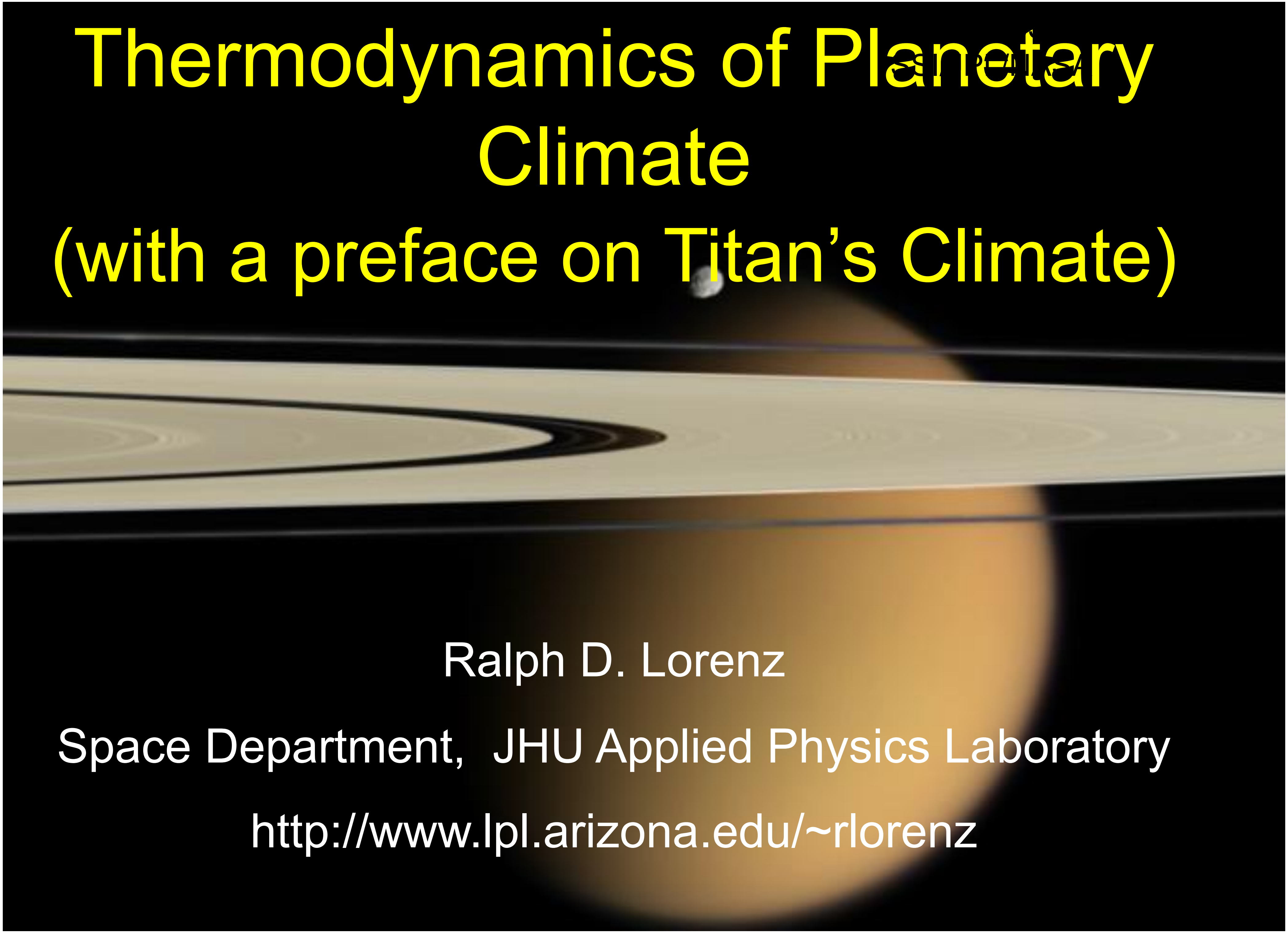
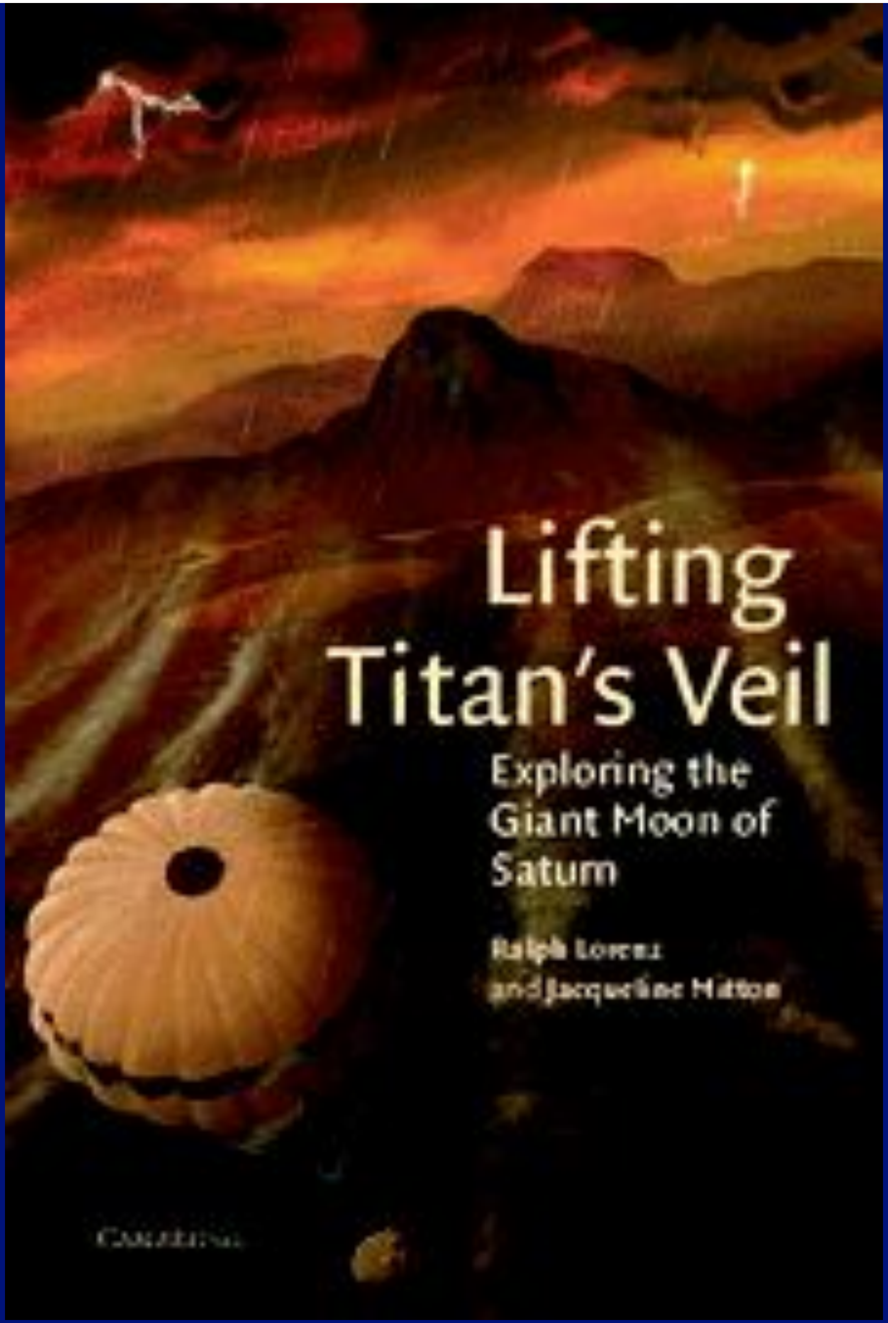


Thermodynamics of Planetary Climate
(with a preface on Titan's Climate)

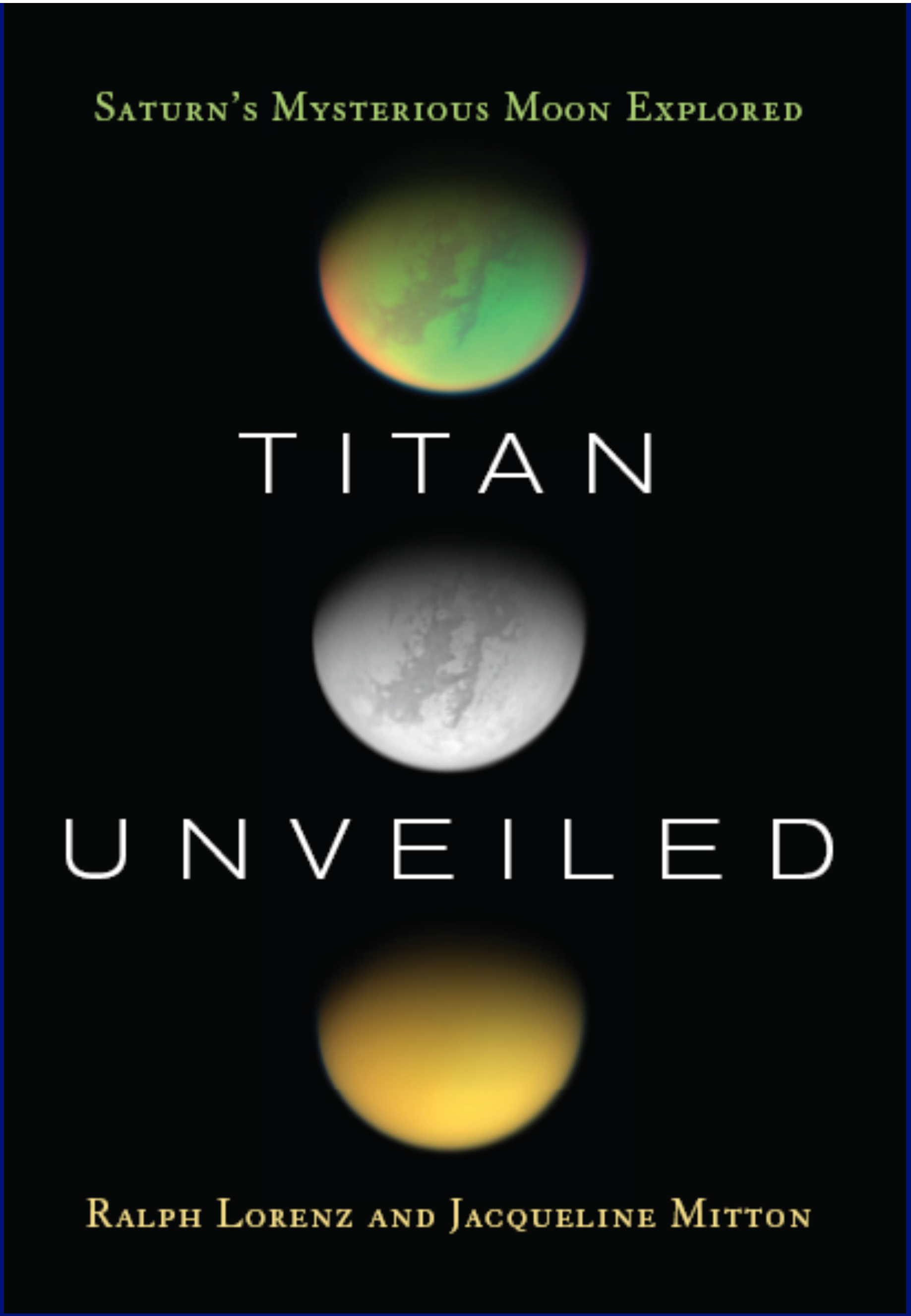
Ralph D. Lorenz

Space Department, JHU Applied Physics Laboratory

http://www.lpl.arizona.edu/~rlorenz



CUP, 2002



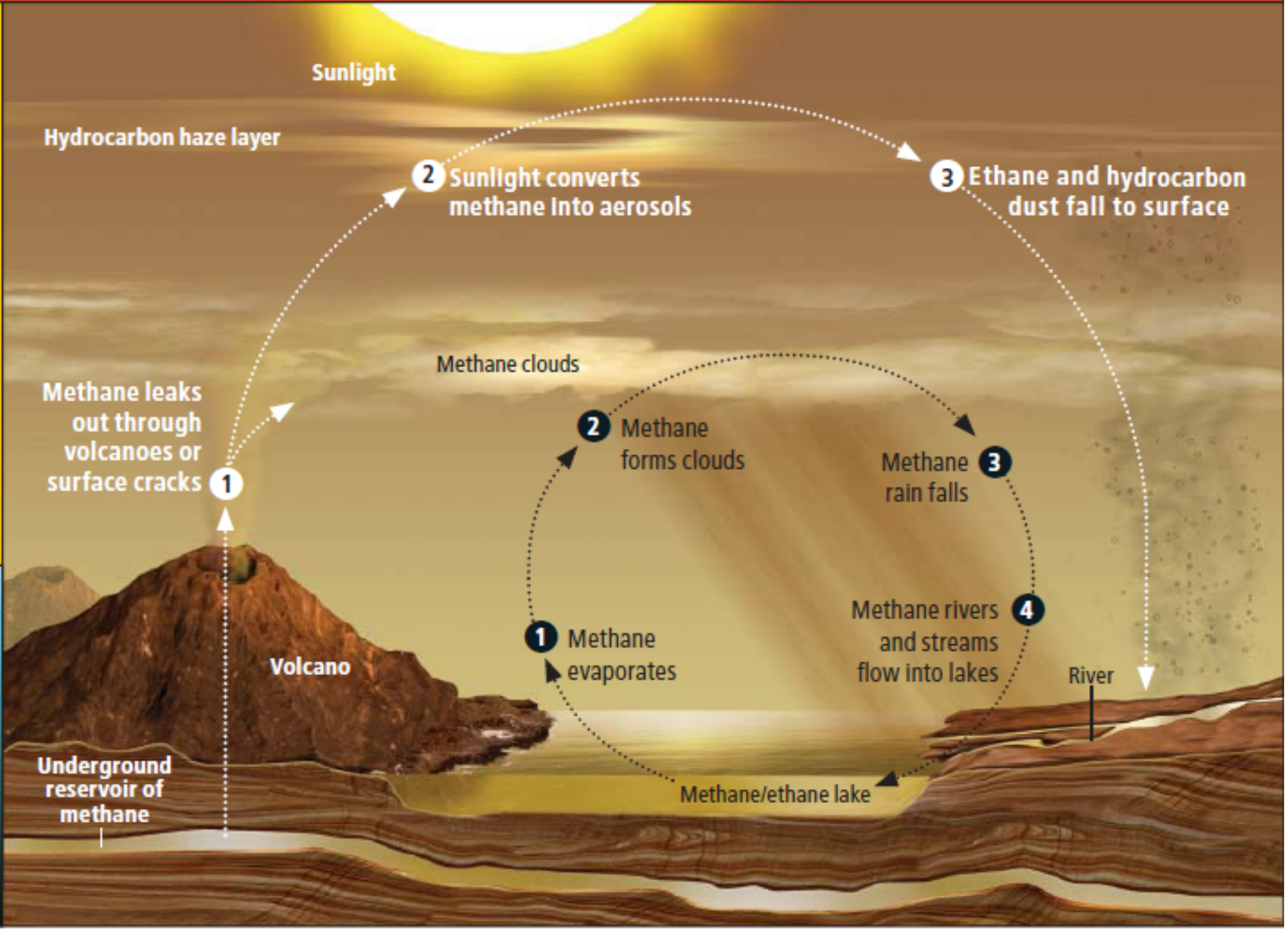
PUP, 2008, 2010

[THE METHANOLOGICAL CYCLE]

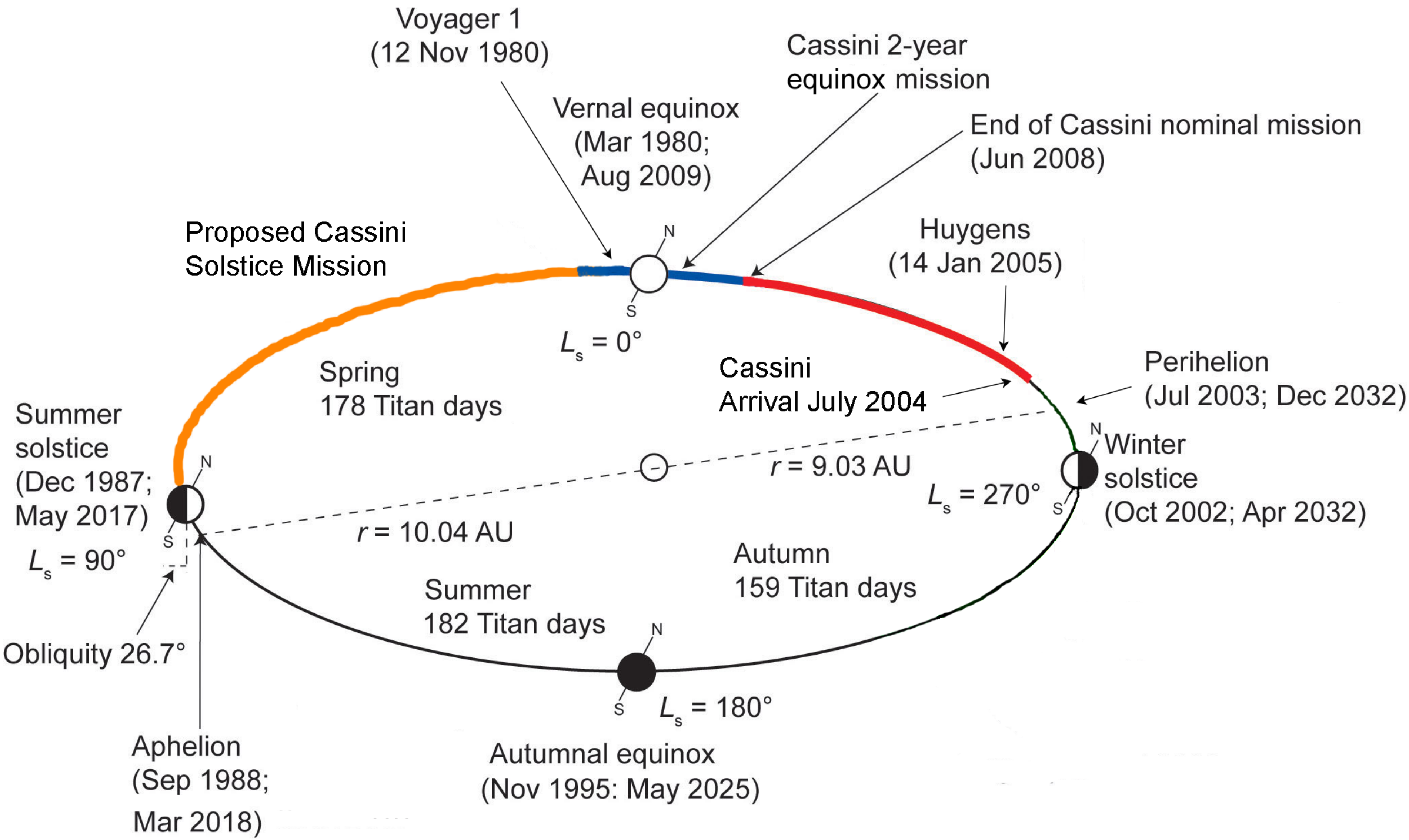
FORECAST: A DELUGE OF METHANE

Methane undergoes a short-term cycle (*black*) much like the water cycle on Earth. Over geologic time there is an episodic one-way flow (*white*) of methane from interior reservoirs to the upper atmosphere, where solar radiation converts it to ethane and heavier hydrocarbon—forming the haze. The particulates settle onto the surface as what Carl Sagan called "manna from heaven."

