Radiative forcing and climate response in the stable polar atmosphere

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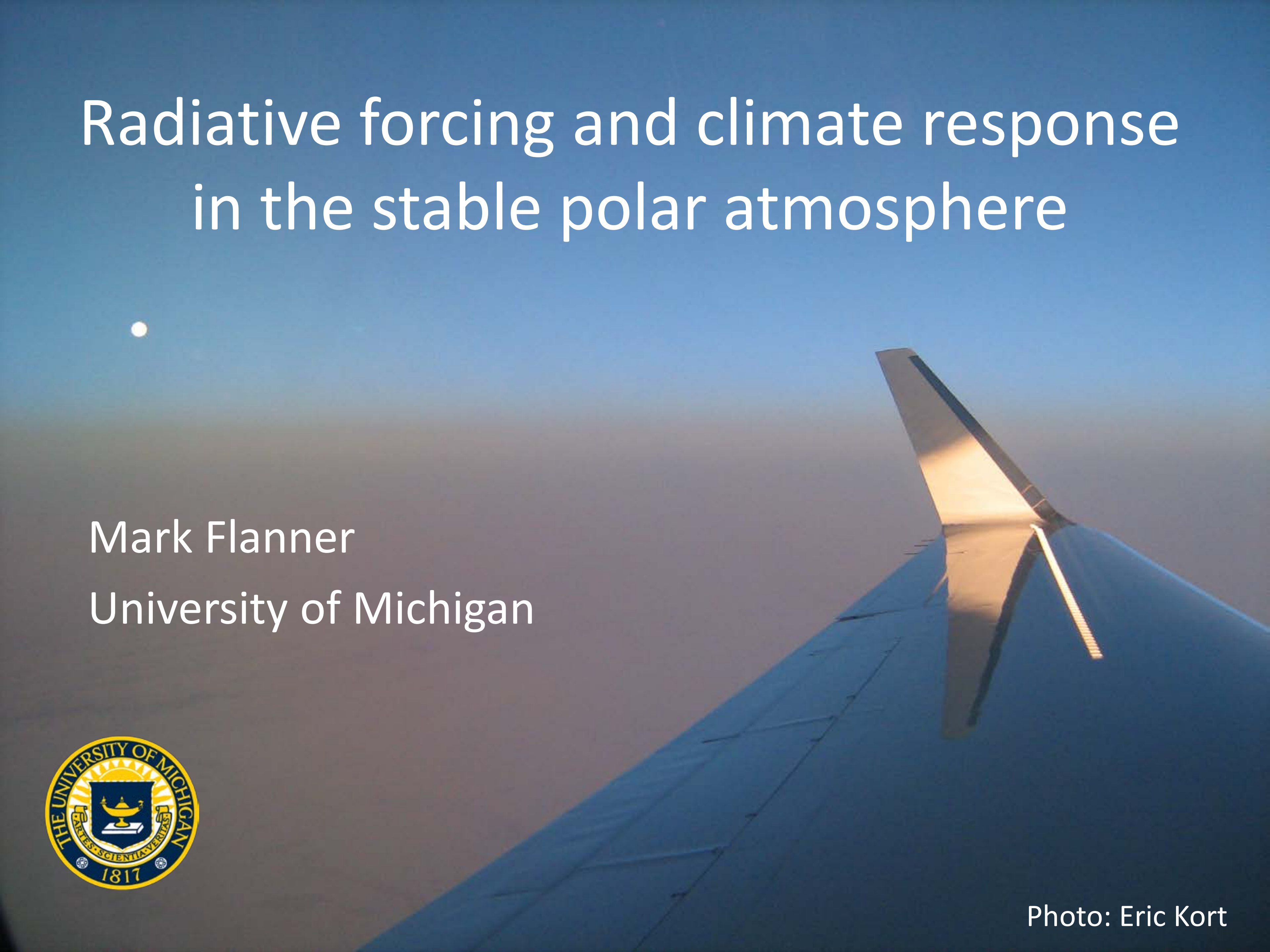
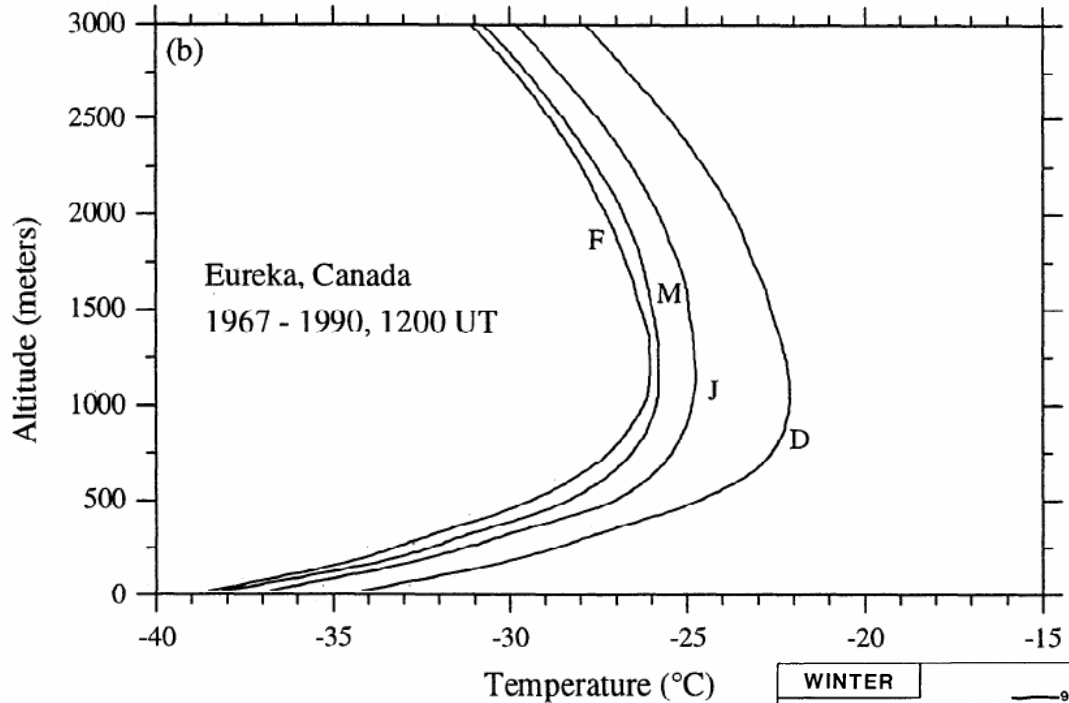


