

Boundary Layers, Transport and Mixing - part 2

Lecture 1, Aarnout van Delden
a.j.vandelden@uu.nl

The role of transport and mixing in the General Circulation of the atmosphere

The question is, how does the non-linear interaction between radiative transfer, transport of water (i.e. the water cycle) and transport of heat, momentum, vorticity and mass, and mixing of potential vorticity, determine the temperature distribution in the atmosphere and, with it, the intensity, position and seasonal cycle of the principal zonal mean jet streams.

This course is inspired by my own research over the last 10-15 years

A.J. van Delden, 2014: PV-theta view of diabatic-dynamical interaction in the general circulation. **Tellus A** 2014, 66, 24880, <http://dx.doi.org/10.3402/tellusa.v66.24880>.

A.J. van Delden and Y.B.L. Hinssen, 2012: PV-theta view of the zonal mean state of the atmosphere. **Tellus A** 2012, 64, 18710, <http://dx.doi.org/10.3402/tellusa.v64i0.18710>.

Lecture 1

The main features of the General Circulation of the atmosphere and overview of some important theoretical concepts

Important theoretical concepts:

potential temperature,
isentropic density, vorticity,
potential vorticity,
thermal wind balance

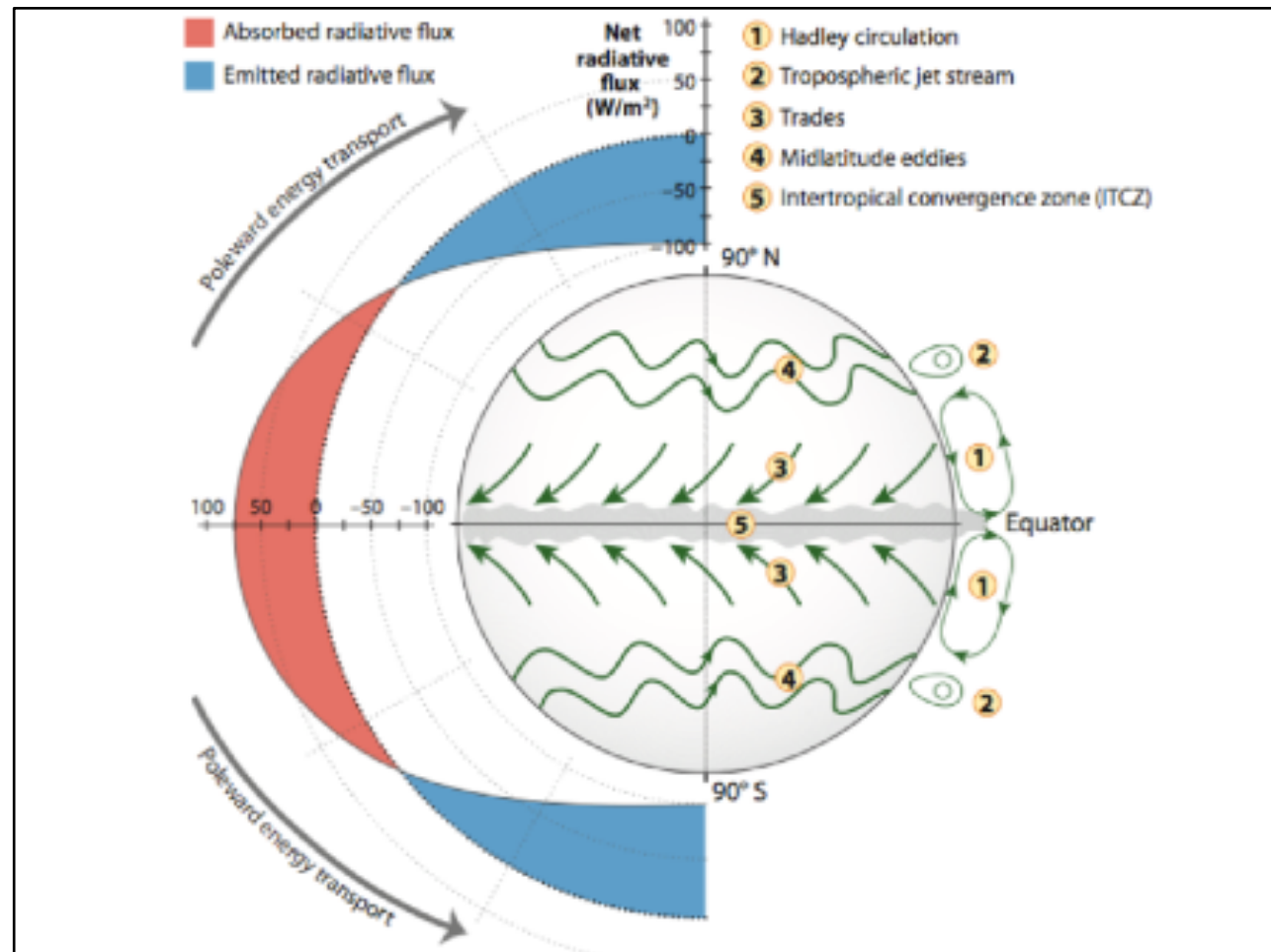
troposphere, stratosphere and tropopause
Underworld, Middleworld and Overworld
jet streams and jet streaks
planetary waves

The General Circulation of the Atmosphere

“Low latitudes experience a net gain of radiative energy, while high latitudes experience a net deficit; as a result of this imbalance, the oceans and the atmosphere transport heat poleward”

Assignment 1:

Is this true ?



Boundary Layers, Transport and Mixing - part 2

BLT&M-2 in Spring 2021 consists of **6 lectures** on the following 6 topics.

- (1) The main features of the General Circulation of the atmosphere (today),
- (2) The influence of radiative transfer and thermal inertia on the temperature distribution in the atmosphere
- (3) Simulations of the general circulation with a two-dimensional statistical-dynamical general circulation model: the role of the radiation, water cycle, ozone and “planetary wave drag”,
- (4) Wave/eddy - zonal-mean flow interaction according to quasi-geostrophic theory and according to the “PV-theta view”,
- (5) The connection between zonal mean jets and the distribution of potential vorticity,
- (6) Some aspects of the philosophy and sociology of science.

Structure of BLT&M part 2

Lectures on 7, 21 and 28 May, and on 4, 11 and 25 June 2021, 10:00-11:45.

Reading and studying specific sections of the lectures notes (especially chapters 11 and 12)

Doing a set of hand-in **assignments**.

The final grade is based on the weighted grades for the following set of 4 assignments or problems (see next slide).

Grading of BLT&M part 2

Problem 12.2 (see page 24) is a small assignment to make you start thinking about the interaction between radiation and dynamics (weight: 5% - **read section 12.1-12.2**).

Problem 12.3 is concerned with the mass/pressure distribution in the atmosphere determined by radiative transfer (see page 29) (weight: 22.5% - **read section 12.3-12.4**).

Problems 12.7, 12.8 & 12.9 are three “what-if questions” (see page 80) (weight: 50% - **read chapter 8 (about the Hadley circulation), sections 12.5-12.8 (about the 2D-GCM) and search the literature on CO₂-doubling model experiments and on the sensitivity of the global water cycle to changes to the character of the earth’s surface**).

Problem 12.18 is concerned with the theory of wave/eddy zonal-mean flow interaction (see page 84) (weight: 22.5% - **read sections 11.6-11.9 and 12.8-12.12**).

Deadlines

Problem 12.2 (page 24): Wed. 12 May 2021

Problem 12.3 (page 29): Wed. 26 May 2021

Problem 12.7, 12.8 & 12.9 (page 80): Wed. 16 June 2021

Problem 12.18 (page 84): Wed. 23 June 2021

All assignments can be handed in in groups of **up to 3 students**.

Hand in the answers to the problems as pdf-files *before or on* the following dates to a.j.vandelden@uu.nl.

Note: these deadlines are not carved in stone! Please let me know if you need more time.

Questions about part 2 of the course can be sent to a.j.vandelden@uu.nl or on TEAMS

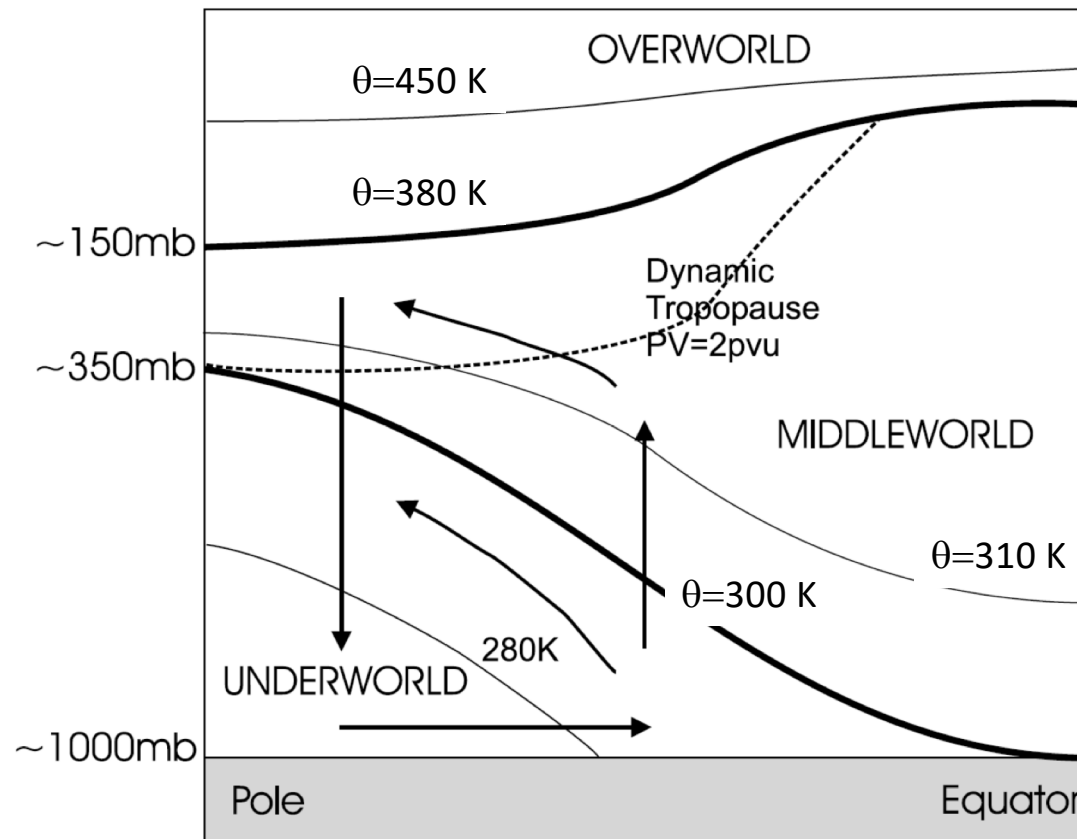
Features of the “General Circulation” of earth’s atmosphere

