ASKEM 18-Month Milestone: Evaluation Scenarios

USE CASE: CLIMATE

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Scenario 1: Connecting Climate with Aircraft Performance

Estimated % of time: 30%

Over the years we've seen increases in both surface temperatures and atmospheric temperatures driven by climate change, and we expect this to continue in the future, as predicted by climate models. This scenario explores how increasing atmospheric temperature directly affects the domain of aircraft performance (specifically landing distance) via physical laws.

This scenario is split into two parts. The first set of questions (Q1-Q6) explores how various factors impact landing distance. The second part (Q7-Q10) applies this knowledge to a hypothetical real-world use-case. All tables and equations are at the end of the scenario.

Calculating Landing Distance (Q1-Q6)

For this part of the scenario, we calculate landing distance for a Boeing 747-8F whose parameters are listed in Table 2. Initially we assume that the altitude is at Mean Sea Level (MSL) and ambient conditions are at Standard Temperature and Pressure (STP) with no wind field present (i.e., the wind speed is zero at and around the airfield). Table 1 contains International Standard Atmosphere (ISA) standard temperature and pressure values that will be used for initial conditions.

Let's begin by plotting historical and forecasted temperature for two airports located at radically different altitudes: Guantanamo Bay, Cuba (roughly at sea level), and La Paz, Bolivia (located high in the Andes mountains).

1. Search for historical data and climate model output (for future projections) for monthly mean of the daily maximum temperature. For climate model data, search for CMIP5 or CMIP6 outputs.
2. If needed, run downscaling algorithms on the climate data found in Q1, to match the spatial scale of the locations of interest.
3. For each of the two different locations (Guantanamo Bay and La Paz), plot the monthly mean of the daily maximum temperature (daily T_{max}) for Jan – Dec, for the following time periods. If there is uncertainty in the climate forecasts in the CMIP outputs, please take that into account and incorporate that into your results.
   a. With historical observed data of T_{max}, 1970 – 1999
   b. Climate model output for T_{max}, 1970—1999. How well does the climate model output match the historical observed data from Q1a?
   c. Climate model output for T_{max}, 2020—2049 (future forecast)
   d. Climate model output for T_{max}, 2040—2069 (future forecast)
   e. Climate model output for T_{max}, 2060—2099 (future forecast)
4. Create the following series of plots. You will use the landing distance equation (Equation 1), also described in Figure 1. Use values from ISA standards (Table 1), where appropriate.
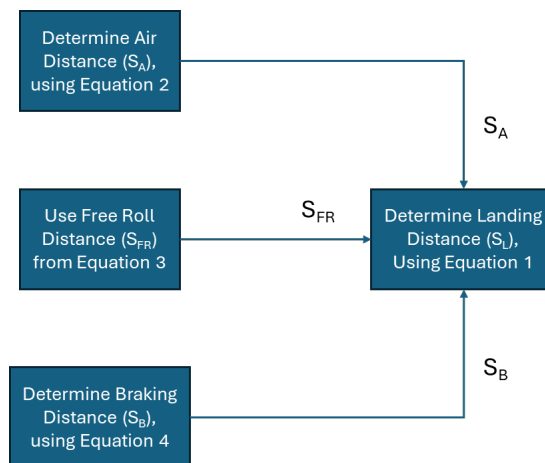

Figure 1. Components supporting the overall Landing Distance equation

   a. Landing Distance versus Temperature
      • Temperature range: $0°C – 70°C$, in steps of $10°C$
      • For altitude and pressure, use values for Sea Level
      • Use the ideal gas law (Equation 5) and the landing distance equations (Equations 1-4); see Figure 2 (which doesn't include terms that are constant through the process and don't need to be calculate)Figure 1

Figure 2. Components supporting Q4a

b. Landing Distance versus Altitude
- T = 15°C
- Altitude range: Sea Level to 11 km, in steps of 2 km
- Use the barometric pressure equation (Equation 8), ideal gas law (Equation 5), and landing distance equations (Equations 1-4); see Figure 3 (which doesn't include terms that are constant through the process and don't need to be calculate)
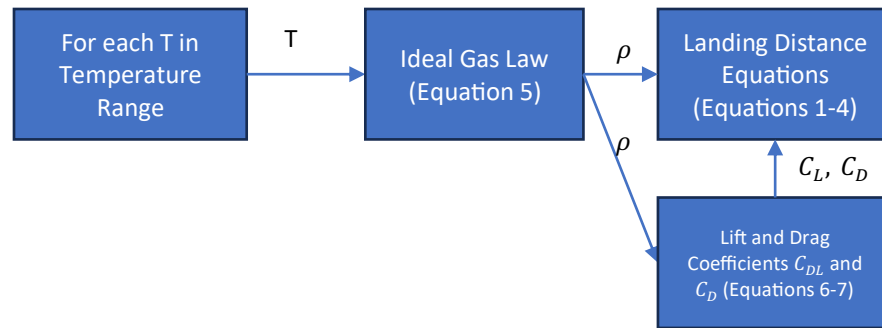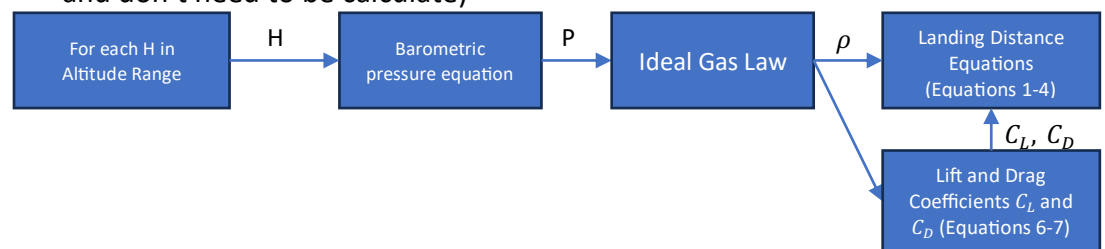