Photo: Eric Kort

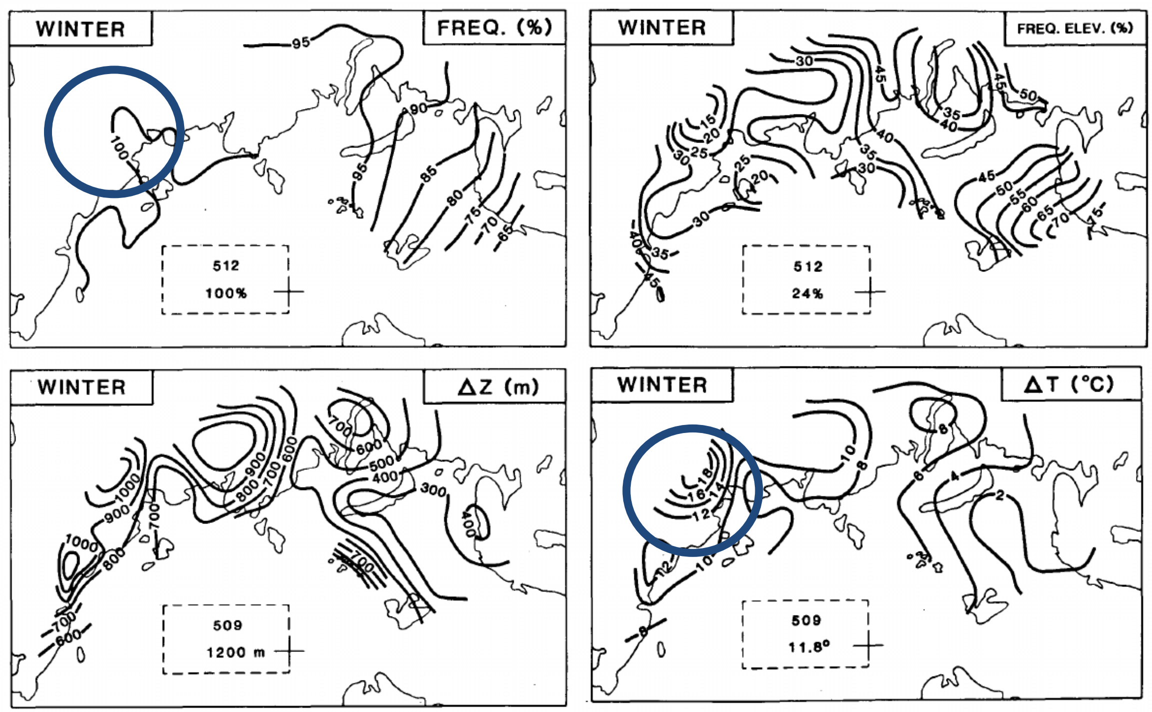
Temperature inversions in polar regions:

Strong and frequent during winter



Walden et al (1996)

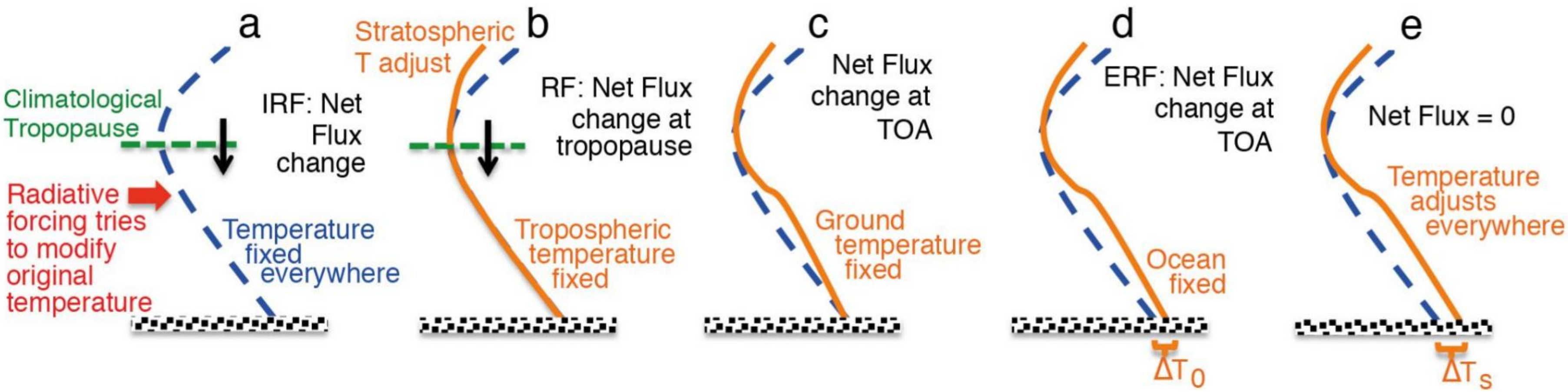
Inversion strength can exceed 25°C, and is >15°C in some climatologies



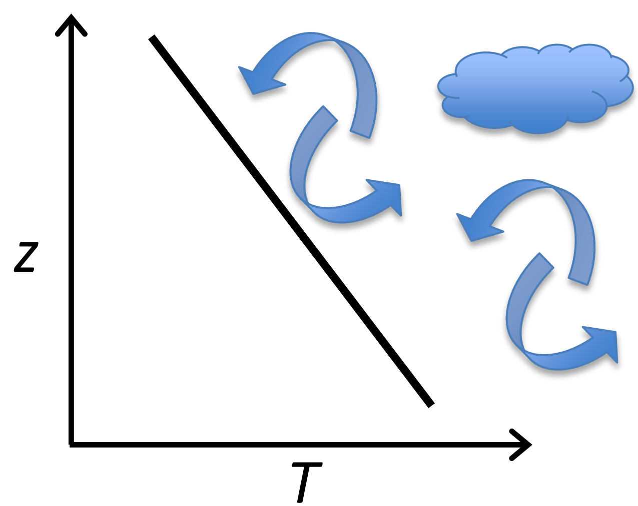
Serreze et al (1992)

FIG. 2. Winter statistics for (a) frequency of all inversions, (b) frequency of elevated inversions, (c) median inversion depths, and (d) median temperature difference across the inversion layer.