Six specific features of the zonal mean “General Circulation” of earth’s atmosphere:

- (1) a **permanent eastward subtropical jet** in both hemispheres
- (2) a **polar winter stratospheric eastward jet**,
- (3) the **stratospheric reversals of the zonal mean zonal wind in Spring and Autumn**,
- (4) the **tropical cold layer** at levels between 10 and 18 km above sea level,
- (5) the existence and most robust characteristics of the **tropopause**. Of special interest is the distinction between the **tropical tropopause** and the **extratropical tropopause**.
- (6) the **seasonal cycle in the intensity of the tropical “Hadley circulation”**.

Theoretical division of the zonal-mean atmosphere

The **Overworld**, **Middleworld** and **Underworld** according to Brian Hoskins (1991) (*Tellus*, **43AB**, 27-35). A Schematic zonal mean view of the atmosphere, between the pole and the equator and between the Earth's surface and $p=30$ hPa. The dynamical tropopause, corresponding to the potential vorticity contour of 2 PVU, is indicated by a dashed line. Selected **isentropes** are shown as thick and thin solid lines. Arrows represent zonal average fluxes of mass in the extratropical troposphere. (T-Y Koh and R.A. Plumb, 2004: *Q.J.R.Meteorol.Soc.*, **130**, 1631-1653).



Potential temperature:

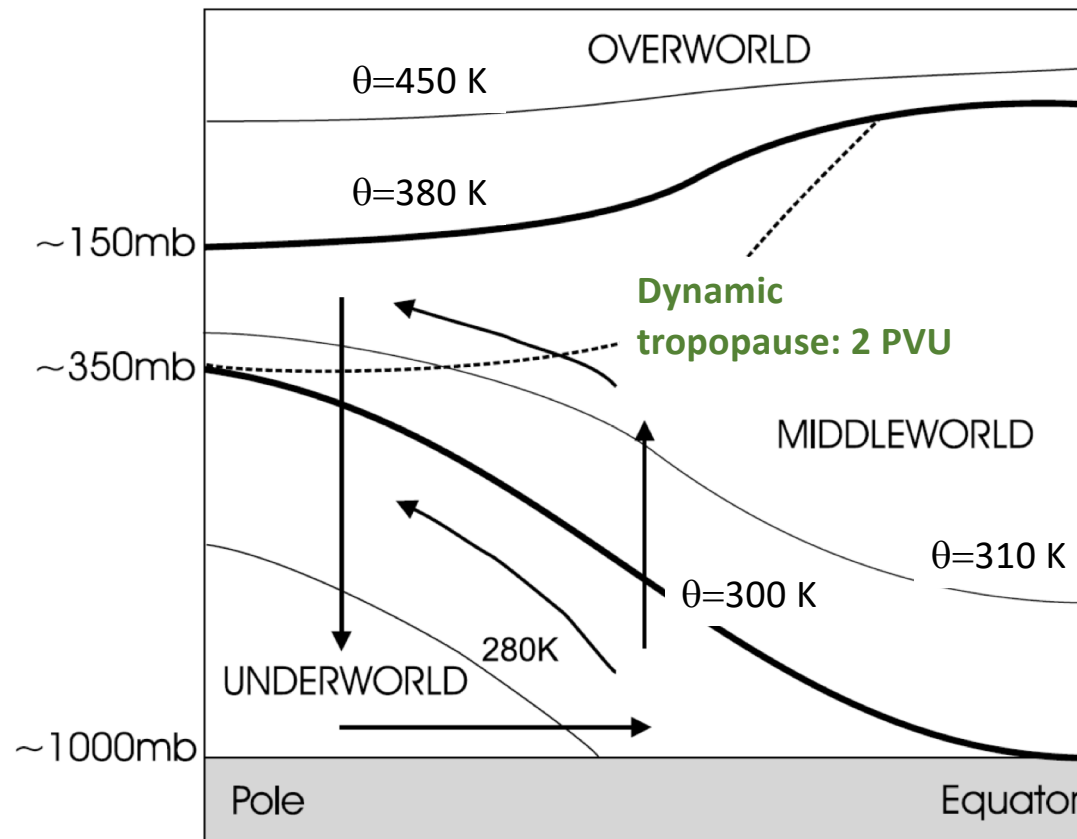
$$\theta = T \left(\frac{p_{ref}}{p} \right)^{\kappa}$$

$$\kappa = \frac{R}{c_p}$$

FIGURE 1.48

Theoretical division of the zonal-mean atmosphere

The **Overworld**, **Middleworld** and **Underworld** according to Brian Hoskins (1991) (*Tellus*, **43AB**, 27-35). A Schematic zonal mean view of the atmosphere, between the pole and the equator and between the Earth's surface and $p=30$ hPa. The dynamical tropopause, corresponding to the potential vorticity contour of 2 PVU, is indicated by a dashed line. Selected **isentropes** are shown as thick and thin solid lines. Arrows represent zonal average fluxes of mass in the extratropical troposphere. (T-Y Koh and R.A. Plumb, 2004: *Q.J.R.Meteorol.Soc.*, **130**, 1631-1653).



Potential vorticity (PV):

$$Z \equiv \frac{\zeta + f}{\sigma}$$

(see slide 23)

