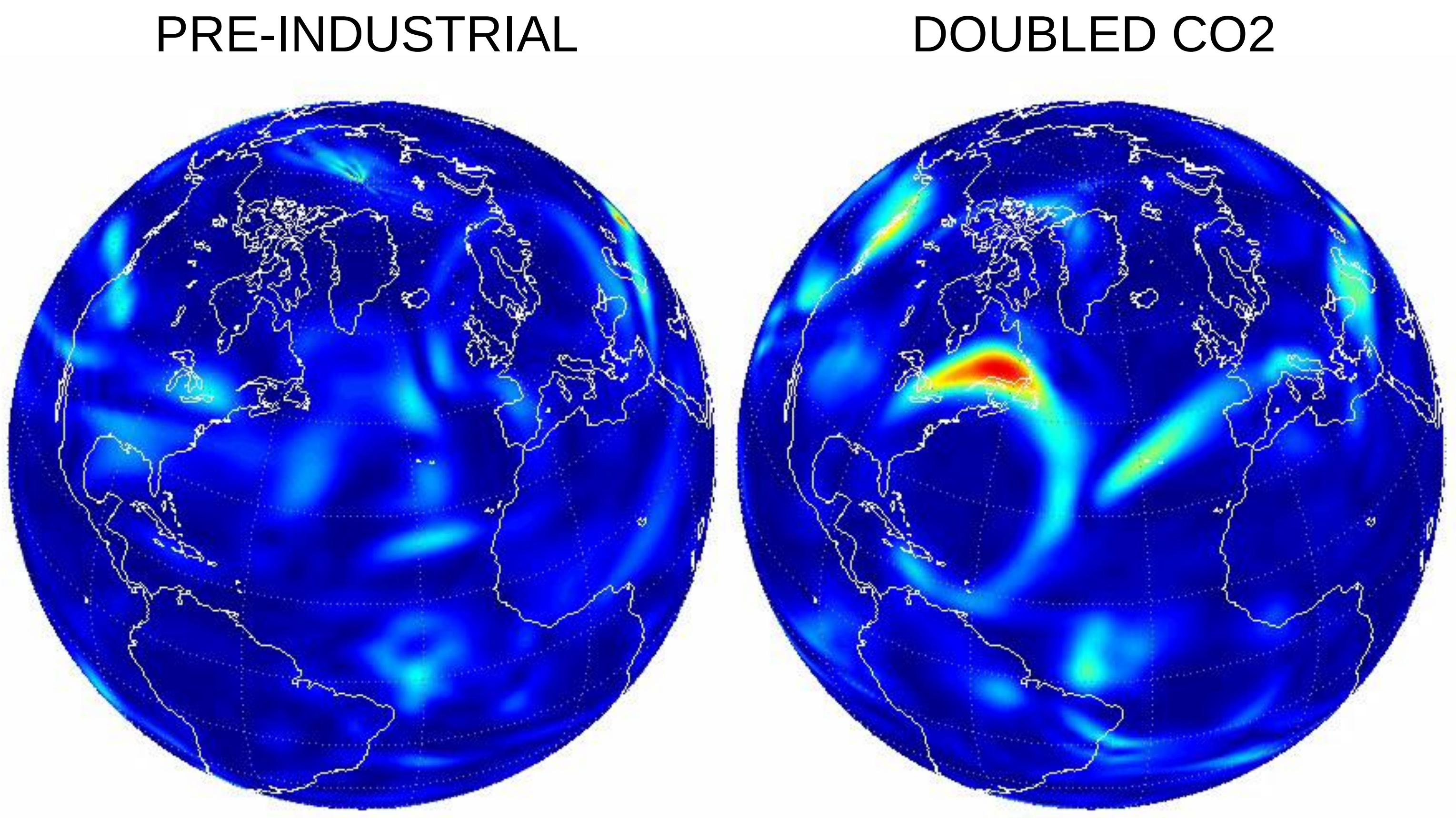
Modified flight time distributions

- Have these changes already begun?
  - The North Atlantic jet stream wind speeds reached 250 mph on 8-12 January 2015
  - An eastbound JFK→LHR crossing took only 5 h 16 min, which is the current non-Concorde record
  - Westbound LHR→JFK crossings took so long that two flights had to make unscheduled refuelling stops in Maine

