

## Diabatic-Dynamical Interaction in the General Circulation (lecture 2)

### Temperature distribution as a function latitude and time

Radiative equilibrium state and radiative determined state

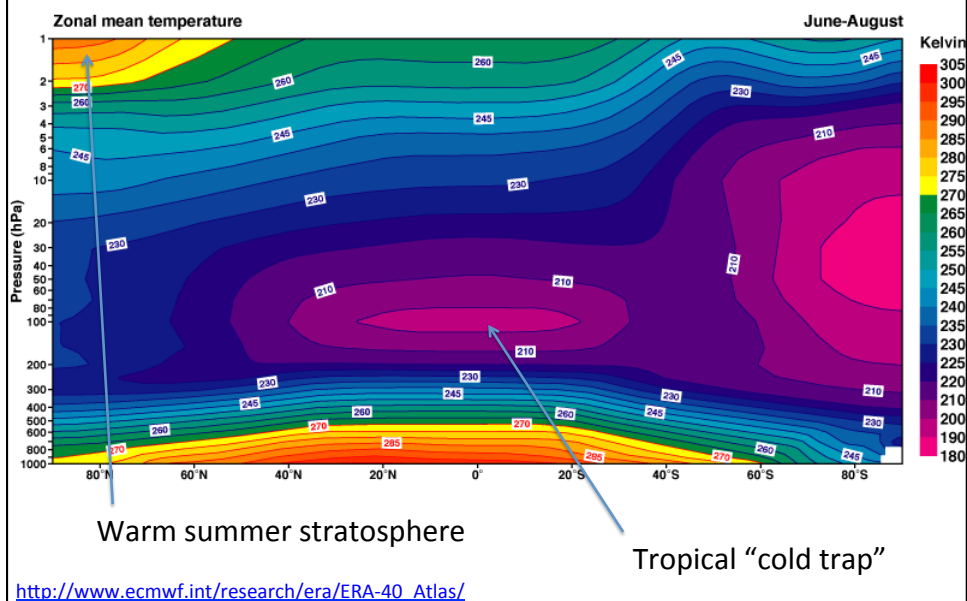
Thermal inertia

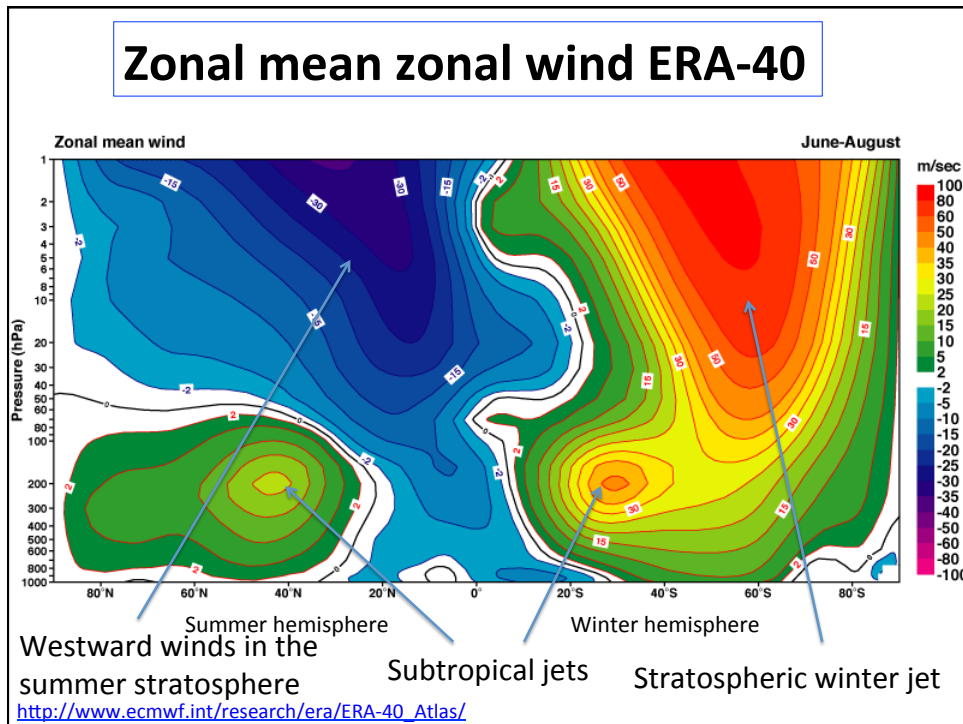
Dynamics of an atmosphere which is devoid of water

Aarnout van Delden

<http://www.staff.science.uu.nl/~delde102/C&HC.htm>

### Zonal mean temperature ERA-40





What is the cause of these features of the general circulation?

