

On the Nature of Climate Change

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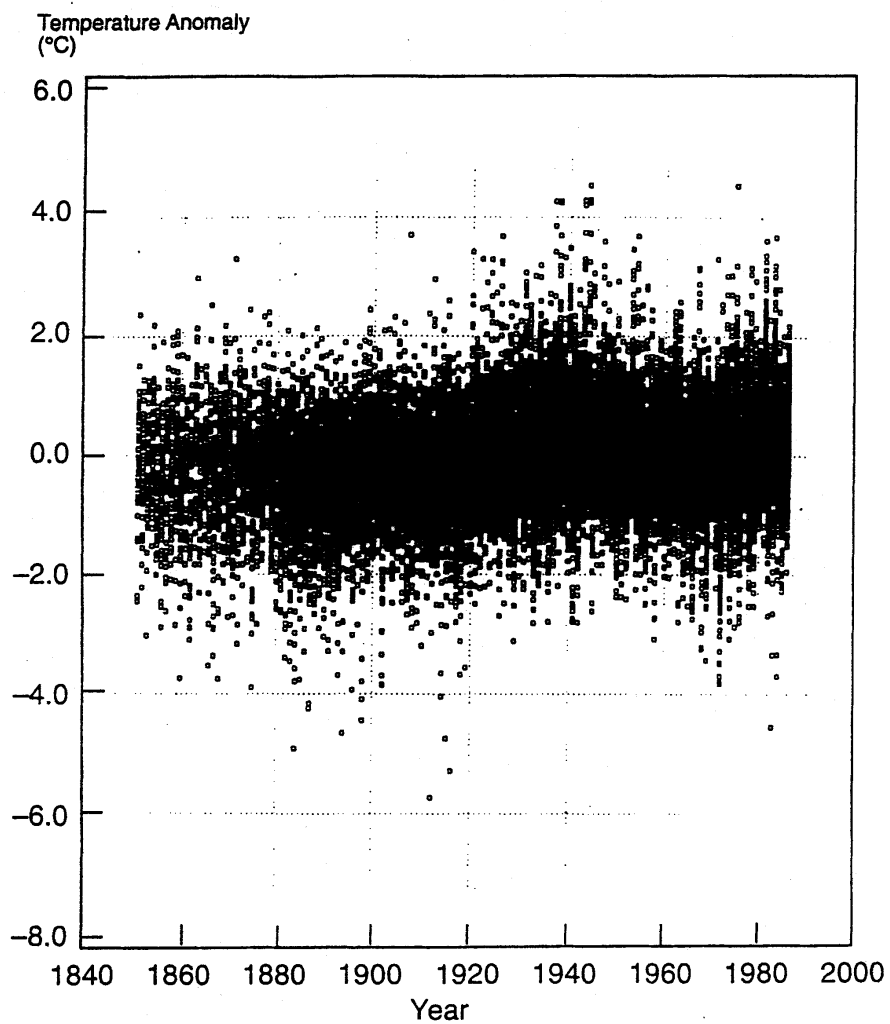
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2 May 2006

Change is the norm in climate. The climate is never standing still. The climate is either cooling or warming. To consider each a cause for alarm is to be perpetually alarmed. A static climate would be a true cause for alarm. However, alarm may also be justified if changes are well beyond the norm, but as we will see, the norm for change is really quite large. Moreover, climate change is more than global warming or cooling. Regional variations are greater than global changes.

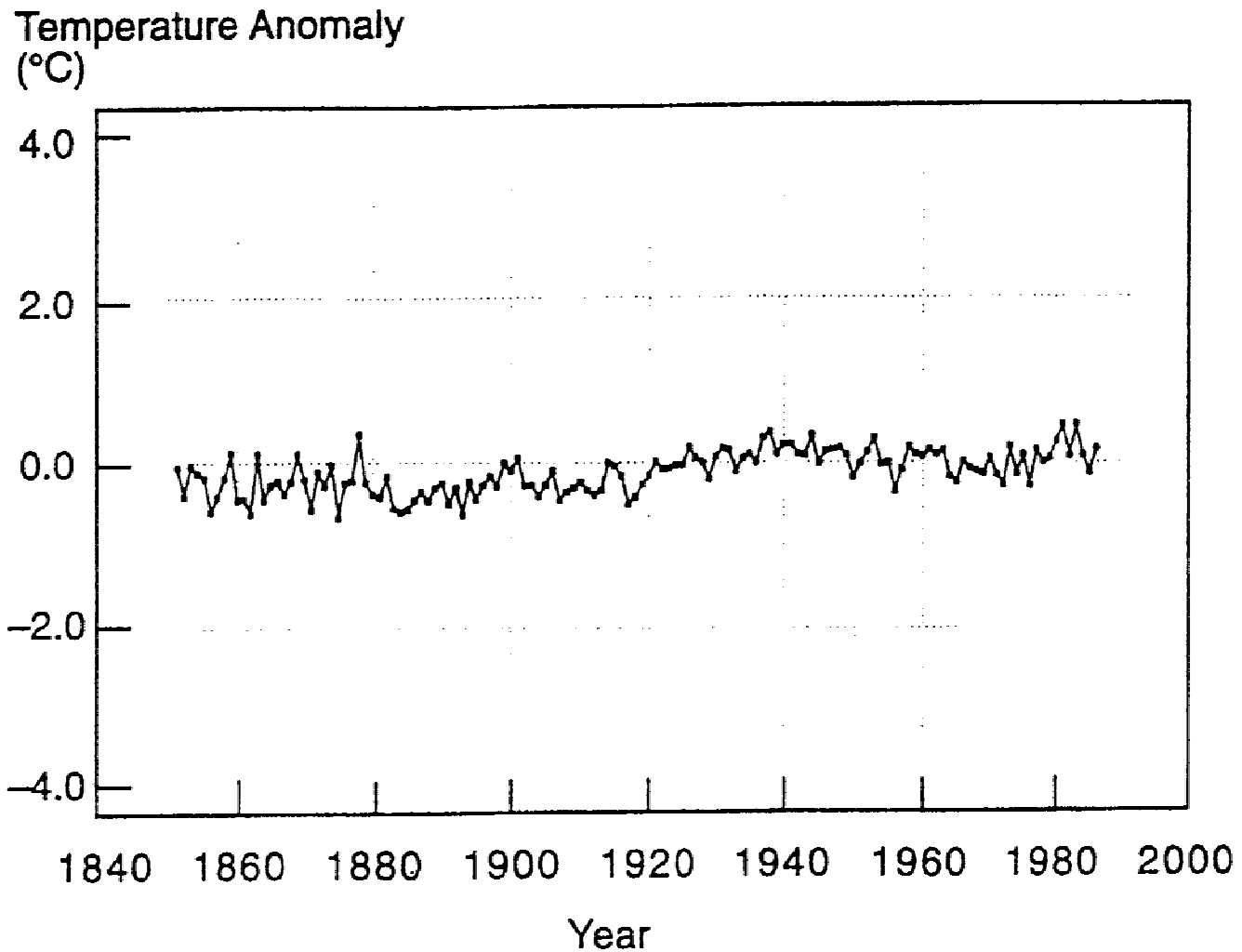
We will begin with some description of observations

Deviations of Annual Mean Temperature from Long-term Average



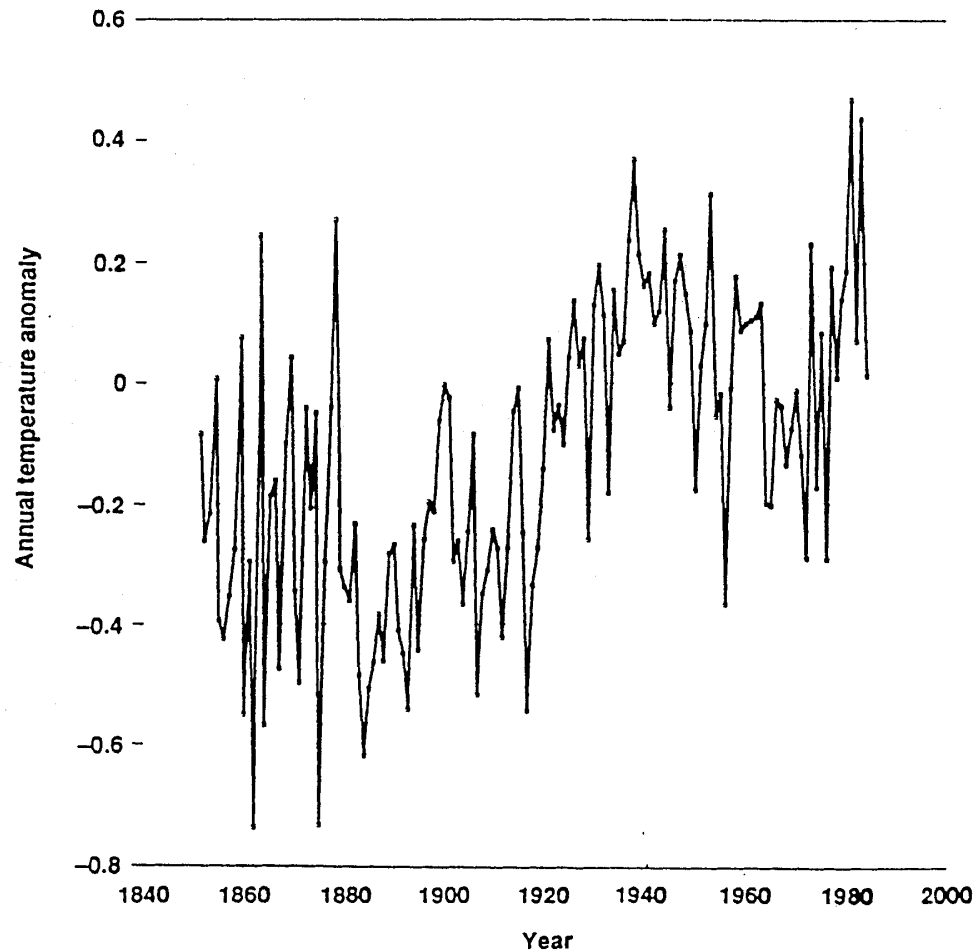
1. Data points averaged to obtain time record of global mean temperature. Note points range from less than -2C to more than +2C.

Globally Averaged Deviations from Average Temperature Plotted on a Scale Relevant to the Individual Station Deviations



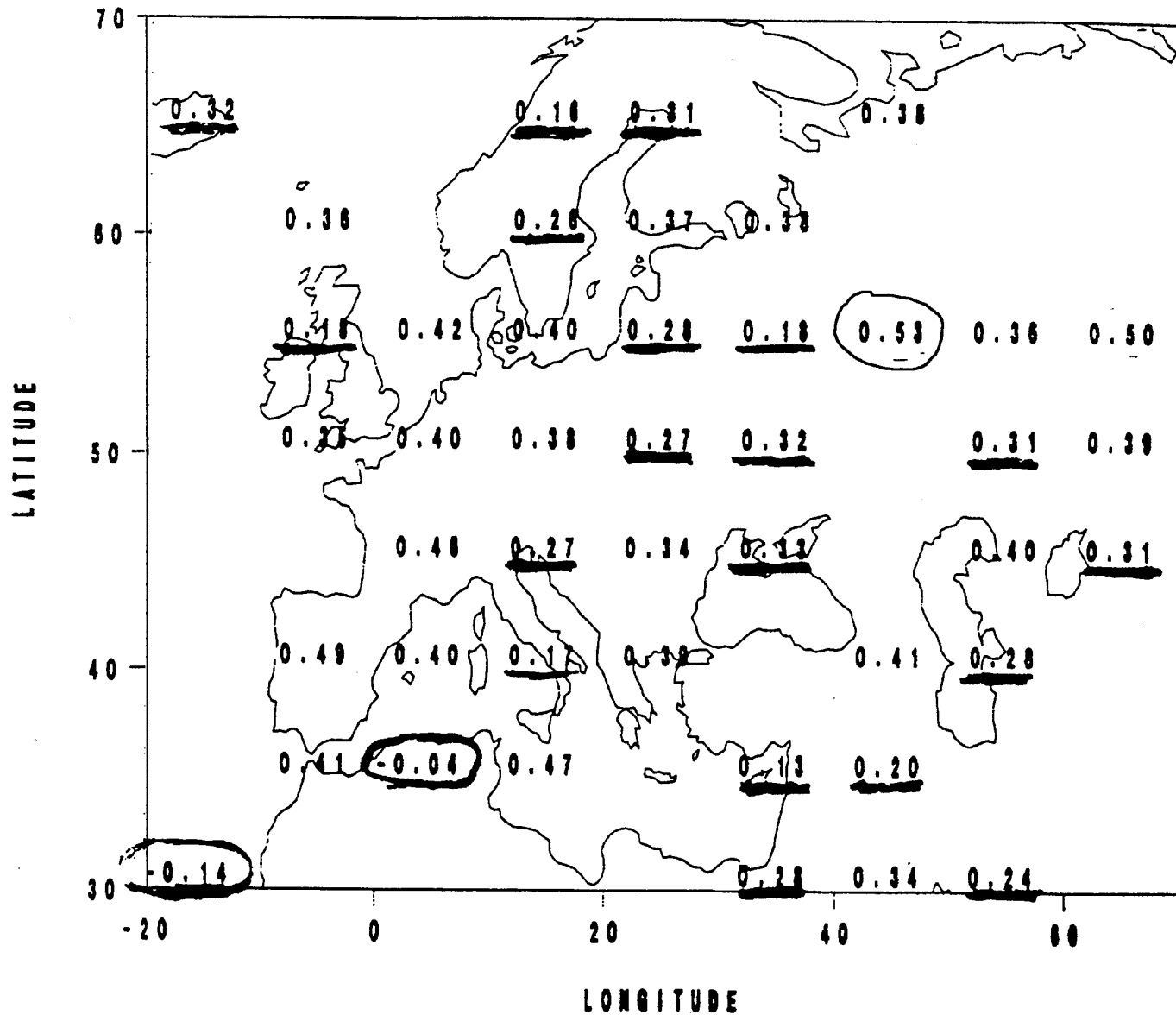
2. Average of points in previous figure.