Features of the “General Circulation” of earth’s atmosphere

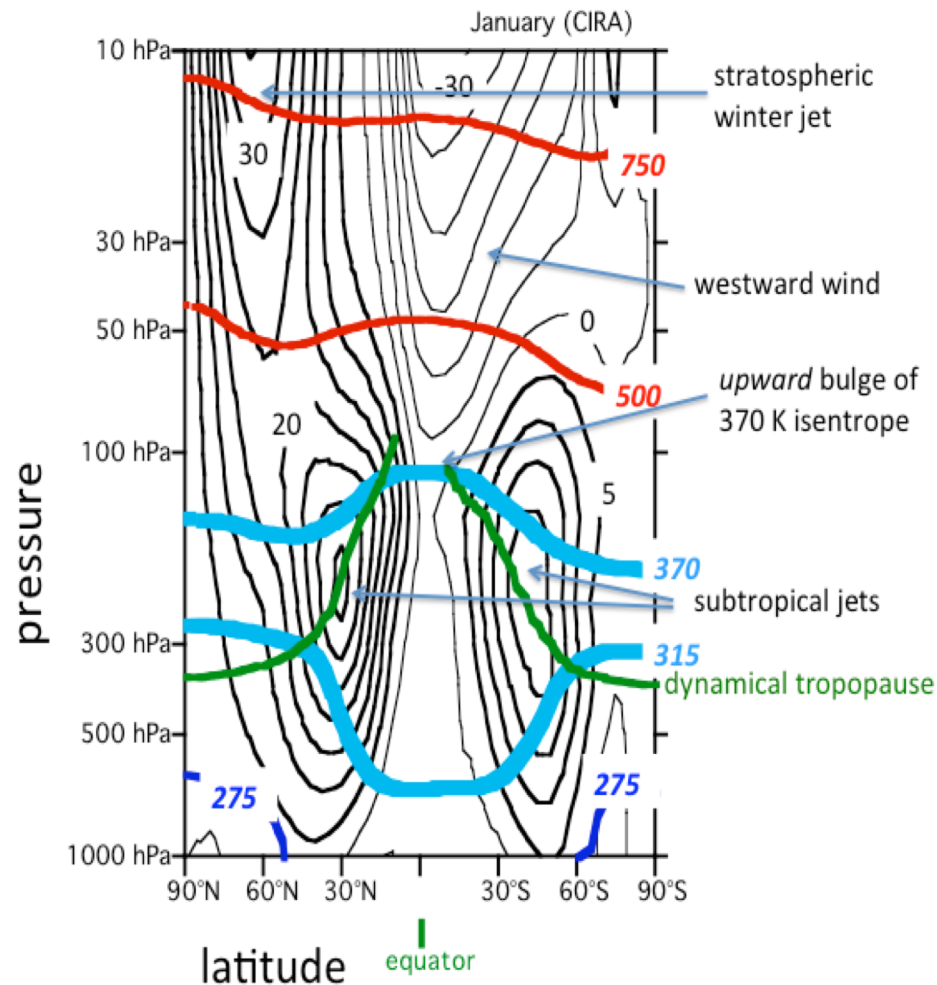
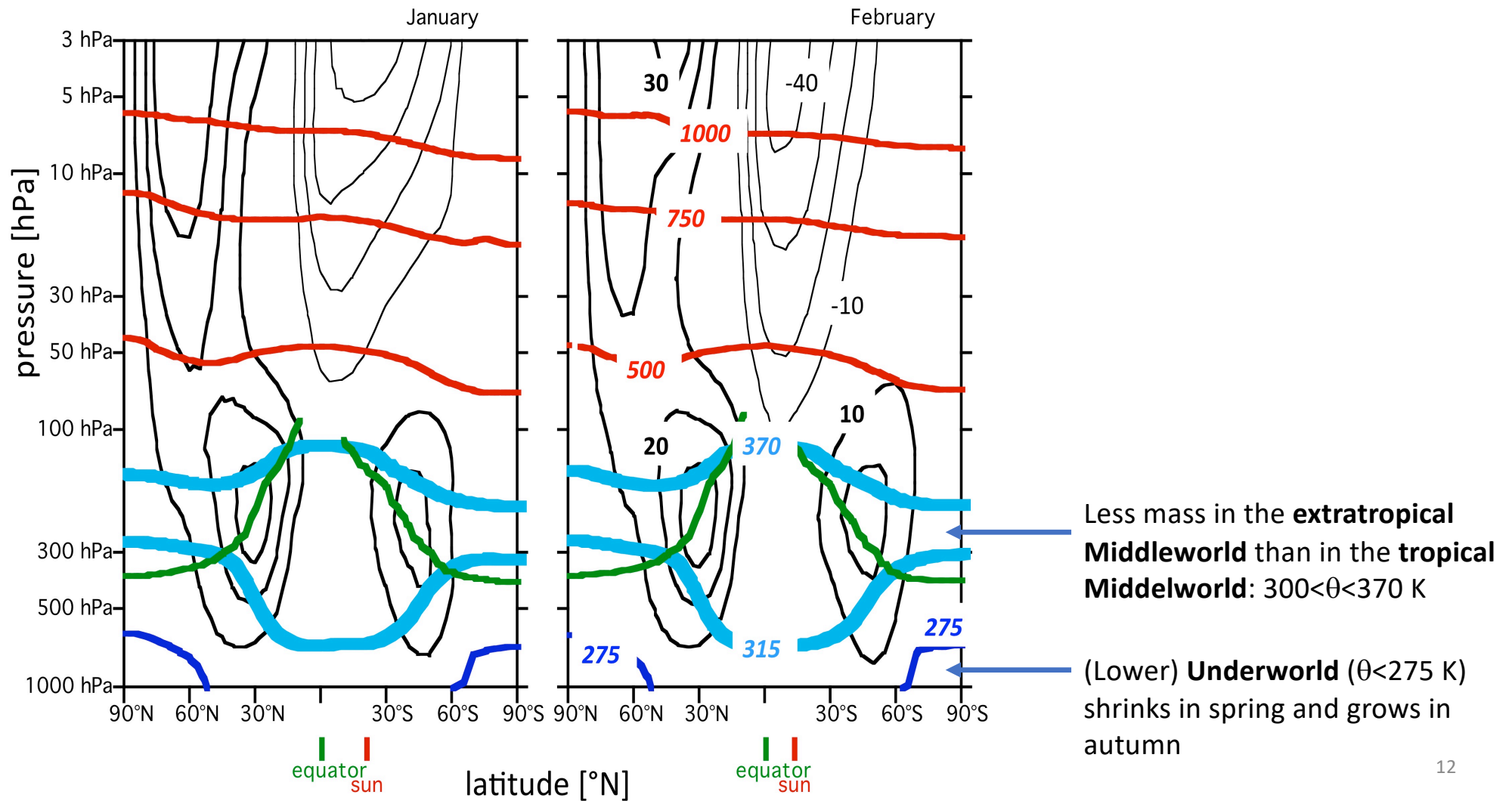
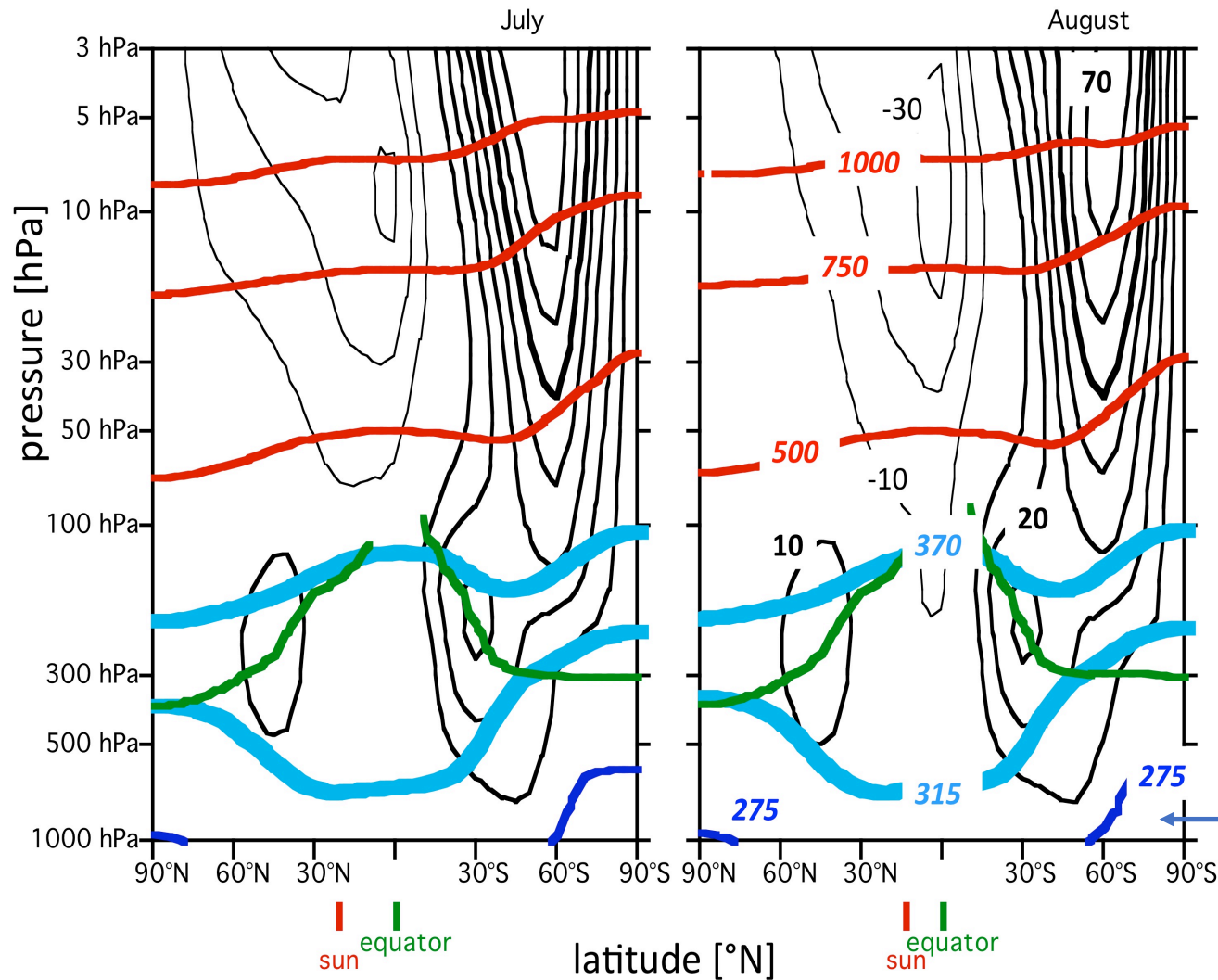


FIGURE 12.30. Zonal mean eastward wind velocity (black contours; labels in m s^{-1}), zonal mean potential temperature (blue contour: “Underworld”; cyan contour: “Middleworld”; red contour: “Overworld”; labeled in degrees Kelvin) and of zonal mean **dynamical tropopause** (green contour) in January, according to the COSPAR Reference Atmosphere (CIRA). The dynamical tropopause is not defined in the tropics. In the “Middleworld”, between approximately 310 K and 380 K, the tropical troposphere stands in adiabatic contact with the extratropical lower stratosphere.

The zonal-mean “General Circulation” of earth’s atmosphere



The zonal-mean “General Circulation” of earth’s atmosphere



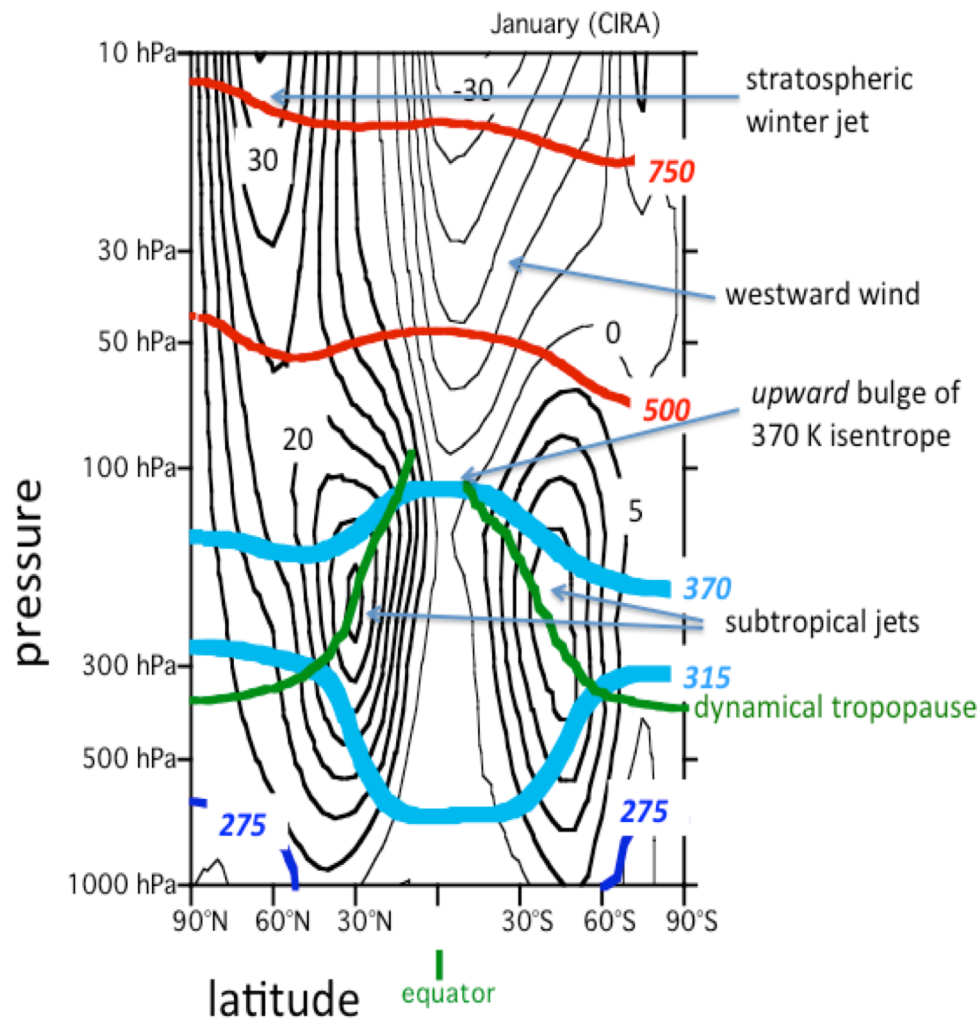
stratospheric reversals of the zonal mean zonal wind in spring and autumn