Figure 3. Components supporting Q4b

c. Landing Distance versus Aircraft Landing Mass/Weight
- Assume ISA standard conditions / parameter values (Table 1)
- Mass/weight (W_L) range: 260,000 kg to 330,000 kg, in steps of 10,000 kg
- Use the landing distance equations (Equations 1-4); see Figure 4 (which doesn't include terms that are constant through the process and don't need to be calculate)
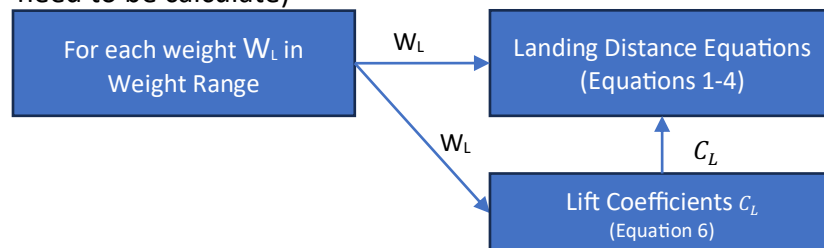

Figure 4. Components supporting Q4c

5. Create a series of similar plots as Q4, this time using the climate model projections from Q3, for the years (a) 2050, (b) 2075 and (c) 2099, and the two locations of interest:

Guantanamo Bay, Cuba, and La Paz, Bolivia. If there is uncertainty in climate forecasts, please take that into account and incorporate that into your results.

    a. Landing Distance versus Altitude
- Altitude Range: Sea Level to 11 km, in steps of 2 km
- For temperature T, use the climate model temperature output for applicable year and location
- Use the barometric pressure equation (Equation 8), ideal gas law (Equation 5), and landing distance equations (Equations 1-4)
- You should produce 6 plots for this question

    b. Landing Distance versus Aircraft Landing Mass/Weight
- Mass/weight (W_L) range: 260,000 kg to 330,000 kg, in steps of 10,000 kg
- Assume ISA standard conditions / parameter values (Table 1), except for temperature T, where you should use the climate model temperature output for applicable year and location
- You should produce 6 plots for this question

6. Explain which factors affect landing distance the most and provide evidence for this answer.

Hypothetical Real-World Use-Case (Q7-Q10)

Imagine a scenario where the 10th Mountain Division from Fort Drum, NY has committed to deploying 240 troops and 400 Short Tons of equipment to the mountains in western Bolivia, to support the Bolivian government needs in responding to a contested mine collapse near Mauri. Due to other demands for airlift, USTRANSCOM can currently only provide either two C-5s, two C-17s, or ten C-130J aircraft for airlift to South America. The aircraft deployment performance data can be found in Table 3. Initially, troops and equipment will be staged at Guantanamo Bay, Cuba, the starting location. The distance from Guantanamo Bay to the region of Bolivia with the collapsed mine, is 2500 nautical miles.

Three airports are available for the US Military to use to access the region. The first is a small temporary airfield that has been cleared by the Bolivian government, nearby to the response zone, to enable direct access to the site for small planes. The second airport is in the nearby town of Charaña (approximately 12 km south of the destination site). The third is the primary international airport in the Bolivia capital city of La Paz, located approximately 230 km to the northeast of the Mauri collapsed mine site. Table 4 lists the alternative runway details. Upon landing in the region, troops are required to transport their equipment via local roads to the response site. See Figure 5 for map of scenario context.
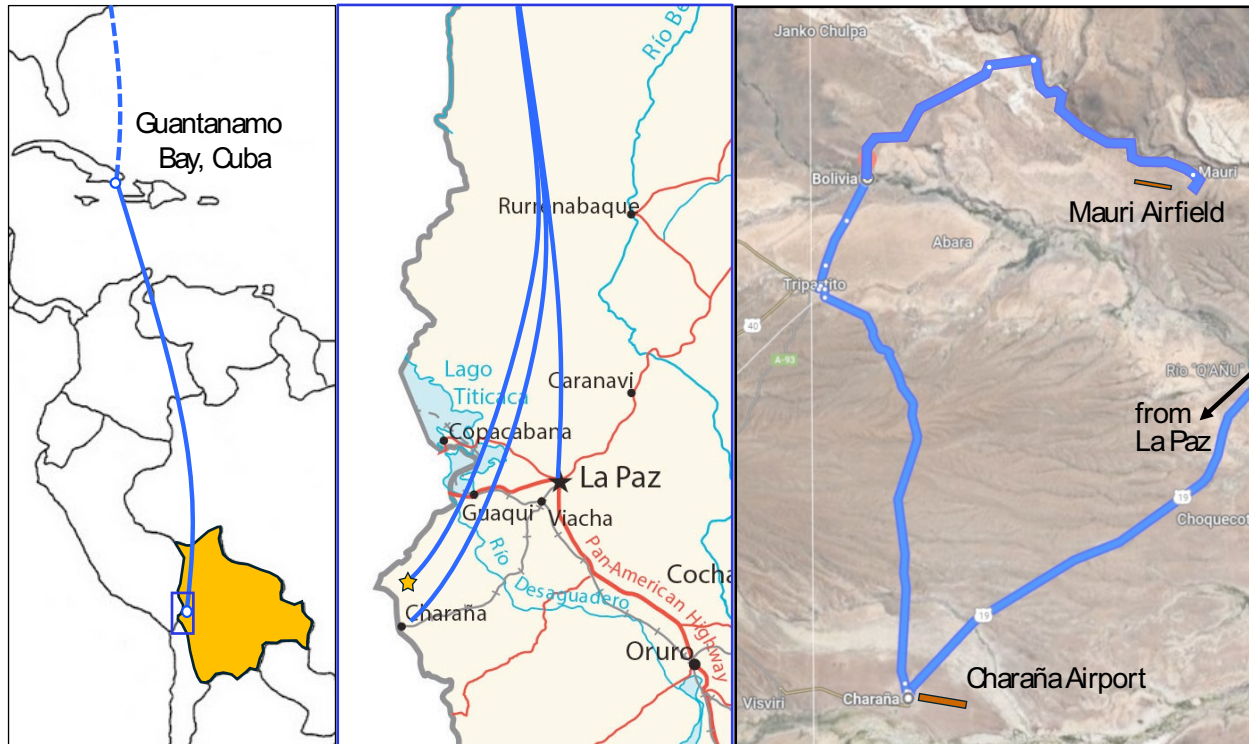
Figure 5. Example Scenario Geographical Details