CRU NH Average Annual Anomalies (1851-1984)

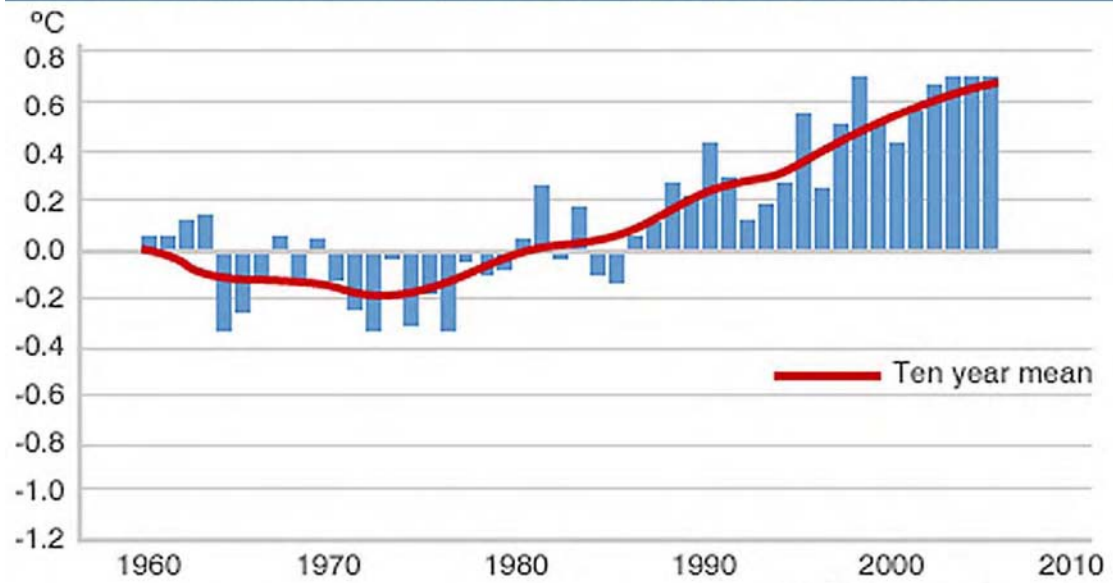


**3. Curve in previous figure stretched to fill graph.
Note that range is now from about -0.6C to +0.3C.**

Individual Gridpoint Correlations with respect to CRU NH Average



NORTHERN HEMISPHERE TEMPERATURE ANOMALY 1960-2005



SOURCE: Hadley Centre/UEA

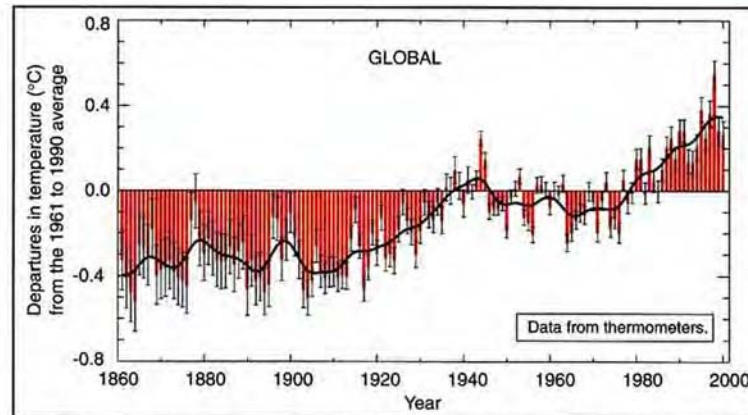


Figure 2: Combined annual land-surface air and sea surface temperature anomalies (°C) 1861 to 2000, relative to 1961 to 1990. Two standard error uncertainties are shown as bars on the annual number. [Based on Figure 2.7c]

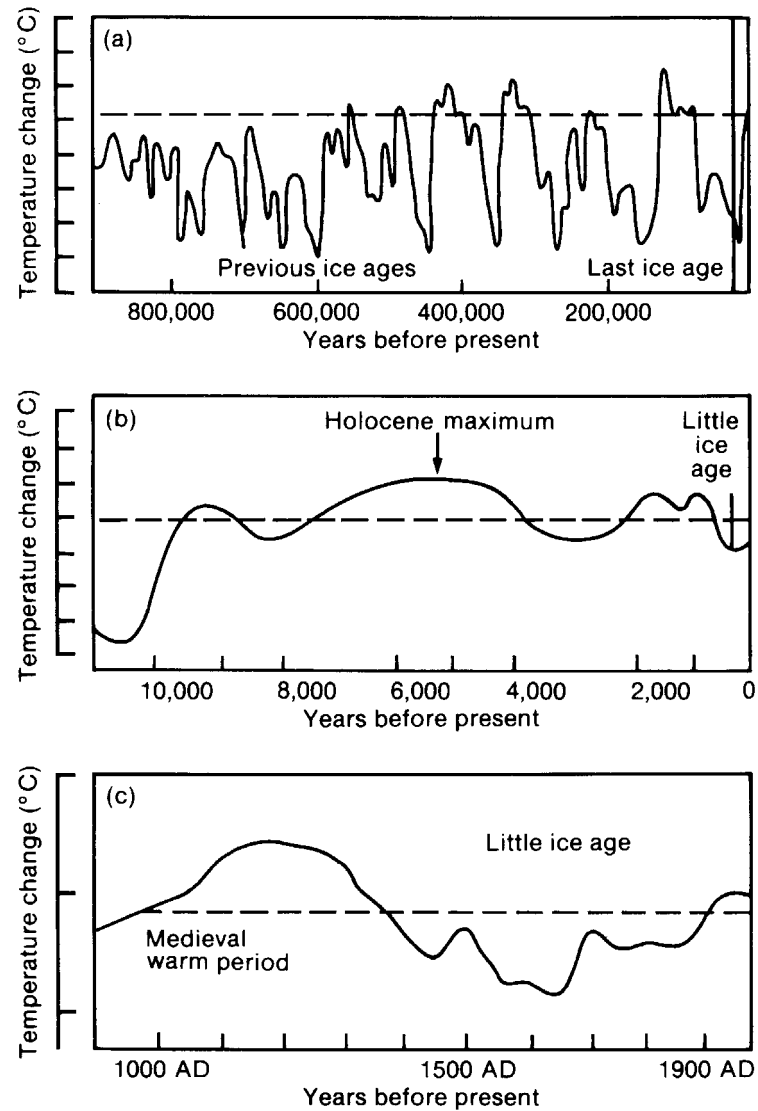


Figure 7.1: Schematic diagrams of global temperature variations since the Pleistocene on three time-scales: (a) the last million years, (b) the last ten thousand years, and (c) the last thousand years. The dotted line nominally represents conditions near the beginning of the twentieth century.

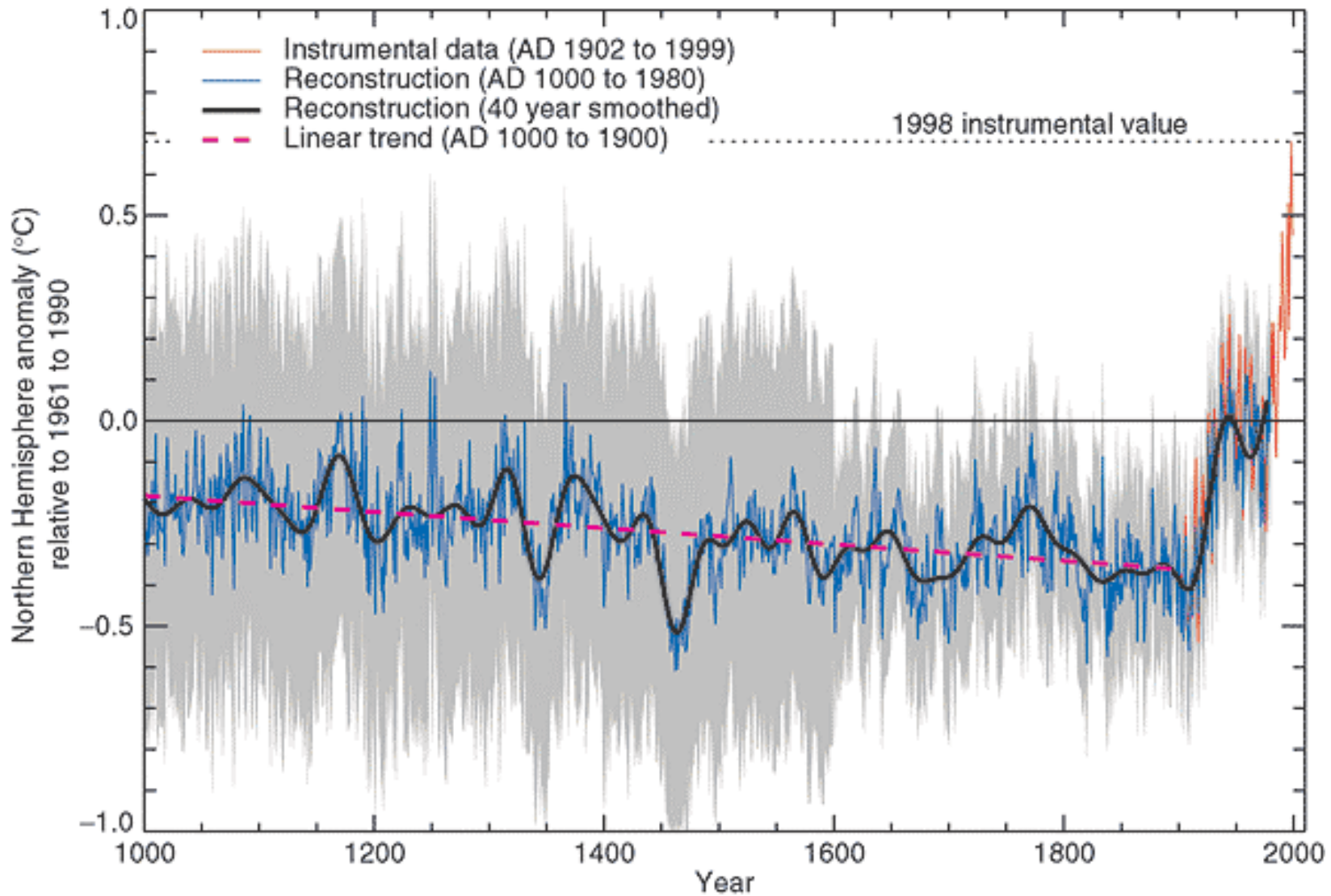
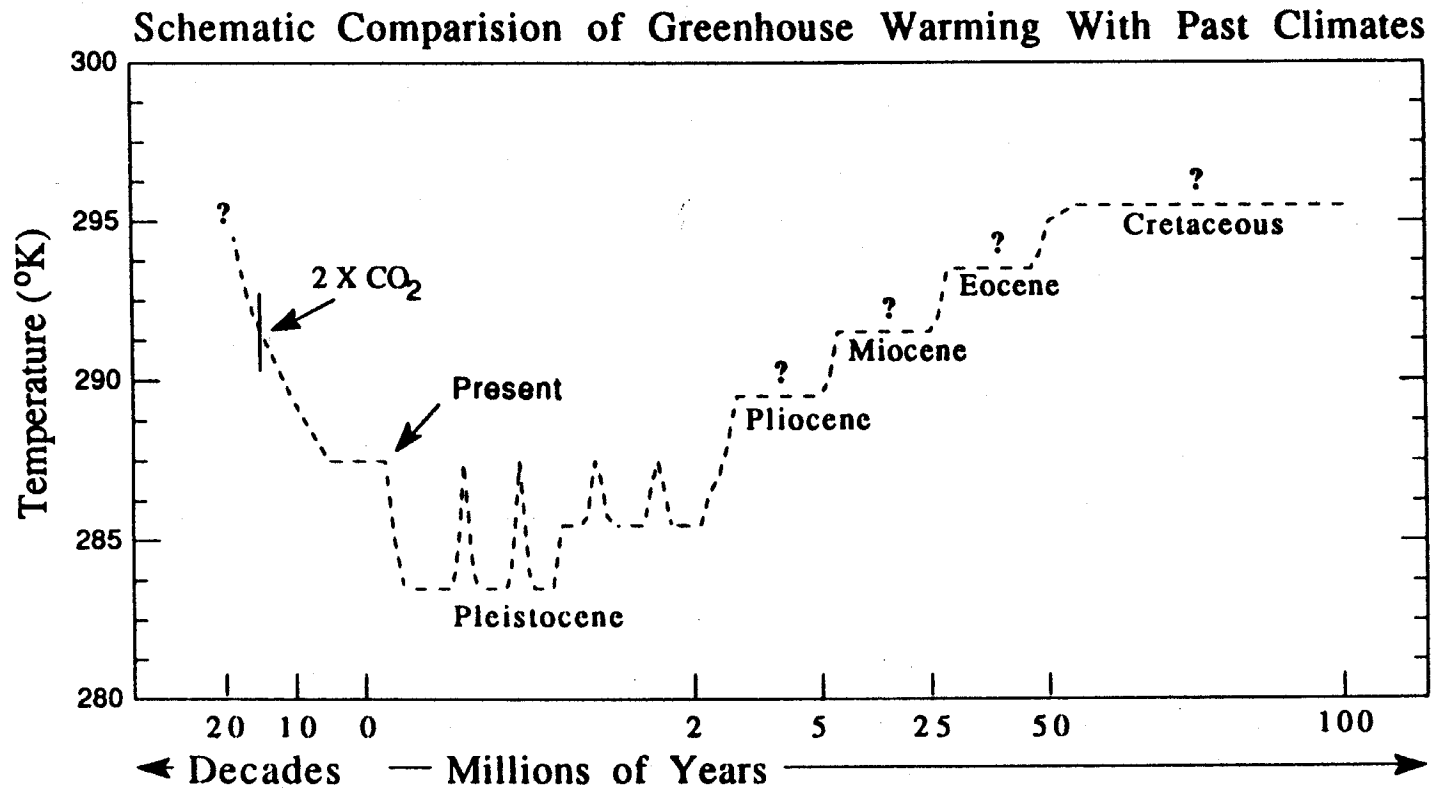
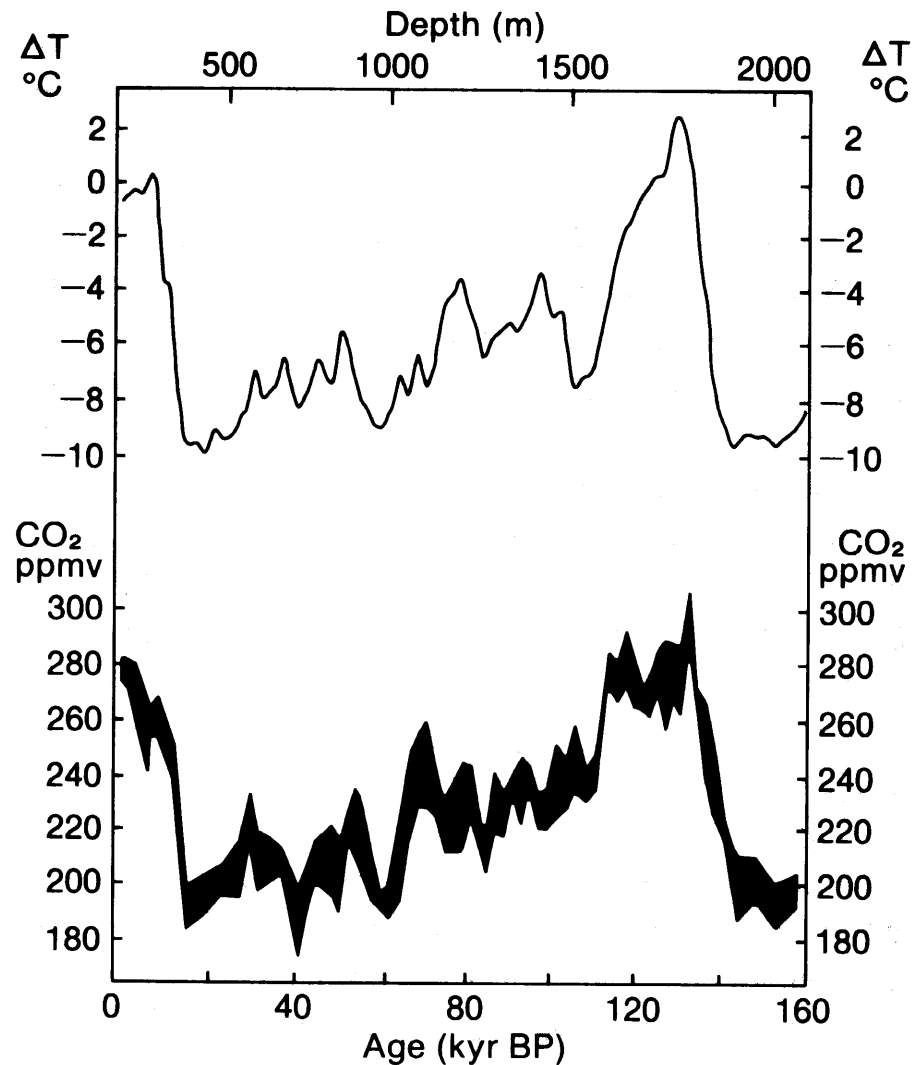