Poleward shift of the “subtropical jet” between spring and summer

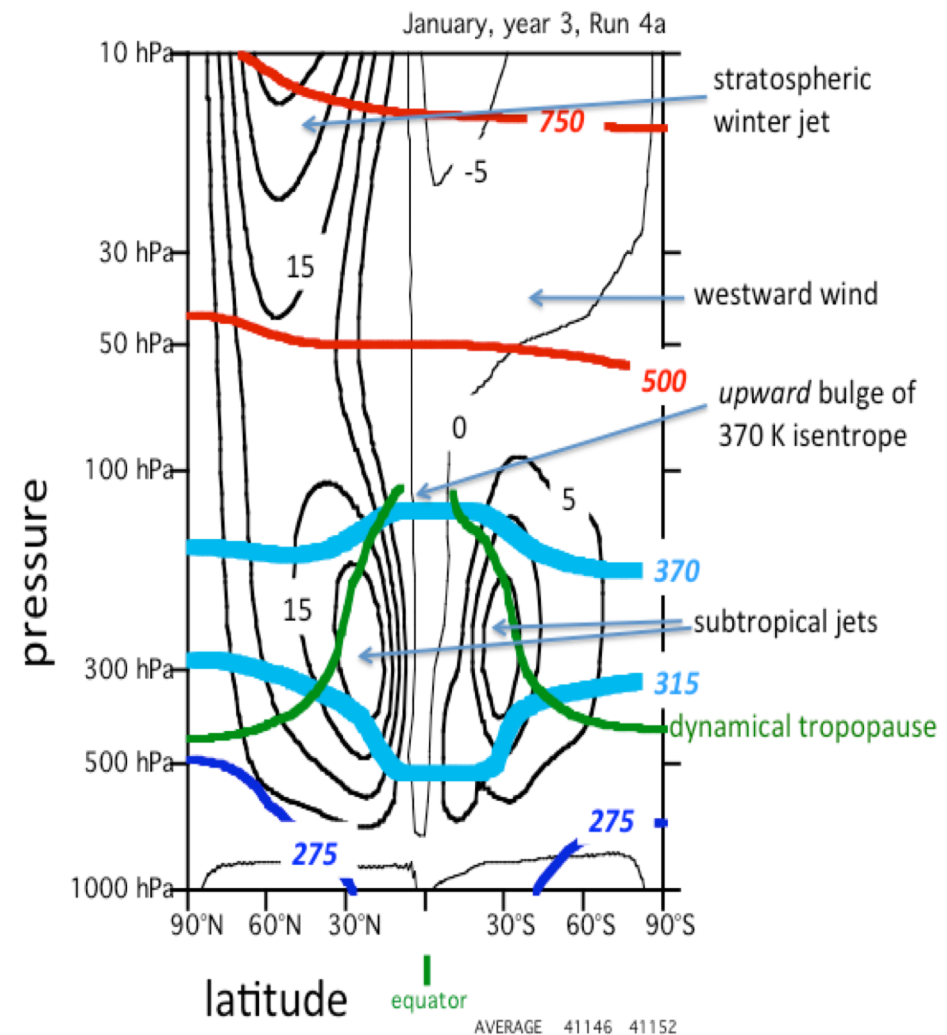
Lower Underworld: $\theta < 275$ K

Simulation of the General Circulation with a 2D-GCM

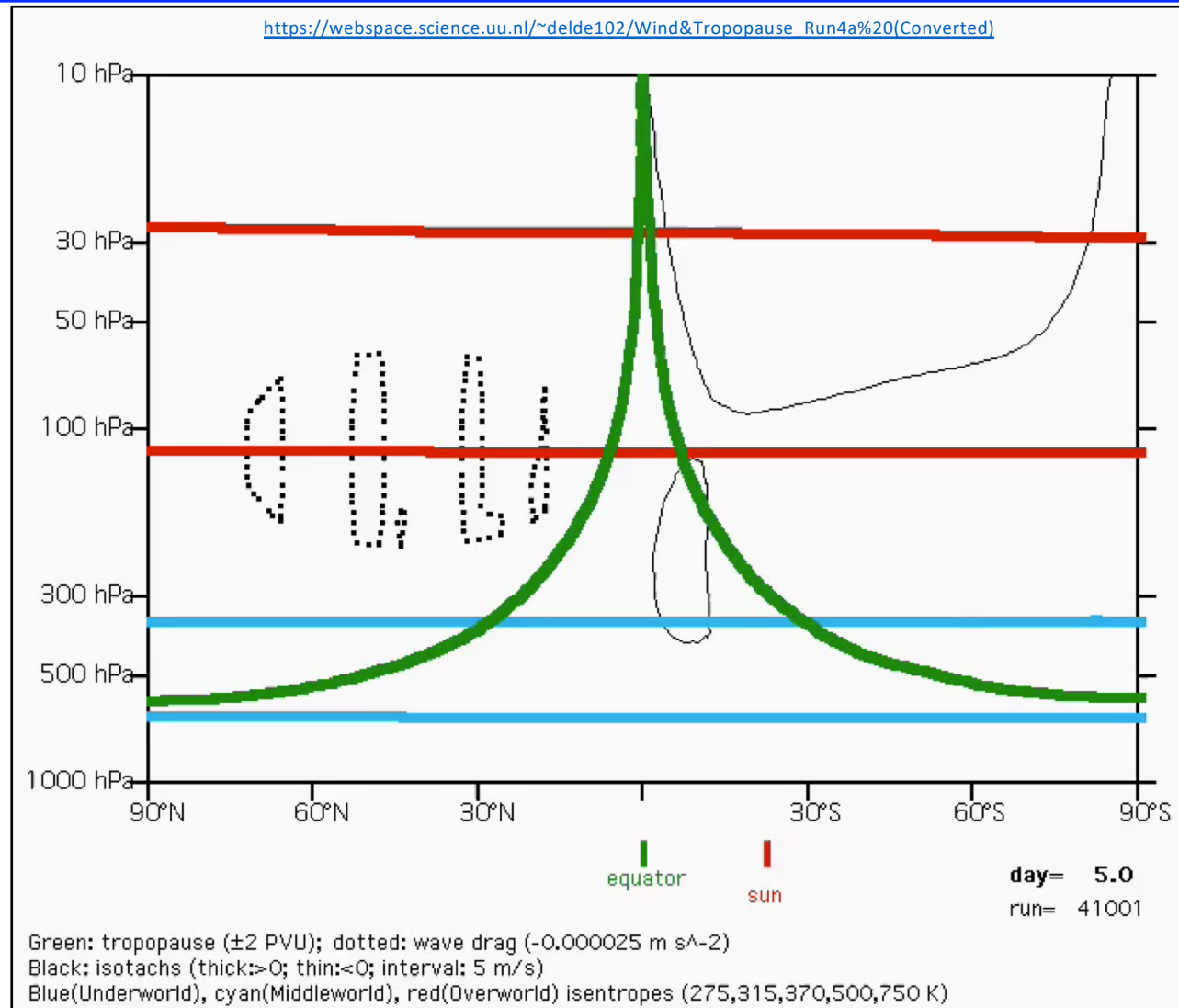
Observation



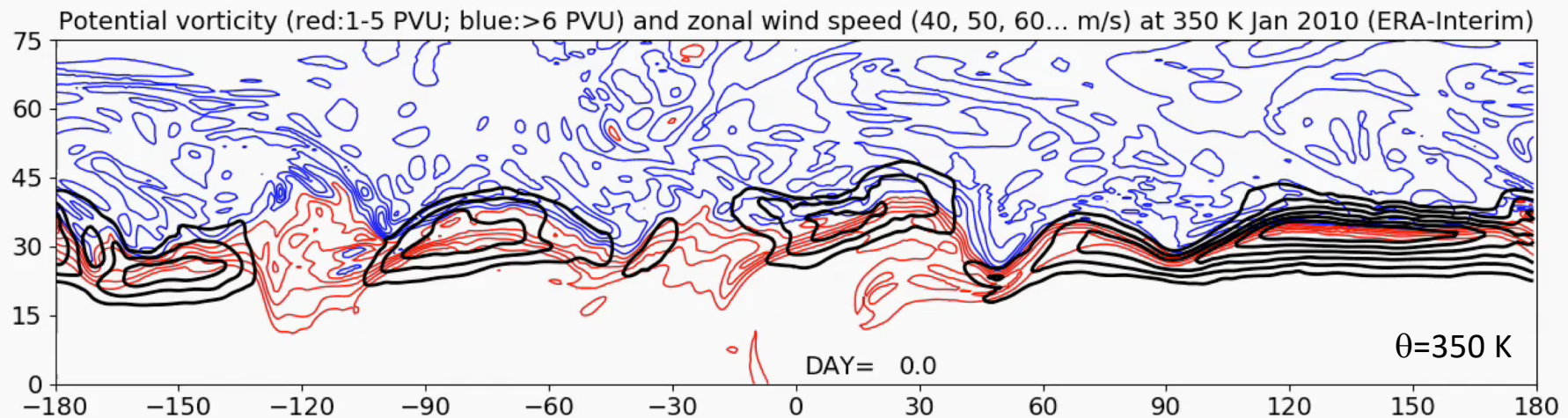
Simulation



Simulation of the General Circulation with a 2D-GCM



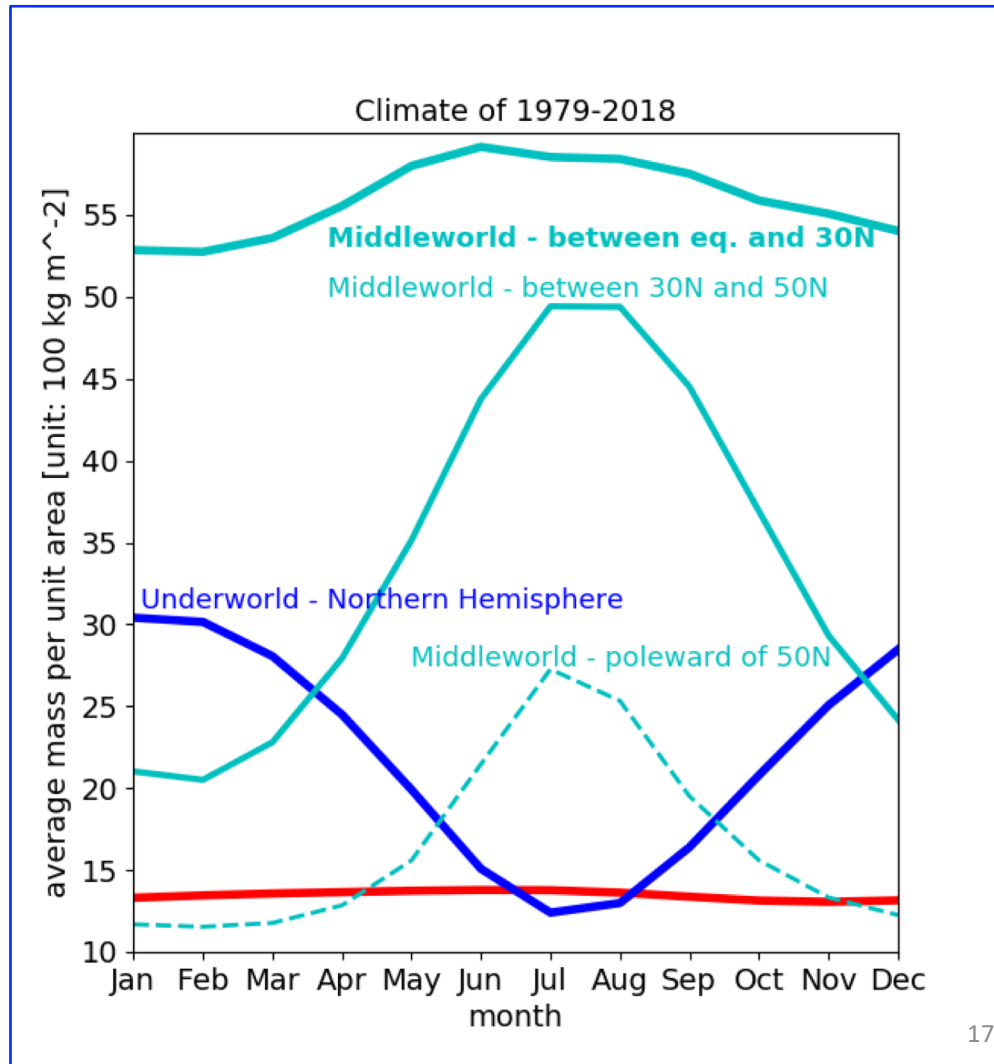
Potential vorticity (Z_θ) and zonal wind velocity (u)



Potential vorticity (Z_θ) and the zonal component of the wind velocity (u) at $\theta=350$ K at 00 UTC, 14 December, 2006. Vertical coordinate is latitude ($^\circ$ N) and horizontal coordinate is longitude ($^\circ$ E). Red contours correspond to isopleths of 1, 2, 3, 4 and 5 PVU (**tropical air**). Blue contours correspond to isopleths of 6, 7, 8, 9, 10 PVU and higher (**extra-tropical air**). Isopleths of u (black) are shown every 10 m/s, starting at 40 m/s (PlanetaryWaveBreaking.py, <http://apps.ecmwf.int/datasets/>).

Seasonal growth and decay of the Underworld

FIGURE 1.66. Ensemble mean (1979-2018) yearly cycle of the monthly mean mass in the **Underworld** ($\theta < 300$ K) in the Northern Hemisphere (**blue line**), in the **Middleworld** ($300 < \theta \leq 370$ K) poleward of 50°N (**dashed, cyan**), in the **Middleworld** between 30°N and 50°N (**thin cyan**), in the tropical (0°N - 30°N) Middleworld (**thick cyan**) and in the **Overworld** ($\theta > 370$ K) in the Northern Hemisphere (**red**). In the left panel the unit is kg m^{-2} . In