You are supporting a DoD decisionmaker who is trying to determine the following:
- Which aircraft types can land at which airfields?
- For each aircraft type and landing site combination, what is the minimum amount of time needed to deliver the required cargo and personnel? Since the total amount of personnel and equipment exceeds the capacity of a single plane load, the timeline will resemble something like that shown in Figure 6.
- Whether the answers to the above could change in the future due to the impacts of climate change; if this is the case, there are big implications for DoD planners as they think about how their equipment needs and logistics will change due to a changing climate, in the coming decades.
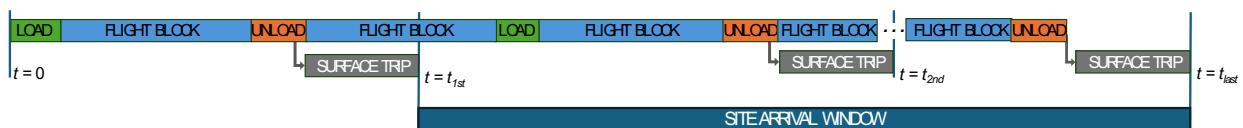

Figure 6. Block timeline of deployment

7. Use the performance characteristics of the three aircraft, the max landing weight from Table 2, and parameters specified in Table 3 and Table 4, for the following questions:
    a. What is the landing distance required by each of the aircraft types?
    b. For each aircraft type, which airfields would allow it to operate into and out of?

See Figure 7 for components needed to answer this question. Assume that the temperature reflects current-day conditions; in Q10 you will redo this with future temperature conditions as forecasted by climate models.
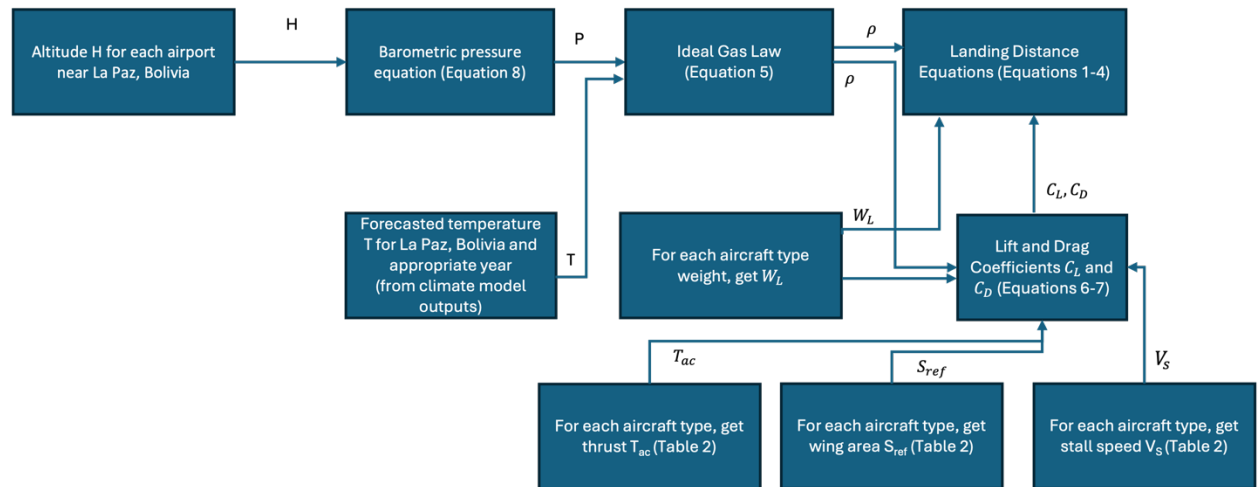

Figure 7. Components needed to support Q7

8. For each of the aircraft types, how many sorties are required? A sortie is defined as loading the aircraft at the origin, flying to the destination airport, unloading, and returning to the origin. Repeated trips are illustrated in Figure 6. For each aircraft, consider passenger flights independently from cargo flights and assume that the total weight of passengers does not exceed the maximum weight capacity of the aircraft. In other words, some flights carry only passengers, and some flights carry only cargo. Also assume that each airfield can accommodate multiple aircraft landing at/around the same time.

9. For each aircraft type, what is the site arrival window (defined as the time that the first deployment arrives at the site, until the last deployment arrives at the site, see Figure 6)? What are the factors that influence this window? Assume that a sufficient mix of passengers and equipment will arrive together to make the surface movements once landed.

10. We would like to understand the impact that the climate will have on the deployment described in this scenario, were it to take place in the future.
    a. Take the forecasted temperatures from Q3 and recalculate the answers for Q7 to Q9, for the years (a) 2050, (b) 2075 and (c) 2099. If there is uncertainty in climate forecasts, please take that into account and incorporate that into your results.
    b. Do the answers change, and if so, in what ways, and what are the implications?

Equations and Tables
(All units are indicated in brackets [ ])

Equation 1. Landing Distance Equation

$$S_L = S_A + S_{FR} + S_B$$	S_L = landing distance [m] S_A = air distance [m] (- Equation 2) S_{FR} = free roll distance [m] (Equation 3) S_B = braking distance [m] (Equation 4)

Equation 2. Air Distance portion of Landing Distance Equation (Equation 1)

$$S_A \approx \frac{W_L}{C_D \frac{1}{2}\rho(1.3V_S)^2 S_{ref}}\left[\frac{(1.3V_S)^2 - (1.15V_S)^2}{2g} + 15[\text{m}]\right]$$	S_A = air distance [m] W_L = landing weight [kg]; as a default use Boeing 747-8F landing weight (330,000 kg) C_D = drag coefficient on approach [dimensionless] ρ = air density [kg/m³] S_{ref} = wing reference area [m²]; as a default use value for Boeing 747-8F (511 m²) g = acceleration due to gravity = 9.80665 [m/sec²] V_S = stall velocity [m/s]; as a default use the value for Boeing 747-8F (101 mph). The "constant" that multiplies the stall velocity is a time factor [units of sec].