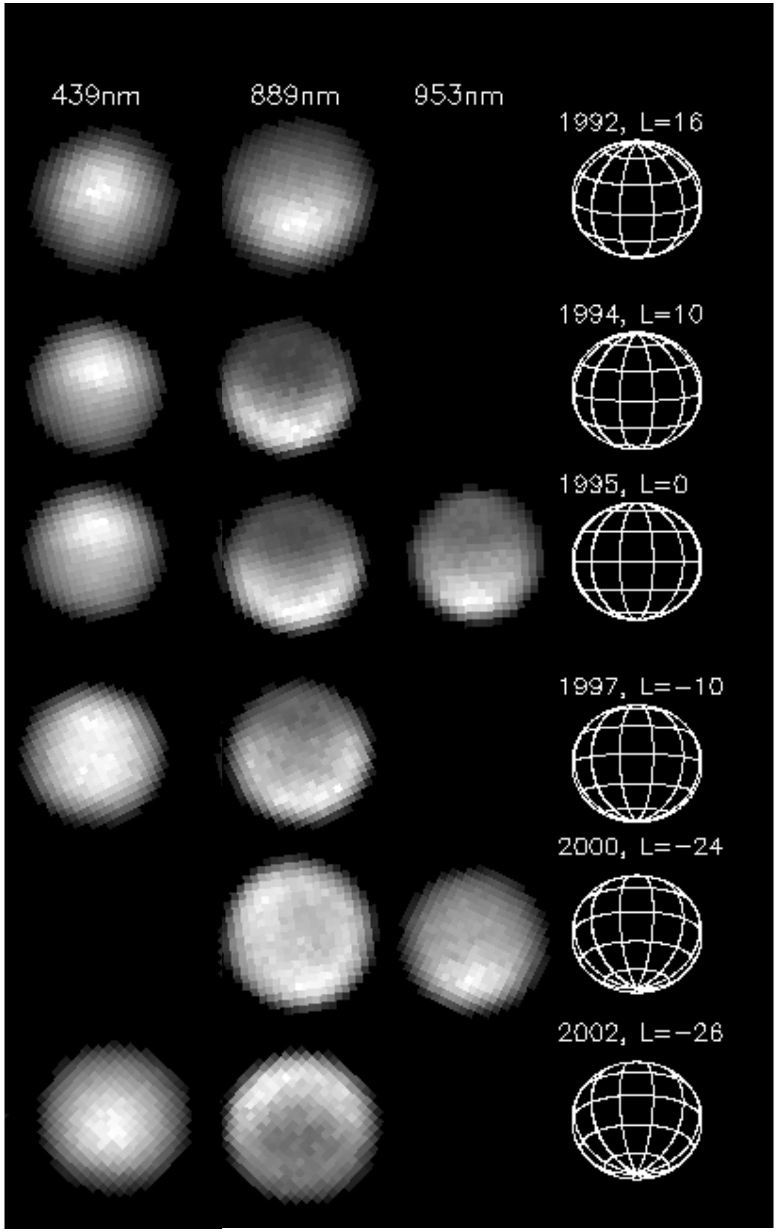
Methane clouds over south polar region

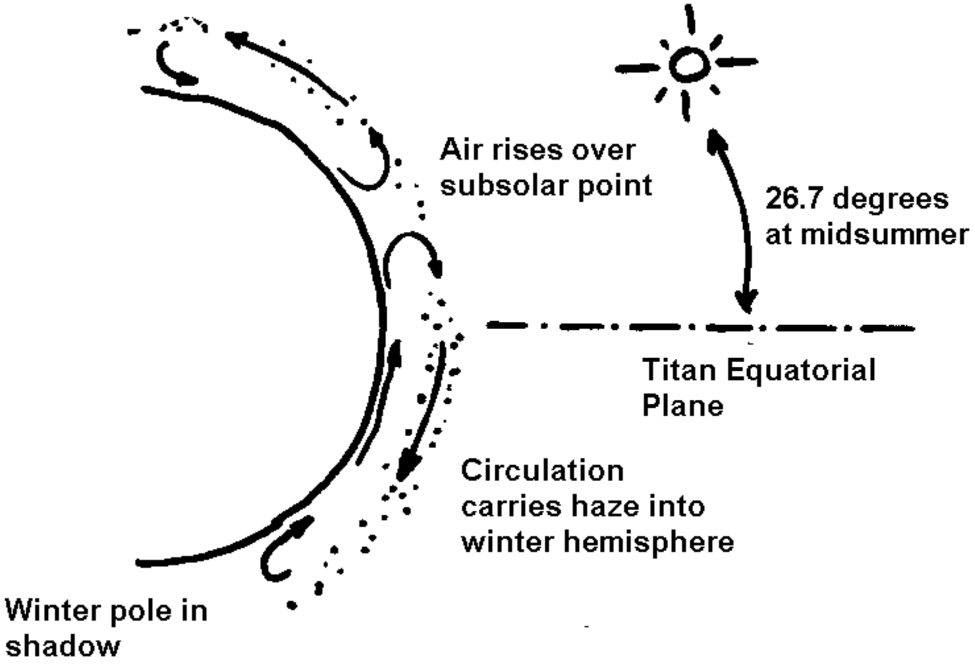


Lorenz and Sotin, Scientific American, March 2010


Voyager 1
(12 Nov 1980)
Vernal equinox
(Mar 1980;
Aug 2009)
Cassini 2-year
equinox mission
End of Cassini nominal mission
(Jun 2008)
Proposed Cassini
Solstice Mission
N
S
$L_s = 0°$
Huygens
(14 Jan 2005)
Cassini
Arrival July 2004
Perihelion
(Jul 2003; Dec 2032)
Spring
178 Titan days
Summer
solstice
(Dec 1987;
May 2017)
N
S
$L_s = 90°$
$r = 9.03$ AU
N
Winter
solstice
(Oct 2002; Apr 2032)
S
$L_s = 270°$
$r = 10.04$ AU
Autumn
159 Titan days
Summer
182 Titan days
Obliquity 26.7°
N
S
$L_s = 180°$
Aphelion
(Sep 1988;
Mar 2018)
Autumnal equinox
(Nov 1995: May 2025)

Titan's North-South Haze Asymmetry and Polar Hood may show their most dramatic year-to-year change shortly after equinox (i.e. now – 2010 !)





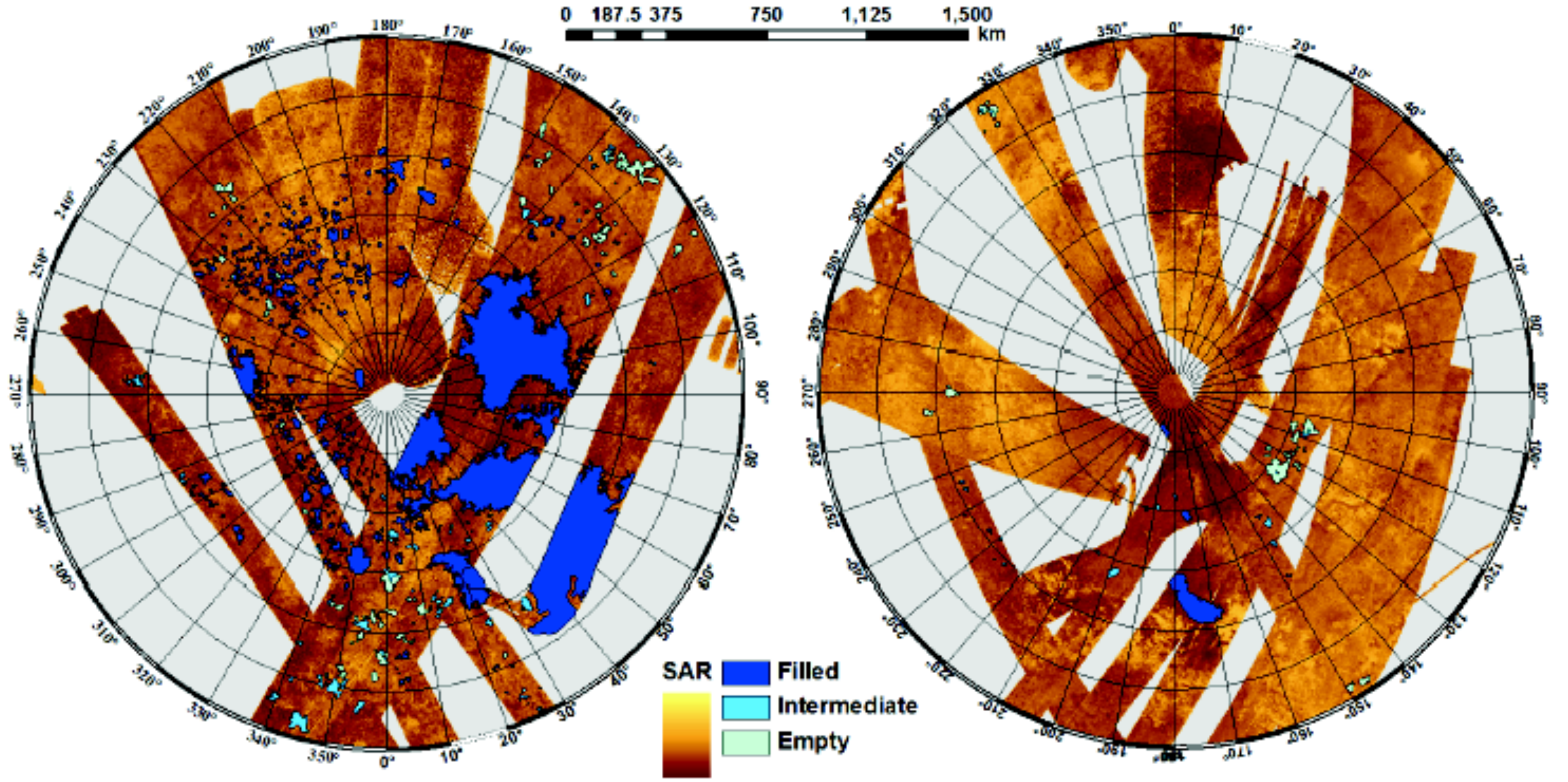
Air rises over subsolar point

26.7 degrees at midsummer

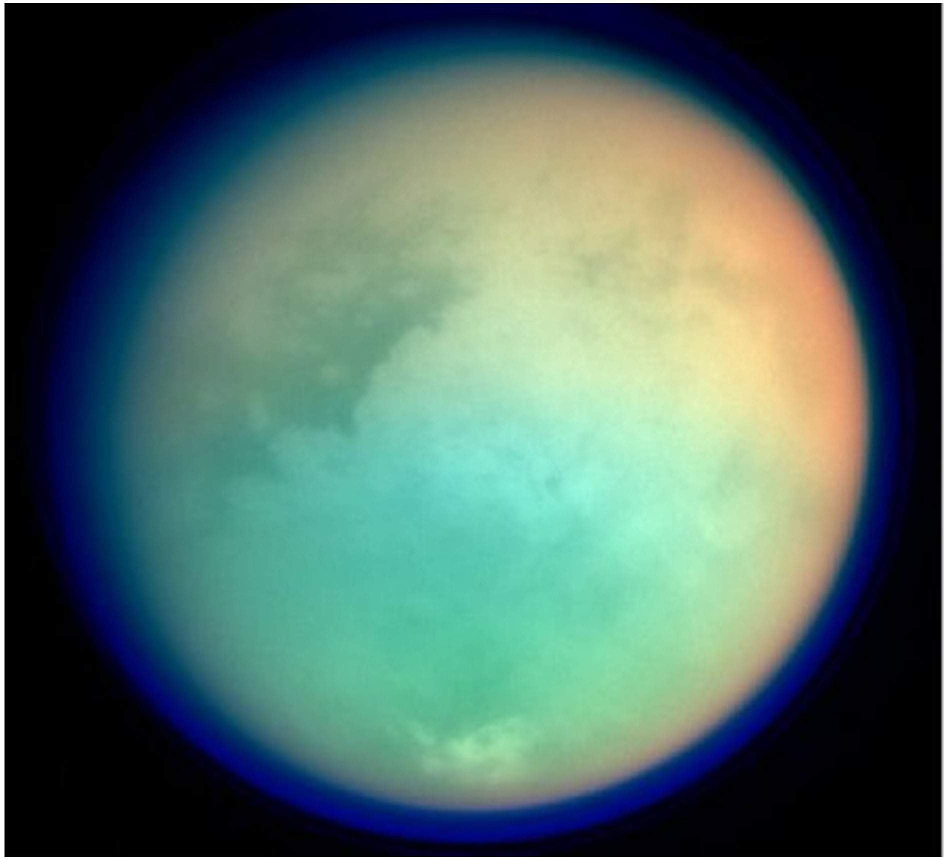
Titan Equatorial Plane

Circulation carries haze into winter hemisphere

Winter pole in shadow

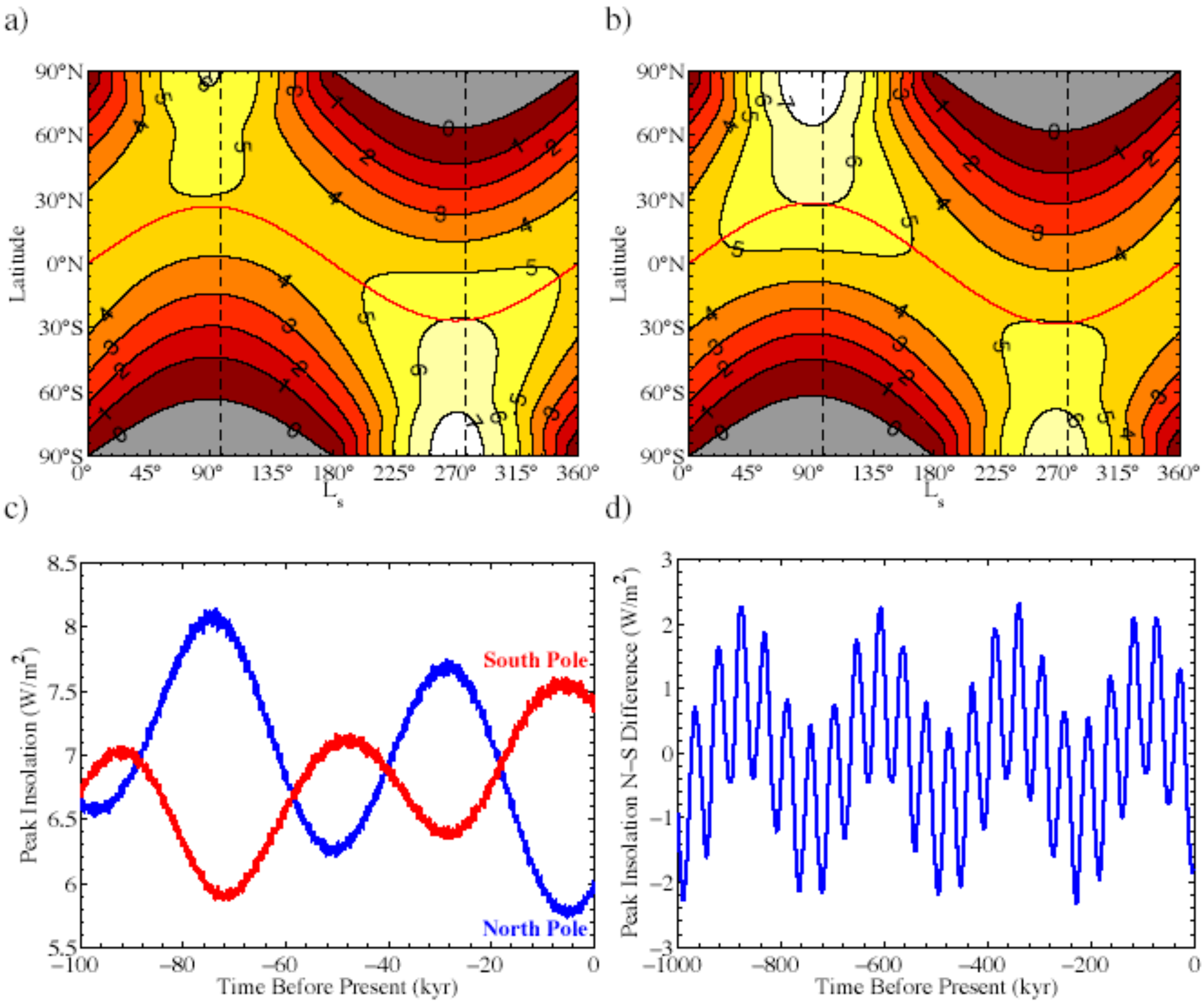


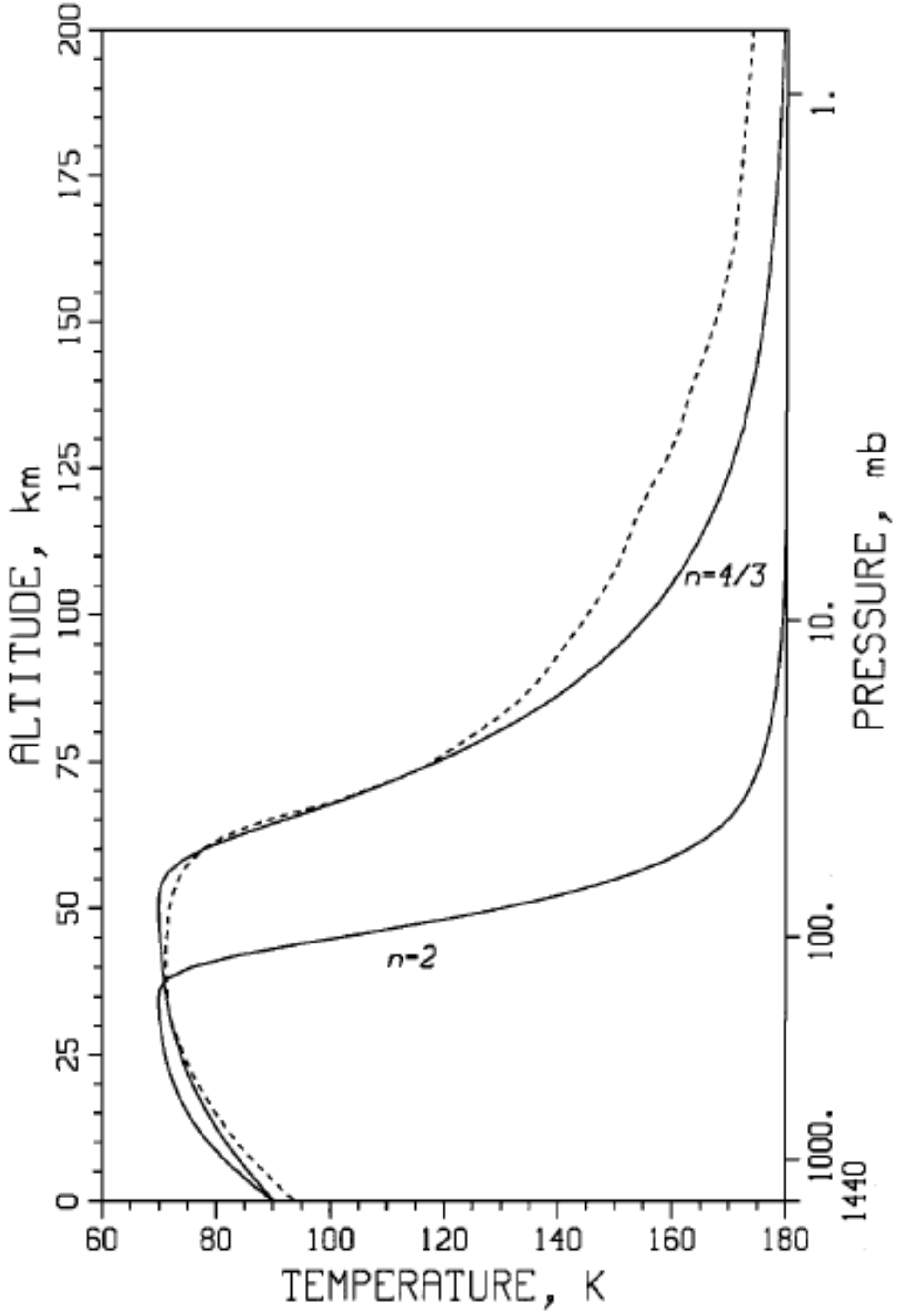
Why are lakes more widespread in northern polar regions? Presently northern spring - seasonal effect (unlikely, can only evaporate few m/yr) ? Surface control (maybe, but not topographical difference N-S) Astrononomical control (S. summer shorter and hotter at present) - Croll-Milankovich cycles on Titan?