Fig. 14.2. Schematic comparison of future greenhouse warming with past changes in temperature. Note that pre-Pleistocene changes are not well fixed in absolute magnitude, but the relative warmth of the intervals is approximately correct. [From Crowley, 1989] *Reproduced with permission of Kluwer Academic Publishers.*



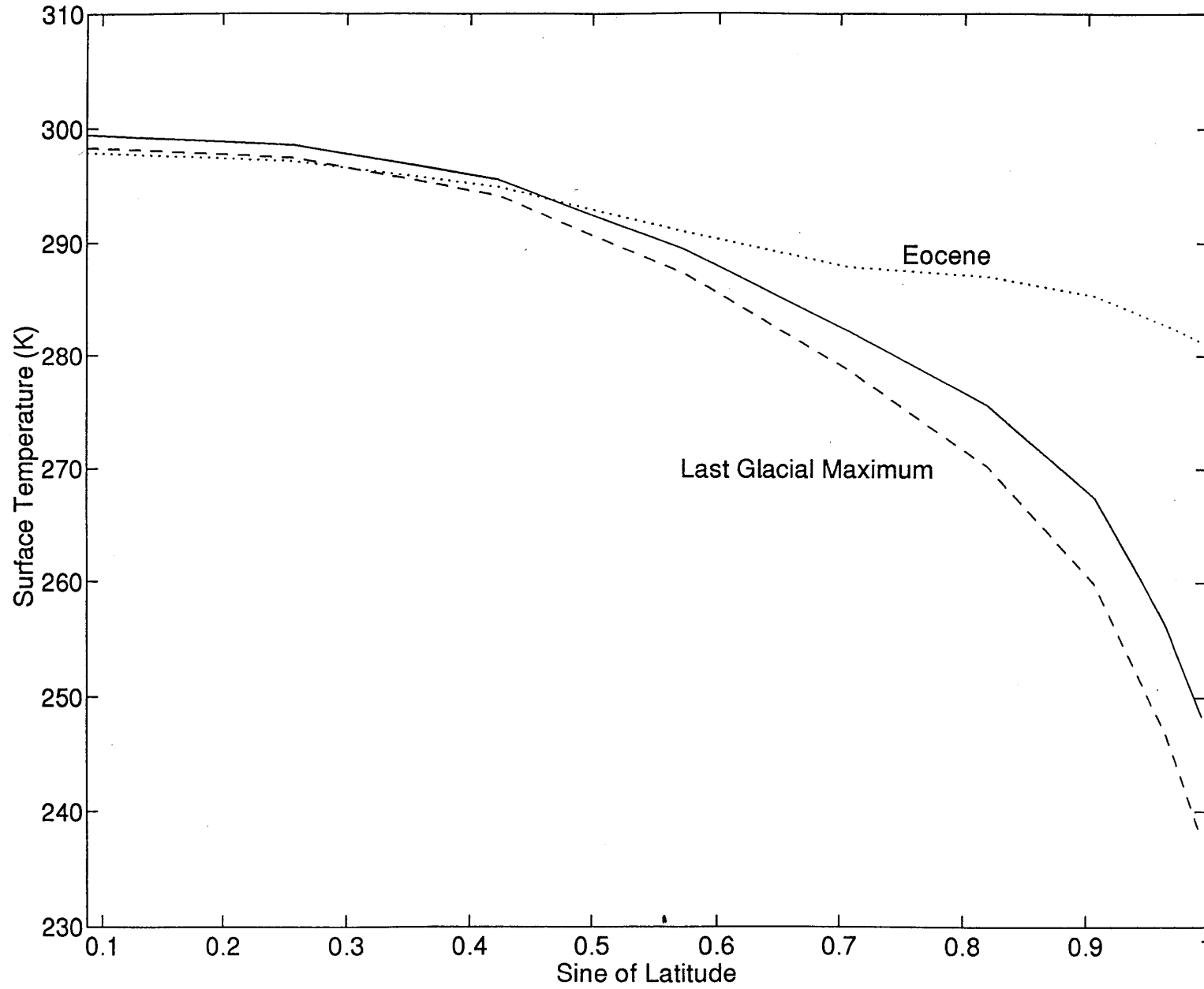


The relation between global mean temperature and CO₂ is suggestive, but by now, we know that changes in temperature preceded changes in CO₂.

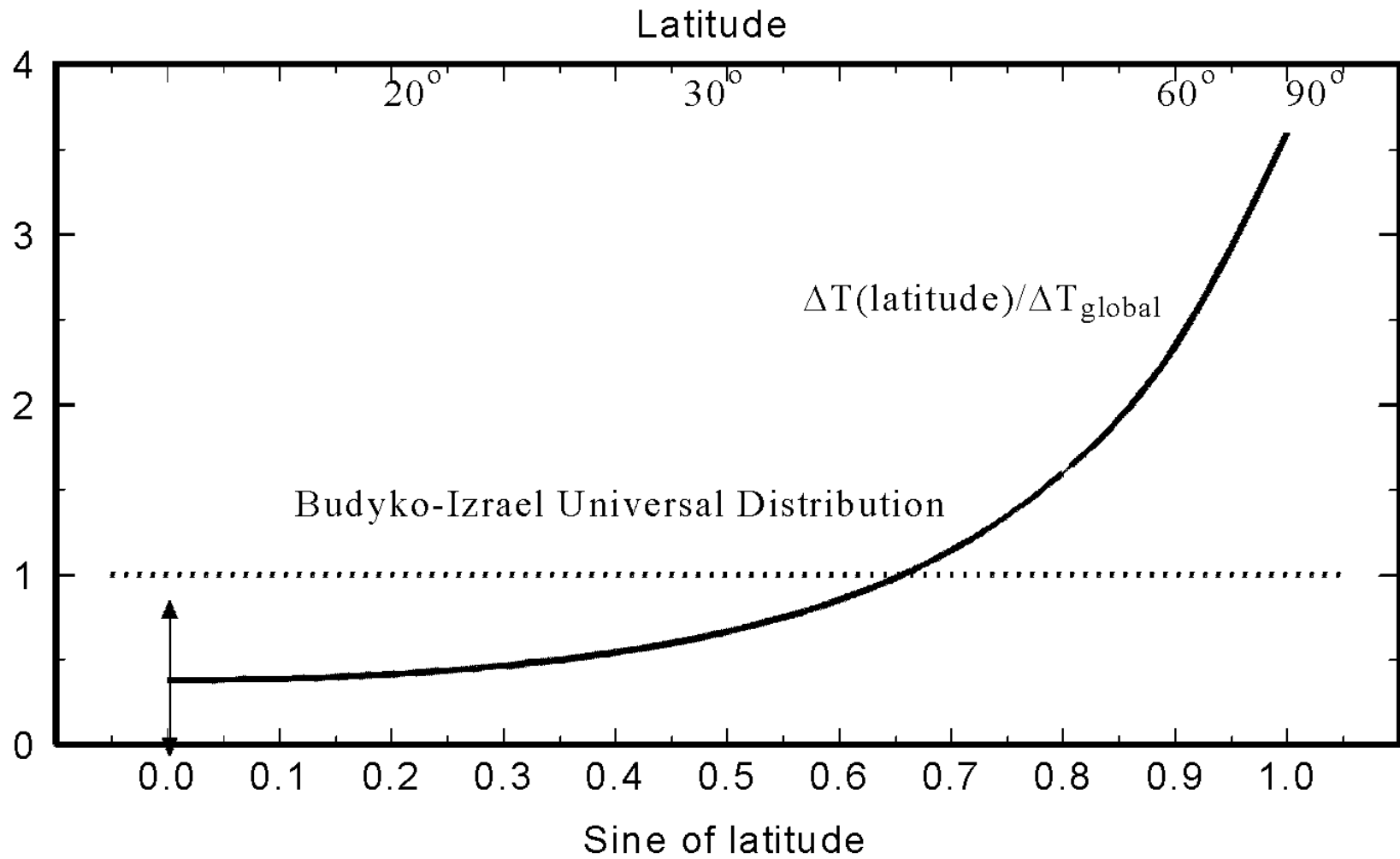
Figure 1.6: CO₂ concentrations (bottom) and estimated temperature changes (top) during the past 160,000 years, as determined on the ice core from Vostok, Antarctica (Barnola et al., 1987). Temperature changes were estimated based on the measured deuterium concentrations.

Of course, as noted some time ago by Budyko and Izrael, climate change is not solely or even primarily described by global mean temperature. Prior to the last decade, we were pretty sure that tropical temperatures changed little while major climate changes were associated with changes in the temperature difference between the equator and the poles.