Equation 3. Free Roll Distance portion of the Landing Distance Equation (Equation 1)

$$S_{FR} = 3V_{TD} \approx 3.45V_S$$	S_{FR} = free roll distance [m] V_{TD} = speed at touchdown during landing ($\approx 1.15V_S$). The "constant" that multiplies the velocity is a time factor [units of sec]. The "3" is 3sec is based on the time a pilot let's the aircraft free roll before applying the brakes. V_S = stall velocity [m/s]; as a default use the value for Boeing 747-8F (101 mph)

Equation 4. Braking Distance portion of the Landing Distance equation (Equation 1)

$$S_B = \frac{W_L}{g\mu\rho S_{ref}\left[\frac{C_D}{\mu} - C_L\right]}\ln\left[1 + \frac{\rho}{2}\frac{S_{ref}}{W_L}\left(\frac{C_D}{\mu} - C_L\right)(1.15V_S)^2\right]$$	S_B = braking distance [m] S_{ref} = wing reference area [m²]; as a default use the value for Boeing 747-8F (511 m²) W_L = landing weight [kg]; as a default use the value for Boeing 747-8F (330,000 kg) ρ = air density [kg/m³] μ = braking friction coefficient = 0.32 [dimensionless]

	- g = gravitational acceleration = 9.80665 [m/sec^2] - V_S = stall velocity [m/s]; as a default use the value for Boeing 747-8F (101 mph) - C_D = drag coefficient ground from Equation 7 [dimensionless] - C_L = ground lift coefficient from Equation 6 [dimensionless]

Equation 5. Ideal Gas Law

$PV = nRT$ (*expressed classically*) $PM = \rho RT$ (*expressed with density*)	- P = pressure [Pa] - V = volume [m³] - n = number of moles of gas (can be considered "mass") - R = universal gas constant = 8.31432 $\left[\frac{N*m}{mol*K}\right]$ - T = temperature [K] - M = molar mass of Earth's air = 0.0289 [kg/mol] - ρ = gas density [kg/m³] - Note: $\rho \propto \frac{1}{T}$ (density is inversely proportional to temperature)

Equation 6. Lift Coefficient

For Braking Distance (S$_B$) use: $$C_L = \frac{2W_L}{\rho(1.15V_S)^2 S_{ref}}$$	- ρ = air density [kg/m³] - S_{ref} = wing reference area [m²]; as a default use the value for Boeing 747-8F (511 m²) - W_L = landing weight [kg]; as a default use the value for Boeing 747-8 (weight = 330,000 kg) - V_S = stall velocity (m/s); as a default use the value for Boeing 747-8F (101 mph)

Equation 7. Drag Coefficient

$$C_D = \frac{2T_{ac}}{\rho(1.3V_S)^2 S_{ref}}$$	- ρ = air density [kg/m³] - S_{ref} = wing reference area [m²]; use the value for Boeing 747-8F (511 m²) - T_{ac} = aircraft thrust [N]. Since <u>landing</u> is being considered in this scenario, the aircraft thrust will be small in comparison to thrust needed for cruise speed at altitude. As a default, use the value for the Boeing 747-8F (13,000 lbf = 59,185 Newtons) - V_S = stall velocity [m/s]; as a default use the value for Boeing 747-8F (101 mph)

Equation 8. Barometric Law, explicit form

This equation is applicable for altitudes from Sea Level to top of Troposphere (tropopause). Calculate air pressure at a given altitude (pressure and temperature at sea level must be known): $$P = P_b \left[1 + \frac{L_b}{T_b}(H - H_b) \right]^{-\frac{gM}{RL_b}}$$ Calculate altitude at a given air pressure (pressure and temperature at sea level must be known): $$H = H_b + \frac{T_b}{L_b} \left[\left(\frac{P}{P_b}\right)^{-\frac{RL_b}{gM}} - 1 \right]$$	• P_b = reference pressure (pressure at sea level) [Pa] • T_b = reference temperature (temperature at sea level) [K] • L_b = temperature lapse rate [K/m] = -0.0065 [K/m] • H = height at which pressure is calculated [m]; this equation is only valid for H up to 11 km • H_b = height at the bottom of the atmospheric layer (11 km, or 36,090 ft) • R = universal gas constant = 8.31432 $\left[\frac{N*m}{mol*K}\right]$ • g = gravitational acceleration = 9.80665 [m/sec^2] • M = molar mass Earth's air = 0.0289 [kg/mol]

Table 1. ISA Standards (ICAO Standard Atmosphere)

Pressure (P)	101,325 [Pa] (Absolute Pressure; Pascal = $\frac{kg}{m \cdot s^2}$)
Altitude (H)	0 [m] (at sea level)
Temperature (T)	288 [°K] (degrees Kelvin)
Air Density (ρ)	1.225 [kg/m^3]

Table 2. Exemplar Aircraft Specification Values

Aircraft	Empty Wt (lb)	Max takeoff Wt (lb)	Max landing Wt (lb)	Max payload (lb)	Wing Area (wing loading, m²)	Per Engine Thrust (lbf)	Max Cruise Speed (mph)	Stall speed (mph)
747-8F	485,000	975,000	761,000	292,400	510.97	66,500 (jet engine)	570	101
C-130J	85,000	175,000	130,000	44,000	162.12	10,200 (turboprop)	400	115
C-17	279,000	585,000	500,000	170,900	353	40,440 (jet engine)	518	104
C-5	400,000	840,000	636,000	263,000	5761	41,100	606	141

Table 3. Aircraft deployment performance data

	Availability	Max Capacity (Short Tons at 2500nm)	Block Speed (kts)	Passenger Capacity (# of people)	Load/Unload Times (hr)	Plane Landing Distance (ft)*
C-130J	10	15	314	124	0.5	3000
C-17	2	80	406	101	1	3500
C-5	2	130	416	73	1.1	6000

* Notional planning distances (at MSL and STP) for reference and should not be used for computations here.