Titan's north and south polar regions appear different. Are we confronting a puzzle similar to that on Mars? What are the relative roles of topography and orbital/radiative forcing on the transport and accumulation of volatiles ?

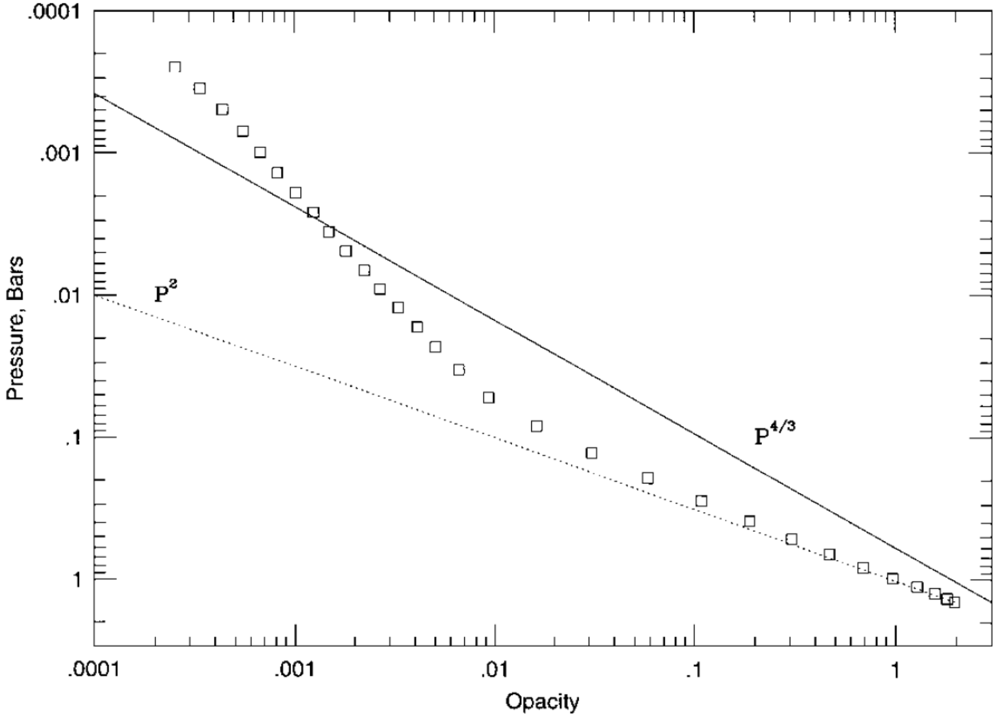
Is this forcing constant with time - Croll-Milankovich cycles on Titan ?


a)
b)
c)
d)
90°N
60°N
30°N
0°N
30°S
60°S
90°S
Latitude
0°
45°
90°
135°
180°
225°
270°
315°
360°
L_s
0
1
2
3
4
5
6
7
Peak Insolation (W/m^2)
South Pole
North Pole
8.5
8
7.5
7
6.5
6
5.5
−100
−80
−60
−40
−20
0
Time Before Present (kyr)
Peak Insolation N−S Difference (W/m^2)
3
2
1
0
−1
−2
−3
−1000
−800
−600
−400
−200
0
Time Before Present (kyr)



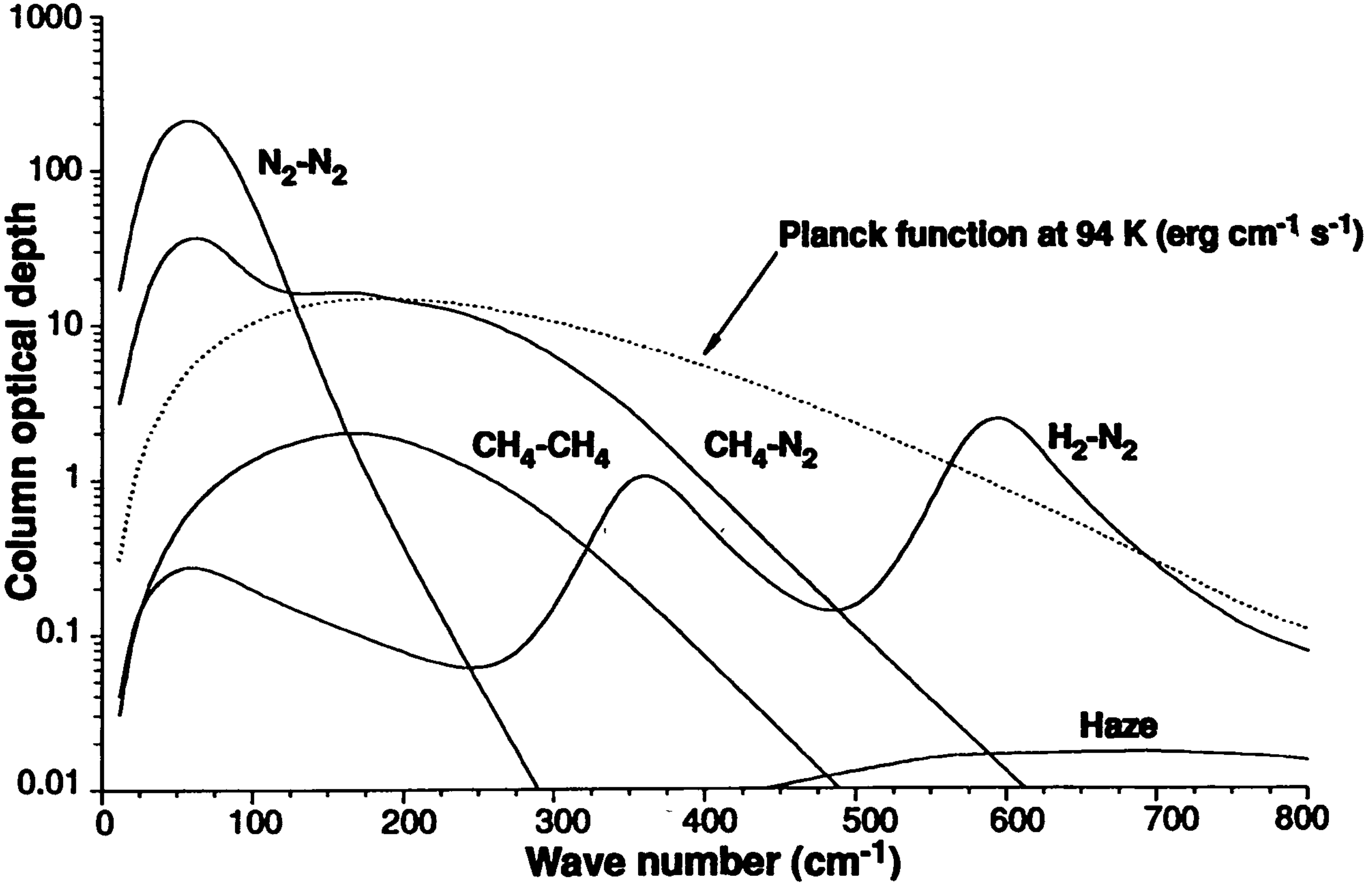
A purely radiative model can roughly reproduce Titan's temperature profile (with shortwave opacity proportional to longwave, depending on pressure)

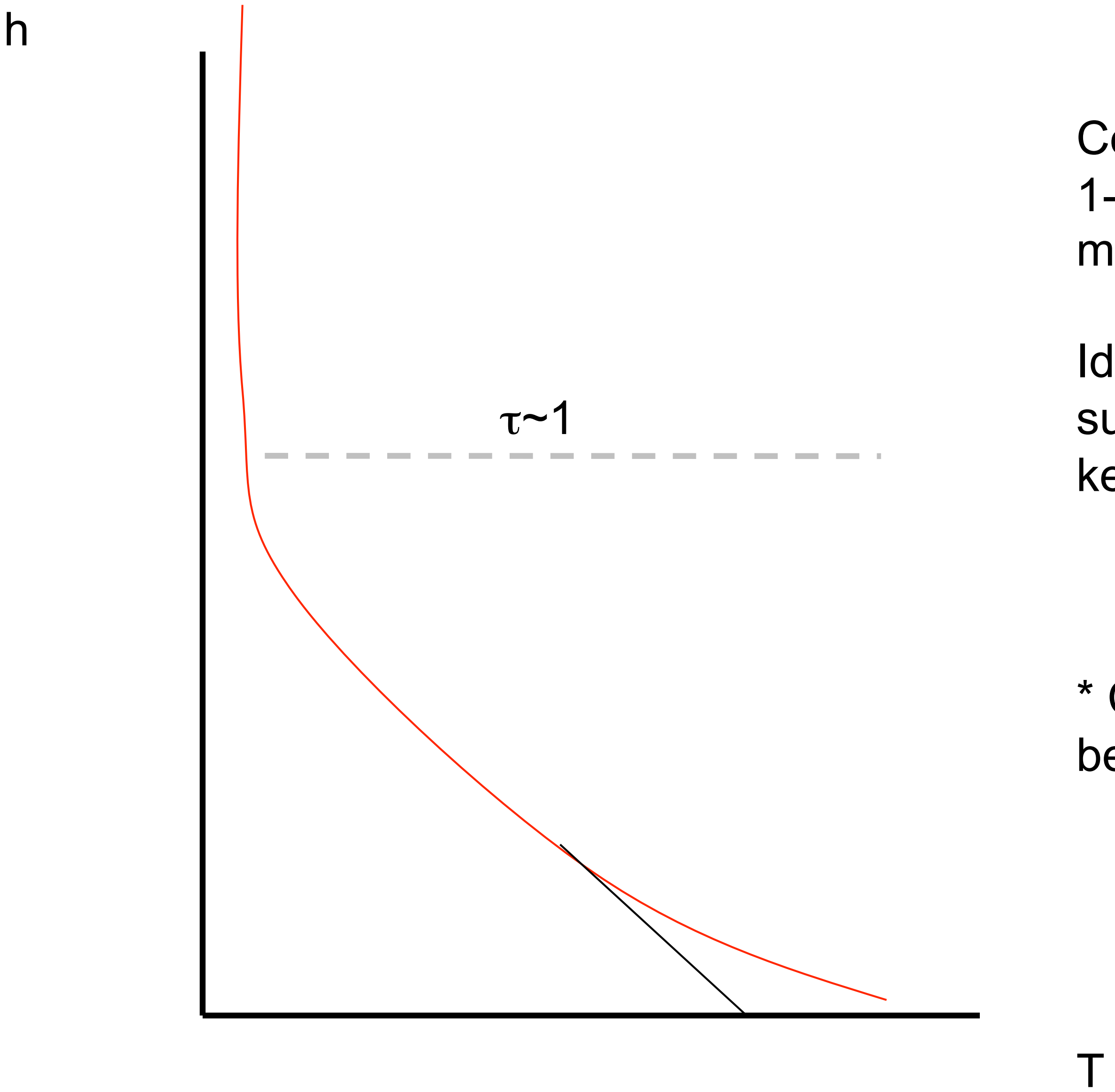
McKay, Lorenz and Lunine, Analytic Solutions for the Antigreenhouse Effect: Titan and the Early Earth, Icarus, 1999



McKay et al. The Thermal Structure of Titan's Atmosphere, Icarus, 1989

Uses laboratory haze optical properties (Khare et al) and CIA opacity from Borysow et al. Then performs radiative equilibrium solution, convective adjustment, haze microphysics, and iterate until converged

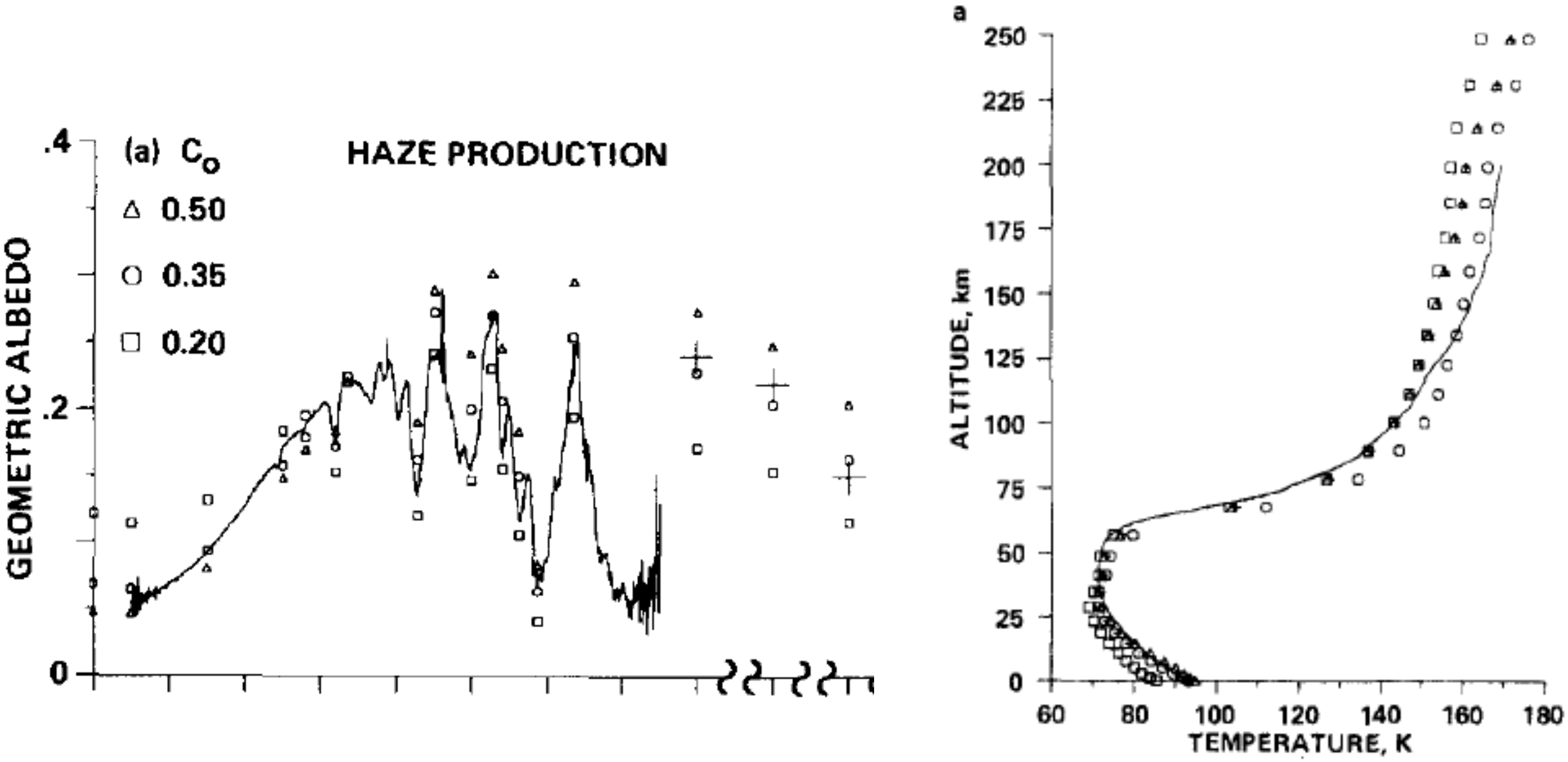




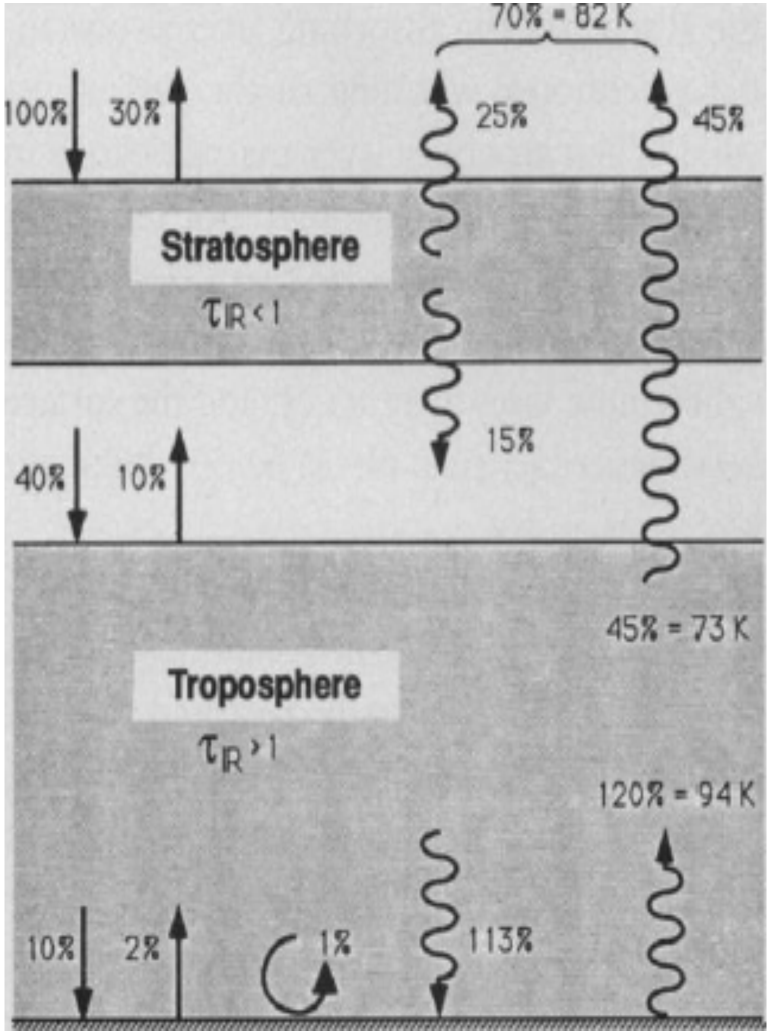
Convective adjustment in 1-D Radiative-Convective models

