

# Fleet Level Assessments & System-Wide Environmental Impacts

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Sustainable Aviation

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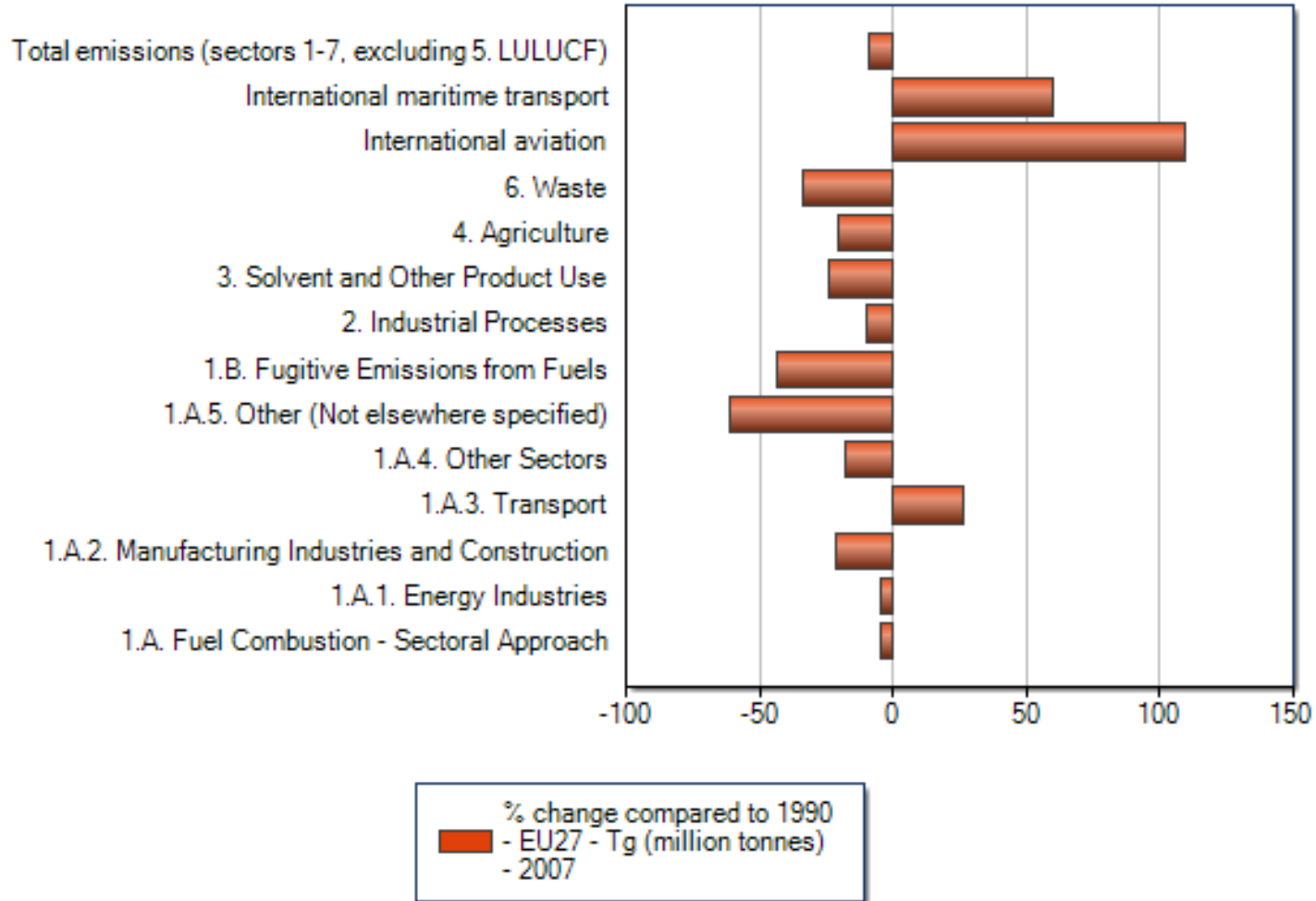
- Introduction
- Aviation Integrated Modelling (AIM) project
- Sample problems
  - Airline fleet replacement funded by a global carbon tax
  - Climate-neutrality versus carbon-neutrality for an aviation biofuel policy
  - A comparison of aviation greenhouse gas emission mitigation policies for Europe

- Air transportation contributes to about 4.5% of global GDP (IATA 2000)
- About 3% of global anthropogenic CO<sub>2</sub> emissions are from aviation (IEA 2008)
  - Non-CO<sub>2</sub> effects on climate potentially significant
- Global aviation RPK growth of ~5%/year forecast (Airbus, Boeing 2009)
  - Even with optimistic reductions in carbon intensity, aviation emissions are likely to grow
- Emissions from other sectors have been decreasing (in some world regions) but continue to grow strongly in aviation
  - Aviation potentially a target for emissions reduction policies





# AIM EU Emissions – Change since 1990

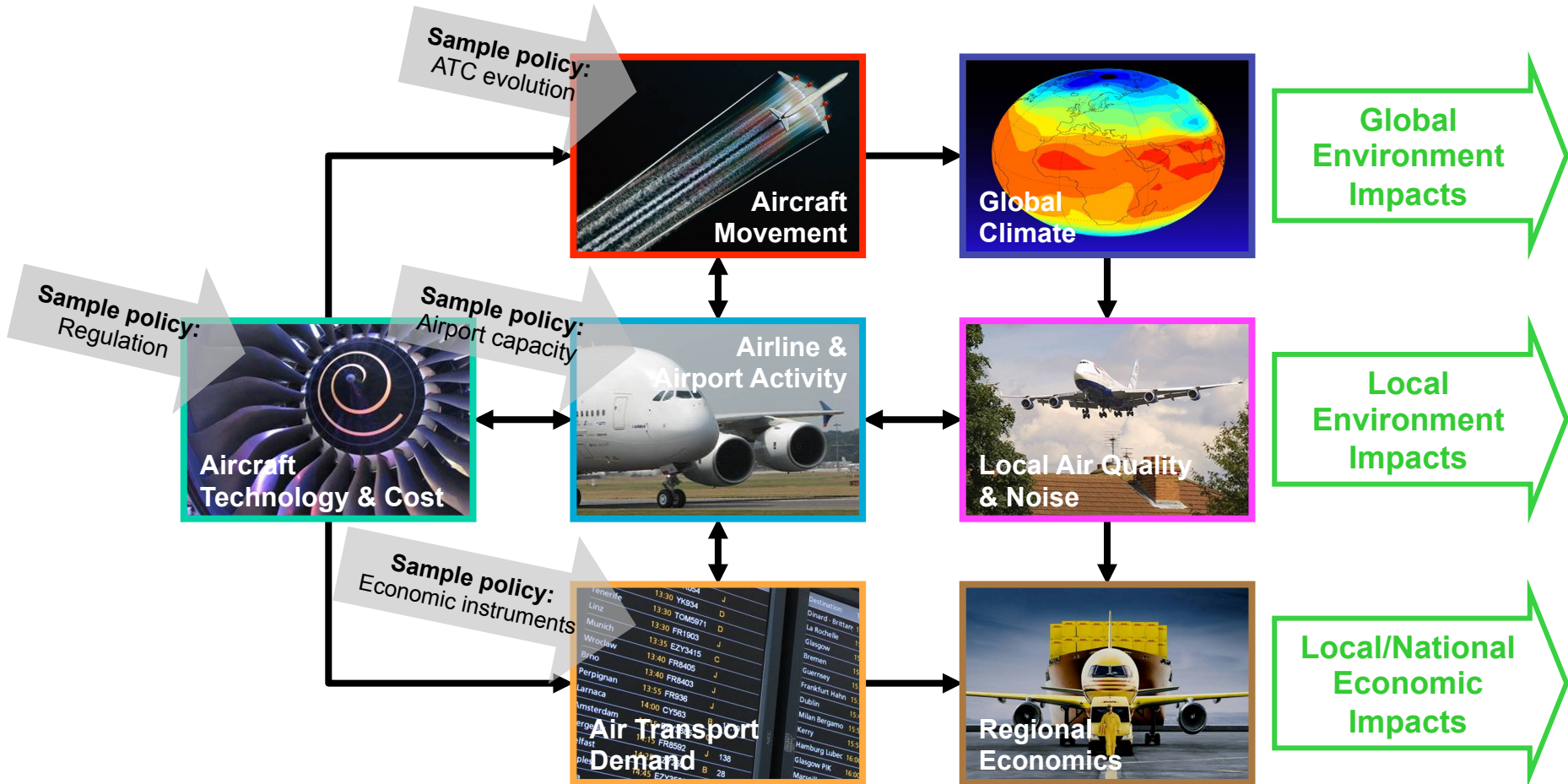


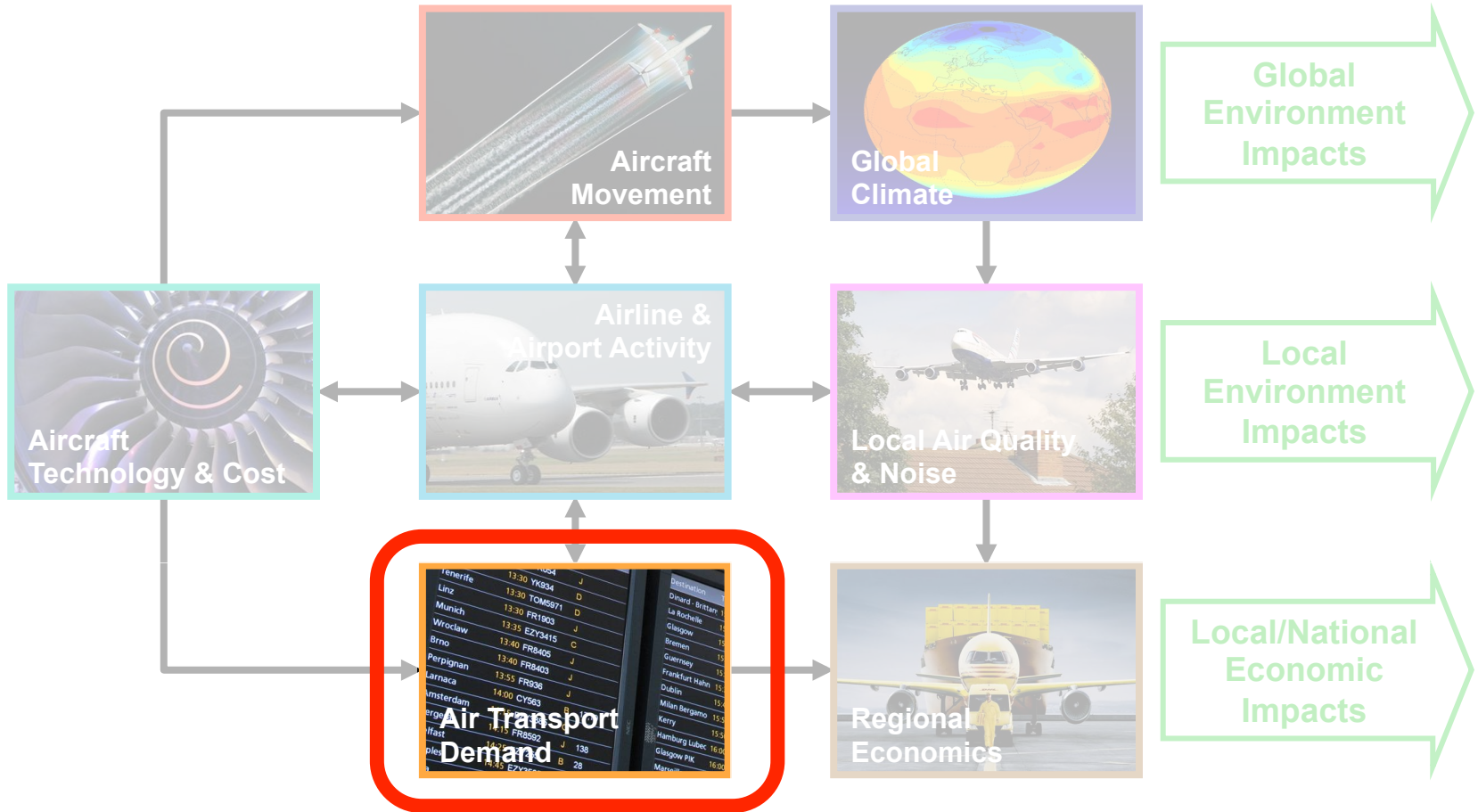
[Source: EEA]

- Air transport system is large, complex and multi-disciplinary involving numerous stakeholders with different agendas
- Range of future trends
  - Developing regions (India, China,...)
  - Developing technologies
- Increasing (and range of) environmental pressures
- Need for tools to analyse trade-offs & assist policymakers



- Goal:** Develop policy assessment tool for aviation, environment & economic interactions at local & global levels, now and into the future





## Goals

- Forecast true origin-ultimate destination passenger and freight demand for air travel

## Methodology

- Apply a simple one-equation gravity-type model
  - Function of income ( $I$ ), population ( $P$ ), fare ( $F$ ), travel time ( $TT$ ), flight delays, special city characteristics ( $A, B$ ), road/high-speed rail links ( $S, R$ ), domestic/international ( $DF$ )

$$D_{ij} = K \cdot (I_i I_j)^\alpha \cdot (P_i P_j)^\beta \cdot e^{\delta A_{ij}} \cdot e^{\varepsilon B_{ij}} \cdot e^{\varphi S_{ij}} \cdot e^{\omega DF_{ij}} \cdot e^{\mu R_{ij}} \cdot (F_{ij} + VoT \cdot TT_{ij})^\tau$$

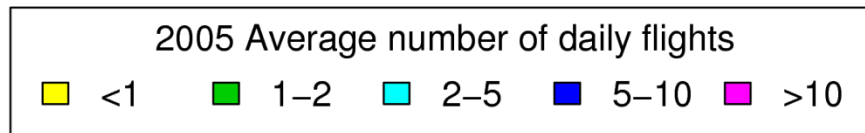
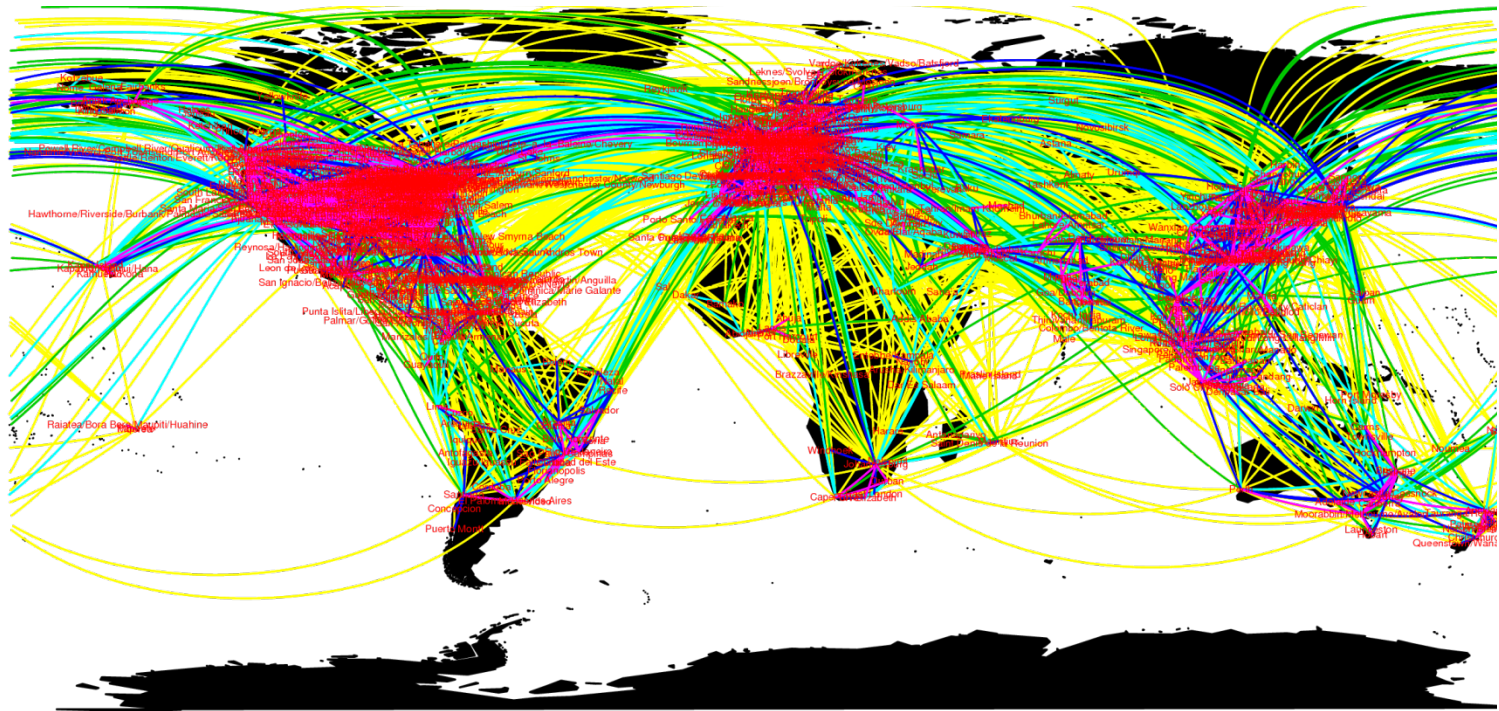
- Estimate explanatory variables using available data separately for short-, medium-, and long-haul, and for different world regions
- Modular – can plug in other projections if required

