Arctic warming feedbacks and amplifications: Northward heat flux feedback hypothesis

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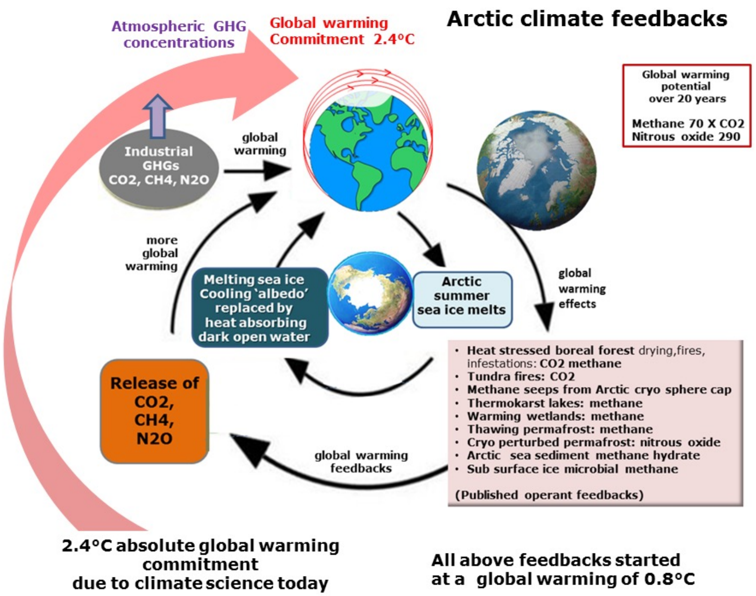
(Updated)

Feedback characteristics

- Negative feedbacks dampen; positive amplify.
- More than half of anthropogenic-induced warming will occur from feedbacks.
- Feedbacks that mainly affect climate change magnitude include cloud, water vapor, ice-albedo, and lapse rate feedbacks.
- Strong positive feedbacks, such as water vapor, amplifies the changes associated with weaker feedback processes. (NRC 2003)



(Carter 2019)

Feedback effects

1. Magnitude of climate change:
- Cloud, water vapor, and lapse rate feedbacks
- Ice albedo feedback
- Biogeochemical feedbacks and the carbon cycle
- Atmospheric chemical feedbacks

2. Transient response of climate:
- Ocean heat uptake and circulation feedbacks

3. Pattern of climate change:
- Land hydrology and vegetation feedbacks
- Natural modes of climate system variability

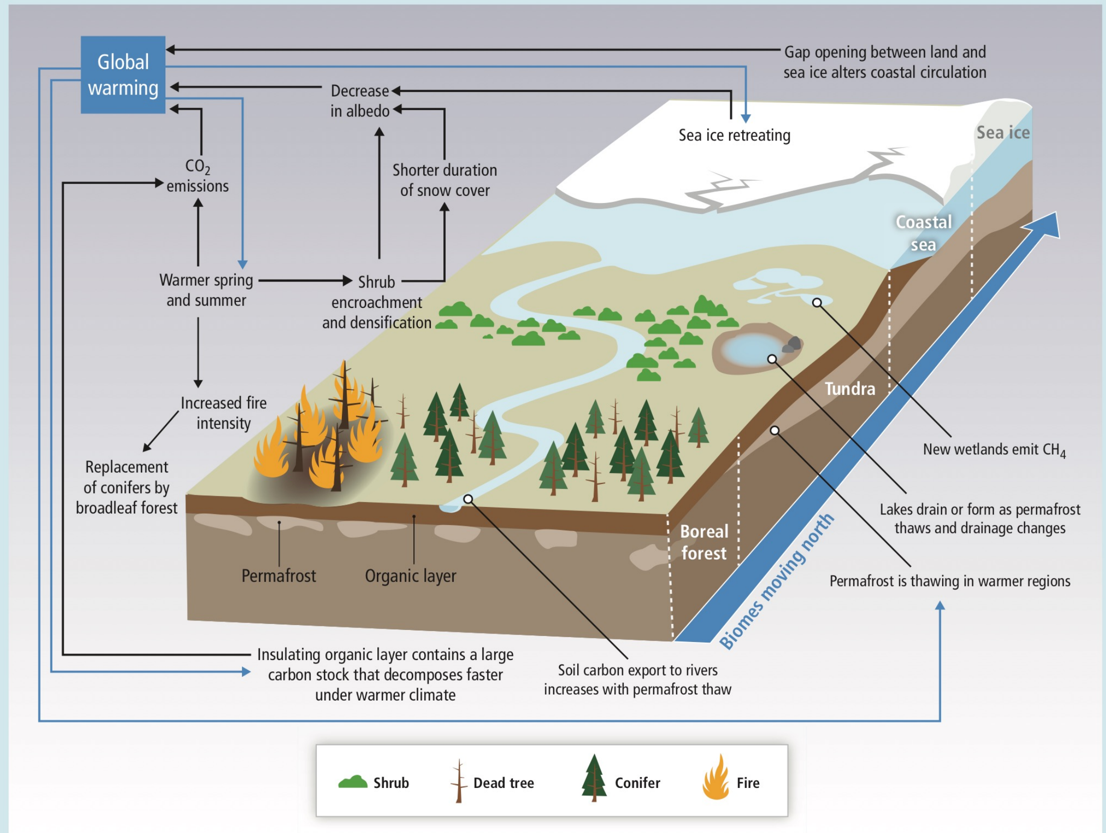


Figure 4-10 | Tundra–boreal biome shift. Earth System Models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra–forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets, and net ecosystem carbon balance, permafrost thawing, and methane emissions, with net feedbacks to additional climate change.

(IPCC WGII 2014)

Climate sensitivity

- Poleward export of the climate sensitivity by atmospheric heat transport from low to high latitudes.
- Analogous to the upward (local) export of climate sensitivity from the surface to the atmosphere by the turbulent sensible and latent heat fluxes and from the lower to upper atmosphere by convections.
- Non-local dynamic heating in high latitudes due to the atmospheric poleward heat transport enhances downward IR energy flux locally.
- Increased atmospheric poleward heat transport both amplifies external forcing, and also local feedbacks in high latitudes.

(Cai and Lu 2007)

Nonlinearities, feedbacks and critical thresholds within the Earth's climate system