- Extrapolation to all transatlantic traffic (600 crossings per day) suggests that aircraft will collectively be:
  - airborne for an extra 2,000 hours each year
  - burning an extra 7.2 million gallons of jet fuel at a cost of $22 million
  - emitting an extra 70 million kg of CO_2 into the atmosphere, equating to 7,100 British homes

Williams (2016), see also Irvine et al. (2016)

More clear-air turbulence (CAT)



$$\mathrm{TI1} = \left|\frac{\partial \mathbf{u}}{\partial z}\right| \sqrt{\left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2}$$

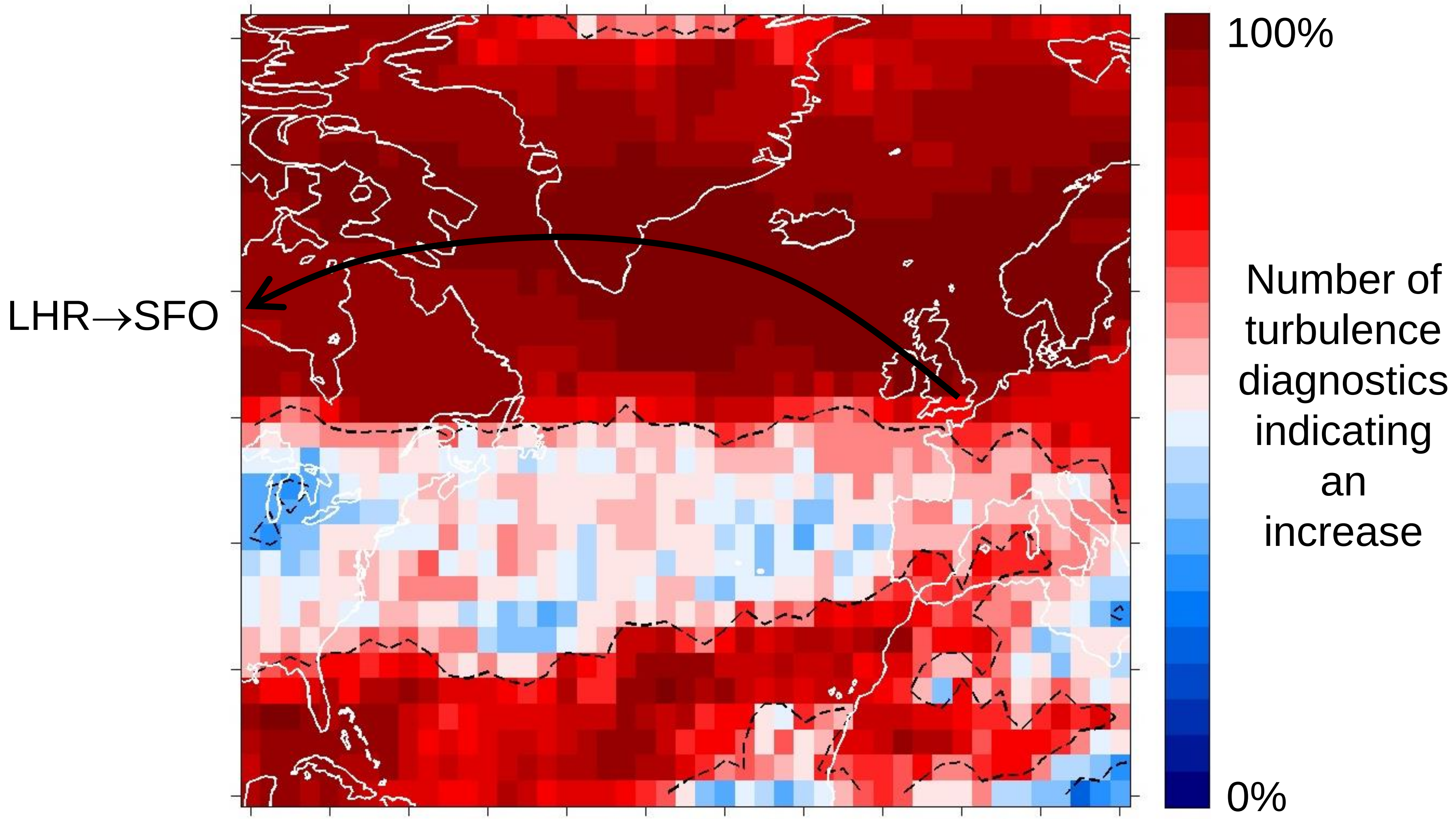
Diagnostic	Units	Pre-Industrial Median	Doubled-CO_2 Median	Change (%) in Median	Change (%) in Frequency of MOG
Magnitude of potential vorticity	PVU	6.84	6.86	+0.3	+106.0
Colson–Panofsky index	10^3 kt^2	-34.8	-34.3	+1.5	+167.7
Brown index	10^{-6} s^{-1}	77.1	79.2	+2.7	+95.5
Magnitude of horizontal temperature gradient	10^{-6} K m^{-1}	5.75	6.46	+12.2	+45.3
Magnitude of horizontal divergence	10^{-6} s^{-1}	[illegible]	3.17	+12.3	+110.4
Magnitude of vertical shear of horizontal wind	10^{-3} s^{-1}	[illegible]	2.14	+13.8	-1.0
Wind speed times directional shear	10^{-3} rad s^{-1}	[illegible]	1.088	+14.2	+142.8
Flow deformation	10^{-6} s^{-1}	[illegible]	21.5	+15.6	+96.0
Wind speed	m s^{-1}	14.9	17.3	+16.3	+94.8
Flow deformation times vertical temperature gradient	10^{-9} K m^{-1} s^{-1}	8.17	9.97	+22.0	+147.3
Negative Richardson number	-	-127.2	-97.9	+23.0	+3.2
Magnitude of relative vorticity advection	10^{-10} s^2	[illegible]	2.95	+26.7	+138.2