Route Group	Distance, mi	$2\alpha^a$ Income	$2\gamma^a$ Population	$\tau^b$ Gener. Cost	R <sup>2</sup>
Intra-North America	<500	1.6	0.86	-2.04	0.53
	500-1000	1.7	0.84	-2.61	0.77
	>1000	1.8	0.86	-2.61	0.57
Intra-Europe	<500	1.3	0.75	-1.24	0.47
	500-1000	1.4	0.85	-1.27	
	>1000	1.5	0.75	-1.08	
Intra-Asia	<500	1.8	0.80	-0.62	0.66
	500-1000	1.8	0.95	-0.89	
	>1000	2.0	0.83	-1.00	
Intra-Central/South America	<500	1.8	0.87	-0.58	0.74
	500-1000	1.8	1.16	-1.65	
	>1000	2.0	1.18	-0.98	
Intra-Africa	All	1.8	1.18	-0.98	0.70
Intra-Middle East	All	1.5	0.43	-1.60	0.75
North Atlantic	All	2.0	1.40	-2.45	0.76
South Atlantic	All	2.2	0.99	-1.93	
Pacific	All	2.0	0.55	-1.69	
North-Central/South America	All	2.0	0.80	-1.37	0.71
Europe-Middle East	All	1.5	0.66	-2.58	0.65
Europe-Africa	All	2.0	0.82	-1.92	0.46
Other Routes	All	2.0	0.78	-0.42	0.45

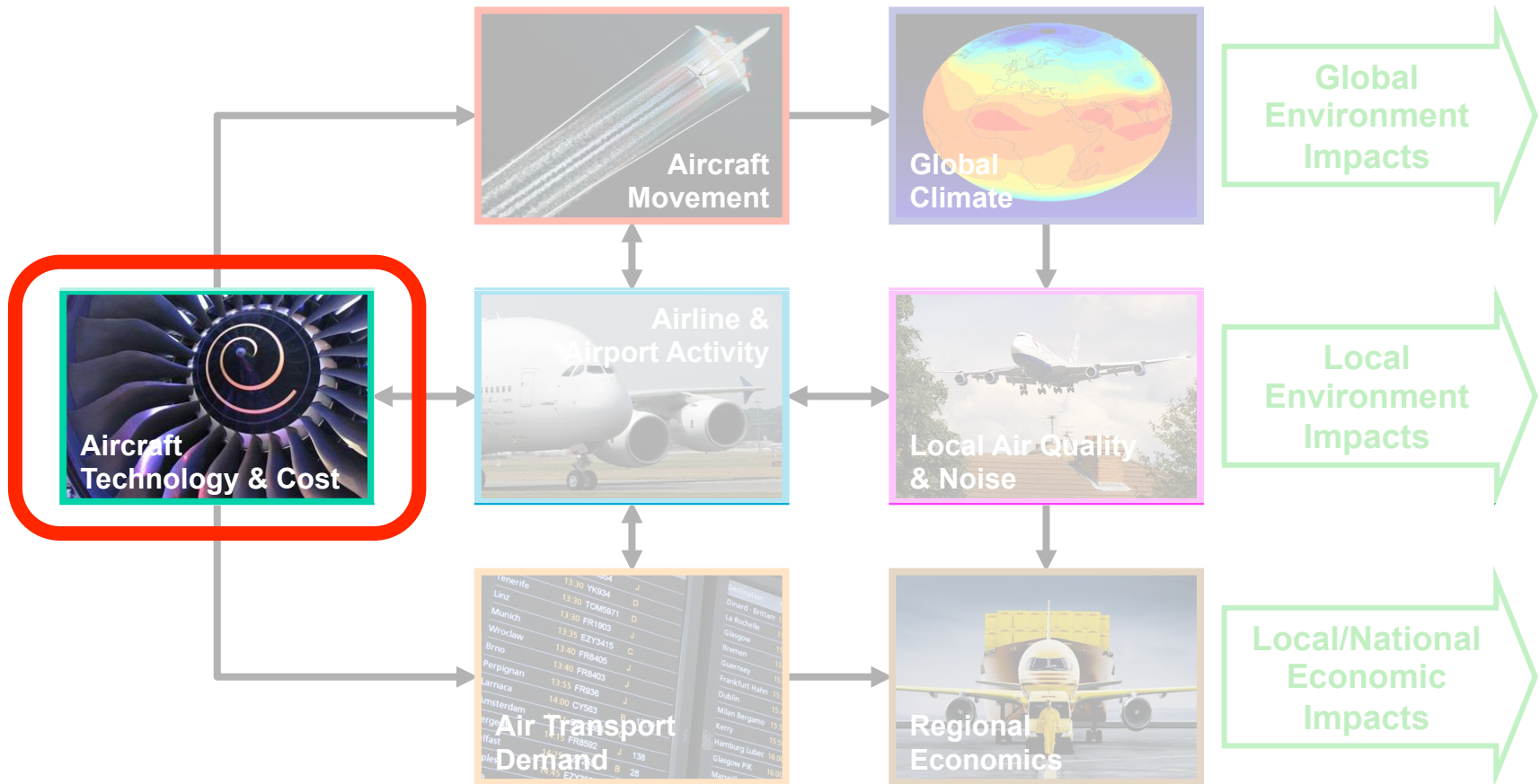
<sup>a</sup> Because the demand equation contains two income terms multiplied, the true elasticity which would apply to variation in a single income term is  $2\alpha$ . The same is true for population ( $2\gamma$ ).

<sup>b</sup> Note that this is generalised cost elasticity, not fare elasticity. Fare-only elasticities are typically slightly less negative. Given this, the generalised cost elasticity estimates here are broadly consistent with the price elasticity recommendations in IATA (2007).

- Geographic Scope: 95% of global scheduled RPK, 700 cities



[Data: OAG(2005)]



## Goals

- Simulate fuel burn, emissions and operating costs for airframe and engine technologies to 2050

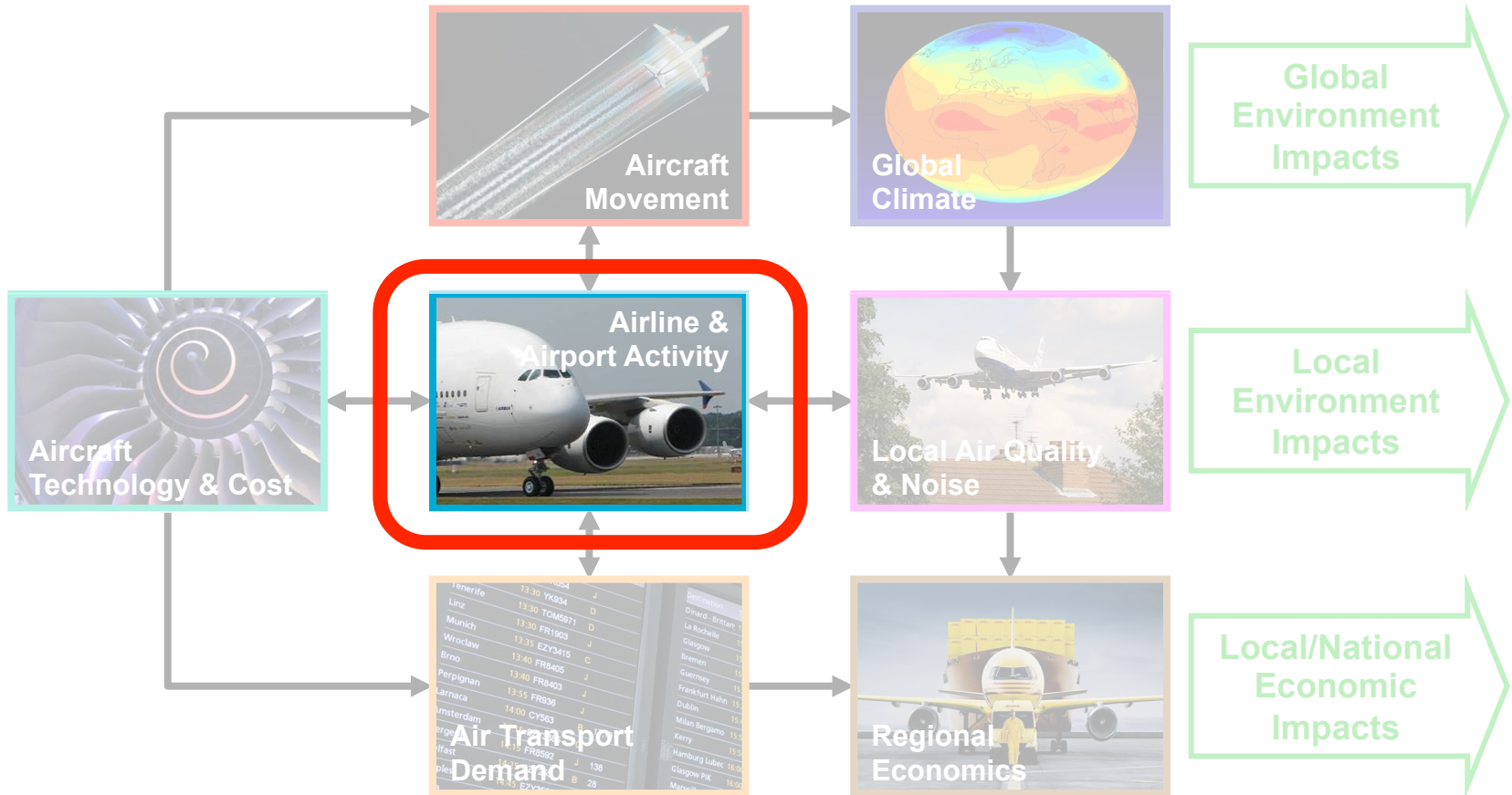
## Methodology

- Three aircraft size categories simulated
  - < 190 seats, 190-300 seats, >300 seats
- For existing types, two technology-age categories simulated (before 1995, after 1995)
  - Fuel burn and emissions below 3,000ft estimated from ICAO Engine Exhaust Emission Data, Reference LTO Cycle
  - Fuel burn and emissions above 3,000ft estimated using EUROCONTROL Base of Aircraft Data
  - Non-fuel related operating costs estimated using US DOT Form 41 airline financial data adjusted for global differences based on ICAO data
- Future technology modelled separately

- Biofuels
  - 20% to 50% biofuel blend (generally assumed to be from cellulosic biomass feedstock) possible by 2020
- New aircraft technology
  - Fuel burn of new aircraft models predicted to improve by 1% per year
  - Retrofits, e.g., winglets
  - Improved aerodynamic and engine maintenance procedures
  - Specific new technologies have significant potential to reduce fuel burn



New Technology	Year of Introduction	% Reduction in Fuel Burn over existing Technology
Composite Evolutionary Replacement Narrowbody	2025	22%
Open Rotor Narrowbody	2025	35%
Optimized Open Rotor Narrowbody	2025	45%
Blended Wing Body Widebody	2037	30%



## Goals

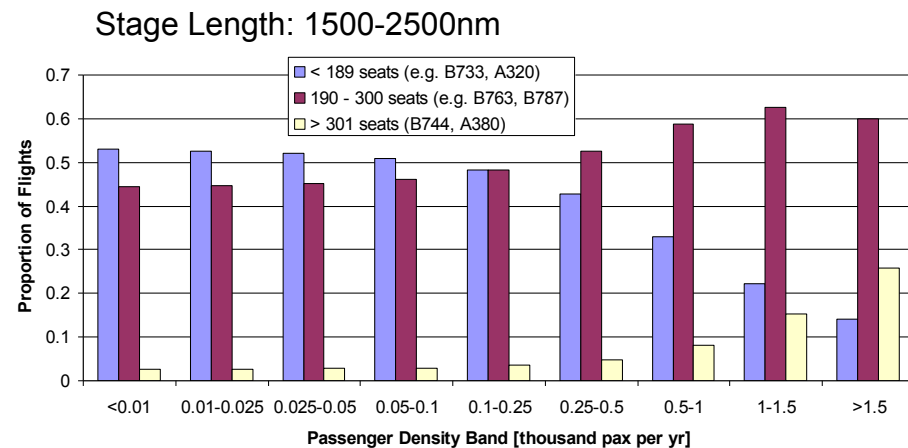
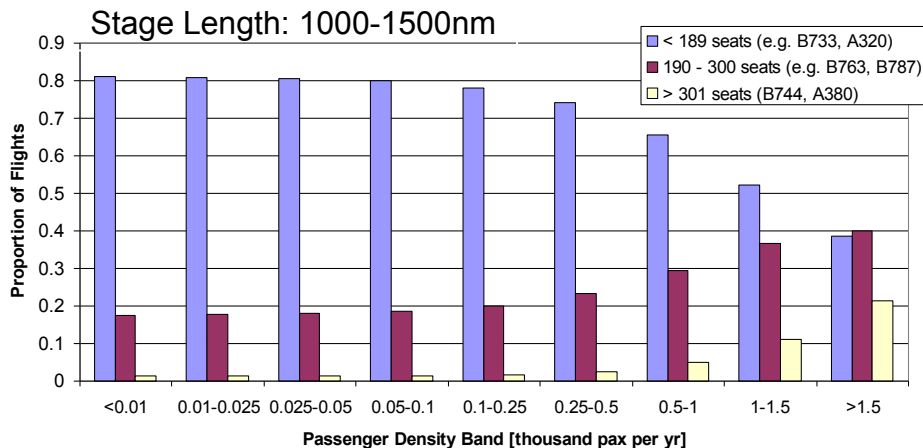
- Generate future flight schedules
- Estimate future fleet
- Estimate future airfares
- Predict average flight delays
- Predict LTO emissions

## Methodology

- Flight network and scheduling modeled according to forecast passenger demand
  - Mode 1: Basic model forecasting global traffic
  - Mode 2: High fidelity model simulating airline response to constraints
- Fleet changes modelled based on historical fleet turnover and NPV model
- Average airfares modelled assuming a constant airline rate of return
- Flight delay modelled using queuing theory
- Landing Take-Off (LTO) emissions estimated according to schedule, delays, and engine emission rates

## MODE 1: BASIC MODEL

- Base year routing network applied for all forecasts
  - No network change modelled
- Aircraft size distribution calculated according to multi-nomial logit regression on base year data, as a function of:
  - Segment passenger demand
  - Stage Length
  - Type of route (Hub, spoke etc.)
- Flight frequency scaled from segmented passenger demand according to base year load factors, by flight segment



## MODE 2: HIGH FIDELITY MODEL

- Model simulating airline operational response to constraints
- Simulates airline aircraft, frequency and network choice to maximize profit
- Simulates a Myopic Nash best-response game between competing airlines to capture effects of frequency competition
- Airline profit function:

$$\max \left( \sum_{i,j} \sum_{p \in \text{itin}_{i,j}} \overline{\text{Fare}}_{i,j} \cdot \text{Pax}_{i,j,p,a} - \sum_{m,n,k} \text{Cost}_{\text{flt}_{m,n,k,a}} \cdot \text{Fltfreq}_{m,n,k,a} - \sum_{i,j} \sum_{p \in \text{itin}_{i,j}} \text{Cost}_{\text{pax}_{i,j,a}} \cdot \text{Pax}_{i,j,p,a} \right)$$