Zonally Averaged Surface Temperature in Various Epochs



Temperature change scaled by global mean change



In point of fact, the equator to pole temperature difference is always much less than would expect on the basis of radiative considerations. This is due to the transport of heat by the atmosphere and oceans.

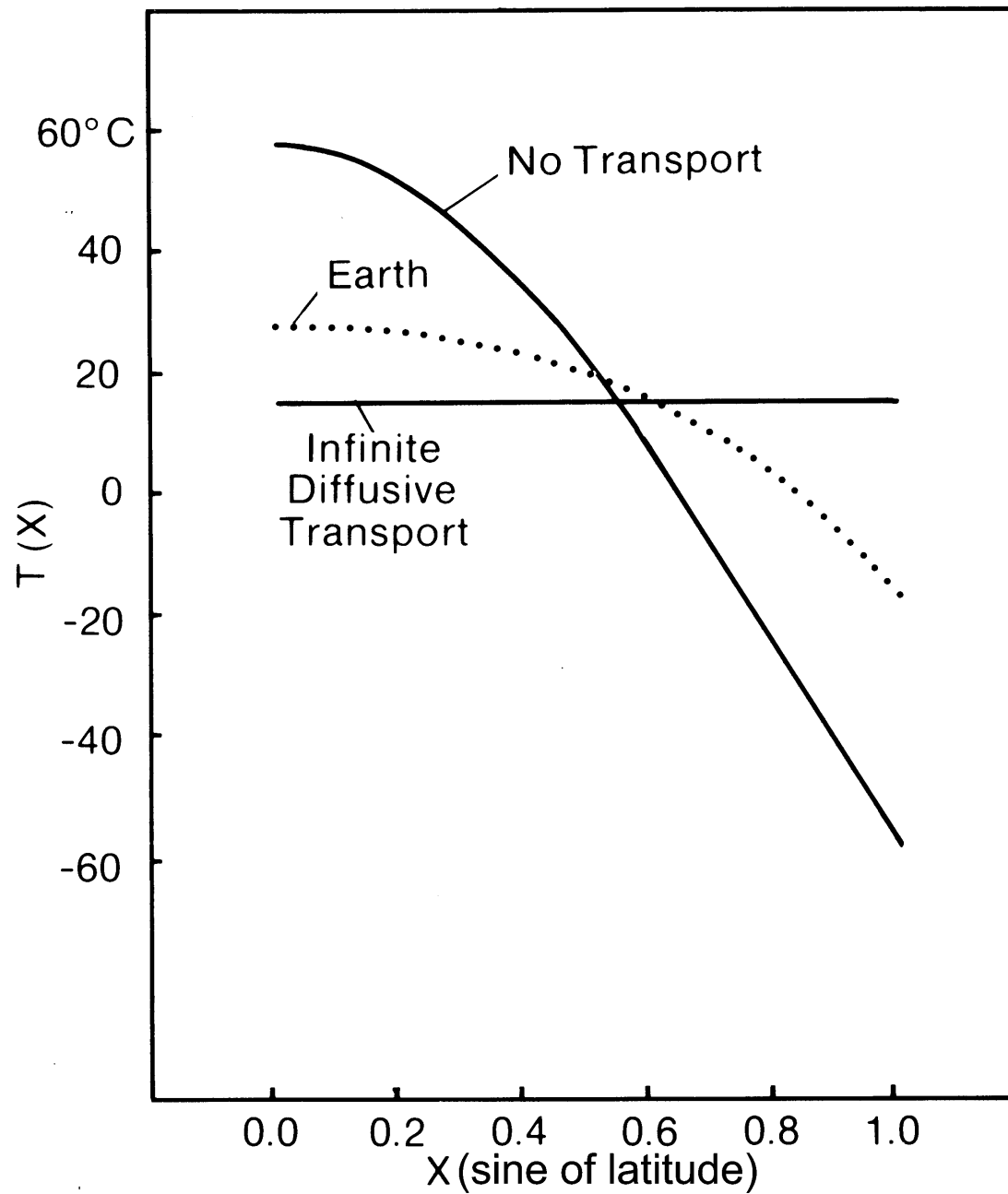


Fig. 1.6. Energy balance temperature ($^{\circ}\text{C}$) versus sine of latitude (x) for the cases of no transport, infinite transport, and present case (schematic). [From North et al., 1981] *Courtesy of American Geophysical Union.*

The cycles of ice ages are themselves an indication of the importance of transport - at least to the extent that the Milankovic hypothesis is correct.

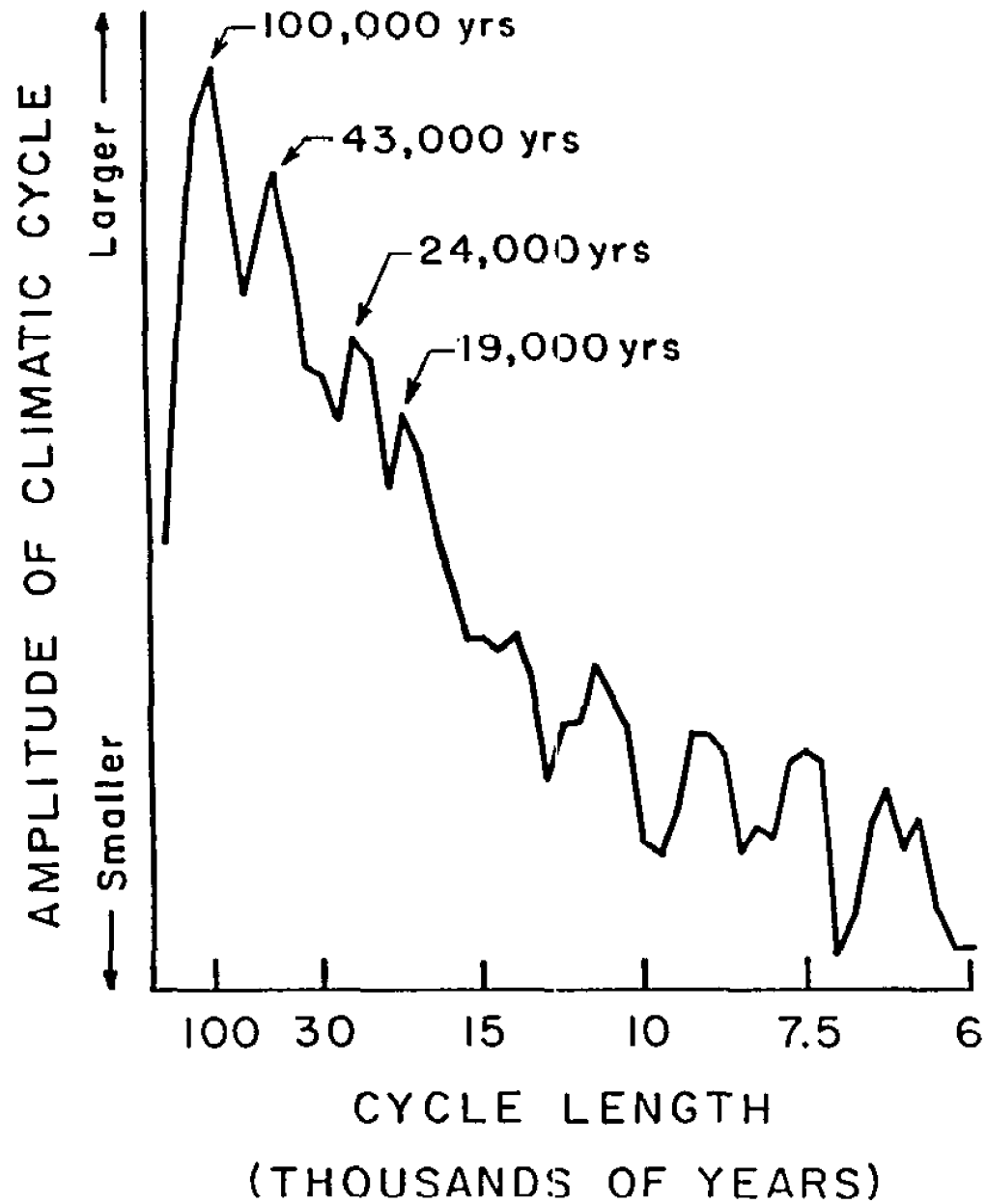


Figure 4 Normalized power spectrum of time series shown in Figure 3. (From Imbrie & Imbrie 1980.)

These orbital variations provide very little change in net radiation, but they profoundly impact regional and seasonal distributions of radiation, thus changing the pressure gradients that lead to motion changes.

These results should have resulted in two obvious questions:

What changes the heat flux between the tropics and high latitudes?

What keeps tropical temperatures from changing much?

What determines the global mean temperature?

Instead, the most common approach has been to assume changes are due to changes in CO₂, and to assume that heat fluxes automatically follow Budyko-Izrael curve.

COMPARISON OF CRETACEOUS TEMPERATURES: MODEL AND LIMITS

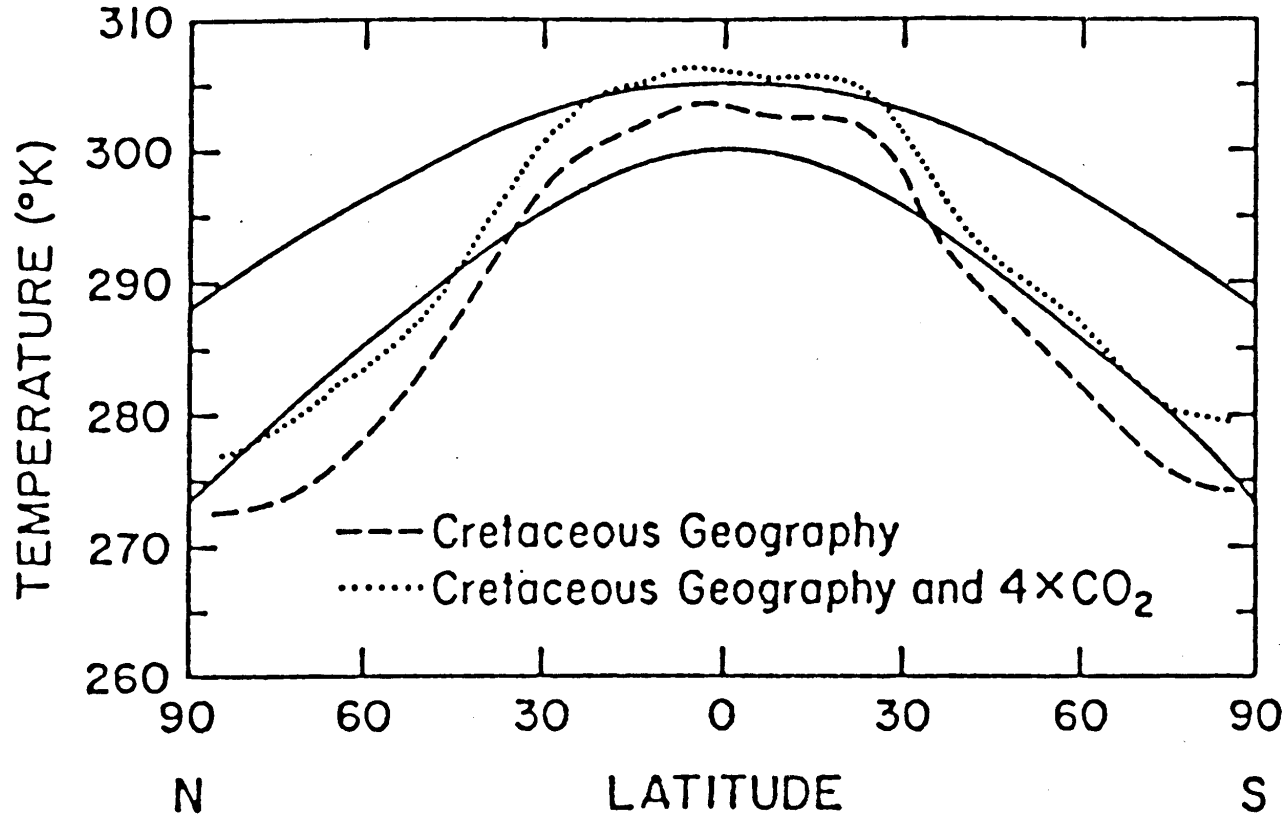
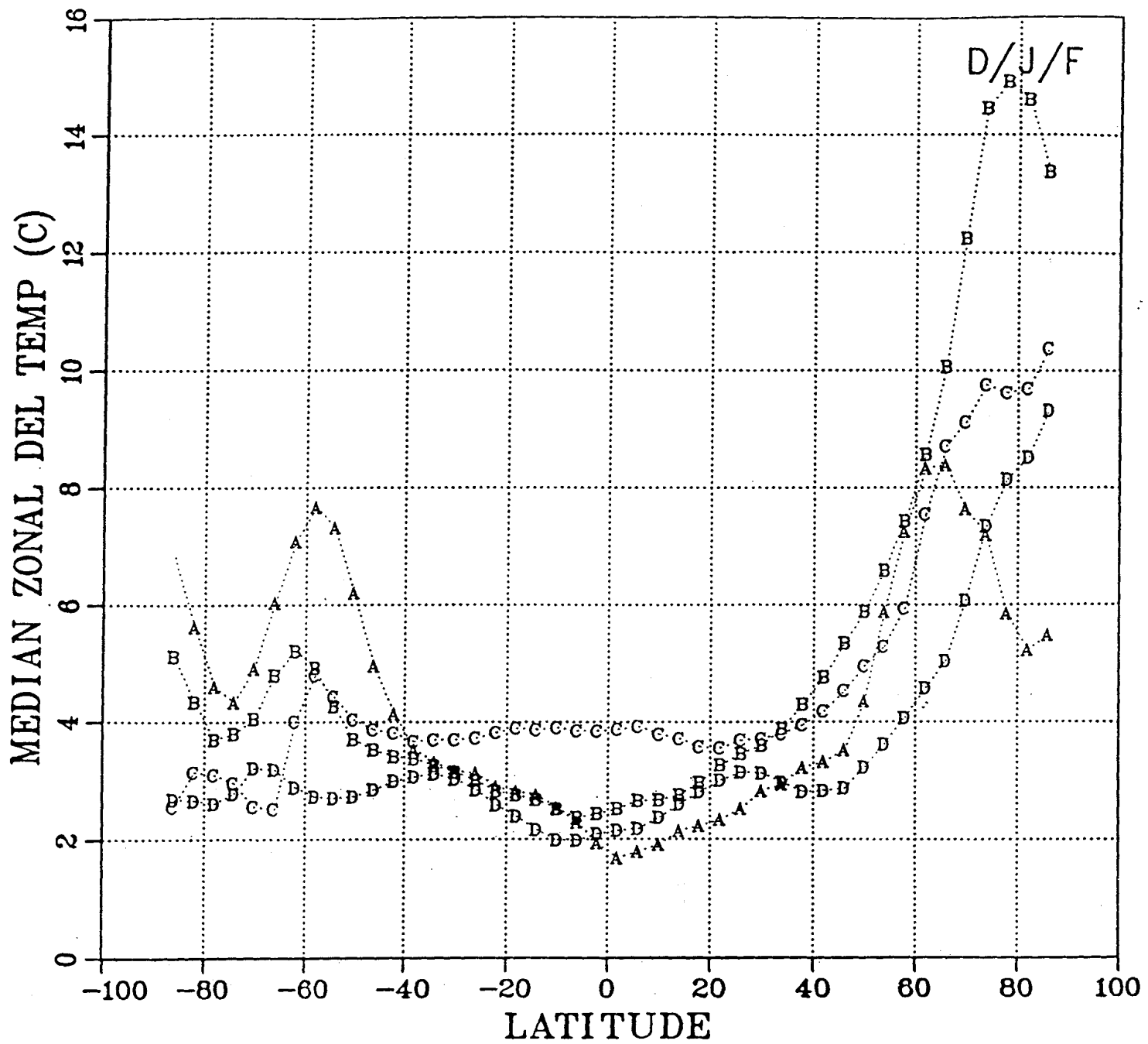


