Q1) We notice the planet loses about $5 \times 10^5\ km^2$ of ice area for each 1 K change in surface temperature. Further, the change in radiative forcing per square kilometre of arctic ice ΔR/Δ(ice area) is $-10^{-6} Wm^{-2}/km^2$. Use this information to calculate the strength of the ice-albedo feedback f_{ice}. Choose the closest answer.

A) 0.2 $\mathrm{Wm}^{-2}K^{-1}$
B) 0.5 $\mathrm{Wm}^{-2}K^{-1}$
C) 0.75 $\mathrm{Wm}^{-2}K^{-1}$
D) 2 $\mathrm{Wm}^{-2}K^{-1}$
E) 5 $\mathrm{Wm}^{-2}K^{-1}$

Q1 answer B)

$$f_{ice} = \left(\frac{\Delta R}{\Delta \text{climate}}\right)\left(\frac{\Delta \text{ climate}}{\Delta T}\right)$$

```
-5.0e5 * (-1.0e-6)  # B
```

```
0.5
```

Q2) Suppose a climate scientist establishes that her group's model has a total climate sensitivity of λ=0.65 K/(Wm^{-2}). She then makes a change to the cloud routine that increases the strength of the cloud feedback from +0.5 $\mathrm{Wm}^{-2}K^{-1}$ to +0.75 $\mathrm{Wm}^{-2}K^{-1}$. What is the new total feedback of the model?

A) 0.90 $\mathrm{Wm}^{-2}K^{-1}$
B) -0.90 $\mathrm{Wm}^{-2}K^{-1}$
C) 1.29 $\mathrm{Wm}^{-2}K^{-1}$
D) -1.29 $\mathrm{Wm}^{-2}K^{-1}$
E) 1.79 $\mathrm{Wm}^{-2}K^{-1}$

```
f = -1 / 0.65
f_new = f + 0.25
lambda_new = 1 / f_new
print(lambda_new, f_new)  # D
```

```
-0.7761194029850748 -1.2884615384615383
```

Q3) How long does it take for a constant forcing of 3 $W\,m^{-2}$ to warm a 150 m thick ocean layer by 0.75 K? (A year has 31,536,000 seconds)

A) 5 years
B) 7.5 years
C) 10 years
D) 15 years
E) 25 years

```
D = 150
cw = 4186
rhow = 1000.0
delTemp = 0.75
delF = 3
delt = rhow * D * cw * delTemp / delF
sec2years = 1 / (31536000)
print(delt * sec2years)  # A
```

```
4.977644596651446
```

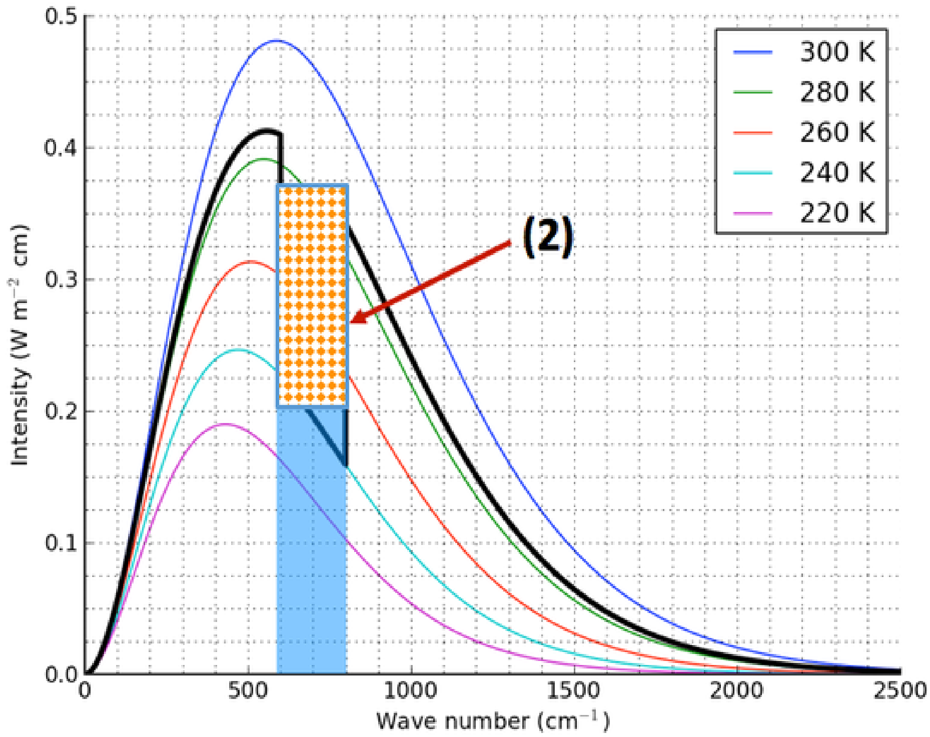
Q4) Imagine we end up burning the rest of the available coal (2800 Gton carbon) **and** the oil and natural gas (200 Gton carbon), but we don't burn any other fossil carbon. What will the atmospheric concentration of CO_2 be when we're finished? Assume we burn everything instantaneously, that all of the emitted carbon stays in the atmosphere, and that today's atmospheric CO_2 concentration is 400 ppm.