Radiative forcing (IPCC) is calculated at the tropopause or top-of-atmosphere

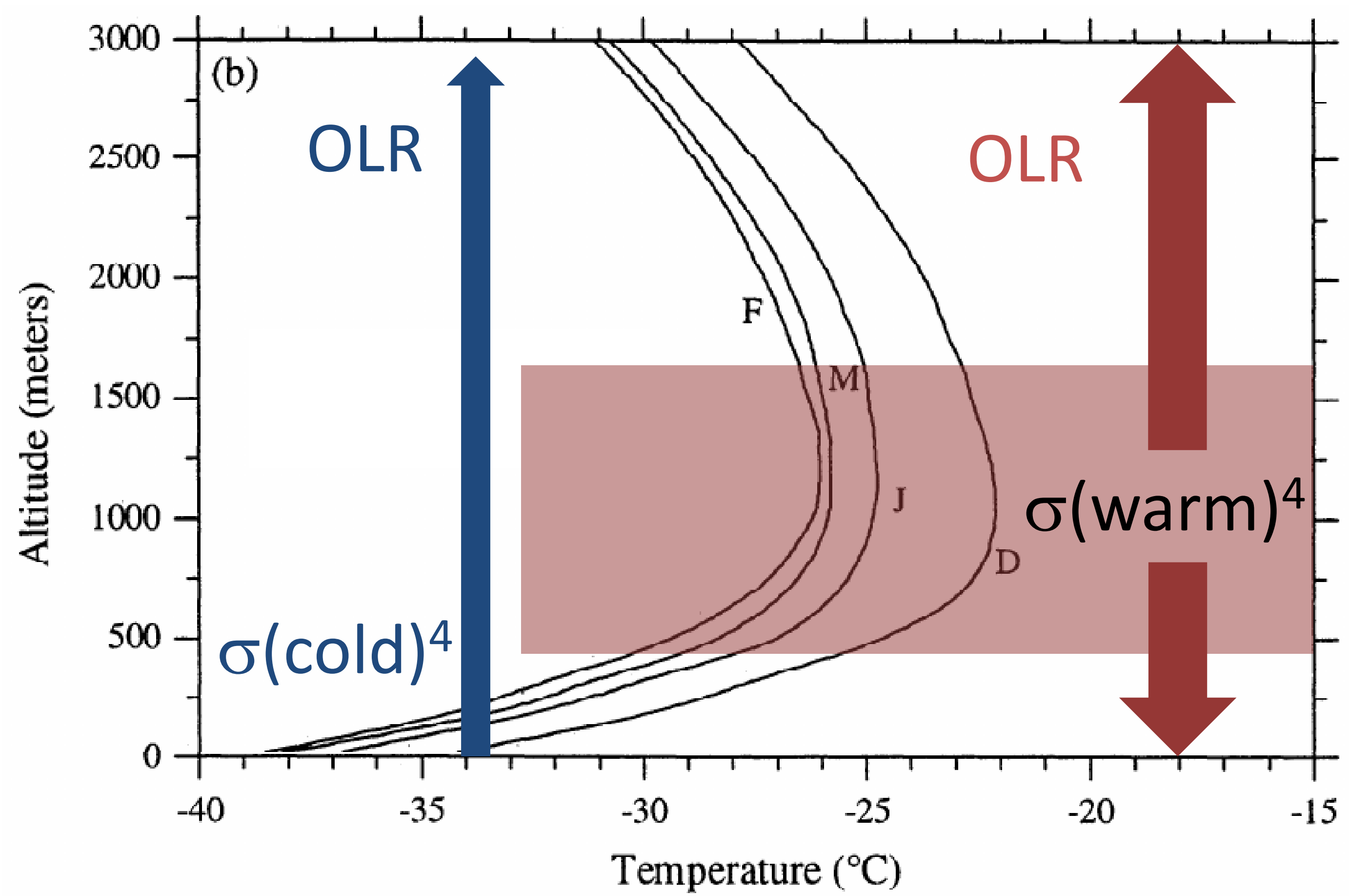


IPCC AR5 Fig 8.1



Rationale: Turbulent mixing in the troposphere will distribute energy throughout the troposphere

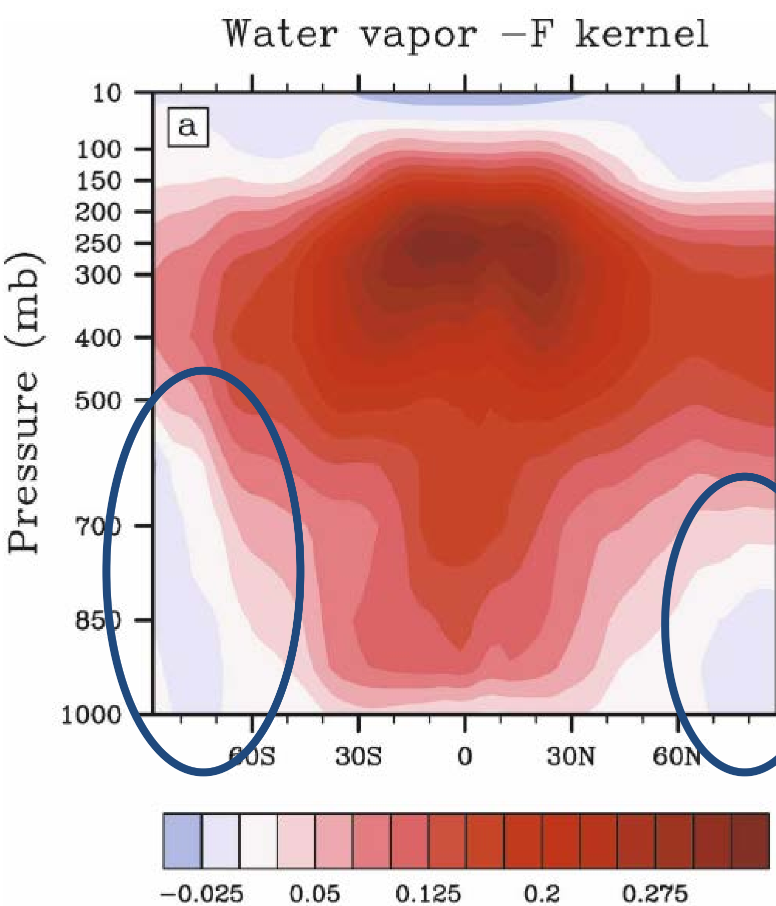
RF in the presence of an inversion



- OLR can *increase* with a GHG increase, exerting negative RF at the top-of-atmosphere

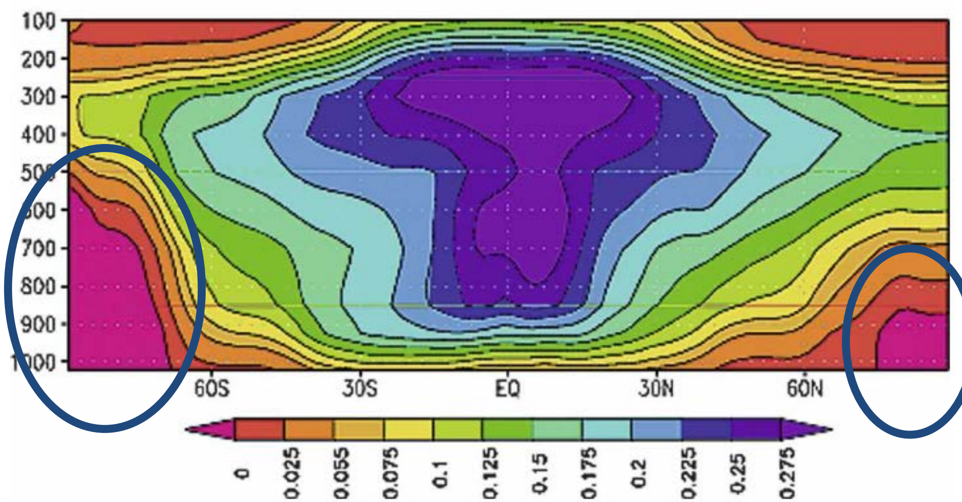
Negative RF from water vapor

- We can see this effect in water vapor radiative kernels used widely to decompose climate feedbacks



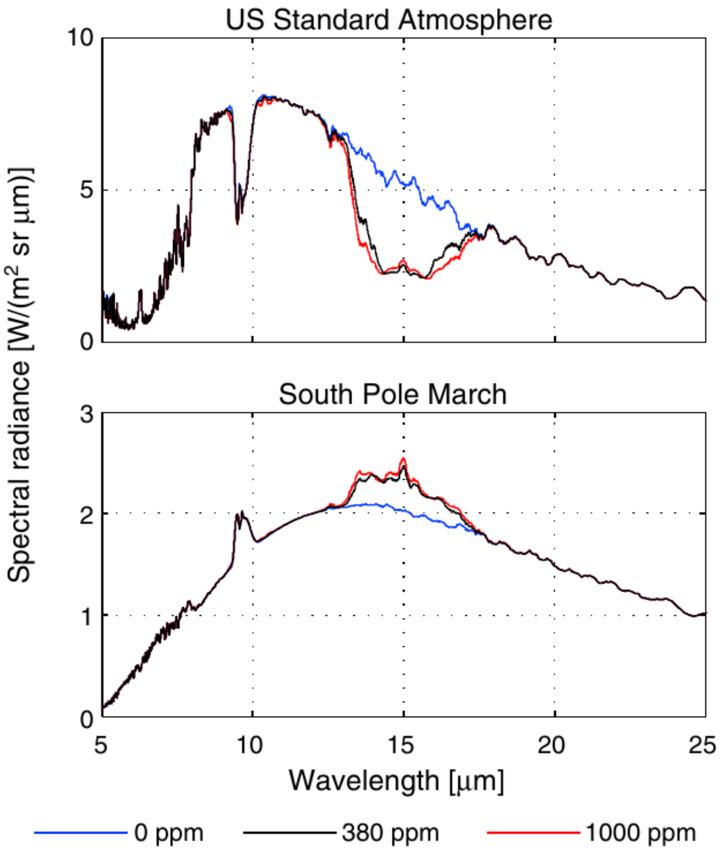
Shell et al (2008)

Negative values indicate that an increase in water vapor causes *negative* RF



Soden et al (2008)

Small or negative RF from whole-column CO_2 over polar regions



Schmithüsen et al (2015, GRL)