Fig. 4. Cretaceous zonally averaged surface temperature limits (degrees Kelvin) in comparison with Cretaceous model-derived surface temperatures for the geography and geography plus CO₂ quadrupling experiments.

| Eocene/Cretaceous | Models with greatly increased CO ₂ |
|--|--|
| Global mean temperatures increased about 8C | Global mean temperatures increase about 8C |
| Equator-to-pole temperature difference reduced from about 45C to 18C | Equator-to-pole temperature difference reduced MUCH less |
| Equatorial temperatures were previously measured to be 5C cooler than present. New analysis suggests temperature were from 2C cooler to possibly slightly warmer than present. | Equatorial temperatures much warmer than present. |

N.B. Reduction of equator-to-pole temperature differences require increase in poleward heat flux from 5 petawatts to 6 petawatts.



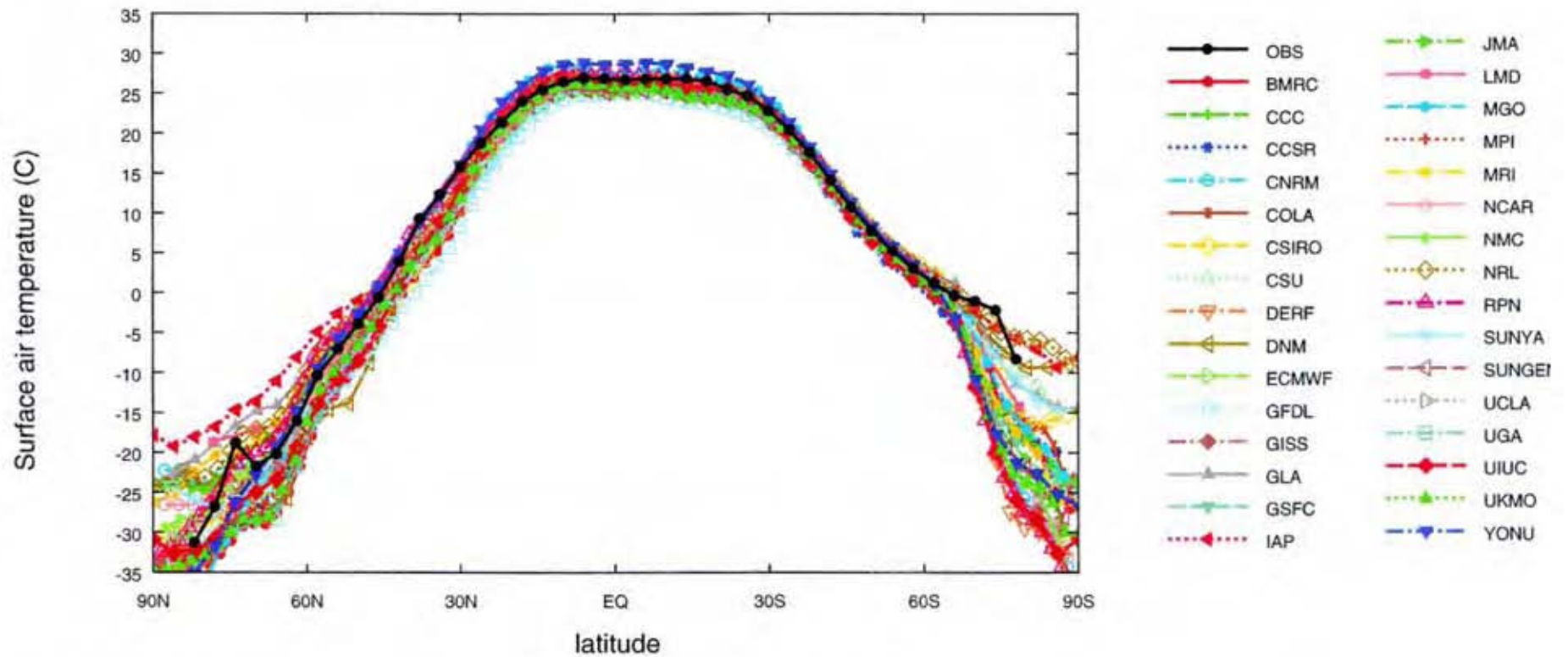
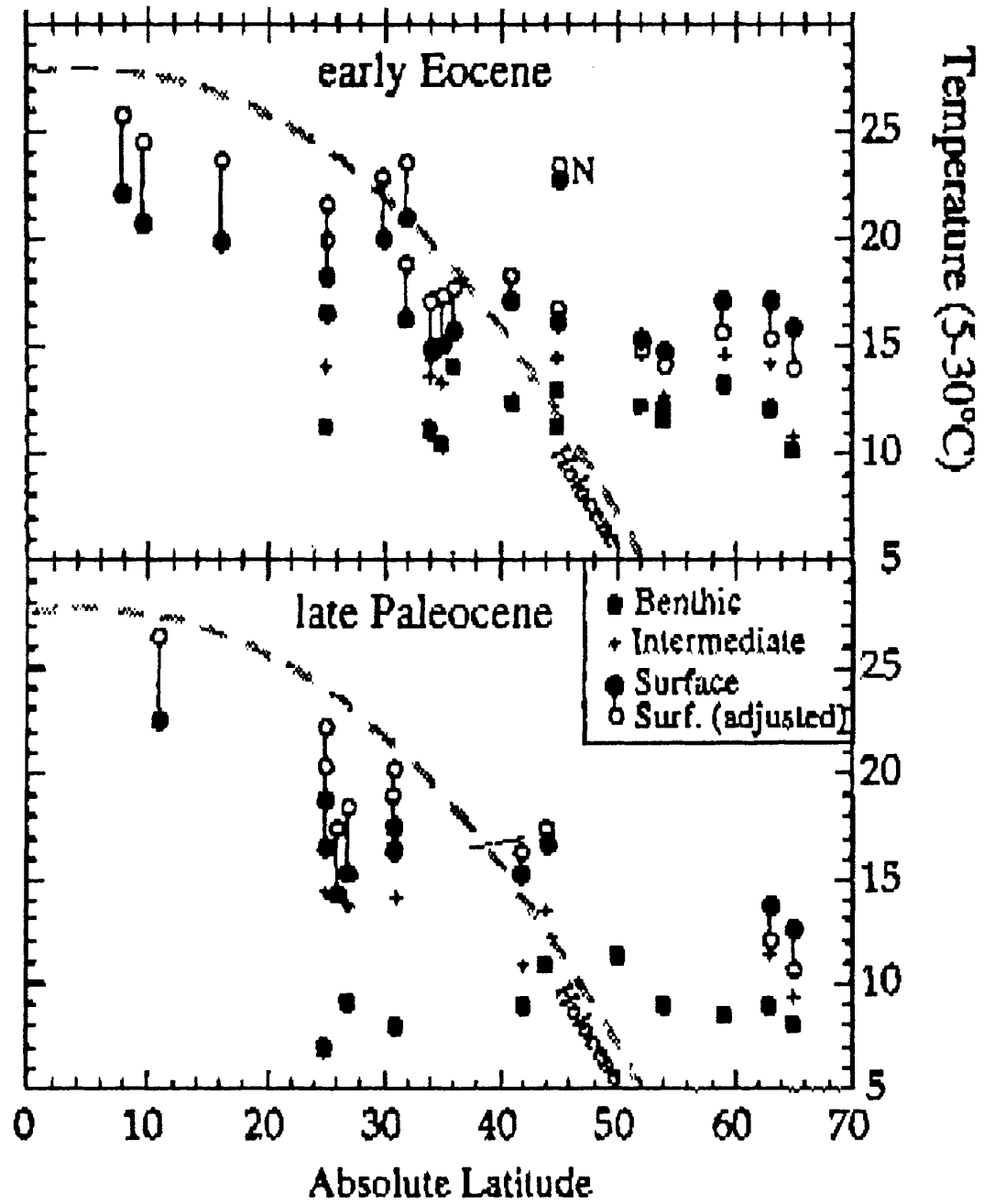


FIG. 6. The zonally averaged distribution of selected variables simulated by the AMIP models (see appendix A) for DJF of 1979–88 and that given by the ECMWF reanalysis for the same period (Gibson et al. 1997) (solid black line).
the surface air temperature, with observed data as merged by Fiorino (1997) from data of da Silva et al. (1994a), Jones (1988), and Schubert et al. (1992).



It should be clear by now that one cannot answer all three questions by simple reference to the greenhouse effect. Nonetheless, the greenhouse effect is undoubtedly important to setting the overall temperature. That said, it should be emphasized that the natural greenhouse effect is mostly due to water vapor and clouds.

Solar Flux at r_{es} :

$$\sigma T_s^4 \left(\frac{r_s}{r_{es}} \right)^2$$

Earth's cross section:

$$a_{cs} = \pi r_e^2$$

Thermal Balance:

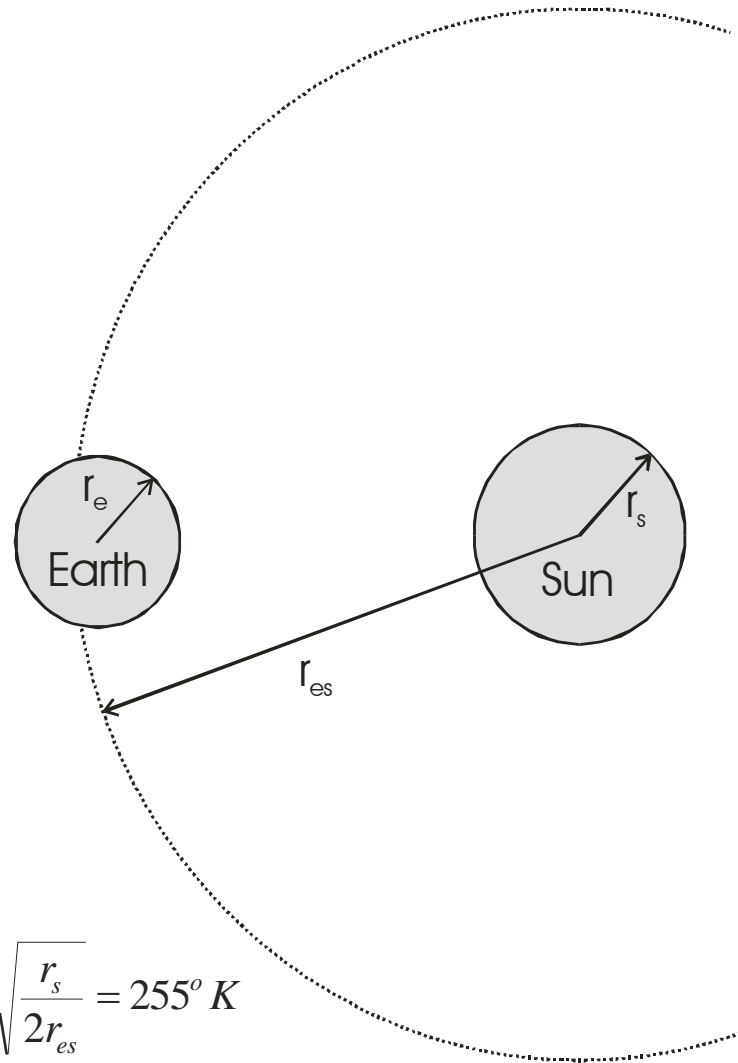
$$\sigma T_e^4 \times 4\pi r_e^2 = a_{cs} \times \sigma T_s^4 \left(\frac{r_s}{r_{es}} \right)^2$$

$$r_s = 6.599 \cdot 10^5 \text{ km} \quad r_e = 6.378 \cdot 10^3 \text{ km}$$

$$r_{es} = 1.496 \cdot 10^8 \text{ km} \quad T_s = 5783^\circ \text{K}$$

$$T_e = T_s \sqrt{\frac{r_s}{2r_{es}}} = 272^\circ \text{K}$$

$$\text{OR } (1 - 0.31)^{0.25} \times T_s \sqrt{\frac{r_s}{2r_{es}}} = 255^\circ \text{K}$$