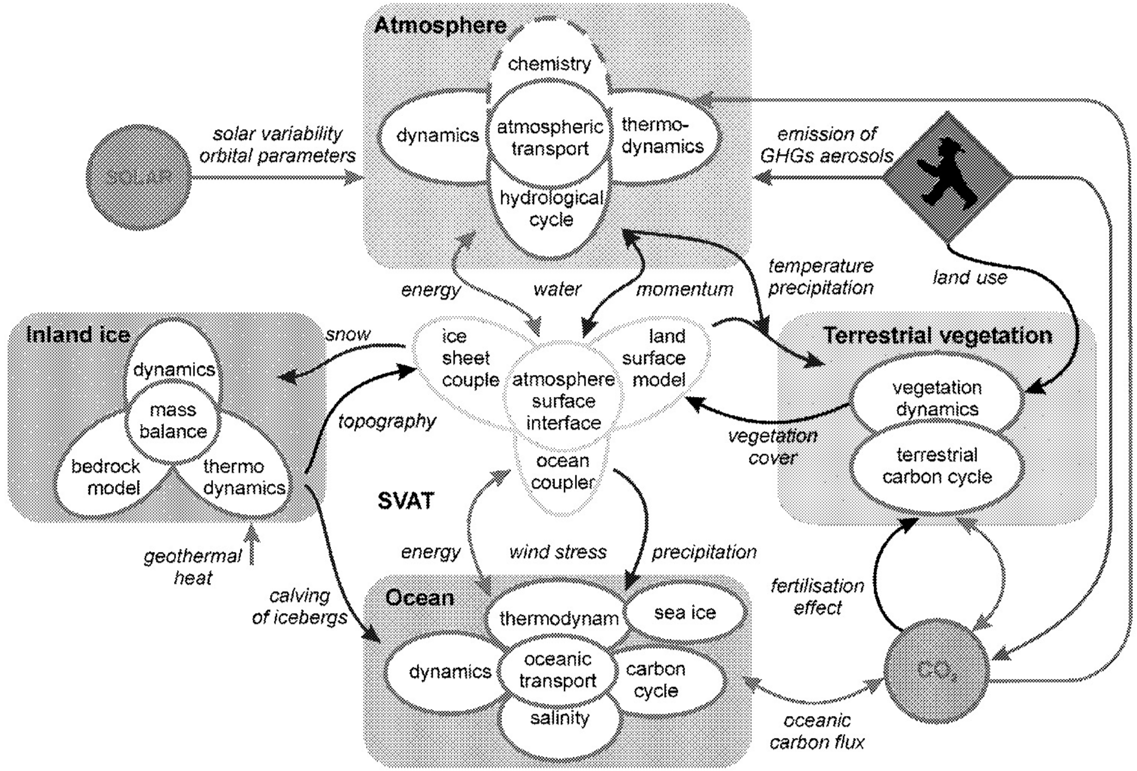


Figure 1. Structure of CLIMBER-2, an Earth System Model of Intermediate Complexity (EMIC; Claussen et al., 2002). The model consists of four modules which describe the dynamics of the climate components atmosphere, ocean, terrestrial vegetation, and inland ice. These components interact via fluxes of energy, momentum (e.g., wind stress on the ocean), water (e.g., precipitation, snow, and evaporation), and carbon. Also, the land-surface structure is allowed to change in the case of changes in vegetation cover or the emergence and melting of inland ice masses, for example. The interaction between climate components is described in a so-called Soil Vegetation Atmosphere Transfer Scheme (SVAT). CLIMBER-2 is driven by insolation (which can vary owing to changes in the Earth orbit or in the solar energy flux), by the geothermal heat flux (which is very small, but important in the long run for inland ice dynamics), and by changes imposed on the climate system by human activities (such as land use or emission of greenhouse gases (GHG) and aerosols).

(Rial *et al.* 2004)

Formulation

Climate forcing and sensitivity can be related as $\Delta T_{eq} = \lambda \cdot \Delta Q$

where ΔT_{eq} is equilibrium temperature, λ climate sensitivity parameter, and ΔQ applied forcing.

Blackbody case: If a linear model is assumed, and only the temperature dependence of blackbody emission is considered, then the sensitivity parameter is

$$\lambda_0 = \left(4\sigma T_e^3\right)^{-1}$$

The gain factor, g, is the fraction of the equilibrium climate change associated with feedback processes in addition to basic blackbody feedback:

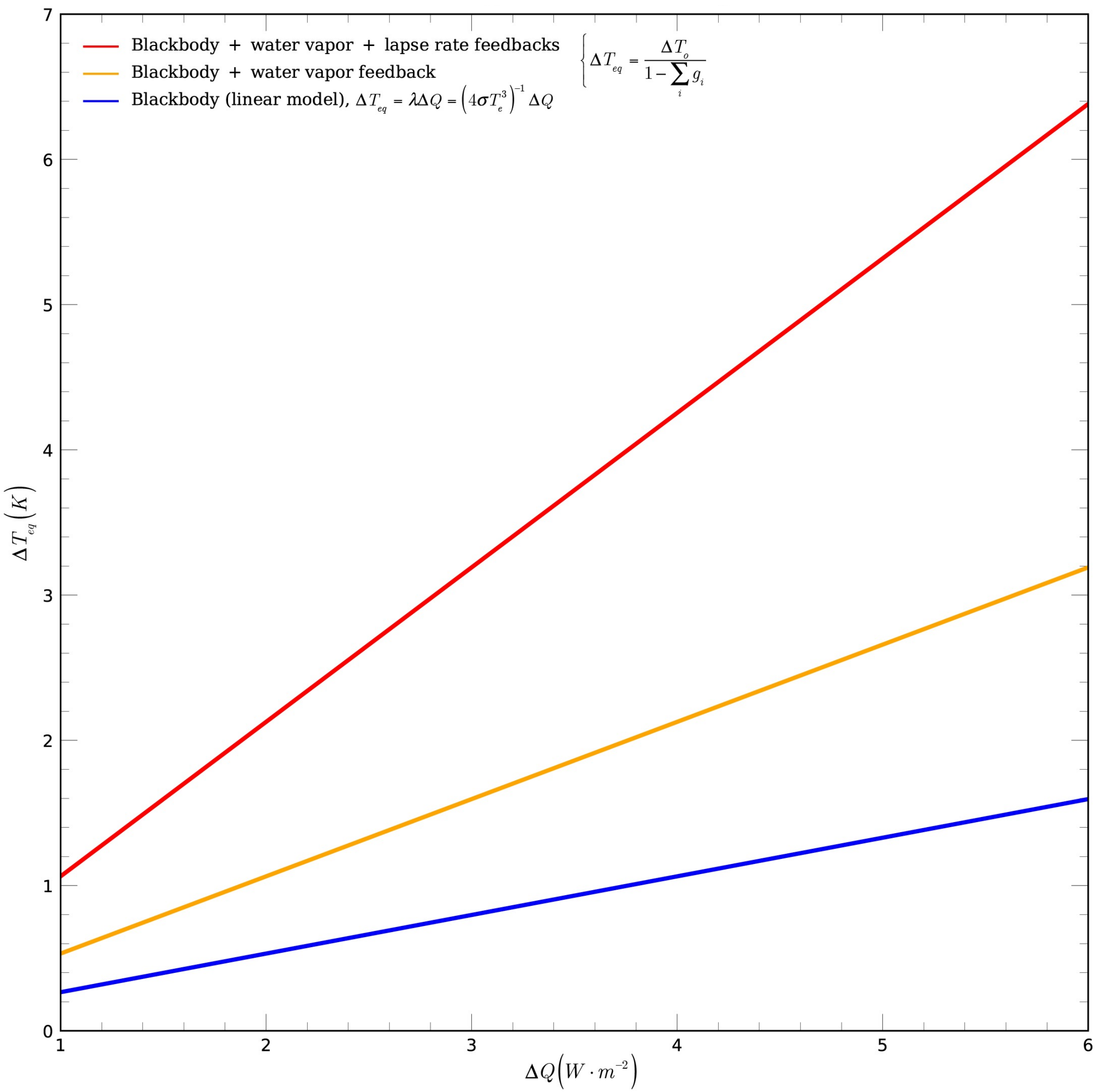
$$g = \frac{\Delta T_{eq} - \Delta T_o}{\Delta T_{eq}} = \frac{\Delta T_{feedbacks}}{\Delta T_{eq}}$$

If various feedback processes with feedback factors, g_i , are assumed to be linearly additive, it can be shown that

$$\Delta T_{eq} = \frac{\Delta T_o}{1 - \sum_i g_i}$$

(NRC 2003)

Climate change feedback amplification



(Noble 2024; NRC 2003)

Global warming magnitude

- The magnitude of global warming over the next 40 years is insensitive to the rate of greenhouse gas releases; in their study the range of possible warmings is determined by the range of estimates of the strength of climate feedbacks and not by the range of estimates of climate forcing.

- Even in a simple linear analysis the temperature response is not linear in the strengths of the feedbacks, because all the other feedback processes modify the temperature change associated with one feedback process (Hansen *et al.,* 1984).

- In a system with a strong positive feedback, such as water vapor feedback in the climate system, the strong positive feedback process amplifies the changes associated with weaker feedback processes.

(NRC 2003)

Planetary scale feedbacks

Tropics

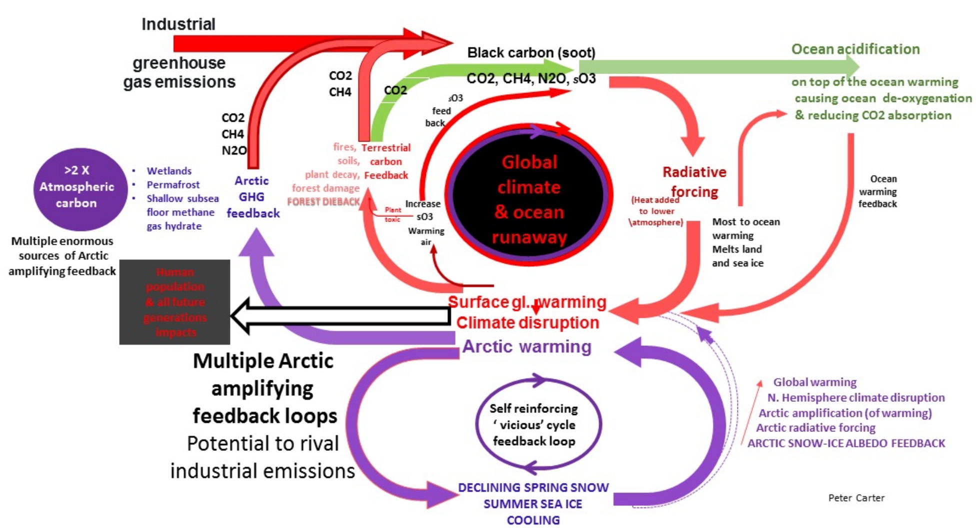
- Small climate sensitivity
- Tropical stabilization
  - Evaporative cooling stabilizes tropical SSTs

Polar regions

- Large climate sensitivity
- Polar amplification
  - Ice-albedo feedback
  - ↑ poleward oceanic heat transport at high latitudes

Non-local dynamic heating in high latitudes due to the atmospheric poleward heat transport enhances downward IR energy flux locally.