*Radiation* (greenhouse effect, ozone)  
*Water cycle* (evaporation, condensation)  
*Wave drag*

Last week:

BOX 2.3

## Radiative equilibrium: full solution

Atmospheric temperature:

$$T = T_{skin}(\delta + 1)^{1/4}$$

Surface temperature:

$$T_S = T_{skin}(\delta_S + 2)^{1/4}$$

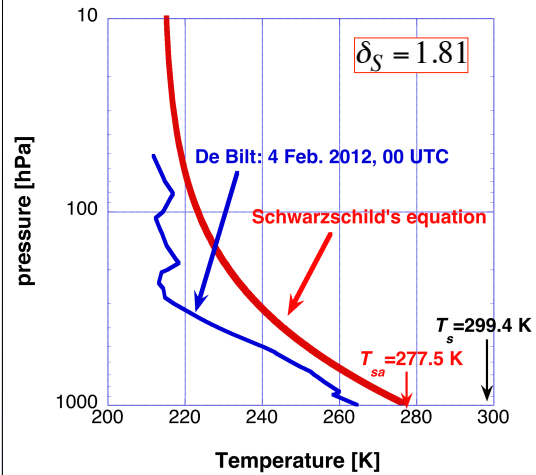
$$\delta = \sigma_a q_a p / g$$

$$T_{skin} \equiv \sqrt[4]{\frac{Q}{2\sigma}}$$

$$Q \equiv \frac{1}{4} S_0 (1 - \alpha_p)$$

$$\sigma_a = 0.3 \text{ m}^2 \text{ kg}^{-1}; r_a = 390 \text{ ppmv}$$

$$\alpha_p = 0.3; S_0 = 1366 \text{ W m}^{-2}; p_s = 1000 \text{ hPa}$$

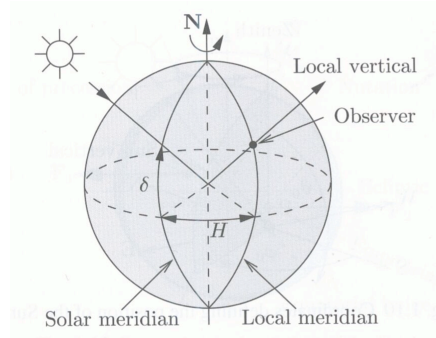


## Calculating daily average Solar irradiance

The daily average Solar irradiance,  $Q$  (expressed in  $\text{W m}^{-2}$ ), is calculated according to

$$Q = \frac{S_0}{\pi} \left( \frac{d_m}{d} \right)^2 (\Delta H \sin \phi \sin \delta + \cos \phi \cos \delta \sin \Delta H)$$

$S_0$  represents the **solar constant** ( $=1366 \text{ W m}^{-2}$ ),  $d_m$  is the average **distance between the Sun and the Earth** in metres,  $d$  represents the '**actual**' **distance between the Sun and the Earth**,  $\phi$  is **latitude**,  $\delta$  is the **declination angle of the Sun** and  $\Delta H$  is the **length of the day** in radians



Box 2.1

## Orbital parameters

$d_m$  is the average **distance between the Sun and the Earth** in metres,  $d$  represents the **'actual' distance between the Sun and the Earth**,  $\phi$  is **latitude**,  $\delta$  is the **declination** angle of the Sun,  $\Delta H$  is the **length of the day** in radians,  $e$  is the **eccentricity** and  $\delta_{\max}$  is the **axial tilt or obliquity**

$$d(t) = d_m (1 + e \sin\{(2\pi / 365) \cdot (272 + t)\})$$

$$d_{\min} = d_m (1 - e); \quad d_{\max} = d_m (1 + e)$$

$$e = 0.017$$

$$\delta(t) = (\pi \delta_{\max} / 180) \sin\{(2\pi / 365) \cdot (285 + t)\}$$

↑  
eccentricity

$$\Delta H = \arccos(-\tan \phi \tan \delta)$$

Box 2.1

↙ Axial tilt or obliquity

## Absorbed Solar radiation

$$\alpha_p = 0.3; \quad S_0 = 1366 \text{ W m}^{-2}$$

Absorbed Solar radiation (ASR) (indicated in  $\text{W m}^{-2}$ ) as a function of latitude and time for a planet with a uniform albedo equal to 0.3. Contour interval is  $25 \text{ W m}^{-2}$ . Thick contour corresponds to  $250 \text{ W m}^{-2}$ .

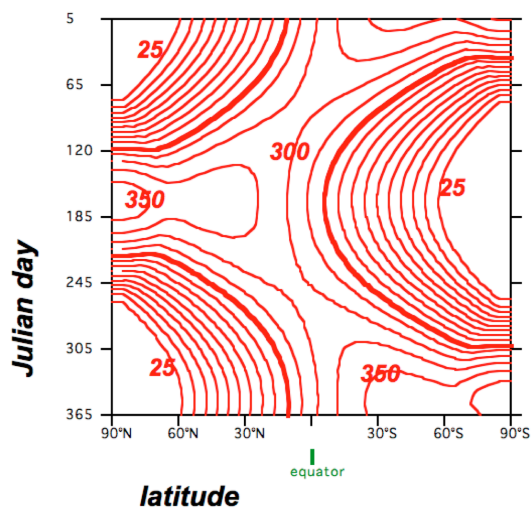
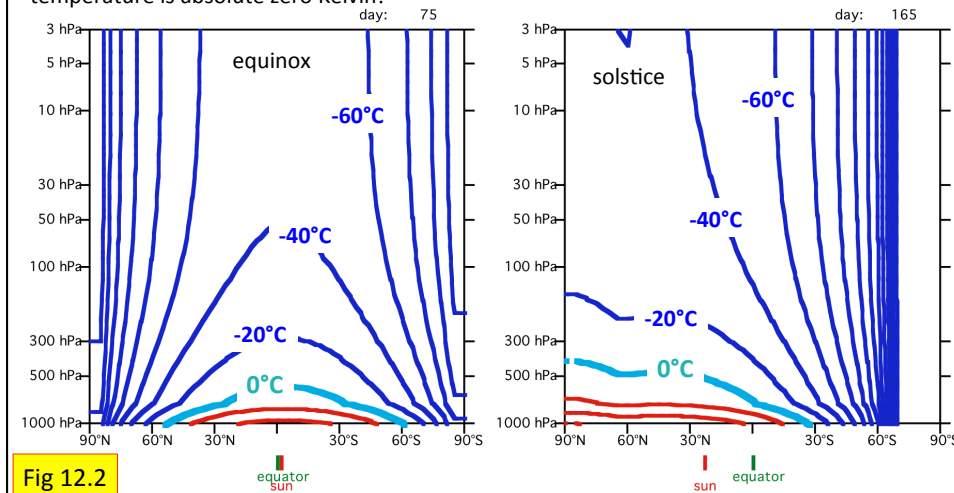