The above illustrates a number of points. 1) If we omit the albedo due mostly to clouds, then the earth would only be about 16K colder than it is. 2) If we include both the visible AND the infrared impact of clouds, then the temperature will be similar to today's. 3) If one changes the solar output about 2% (which is roughly equivalent to doubling CO₂, then T_e changes about 1K,

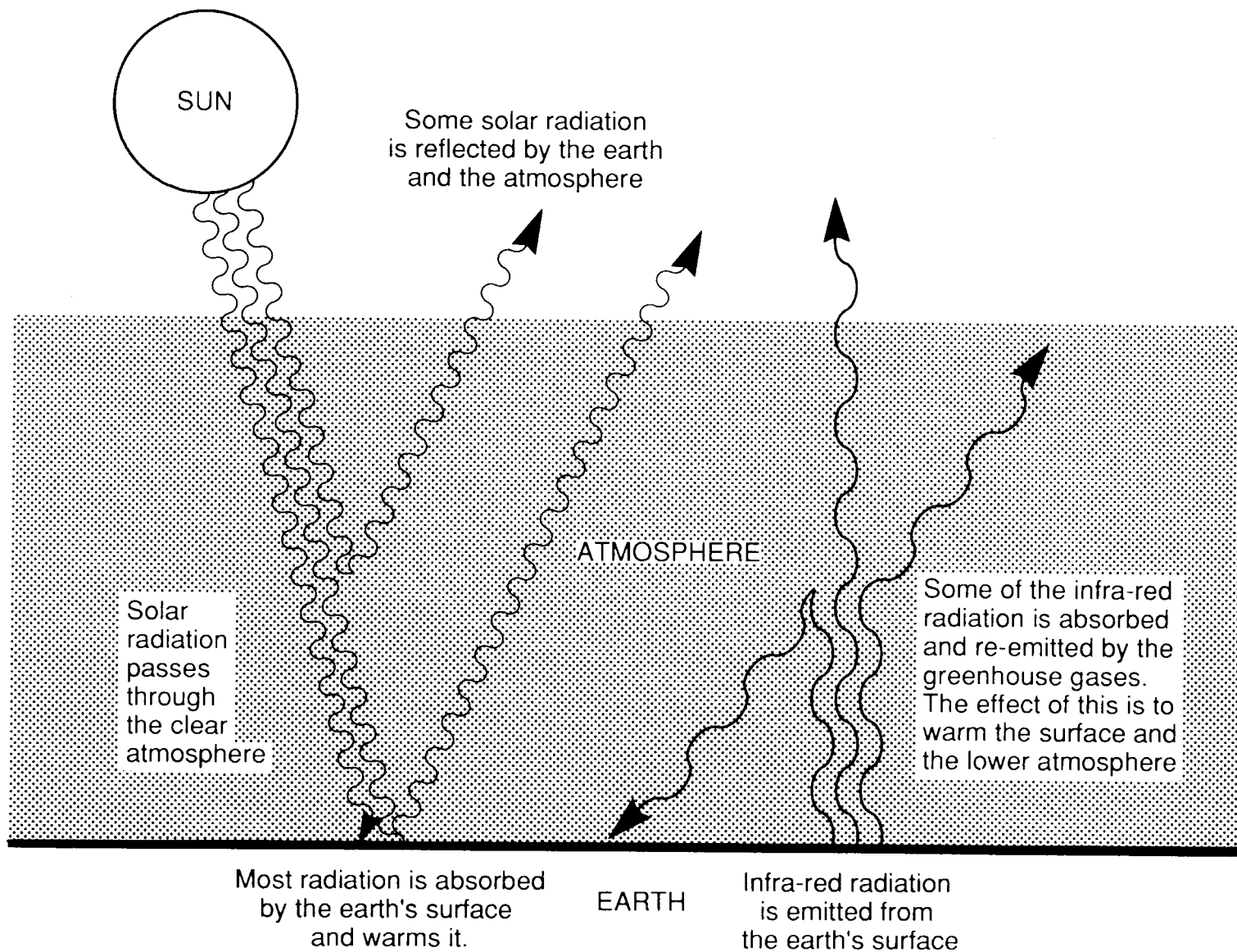
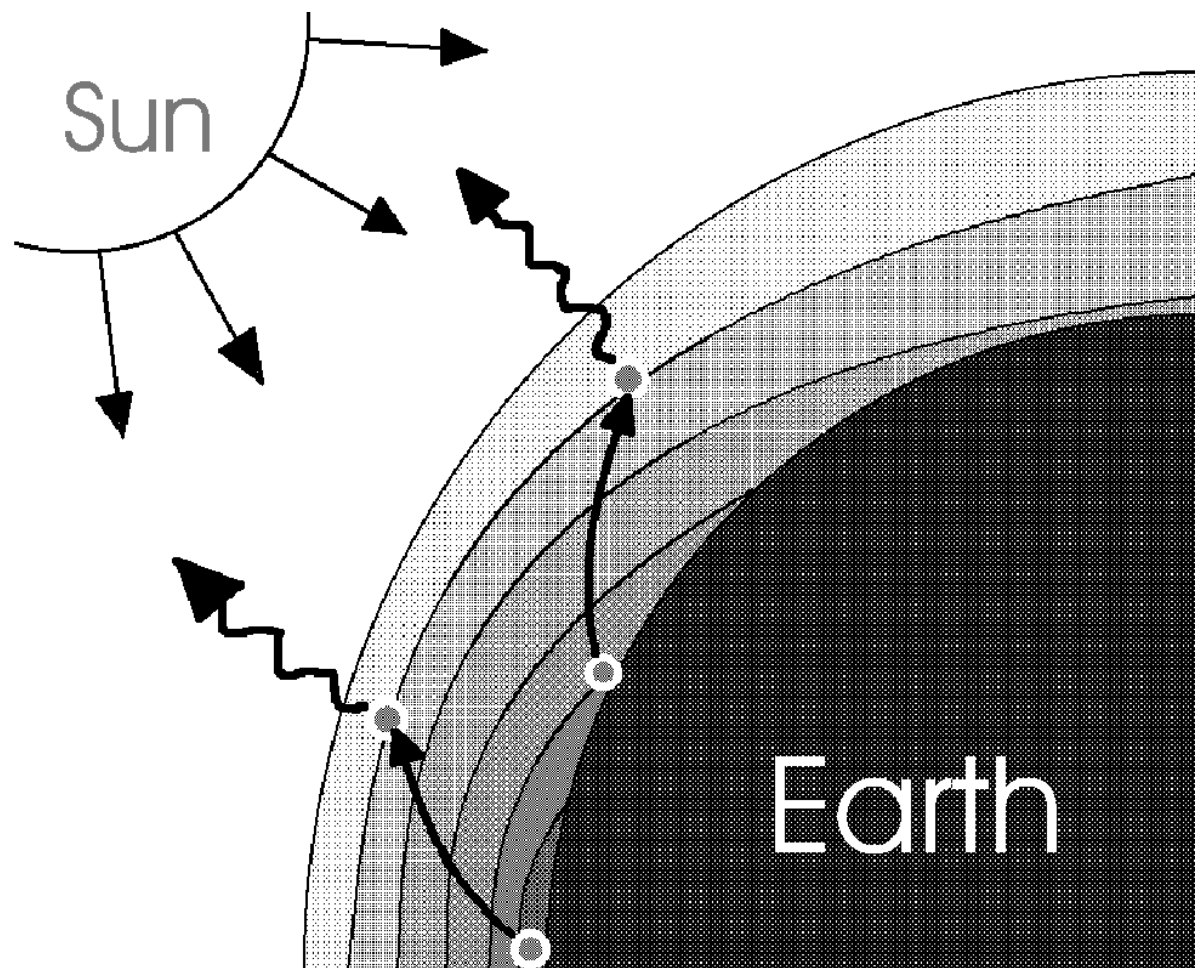
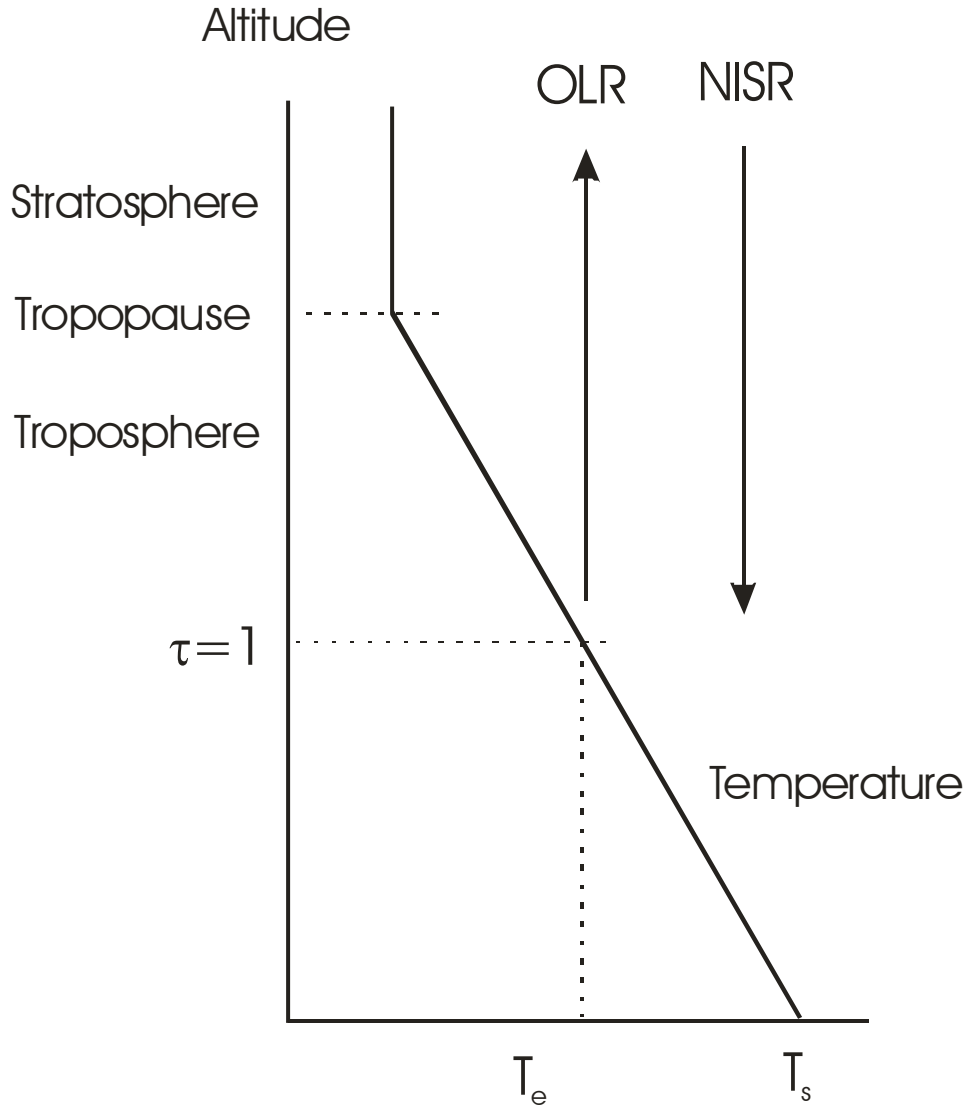


Figure 1: A simplified diagram illustrating the greenhouse effect.