Magnitude of residual of nonlinear balance equation	10^{-12} s^{-2}	[illegible]	204	+27.1	+73.8
Negative absolute vorticity advection	10^{-10} s^{-2}	[illegible]	2.63	+28.2	+144.0
Brown energy dissipation rate	10^{-6} J kg^{-1} s^{-1}	[illegible]	151	+30.0	+7.9
Relative vorticity squared	10^{-9} s^{-2}	0.221	0.293	+32.5	+86.2
Variant 1 of Ellrod's Turbulence Index	10^{-9} s^{-2}	31.5	41.9	+32.8	+10.8
Flow deformation times wind speed	10^{-3} m s^{-2}	0.251	0.341	+35.9	+92.9
Variant 2 of Ellrod's Turbulence Index	10^{-9} s^{-2}	28.8	39.4	+36.8	+11.6
Frontogenesis function	10^{-9} m^2 s^{-3} K^{-2}	56.6	86.1	+52.1	+125.6
Version 1 of North Carolina State University index	10^{-18} s^{-3}	11.1	22.5	+102.9	+63.6

mostly in range 10-40%

mostly in range 40-170%

Williams & Joshi (2013)

More clear-air turbulence (CAT)



Williams & Joshi (2013)

Summary

- A basket of 21 CAT measures diagnosed from climate simulations is significantly modified if the CO_2 is doubled
- At cruise altitudes within 50-75°N and 10-60°W in winter, most measures show a 10-40% increase in the average CAT strength and a 40-170% increase in the volume of airspace containing moderate CAT
- We conclude that climate change will lead to bumpier transatlantic flights by the middle of this century
- Flight paths may become more convoluted to avoid stronger and more frequent patches of turbulence, in which case journey times will lengthen and jet fuel consumption will increase

Questions?

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