Fig 12.1

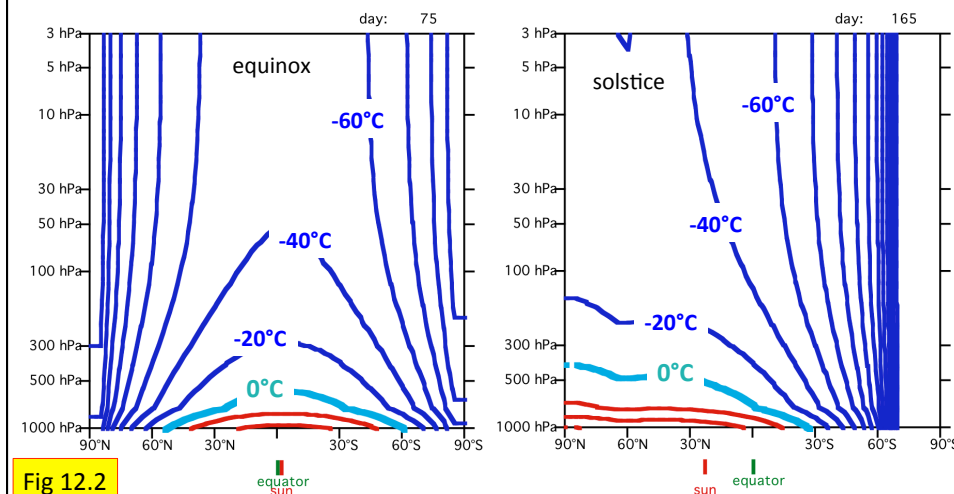
## Radiative equilibrium temperature

Atmosphere which is transparent to Solar radiation and contains one well-mixed greenhouse gas. Contour interval is 20°C. The cyan contour represents the 0°C isotherm. Temperatures below 0°C are indicated by blue contours. Temperatures above freezing (0°C) are indicated by red contours. In the Polar night poleward of 66°S (right panel) the radiative equilibrium temperature is absolute zero Kelvin!



## Radiative equilibrium temperature

Summer pole warmer than tropics  
 No tropical "cold trap"  
 Polar night temperature: absolute zero K!



## The influence of thermal inertia

### Radiative determined state

Divide the atmosphere into a finite number of layers of equal mass

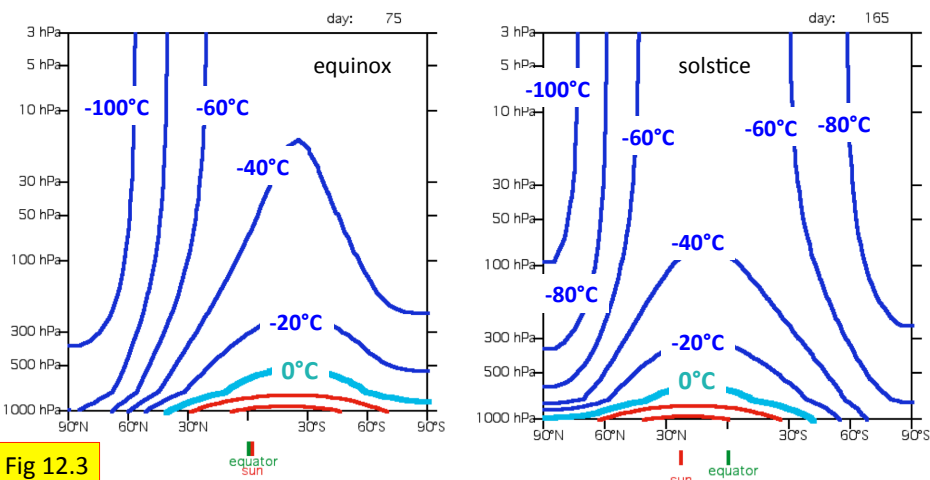
Formulate radiative transfer equations for each layer plus the earth's surface (see e.g. section 2.7)

Integrate these time-dependent equations, imposing the seasonal cycle in Solar radiation

This leads to the so-called "radiative determined state"