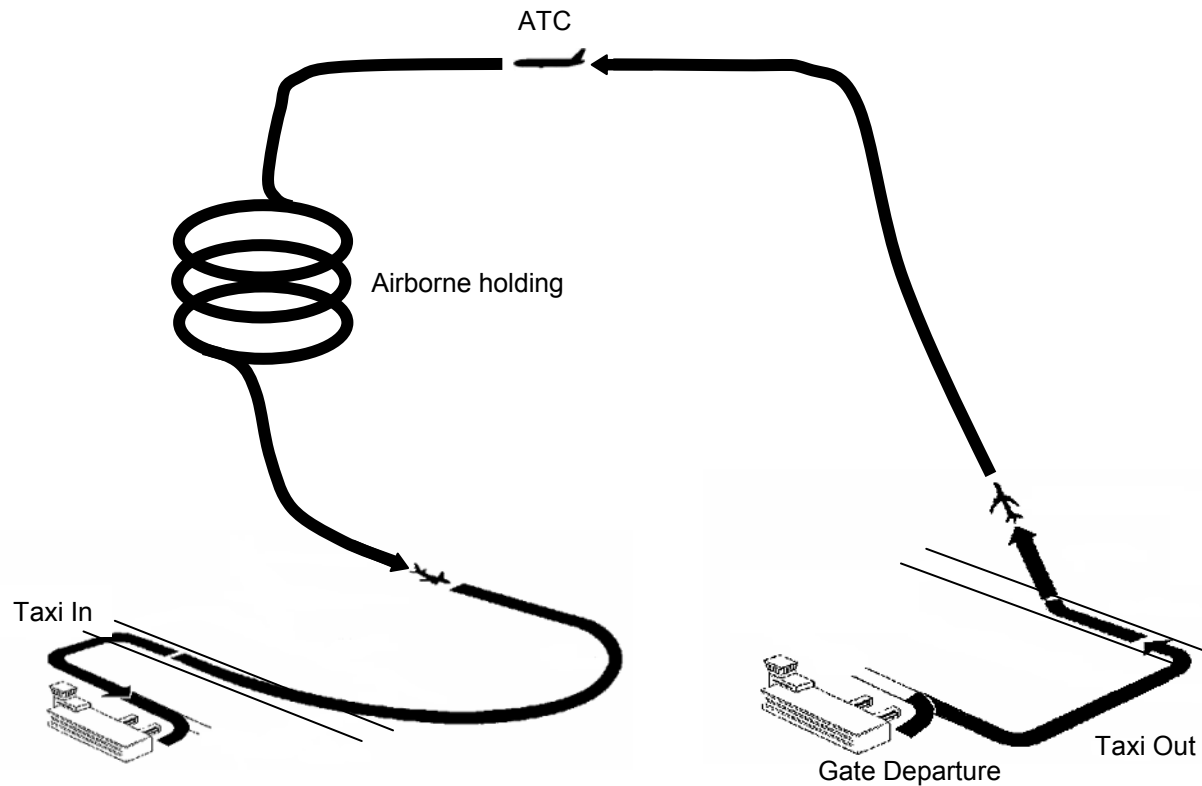
- Decision variables: Segment flight frequency ( $\text{Fltfreq}_{m,n,k,a}$ ), passenger itinerary demand ( $\text{Pax}_{i,j,p,a}$ )
- Constraints
  - Demand constraint:  $\sum_{p \in \text{itin}_{i,j}} \text{Pax}_{i,j,p,a} \leq \frac{\text{Fltfreq}_{i,j,a}}{\sum_{a \in A} \text{Fltfreq}_{i,j,a}} \times D_{i,j}$
  - Seat constraint
  - Airport balance constraint
  - Only non-stop and single connection itineraries modeled

- Orders peak during periods of airline profit/expansion
  - Potential fuel cost savings not necessarily the most important factor
- Aircraft lifetimes around 30 years
- Retirement behaviour remarkably consistent over time
- Reducing historical peak retirement age by 1 year → 2005 emissions 0.35% lower (for same RPK)
- Historically changing fuel price has only a small effect on fleet
- New aircraft technology does affect fleet fuel burn
  - Long timescales
- For fast-growing fleet, retirements are relatively unimportant compared to demand for new aircraft
- Retrofits have historically only had a small effect on emissions
  - Limited applicability
  - Relatively short timescale

- Simple fleet turnover model used to simulate introduction of new technology
- Fleet turnover based on historical behavior of the global fleet
  - Aircraft retirement rates based on historical retirement curves
- Adjustments to regional fleets also made based on the historical behavior of second-hand aircraft sales between regions at different GDP levels
- Simulated airline acquisition of new technology using NPV model
  - Based on fuel price, acquisition and operating costs of new technology
- New technology adoption also impacted by other available technology
- Can also assume fixed annual fleet fuel burn improvement, e.g., 1%

- Airline fare setting governed by complex revenue management in order to capture consumer surplus
- Instead, average city-pair fares estimated assuming constant rate of return
  - Ratio of operating cost and fares remains constant
  - Rate of return does not vary significantly across most networks
  - Tight linear relationship between observed operating cost per revenue passenger kilometer (RPK) and observed yield (fare per kilometer)
  - In many markets network-wide rate of return is low, suggesting that these markets experience high fare competition

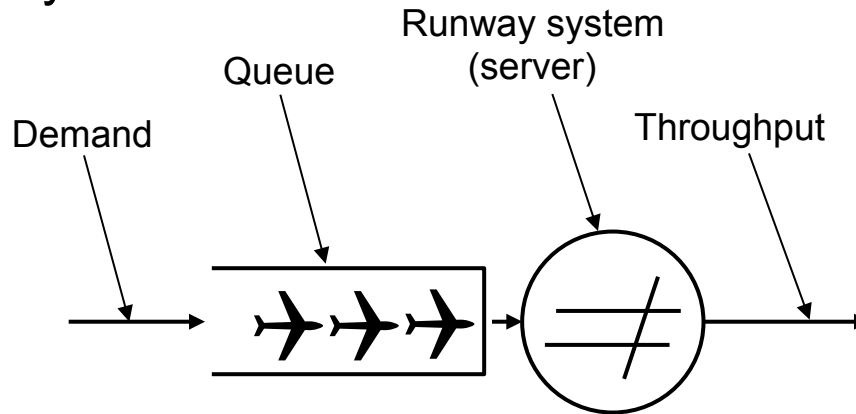
# Modelling Delay



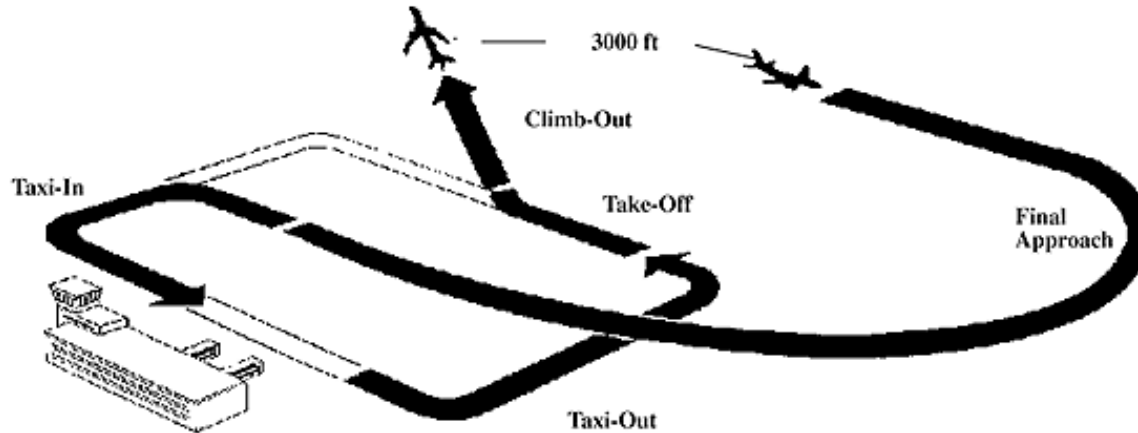
$$\bar{D}_{Arrival}^{i,j} = \bar{D}_{Gate}^i + \bar{D}_{Taxi\ Out}^i + \bar{D}_{Airborne\ ATC}^{i,j} + \bar{D}_{Airborne\ Holding}^{i,j} + \bar{D}_{Taxi\ in}^j$$

Figure developed from figure in IPCC Report on Aviation and the Global Atmosphere, 1999

- Runways typically primary bottleneck in system
- Delays resulting from airport capacity constraints modelled applying queuing theory

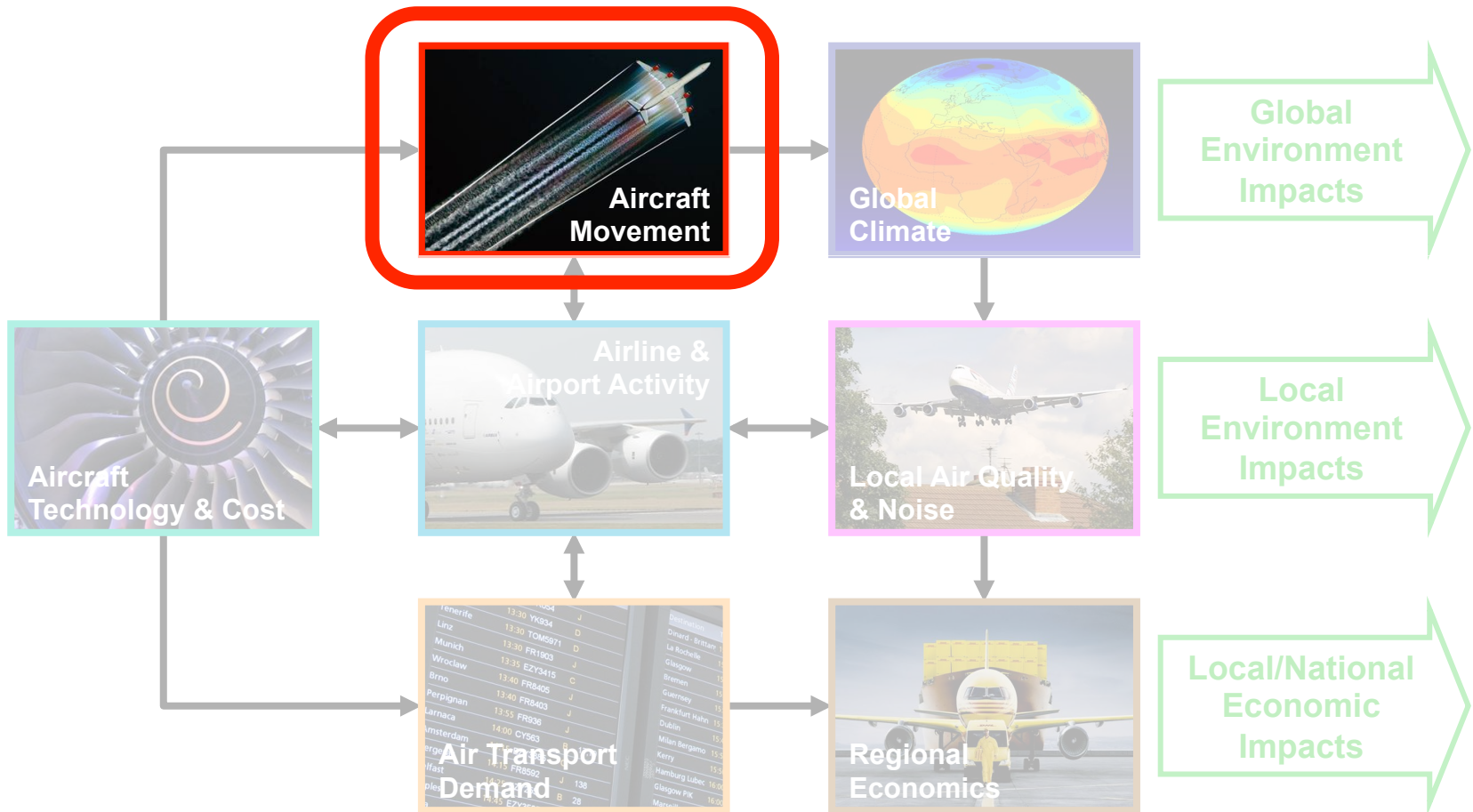


- Location of delay (airborne, taxi-out, or at the departure gate) based on calculated thresholds estimated for each airport
- Delays also affect airline costs and passenger travel time
- Data requirements:
  - ❑ Airport capacities (aircraft per hour)
  - ❑ Delay statistics (average gate, taxi-out, airborne delays)



- Estimate emissions from taxi-out, take-off, climb-out, final approach, landing & taxi-in
  - LTO emissions have a direct impact on Local Air Quality
    - $\text{NO}_x$ ,  $\text{PM}_{2.5}$
  - Taxi emissions impacted by delays at congested airports
  - Detailed delay modelling required
  - LTO emissions estimated based on ICAO Engine Exhaust Emission Data

Figure from IPCC Report on Aviation and the Global Atmosphere, 1999

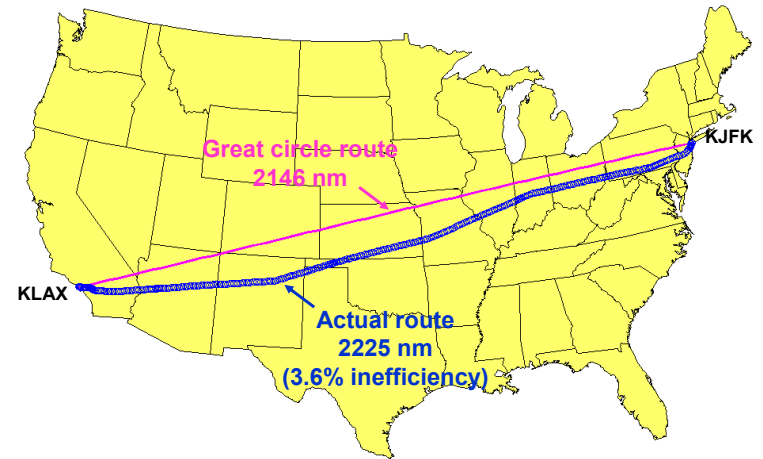


## Goals

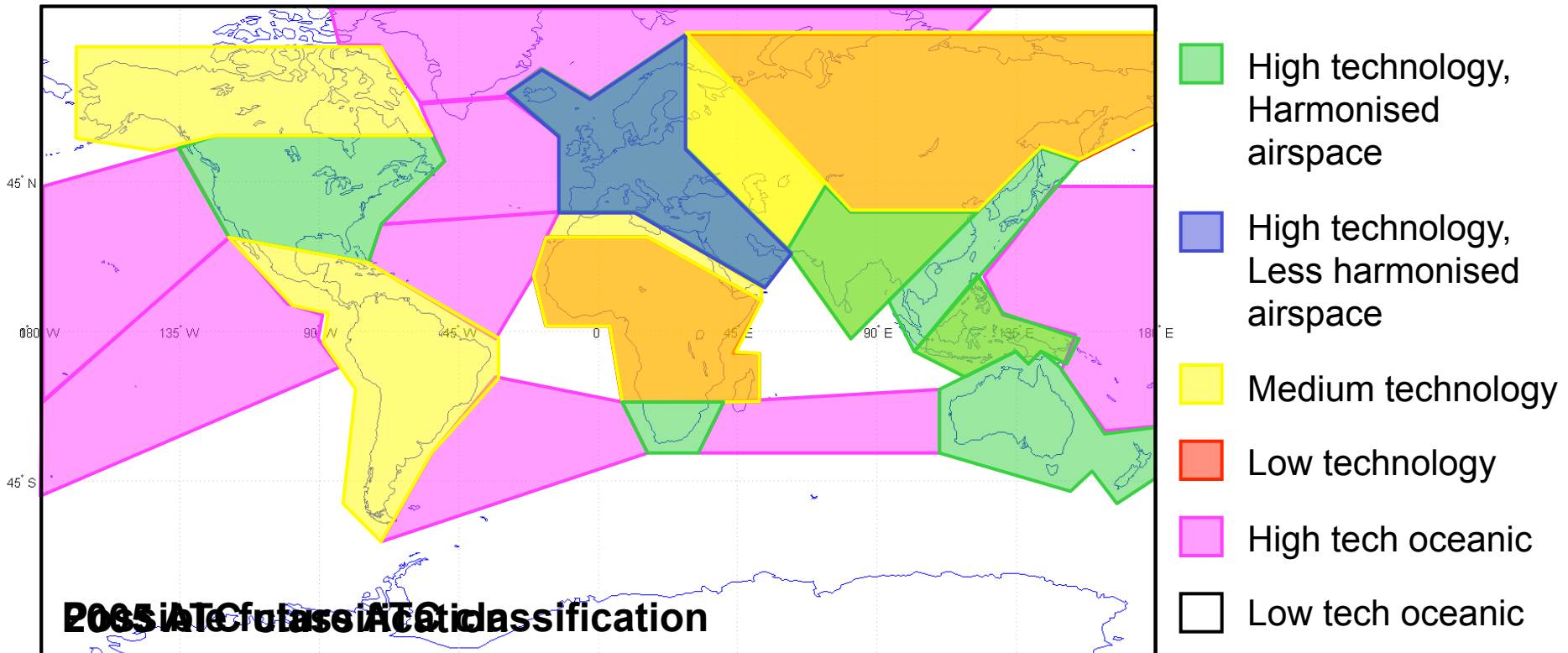
- Simulate the location of emissions release from aircraft in flight, accounting for ATM inefficiencies