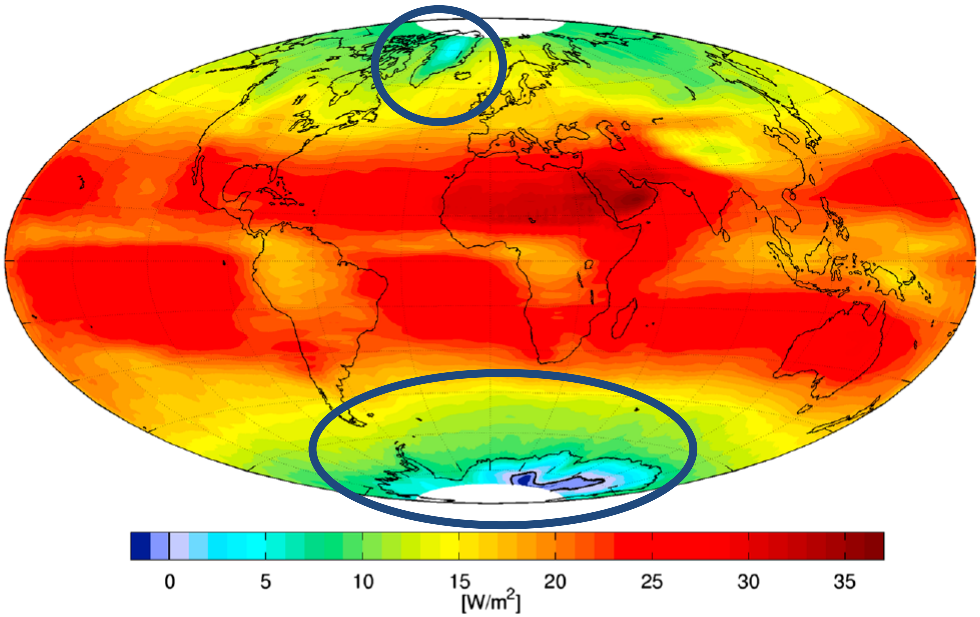
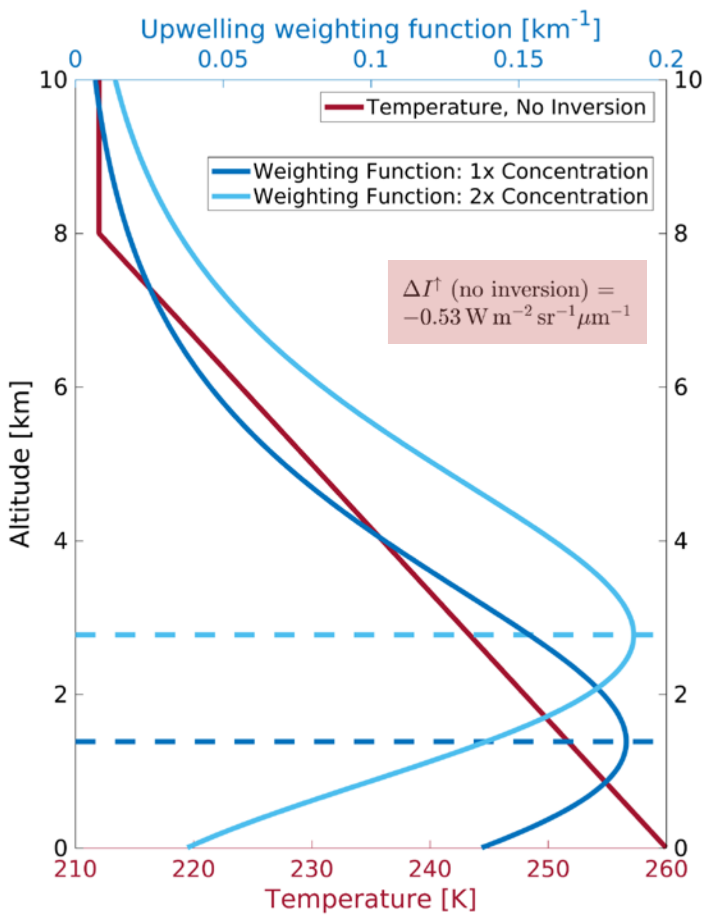


Figure 4. RF from all CO_2, derived from spaceborne TES measurements

In this case, negative RF is due to the upper troposphere / lower stratosphere being warmer than the surface

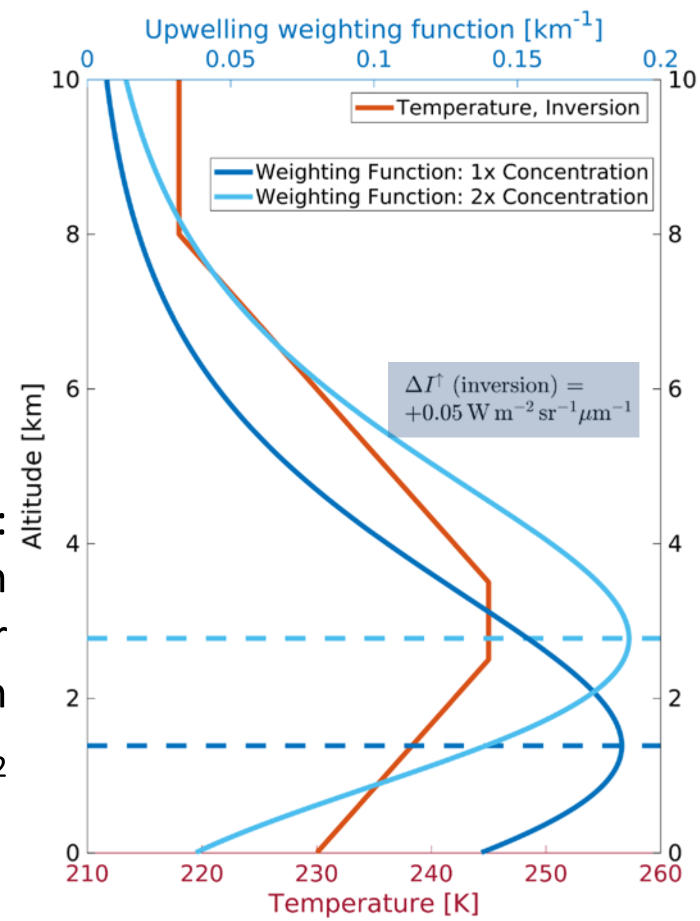
An analytical demonstration

$$I_\lambda^{\uparrow}(\infty) = B_\lambda[T_s]\,\mathcal{T}_\lambda^* + \int_0^\infty B_\lambda[T(z)]\,\frac{\partial \mathcal{T}_\lambda(z,\infty)}{\partial z}\,dz$$



Left, No inversion: Weighting function shifts to a higher **colder** layer with doubled CO_2

Right, Inversion: Weighting function shifts to a higher **warmer** layer with doubled CO_2



Flanner, M., X. Huang, X. Chen, and G. Krinner (2018, GRL)