A) about 580 ppm
B) about 640 ppm
C) about 1050 ppm
D) about 1200 ppm
E) about 1830 ppm

```
3000 / 2.1  # E
```

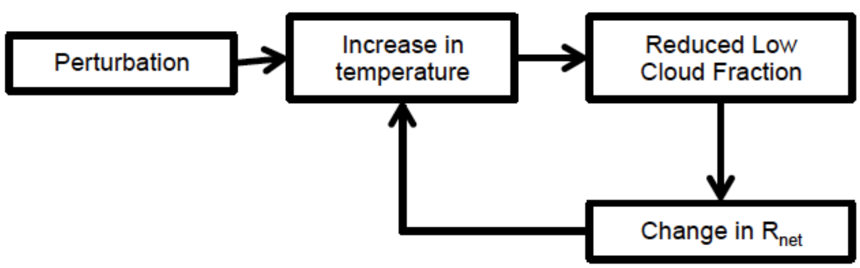
```
1428.5714285714284
```

Q5) For the figure below, pick the most accurate description of the rectangular region labeled (2). Assume the instrument is looking down from the top of this atmosphere



A) The radiation emitted by the gas that reaches the top of the atmosphere
B) The radiation absorbed by the gas
C) The greenhouse effect from the gas in this wavenumber range
D) The surface radiation absorbed by the gas
E) The radiation emitted by the gas that reaches the surface

Q6) For this feedback loop:



Choose the best characterization, keeping in mind that feedbacks work in both directions. (R_{net} is the net downward radiation at the top of the atmosphere)

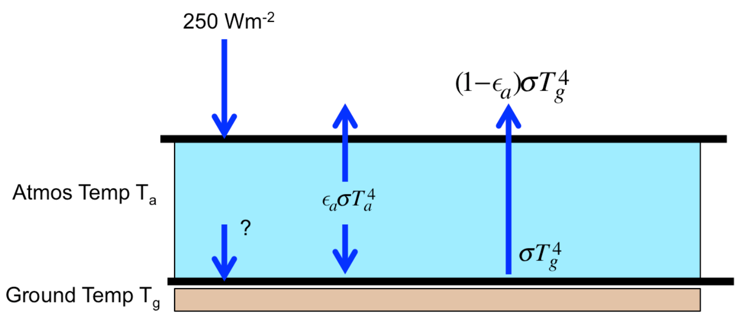
A) Amplifying because increasing low clouds heat the surface through longwave emission
B) Stabilizing because increasing low clouds reduce the surface heat flux
C) Amplifying because increasing low clouds reflect more incoming shortwave
D) Amplifying because increasing low clouds increase atmospheric mixing
E) Stabilizing because increasing low clouds emit more radiation to space

#C

Q7) Consider the following shallow, nocturnal atmospheric layer with emissivity ε_a**=0.8** over ground with emissivity of ε=1. If the ground temperature T_g is 300 K and the air temperature T_a is 260 K, what is the heating/cooling rate **of the ground** in $W\,m^{-2}$?

(Note 250 $W\,m^{-2}$ in longwave flux is entering the layer from above)

Shortcut: $\sigma \times 300^4 = 460\ W\,m^2$



A) -251 $W\,m^{-2}$
B) -202 $W\,m^{-2}$
C) +101 $W\,m^{-2}$
D) +202 $W\,m^{-2}$
E) +251 $W\,m^{-2}$

```
sigma = 5.67e-8
250 * (1 - 0.8) + 0.8 * sigma * 260 ** 4.0 - 460.0   # B
```

```
-202.71568639999998
```

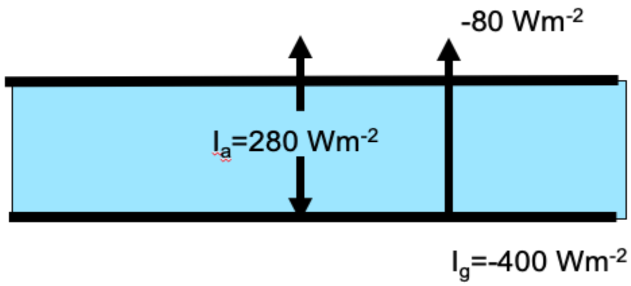
Q8) Which of the following climate feedbacks are always stabilizing?

```
i. Water vapour feedback
ii. Lapse rate feedback
iii. Planck feedback
iv. cloud feedback
```