Table 4. Alternative runway details

Available Airfields:	Response Site	Charaña	La Paz
Usable Length (ft)	3100	3600	10007
Altitude (m)	4308	4057	4061
Access to Site (min)	2	98	342

Scenario 1 Summary Table

Question	Inputs	Tasks	Outputs
Q1	Scenario details for locations, and required output variable (T)	Search for historical and climate model output data that includes T	Relevant climate dataset(s)
Q2	Target locations	Run downscaling algorithms and processes	Downscaled climate dataset(s)
Q3	• Locations • Years	Calculate and plot monthly mean daily maximum	Plot of monthly mean of daily maximum temperature for 5 time periods and two locations
Q4	• Table 1 • Equations	Calculate landing distance versus temperature, altitude, and aircraft landing mass/weight	3 plots: landing distance versus (1) temperature, (2) altitude, and (3) aircraft landing mass
Q5	• Temperature data from Q3 • Equations	Calculate landing distance versus altitude and aircraft landing mass/weight for two locations and three different years	• 6 plots for landing distance versus altitude (3 different years, 2 locations) • 6 plots for landing distance versus aircraft landing mass/weight (3 time periods, 2 locations)
Q6	Answers to Q4-5	Explain what affects landing distance the most	Explanation with evidence
Q7	• Equations • Tables 2-4 • Temperature data from Q3	• Calculate landing distance for each aircraft • Determine which aircrafts can land where	Table with each aircraft's required landing distance and where they can land

Q8	• Answer to Q7 • Aircraft performance (Table 3) • Figure 6	Calculate number of sorties for each aircraft	Number of sorties required for each aircraft
Q9	• Answer to Q8 • Aircraft performance (Table 3) • Figure 6	Calculate site arrival window	Length of site arrival window for each aircraft
Q10	Answers to Q3, Q7-9	For each aircraft and year: • Re-calculate landing distance using the forecasted temperature and id where it can land • Re-calculate the number of sorties required • Re-calculate the length of arrival window	For each aircraft and year: • Landing distance and where it can land • Number of sorties required • Arrival window

Decisionmaker Panel Questions

1. What is your confidence that the modeling team found and selected an appropriate starting point (data or models, etc.) for the scenario/problem? Select score on a 7-point scale.

1. Very Low
2. Low
3. Somewhat Low
4. Neutral
5. Somewhat High
6. High
7. Very High

The decisionmaker confidence score should be supported by the answers to the following questions:

- Is the climate model output or data chosen for the scenario appropriate/fit-for-purpose for the given problem, in terms of locations, spatial scale, and time periods of interest?
- Did modelers assess climate data source quality?
- Was climate data processed in an appropriate way, to support the temporal and spatial aspects of the scenario questions?
- If there was uncertainty present in input data sources, did the modelers incorporate this into their process and downstream results in a sensible way?
- Is it clear how to interpret uncertainty in the results? Do you understand the key drivers of uncertainty in the results?

2. What is your confidence in understanding scenario results? Select score on a 7-point scale.
    1. Very Low
    2. Low
    3. Somewhat Low
    4. Neutral
    5. Somewhat High
    6. High
    7. Very High

The decisionmaker confidence score should be supported by the answers to the following questions:

- Are you confident that the modelers approached the scenario in a reasonable and logical way?
- Are you confident in making decisions as indicated in the scenario, based on their results?
- Is it clear how to interpret uncertainty in the results? Do you understand the key drivers of uncertainty in the results?
- How confident are you that the analysis correctly identified and attributed responsibility to key factors?

Scenario 2: Ice and Ocean Modeling
Estimated % of time: 40%

This scenario involves multiphysics modeling and simulation, with ice and ocean models.

1. Refer to Section 8.1.1 on the Halfar Dome, in the Community Ice Sheet Model (CISM) documentation. See the relevant equations to model a dome of ice analytically (Equations 8.1-8.4). Further reading can be found at Halfar 1984 and in Buehler's notes (provided as a file in the S2 Supplementary folder). For baseline modelers, code of the Halfar model is provided, and for workbench modelers, the Halfar model is already part of the ASKEM system. Please list out the equations that this model is comprised of, and define all the variables and parameters, with units. Also list default initial and boundary conditions, and parameter values, and anything else required to configure and execute the model.

2. As a unit test, recreate the following plot using the initial conditions and parameters provided in the CISM documentation:
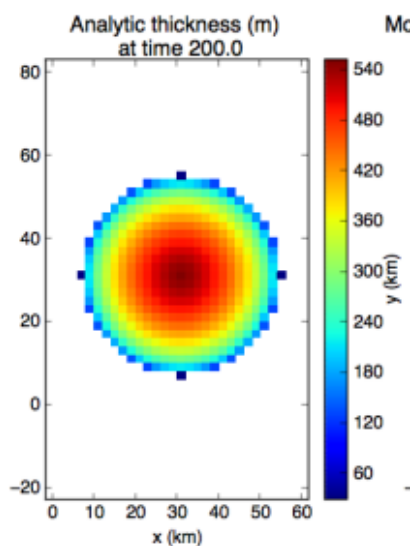

3. We would like to represent Greenland with the Halfar ice model. Create a mesh (for the workbench evaluation) or create an appropriate discretized grid (for the baseliners) and transform the data as needed to be used with the Halfar model. Set initial conditions and boundary conditions using ice thickness data for Greenland, from the year 2019. Make any assumptions about the boundary and initial conditions that you believe are reasonable.