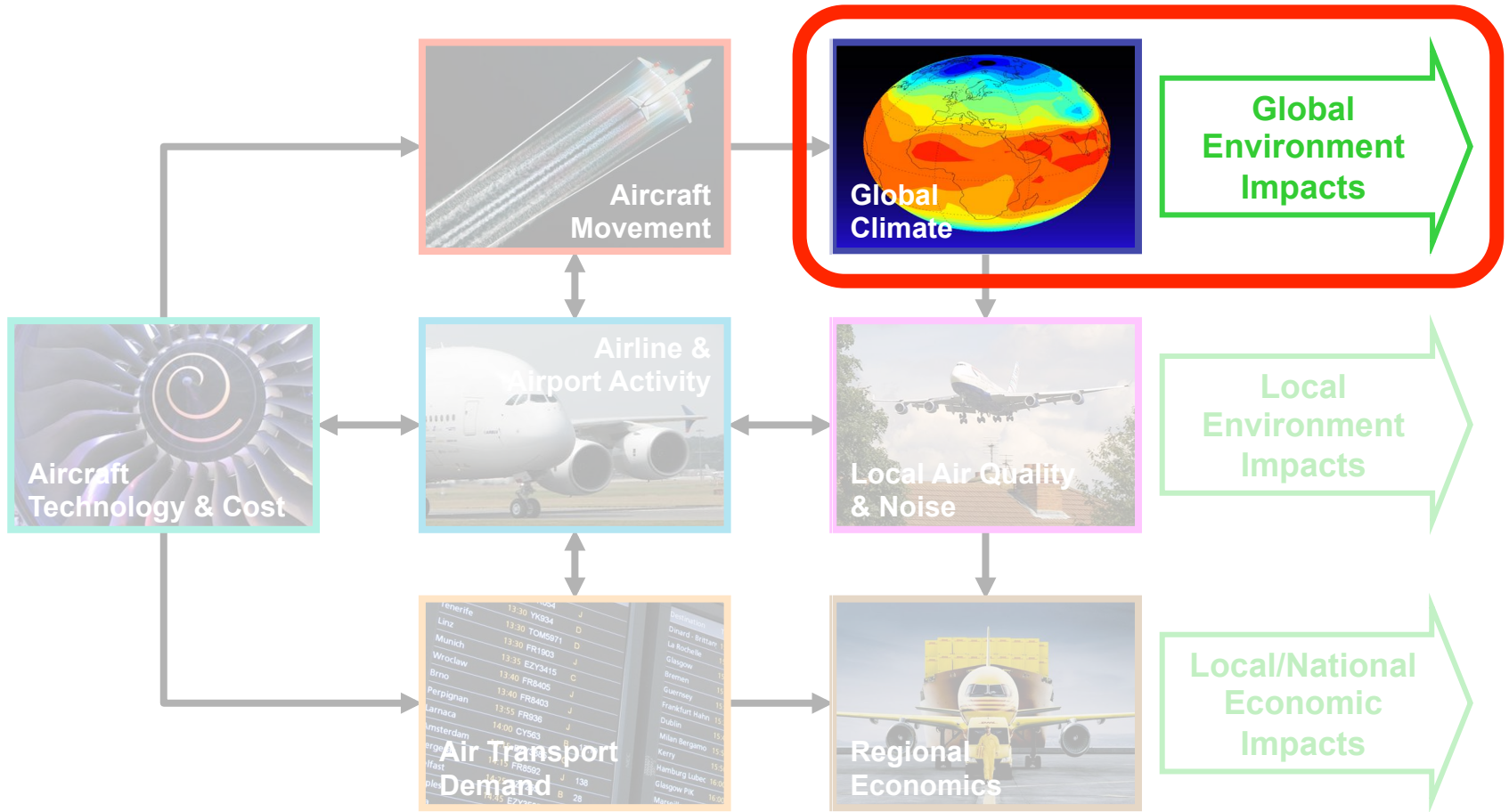
## Methodology

- Calculate optimal routes between given airport pairs, e.g. great circle
- Add “inefficiency factors” to account for air traffic control
- Efficiency factors vary by region and time

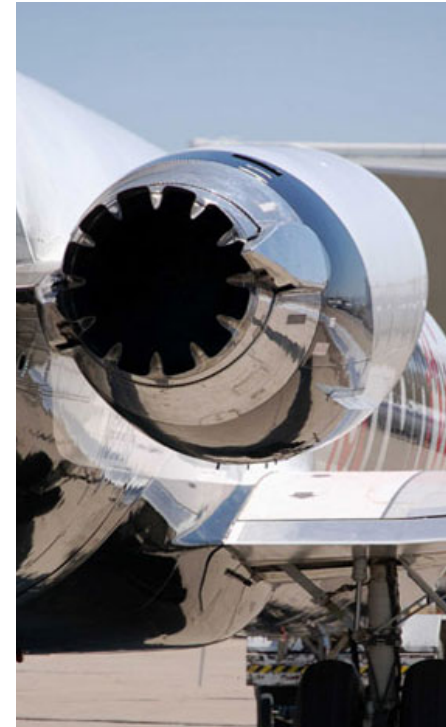
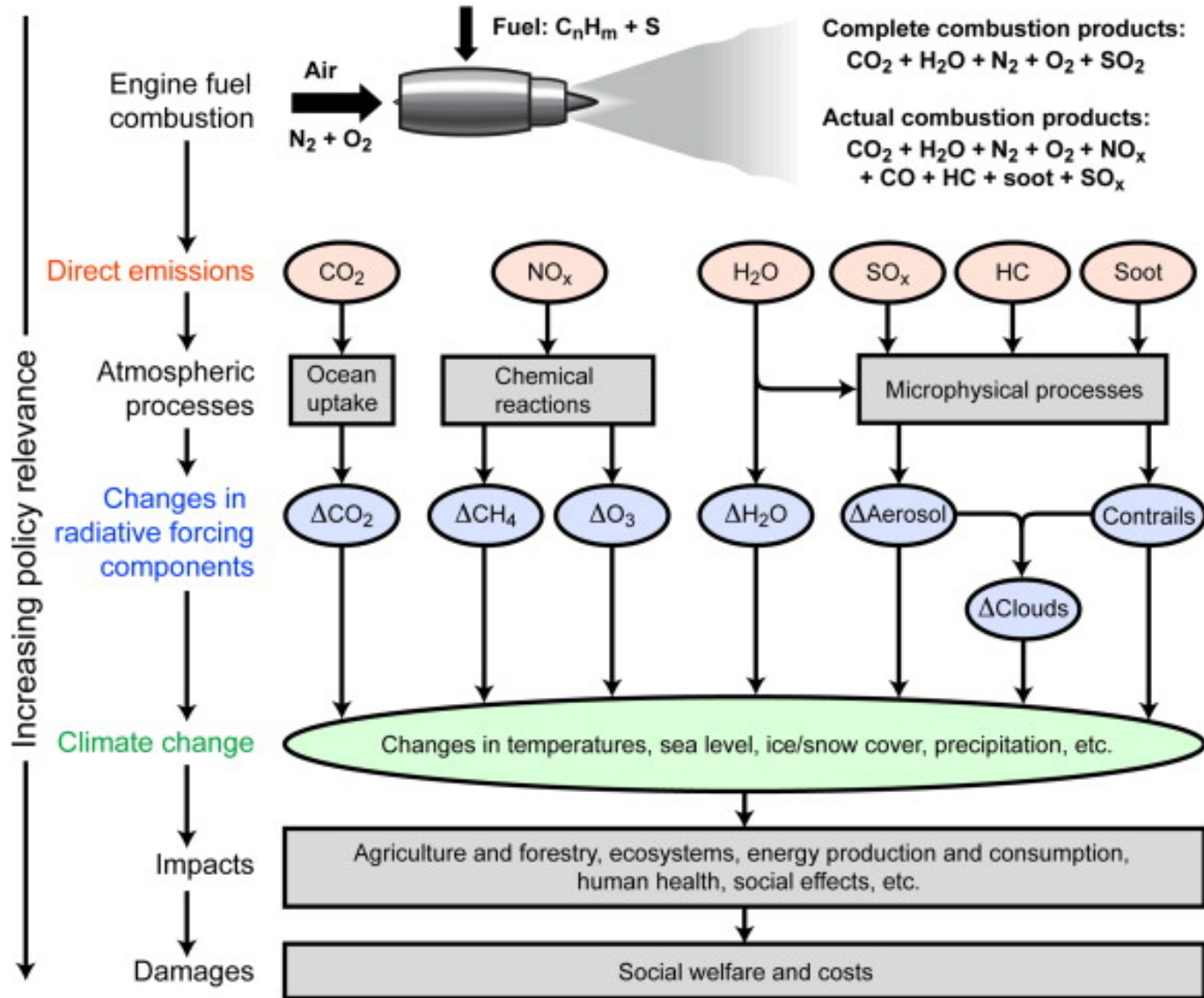


- Optimal trajectories degraded by “real world” inefficiency factors
  - Airspace route structures; restrictions (military areas, convective weather); conflict avoidance (separation minima)
- Inefficiency factors defined for different world regions, now and in future





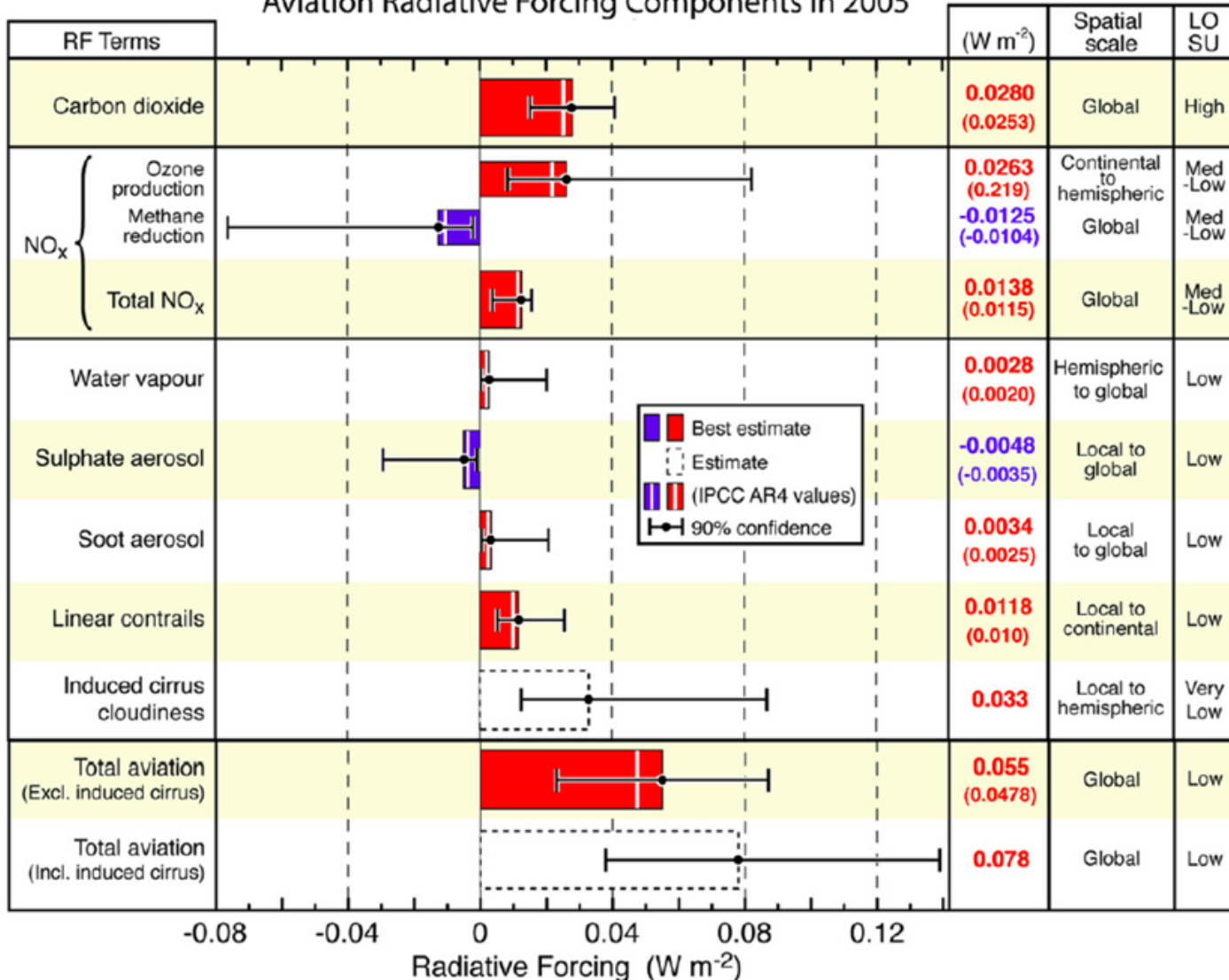
# Climate Impact of Aviation



Wuebbles *et al.*, 2010  
Lee *et al.*, 2009

- Radiative forcing refers to the difference between radiant energy received by the earth and energy re-radiated to space
  - Units  $W/m^2$
  - Positive forcing warms
  - Negative forcing cools

Aviation Radiative Forcing Components in 2005



Lee et al., 2010

- Radiative Forcing (RF) refers to the difference between radiant energy received by the earth and energy re-radiated to space
  - Units  $W/m^2$
  - Positive forcing warms
  - Negative forcing cools
- Radiative forcing metric does not account for timescales of impact

<b>Perturbation in Mechanism</b>	<b>Atmospheric Lifetime</b>
CO <sub>2</sub>	> 100 years
CH <sub>4</sub>	~12 years
O <sub>3</sub>	Weeks
Contrails	Hours

- Radiative Forcing (RF) refers to the difference between radiant energy received by the earth and energy re-radiated to space
  - Units  $W/m^2$
  - Positive forcing warms
  - Negative forcing cools
- Radiative forcing metric does not account for timescales of impact
- Climate impact can instead be quantified by Global Warming Potential (GWP) or Global Temperature Change Potential (GTP)
  - GWP compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of  $CO_2$  over a specific time interval (time integrated radiative forcing)
  - GTP is change in global temperature due to a certain mass of the gas in question over a specific time interval

## Goals

- Determine impact of aircraft emissions on the global climate system ( $\text{CO}_2$ ,  $\text{NO}_x$ ,  $\text{SO}_x$ ,  $\text{H}_2\text{O}$ )

## Methodology

- Three configurations
  - Global Climate Model
  - Chemistry Transport Model
  - Parametric Model
- Model must account for:
  - Combining emissions, i.e., aircraft, lightning, ground-based
  - Atmospheric dynamics, i.e., advection, convection, diffusion, deposition
  - Atmospheric chemistry, i.e., homogenous, heterogenous and photolytic
  - Atmospheric radiation, i.e., radiative forcing

## Configuration 1

### Global Climate Model

#### General Circulation Model

Calculates meteorological data – particularly suitable for realistic future climate simulations

#### Chemistry Module

Whole-atmosphere chemistry, useful for subsonic or supersonic aircraft fleet

#### Radiation Module

Built-in radiation scheme allows feedback on chemistry & transport

## Configuration 2

### Chemistry Transport Model

Forced by actual meteorological analyses – particularly suitable to simulate specific meteorological situations

Primarily aimed at simulating effects from subsonic fleet

Vertical limit 30 km

Flexible grid resolution

### Radiation Model

Off-line radiative code to calculate radiative impact

## Configuration 3

### Parametric Model

Parametric version of Chemistry Transport Model

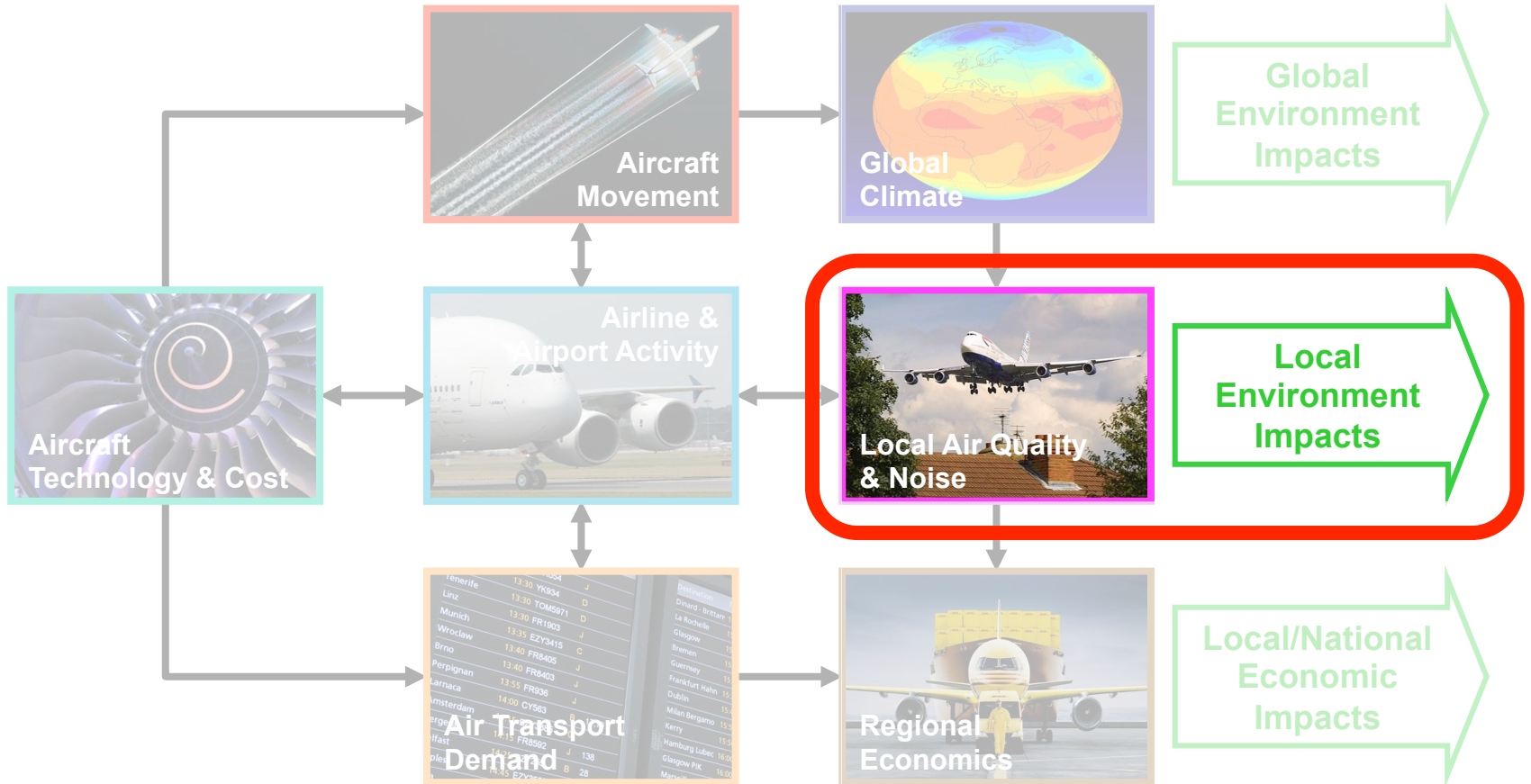
Allows large number of sensitivity studies at low computational costs