right panel the unit is kg. The seasonal cycle of the total mass in the Underworld is due mainly to exchange with the Middleworld. The mass budget in January is in an approximate stationary state. Based on the monthly mean ERA-Interim reanalysis.



Assignment 2: PROBLEM 12.3

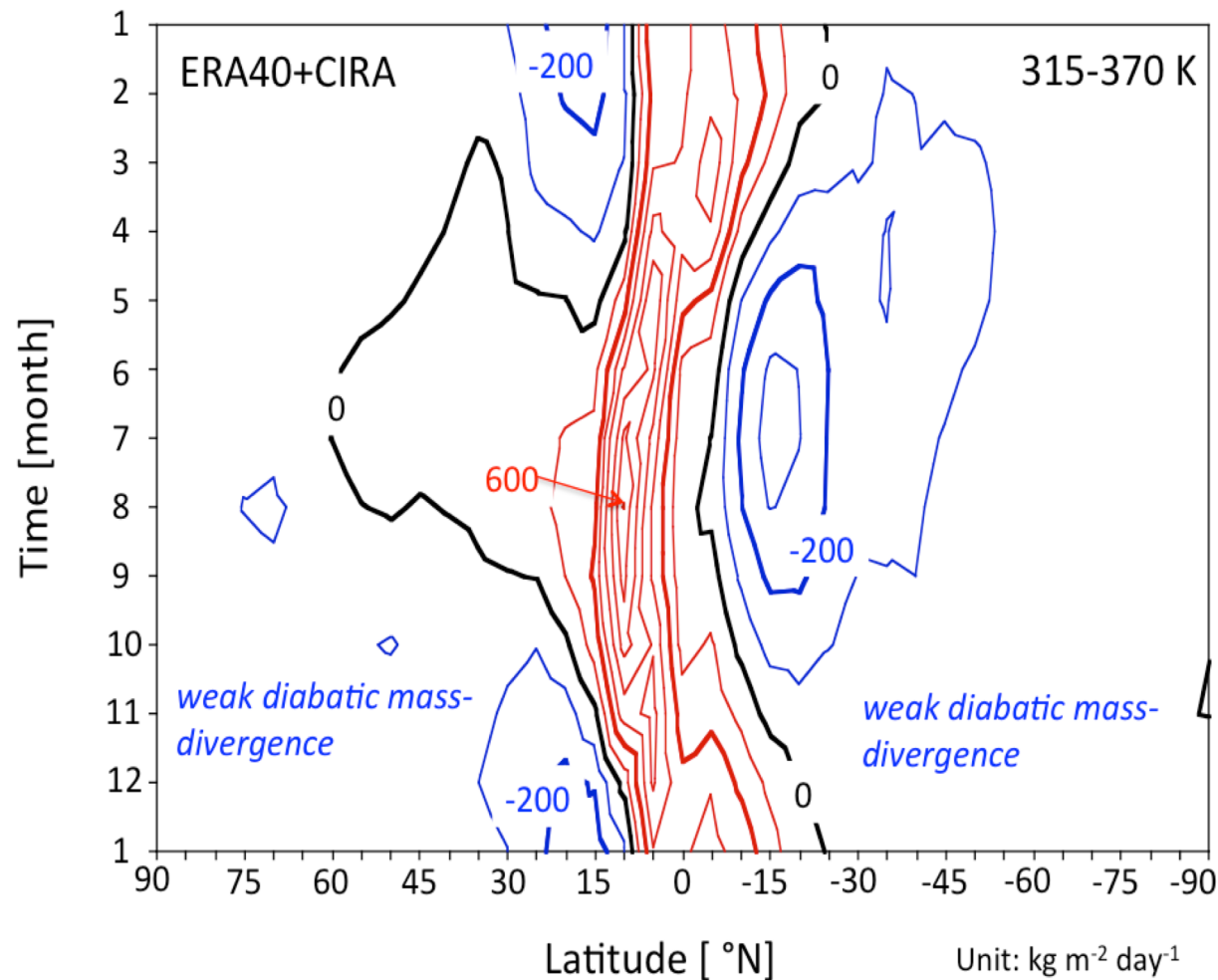
Radiatively determined mass distribution (read sections 12.3-4)

Compute and plot the area-weighted average mass per unit area in the Underworld ($\theta < 300$ K) in the Northern Hemisphere in the “radiatively determined atmosphere” as function of time. The temperature as a function of pressure in the “radiatively determined atmosphere” is computed by running the radiation model (described in **section 2.7**) for fixed latitudes for two years with seasonally varying insolation (**Box 2.1**), starting on 1 January with an atmosphere with constant temperature of 300 K. The surface pressure is 1000 hPa at all latitudes. The “radiatively determined atmosphere” reacts to seasonal insolation variations with a certain (thermal) inertia, which depends on the heat capacity of the earth’s surface (C) and the greenhouse gas content of the atmosphere. Output of two model runs is provided. Both runs assume that the well-mixed greenhouse gas (proxy for CO_2) concentration is 400 ppmv. In run 1, $C=10^7 \text{ J kg}^{-1} \text{ m}^{-2}$. In run 2, $C=10^6 \text{ J kg}^{-1} \text{ m}^{-2}$. You will get the results of these runs. Compare the outcome with the dark blue curve in the left panel of **figure 1.66**.