A) i, iii
B) ii,iii
C) iv
D) i, iii, iv
E) ii, iv

#B

Q9) Given the fluxes in the following figure, the Greenhouse effect of this atmosphere is



A) 20 $W\,m^{-2}$
B) 40 $W\,m^{-2}$
C) 120 $W\,m^{-2}$
D) 320 $W\,m^{-2}$
E) 400 $W\,m^{-2}$

```
-280 - 80 + 400  # B
#
```

```
40
```

$$
\begin{aligned}
\text{Layer energy equation:}\quad & \frac{dE}{dt} = I_{\downarrow} + I_{\uparrow} \\
\text{Solar constant:}\quad & S = \frac{S_0}{4}(1-\alpha) \\
\text{Total grey body flux}\quad & I = \varepsilon\sigma T^4 \\
& \text{where}\quad \sigma = 5.67\times10^{-8}\mathrm{Wm^{-2}K^{-4}} \\
\text{transmissivity tr:}\quad & I_{\text{transmitted}} = \mathrm{tr} I_0 \\
\text{reflectity } \alpha\quad & I_{\text{reflected}} = \alpha I_0 \\
\text{absorbtivity abs}\quad & I_{\text{absorbed}} = \mathrm{abs} I_0 \\
\text{Kirchoff's law}\quad & \varepsilon = \mathrm{abs} \\
CO_2 \text{ radiative forcing}\quad & \Delta F = \left(3.8\mathrm{Wm^{-2}}\right)\frac{\ln(\text{newp CO 2/ origp CO2})}{\ln(2)} \\
\text{Conservation of Energy:}\quad & \alpha \mathrm{I_0} + abs\mathrm{I_0} + \mathrm{trI_0} = \mathrm{I_0} \\
\text{moist static energy:}\quad & h_m = c_pT + l_v w_v + gz \\
\text{moist adiabatic lapse rate:}\quad & \Gamma = \frac{dT}{dz} = \frac{-g}{c_p + l_v\frac{dw_v}{dT}} \\
\text{hydrostatic balance:}\quad & dp = -\rho g dz \\
\text{mass in a layer in } kg/m^2\text{:}\quad & M = \int_{z_1}^{z_2}\rho(z)dz \\
\text{energy in an ocean layer:}\quad & \Delta E = \rho_w D c_w \Delta T \\
\text{Conservation of energy for layer:}\quad & \frac{d\Delta E}{dt} = \Delta F \\
\text{change of temperature for an ocean layer:}\quad & \frac{d\Delta T}{dt} = \frac{\Delta F}{\rho_w c_w D} \\
\text{Planck feedback:}\quad & \frac{dI_G}{dT} = \frac{d\left(-\sigma T^4\right)}{dT} = f_{planck} = -4\sigma T^3 = -1/\lambda \\
\text{Conservation of energy with feedback:}\quad & \frac{\Delta E}{dt} = \Delta F - 4\sigma T^3\Delta T \\
\text{Climate adjustment to abrupt forcing:}\quad & \Delta T(t) = \lambda\Delta F\left(1 - e^{-t/\tau}\right) \\
\text{Climate adjustment timescale:}\quad & \tau = \rho_w c_w D\lambda \\
\text{Climate sensitivity:}\quad & \Delta T = \lambda\Delta F \\
\text{Climage mean temperature budget:}\quad & \rho_w c_w D\frac{dT}{dt} = \Delta F + \sum f_n\Delta T \\
\text{Climate feedback factor:}\quad & f_n = \frac{\Delta R}{\Delta T} = \left(\frac{\Delta R}{\Delta\text{ climate}}\right)\left(\frac{\Delta\text{ climate}}{\Delta T}\right) \\
\text{Climate sensitivity with feedbacks:}\quad & \lambda = -\frac{1}{\sum f_n}
\end{aligned}
$$

Quiz 2 constants

$$
\begin{aligned}
&1\text{ ppm} = 2.1\text{ Gtonnes Carbon} = 7.6\text{ Gtonnes } CO_2 \\
&\sigma = 5.67\times10^{-8}\mathrm{Wm^{-2}K^{-4}} \\
&c_p = 1004\ J\,kg^{-1}\,K^{-1} \\
&c_w = 4186\ J\,kg^{-1}\,K^{-1} \\
&\rho_w = 1000\ kg\,m^{-3} \\
&l_v = 2.5\times10^6\ J\,kg^{-1}
\end{aligned}
$$