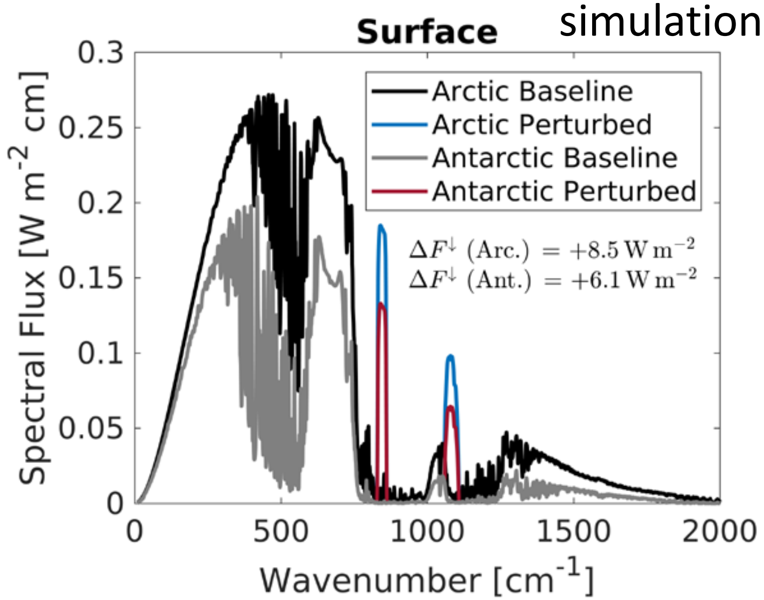
Questions raised

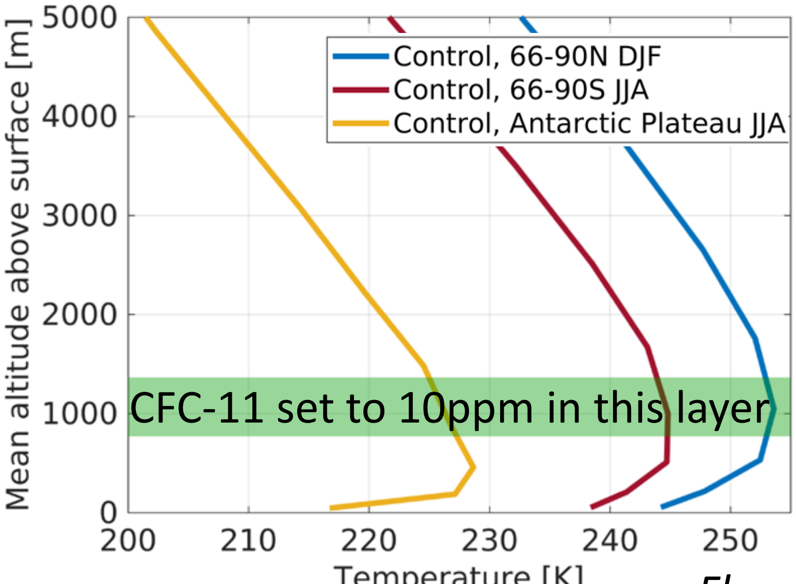
- How does the climate system respond to GHG increases occurring in tropospheric temperature inversion environments?
- Is the standard concept of RF even useful for these environments (i.e., polar winter)?
- Could the surface actually *cool* from a targeted increase in short-lived GHG?
  - Possible geoengineering strategy?

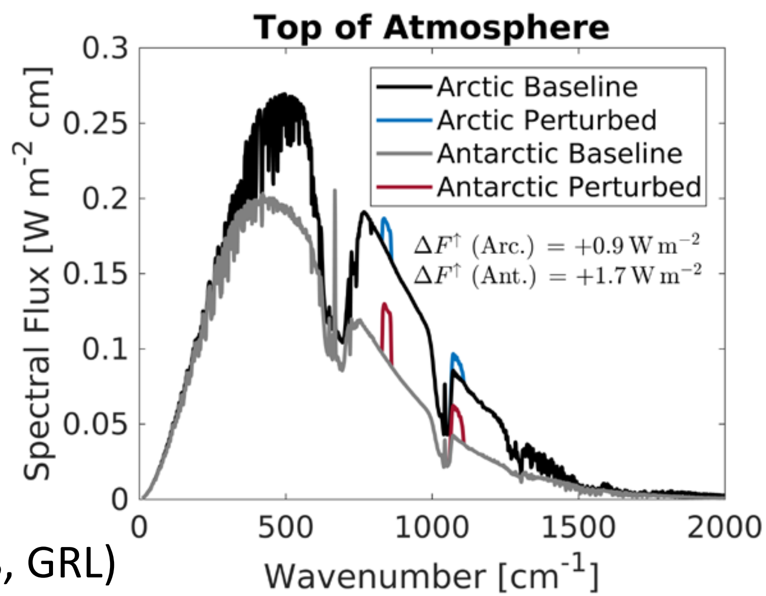
An extreme experiment

MODTRAN simulations

- Fully-coupled CESM simulations (B_1850) with and without a GHG perturbation occurring ***only*** within the wintertime polar near-surface inversion layer

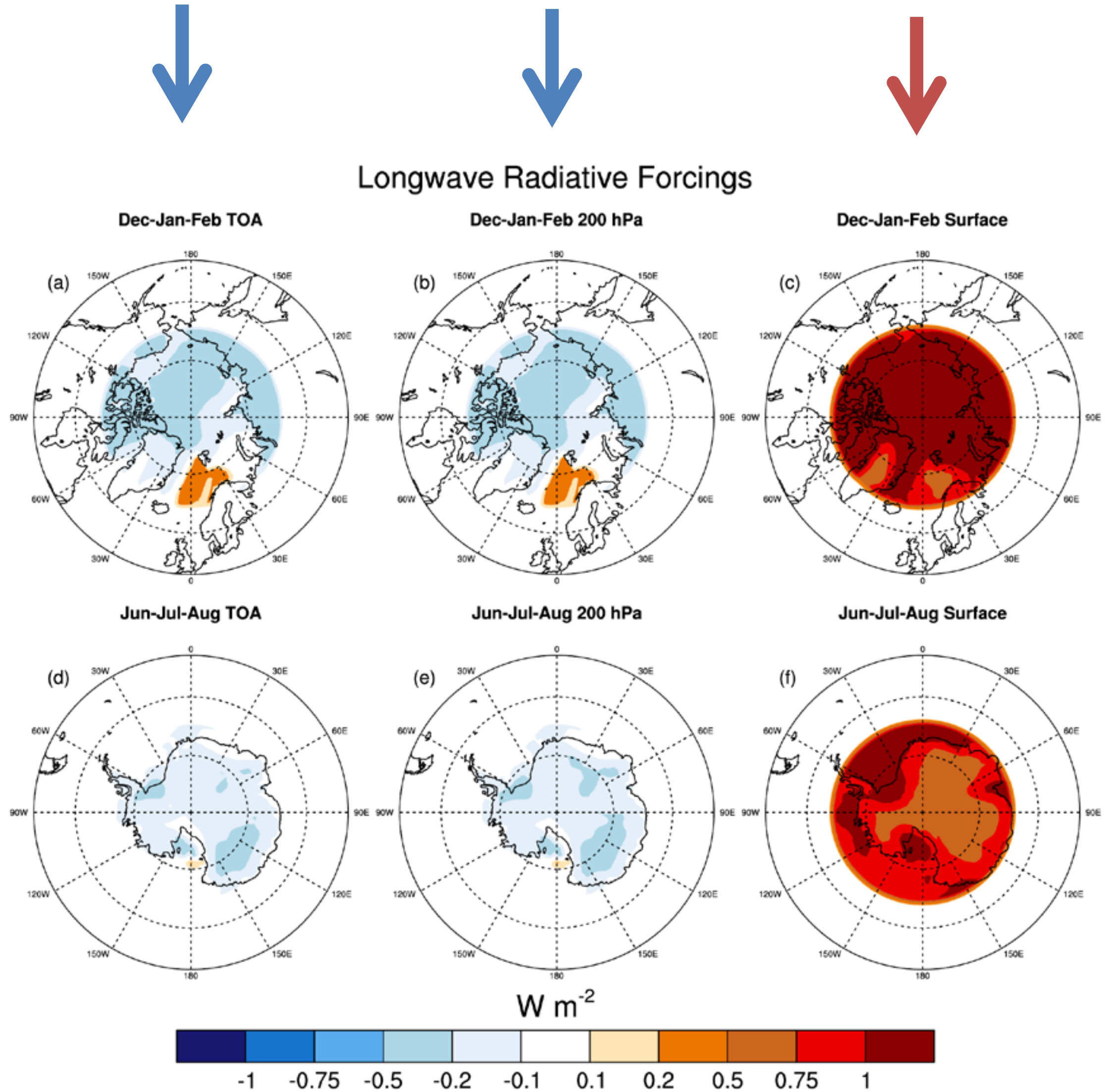






Flanner et al (2018, GRL)