Identify where profile is superadiabatic*, adjust to keep energy balance

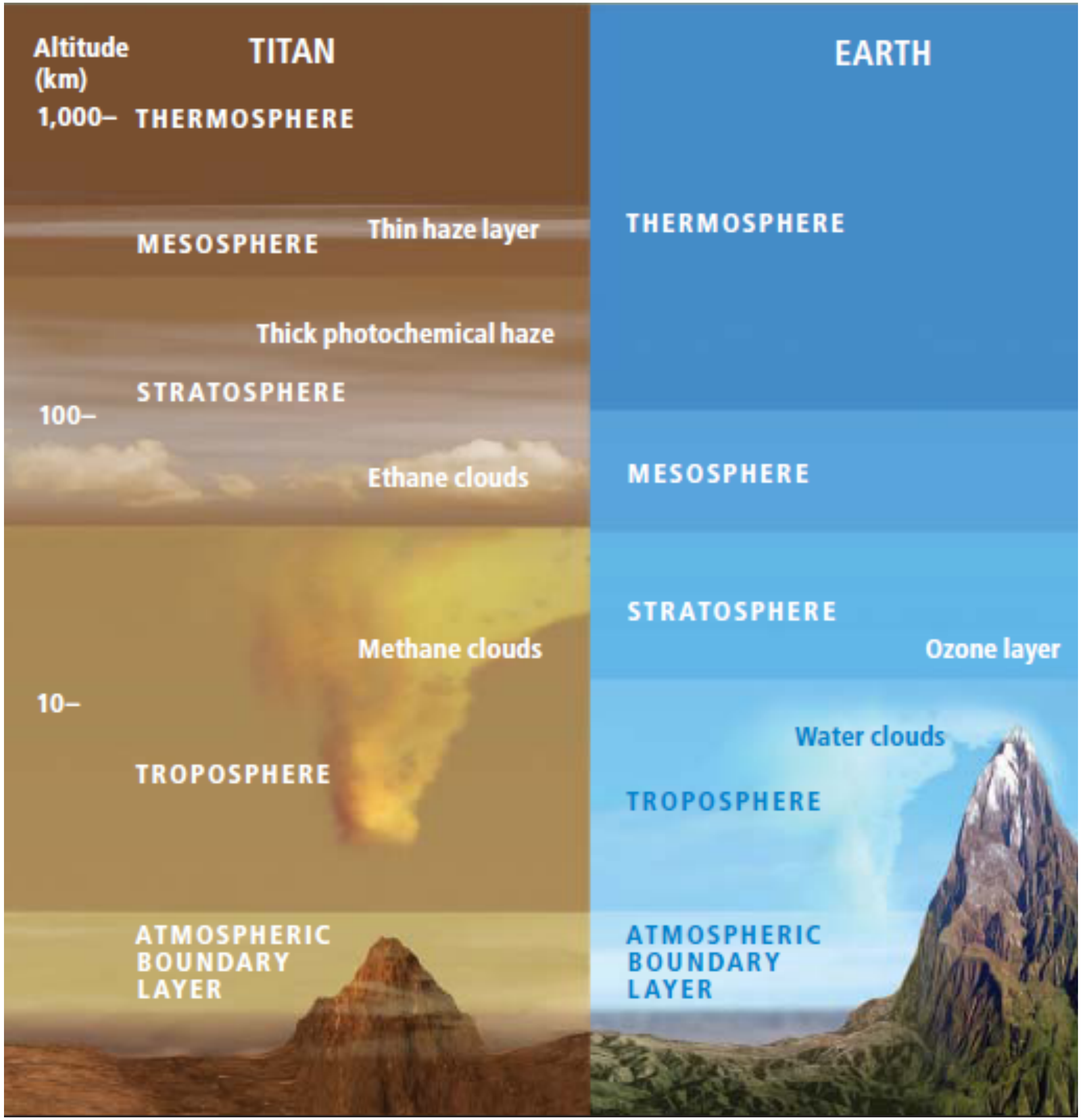
* Choice of adiabat may be judicious



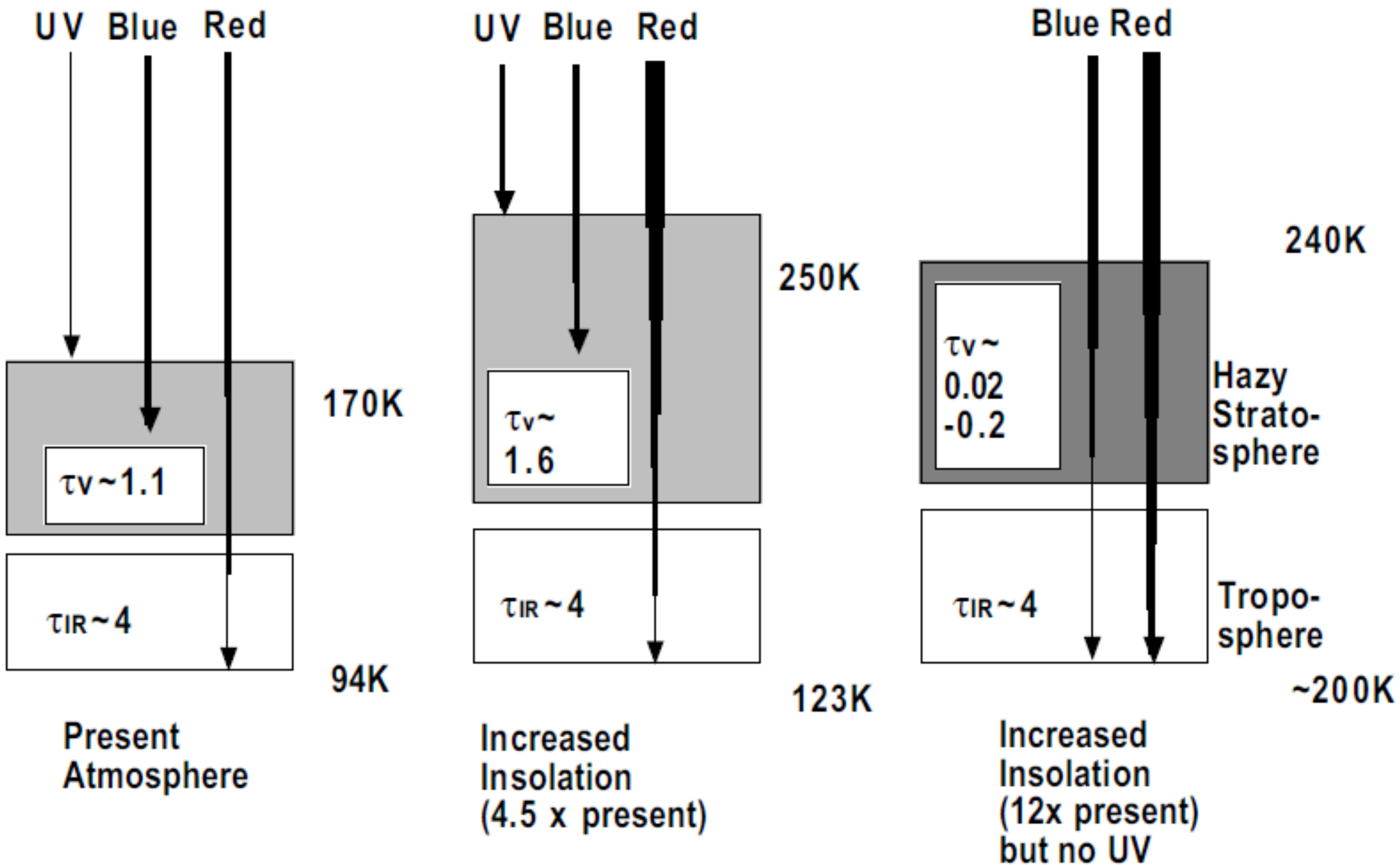
Model parameters adjusted to match disk-integrated albedo measured from Earth, radio occultation profile, and Voyager thermal IR (not shown)

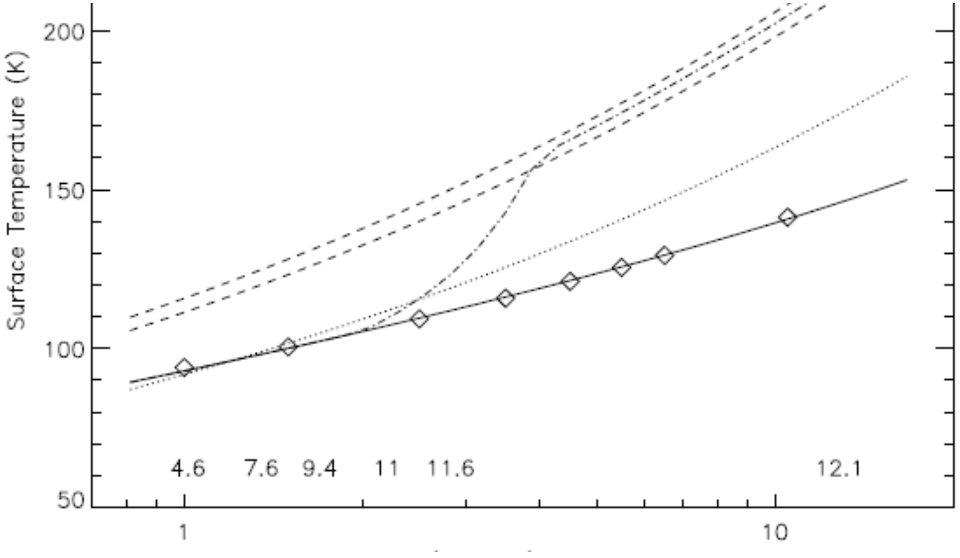


McKay et al., Science, 1990



Lorenz and Sotin, Scientific American, March 2010

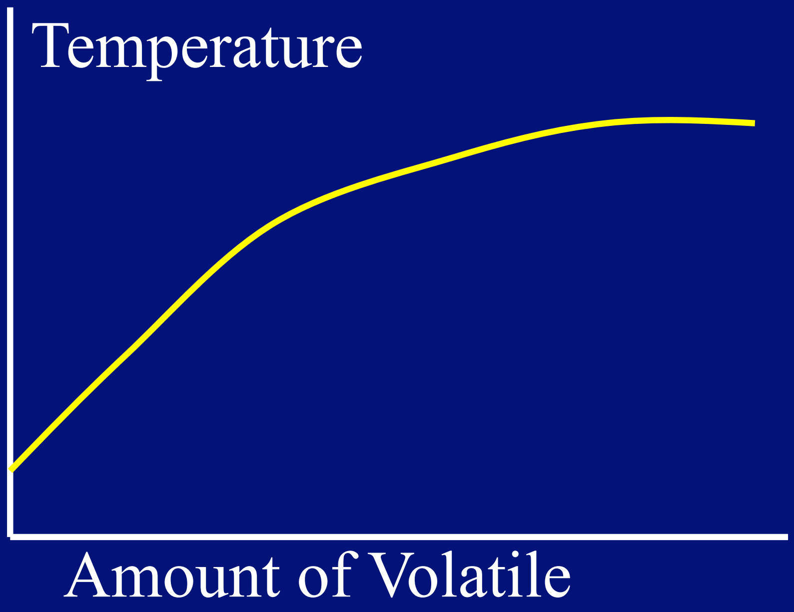




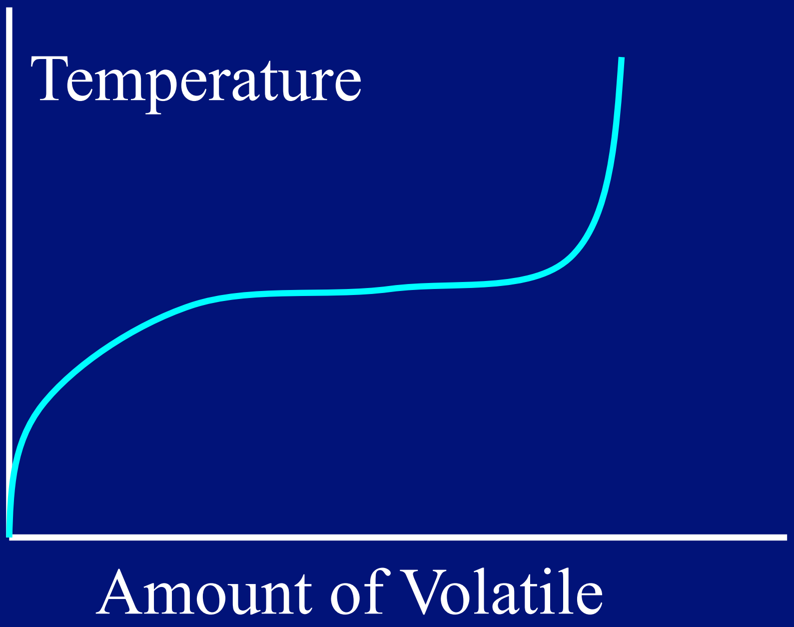
Lorenz et al., GRL, 1997

Hazy atmosphere ‘puffs up’ under insolation increase – only modest increase in surface temperature.
But when star reddens, photochemical production drops, atmosphere clears, temperature jumps

Greenhouse Effect

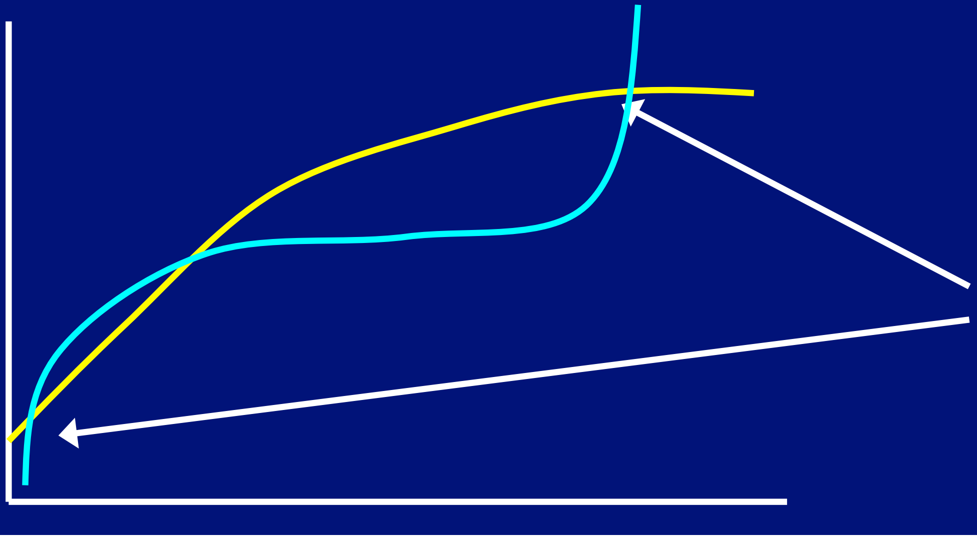


Surface-Atmosphere Equilibrium

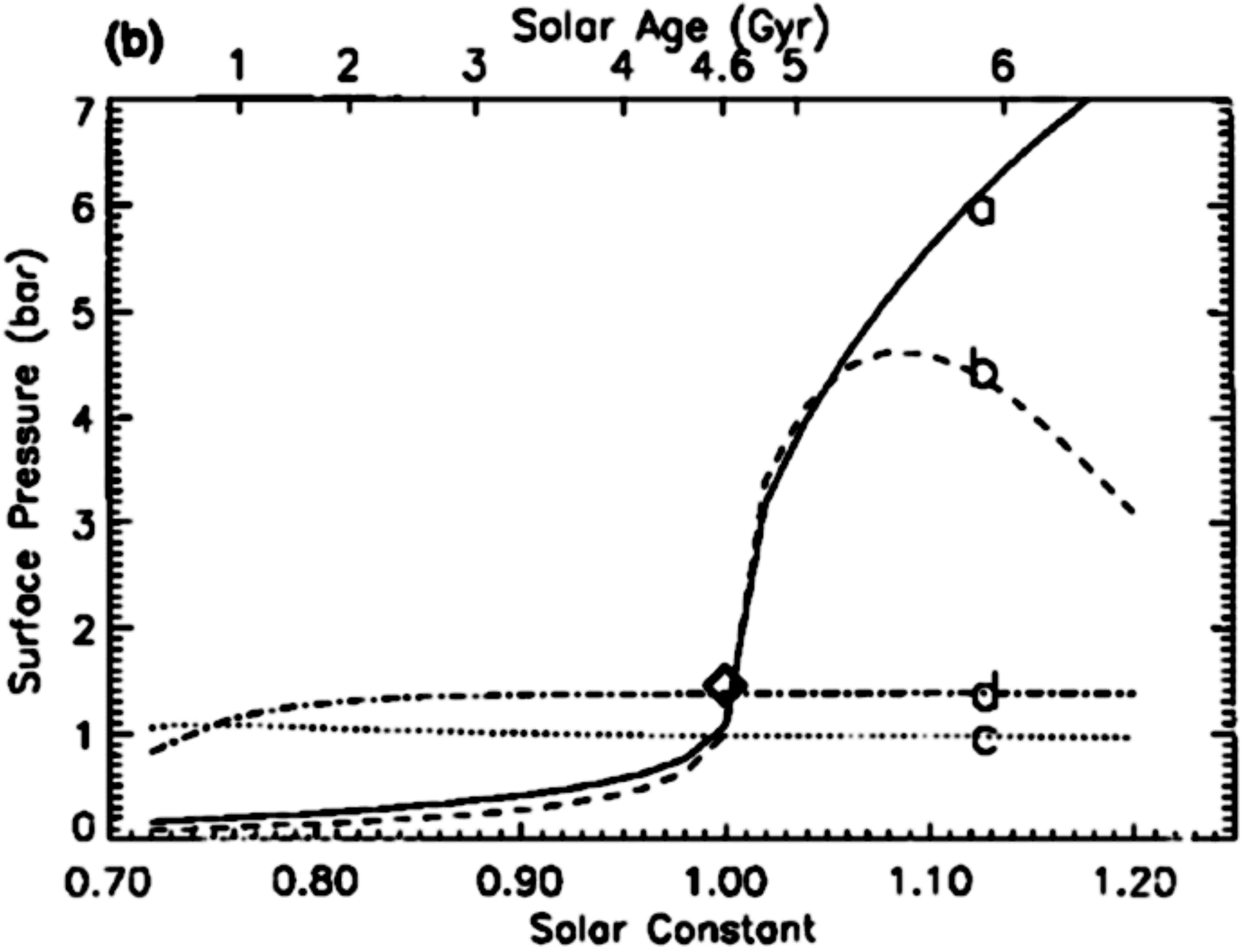


Climate (in)stability

Runaway Greenhouse vs collapse



2 stable equilibria (+1 unstable)

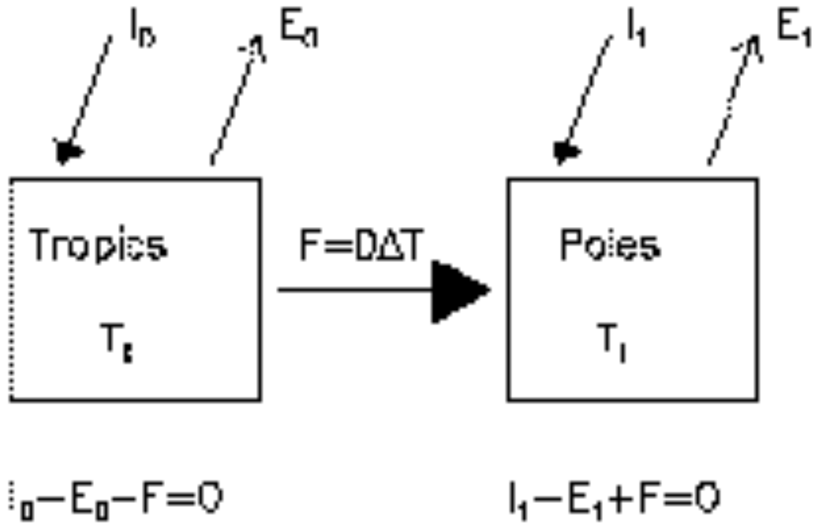


Introduction of condensible greenhouse feedback means that wide excursions in surface temperature and pressure are possible…

But this is just a 1-D model..