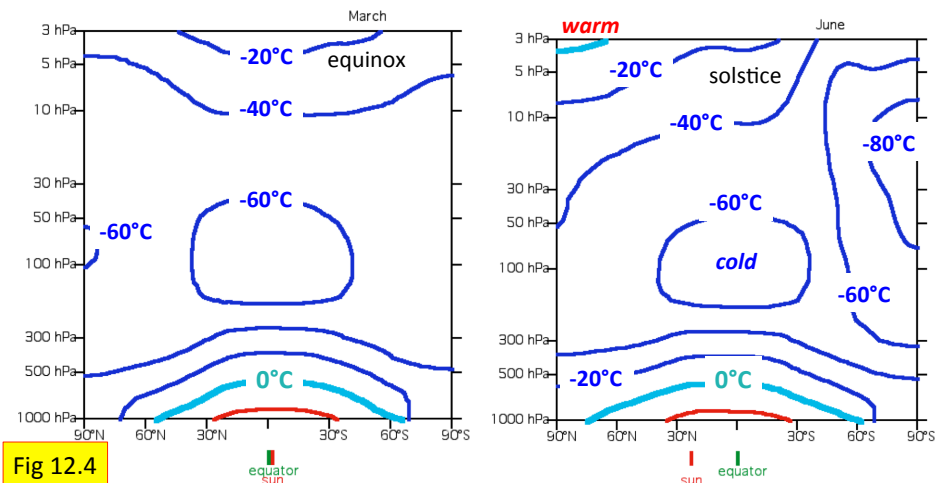
## Radiative determined temperature

Radiatively determined temperature [°C] as a function of latitude and pressure for day 75 (left) and for day 165 (right) in an atmosphere, which is transparent to Solar radiation and contains one well-mixed greenhouse gas. The cyan contour represents the 0°C isotherm. Temperatures below 0°C are indicated by blue contours. Temperatures above freezing (0°C) are indicated by red contours. The **heat capacity of the Earth's surface** is  $10^7 \text{ J K}^{-1} \text{ m}^{-2}$ .



## Observed temperature distribution

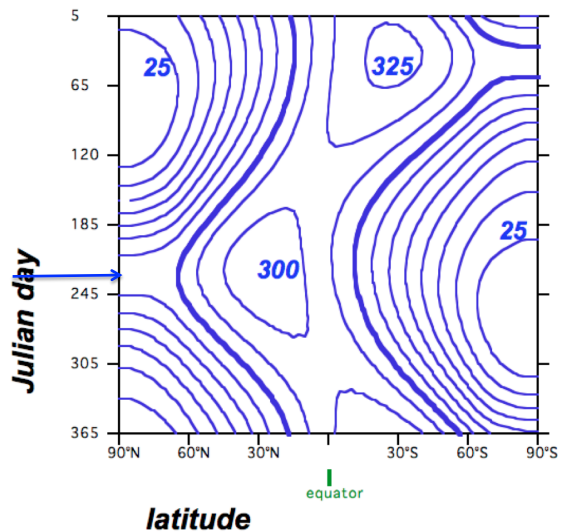
Observed (COSPAR International Reference Atmosphere) monthly average zonal average temperature [°C] as a function of latitude and pressure for March (left panel) and for June (right panel). Contour interval is 20°C. The cyan contour represents the 0°C isotherm. Temperatures below 0°C are indicated by blue contours. Temperatures above freezing (0°C) are indicated by red contours. The heat capacity of the Earth's surface is  $10^7 \text{ J K}^{-1} \text{ m}^{-2}$ .



## Outgoing long-wave radiation at TOA

Radiatively determined outgoing long wave radiation at the top of the atmosphere (OLR-TOA) [ $\text{W m}^{-2}$ ] during the second year of integration of a radiation model for a planet with a uniform albedo (0.3). Contour interval is  $25 \text{ W m}^{-2}$ .

The corresponding absorbed (Solar) radiation is shown in the next slide.



## Absorbed Solar radiation at TOA

The corresponding absorbed (Solar) radiation.

Note that OLR-TOA lags ASR by about 60 days. The difference between absorbed radiation and outgoing radiation is shown in the next slide.

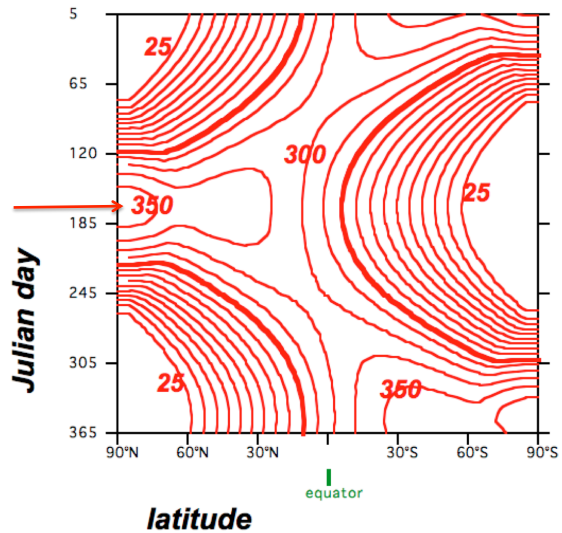


Fig 12.1

## Net absorbed radiation at TOA

Radiatively determined difference between absorbed Solar radiation and outgoing long wave radiation at the top of the atmosphere [ $\text{W m}^{-2}$ ] during the second year of integration of the radiation model, for a planet with a uniform albedo (0.3). Contour interval is  $25 \text{ W m}^{-2}$ .

Heat is gained in spring and lost in Autumn. The radiative imbalance is largest in Spring over the Polar cap. It may be as large as  $250 \text{ W m}^{-2}$ .