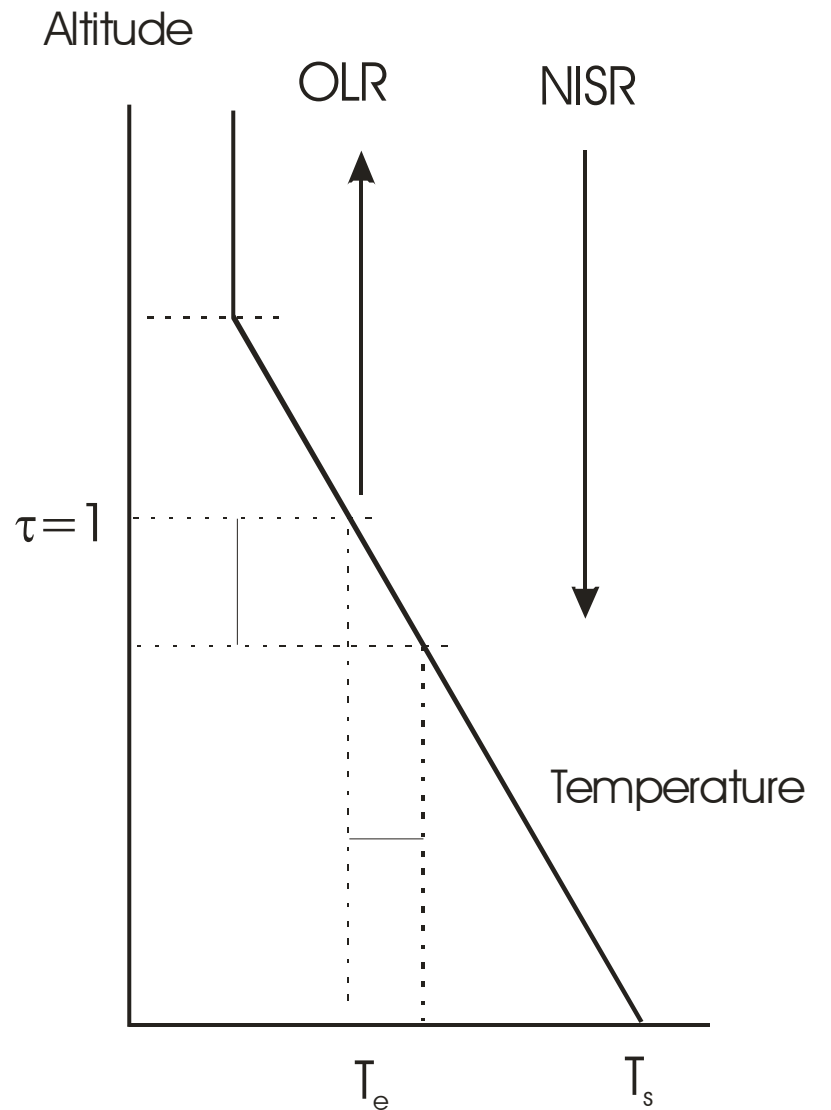
Infrared opacity is greatest at the ground over the tropics, and diminishes as one goes poleward and upward. Air currents bodily carry heat to regions of diminished infrared opacity where the heat is radiated to space -- balancing absorbed sunlight.



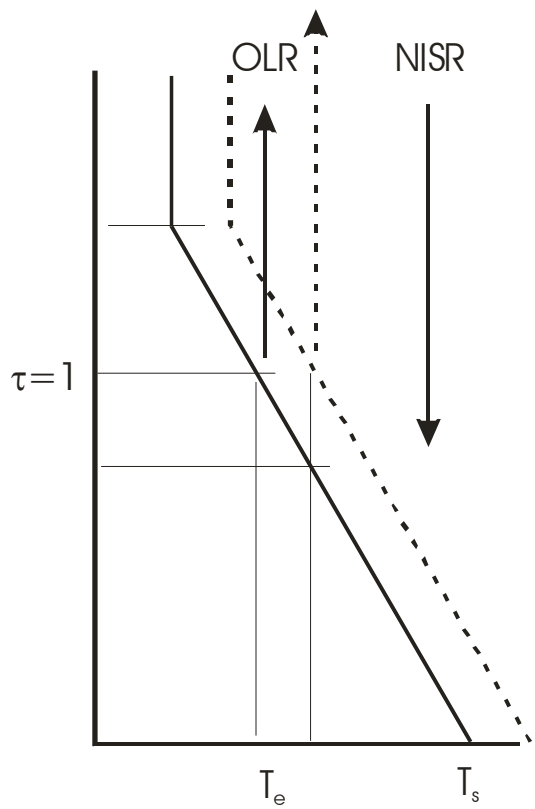
Lighter shading schematically represents reduced opacity due to diminishing water vapor density.



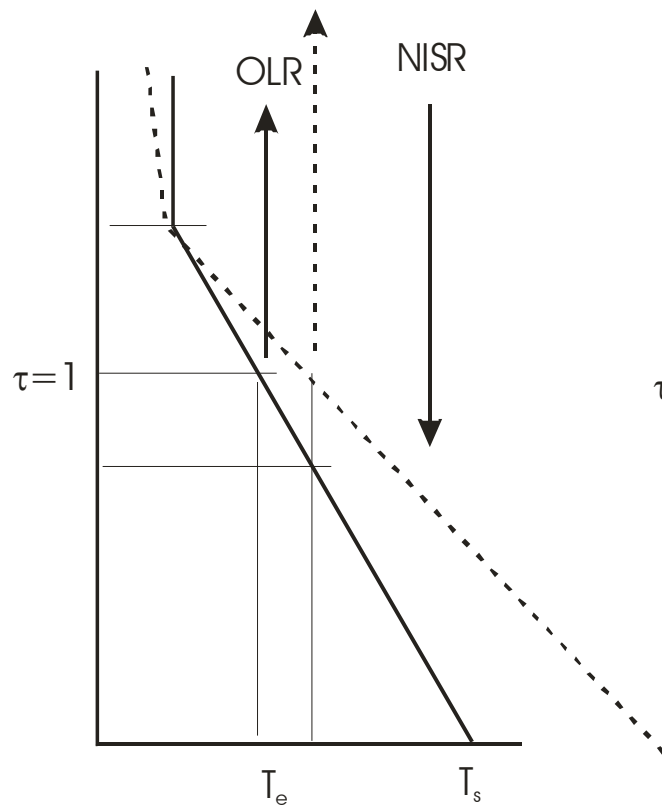
1a



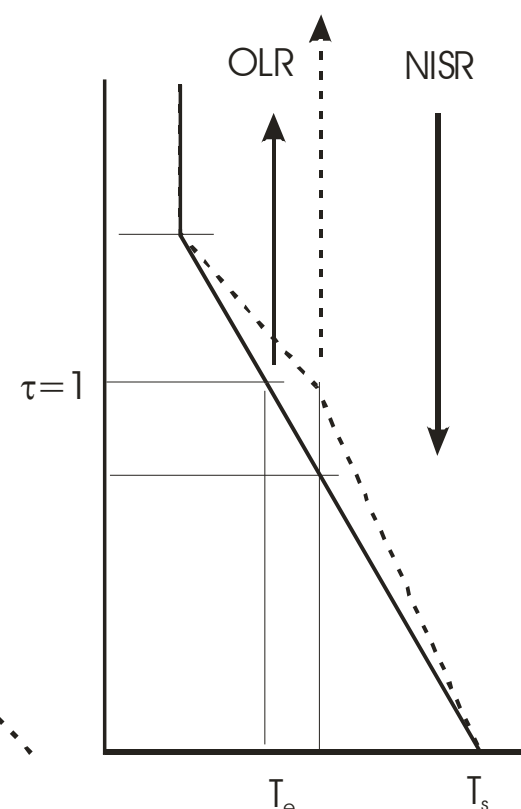
1b



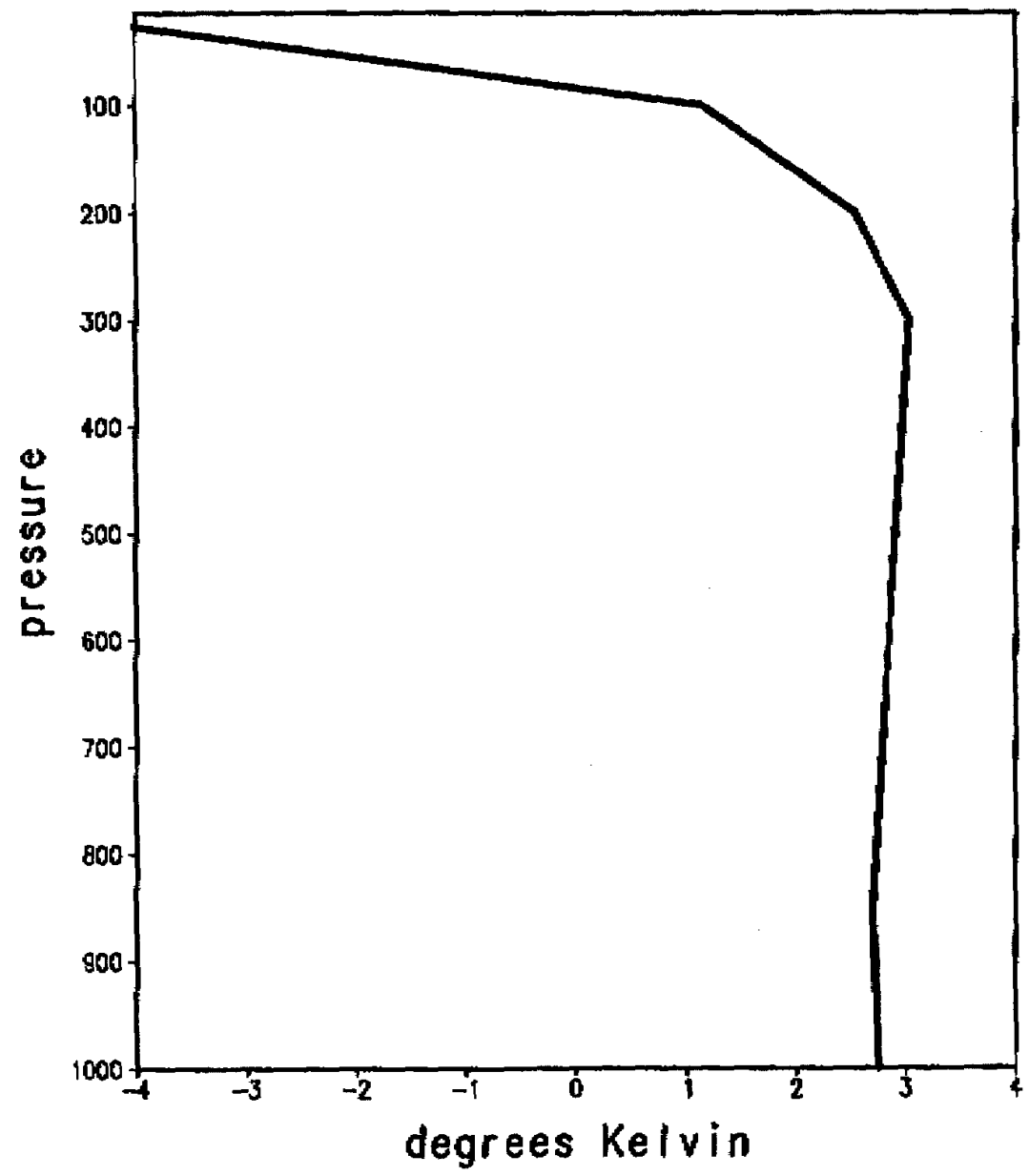
2a



2b



2c



This is at the heart of the controversy over differences between satellite measurements of tropospheric temperature and thermometric measurements of surface temperature.

The fact that the warming trend in the atmosphere is much smaller than the trend at the surface is at odds with the fact that in the greenhouse effect, it is the atmosphere that warms the surface.

As we have seen, if warming were solely due to the greenhouse effect of added CO₂, we would actually know the climate sensitivity. It would be about 1C for a doubling of CO₂. Greater sensitivities require that the main greenhouse substances, water vapor and clouds, act to amplify whatever CO₂ does. There is, in fact, little support for this. We will discuss this further tomorrow.

Let's turn instead to the issue of transport. Why does the equator to pole temperature difference change?

For many years, it has been argued that the change in transport must come from the ocean, and be associated with the thermohaline circulation.

The argument runs as follows. Atmospheric transport is due to midlatitude eddies and these eddies arise from meridional temperature gradients.