Radiative forcing in CESM

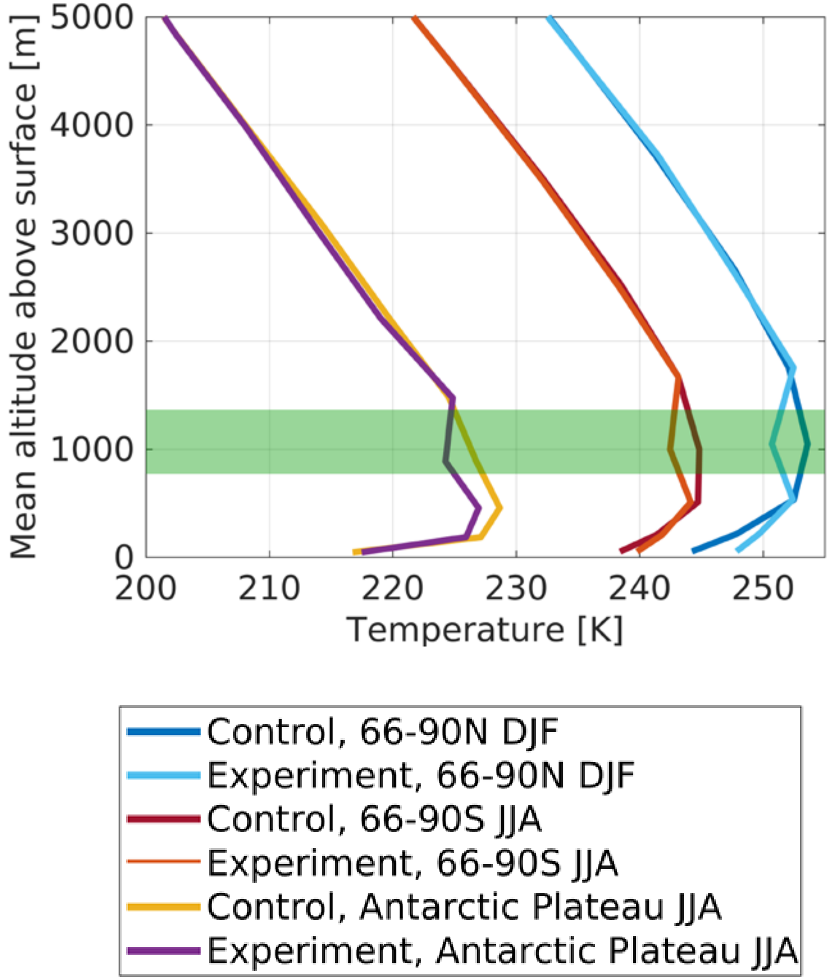


Flanner et al (2018, GRL)

- Instantaneous RF:
  - Negative at the TOA and tropopause
  - Positive at the surface
- Effective radiative forcing (diagnosed with fixed-SST simulations):
  - **Negative**

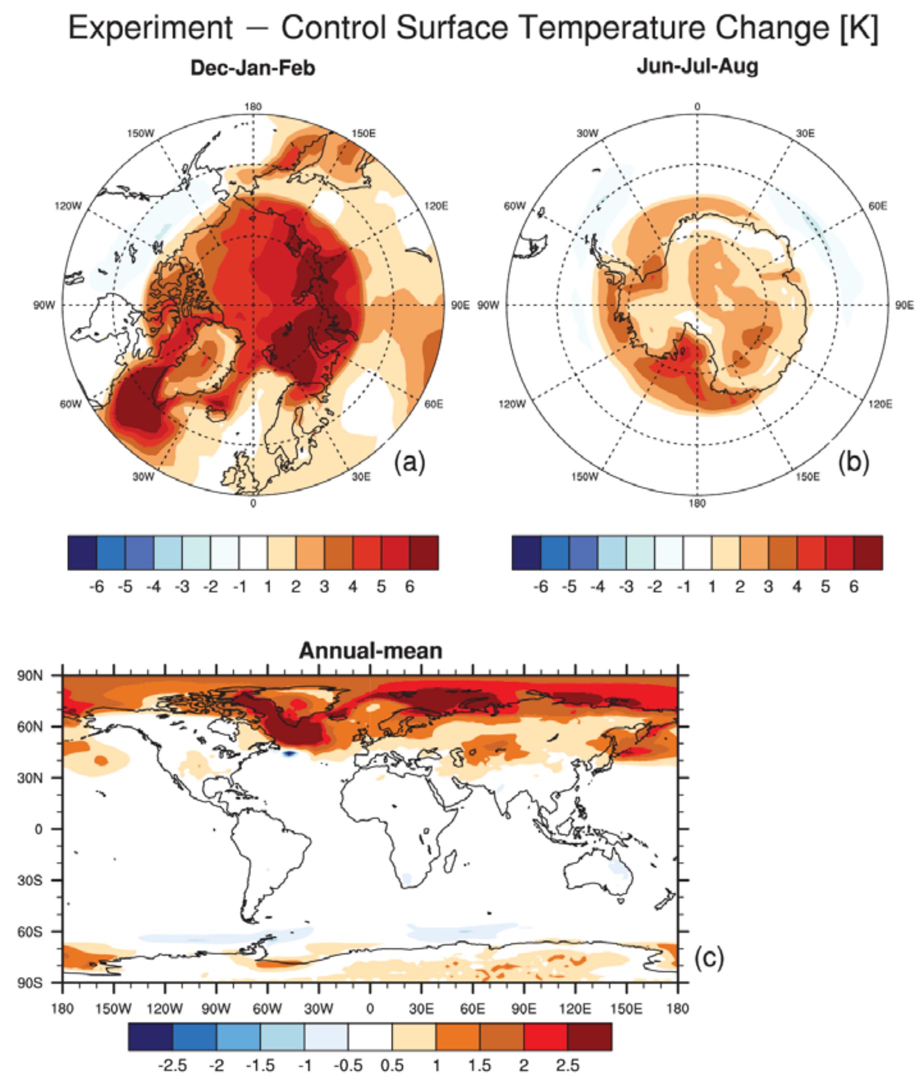
Temperature response

- Troposphere *cools* in vicinity of the gas increase
  - Emission from the layer increases more than absorption by the layer
    - It is the warmest point of the surface-atmosphere column
- Surface *warms*
  - **Increase in downwelling longwave flux outweighs the impact from a cooling troposphere**
  - A unique response facilitated by the stable atmosphere



Surface temperature response

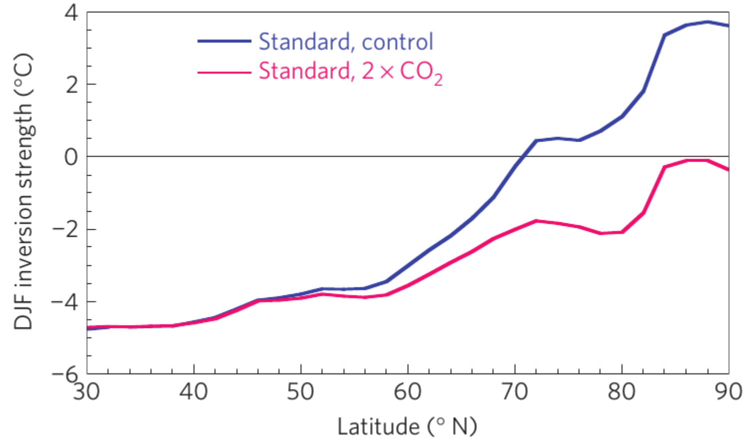
- Surface warms, despite negative ERF and tropospheric cooling
- Reduced sea-ice in the Arctic amplifies its response relative to Antarctic
- Surface RF is weaker over central Antarctica and Greenland because perturbation occurred above the inversion peak
- Temperature inversion weakens as the simulation progresses