Experiments possible within valid range of parameterisation

Provides direct output of global climate metric (RF, GWP)

Decreasing Complexity and Run Time



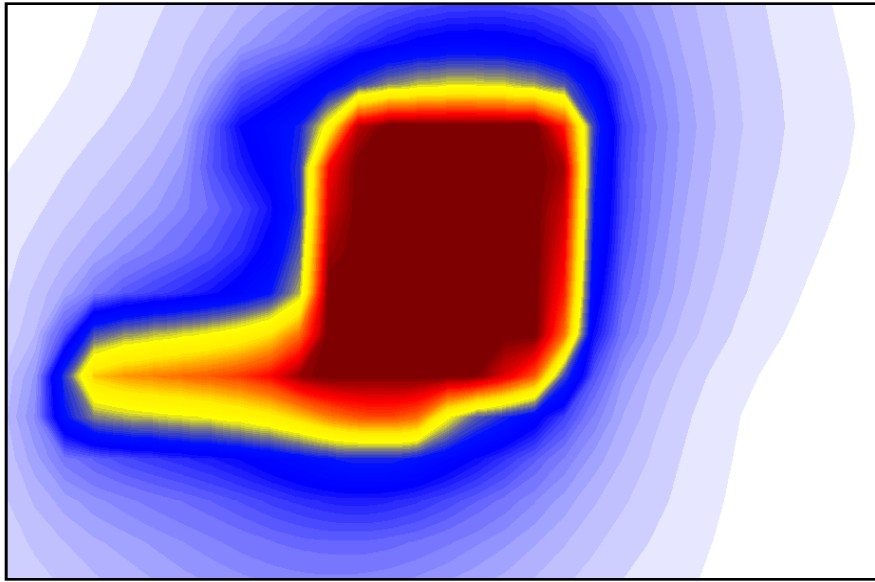
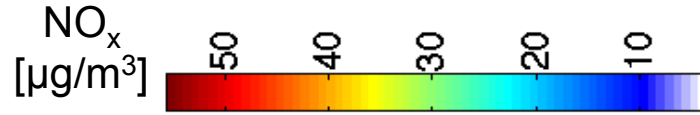


## Goal

- Investigate dispersion of critical pollutants ( $\text{NO}_x$ , PM,  $\text{O}_3$ ) and noise impacts in airport vicinity

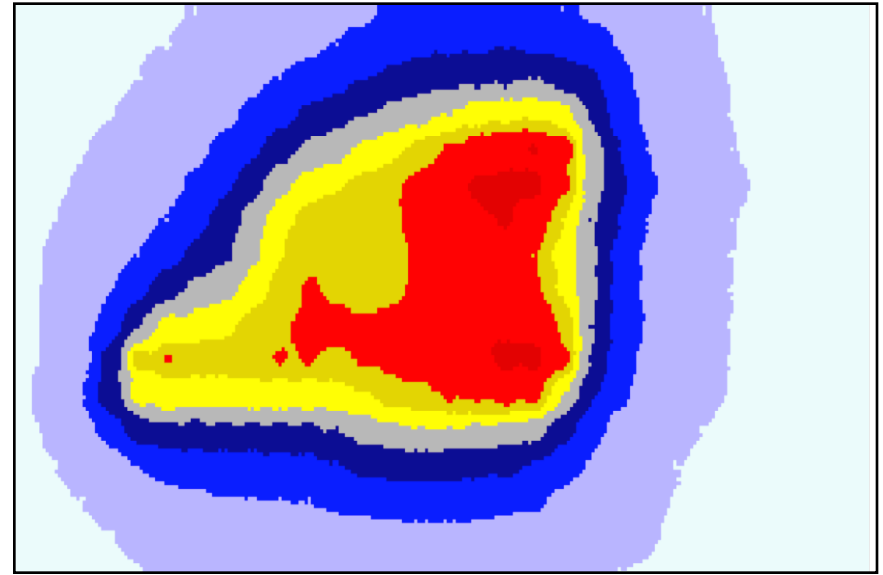
## Methodology

- Emission dispersion impact parameter estimated using meteorology parameterization
  - LTO time, emissions and path inputs from Airline and Airport Activity Module
- Emissions concentrations estimated using dispersion model
  - Dispersion impact parameter and source parameter (from source pre-processing) inputs
- LAQ contours estimated using atmospheric chemistry model based on emission concentrations
- Noise contours estimated using Industry Noise Model
- Outputs:
  - $\text{NO}_x$ ,  $\text{NO}_2$ ,  $\text{PM}_{10}$  &  $\text{PM}_{2.5}$  concentrations, Noise contours/population impacts for metrics of choice



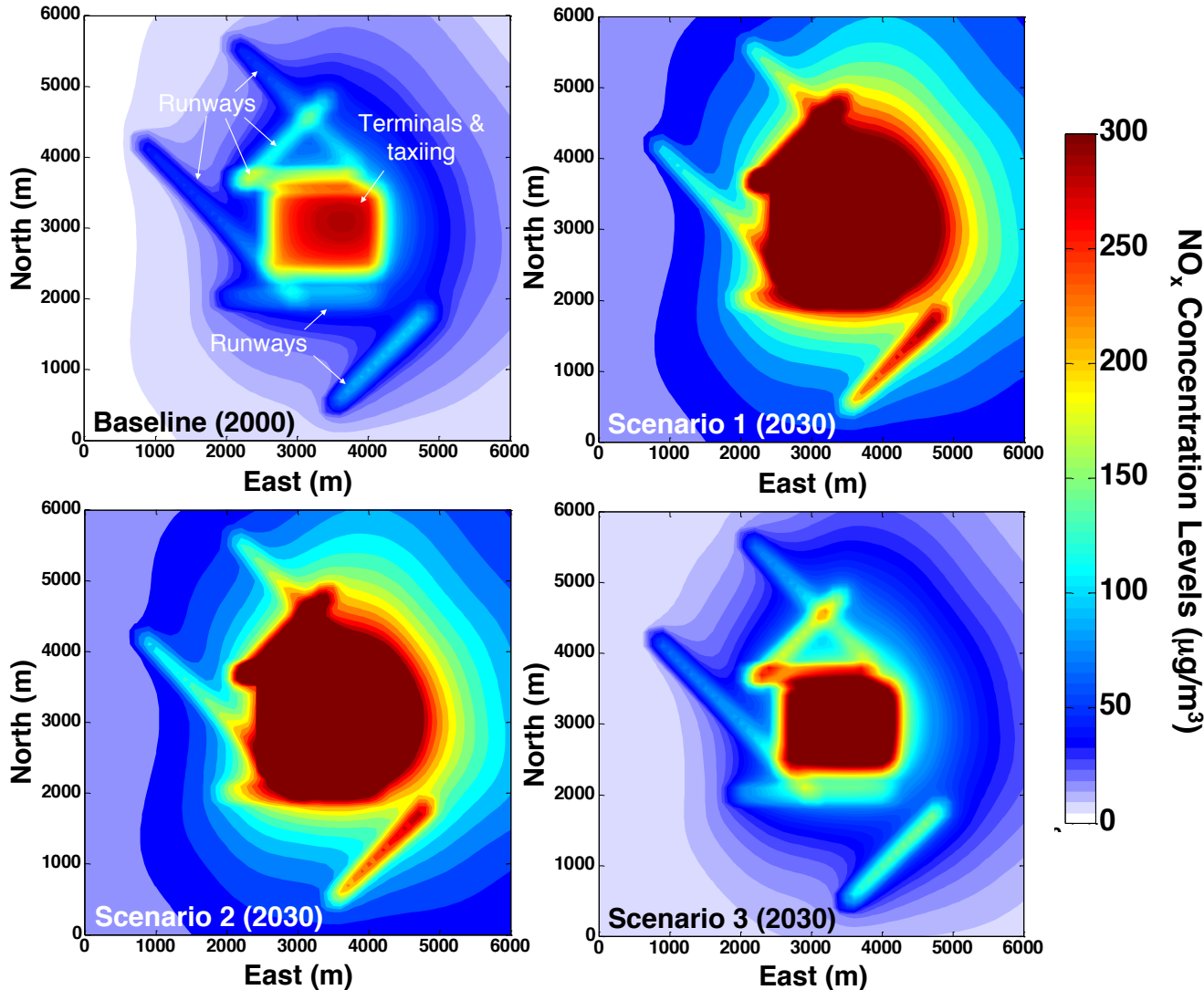
6 km

AIM LAQ Module NO<sub>x</sub> result  
~10 sec

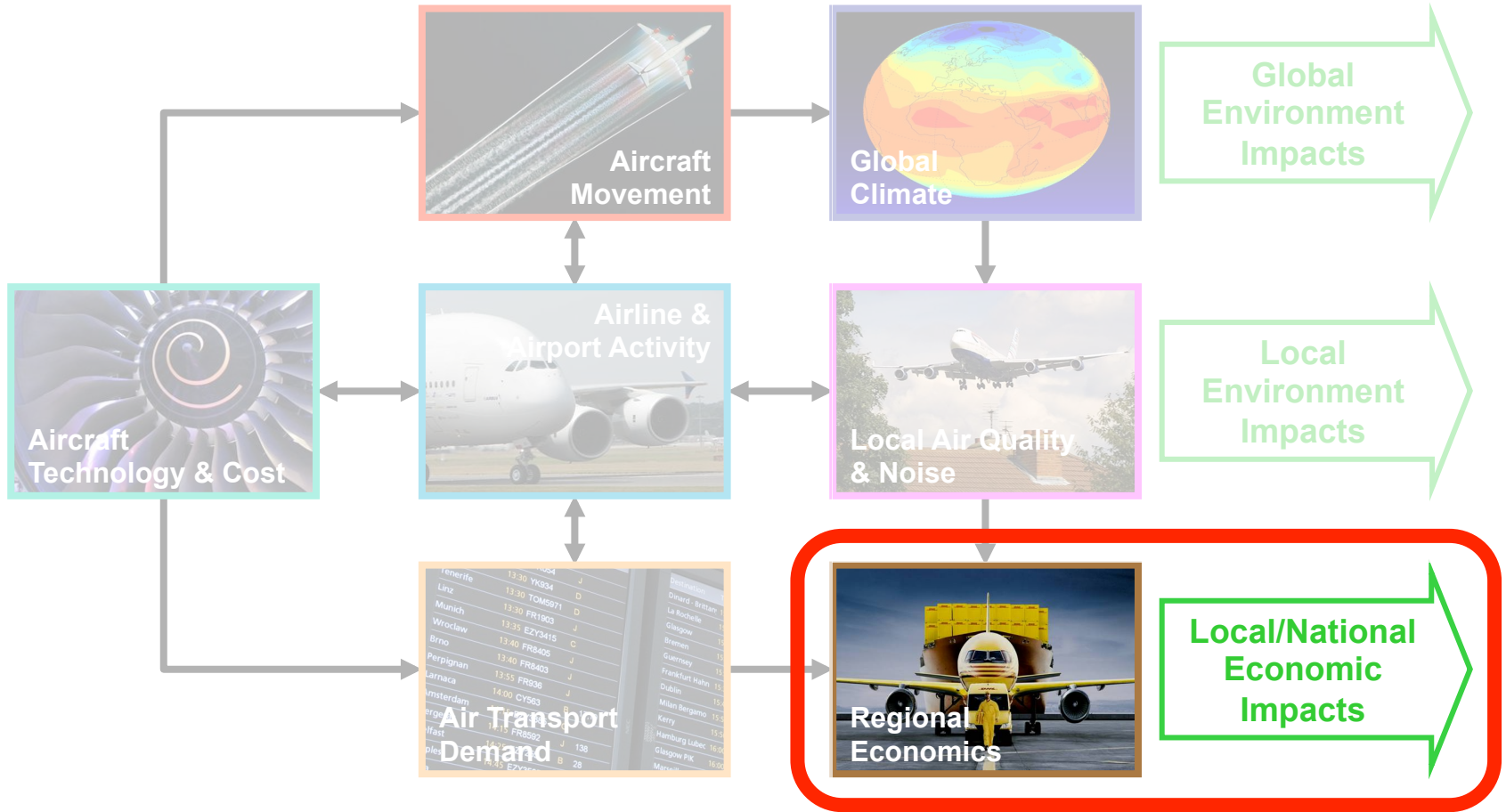


6 km

EDMS NO<sub>x</sub> result  
~1,000,000 sec



- US aviation system evolution scenarios
  - 50 airport set, 2000 – 2030
- **Scenario 1:** Unconstrained
- **Scenario 2:** Capacity Constrained
- **Scenario 3:** Capacity constrained with per-Km tax applied



## Goal

- Quantify positive and negative economic effects of air transport activity on surrounding regions

## Methodology

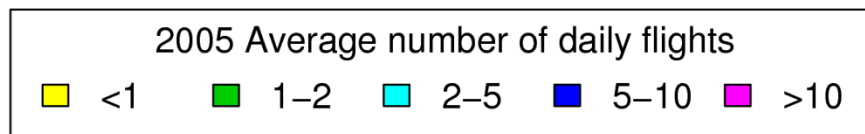
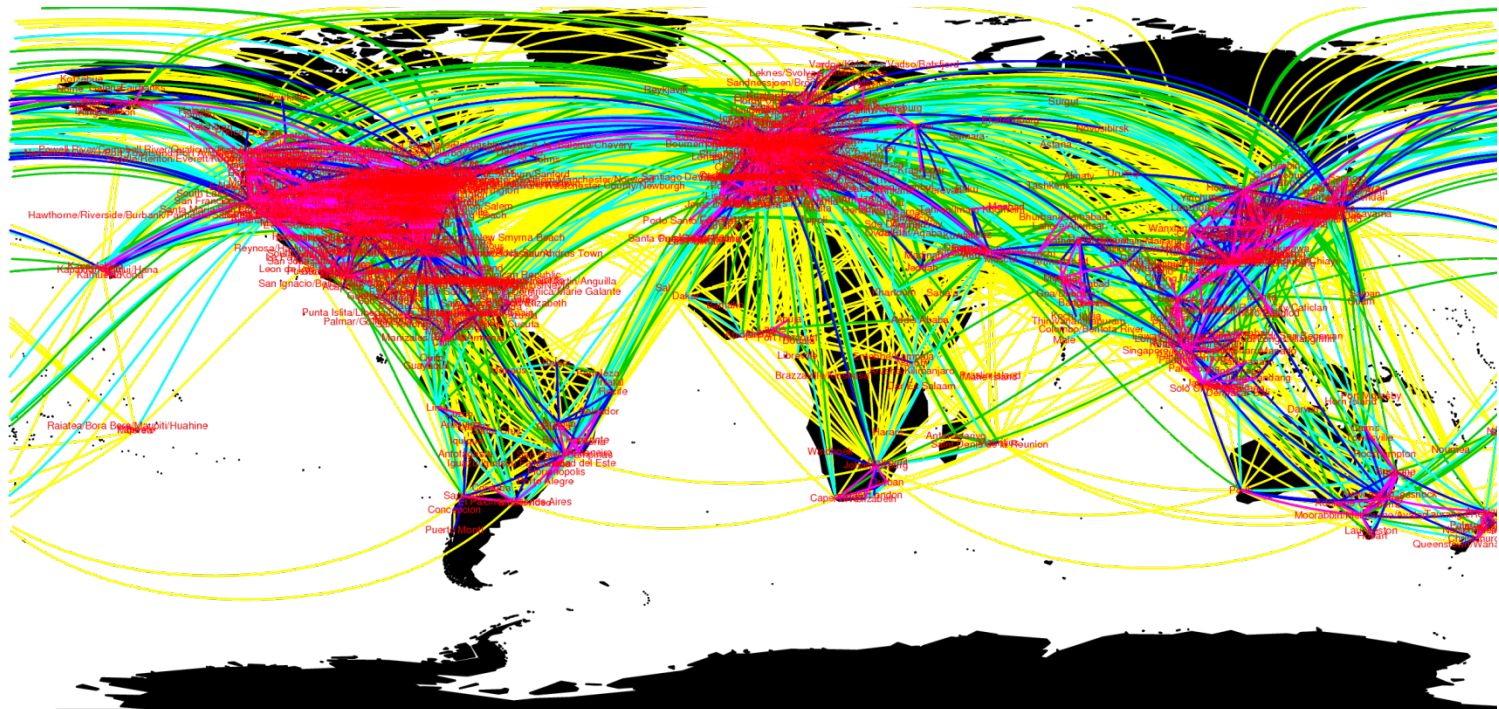
- Noise effects estimated based on estimated noise contours using a noise costing model
- LAQ effects estimated based on estimated LAQ contours using a LAQ costing model
- Employment effects estimated based on passenger and freight flows by airport using a local employment model
- Total economic effects estimated accordingly

