Aarnout van Delden http://www.staff.science.uu.nl/~delde102/C&HC.htm

Diabatic-Dynamical Interaction in the General Circulation (lecture 7)

The diabatic circulation

Associated isentropic mass budget in the Middleworld

Possible implications for potential vorticity

Last week

We identified zonal mean **potential vorticity anomalies** with zonal mean **jets** by the method of **piecewise PV-inversion** (see next slide)

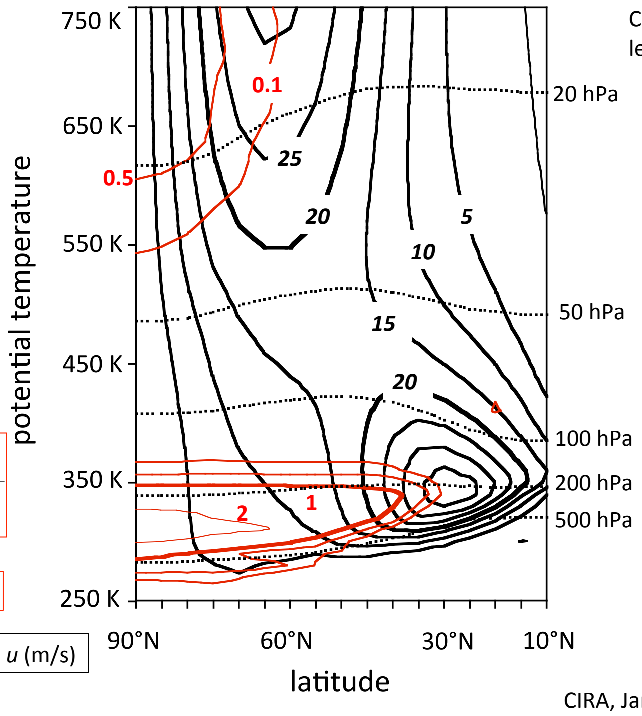
Potential vorticity inversion

Zonal wind determined from total PV

PV-anomaly:

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

Red: PV-anomaly



Black: zonal wind, *u* (m/s)

Chapter 7 lecture notes

CIRA, January mean

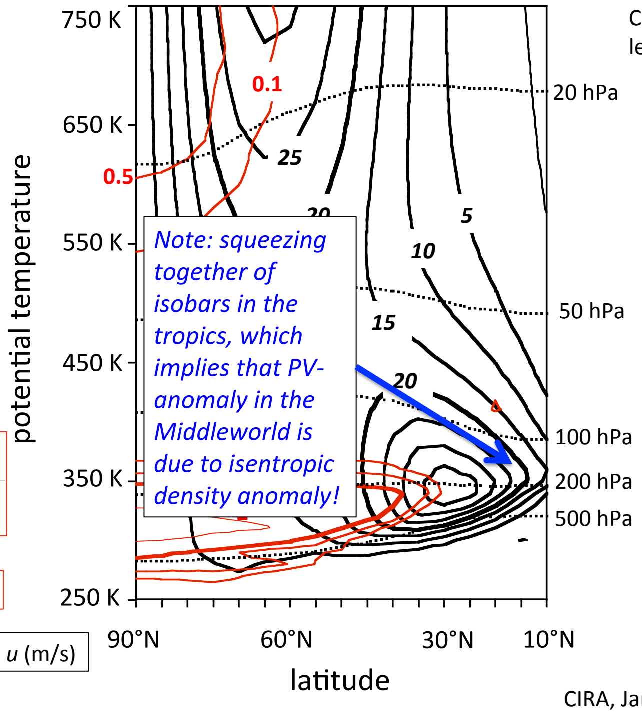
Potential vorticity inversion

Zonal wind determined from total PV

PV-anomaly:

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

Red: PV-anomaly



Note: squeezing together of isobars in the tropics, which implies that PV-anomaly in the Middleworld is due to isentropic density anomaly!