Deadline: Wed. 26 May 2021

22.5%

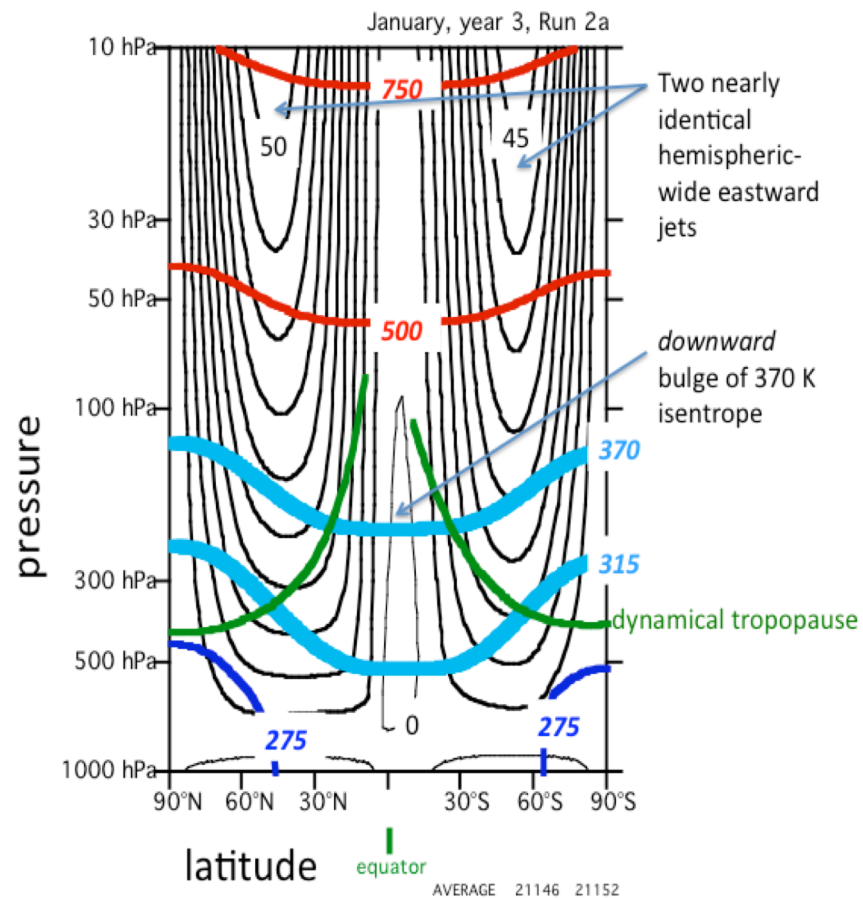
Cross-isentropic convergence of mass into the layer $315 < \theta < 370 \text{ K}$



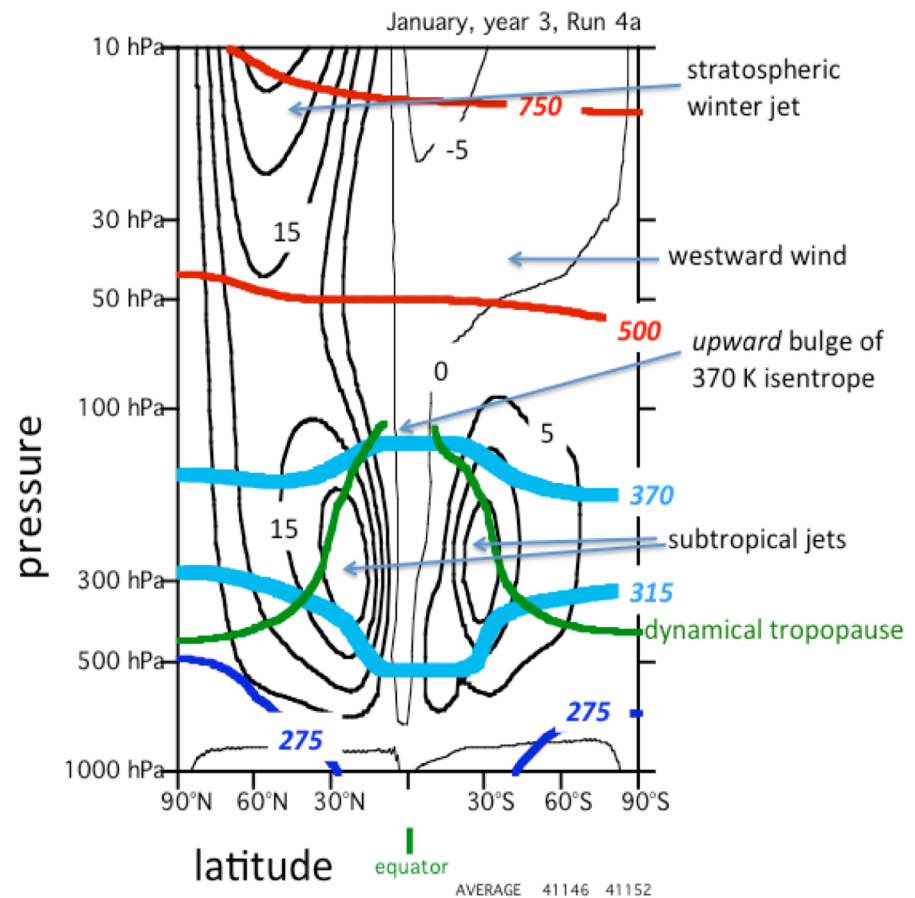
Yearly cycle of the zonal mean diabatic convergence of mass per unit area into the **Middleworld** layer between $\theta=315 \text{ K}$ and $\theta=370 \text{ K}$. Labels indicate diabatic mass flux convergence in units of $\text{kg m}^{-2} \text{ day}^{-1}$. The figure is based on the ECMWF ERA-40 re-analysis (Uppala, S.M., et al. 2005. The ERA-40 re-analysis. **Q.J.R.Meteorol.Soc.** **131**, 2961-3012) of the monthly mean zonal mean diabatic heating and the monthly mean zonal mean isentropic density at $\theta=315 \text{ K}$ and at $\theta=370 \text{ K}$, according to the *CIRA*.

Experiments with this 2D-GCM

No water cycle and no “wave drag”
(only radiation)



With water cycle and no “wave drag”
and radiation



Assignment 3 : "What-if questions"

50%

Deadline: Wed. 16 June 2021

PROBLEM 12.7 Influence of Earth's rotation rate

How would the Hadley circulation and the zonal mean zonal jets be affected if we would double the value of the Coriolis parameter? Will the subtropical jet intensify or weaken? Will the subtropical jet be displaced poleward or equatorward? The Hou-Held theory (**chapter 8**) may give some indications here. **Keep your answer short (no more than 500 words).**

PROBLEM 12.8. Influence of carbon dioxide (CO₂)

How would the Hadley circulation and the zonal mean zonal jets be affected if we would double the carbon dioxide concentration? Will the subtropical jet intensify or weaken? Will the subtropical jet be displaced poleward or equatorward? What will happen to the annual mean global mean temperature at the surface? What will happen to the annual mean global mean temperature at 10 hPa? Will the water cycle intensify or weaken? There is plenty of literature on this problem. Try to find this literature and base your answer on it. **Keep your answer relatively short (no more than 800 words).** See the **animation** of run 4a (similar to run 6 in table 12.2).

PROBLEM 12.9. Influence of thermal inertia

How does the value of the thermal inertia coefficient of the earth's surface (C) affect the (seasonal cycle of the) subtropical jet and the zonal wind in the stratosphere? What will happen (and why) to the modelled subtropical jets and stratospheric zonal winds if we *decrease* the value of C by a factor of 50 compared to run 4a? See the **animation** of run 4a (see problem 12.8). **Keep your answer relatively short (no more than 500 words).**

See the paper: <https://webpace.science.uu.nl/~delde102/DiabaticDynamicalAdjustment.pdf> and the model-animations on <https://webpace.science.uu.nl/~delde102/GeneralCirculation.htm> .

Assignment 4 : Is the phrase “planetary wave drag” a metaphor of reality?

In **sections 12.9-12.11** the established concept, “planetary wave drag”, is criticised. According to a textbook theory (the quasi-geostrophic “TEM-theory”), this phrase describes, in a nutshell, the influence of planetary (Rossby) waves on the zonal-mean zonal flow. In **section 12.11** it is concluded that this phrase is a “scientific metaphor”, which is a figure of speech that describes an action in a way that is not literally true, but helps to explain an idea. A plan exists to turn **sections 12.9-11** into a paper, which will be submitted for publication as a follow-up paper of the third paper in the list of references to this chapter, which has the title, *PV- θ view of diabatic-dynamical interaction in the general circulation*. What title would you give this paper? Do you think that this paper will meet with resistance from the reviewers. In other words, in how far are the arguments, especially in **section 12.11**, consistent and convincing? Is the evidence (based on re-analyses) for the eight ingredients of wave – zonal-mean flow sufficient and convincing. If accepted for publication, will the paper create a controversy (see the list of controversies in Climate Science in problem 12.17), or does the paper stand a chance of being ignored after publication, as is the case until now (2021) with the previous 2014-paper? Why?