Increased atmospheric poleward heat transport both amplifies external forcing, and also local feedbacks in high latitudes.
(Cai and Lu 2007)



(Carter 2019)

Baroclinic eddies and storm tracks

Location and intensity of storm tracks has changed:

- Poleward shift
- Strengthening north of the British Isles

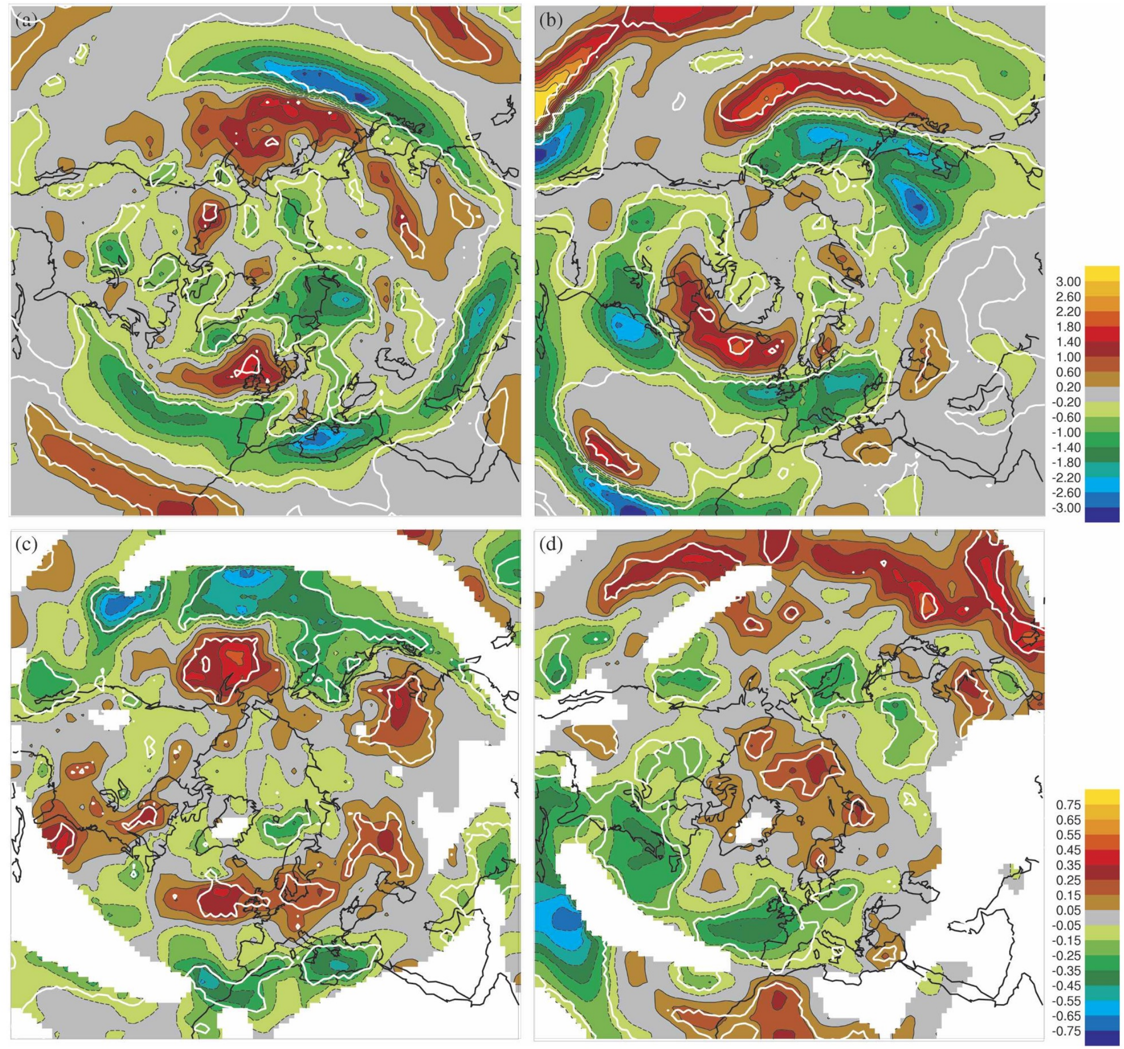


FIG. 10. Difference in NH cyclone track statistics for ξ_{850}, between the 21C and 20C periods (21C – 20C) averaged over the three ensemble members before differencing: (a) DJF track density, (b) JJA track density, (c) DJF mean intensity, and (d) JJA, mean intensity. Track density differences are the number density per month per unit area, where the unit area is equivalent to a 5° spherical cap ($\sim 10^6$ km^2). Mean intensity differences are in units of 10^5 s^{-1}. Mean intensity differences are only plotted where the track density is greater than 1 per month per unit area. The white lines indicate regions where the p values are less than 5%. See text for further details.

(Bengtsson *et al.* 2006)

Arctic climate tipping elements

Arctic change indicators

- Degraded permafrost
- Diminished sea ice
- Increased water vapor

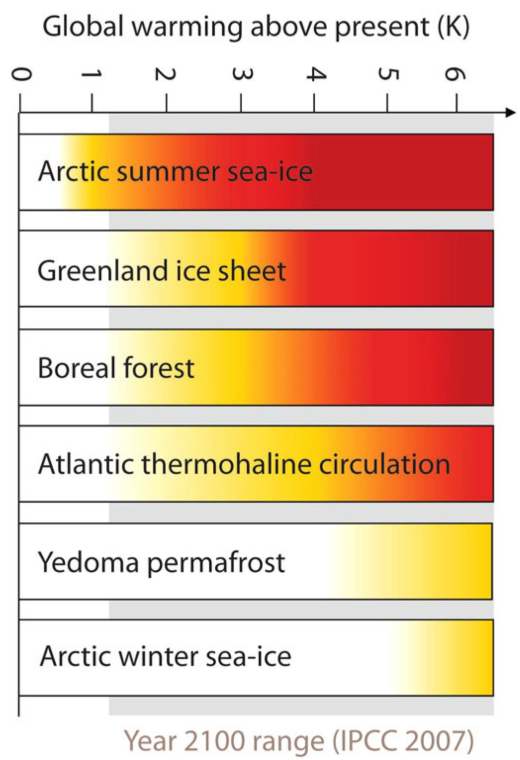


Fig. 3 Proximity of different Arctic climate tipping points. The burning embers capture estimates of the increasing likelihood of passing a tipping point as global temperature increases (above the 1980–1999 mean), and the associated uncertainty. (Lenton 2012)