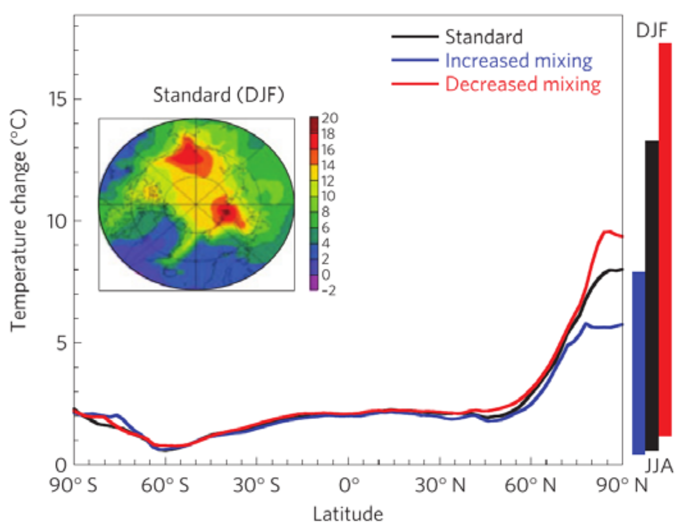


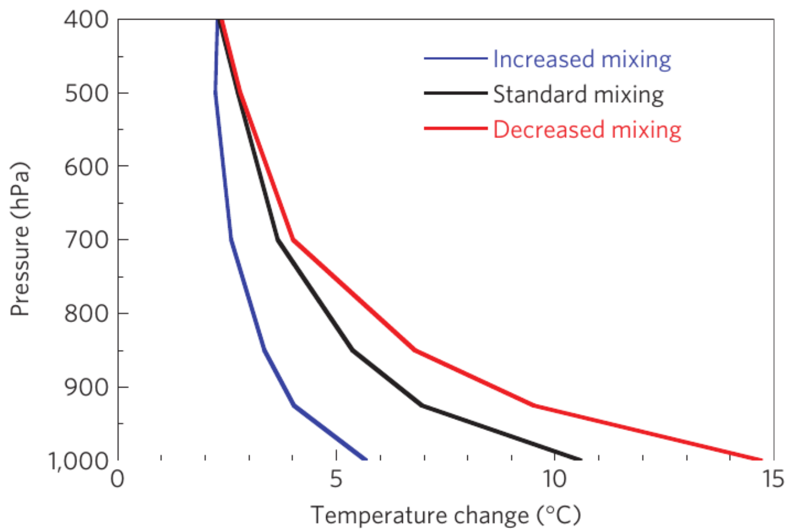
Flanner et al (2018, GRL)

Stability plays a key role in T_S response

- Arctic surface temperature response to $2\times CO_2$ is reduced when boundary-layer mixing is artificially increased (*Bintanja et al*, 2011)
- Surface inversion becomes progressively weaker in the future, thus reducing the amplifying effect of a stable atmosphere







Bintanja et al (2011, Nature Geosci.)

Stability plays a key role in T_S response

- Response of the net surface energy budget and temperature to sea-ice loss is largest during **winter**, when stability is high (*Deser et al*, 2010)

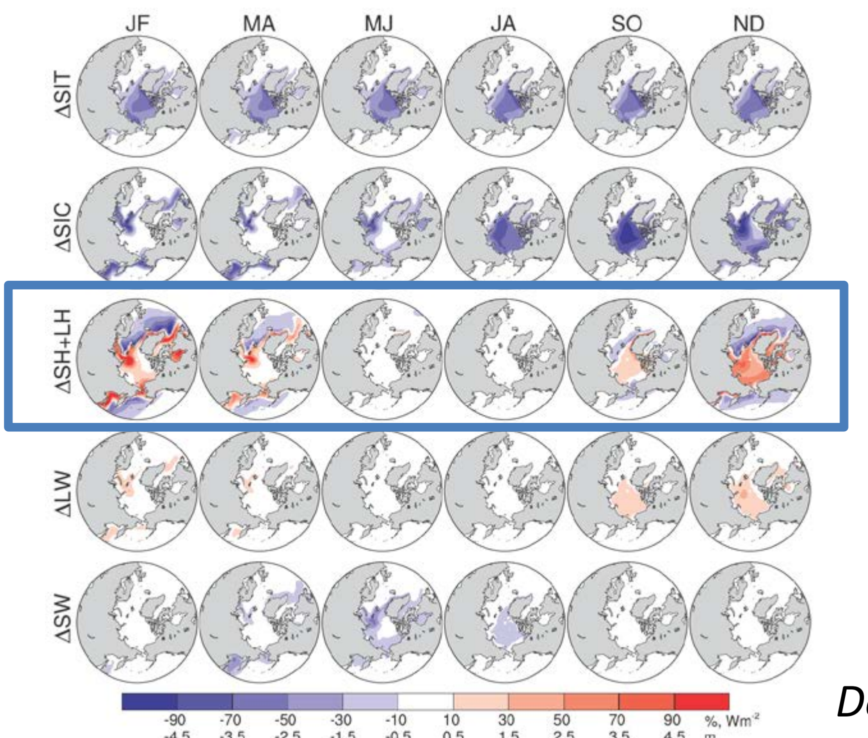


FIG. 2. Bimonthly Arctic (top row) sea ice thickness (ΔSIT; m) and (second row) concentration (ΔSIC; %) differences (2080–99 minus 1980–99) from CCSM3. Bimonthly (third row) turbulent energy flux (ΔSH + LH), (fourth row) longwave radiative flux (ΔLW), and (bottom row) shortwave radiative flux (ΔSW) responses to sea ice cover changes. Fluxes (W m^{-2}) are positive upward.

Deser et al (2010, J. Climate)