- Positive Regional Impacts
  - Direct (e.g. jobs at the airport)
  - Indirect (e.g. jobs at local hotels, business relocation)
  - Induced (e.g. jobs at suppliers of local hotels)
- Negative Regional Impacts
  - Local air pollution ( $\text{NO}_x$ ,  $\text{SO}_x$ ,  $\text{PM}_{2.5}$ ) – health impacts
  - Noise around airports – lowers property values
  - Visual intrusion, landscape degradation
  - Climate impacts through contrails and emissions
- Literature review → ‘Conversion factors’ to convert pollutant concentration or marginal effect of emissions into health effects/economic costs

- **Case Study 1:** Airline fleet replacement funded by a global carbon tax
- **Case Study 2:** Climate-neutrality versus carbon-neutrality for an aviation biofuel policy
- **Case Study 3:** A comparison of aviation greenhouse gas emission mitigation policies for Europe

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- Geographic Scope: 95% of global scheduled RPK, 700 cities, 1127 airports

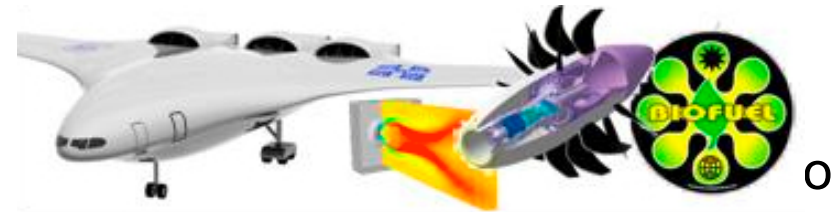


- Based on two existing concepts for emissions reduction
  - Cap and trade / Emissions trading (e.g., European ETS)
  - Subsidized fleet renewal (e.g. road vehicle “scrappage schemes”)
- Apply a global carbon tax to aviation
  - Similar impacts to a global cap and trade scheme in which aviation is a net buyer
- Use revenues from this tax to fund fleet replacement of older aircraft
- Potential effects:
  - Changes in fleet technology composition
  - Reduced fuel costs leading to decreased fares and increased demand
  - Carbon tax leading to increased fares and decreased demand

- Socioeconomic scenarios
  - Describes growth in population, income, oil price etc.
  - MIT IGSM
    - 5.2%/yr global demand growth; high GDP growth in US and Europe; high oil price
  - Stanford MERGE
    - 4.8%/yr global demand growth; medium oil price
  - Joint Global Change Research Institute's MiniCAM
    - 4.6%/yr global demand growth; high growth in Asia; low oil price
- Carbon Tax assumptions
  - Applied from 2015
    - Initially funds replacement of aircraft over 30 years old
    - Age threshold incrementally reduced to 20 years by 2025
  - Varied over time
    - Carbon tax calculated based on number and types of aircraft over age threshold
    - Applied to raise NPV of new aircraft purchase above that of keeping old aircraft, assuming scrappage value 10% of list price

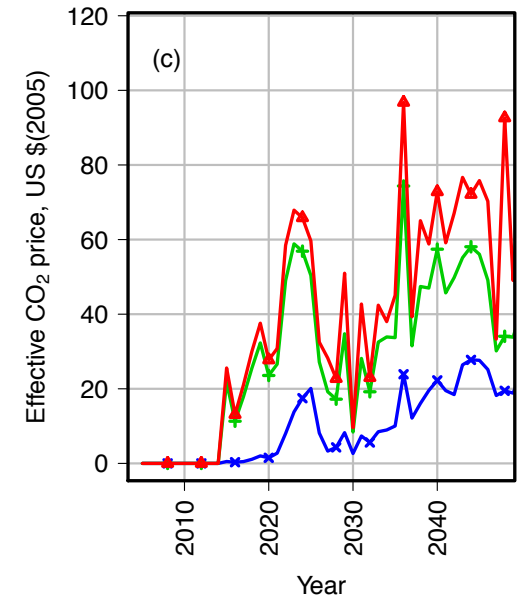
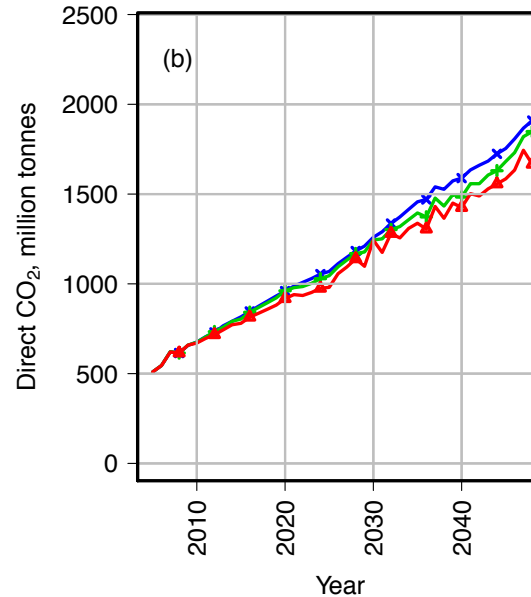
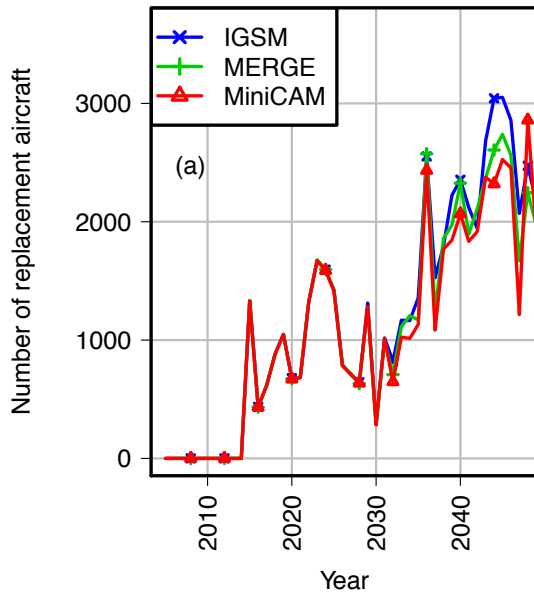
- Technology assumptions

- 20% biofuel blend from cellulosic biomass feedstock be available by 2020
- ATM improvements in US, Europe and Asia applied from 2015-2025
  - Supply 4% global decrease in fuel burn
- Fuel burn of new aircraft models improves by 1% per year
- Specific new technologies also modeled



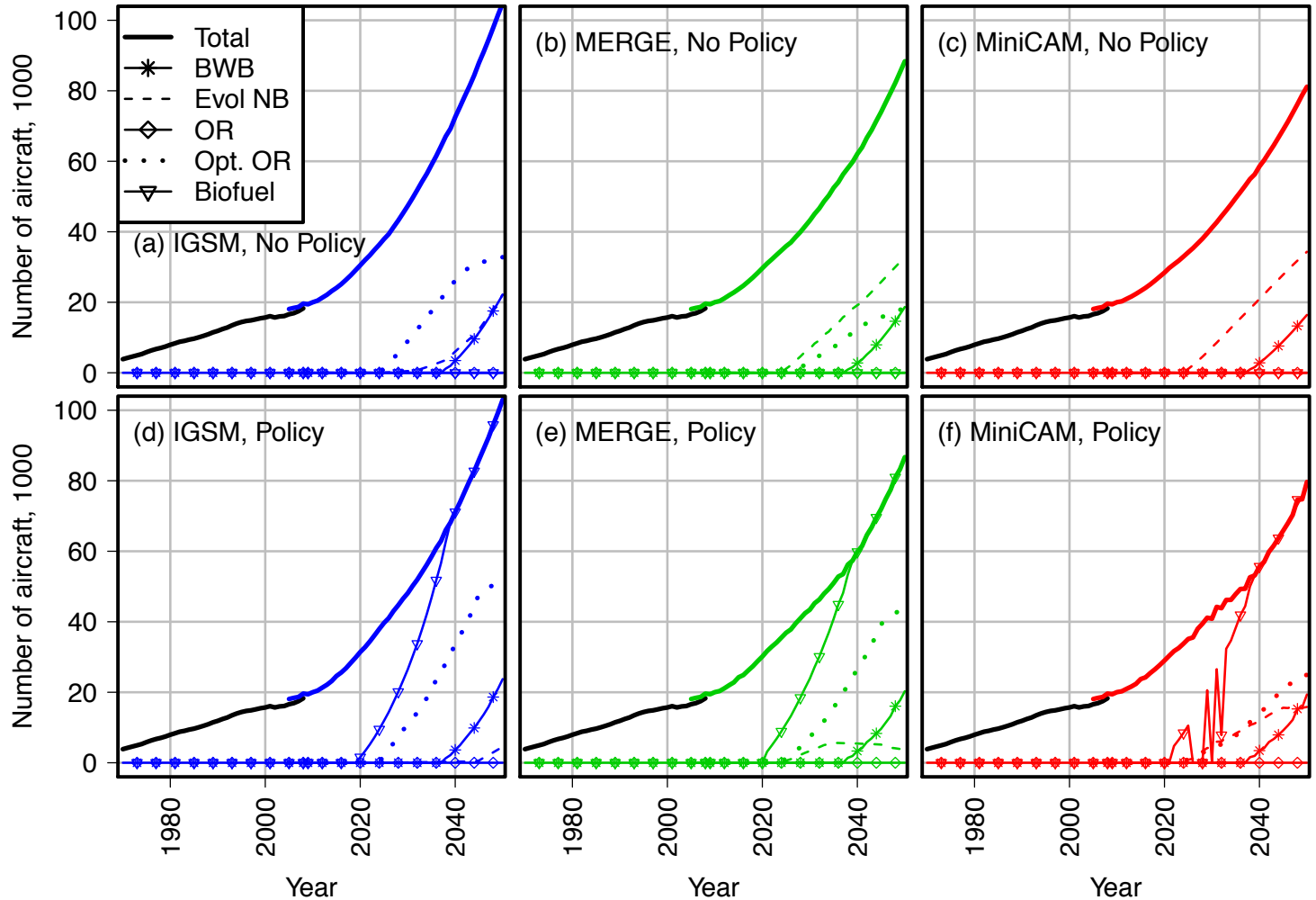
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- Any global cap and trade or emissions trading scheme is likely to see significant political challenges
- Widespread carbon taxation could face legal challenges under Chicago convention
- Policy could be seen as rewarding airlines with old, inefficient fleets
- Possible counterproductive effects
  - As fleet emissions decrease, tax has to increase to maintain fleet replacement
  - Possible reductions in non-policy technology use
- We do not consider emissions from aircraft construction and disposal
- Questions about whether such a tax should be used to fund fleet renewal in all regions?
  - Could fund fleet renewal only in developing economies



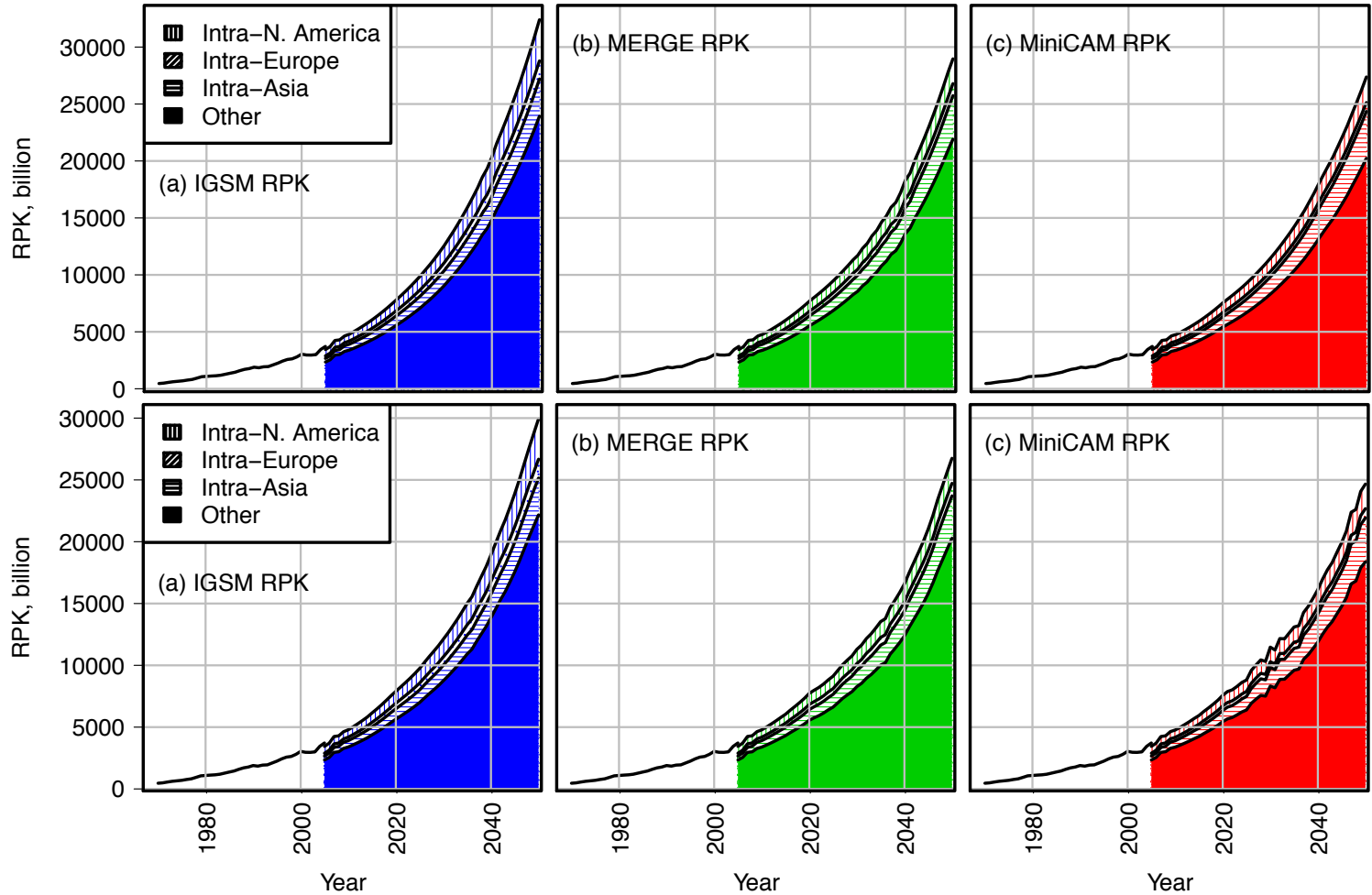
- Number of replacement aircraft highly variable
  - Fleet age structures highly peaked
- Direct emissions totals similar across scenarios
- Effective carbon price also highly variable
  - Within range of projected prices in European ETS
  - IGSM scenario low because of high oil price

Reference Case  
(No Policy)