Black: zonal wind, *u* (m/s)

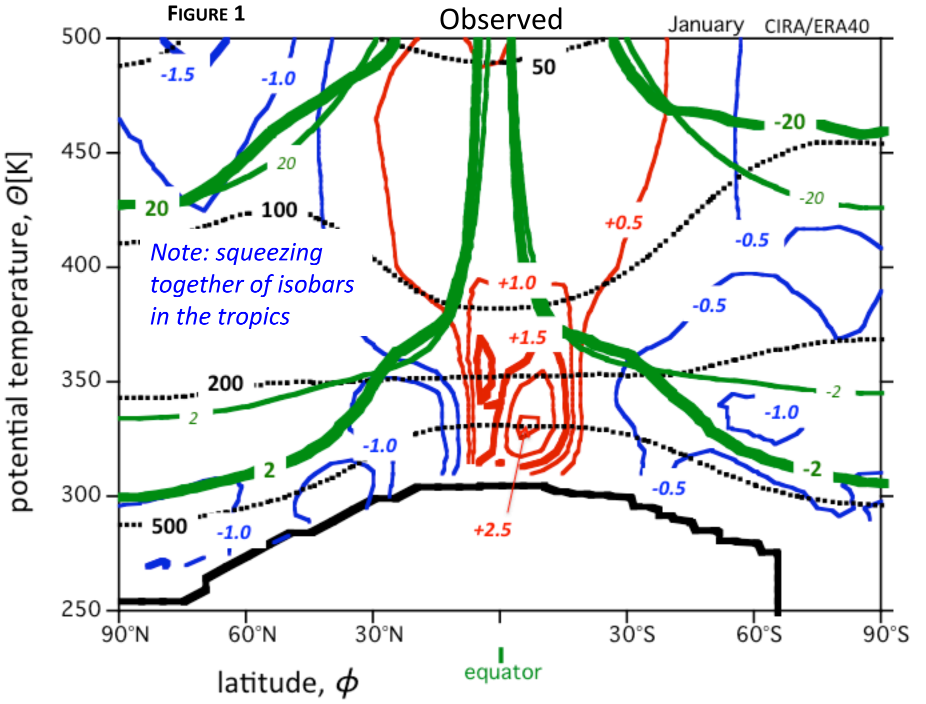
Chapter 7 lecture notes

CIRA, January mean

The “observed” diabatic circulation

Figure 1 (next slide). Monthly average zonal mean pressure (dashed black lines, labelled in units of hPa), potential vorticity (thick green lines, labelled in PVU), reference potential vorticity (thin green lines, labelled in PVU) and cross-isentropic flow (labelled in units of K day^{-1}; blue: downwelling; red: upwelling) as a function of latitude and potential temperature for January, according to the ERA-40 reanalysis and *CIRA* (Fleming et al., 1990). The thick black line indicates the zonal mean position of the earth’ surface. The average is for the period 1979-2002. Contours are not drawn if pressure is greater than 750 hPa. ERA-40 data was provided by Paul Berrisford and Yvonne Hinssen.