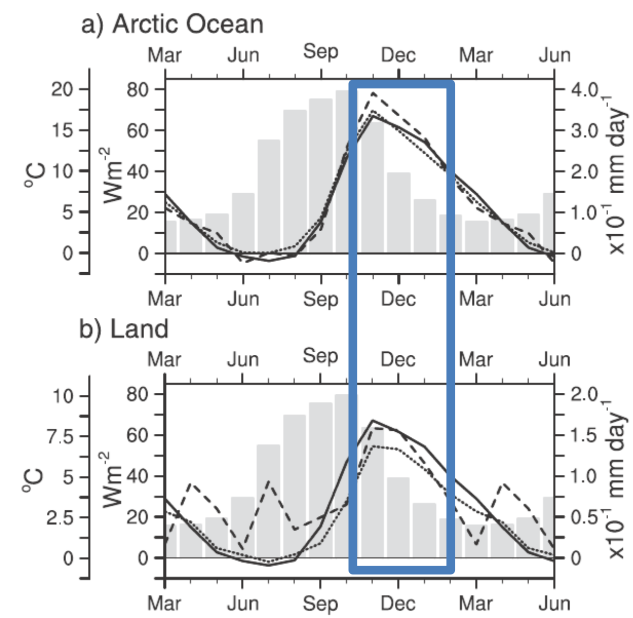
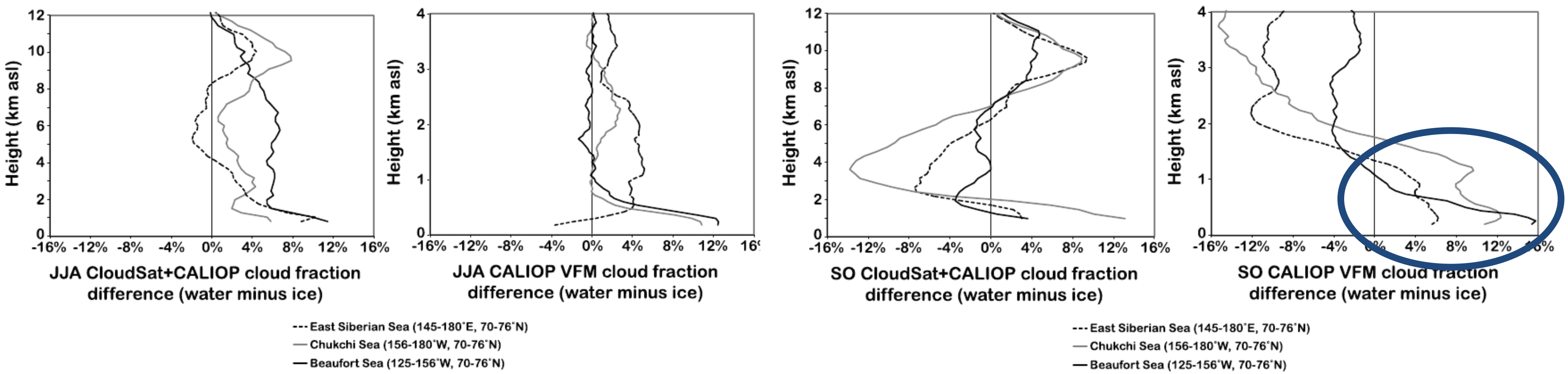


FIG. 4. Seasonal cycles of air temperature (°C; dotted curve) and precipitation (mm day^{-1}; dashed curve) responses area averaged over (a) the Arctic Ocean and (b) the high-latitude continents (65°–80°N; 60°–300°E). The solid curve in both (a) and (b) shows the sum of the turbulent and longwave fluxes area averaged over the Arctic Ocean (W m^{-2}). SIC changes are indicated by the gray bars (scale as in Fig. 3, not shown).

Stability plays a role in cloud response

- Where sea-ice is lost, low clouds form over newly open water in autumn (when stability is low) but not (much) in other seasons, when inversions are still present (*Kay and Gettelman*, 2009)

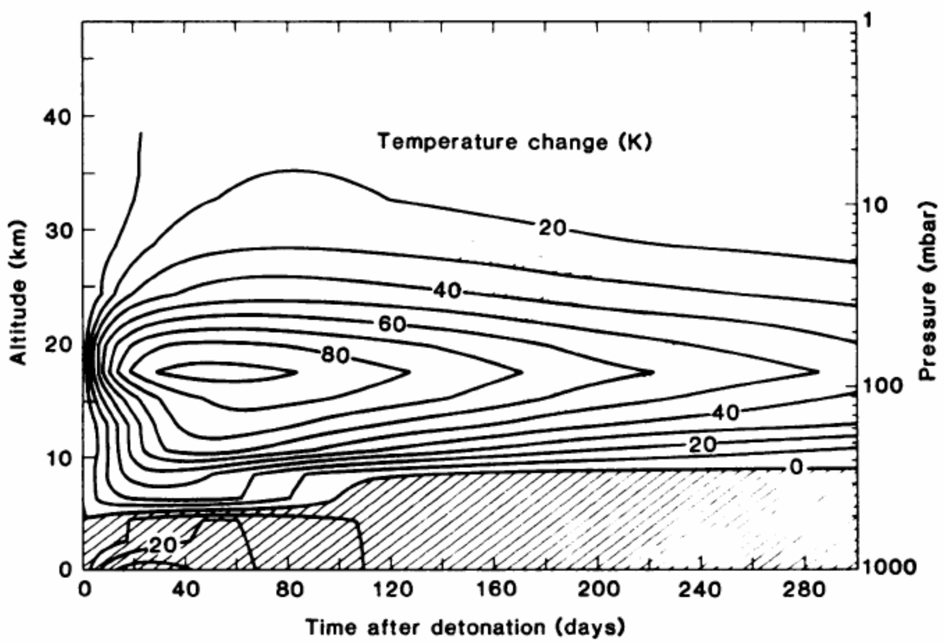


Kay and Gettleman (2009, JGR)

Stability plays a key role in T_S response

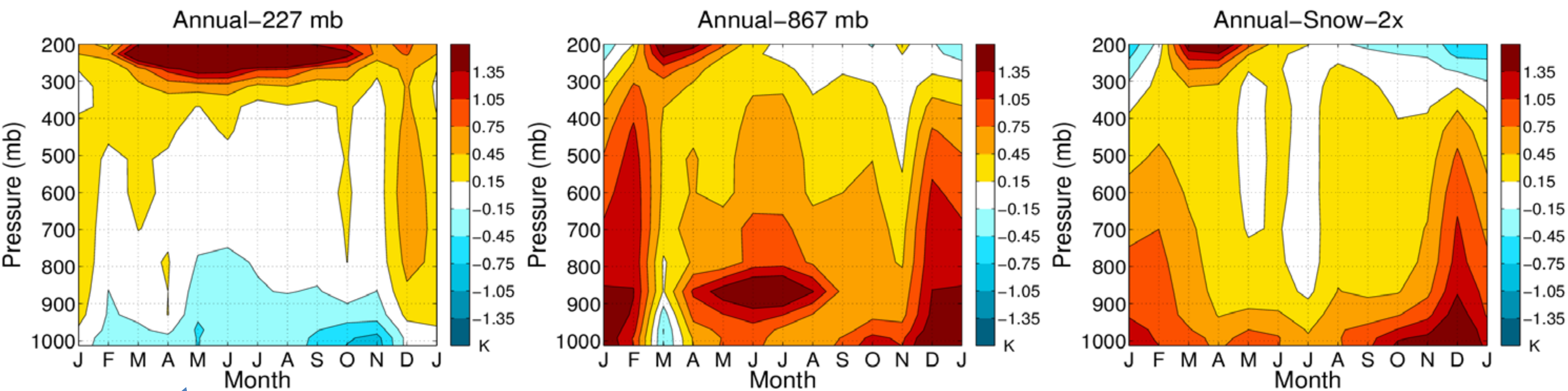
- Even further back… **Convective decoupling** of the surface and troposphere during nuclear winter results in strong warming near the tropopause and **cooling at the surface**, **despite positive RF** (*Turco et al*, 1983, *Cess et al*, 1985)

Fig. 3. Northern Hemisphere troposphere and stratosphere temperature perturbations (in Kelvins; 1 K = 1°C) after the baseline nuclear exchange (case 1). The hatched area indicates cooling. Ambient pressure levels in millibars are also given.



Turco et al (1983, Science)

Another example of ill-behaved forcing: Black carbon in the Arctic atmosphere



Flanner (2013, JGR)

- Black carbon exerts positive TOA RF
  - It warms the atmosphere
- But when located sufficiently high, it cools the surface
  - Less sunlight at the surface and **insufficient coupling** to mix the heat down

Conclusions

- Under highly stable conditions (Arctic winter)…
  - ERF can fail to predict the correct *sign* of surface temperature response to a GHG increase
  - **Surface RF governs surface temperature change more than TOA RF or ERF**
  - Perturbations to the surface energy budget drive disproportionately large surface temperature change
- Simulated polar surface responses to external forcings are sensitive to boundary layer representation
- Polar winter stability will decrease with climate warming
- Injecting short-lived GHGs into polar inversion layers would fail to cool the planetary surface, *despite* exerting negative ERF and cooling the inversion layer