But thickness of atmosphere is controlled by the coldest point on the surface - poles. So need to know how much temperature varies across the surface - equator-to-pole heat transport

Simple 2-box Energy Balance model : low and high latitudes



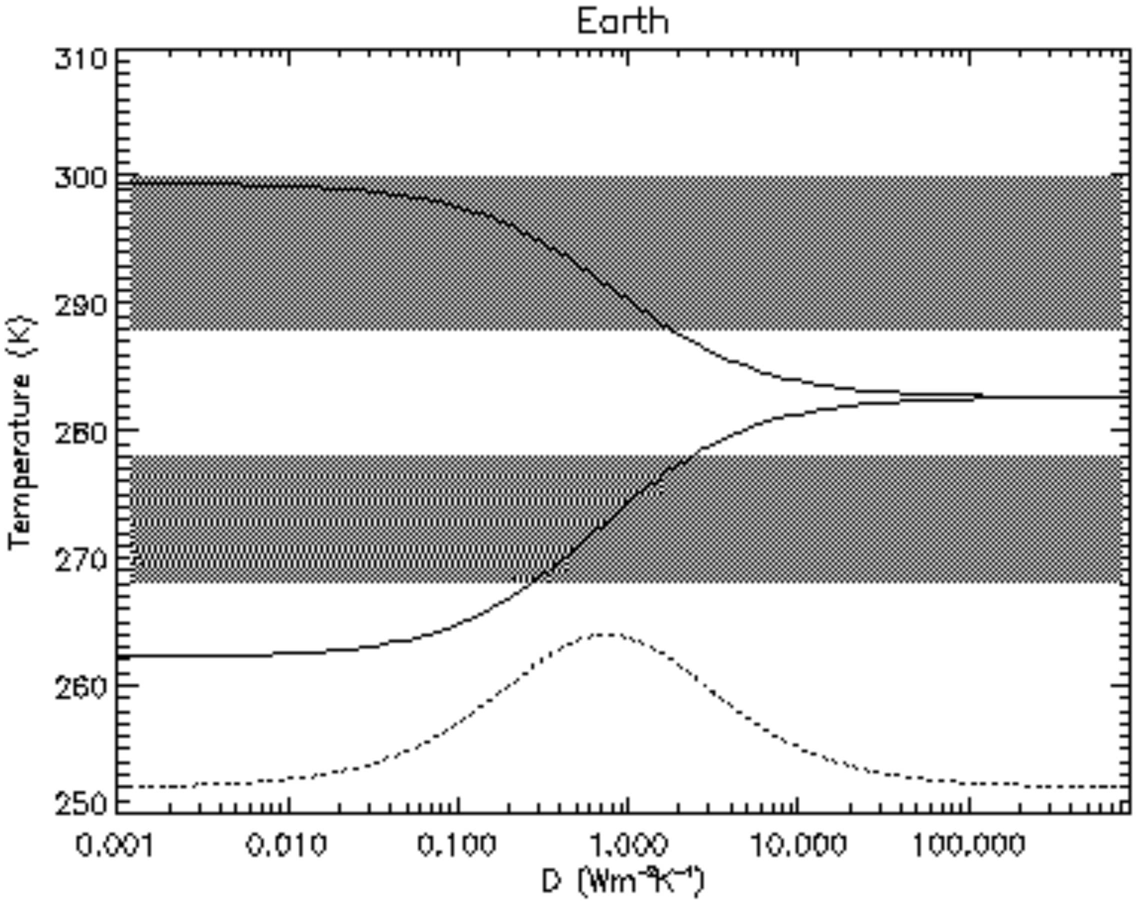
We can solve this problem if we know I_0,I_1, E=f(T) and D

For present Earth, I_0~300 Wm^{-2}, I_1~170 Wm^{-2}

E(T)=A+BT. For present Earth B~2 $Wm^{-2}K^{-1}$, but generally something like $4\sigma T^3/(1+0.75\tau)$

But what is D ?

Lorenz et al, Geophysical Research Letters, 2001



Shaded areas are actual low and high latitude temperatures, averaged over the year. Solid lines are model low and high latitude temperatures (T_0,T_1), converging to an isothermal planet as D->infinity and F->(I_0-I_1)/2. Dotted curve is entropy production (arbitrary scale) F/ T_1-F/T_0. This function has a maximum at the observed climate state.

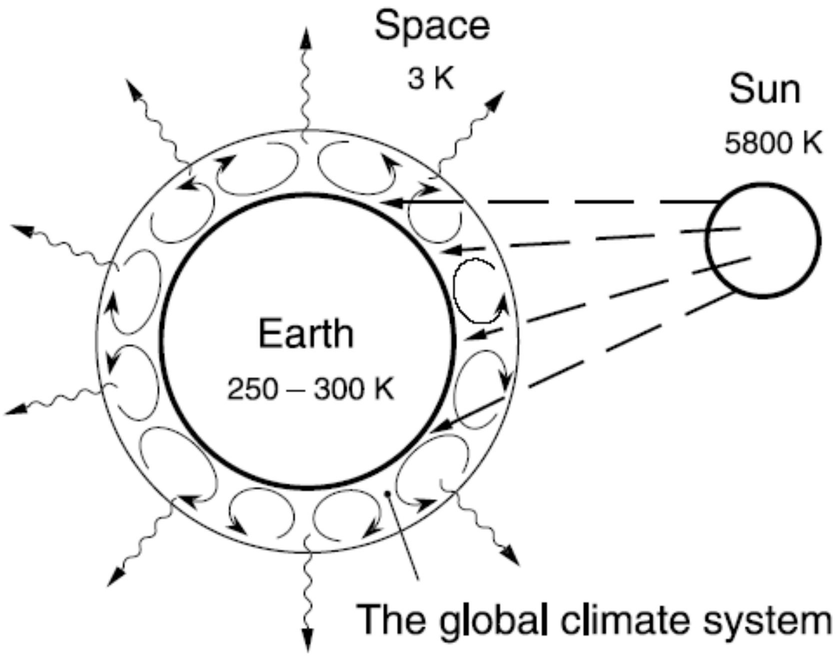
A rescaled curve of work production, F(T_0-T_1)/T_0, is essentially indistinguishable in shape and location of peak. State of maximum entropy production and maximum work production (= maximum dissipation, in steady state) are near-equivalent.

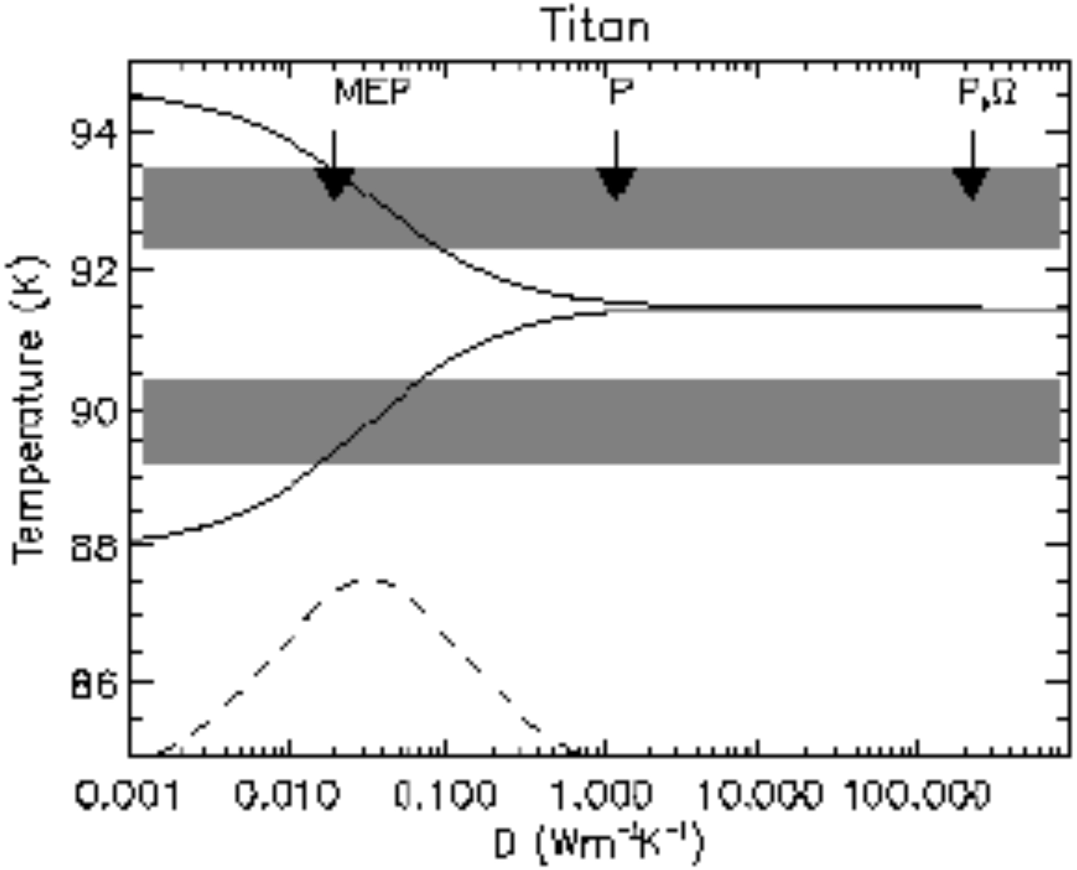
An important clue

Heat transfer coefficient that describes Earth's climate is empirically
$\sim 1\ \mathrm{Wm^{-2}K^{-1}}$

Entropy production of the Earth (since Tearth<<Tsun) is $F/T_{earth} \sim 300\ \mathrm{Wm^{-2}} / 300\mathrm{K}$
$\sim 1\ \mathrm{Wm^{-2}K^{-1}}$

Coincidence ?
I think not.





What about Titan?

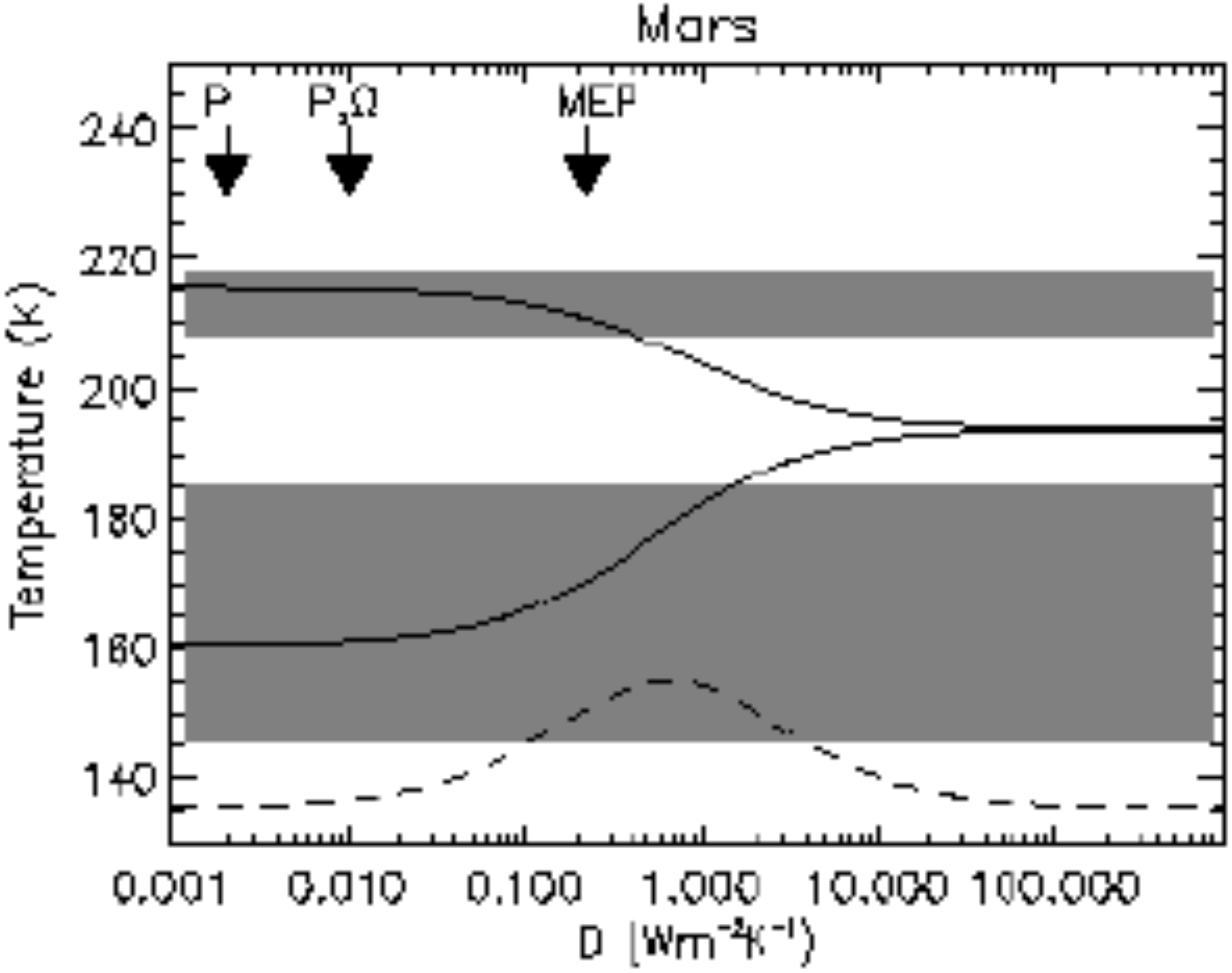
Titan data suggests (now confirmed by better data) 2-4K ΔT

Yet Pressure, rotation rate, planetary size all suggest $D_{titan} > D_{earth}$

But $D \sim D_{earth}$ gives $\Delta T \sim 0.01K$.

Get $\Delta T \sim 1\text{-}2K$ for $D \sim 0.02\ Wm^{-2}K^{-1}$

$T \sim 100K$ $F \sim 4\ Wm^{-2}K^{-1}$ .d $S/dt \sim F/T \sim 0.04\ Wm^{-2}K^{-1}$!



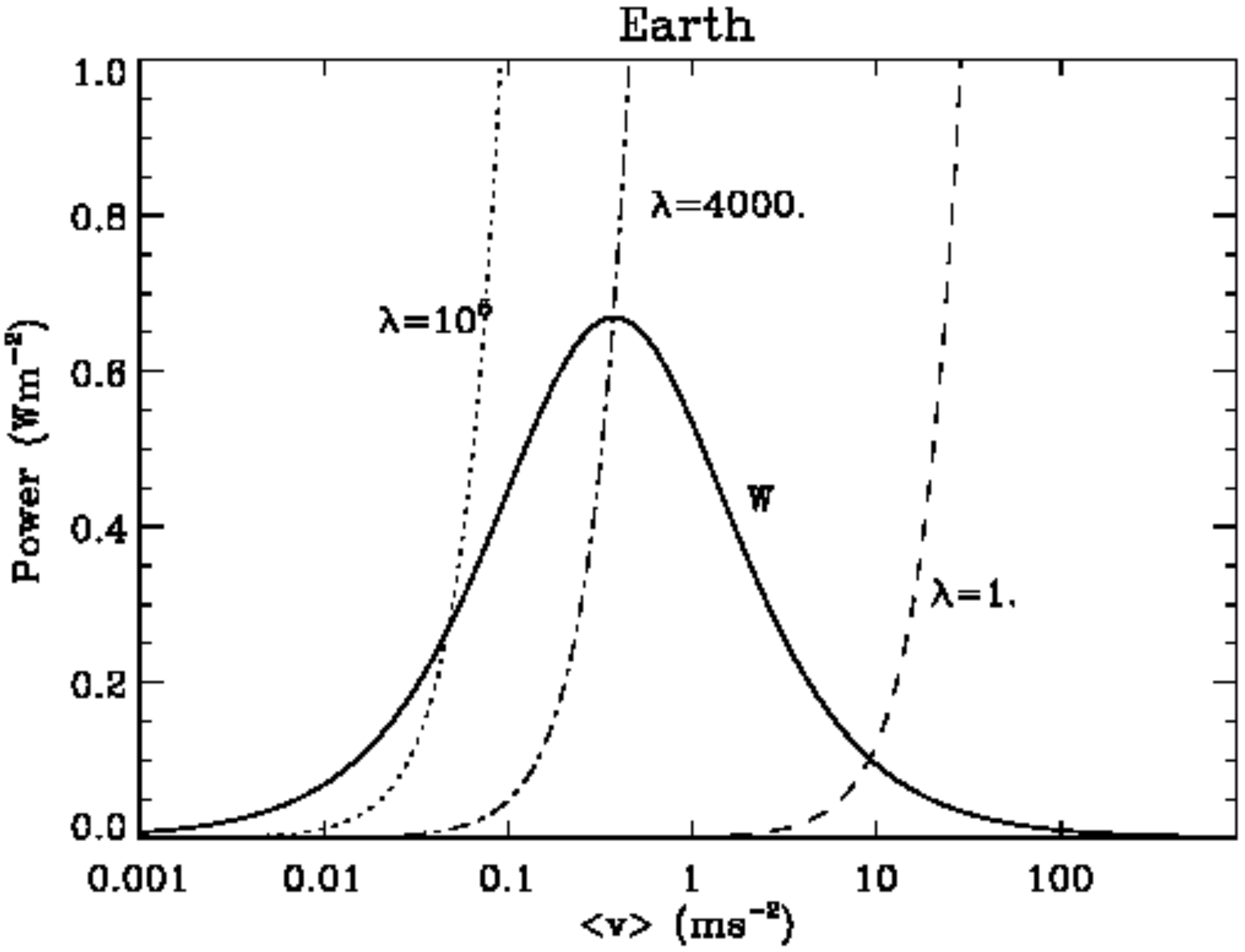
Mars - Hard to say on basis of annual average temperatures - low D seems to work, as approximately does ~Dearth/2

But, Mars models using P-scaling predict very cold winter temperatures.

Models are then ‘corrected’ by pinning to CO_2 frost-point : a justifiable procedure, since seasonal polar caps can be observed (corresponding to ~1m of CO_2 frost)

But.... 1m of CO_2 frost represents latent heat transport of ~10^9 Jm^{-2} over half a martian year, or about 25 Wm^{-2}. This is consistent with the heat flow suggested by MEP...