Figure 1



Observed

January CIRA/ERA40

Note: squeezing together of isobars in the tropics

FIGURE 1 Observed January CIRA/ERA40

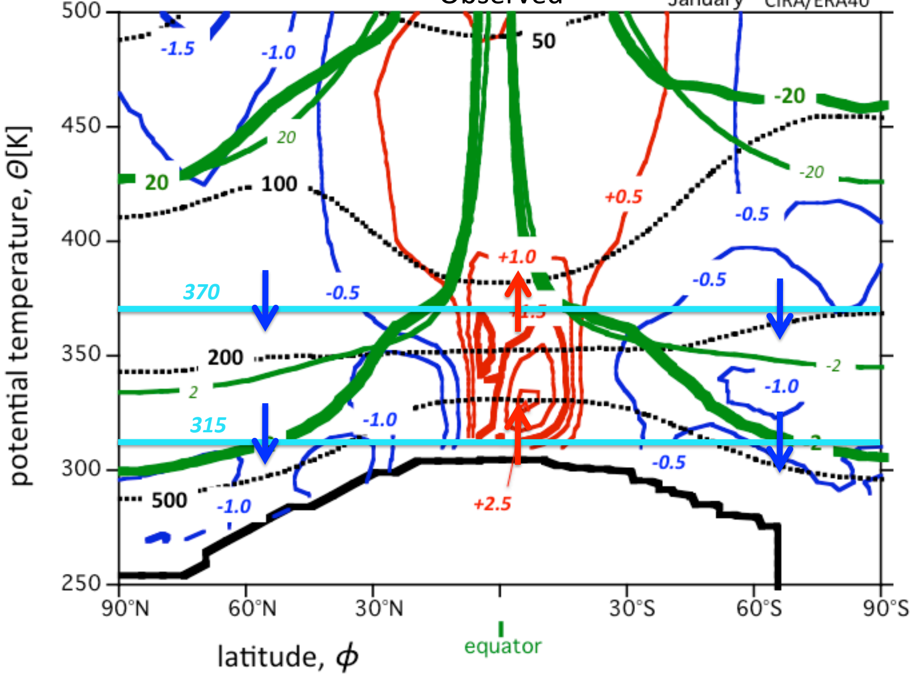
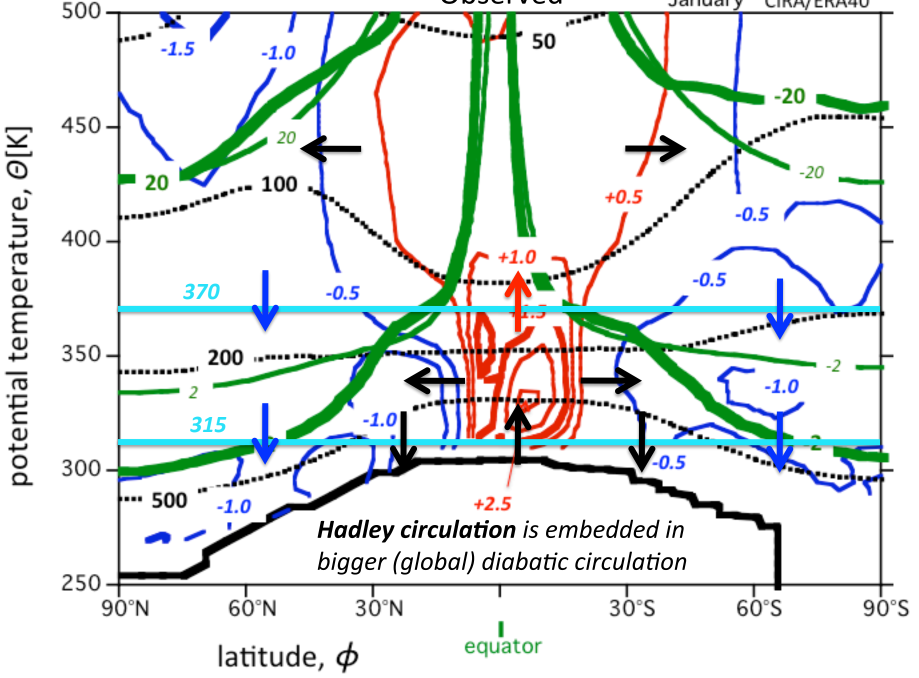


FIGURE 1 Observed January CIRA/ERA40



***Hadley circulation** is embedded in bigger (global) diabatic circulation*

Section 7.3

Mass conservation equation

$$\frac{\partial p}{\partial z} = -\rho g$$

Column of air between "isentropic" surfaces θ and $\theta+\delta\theta$ has mass δm :

$$\delta m = \sigma \delta x \delta y \delta \theta$$

"isentropic density": $\sigma \equiv -\frac{1}{g}\frac{\partial p}{\partial \theta}$

Following the motion, mass is conserved

$$\frac{1}{\delta m}\frac{d}{dt}(\delta m) = \frac{1}{\sigma \delta x \delta y \delta \theta}\frac{d}{dt}(\sigma \delta x \delta y \delta \theta) = 0$$

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↓

$$\frac{1}{\sigma}\frac{d\sigma}{dt} + \left(\frac{\partial u}{\partial x}\right)_\theta + \left(\frac{\partial v}{\partial y}\right)_\theta + \frac{\partial}{\partial \theta}\left(\frac{d\theta}{dt}\right) = 0$$

Analogous to continuity equation in *z*-coordinate system, σ replaces ρ and dθ/dt replaces *w*.

↓

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

Flux form of the continuity equation

Mass conservation equation

$$\frac{\partial \sigma}{\partial t} = -\left(\frac{\partial \sigma u}{\partial x}\right)_{\theta} - \left(\frac{\partial \sigma v}{\partial y}\right)_{\theta} - \frac{\partial}{\partial \theta}\left(\sigma \frac{d\theta}{dt}\right) = -\vec{\nabla} \cdot \vec{I}$$

Mass flux vector: $\vec{I} \equiv \left(\sigma u, \sigma v, \sigma \dot{\theta}\right)$

Vertical diabatic component due to cross-isentropic flow

Equation in short: $\frac{\partial \sigma}{\partial t} = -\vec{\nabla} \cdot \vec{I}$

Diabatic convergence of mass into the Middleworld

FIGURE 2 (next slide). Average yearly cycle of the *diabatic convergence of mass per unit area into the Middleworld layer between θ=315 K and θ=370 K*. Labels indicate diabatic mass flux convergence in units of kg m^{-2} day^{-1}. The figure is based on the ERA-40 reanalysis of the monthly mean zonal mean diabatic heating and the monthly mean isentropic density at θ=315 K and at θ=370 K, according to the *CIRA* (Fleming et al., 1990). ERA-40 data was provided by Paul Berrisford and Yvonne Hinssen.