22.5%

Deadline: Wed. 23 June 2021

Some important variables (see section 1.41, Dynamical Meteorology):
potential temperature, **isentropic density** and **potential vorticity**

$$\theta = T \left(\frac{p_{ref}}{p} \right)^{\kappa}$$

$$\kappa = \frac{R}{c_p}$$

$$\sigma \equiv -\frac{1}{g} \frac{\partial p}{\partial \theta}$$

$$\sigma_{ref} \equiv \frac{\int [\sigma] \cos \phi d\phi}{\int \cos \phi d\phi}$$

$$Z \equiv \frac{\zeta + f}{\sigma}$$

$$Z_{ref} \equiv \frac{f}{\sigma_{ref}}$$

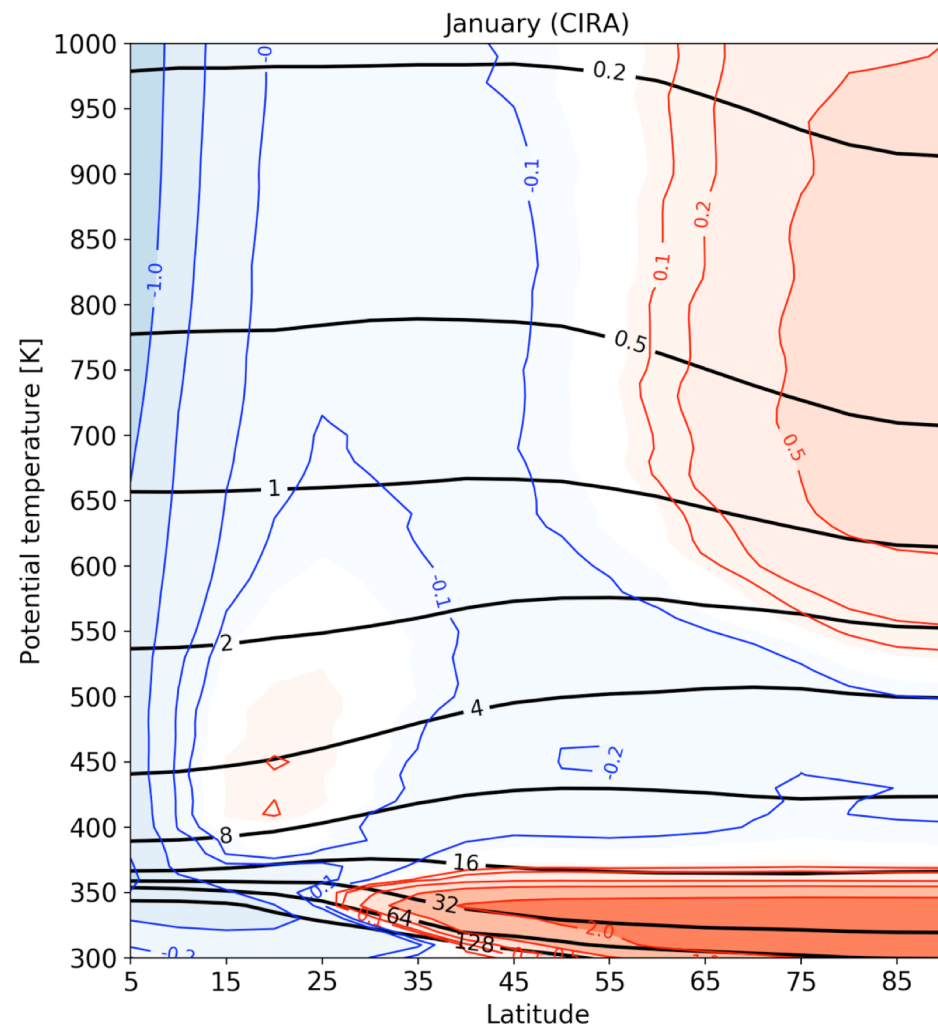
$$Z' \equiv Z - Z_{ref}$$

Zonal mean isentropic density and potential vorticity (PV) anomaly

Non-dimensional PV-anomaly:

$$Z^+ \equiv \frac{Z'}{Z_{\text{ref}}}$$

FIGURE 1.121. January average zonal mean isentropic density (black contours, labeled in units of $\text{kg m}^{-2} \text{K}^{-1}$) and the non-dimensional zonal mean PV-anomaly, Z^+ (shading: red – positive – and blue – negative; contours labeled in non-dimensional units) as a function of potential temperature and latitude, according to the COSPAR International Reference Atmosphere (**Table 1.1**).
(ReadCIRA_Sigma.py)



Cross-isentropic mass flux and pressure in January 2007

$$\sigma \frac{d\theta}{dt}$$

Time mean, zonal mean **cross-isentropic mass flux** in January 2007 as a function of latitude and potential temperature. Labels are indicated in **units of 10^8 kg day^{-1} per metre in latitude**. **Red: upwelling; blue: downwelling**. Also shown is **zonal mean pressure (black contours; labels in units of hPa)**.

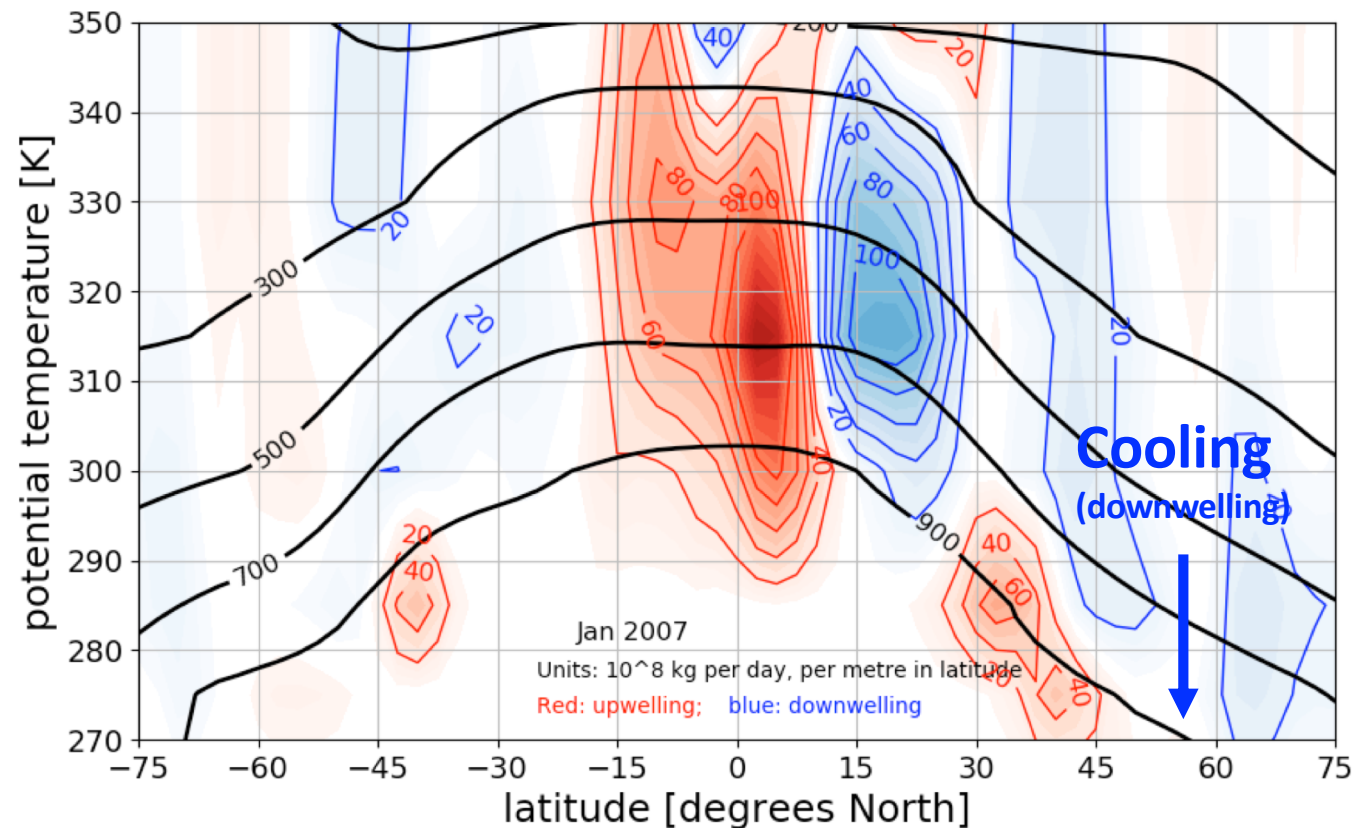
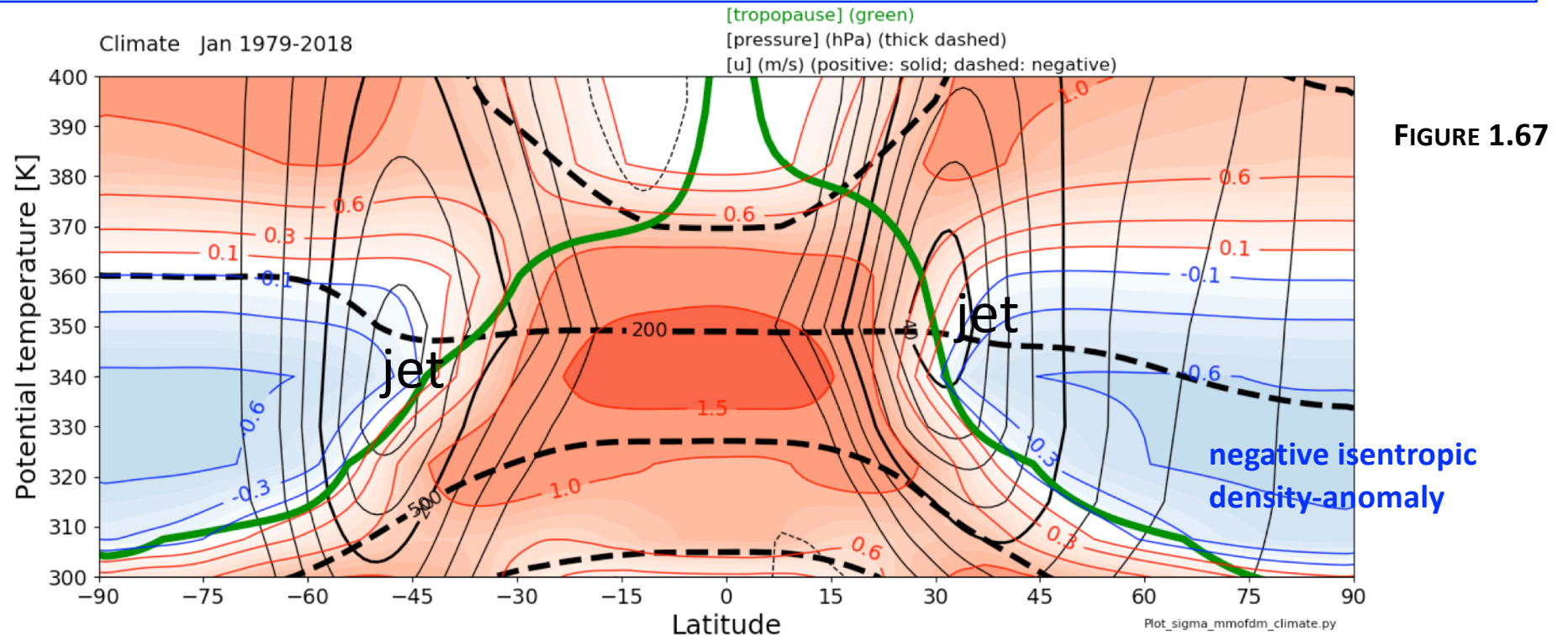