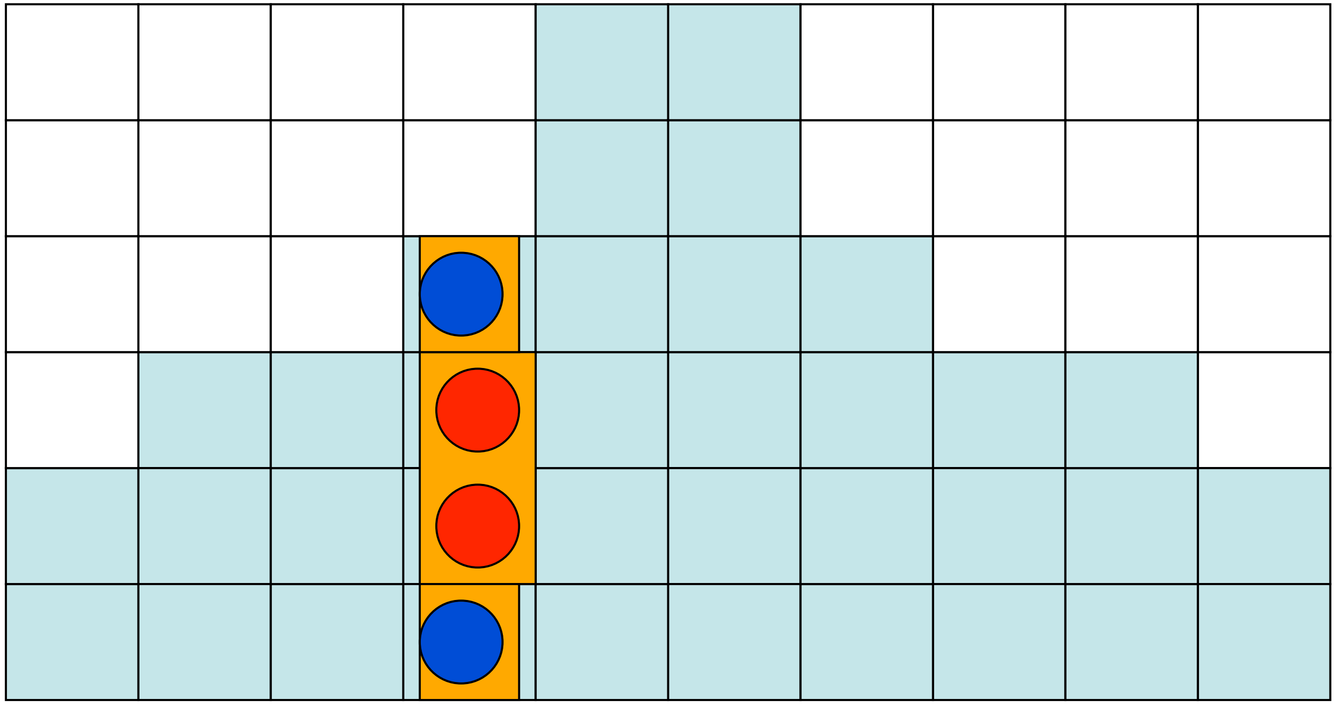
MEP predicts atmosphere must ‘do something’ to transport the heat…. so Mars consistent with MEP



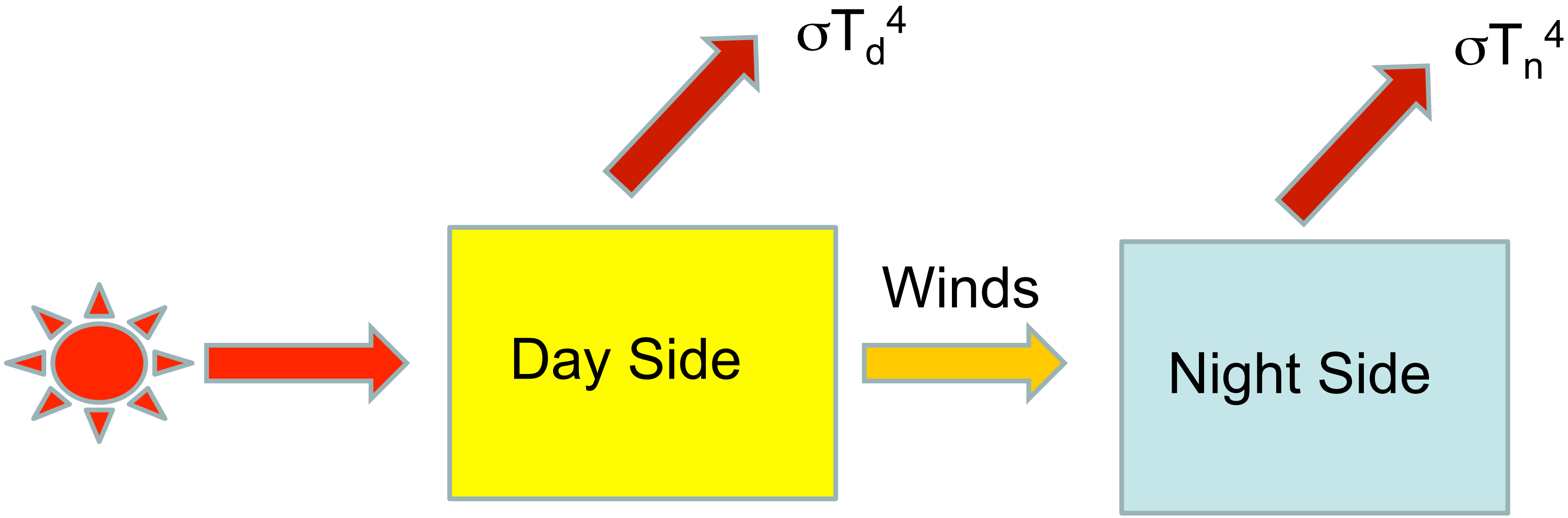
Early attempts at Malkus wheel type model – balance work output from climate system against friction. But get a unique answer which depends on friction coefficient, not on MEP.

System too constrained.

Heuristic model. Many different modes of heat transport, with different amounts of dissipation (vertical axis) for each unit of heat transport (horizontal axis). More combinations possible at maximum work output, therefore more probable ?



Simpler case even than planetary climate



σT_d^4

σT_n^4

Day Side

Winds

Night Side

$$D_{mep}=B/4.$$

$$\Delta T \sim T/3$$

Lunine and Lorenz, LPSC Conference. Submitted/rejected from Ap.J
Submitted/rejected from Icarus… gave up.

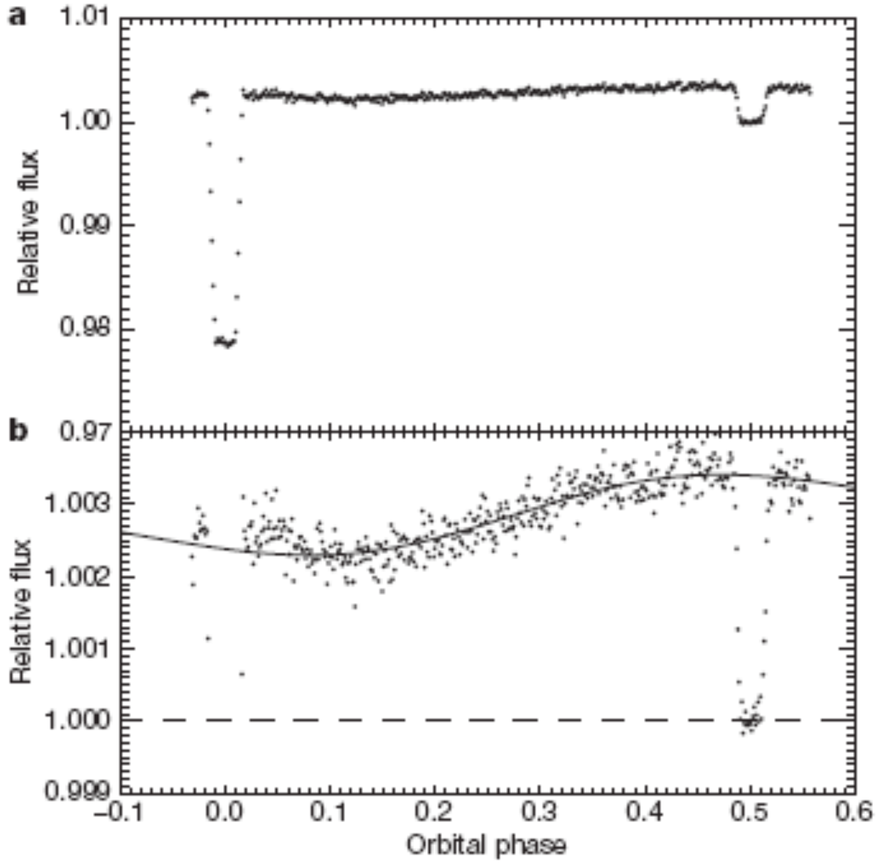
Vol 447|10 May 2007|doi:10.1038/nature05782 nature

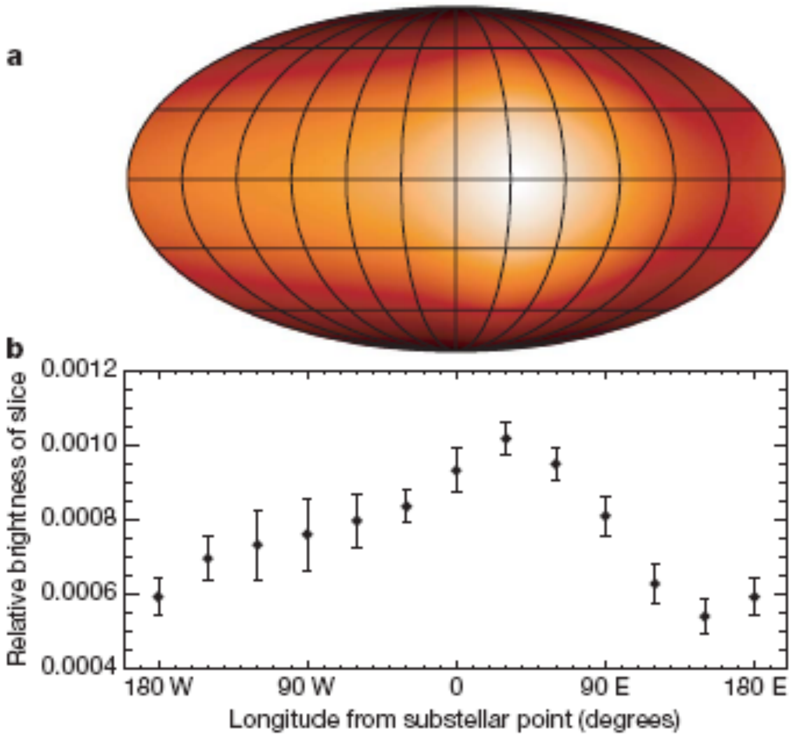
LETTERS

$\Delta T \sim T_{eff}/3$

A map of the day–night contrast of the extrasolar planet HD 189733b

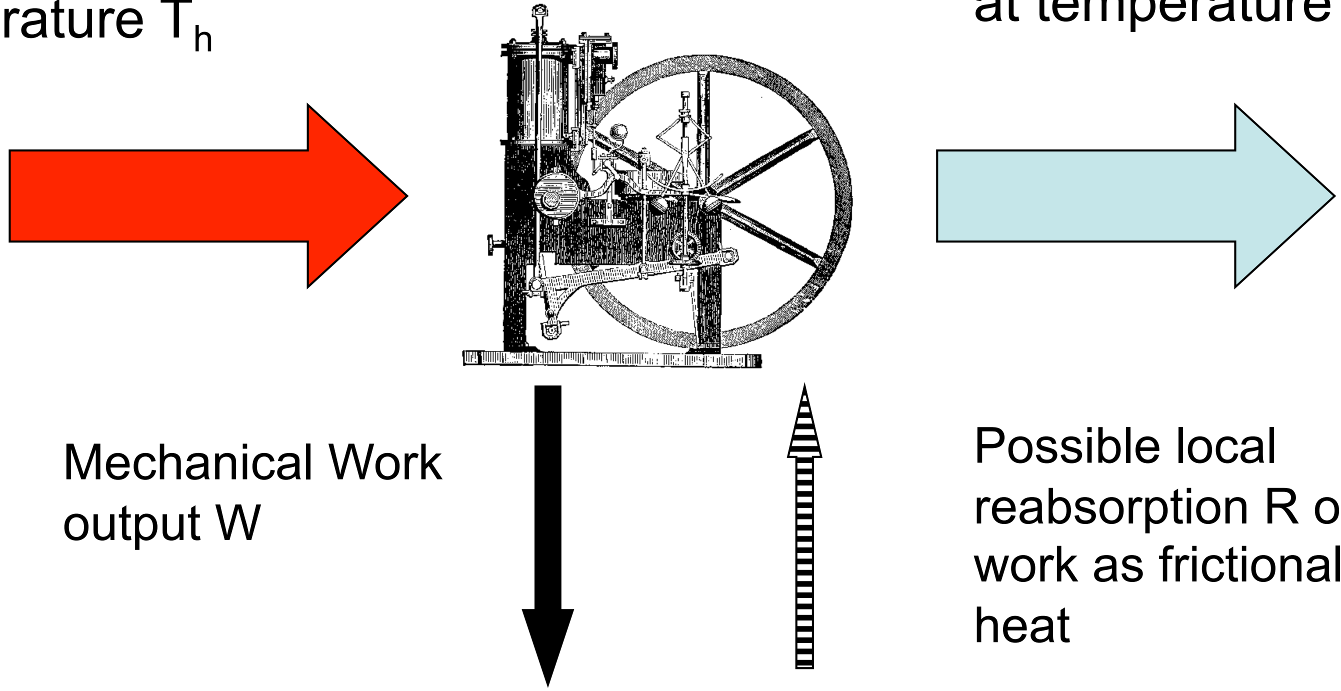
Heather A. Knutson[1], David Charbonneau[1], Lori E. Allen[1], Jonathan J. Fortney[2,3], Eric Agol[4], Nicolas B. Cowan[4], Adam P. Showman[5], Curtis S. Cooper[5] & S. Thomas Megeath[6]





brightness temperature of 973 ± 33 K and a maximum brightness temperature of 1,212 ± 11 K at a wavelength of 8 μm, indicating that energy from the irradiated dayside is efficiently redistributed

Heat Engine



Heat Flow F_{in} applied at temperature T_h

Heat F_{out} rejected at temperature T_c

Mechanical Work output W

Possible local reabsorption R of work as frictional heat

Energy Balance : $F_{in} = F_{out} + (W - R)$, but usually $R << W$, $W << F$

2nd Law : $W < F_{in} (T_h - T_c)/T_h$

Day:Night transport on HD189733b is ~50 kW/m^2

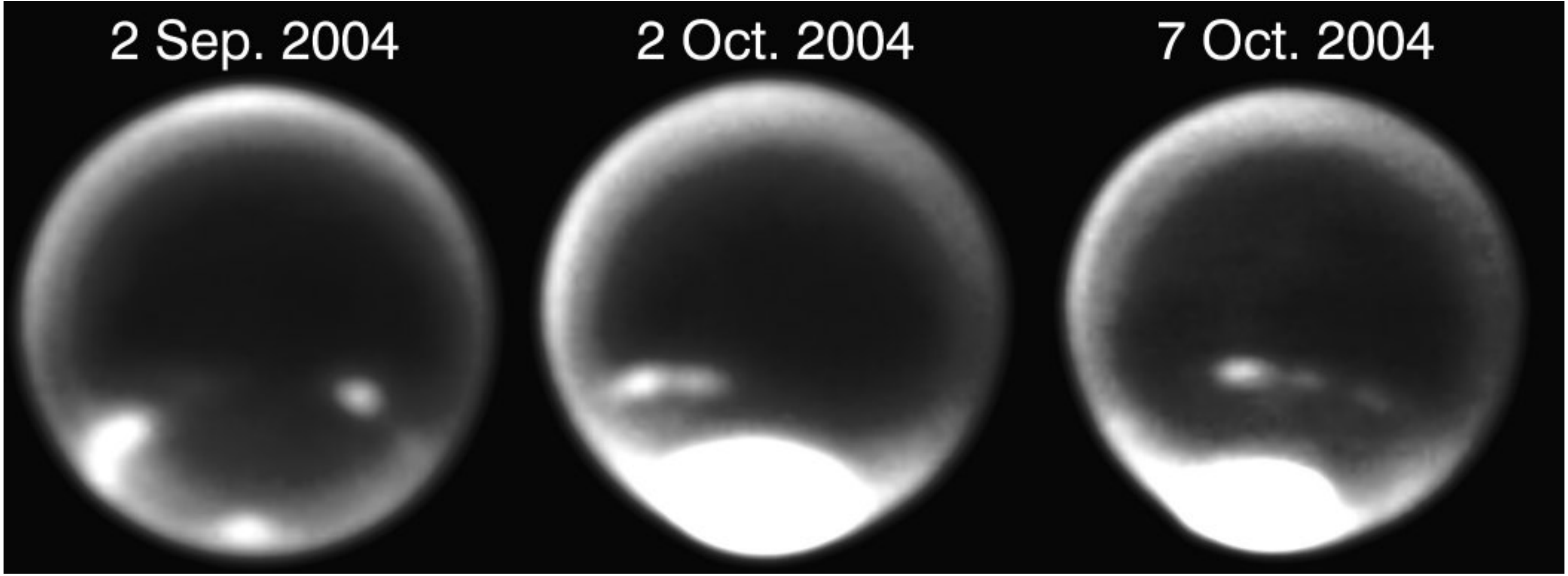
Implies Dissipation (mechanical ?) of ~ 10kW/m2

Could this be buried in the interior (see poster by Pont et al; see also Guillot and Showman, 2002)

Goodman (Ap J, 2009) notes that dissipation must occur for steady state

On Earth, climate work ~few Wm^{-2}. Frictional dissipation ($0.5\rho C_d V3$) ~ $1Wm^{-2}$ [Not always book-kept in climate models, despite being comparable with some greenhouse gas forcings].
Mechanical work in falling precipitation ~mgh
~$1000kg x 10ms^{-2} x 3000m$ / yr ~ 1 Wm^{-2}
(see ‘dehumidifier’ discussion in Pauluis and Held, Renno)

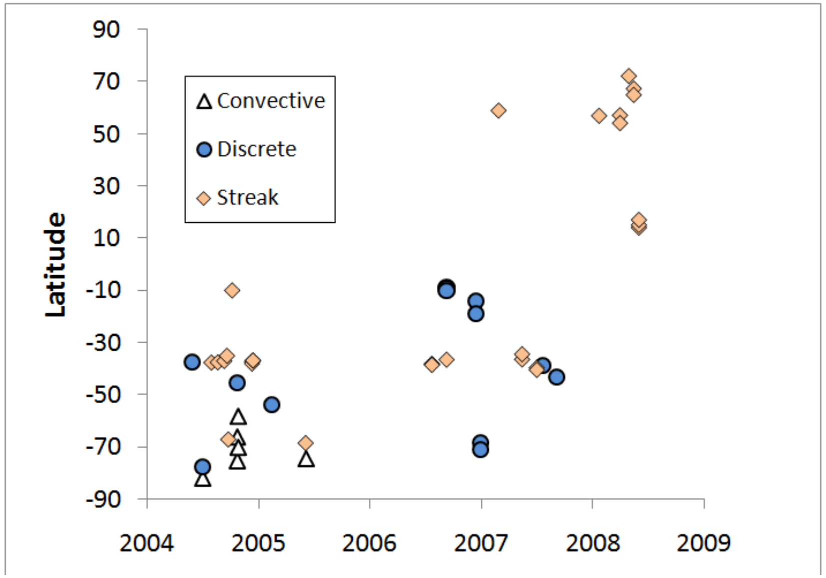
Methane clouds detected spectroscopically since 1995. Near-IR imagery showed massive solstice cloud activity around south pole



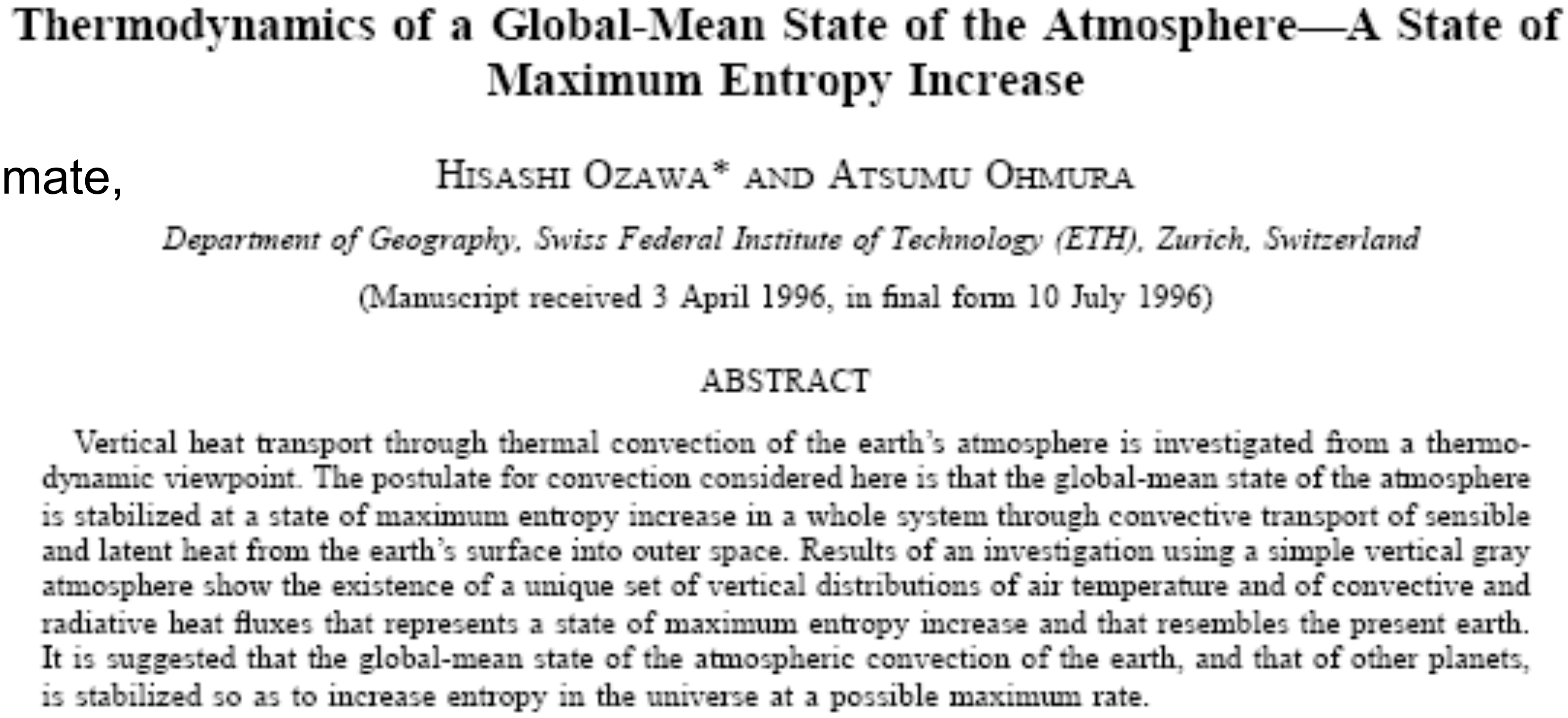
Titan weather - big storms, long droughts

Cloud patterns changing - northern hemisphere clouds picking up as we move to equinox.