The tropics are close to radiative equilibrium

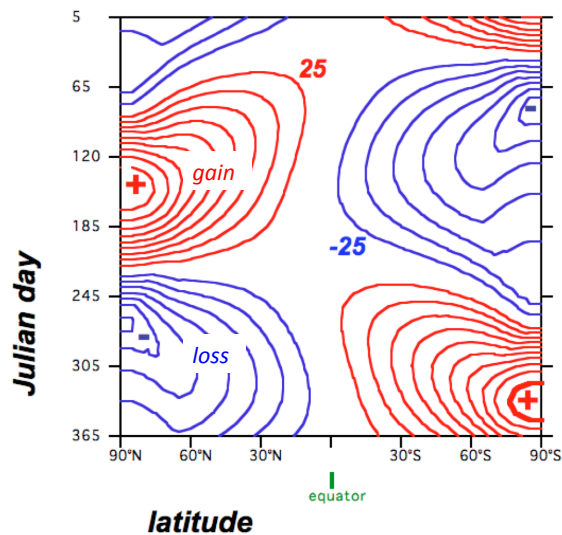


Fig 12.6



## Radiative determined diabatic heating

Radiatively determined tendency of the *potential* temperature [ $\text{K day}^{-1}$ ] (also called **cross-isentropic flow**) as a function of latitude and pressure for day 75 (second year) (just before Equinox) (left panel) and for day 165 (second year) (just before Solstice) (right panel) in an atmosphere, which is transparent to Solar radiation and contains one well-mixed greenhouse gas. Contour interval is  $0.25 \text{ K day}^{-1}$  (zero contour not drawn).

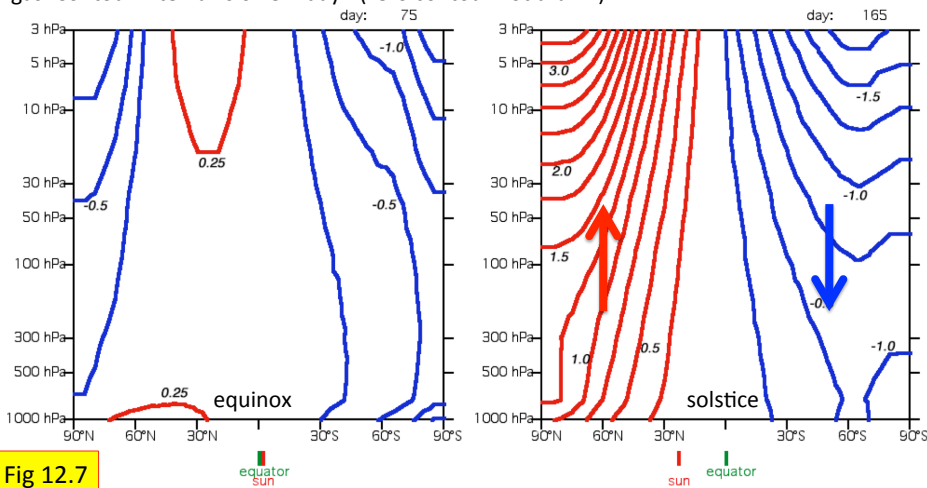


Fig 12.7

## “Observed” (reanalysis) diabatic heating

June average isobars (dashed black lines[hPa]) and June average tendency of the *potential* temperature [ $\text{K day}^{-1}$ ] (contour interval:  $0.5 \text{ K day}^{-1}$ ), according to the ERA-40 reanalysis. The thick black line indicates the zonal mean position of the Earth's surface.

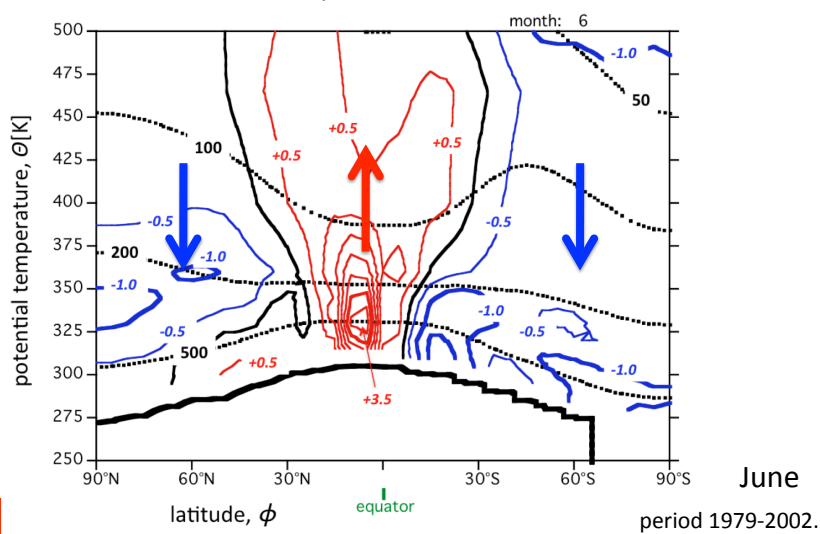


Fig 12.8

## Assignment 2

**Problem 12.2. Radiation balance at the top of the atmosphere in reanalyses**

Investigate the *zonal mean, monthly mean* absorbed Solar radiation (ASR or top net Solar radiation) and outgoing long wave radiation at the top of the atmosphere (OLR-TOA or top net thermal radiation) as a function latitude in the ERA-interim reanalysis ([http://data-portal.ecmwf.int/data/d/interim\\_full\\_mnth/](http://data-portal.ecmwf.int/data/d/interim_full_mnth/)) for a period of at least 5 years, *for instance* the period 1996-2000. What important climate event characterizes this period? Compare the reanalysis data with the radiatively determined ASR and OLR-TOA, and their difference. Discuss interpret the differences between the radiatively determined state and the reanalyzed state.