FIGURE 1.60

Isentropic density anomaly and pressure in January 1979-2018



The 40-year mean (1979-2018) zonal mean distribution of mass, in terms of the normalised isentropic density-anomaly, $\sigma^+ = [\sigma'] / \sigma_{\text{ref}}$ in **January** (upper panel) and in **July** (lower panel). Red shading indicates a **positive isentropic density-anomaly**, while blue shading indicates a **negative isentropic density-anomaly**. Contours are drawn at $\sigma^+ = -0.6, -0.3, -0.1, +0.1, +0.3, +1, +1.5$. The **dynamical tropopause**, indicated by the **green contour**, coincides with $Z_0 = \pm 2$ PVU. The **dashed contours** represent **isobars**, labeled in hPa drawn at 850, 500, 200 and 100 hPa. The black contours represent isopleths of equal $[u]$, labeled in m/s (contour interval is 5 m/s). Note that the dynamical tropopause coincides with the lower and tropical boundary of the negative isentropic density anomaly in both hemispheres

Thermal wind balance and jet streams

$$\frac{\partial[u_g]}{\partial\theta} = -\frac{1}{f}\left(\frac{\partial[\Pi]}{\partial y}\right)_\theta$$

$$\Pi = -c_p \left(\frac{p}{p_{ref}}\right)^\kappa$$

Monthly mean, zonal mean fields of **pressure** (**dashed contours**, representing 900 hPa, 700 hPa, 500 hPa, 300 hPa, 200 hPa and 150 hPa), of the absolute value of the isentropic meridional pressure gradient ("**baroclinicity**") (**red shading**; contour interval is $3 \times 10^{-3} \text{ Pa m}^{-1}$; **first contour corresponds to $3 \times 10^{-3} \text{ Pa m}^{-1}$**) and of the **zonal-mean zonal wind velocity** (solid contours at 5 m/s intervals; zero contour not shown), as a function of potential temperature and latitude, for **January 2007**.

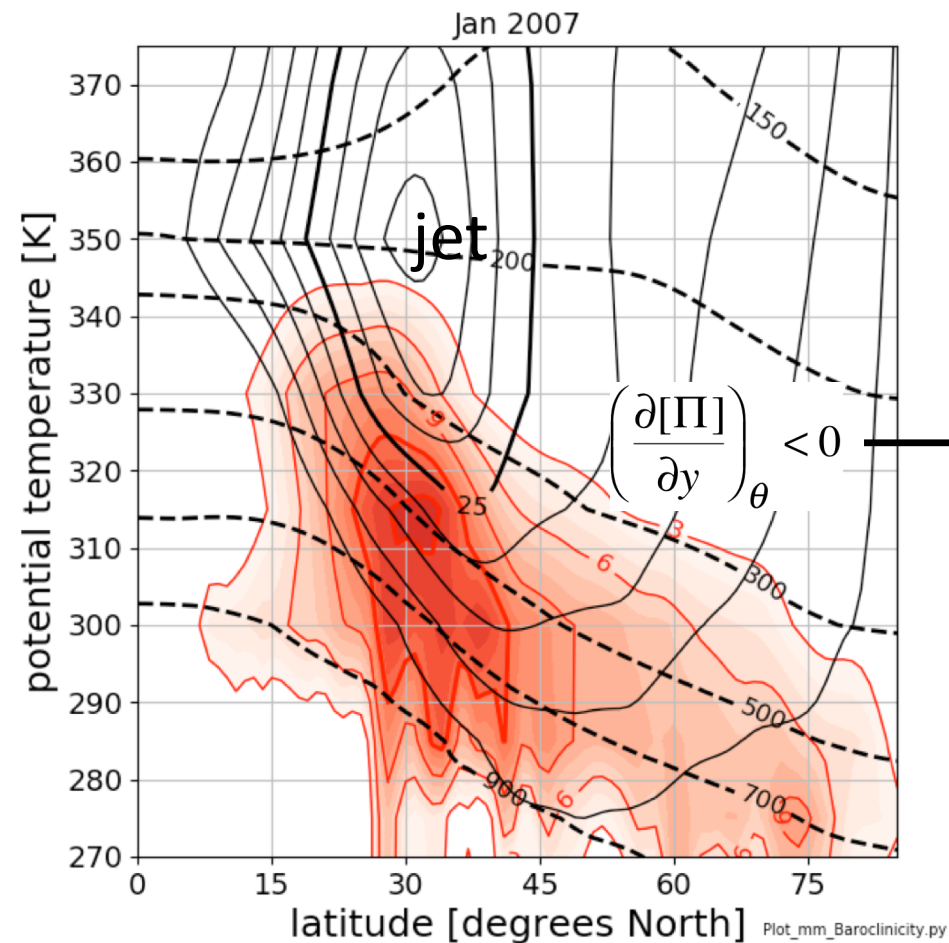


FIGURE 1.65

Thermal wind balance and jet streams

$$\frac{\partial[u_g]}{\partial\theta} = -\frac{1}{f}\left(\frac{\partial[\Pi]}{\partial y}\right)_\theta$$

$$\Pi = -c_p\left(\frac{p}{p_{ref}}\right)^\kappa$$

Downward slope of isobars
("baroclinicity") is due to cross-
isentropic downwelling

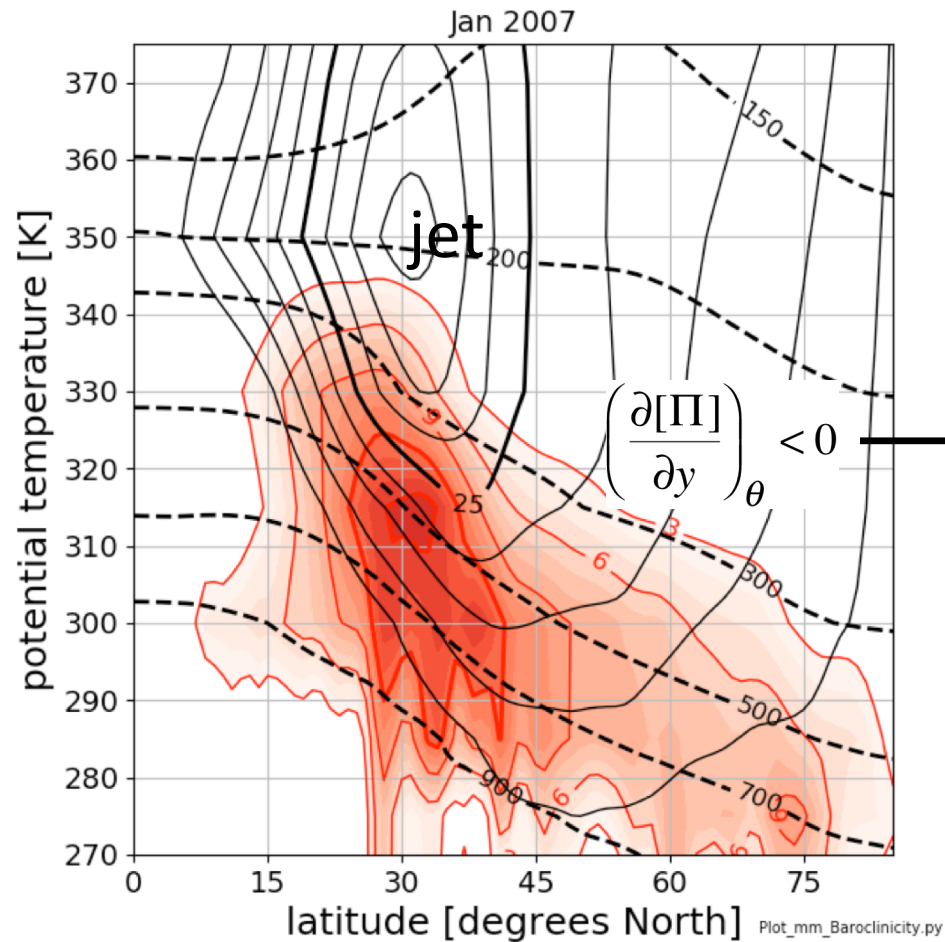


FIGURE 1.65

Next: first lecture BLT&M-1 by Michiel van den Broeke

Wednesday, 12 May, 15:15-17:00 (online)

Topic of lecture 2 BLT&M-2 (21 May, 10:00-11:45)

Radiation and the radiatively determined state (assignment 12.3)

Thermal inertia

Radiatively determined isentropic density

Assignment 1 BLT&M-2 (5%)

PROBLEM 12.2 (p. 24). Accuracy of a statement in a well-known scientific journal

A relatively recent (2013) paper in Quarterly Journal of the Royal Meteorological Society starts with the following statement.

“Low latitudes experience a net gain of radiative energy, while high latitudes experience a net deficit; as a result of this imbalance, the oceans and the atmosphere transport heat poleward”.

Explain in no more than 100 words why this statement is not true.