4. Now simulate the evolution of Greenland using the Halfar model, starting from 2019. What will Greenland look like after 20 and 50 years? Plot Greenland's ice loss over the mesh or grid, as a function of time.
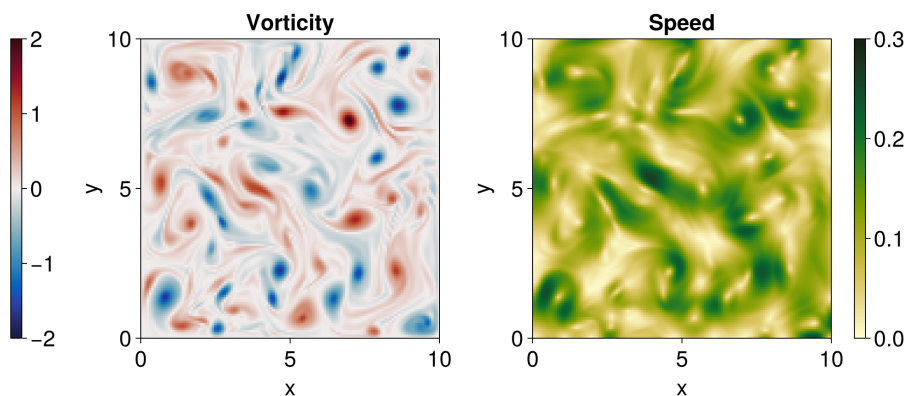
5. Next, use the Oceananigans nonhydrostatic model, which solves the incompressible Navier-Stokes equations under the Boussinesq approximation. The Boussinesq approximation assumes that density is constant except in terms multiplied by gravity. To ensure the model was built/loaded correctly, reproduce a variation of the 2D turbulence example found here, with the following configuration:

    - 128x128 size rectangular grid, in arbitrary units of length, over a 10x10 extent
    - Neumann boundary conditions (0 flux) for the edges of the ocean, in the *x* and *y* directions
    - Random initial velocities at each grid point, with zero mean velocity
    - Scalar diffusivity $\nu = 1e - 5 \left[\frac{unit\ of\ length^2}{units\ of\ time}\right]$
    - The outputs are time-varying simulations of vorticity and speed (which are calculated from velocity)
    - Your outputs should look similar to the following plots (snapshots from early in the simulation, and later in the simulation)

t = 10.0
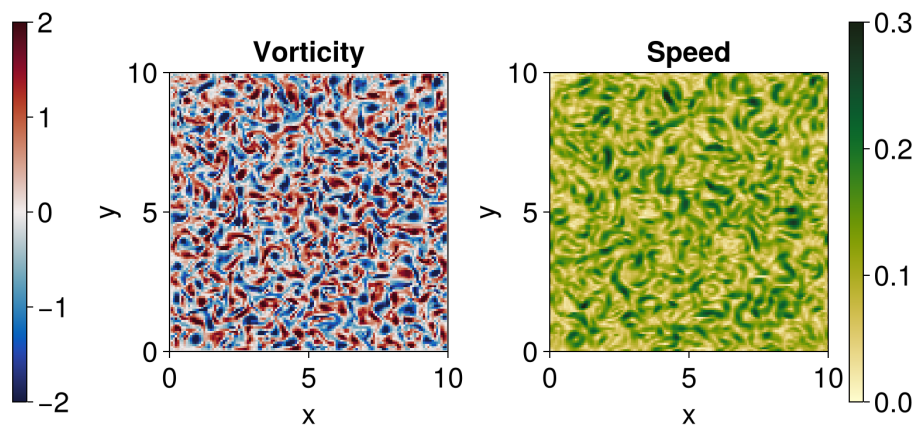
t = 100.0

For baseline modelers, this question involves installing and running Oceananigans. For workbench modelers, this requires running the version of the Oceananigans nonhydrostatic model in the ASKEM system.

6. We would like to simulate a hypothetical world where Greenland is the only piece of land, surrounded by an 2D rectangular planet ocean. Extend the grid size as needed to ensure the ocean is quite a bit larger than Greenland, and set initial and boundary conditions similar to the example in Q5. Make reasonable assumptions for parameter values. As with previous questions, we represent Greenland with the Halfar ice model, and we represent the ocean with the Oceananigans nonhydrostatic model. To represent the hypothetical world, we need to couple the Halfar and nonhydrostatic ocean models together. Assume that the water does not flow where there is ice (i.e. treat ice as an obstruction, and water doesn't flow under it) and we are using no-slip boundary conditions between the ocean and ice (water velocity field at the water-ice interface is 0). Repeat Questions 3-4, simulating the coupled model. How does the ice evolution of Greenland in this coupled model compare to the result from Questions 3-4? If you run into challenges with simulating a stiff system, you may make adjustments to your model configuration and simulation parameters, as needed.

7. Now couple the Halfar and the nonhydrostatic ocean model in a different way. This time, treat the ice dome as existing on top of the water, so flow is not obstructed. The rest of the boundary and initial conditions should be the same as Q6. Now add an exogenous thermal source term to the Halfar ice model, to represent exogenous ice melting. Repeat Questions 3-4 with this coupled model. How does the ice evolution of Greenland in this coupled model compare to the result from Questions 3-4?

8. [Mohamed et. al. 2016](#) lays out an exterior calculus form of the incompressible Navier-Stokes solution. Create a solution to the incompressible Navier Stokes equations as represented in Equations 1a and 1b (from the paper), in two dimensions. For baseline modelers, you can begin with the 2D solution of the incompressible Navier Stokes equations as described here (https://nbviewer.org/github/barbagroup/CFDPython/blob/master/lessons/14_Step_11.ipynb) or with any other approach you're familiar with. Workbench modelers should begin with Mohamed et. al.'s Navier Stokes model already represented in the ASKEM system. Configure the model to recreate the same unit test as in Q5, setting initial and boundary conditions appropriate to the unit test definition. How do your results compare against the Oceananigans nonhydrostatic ocean model in Q5?

9. Couple the Halfar ice model to the ocean model represented by the incompressible Navier Stokes model from Question 8, and once again repeat Questions 3-4 with the coupled system. How does the ice evolution of Greenland in this coupled model compare to the result from Questions 3-4?