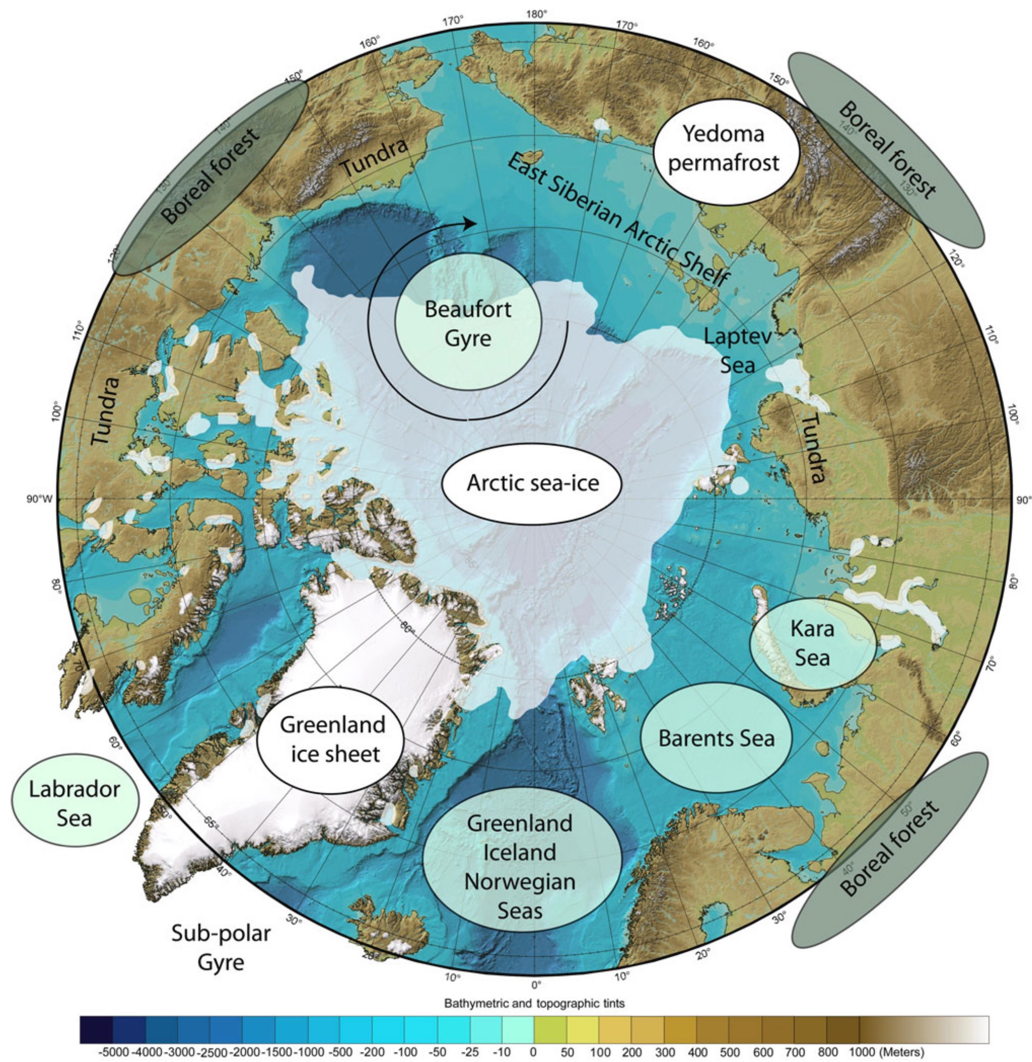


Fig. 2 Map of Arctic climate tipping elements. Based on the International Bathymetric Chart of the Arctic Ocean (IBCAO) with land topography, and the September 2008 minimum sea-ice extent overlain. Systems ringed are tipping elements suggested herein or elsewhere in this special issue, other labels are to help guide the reader (systems discussed herein). Tipping elements are *colour coded*; *white* ice melting, *aqua green* changes in ocean circulation (often coupled to sea-ice/atmospheric circulation), *dark green* involves biome change

(Lenton 2012)

Northward heat flux

Eddies are responsible for positive northward heat flux, $\left(\overline{v'T'}\right)$

– Baroclinic eddies, turbulence, stationary waves, transient waves, hurricanes, …

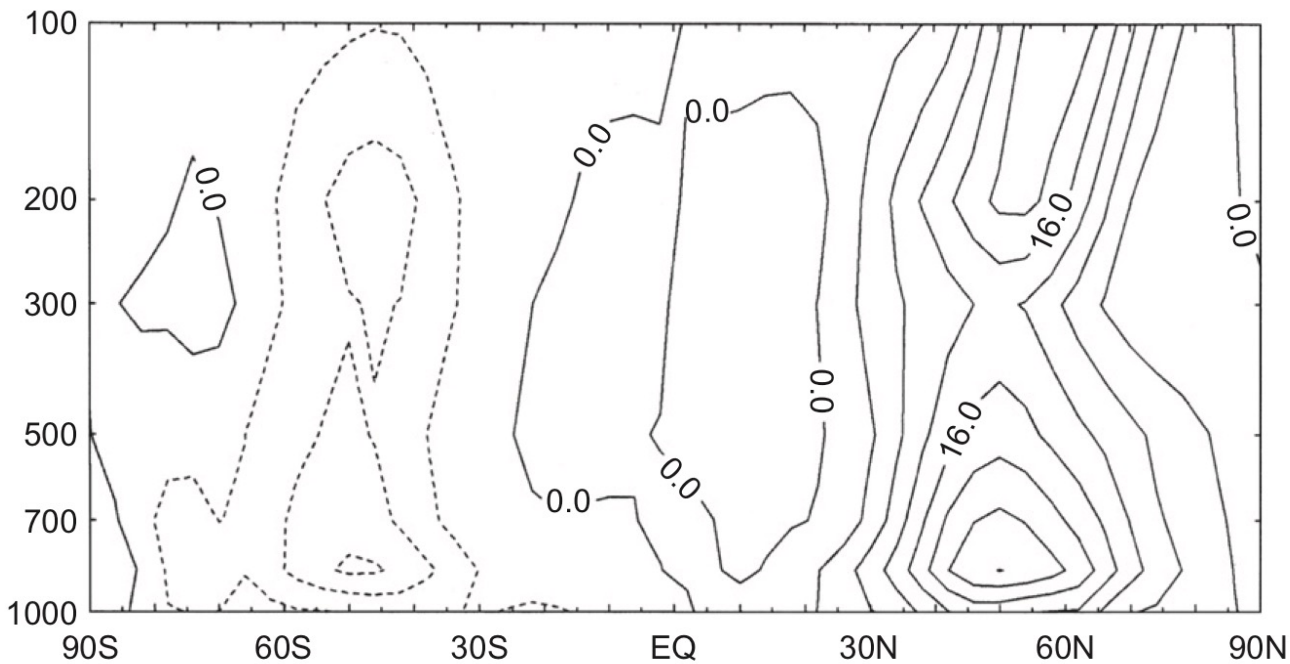
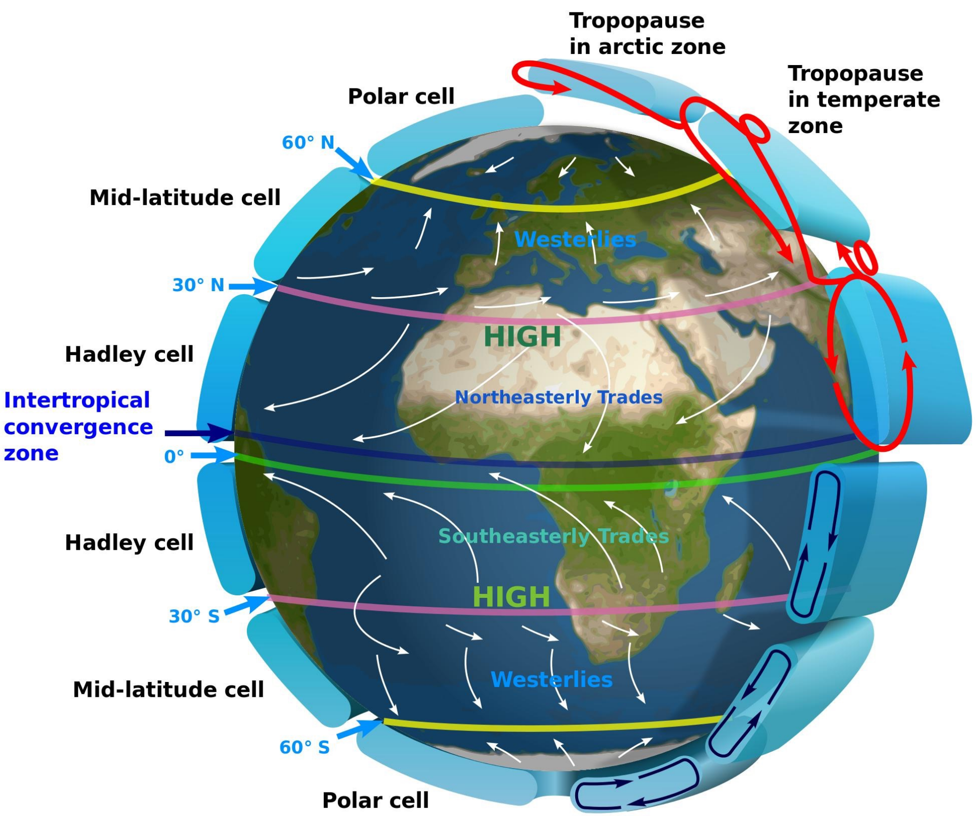