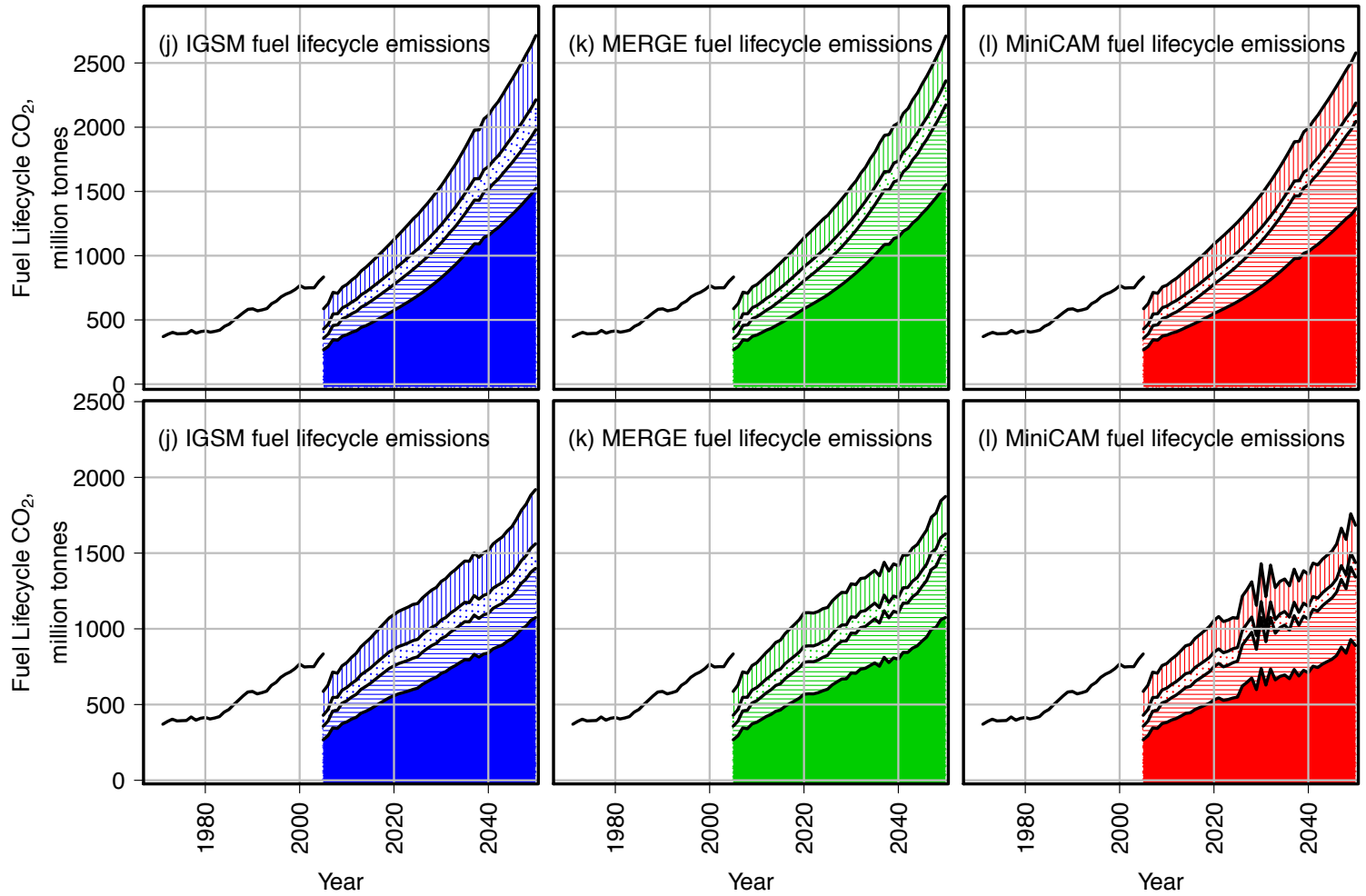
Policy Case

Reference Case  
(No Policy)



Policy Case

Reference Case  
(No Policy)

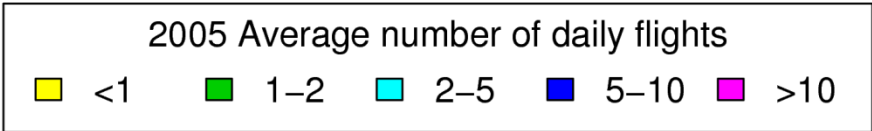
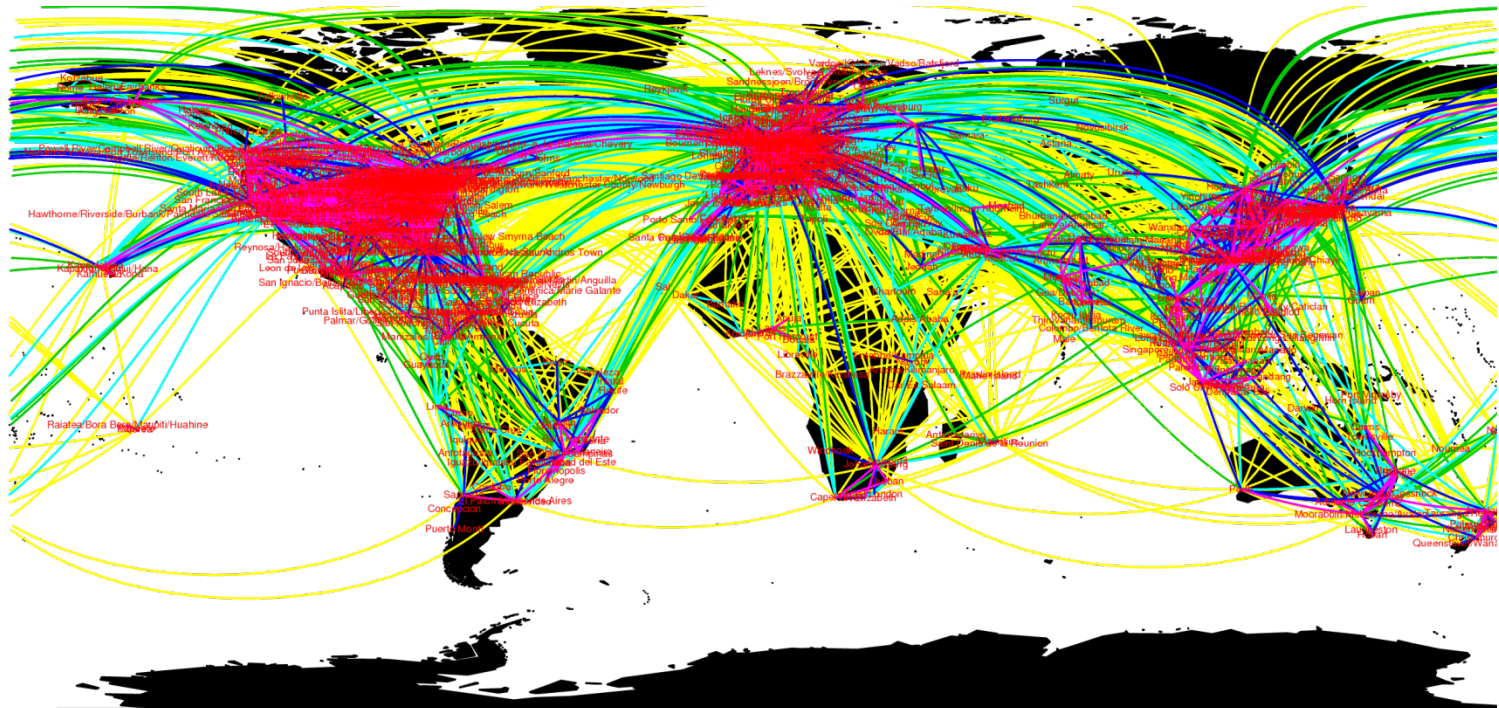


Policy Case

- Airline fleet replacement funded by carbon tax
  - A carbon tax used to fund fleet renewal could reduce lifecycle CO<sub>2</sub> emissions due to aviation by up to 35% relative to a no-policy case
    - ~1/3 due to demand reduction
    - ~1/3 due to increased use of biofuels
    - ~1/3 due to fleet replacement
  - Results are robust across different socioeconomic scenarios
  - There are significant drawbacks
    - Increasing carbon price with reduces emissions
    - High variation in carbon price
- AIM applied to perform integrated assessment of complex global policy
- Integrates a number of complex models of different systems, including fleet turnover, demand growth & airline behavior

- **Case Study 1:** Airline fleet replacement funded by a global carbon tax
- **Case Study 2:** Climate-neutrality versus carbon-neutrality for an aviation biofuel policy
- **Case Study 3:** A comparison of aviation greenhouse gas emission mitigation policies for Europe

- Geographic Scope: 95% of global scheduled RPK, 700 cities, 1127 airports



- The EU Emissions Trading Scheme consider aviation biofuel to have zero emissions for the purposes of carbon trading
- However, drop-in biofuels address only aviation CO<sub>2</sub>
- Non-CO<sub>2</sub> climate impacts may still be significant
  - NO<sub>x</sub> impacts on ozone and methane
  - Contrails and contrail induced cirrus
- We compare estimated total climate impact with and without biofuels
  - Under a future global emissions trading policy
  - Flights using biofuel are exempt
- A drop-in Fischer-Tropsch fuel derived from cellulosic biomass assumed

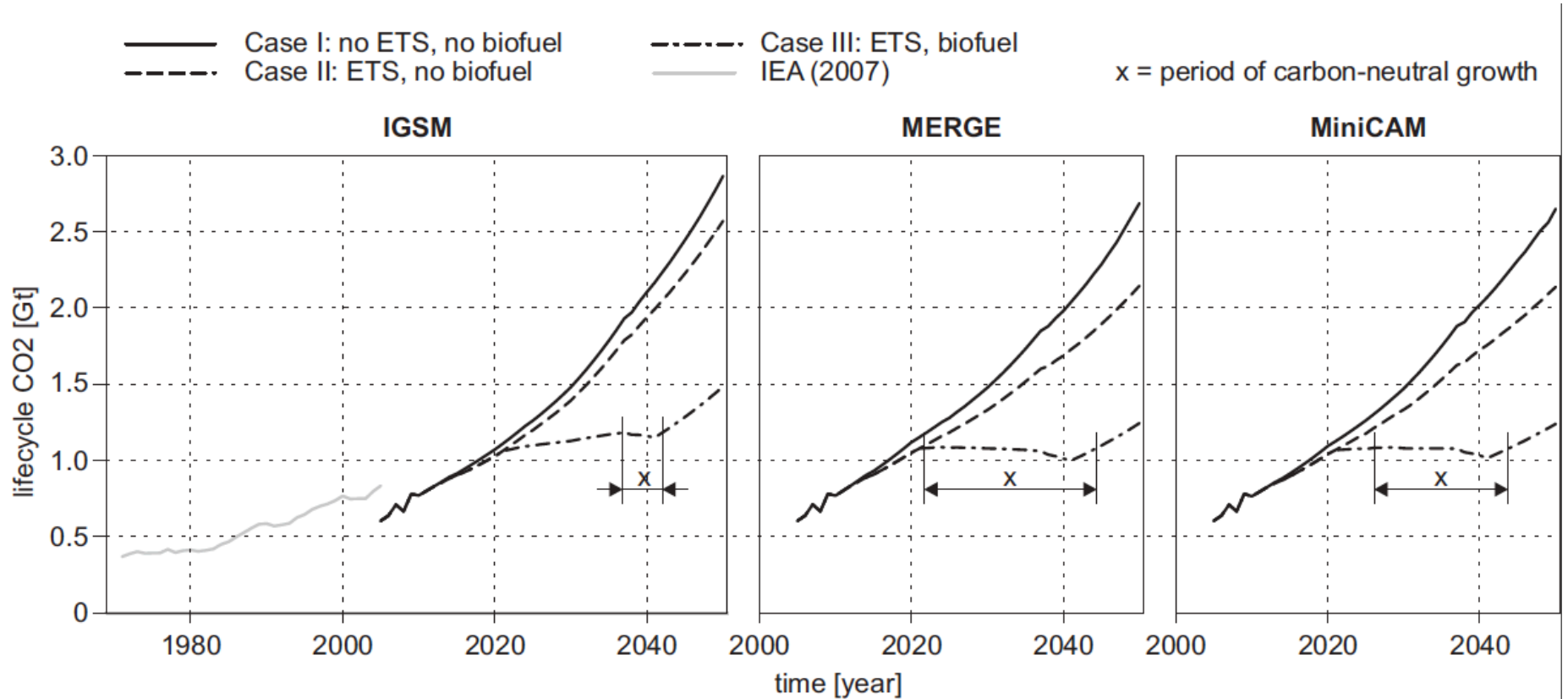
- Absolute Pulsed GWP estimated
  - A pulse of emissions is total emissions from aviation for one year
- Non-CO<sub>2</sub> climate impacts modelled:
  - NO<sub>x</sub> impacts on ozone and methane
    - Calculated by flight level
  - Contrails and contrail induced cirrus
    - Linear scaling with distance flown over altitude
  - (Other non-CO<sub>2</sub> effects neglected)
- Climate conditions, affecting atmospheric background concentrations not assumed to change with time
- A *date fixed* time horizon is applied of 100 yrs
  - E.g., For annual emissions in 2011, time horizon 2011-2111 considered; annual emissions in 2012, time horizon 2012-2111 considered (not 2012-2112); etc.

- Technology assumptions
  - Biofuel blend from cellulosic biomass feedstock assumed to available from 2020
    - Biofuel production initially limited
    - No more than 50/50 blend applied
  - ATM improvements in US, Europe and Asia applied from 2015-2025
    - Supply 4% global decrease in fuel burn
  - Fuel burn of new aircraft models improves by 1% per year
  - Specific new technologies also modeled

New Technology	Year of Introduction	% Reduction in Fuel Burn over existing Technology
Composite Evolutionary Replacement Narrowbody	2025	22%
Open Rotor Narrowbody	2025	35%
Optimized Open Rotor Narrowbody	2025	45%
Blended Wing Body Widebody	2037	30%

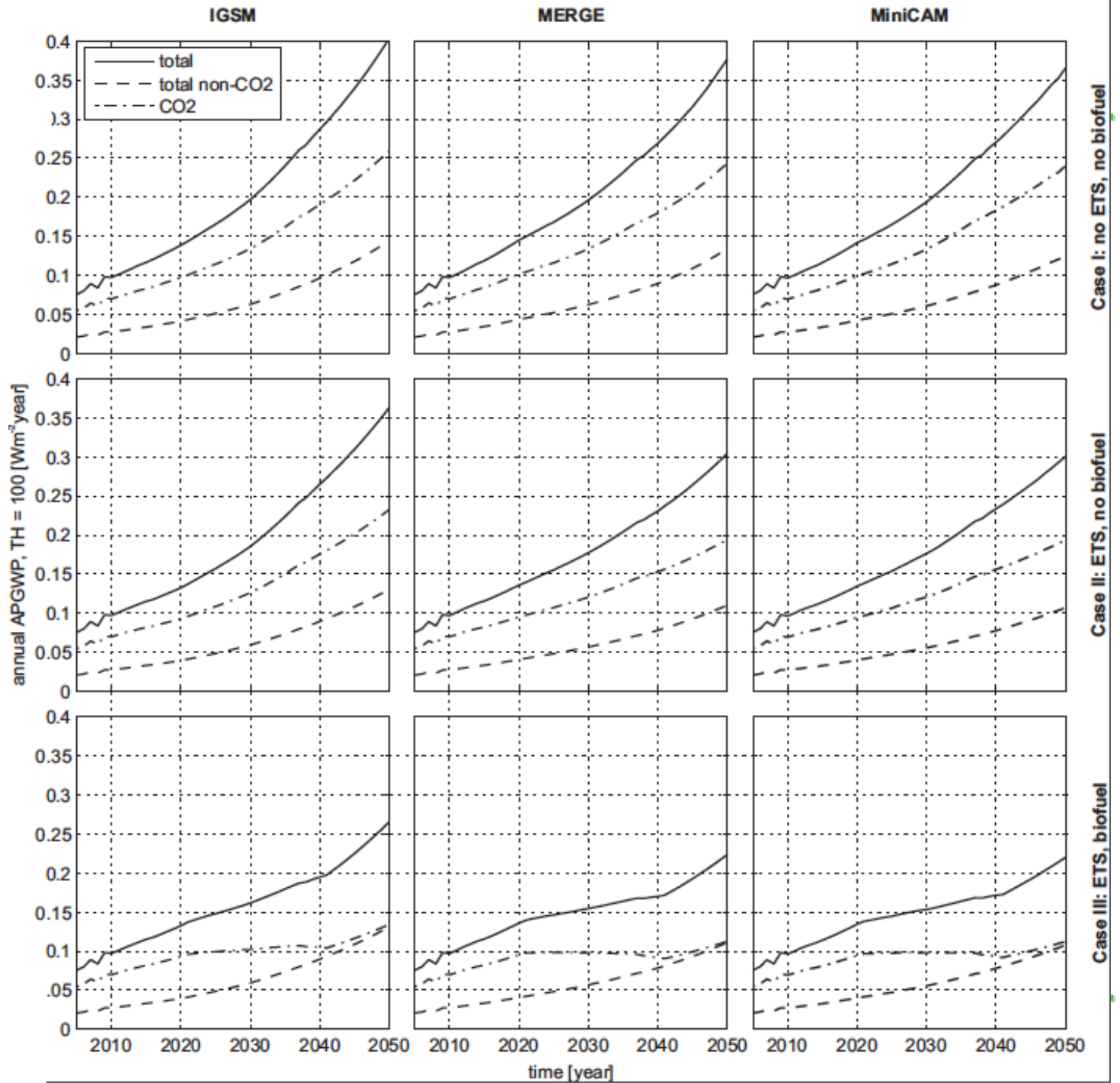
- Socioeconomic scenarios
  - Describes growth in population, income, oil price etc.
  - MIT IGSM
    - 5.2%/yr global demand growth; high GDP growth in US and Europe; high oil price
  - Stanford MERGE
    - 4.8%/yr global demand growth; medium oil price
  - Joint Global Change Research Institute's MiniCAM
    - 4.6%/yr global demand growth; high growth in Asia; low oil price
- Carbon Tax assumptions
  - Global emissions trading scheme applied
  - Carbon taxes applied to achieve long-term atmospheric CO<sub>2</sub> concentrations of 550 ppmv and 450 ppmv
    - Similar in magnitude to EU ETS carbon prices
  - Socioeconomic inputs internationally consistent with oil and carbon prices
  - Biofuels are exempt