*Hand in answer to problem 12.2 on or before 7/5/2014*

## ERA-reanalysis

ERA-interim reanalysis: [http://data-portal.ecmwf.int/data/d/interim\\_full\\_mnth/](http://data-portal.ecmwf.int/data/d/interim_full_mnth/)

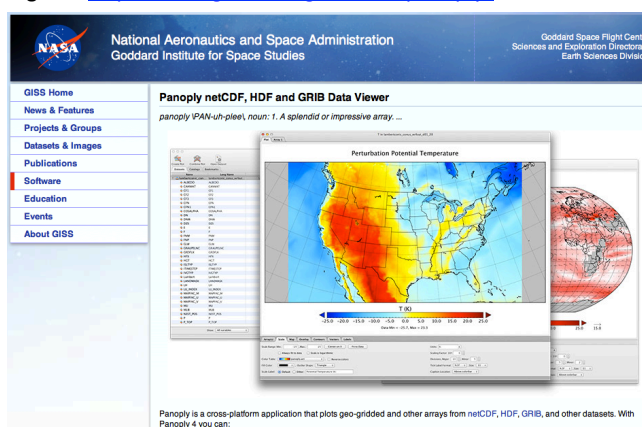
**ERA Interim, Synoptic Monthly Means, Full Resolution**

<p>Type of level</p> <p>Model levels</p> <p>Potential temperature</p> <p>Potential vorticity</p> <p>Pressure levels</p> <p>Surface</p> <p>ERA Interim Full Resolution</p> <p>Daily</p> <p>Invariant</p> <p>Synoptic Monthly Means</p> <p>Monthly Means of Daily Means</p> <p>Personal</p> <p>Your Requests</p> <p>Data usage</p> <p>Conditions</p> <p>See also...</p> <p>Data FAQ</p> <p>Data Servers</p> <p>Data Services</p> <p>GIBB recorder</p>	<p><b>NEW: experimental batch access</b></p> <p>Batch access is now available from a new more powerful server. Please visit <a href="https://software.ecmwf.int/wiki/display/WEBAPI/Accessing+ECMWF+data+servers+in+batch">https://software.ecmwf.int/wiki/display/WEBAPI/Accessing+ECMWF+data+servers+in+batch</a> for more details.</p> <p><b>NEW Data Server</b></p> <p>This server is been replaced by a more powerful system that can be found at <a href="http://apps.ecmwf.int/datasets/">http://apps.ecmwf.int/datasets/</a>. Please start using this new system, as this server will be discontinued in the near future.</p> <p><b>Select month</b></p> <table border="0" style="width: 100%; text-align: center;"> <thead> <tr> <th></th> <th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th> <th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th> </tr> </thead> <tbody> <tr> <td>1978</td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td><td><input type="checkbox"/></td> <td><input type="checkbox"/></td><td><input 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You need Top Net Thermal Radiation and Top Net Solar Radiation from menu "Surface" and "Synoptic Monthly Means" (I always work with net-cdf file format)

## Panoply-program

Panoply-program: <http://www.giss.nasa.gov/tools/panoply/>



## A model of zonally symmetric radiative-dynamical adjustment

### *Couple radiation to dynamics*

Assumptions radiation identical to previous assumptions

Dynamics: take primitive equation dynamical core model (see chapter 10 lecture notes of dynamical meteorology)

<http://www.staff.science.uu.nl/~delde102/AtmosphericDynamics.htm>

## Model Equations (dynamical core)

Model is 2 dimensional ( $y, \sigma$ ) ( $\sigma = p/p_s$ )

Governing equations of the “dynamical core”:

$$\frac{\partial p_s}{\partial t} + \frac{\partial p_s v}{\partial y} + p_s \frac{\partial}{\partial \sigma} \left( \frac{d\sigma}{dt} \right) = 0$$

$$\frac{\partial p_s \theta}{\partial t} = - \frac{\partial p_s v \theta}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s \theta \frac{d\sigma}{dt} \right)$$

$$\frac{\partial p_s u}{\partial t} = - \frac{\partial p_s u v}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s u \frac{d\sigma}{dt} \right) + \left( f + \frac{u \tan \phi}{a} \right) p_s v$$

$$\frac{\partial p_s v}{\partial t} = - \frac{\partial p_s v^2}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s v \frac{d\sigma}{dt} \right) - \left( f + \frac{u \tan \phi}{a} \right) p_s u - p_s \frac{\partial \Phi}{\partial y} + RT \frac{\partial p_s}{\partial y}$$

$$\frac{\partial p_s}{\partial t} = - \int_0^1 \frac{\partial p_s v}{\partial y} d\sigma$$