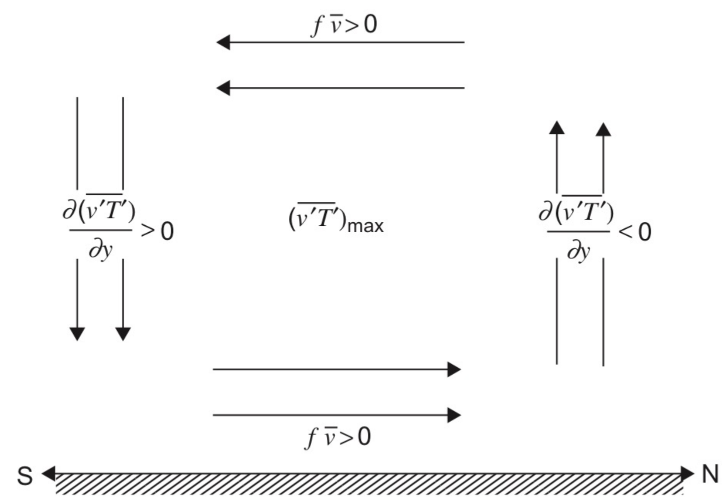
FIGURE 10.3 Observed northward eddy heat flux distribution ($^{\circ}\mathrm{C\,m\,s^{-1}}$) for Northern Hemisphere winter. (*Adapted from Schubert et al., 1990.*)

(Holton, 2004)

Circulation

Eddies are responsible for driving mid-latitude thermally-indirect circulation



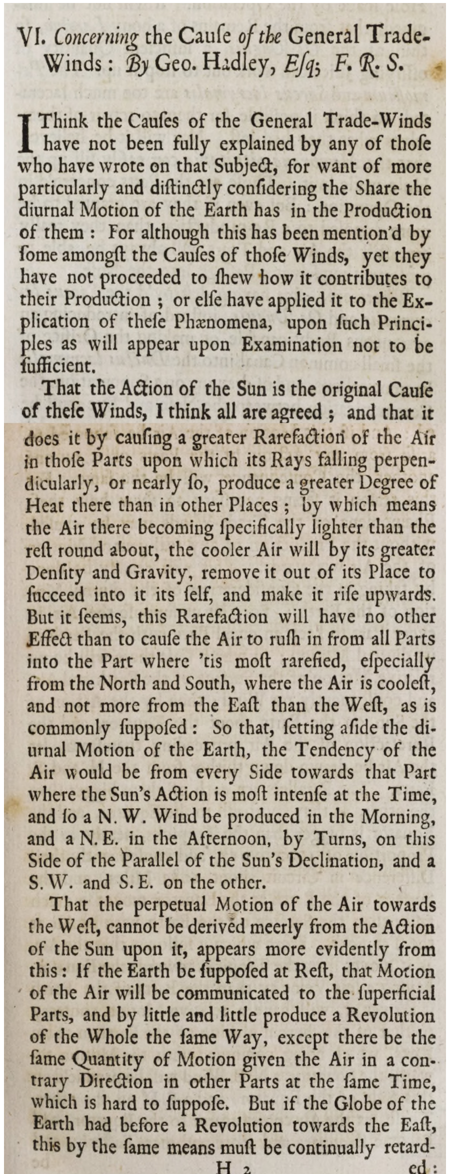


Schematic Eulerian mean meridional circulation forced by poleward heat fluxes.

(Holton, 2004, Fig. 10.4)

History

George Hadley proposed a mechanism for the trade winds in his 1735 paper, "On the Cause of the General Trade Winds".



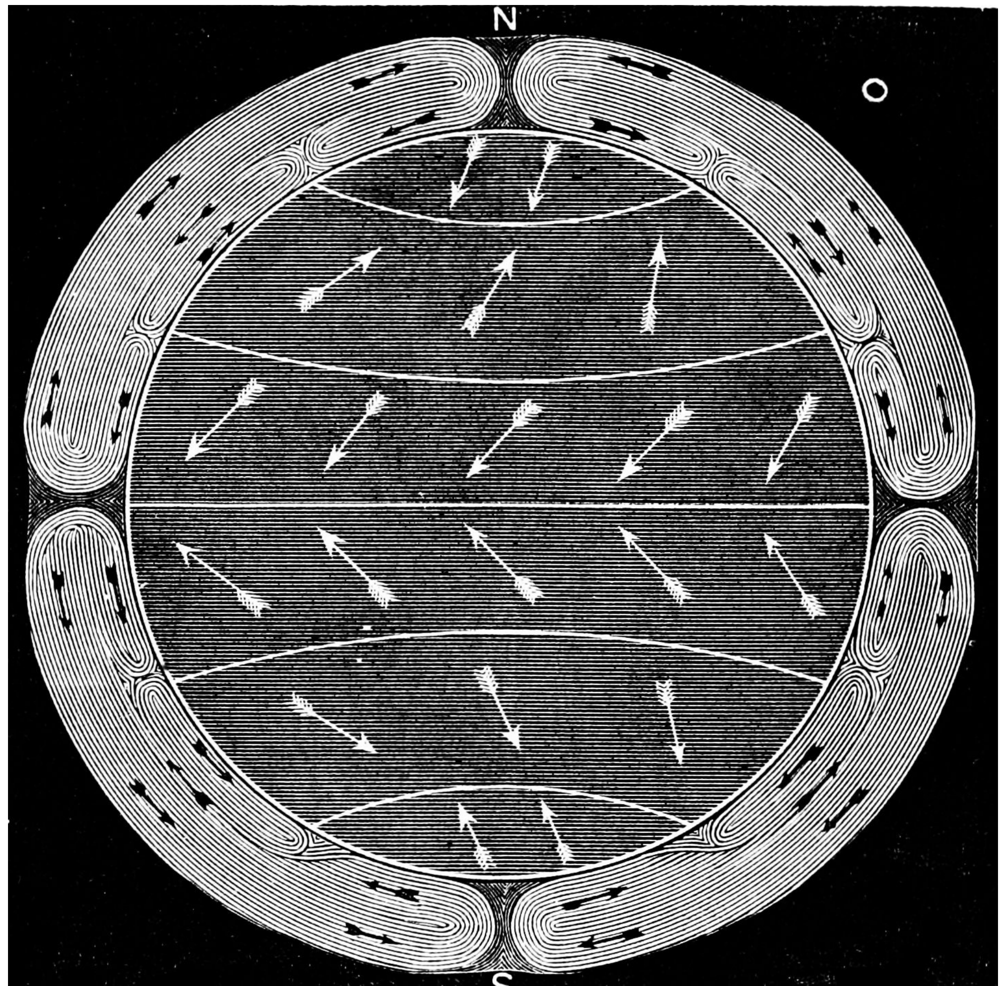
VI. *Concerning* the Cauſe *of the* General Trade-Winds: *By* Geo. Hadley, *Eſq;* *F. R. S.*

I Think the Cauſes of the General Trade-Winds have not been fully explained by any of thoſe who have wrote on that Subject, for want of more particularly and diſtinctly conſidering the Share the diurnal Motion of the Earth has in the Production of them: For although this has been mention'd by ſome amongſt the Cauſes of thoſe Winds, yet they have not proceeded to ſhew how it contributes to their Production; or elſe have applied it to the Explication of theſe Phænomena, upon ſuch Principles as will appear upon Examination not to be ſufficient.

That the Action of the Sun is the original Cauſe of theſe Winds, I think all are agreed; and that it does it by cauſing a greater Rarefaction of the Air in thoſe Parts upon which its Rays falling perpendicularly, or nearly ſo, produce a greater Degree of Heat there than in other Places; by which means the Air there becoming ſpecifically lighter than the reſt round about, the cooler Air will by its greater Denſity and Gravity, remove it out of its Place to ſucceed into it its ſelf, and make it riſe upwards. But it ſeems, this Rarefaction will have no other Effect than to cauſe the Air to ruſh in from all Parts into the Part where 'tis moſt rarefied, eſpecially from the North and South, where the Air is cooleſt, and not more from the Eaſt than the Weſt, as is commonly ſuppoſed: So that, ſetting aſide the diurnal Motion of the Earth, the Tendency of the Air would be from every Side towards that Part where the Sun's Action is moſt intenſe at the Time, and ſo a N. W. Wind be produced in the Morning, and a N. E. in the Afternoon, by Turns, on this Side of the Parallel of the Sun's Declination, and a S. W. and S. E. on the other.