Diabatic convergence of mass - Middleworld

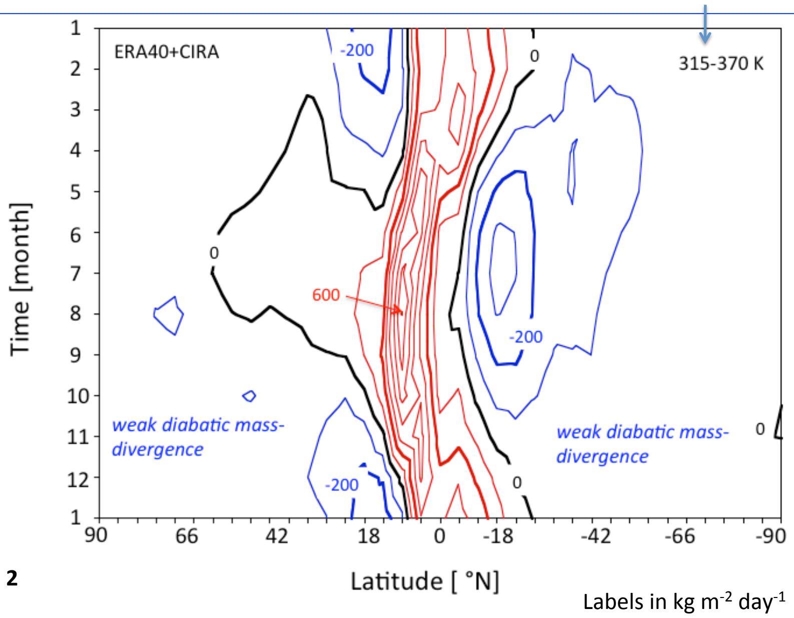
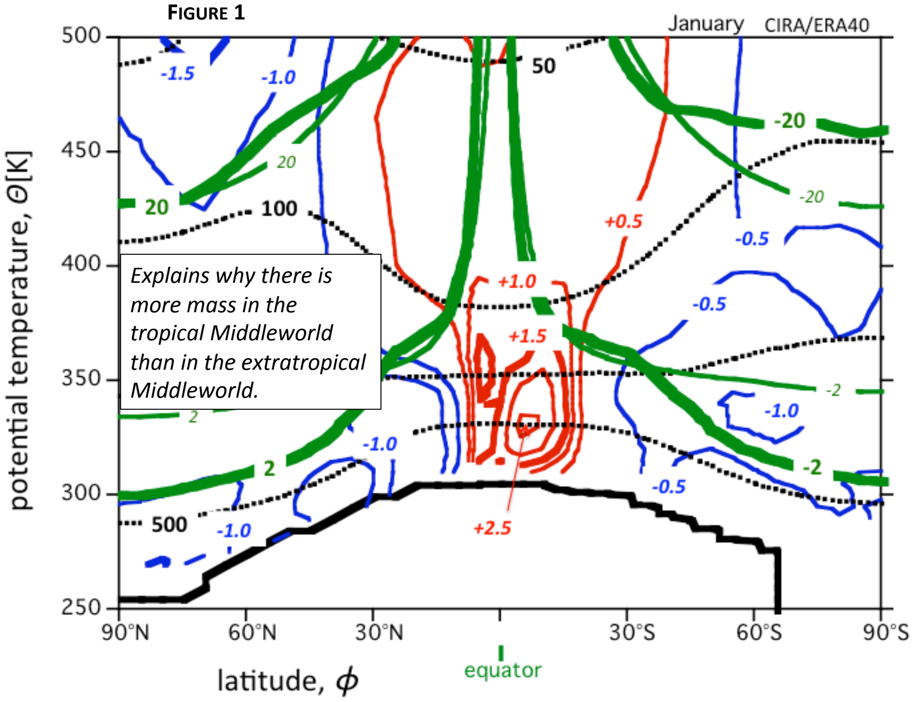


FIGURE 2

Labels in kg m^{-2} day^{-1}

FIGURE 1



Explains why there is more mass in the tropical Middleworld than in the extratropical Middleworld.

But, why does mass converge into the Middleworld in the tropics?