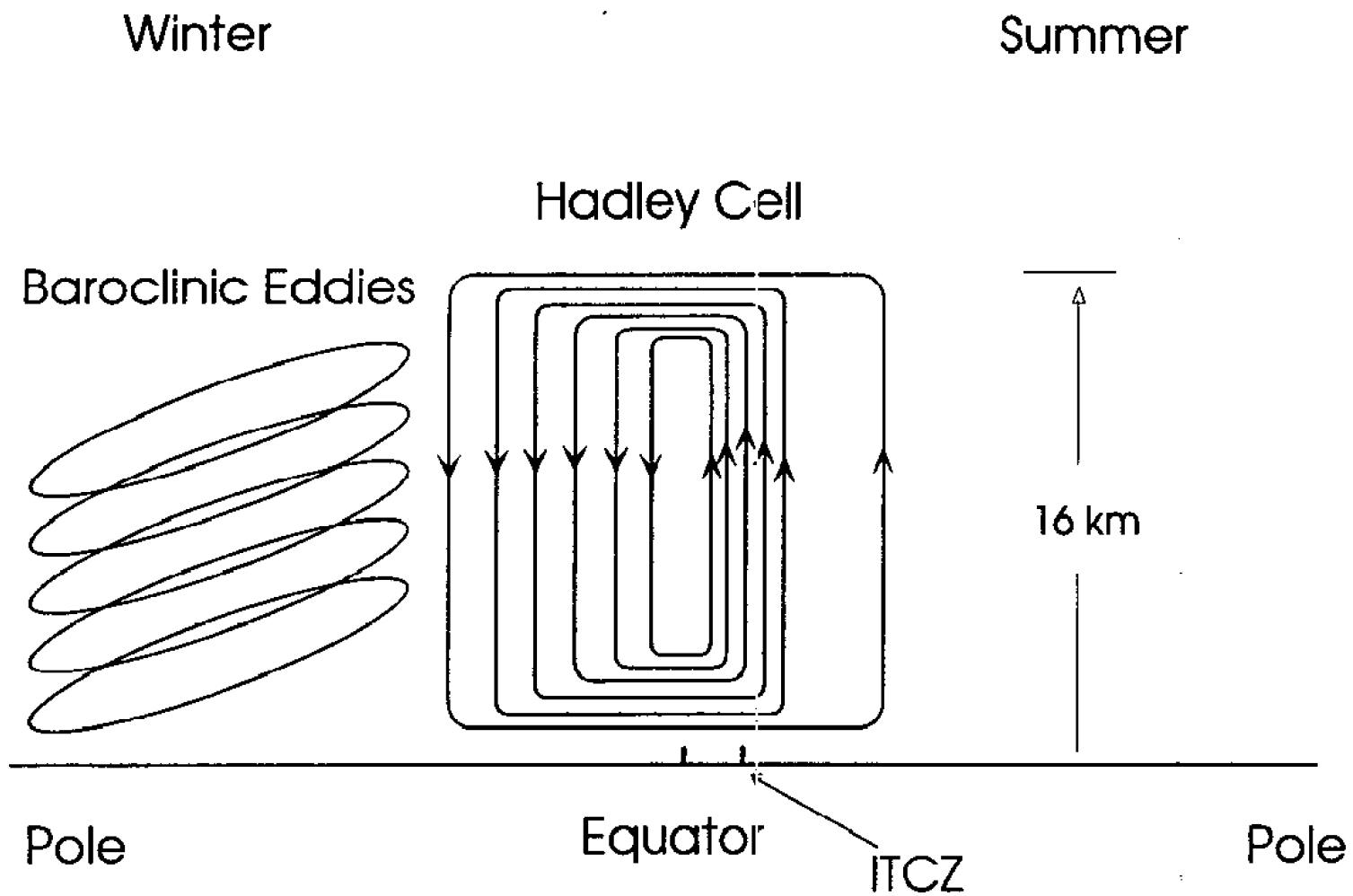


Figure 8 Schematic illustration of major dynamic mechanisms for meridional heat transfer in the atmosphere.

In a warmer world, the meridional temperature gradient is reduced and yet, this reduced gradient requires a greater heat flux. This would seem to preclude the atmospheric eddies from being the mechanism.

A similar argument can be used against the wind driven surface ocean circulation that we generally associate with the Gulf Stream.

Thus, we are left with the thermohaline circulation which depends on deep water formation in the North Atlantic, which in turn depends on the presence of fresh water rather than meridional temperature gradients.

This appears reasonable but



The required total northward energy transport (RT) determined from the Earth radiation budget experiment (ERBE) top-of-the-atmosphere radiation data compared with estimates of the oceanic energy transport (OT) and the atmospheric transport (AT). OT is derived from the net surface heat flux determined from the NCEP–NCAR (National Center for Environmental Prediction–National Center for Atmospheric Research) re-analysis of meteorological data and the AT is determined as the difference between RT and OT.

Assuming the observational analysis is correct (and it has been confirmed by the WOCE program), where has our thinking gone wrong?

An idea that was suggested in the 50's and returned to popularity in the 70's and 80's, and is again coming to be of interest in somewhat modified form, is that the atmosphere acts to bring its state close to what would be neutral for the baroclinic eddies. However, given that the meridional gradient varies for different climates, we might reasonably wonder which of these climates represents the adjusted state, and how does the climate get to other states.

Lindzen and Farrell in 1981 found the following:

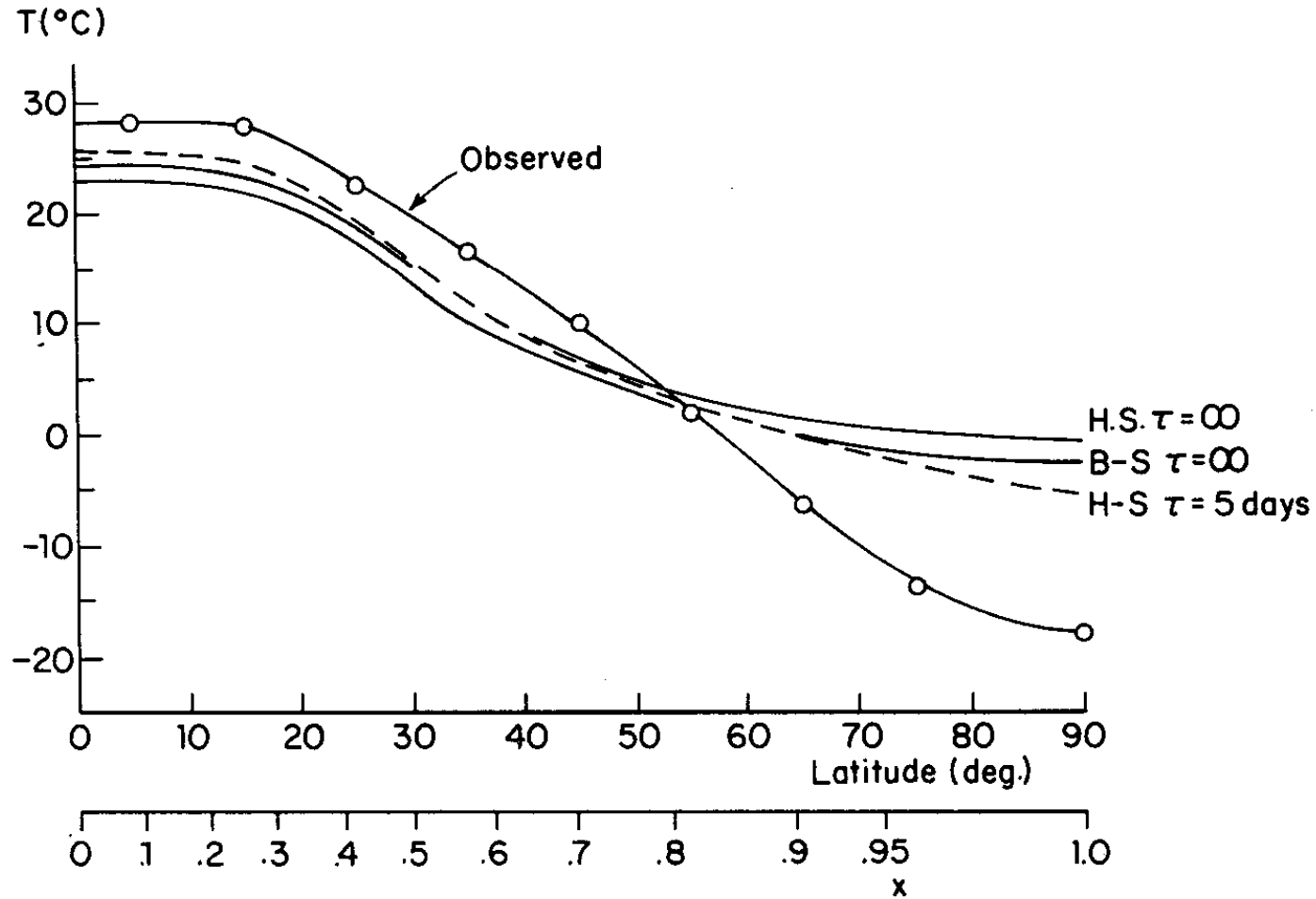


FIG. 12. T_{BH} vs ϕ for HS and BS radiative parameters without dissipation for HS parameters with $\tau_{diss} = 5$ days. Also shown is the observed $T(\phi)$.

The pole to equator temperature difference was about 25C.

This is approximately correct for the Eocene, but at present the difference is more like 40C and during the peak of the ice age, it was more nearly 60C.

Following a suggestion by Held and Suarez (1976), we assumed that an ice surface was associated with an inversion (and hence much increased static stability) in the lowest 2 km or so. This, in turn, served to significantly reduce the impact of heat transport on the arctic surface. With this 'correction,' we got the following:

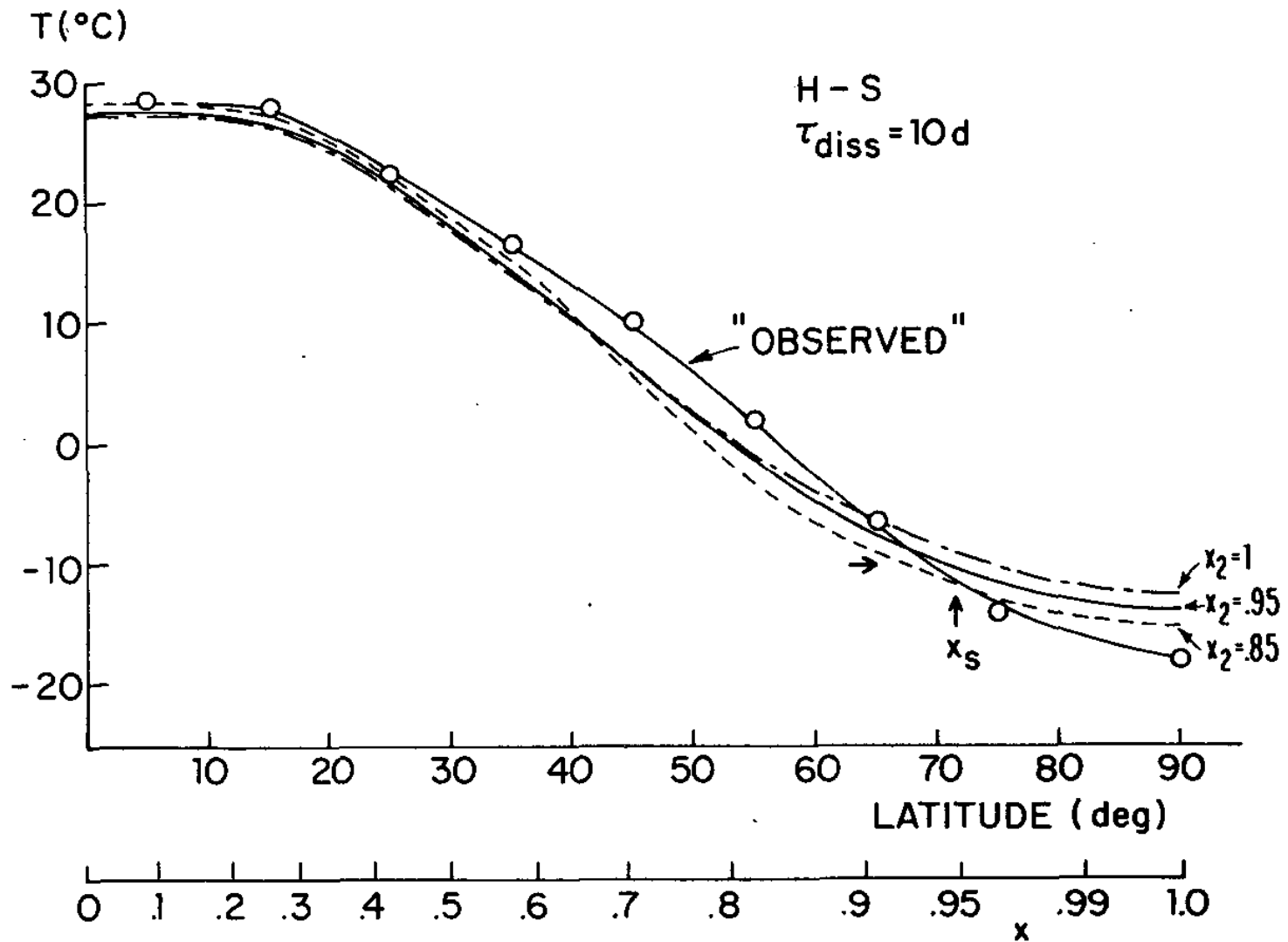


FIG. 13. T_{BH} (corrected for variations in static stability) vs ϕ for HS radiative parameters, $\tau_{diss} = 10$ days, and various choices of x_2 [see Eq. (23)]. Also shown is the observed $T(\phi)$.

The notion that baroclinic adjustment could replicate equable climates, and that the onset of ice provides a positive feedback through its inhibition of meridional heat transfer forms an interesting hypothesis that is worth exploiting.

Finally, there is the question of whether there is anything that is constraining the variation of tropical temperatures. The answer appears to be yes, but this is something I will discuss tomorrow when I describe the Iris Effect. However, it is worth noting that if tropical temperatures are constrained, then changes in the meridional gradient will automatically lead to changes in global mean temperature (rather than what is currently assumed.)

In concluding this lecture, I would like you to take away the following:

1. The normal behavior of our climate is rich in variety.
2. We still do not understand the climate well enough to explain its remarkable behavior.
3. Nevertheless, there is good reason to believe that we can understand its behavior. General Circulation Models may play a role in this understanding, but, so far, that role has been small. On the other hand, understanding climate may not depend on GCMs. That has certainly been the case for what understanding we currently have.
4. Climate alarm has likely slowed rather than accelerated our understanding of climate.