Scenario 2 Summary Table

Question	Inputs	Tasks	Outputs
Q1	• Code or workbench representation of model • Documentation	Familiarize yourself with Halfar model, and list out its mathematical representation with metadata	Time to familiarize yourself with model
Q2	• Code or workbench representation of model • Parameter and initial values from documentation	Configure Halfar model and execute unit test	• Output plot • Time for model configuration and execution
Q3, Q5, Q8	• Equations • Paper/code	• Create model • Create mesh/grid • Configure model with initial conditions (ICs) and boundary conditions (BCs) • Execute unit tests	• Configured models • Outputs of unit tests • Time to create a mesh from data/set appropriate grid • Time to create and configure model (w/ ICs/BCs) to run unit tests • Total time to pass unit tests (including any iteration)
Q4, Q6, Q7, Q9	• Model(s) • Parameter values • ICs • BCs • Greenland data/mesh • Relevant mesh/grid for ocean components	Model Greenland in individual or coupled multiphysics system, 20 and 50 years after 2019 • Compare to previous version of the same question	• Greenland ice thickness over time • Time to link data to model • Time to do model coupling • Time for model execution/simulation • Time for comparison to previous question outputs

Decisionmaker Panel Questions

1. What is your confidence that the modeling team developed an appropriate set of models to sufficiently address the scenario/problem? Select score on a 7-point scale.
    1. Very Low
    2. Low
    3. Somewhat Low
    4. Neutral
    5. Somewhat High
    6. High
    7. Very High

    Explanation: The scenario involves updating, extending, or modifying a model, and decisionmakers will evaluate whether this was done in a sensible way.

    The decisionmaker confidence score should be supported by the answers to the following questions:

    *   How confident are you that individual models (for ice and ocean components) were correctly implemented and simulated?
    *   Were initial and boundary conditions chosen and implemented appropriately for the scenario questions being asked?
    *   Did the approach to multiphysics model coupling seem reasonable to you? Do you trust that it was done correctly?
    *   Are you confident that coupling was done in a way that makes physical sense?

2. What is your confidence in understanding model results? Select score on a 7-point scale.
    1. Very Low
    2. Low
    3. Somewhat Low
    4. Neutral
    5. Somewhat High
    6. High
    7. **Very High**

    This score should be supported by the answers to the following questions:
    *   Did simulation results make sense? If results did not match your intuition or expectations, did modelers explain the reason(s)? Did their explanations make sense?

Scenario 3: FUND Integrated Assessment Model
Estimated % of time: 20%

The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) is an Integrated Assessment Model (IAM), which represents climate dynamics with a simplified climate model, and also couples the climate equations with various other modules, to represent a framework that can incorporate societal-level policy interventions and simulate the impacts on the climate system, as well as the climate system's impact on various domains, such as agriculture, human health, and more. Publications, documentation, and code for the FUND model are available at https://www.fund-model.org/. FUND is one of the IAMs implemented in the Mimi Framework.

For this scenario, imagine that you are supporting a decisionmaker who has asked you to become familiar with the FUND model, provide explanations about key elements of the model, and explore various questions related to the impact of policy interventions on global temperature changes.

1. Get access to the FUND model, either by installing it in a local environment, or getting access to the instantiation in the workbench.
2. First, using the documentation, code repositories, and the installed model itself, inspect the *climate* and *emissions* modules. List out the set of equations in each module, and define each variable and parameter, including units and default parameter values.
3. Create a model flow diagram to explain how the emissions and climate modules are interdependent. Using your diagram, explain how the climate dynamics depend on emissions, and where policy interventions fit into the picture.
4. Using only the default parameter values, run the FUND model through at least the year 2200, and plot the results for the following variables:
   - Emissions and atmospheric concentration for the major greenhouse gases (GHGs) included in the FUND model (CO_2, CH_4, N_2O, SF_6). For emissions, show the global results as well as emissions for each region. Export the emissions data for use in Q6. What are the top 5 CO_2-emitting regions for the current year, and is this projected to change over time?
   - Global temperature increase over time
   - Reduction in GHGs due to tax policies (e.g. carbon tax)
   - Mitigation costs for reducing GHGs, for each region
5. In Q4, you should have found that there was no reduction in GHGs, because the default configuration of the model had no explicit tax policies in place.
   a) Now implement a carbon tax of \$15/tC (tC = ton of carbon) for parameter $\tau_{t,r}$ (see Equation CO2.6), only for the region currently emitting the greatest amount of CO_2, and rerun the model. Note that this tax only plays a role in CO_2 reduction.

b) What is the impact of this region-specific policy on regional and global CO_2 emissions, compared to Q4? Include plots.

c) What are the mitigation costs for reducing GHGs, with the policy in Q5a in place? Compare with Q4.

d) Now implement a carbon tax that's applied more broadly: For each year, apply a $15/tC tax for the top 5 emitters of CO_2-emitting regions that year (as identified in the baseline forecast from Q4). Rerun the model.

e) What is the impact of the policy specified in Q5d, on regional and global CO_2 emissions? Compare with the baseline output (where no tax was in place) from Q4.

6. The decisionmaker you're supporting, asks you to optimize the carbon tax policy from Q5d. Still apply this tax to the top 5 emitters of CO_2 each year, but now we will optimize the tax amount. Assume that the tax amount doesn't change over time, but only the regions it applies to for a given year. With the goal of ensuring global temperature increase does not surpass 3°C over the course of the 21st century (2000-2100), what is the minimum carbon tax that should be implemented? Run model with optimized value and include a temperature forecast plot to demonstrate your final answer meets the goal.

7. To better understand the climate aspects of the FUND model, you focus your analysis on that module by itself.

a) Extract the equations from the climate module (either from the documentation or code, or both together), and implement them as a separate model outside of the MimiFUND framework; this way you can more easily modify the model and do exploratory work, independently from the rest of the FUND framework. You can find the climate module equations in Section 4 of the documentation (Equations C.1-C.5). Please note that there is an error in Equation C.2b – there should not be any α_i term in this equation.

b) Run the climate model separately, using GHG emissions from the default configuration of FUND. You can treat these emissions as exogenous inputs into the climate equations. For other parameter values in the climate equations, use the defaults values provided in the documentation. Do the GHG atmospheric concentrations and global temperature increase results, match what you found in Q4? So you can be confident that your implementation of the climate module is correct, iterate on your implementation until your results for atmospheric concentrations and global temperature increase, match the results of Q4.

c) You notice that the climate model includes several parameters, and you wonder how sensitive the model is to the various parameters, especially those that have uncertainty associated with them. Do a sensitivity analysis to determine how sensitive the radiative forcing (RF) and temperature increase T, are to the following parameters: CS (climate sensitivity), α, β, and ρ for each GHG, and for the individual boxes in the box model. While all these parameters have default

values in the documentation, only some also have uncertainty information reported. For those parameters that don't have uncertainty information, you can make reasonable assumptions about how much to vary them. What are the implications of your sensitivity analysis results?