That the perpetual Motion of the Air towards the Weſt, cannot be derived meerly from the Action of the Sun upon it, appears more evidently from this: If the Earth be ſuppoſed at Reſt, that Motion of the Air will be communicated to the ſuperficial Parts, and by little and little produce a Revolution of the Whole the ſame Way, except there be the ſame Quantity of Motion given the Air in a contrary Direction in other Parts at the ſame Time, which is hard to ſuppoſe. But if the Globe of the Earth had before a Revolution towards the Eaſt, this by the ſame means muſt be continually retard-

H 2 ed:



Hadley, mid-latitude, & polar cells

1st cell: Hadley cell

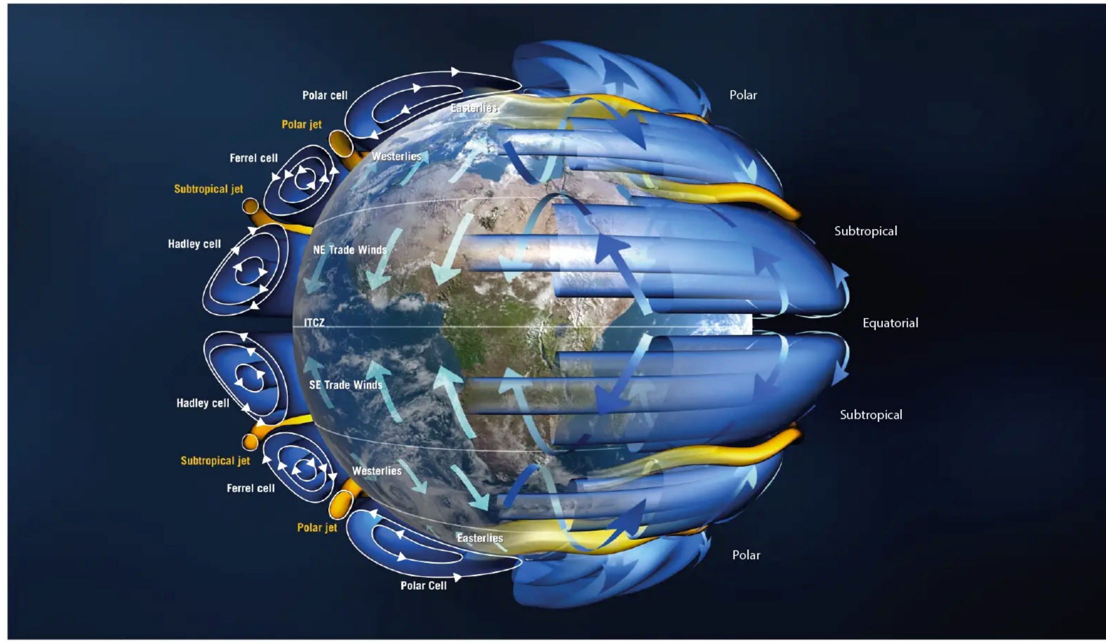
- Thermally direct
- Strengthening and widening with global warming

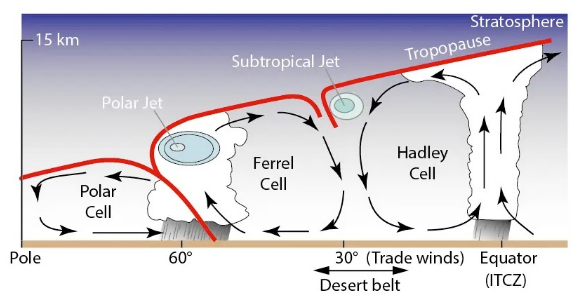
2nd cell: Mid-latitude or Ferrel cell

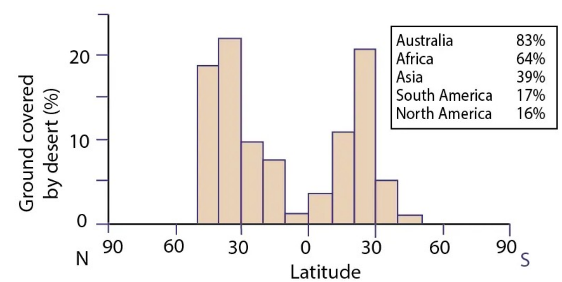
- Thermally indirect, therefore requires other mechanism.
- Stationary waves and transient eddies are responsible for this.
- Collapse of eddies give rise to this circulation.
- Strengthening and expanding poleward with global warming

3rd cell: Polar

- Thermally direct







Ice-albedo feedback

Sea-ice affects

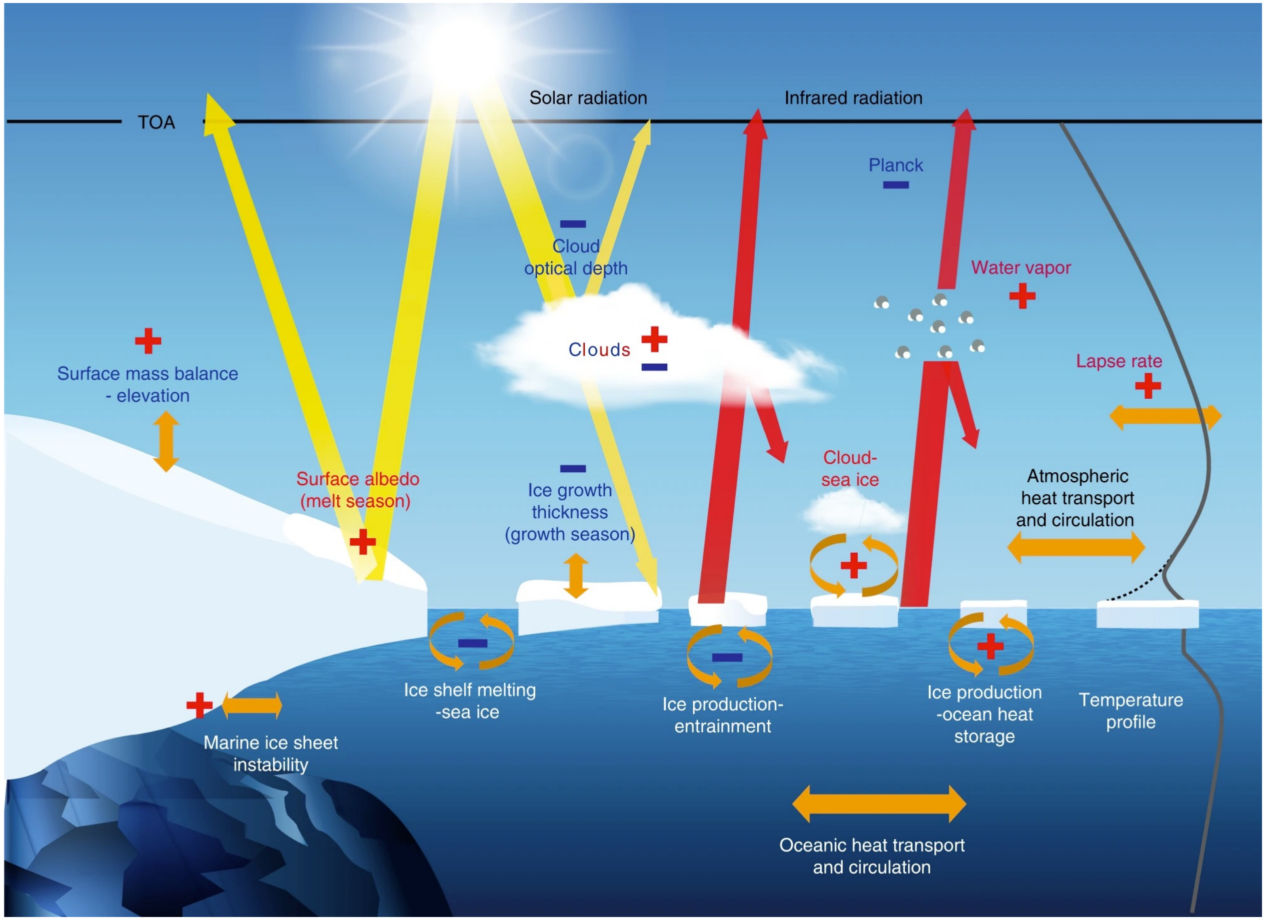
- Ocean-atmosphere sensible and latent heat fluxes
- Absorbed solar radiation

Ice-albedo feedback is a positive feedback that amplifies the temperature response to global warming.

Strongly coupled to

- Polar cloud processes
- Ocean heat transport

(NRC 2003)



A schematic of some important radiative and non-radiative feedbacks in polar regions involving the atmosphere, the ocean, sea ice and ice sheets. TOA refers to the top of the atmosphere. Solar radiation (in yellow) and Infrared Radiation (in red) represent the shortwave (solar) and longwave (infrared) radiation exchanges. A red plus sign means that the feedback is positive, a negative blue sign corresponds to a negative feedback. Both signs are present for cloud feedbacks as both positive and negative feedbacks are occurring simultaneously and the net effect is not known. The gray line on the right represents a simplified temperature profile in polar regions for the atmosphere and the ocean, the dashed line corresponding to a strong surface inversion. Oceanic and atmospheric heat transport are mentioned but without signs as the processes involved are not restricted to polar regions and it is not clear if they could be formally expressed using a closed feedback loop.