## Inclusion of diabatic effects

Heating flux due to dry convective adjustment

diabatic heating due to absorption/emission radiation & latent heat release

Wave drag

Friction in boundary layer

$$\frac{\partial p_s}{\partial t} + \frac{\partial p_s v}{\partial y} + p_s \frac{\partial}{\partial \sigma} \left( \frac{d\sigma}{dt} \right) = 0$$

$$\frac{\partial p_s \theta}{\partial t} = - \frac{\partial p_s v \theta}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s \theta \frac{d\sigma}{dt} \right) + p_s H + \frac{p_s J}{\Pi}$$

$$\frac{\partial p_s u}{\partial t} = - \frac{\partial p_s u v}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s u \frac{d\sigma}{dt} \right) + \left( f + \frac{u \tan \phi}{a} \right) p_s v + p_s D + p_s F_x$$

$$\frac{\partial p_s v}{\partial t} = - \frac{\partial p_s v^2}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s v \frac{d\sigma}{dt} \right) - \left( f + \frac{u \tan \phi}{a} \right) p_s u - p_s \frac{\partial \Phi}{\partial y} + RT \frac{\partial p_s}{\partial y} + p_s F_y$$

$$\frac{\partial p_s}{\partial t} = - \int_0^1 \frac{\partial p_s v}{\partial y} d\sigma$$

## This lecture: only radiation and convective adjustment

Heating flux due to dry convective adjustment

$$\frac{\partial p_s}{\partial t} + \frac{\partial p_s v}{\partial y} + p_s \frac{\partial}{\partial \sigma} \left( \frac{d\sigma}{dt} \right) = 0$$

$$\frac{\partial p_s \theta}{\partial t} = - \frac{\partial p_s v \theta}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s \theta \frac{d\sigma}{dt} + p_s H + \frac{p_s J}{\Pi} \right)$$

$$\frac{\partial p_s u}{\partial t} = - \frac{\partial p_s u v}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s u \frac{d\sigma}{dt} \right) + \left( f + \frac{u \tan \phi}{a} \right) p_s v$$

$$\frac{\partial p_s v}{\partial t} = - \frac{\partial p_s v^2}{\partial y} - \frac{\partial}{\partial \sigma} \left( p_s v \frac{d\sigma}{dt} \right) - \left( f + \frac{u \tan \phi}{a} \right) p_s u - p_s \frac{\partial \Phi}{\partial y} + RT \frac{\partial p_s}{\partial y}$$

$$\frac{\partial p_s}{\partial t} = - \int_0^1 \frac{\partial p_s v}{\partial y} d\sigma$$

diabatic heating due to absorption/emission radiation & latent heat release

Wave drag

Friction in boundary layer

## Influence of dynamics on temperature

Temperature [°C] determined by radiation only (left panel) and temperature determined by dynamics *and* radiation (right panel) for day 50 after initialization on January 1 of a two-dimensional model of a **dry isothermal (290 K) atmosphere in rest** containing one well-mixed greenhouse gas and no ozone. Contour interval is 20°C. The cyan contour represents the 0°C isotherm. The heat capacity of the Earth's surface is 10<sup>7</sup> J kg<sup>-1</sup> m<sup>-2</sup>.

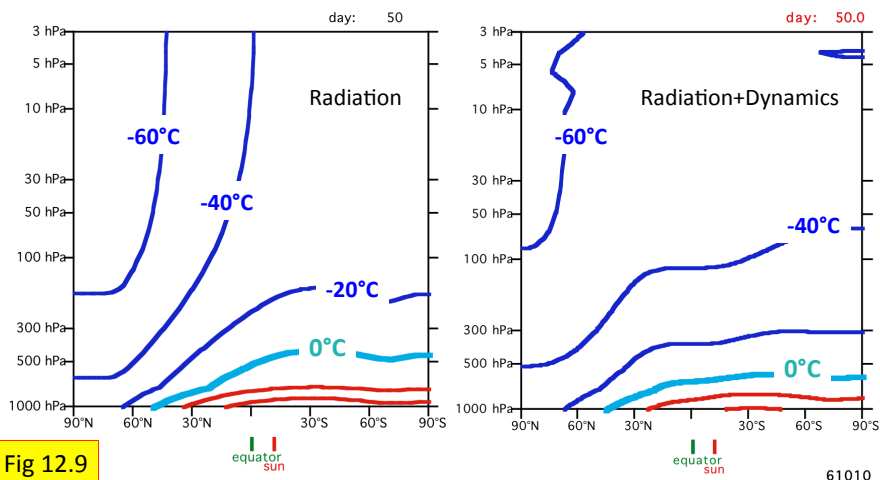


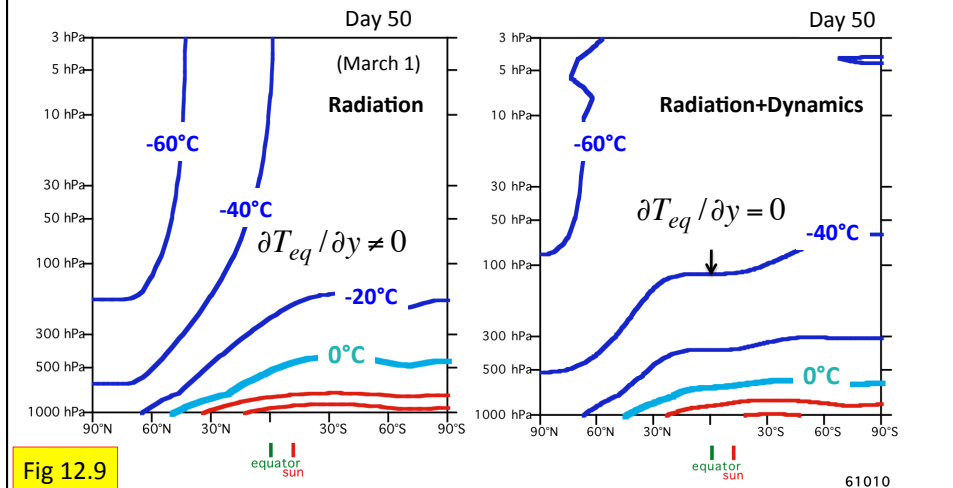
Fig 12.9

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## Influence of dynamics on temperature