Scenario 3 Summary Table

Question	Inputs	Tasks	Outputs
Q1	• Code • Documentation • Workbench instantiation of model	Install FUND or get access to workbench version	Time to install model/get access
Q2	• Code • Documentation • Model	Familiarize yourself with the climate and emissions modules, and list out their mathematical representations, with metadata	• List of equations with all variables and parameters defined, with units, and default configuration (parameter values and initial conditions) • Time to familiarize yourself with model
Q3	• Code • Documentation • Model	Create model flow diagram	• Model flow diagram • Time to create diagram • Explanation of how climate and emission modules are interconnected, and where policies fit in
Q4	Model	• Run model with default configuration • Plot select variables	• Time to run model and get plots • Plots for indicated variables
Q5	Model	• Implement interventions • Plot outcomes (emissions and mitigation costs) and compare with Q4	• Time to implement interventions and plot results • Plots for emissions and mitigation costs, with the various interventions in place
Q6	Model	• Optimize carbon tax parameter • Run model with optimized parameter value	• Time to optimize parameter • Time to run model • Minimum carbon tax value • Temperature plot

Q7	• Code • Documentation	• Extract equations and implement model • Iterate on your implementation and execute model until results match Q4 • Sensitivity analysis	• Time to do model extraction • Time to iterate on implementation • Sensitivity analysis results for each of the indicated parameters

Decisionmaker Panel Questions

1. What is your confidence in understanding model results, and tradeoffs between potential interventions? Select score on a 7-point scale.
   1. Very Low
   2. Low
   3. Somewhat Low
   4. Neutral
   5. Somewhat High
   6. High
   7. Very High

Explanation: Determine your confidence in being able to assess effectiveness of all interventions considered in the scenario and understand how uncertainty factors into results.

The decision-maker confidence score should be supported by the answers to the following questions:

- Do you understand the effects of interventions on trajectories? Was the effectiveness of interventions communicated?
- Is it clear how to interpret uncertainty in the results? Do you understand the key drivers of uncertainty in the results?
- Did models help you to understand what would have happened had a different course of action been taken? How confident are you that the modelers correctly explained what would have happened had a different course of action been taken in the past, or what will happen in the future if a different course of action is taken?
- How confident are you that the analysis correctly identified and attributed responsibility to causal drivers in the model? Did modelers explain the causal pathways represented in the model?

Scenario 4: Photosynthesis Model *

Estimated % of time: 10%

This scenario will not be part of the Decision-maker Panel.

This scenario revolves around Salvatori et al. 2022's model of photosynthesis.

1. Extract the photosynthesis model from the paper (Equations 1-6, along with the unnumbered equations in the Materials and Methods section describing the observables from the experimental setup).
2. Extract the parameters and parameter values from Table 1 in the paper. Make sure to keep track of both sets of parameter values (Eiko and MinnGold). Note that there may be a *parameter* or two that are missing from this table.
3. Simulate a constant light source by setting PAR equal to 650 µmol $m^{-2}s^{-1}$. Plot ETR and A (save NPQ for Q4) over a period of 60 minutes. Do this for both parameter sets and compare the outputs to Figure 5 (top plots) for the Eiko parameter set, and Figure 6 (top plots) for the MinnGold parameter set. What are the differences between your model outputs and the paper figures?
4. Now try to recreate the plots of NPQ from Figure 5 (in the top plots) and Figure 6 (in the top plots) using both parameter sets. If this is not possible, what is missing from the model or parameters you extracted? If there is required information that is missing, perform a literature search to see if the necessary values are able to be determined.
5. Next, simulate a varying light source by setting PAR equal to 780 µmol $m^{-2}s^{-1}$ and then 520 µmol $m^{-2}s^{-1}$, switching every minute. Plot ETR, A, (and NPQ if possible) over a period of 60 minutes. Do this for both parameter sets and compare the outputs to Figure 3 (top three plots) for Eiko parameters and Figure 4 (top three plots) for MinnGold parameters. What are the differences between your model outputs and the paper figures?
6. Change the light fluctuation frequency, increasing it and decreasing it. How do A, ETR, and NPQ change with light frequency?

Scenario 4 Summary Table

Question	Inputs	Tasks	Outputs
Q1, Q2, Q3	• Publication • Equation numbers • Parameter table	• Extract equations • Extract parameter values • Iterate/curate extraction and execute model until model output is correct according to paper Figures 5 and 6 for ETR and A	• Extracted model grounded with all variables and parameters defined and with units • Extracted parameter values • Simulation plots comparable to Figures 5 and 6 • Time to do model extraction • Time to do parameter extraction • Time to execute extracted model • Time to plot results

Q4	• Publication • Equation numbers • Parameter table	Extract and simulate equation for NPQ • Perform literature search for missing parameters (if needed) • Execute model if possible until correctly matching Figures 5 and 6	• Simulation plots comparable to Figures 5 and 6 for NPQ • Time for literature search • Time to execute extracted model and plot results
Q5	• Paper • Equation numbers • Parameter table	Iterate/curate extraction and execute model until model output is correct according to paper Figures 3 and 4 for ETR and A (and NPQ if possible) by varying PAR in time	• Simulation plots comparable to Figures 3 and 4 • Time to modify PAR to be piecewise • Time to execute model and plot results
Q6	• Paper • Equation numbers • Parameter table	• Change the PAR parameter frequency • Create plots showing the effect of frequency on ETR, A, and NPQ if possible	• Simulation plots showing the effect of frequency • Time to modify PAR's frequency • Time to execute model and plot results