(Goosse *et al.* 2018)

Ice-albedo feedback

- $\downarrow \text{Area}_{\text{sea ice}} \Rightarrow \uparrow I(\text{absorbed})_{\text{ocean sfc}}$
- $\uparrow \text{Length}_{\text{melt season}} \Rightarrow \downarrow \alpha_{\text{sea ice}}$

  $\Rightarrow \uparrow$ solar heating (summer)

The observed changes above are causing:

- Accelerating ice melt
- Decreasing sea ice concentration/cover

(Perovich 2009)

Water vapor-temperature feedback

Warming troposphere $\Rightarrow$

$\uparrow$ evaporation and $\uparrow$ latent heat release $\Rightarrow$

$\uparrow$ moisture storage capacity $\Rightarrow$

Increased water vapor absorbs and re-emits more IR $\Rightarrow$

$\uparrow$ tropospheric warming

- Water vapor feedback is the most important positive feedback in climate models. It is important in itself, and also because it amplifies the effect of every other feedback and uncertainty in the climate system.
- Water vapor and ice/snow albedo perturbations feed on each other, with less ice => warmer temperatures, => more water vapor… water vapor feedback increases the importance of other temperature dependent feedbacks in the system.

(Jacobson *et al.* 2000, NRC 2003, Held and Soden 2000)

Vegetation-radiation feedback

Forests influence climate through:

- Physical, chemical, and biological processes that affect:
  - Planetary energetics
  - Hydrologic cycle
  - Atmospheric composition

- Complex and nonlinear forest-atmosphere interactions in the high-latitudes can amplify anthropogenic climate change.
  - Earlier snowmelt
  - Low albedo of boreal forests is a positive climate forcing

- Boreal forest is growing farther northward, and may replace current tundra.

- Reduction in snow cover & albedo adds ~3 W/m^2 of local heating to atmosphere.

(Foley 2005)

Taiga-Tundra effect

The albedo for snow decreases in a forest to about 0.35. A forest will temper the cooling effect associated with high reflective snow.

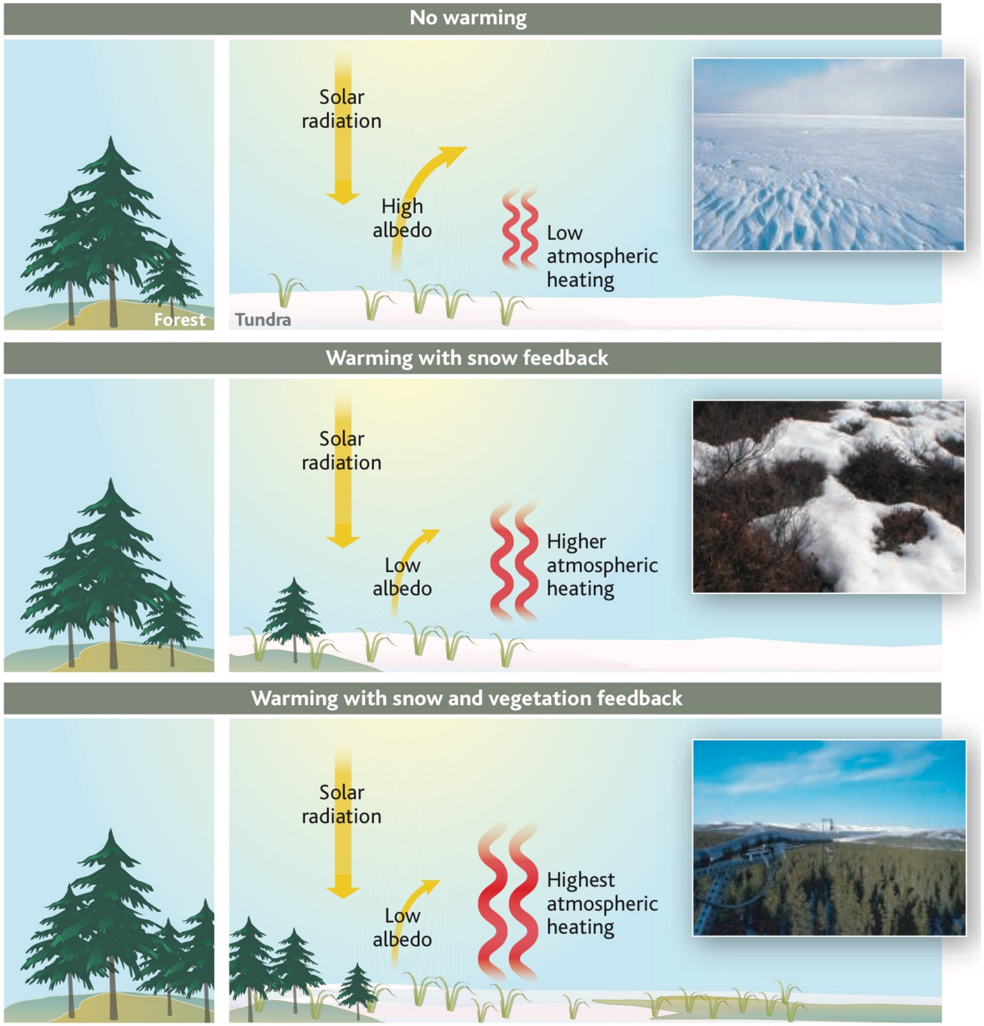
(Clausen 2006)

Tipping points in the tundra

Chapin *et al.,* suggest that greenhouse warming is now:

- Reducing the duration of seasonal snow cover in the Arctic.
- Shortening the snow-covered season by roughly 2.5 days per decade, thereby shifting the albedo of the landscape away from bright snow toward darker vegetation and soil.
  - This decrease in albedo allows the ground to absorb more solar radiation, warm the surface, and then provide additional heat to the atmosphere
  - This adds another ~3 W/m^2 of local heating to the atmosphere.
- Encouraging more shrubs to grow in the tundra, and boreal forest to grow farther northward, replacing the tundra ecosystems that exist there today.
  - These changes in the land surface also profoundly affect the heat transfer between the surface and the atmosphere.

(Foley 2005)



Vicious cycle. Chapin *et al.* describe positive-feedback mechanisms from changing snow and vegetation cover on the climate of the Arctic. These mechanisms work to amplify global warming in the Arctic by reducing the highly reflective snow cover (**top** and **middle**) and expanding the cover of shrubs and trees (**top** and **bottom**).

Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests

The world's forests influence climate through physical, chemical, and biological processes that affect planetary energetics, the hydrologic cycle, and atmospheric composition.

These complex and nonlinear forest-atmosphere interactions can dampen or amplify anthropogenic climate change.

- Tropical, temperate, and boreal reforestation and afforestation attenuate global warming through carbon sequestration.
- Biogeophysical feedbacks can enhance or diminish this negative climate forcing.
- Tropical forests mitigate warming through evaporative cooling, but the low albedo of boreal forests is a positive climate forcing. The evaporative effect of temperate forests is unclear.

The net climate forcing from these and other processes is not known.

(Bonan *et al.* 2008)