But why only ~1% coverage on Titan compared with >30% on Earth?   Is mechanical work more constraining than heat flux?)



Journal of Climate, 1997



Thermodynamics of a Global-Mean State of the Atmosphere—A State of Maximum Entropy Increase

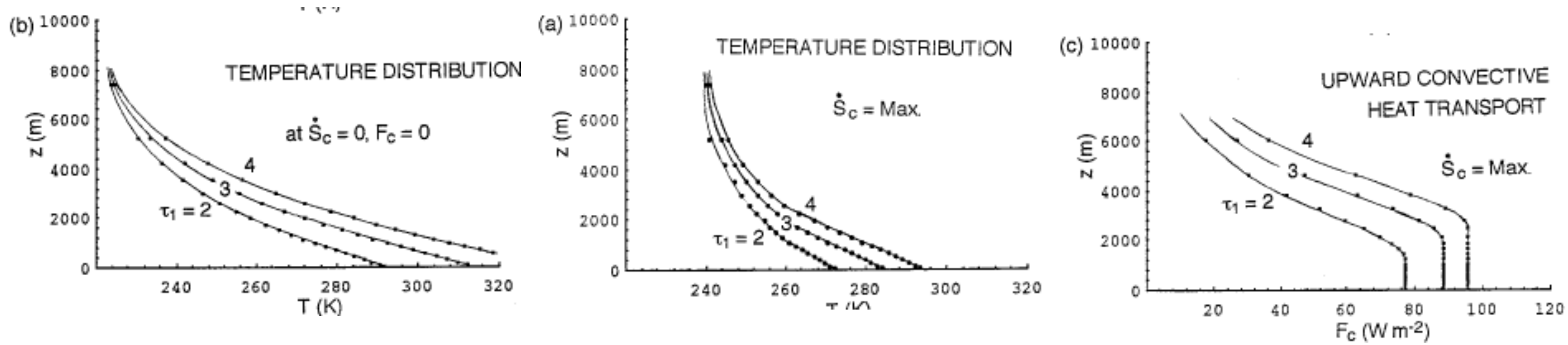
HISASHI OZAWA* AND ATSUMU OHMURA

Department of Geography, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland

(Manuscript received 3 April 1996, in final form 10 July 1996)

ABSTRACT

Vertical heat transport through thermal convection of the earth's atmosphere is investigated from a thermodynamic viewpoint. The postulate for convection considered here is that the global-mean state of the atmosphere is stabilized at a state of maximum entropy increase in a whole system through convective transport of sensible and latent heat from the earth's surface into outer space. Results of an investigation using a simple vertical gray atmosphere show the existence of a unique set of vertical distributions of air temperature and of convective and radiative heat fluxes that represents a state of maximum entropy increase and that resembles the present earth. It is suggested that the global-mean state of the atmospheric convection of the earth, and that of other planets, is stabilized so as to increase entropy in the universe at a possible maximum rate.

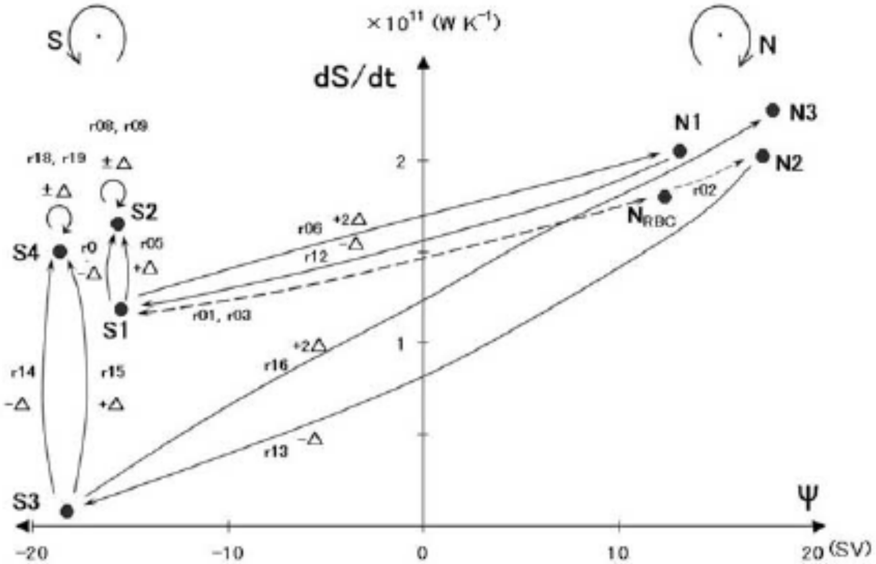


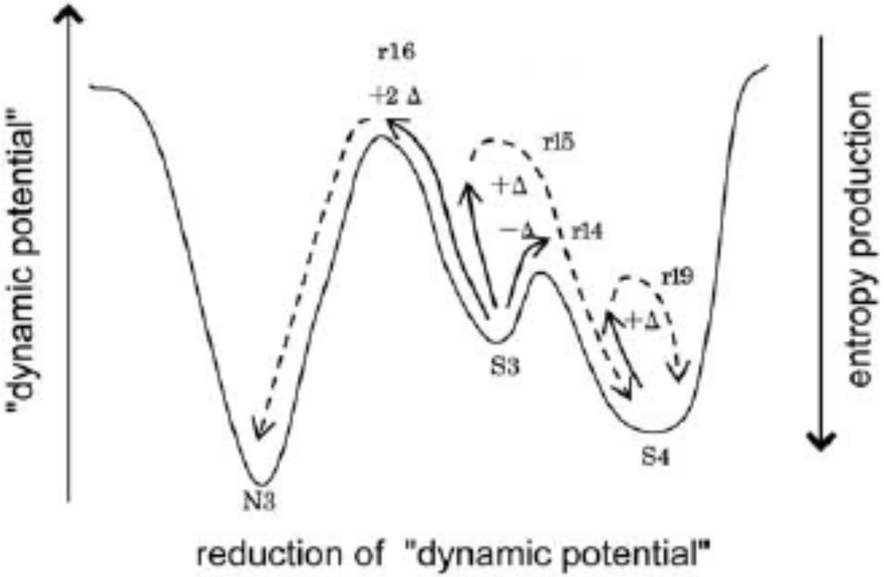
Usual approach 'convective adjustment' is to compute radiative equilibrium, then adjust where lapse rate exceeds threshold and recompute. Ozawa and Ohmura suggest instead choose Fc to maximize E.P. - both methods seem to work, but O&O is more general.

GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L12606, doi:10.1029/2007GL030208, 2007

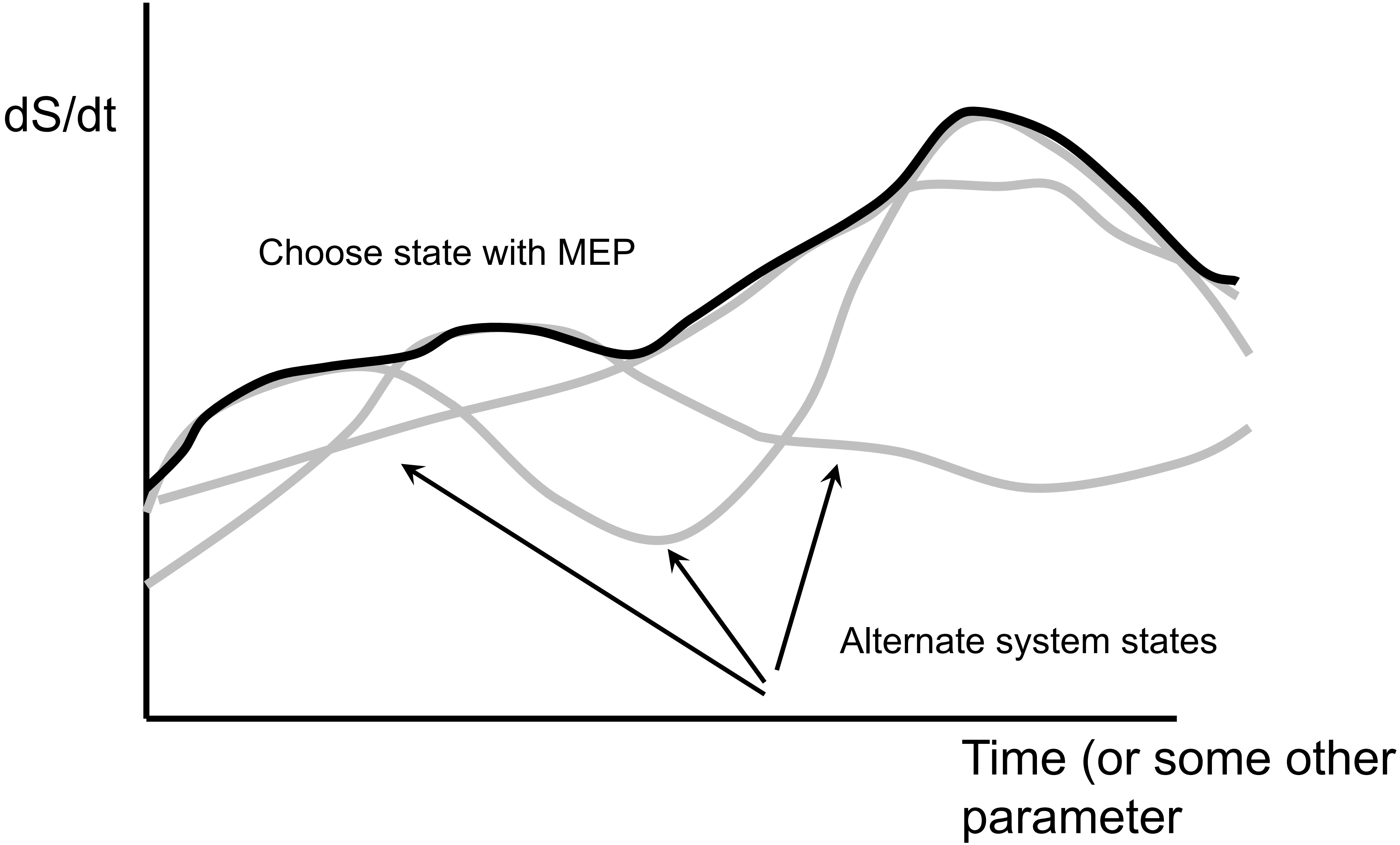
Thermodynamics of irreversible transitions in the oceanic general circulation

Shinya Shimokawa[1] and Hisashi Ozawa[2]





MEP as a selection criterion among ensemble runs ?



Choose state with MEP

Alternate system states

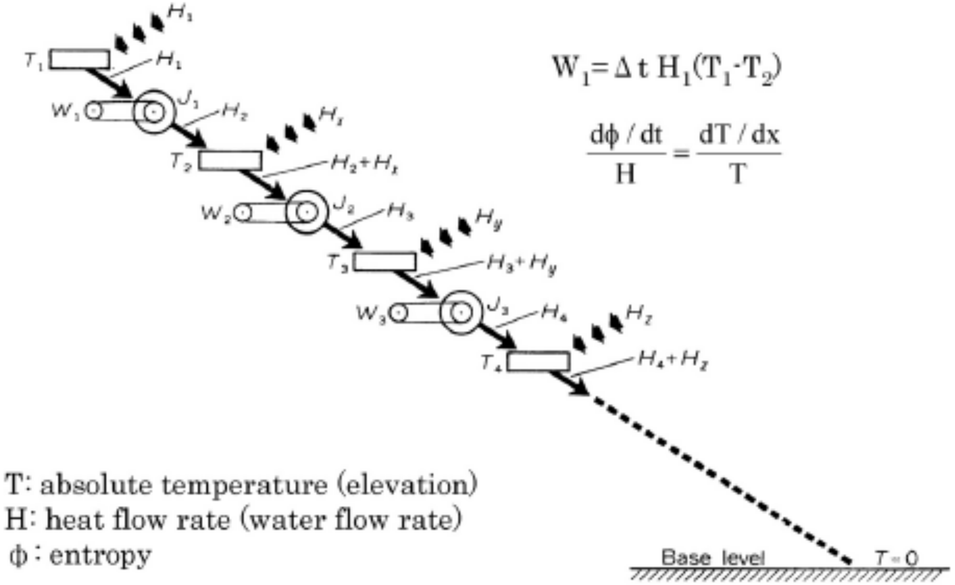
e.g. Ammonium Chloride Crystal growth appears to select between modes using an EP criterion

Dissipation in River Networks

Minimum-length spanning trees can be discriminated by dissipation $\Sigma H \Delta L$

(Fixed boundary condition – unit rain flux in each position, constrained to drain into single sink at center)

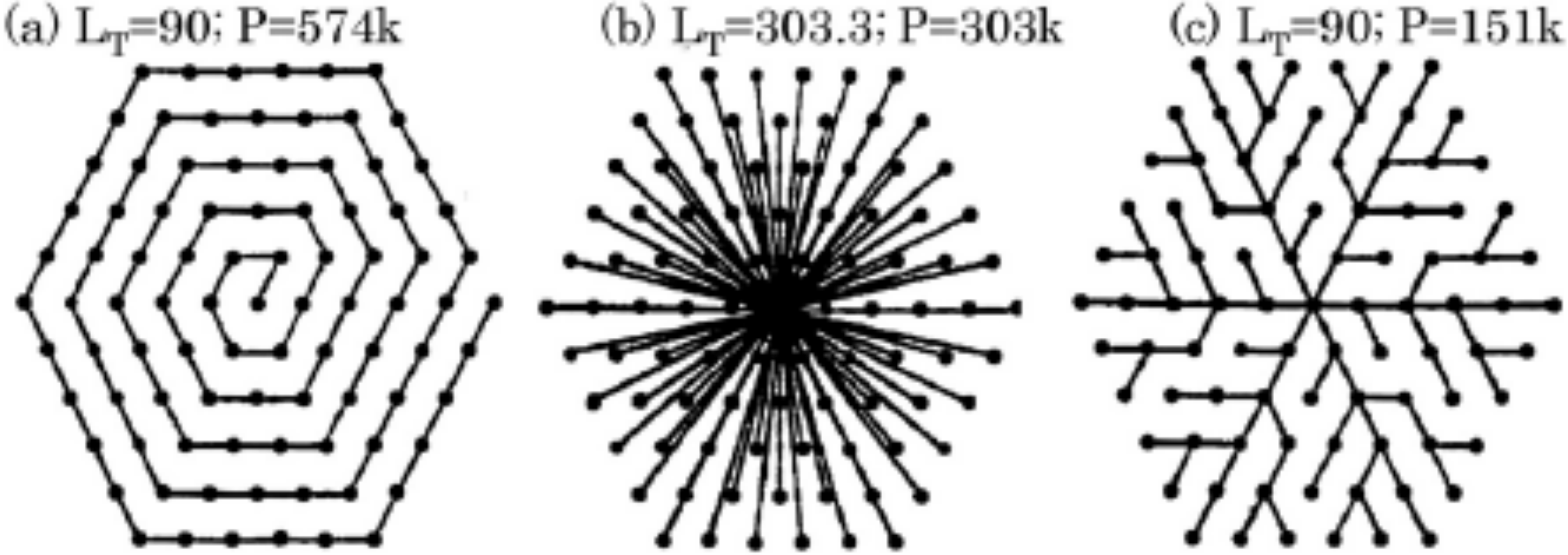
Real systems adjust topography too….