# Lifecycle CO<sub>2</sub> Emissions





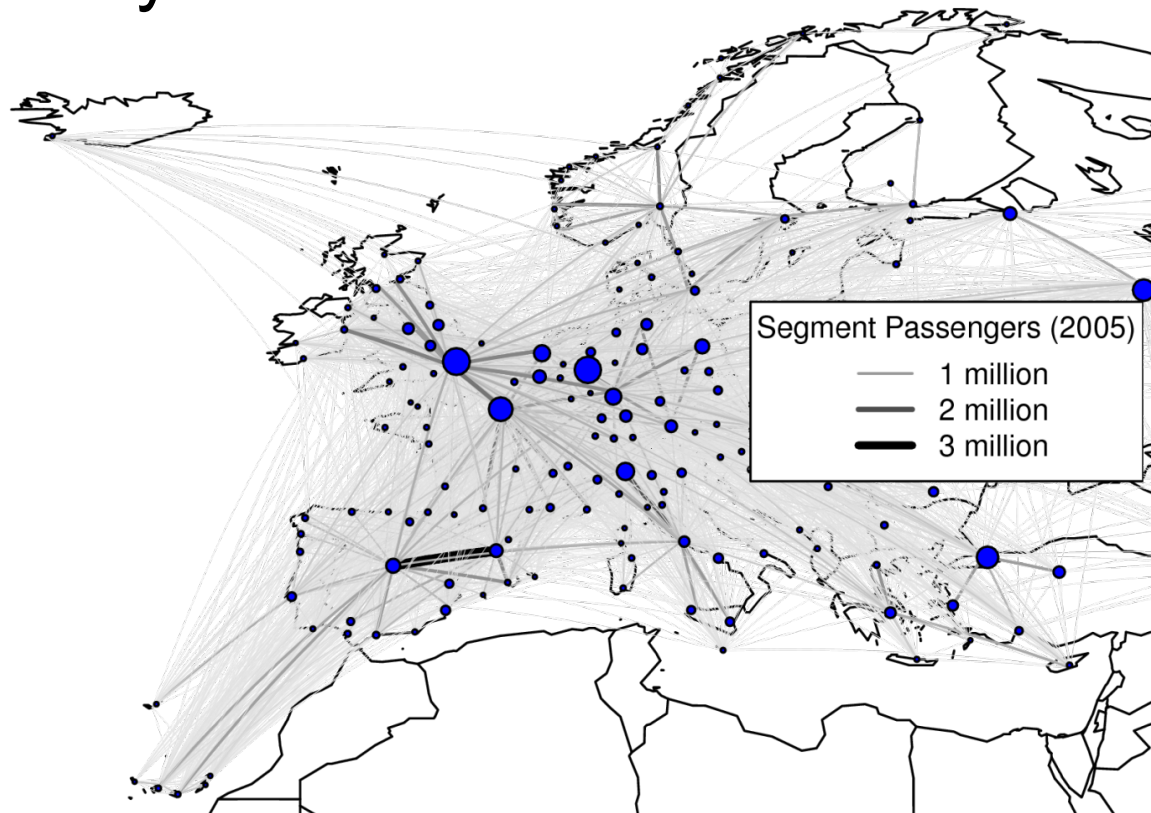
# Global Warming Potential



- With a 50/50 biofuel blend and emissions trading at EU ETS levels, 2050 CO<sub>2</sub> emissions can be reduced by ~50%
  - Demand reduction
  - Biofuel uptake
  - Uptake of other mitigation technologies
- A period of carbon-neutral growth is possible, but not sustainable indefinitely
- Reduction in total climate impact (APGWP) significantly lower: ~30% (only 15% with 20 year time horizon)
- Potential for biofuel to provide climate-neutral growth limited
- Emissions trading exemptions for biofuel may not be justified

- **Case Study 1:** Airline fleet replacement funded by a global carbon tax
- **Case Study 2:** Climate-neutrality versus carbon-neutrality for an aviation biofuel policy
- **Case Study 3:** A comparison of aviation greenhouse gas emission mitigation policies for Europe

- Europe: 173 Cities (337 airports)
- Destinations outside Europe modelled at region level only



- **Reference case** – no measures
- **Case 1:** EU ETS only (from 2012)
- **Case 2:** Case 1 plus SESAR & airline responses
  - SESAR, open rotors from 2020
  - Retrofits and increased maintenance from present day
- **Case 3:** Case 2 plus biofuels (from 2020)
  - Production capacity increase limited
- **Case 4:** Case 3 plus High-Speed Rail
  - UK, French, German, Spanish and Italian proposed new lines

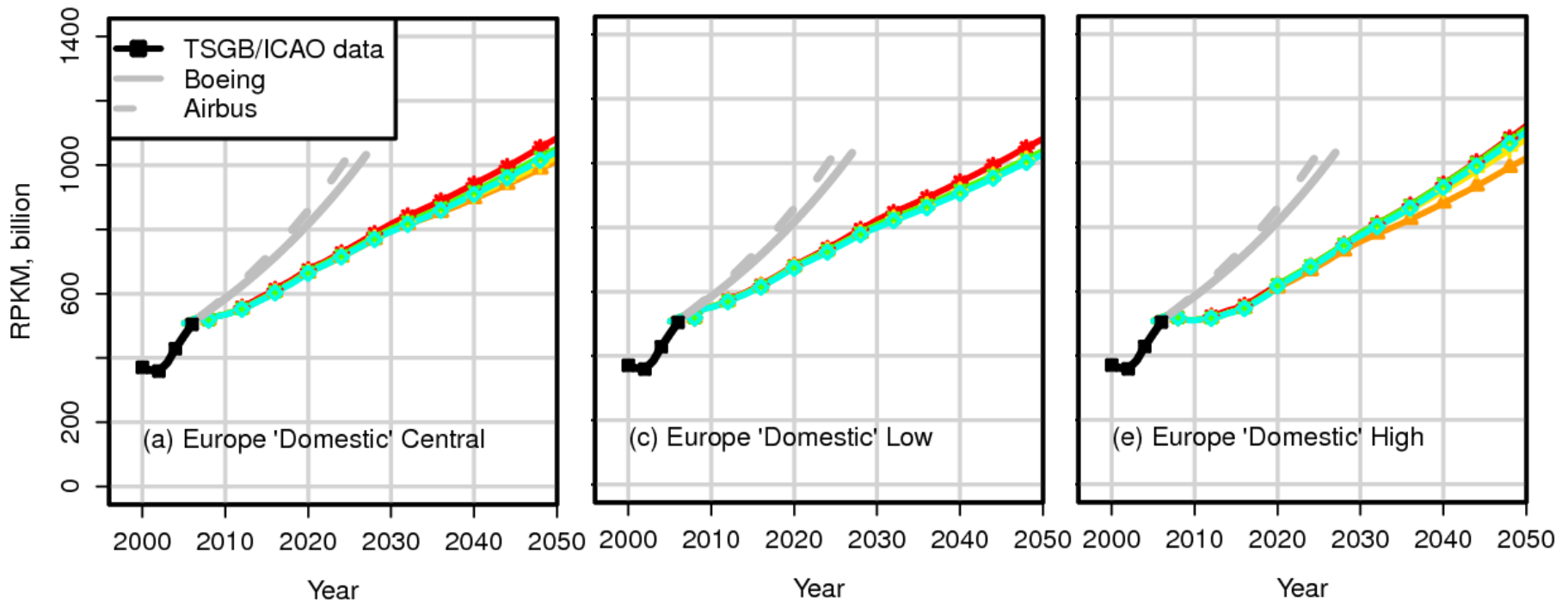
All cases use OMEGA data



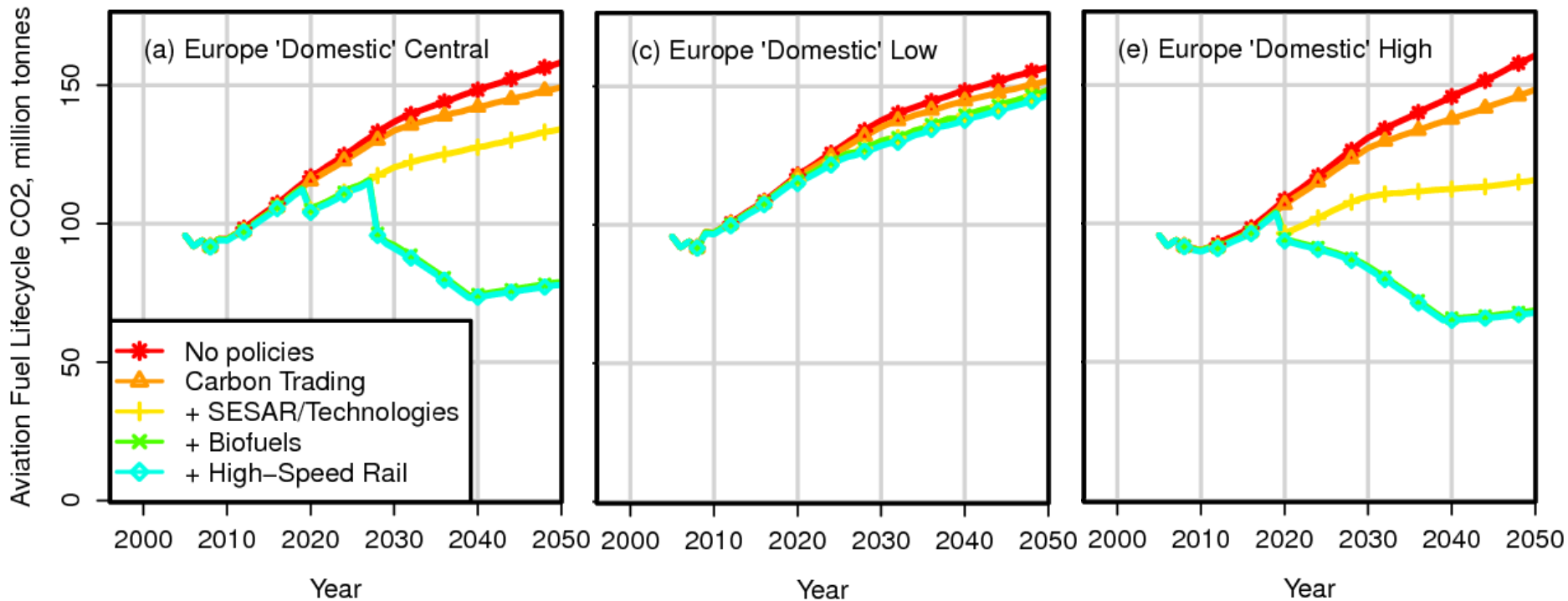
Three economic growth scenarios, using preliminary UK CCC data:

- **CENTRAL**
  - ❑ Mid-range GDP growth, oil and carbon prices
  - ❑ 2020 Oil price: \$74/bbl, Carbon price \$63/tonne CO<sub>2</sub>
- **LOW**
  - ❑ Low GDP growth, oil and carbon prices
  - ❑ 2020 Oil price: \$56/bbl, Carbon price \$27/tonne CO<sub>2</sub>
- **HIGH**
  - ❑ High GDP growth, oil and carbon prices
  - ❑ 2020 Oil price: \$139/bbl, Carbon price \$86/tonne CO<sub>2</sub>
- Biofuel price assumed \$0.70/l (or oil price if higher)

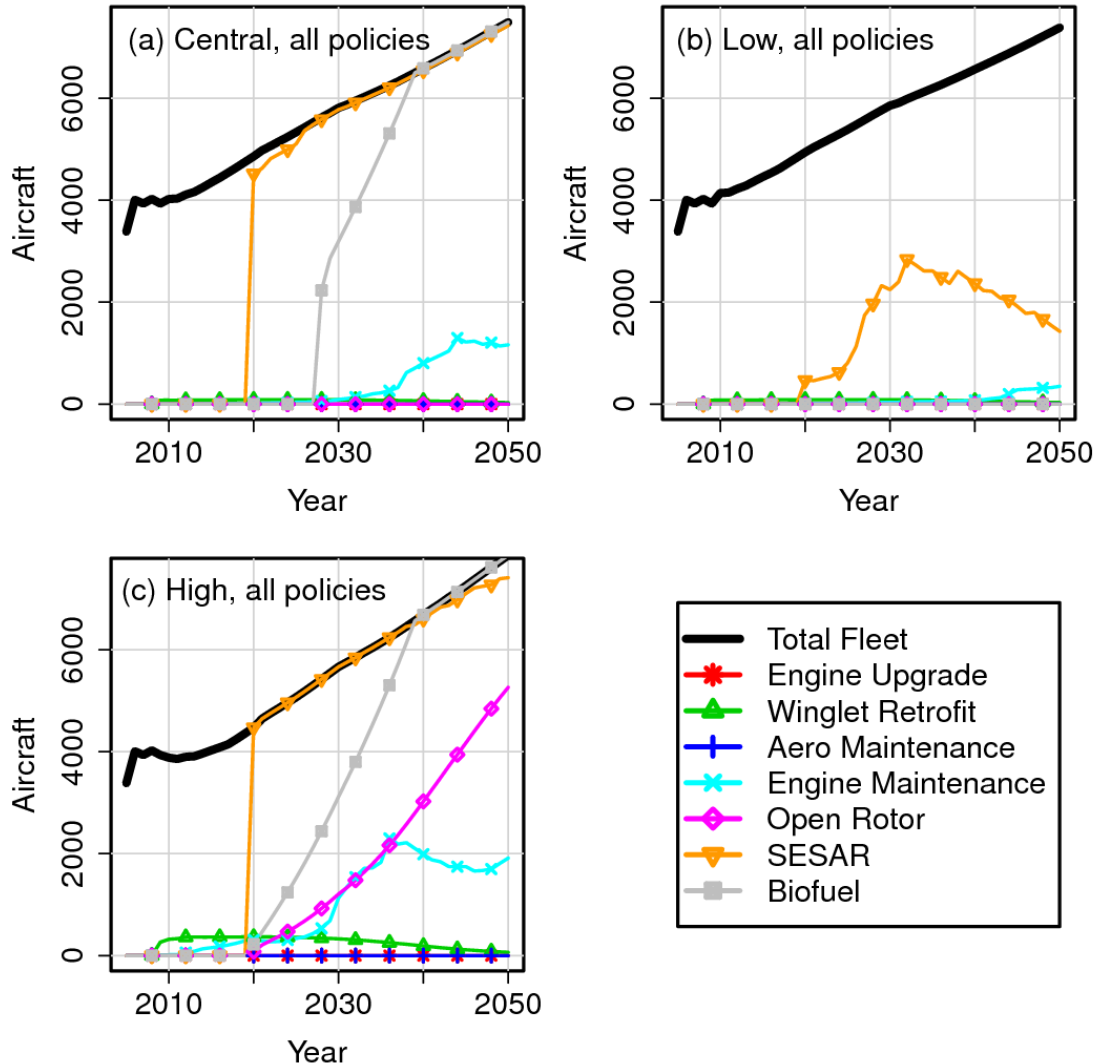
- Most measures have small effect on RPKM only (<10%)
- Greatest effects:
  - Carbon trading with high prices and low technology availability
  - High-speed rail



- Lifecycle CO<sub>2</sub> results differ strongly by scenario



# Measure Uptake by Scenario



- Reducing year-2050 fuel lifecycle CO<sub>2</sub> emissions in Europe to below year-2005 levels may be possible *if*:
  - Aviation-suitable biofuels are developed, and
  - Aviation is added to the EU ETS, and
  - Future carbon+oil prices follow Central or High trajectories
- SESAR, high-speed rail (all scenarios) and open rotors (High scenario only) can also make significant contributions to emissions reductions
- However, noise, local and airborne emissions will be little-changed from reference case
- Land-use questions over Biofuel use

- The Aviation Integrated Model (AIM) can be applied to regional and global policy assessment
  - Captures feedback between key elements of the air transport system
- AIM has also been used for high fidelity regional studies
  - Airline response to airport capacity constraints in the United States
  - Quantifying the rebound effect in the aviation sector in the United States
- Future developments include:
  - Increased aircraft size categorization
  - Greater integration of the high fidelity airline response model into AIM
  - Simulating effects in developing regions in higher fidelity
  - Capturing passenger choice effects in inter-continental connecting traffic

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