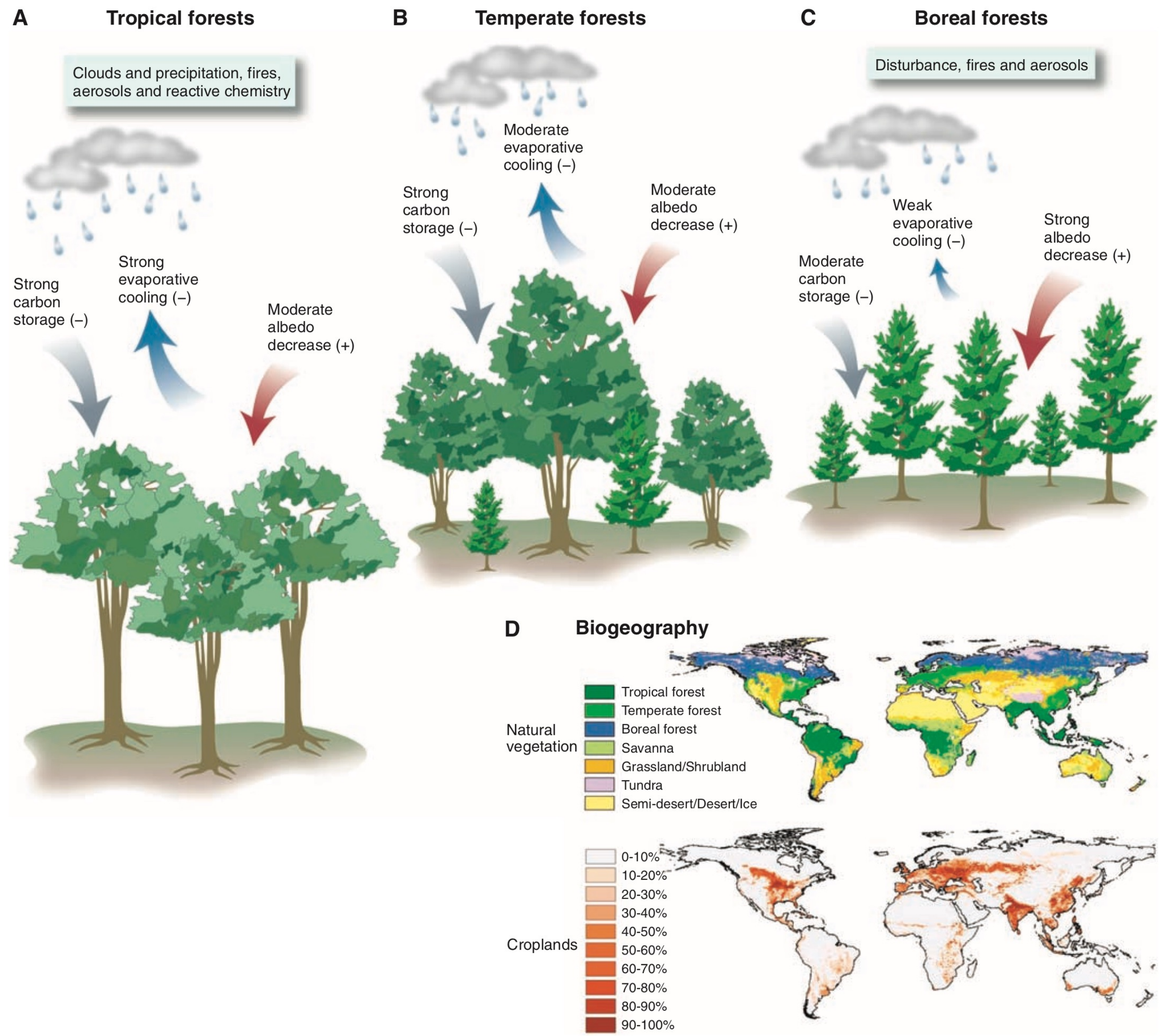
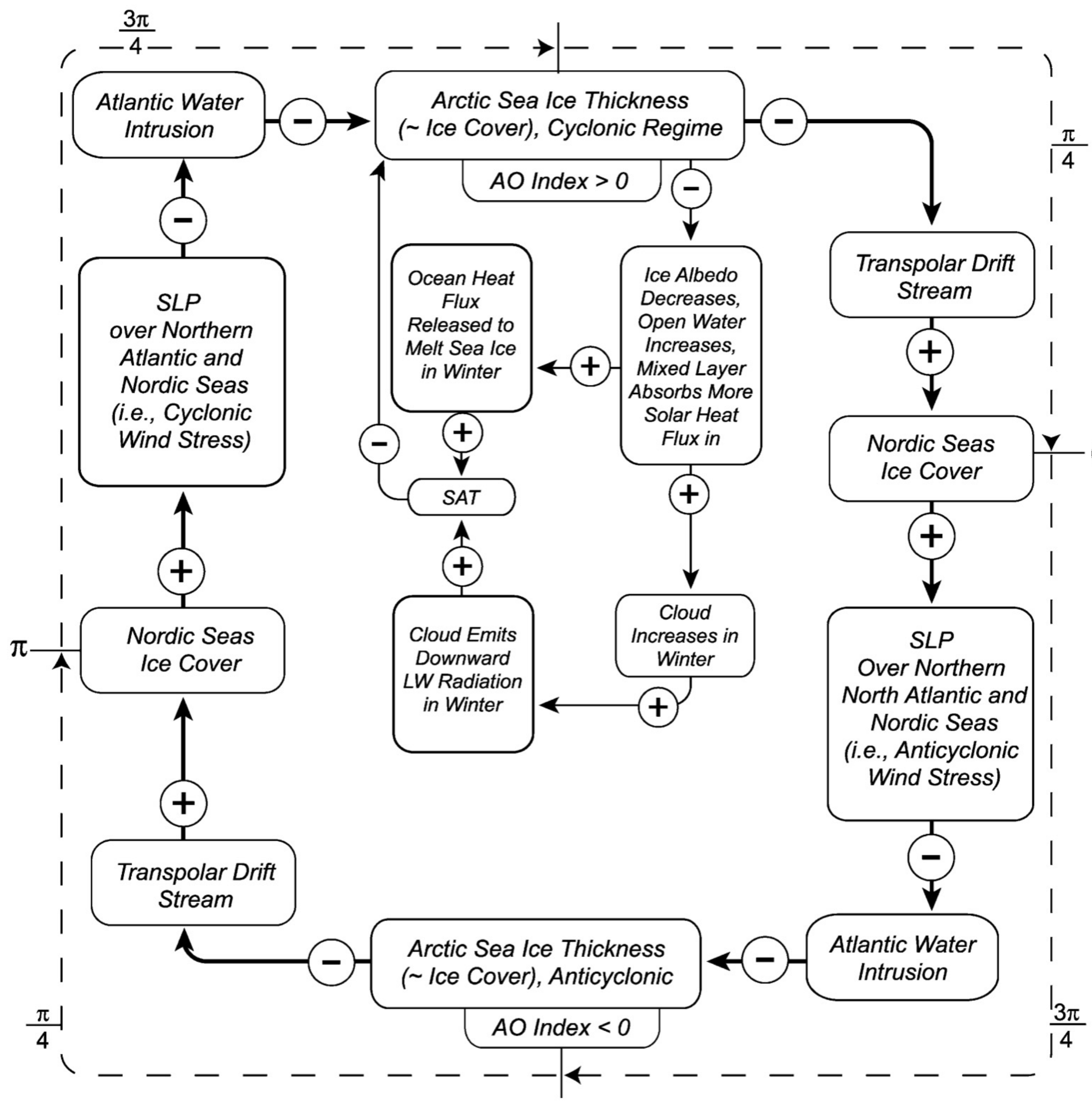


Fig. 3. Climate services in (**A**) tropical, (**B**) temperate, and (**C**) boreal forests. Text boxes indicate key processes with uncertain climate services. (**D**) Natural vegetation biogeography in the absence of human uses of land and cropland (percent cover) during the 1990s. Vegetation maps are from (*51*).

Feedback loop for the observed decadal Arctic climate cycle

Fig. 13 The proposed modified feedback loop for the observed decadal Arctic climate cycle (Mysak and Venegas (1998) and the observed long-term downward trend due to a positive feedback of sea ice (Ikeda et al. 2001) and clouds (Miller and Russell 2003; Ikeda et al. 2003). An *arrow* with a *plus sign* between *box A* and *box B* means that a positive (negative) anomaly in A would cause a positive (negative) anomaly in B after a certain delay, while an *arrow* with a *minus sign* would results in a negative (positive) anomaly in *B*



(Wang *et al.* 2005)

Northward heat flux feedback hypothesis

Northward heat flux = $\left(\overline{v'T'}\right)$

Planetary and Arctic feedbacks

$+\Delta T_{sfc}$ (global) $\Rightarrow +\Delta\left(\overline{v'T'}\right) \Rightarrow$ amplifies arctic feedbacks

- Ice-albedo feedback
  $-\Delta \text{Area}_{\text{Sea ice}} \Rightarrow +\Delta I\left(\text{absorbed}\right)_{\text{ocean sfc}}$
  $\Rightarrow$ amplifies $+\Delta T_{sfc}$
- Taiga-tundra feedback
  $\Rightarrow$ amplifies $+\Delta T_{sfc}$
- Water vapor feedback
- Other Arctic feedbacks...

Climate sensitivity "export"

⇖ ⇙

$+\Delta T_{sfc}$
(high-latitudes)

(Noble 2009)

Discussion

Northward heat flux feedback hypothesis

Climate sensitivity "export" ⇒

- Eddies, including baroclinic eddies, turbulence, stationary waves, transient waves, and hurricanes, are responsible for positive northward heat flux.
- A poleward shift of baroclinic eddies, storm tracks, etc. has been observed.
- A positive northward heat flux may amplify other arctic feedbacks, including, but not limited to, ice-albedo, taiga-tundra, and water vapor feedback.

- Hypothesis can be tested by coupled atmosphere-ocean climate model simulations.
- Arctic system is moving into a new state.
- The change appears to be driven largely by feedback-enhanced global warming.
- There seem to be few if any processes or feedbacks within the Arctic system that are capable of changing the current trajectory.

(Foley 2005, Noble 2009)

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