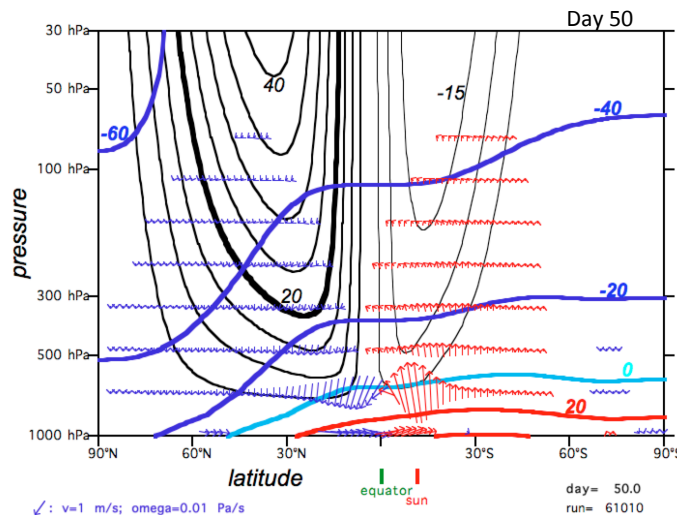
Radiatively determined cross-equatorial temperature gradient is reduced to zero by dynamics.

Summer hemisphere is cooled, while tropics and winter hemisphere are warmed by dynamics



## Meridional Circulation in the model

Meridional circulation (arrows), temperature [°C] and zonal wind velocity (black contours) after 50 days of integration. Red arrows indicate upward motion; blue arrows indicate downward motion. Arrows are drawn only if  $|w| > 0.001 \text{ Pa s}^{-1}$ . Isotachs [ $\text{m s}^{-1}$ ] (contour interval:  $5 \text{ m s}^{-1}$ ). Thin black contours correspond to negative values of the zonal wind velocity (i.e. westward wind).



## Meridional Circulation in the model

Radiatively determined cross-equatorial temperature gradient is reduced to zero by dynamics.

### Winter Hadley cell:

Upward motion in summer hemisphere;  
Downward motion in winter hemisphere

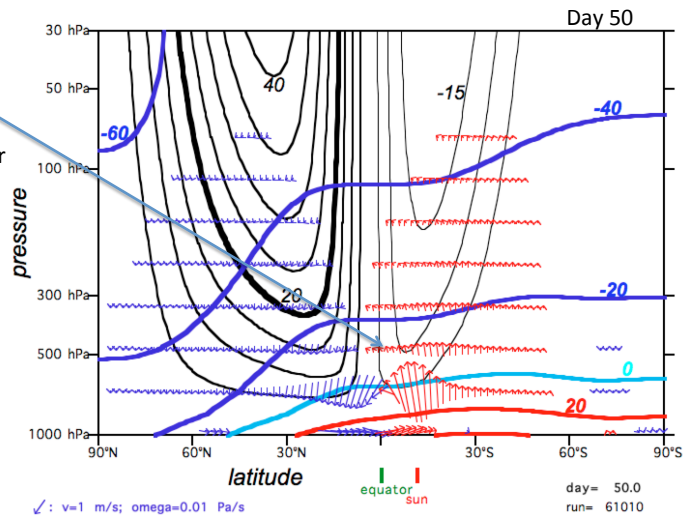


Fig 12.10

## Meridional Circulation in the model

Some aspects of the solution are not realistic.

The subtropical jet and the stratospheric winter jet do not develop into separate entities.

No tropical "cold trap"

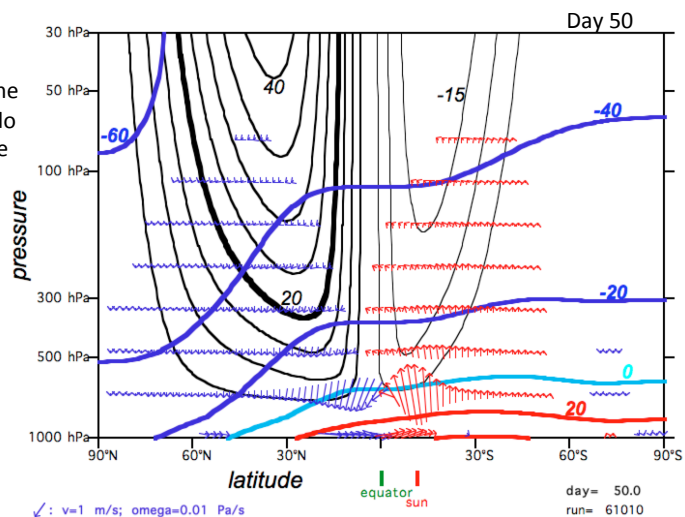


Fig 12.10

## Next lecture

Wednesday 7/5, 2014, 13:15-15:00

*Introducing the water cycle and investigating role of water in diabatic dynamical interaction.*

*With wave drag everything falls into place!!*

*Simulation of seasonal cycle with wind reversals is very realistic!*

**Obligatory assignment:** Problem 12.2  
Hand in answer on Wednesday May 7

<http://www.staff.science.uu.nl/~delde102/C&HC.htm>