$$W_1 = \Delta t\, H_1 (T_1 - T_2)$$

$$\frac{d\phi / dt}{H} = \frac{dT / dx}{T}$$

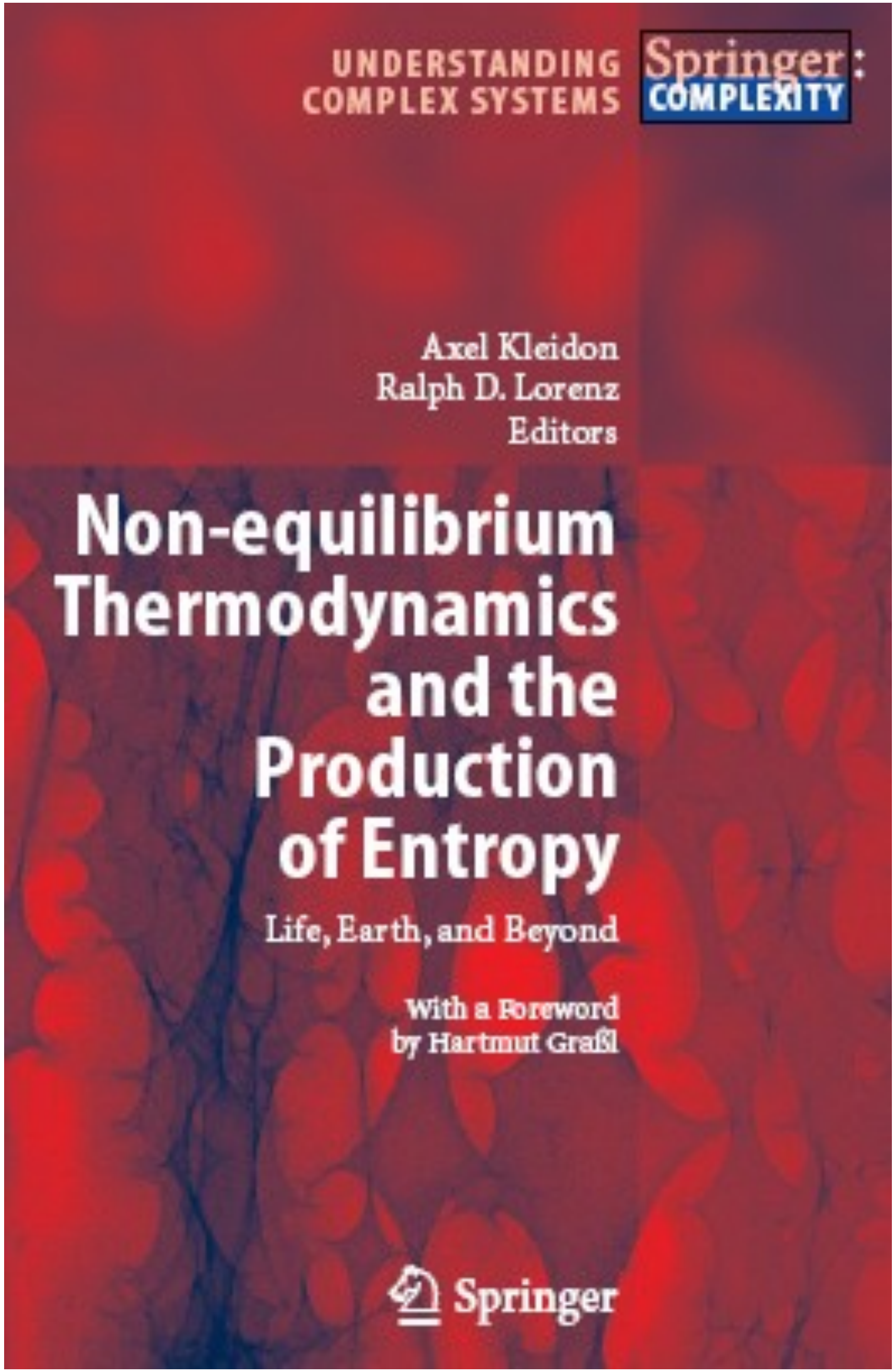
T: absolute temperature (elevation)
H: heat flow rate (water flow rate)
ϕ: entropy



(a) $L_T=90$; $P=574k$

(b) $L_T=303.3$; $P=303k$

(c) $L_T=90$; $P=151k$



UNDERSTANDING COMPLEX SYSTEMS
Springer: COMPLEXITY

Axel Kleidon
Ralph D. Lorenz
Editors

Non-equilibrium Thermodynamics and the Production of Entropy

Life, Earth, and Beyond

With a Foreword
by Hartmut Graßl

Springer

Non-Equilibrium Thermodynamics
and the Production of Entropy

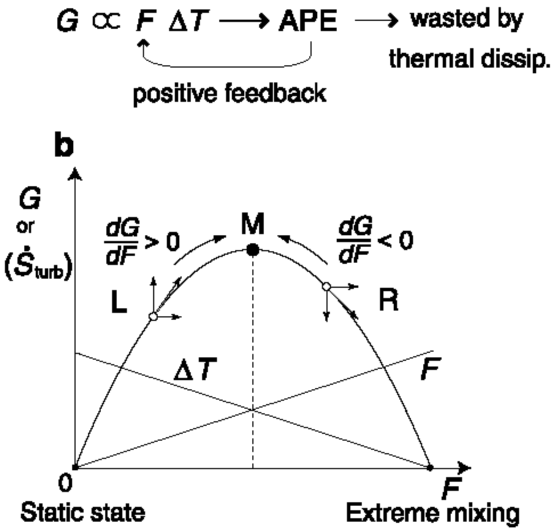
Life, Earth and Beyond

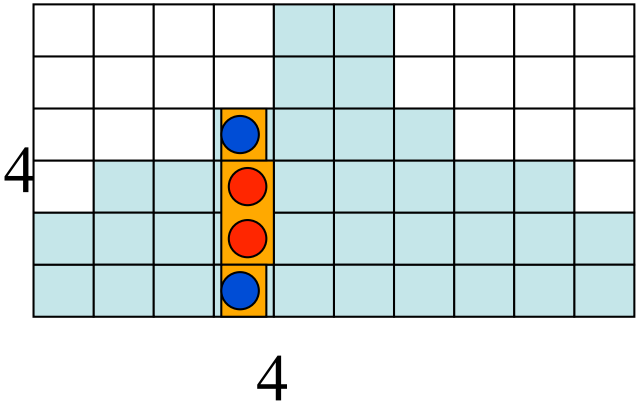
Springer, 2005   260pp

Includes discussion on many of the topics raised in this talk (Plus entropy budget in photosynthesis, biotic feedbacks, Daisyworld, cosmic evolution etc..)

'Darwinian' - high-throughput systems grow faster than low-throughput systems and therefore supplant them

'Statistical' - system displays a range of modes which run in combinations, whos probabilities are largest for a maximum throughput

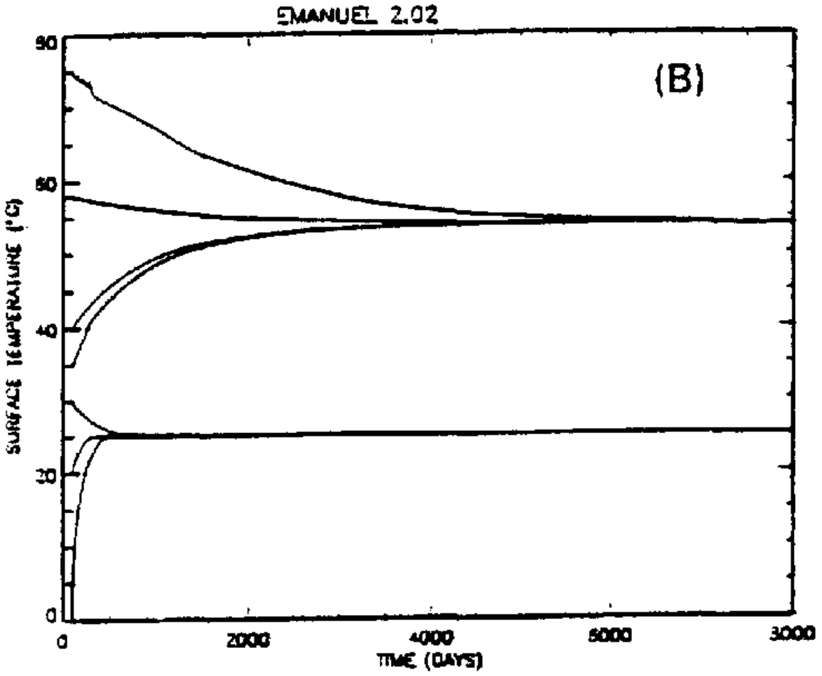


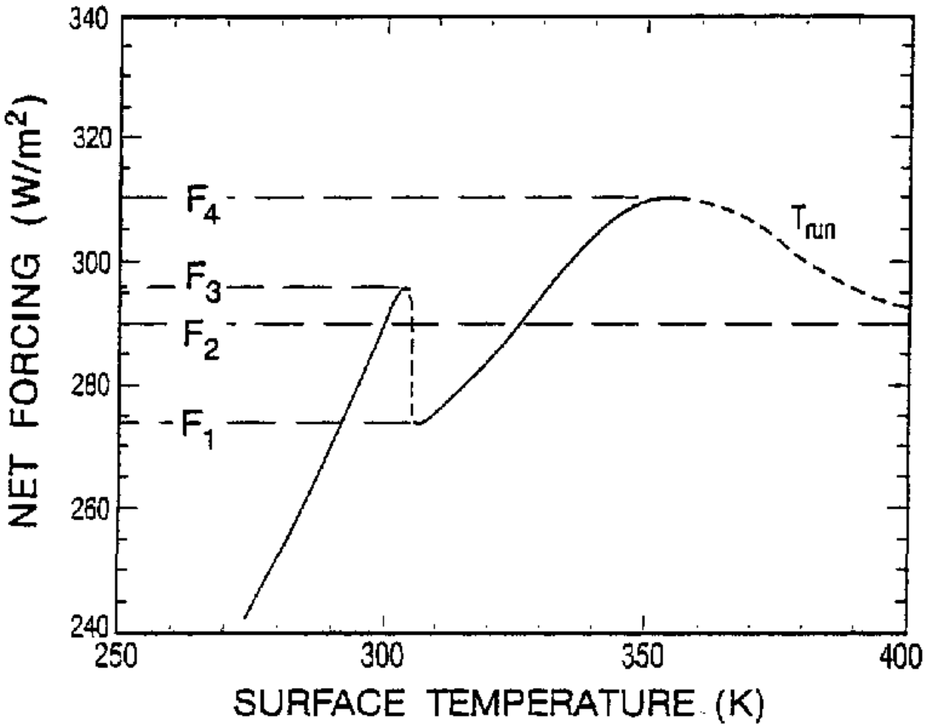


Cf Intelligent Design vs Evolution. Does it really matter what you believe is 'true'? Question is what lets you make useful predictions……

N. Renno, Multiple Equilibria in radiative-convective atmospheres, Tellus, 49A, 423-438, 1997

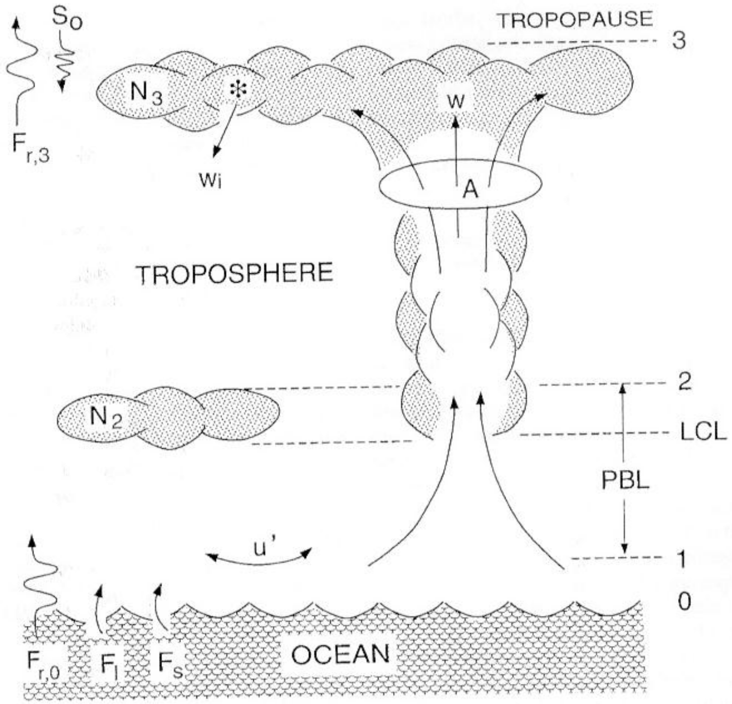
Finds optically thin atmosphere behaves linearly and has small dissipation. The optically thick solution (runaway greenhouse) is highly nonlinear and is in a state of large dissipation. (But these require explicit hydrological cycle controlling humidity - typical radiative-convective models impose a humidy profile.)

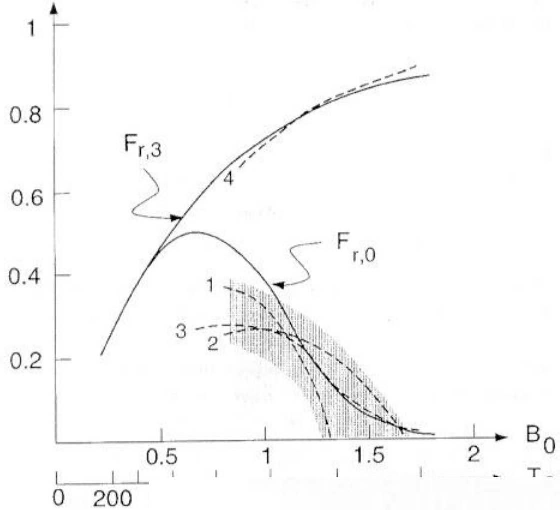


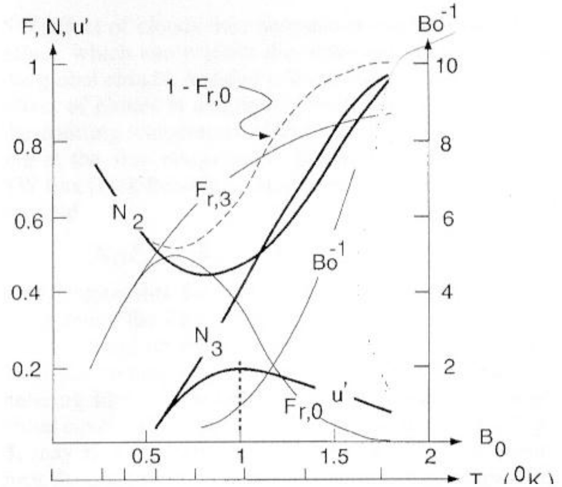


Possible Bounds on the Earth's Surface Temperature: From the Perspective of a Conceptual Global-Mean Model*

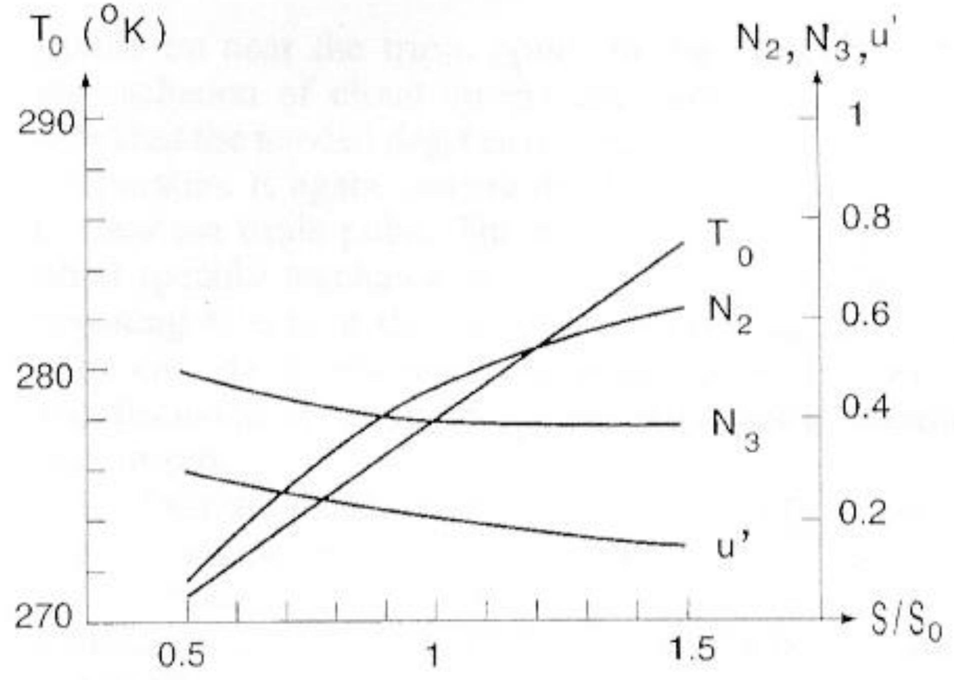
HSIEN-WANG OU







Uses MEP to select Bowen ratio for model closure. Result is Earth temperature that is fairly insensitive to solar evolution



Conclusions – Titan

Several Titan GCMs being used to explore aspects of current climate. Observation of seasonal change under way
-Predict winds for future missions
- Explore angular momentum balance (spin up/down of solid body rotation measured by Cassini radar)
- Evaluate near-surface winds and dune formation
- Examine seasonal changes in atmospheric main and detached haze layers
- Study methane hydrology and Croll-Milankovich forcing of liquid methane/ethane distribution

However, all Titan GCMs use a version of the McKay R-C code (or even simpler models)

No ‘real’ paleoclimate work underway (e.g. different solar constant)

Collision-Induced Opacity coefficients need re-examination (e.g. De Kok et al, 2010)

Conclusions – Thermodynamics

MEP a useful approach for choosing transfer coefficient in 1-D EBMs? But optimization is only as clever as the constraints it is performed under. (challenging if vertical+horizontal flows)

MEP a useful selection principle among dynamically-permitted states in GCMs ?
Thermodynamic constraints useful in defining subscale parameterizations? Useful in defining clouds ?

Book-keeping of mechanical energy may be important for terrestrial climate models and for Exoplanet temperatures and evolution.

The complexity of the universe around us arises because of the laws of thermodynamics, not in spite of them.

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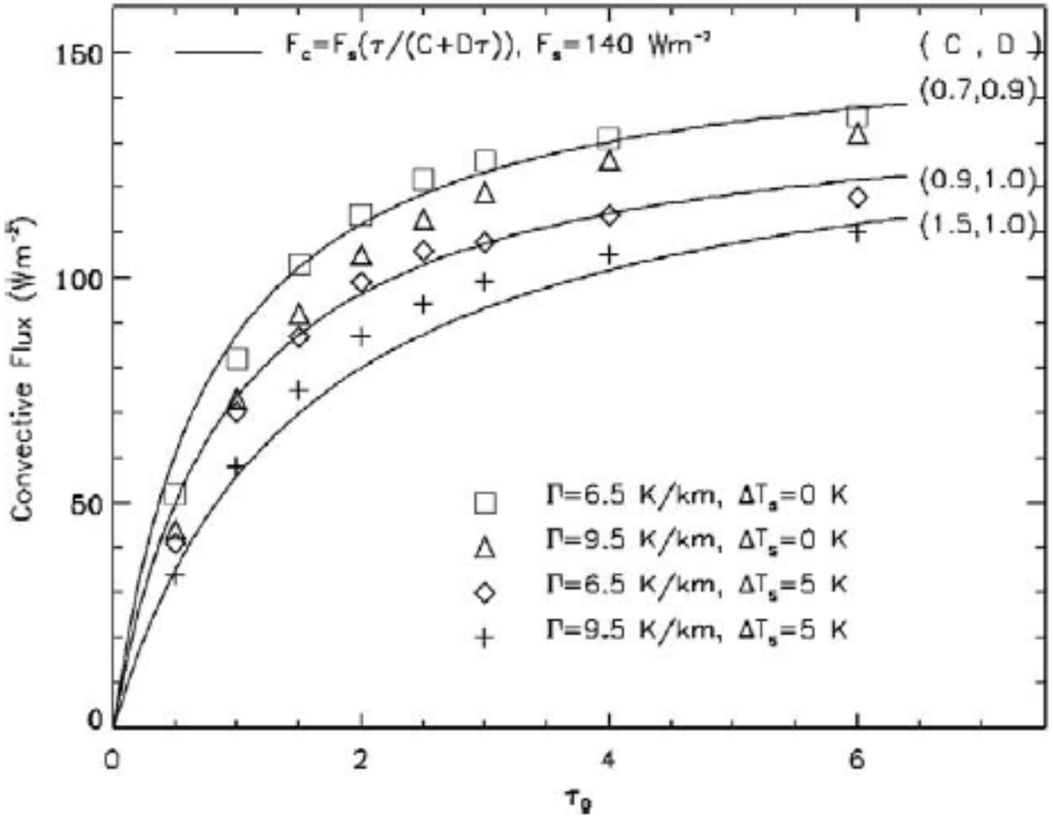
A simple expression for vertical convective fluxes in planetary atmospheres

Ralph D. Lorenz[a,*] and Christopher P. McKay[b]



Empirical fit to grey radiative-convective model

$F_c \sim F_s(\tau/(1+\tau))$ where τ is infrared opacity, F_s is shortwave flux deposited at base of atmosphere and F_c is the vertical convective flux.