FIGURE 7 (next slide). *Radiatively determined isentropic density* as function of potential temperature at the equator and at 60°N, for four different ordinal dates in year 3 of the integration of the radiation model for an atmosphere containing one well mixed greenhouse gas (see the text) and with C=5×10^7 J K^{-1} m^{-2}. The ordinal dates are 20 March, 20 June, 20 September and 20 December. The isentropic density profile at the equator is nearly identical for all four dates.

Radiative equilibrium potential temperature: $\boxed{\theta_{eq} = \left(\frac{Q(\delta+1)}{2\sigma_{\mathrm{B}}}\right)^{1/4}\left(\frac{p_{ref}}{p}\right)^{\kappa}}$ (box 2.4)

$$\rightarrow \boxed{\sigma_{eq} = -\frac{1}{g}\left(\frac{\partial\theta_{eq}}{\partial p}\right)^{-1} = \frac{1}{g}\left(\frac{2\sigma_{\mathrm{B}}}{Q}\right)^{1/4}\left(\frac{p}{p_{ref}}\right)^{\kappa} p(\delta+1)^{3/4}\left\{\kappa(1+\delta)-\delta/4\right\}^{-1}}$$

$$\longrightarrow \boxed{\sigma_{eq} = 0 \text{ at TOA } (p=0)}$$

Radiatively determined σ

Isentropic density decreases practically exponentially with height!!

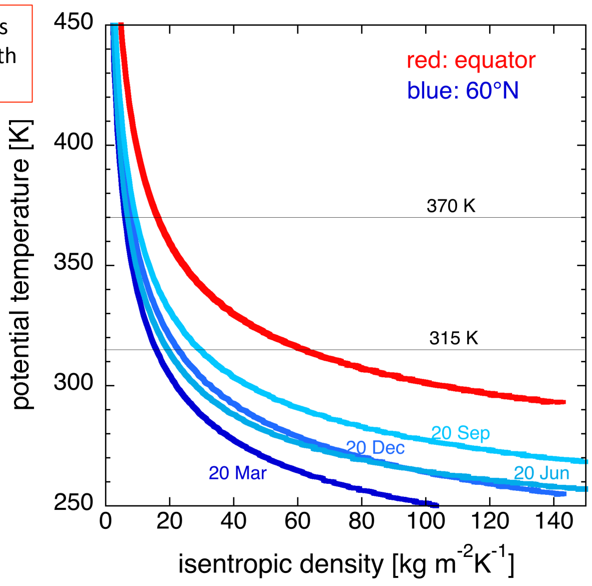
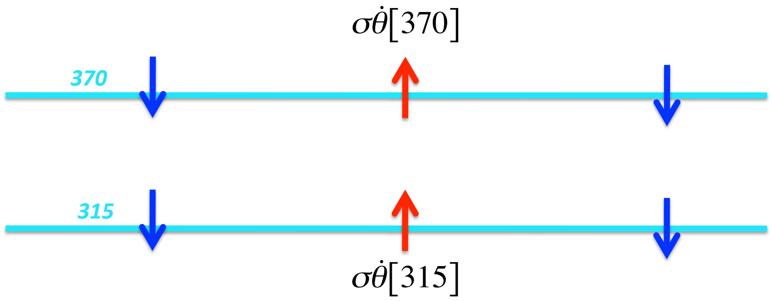


FIGURE 7

Mass budget Middleworld



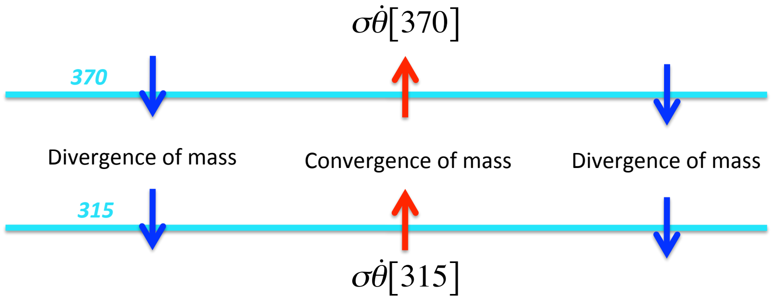
$\sigma\dot{\theta}[370]$

$\sigma\dot{\theta}[315]$

Because $\sigma[315] >> \sigma[370]$ $\quad |\sigma\dot{\theta}[315]| >> |\sigma\dot{\theta}[370]|$

Mass converges into the isentropic layer if there is diabatic heating, while it diverges out of the isentropic layer if there is diabatic cooling

Mass budget Middleworld



$\sigma\dot{\theta}[370]$

Divergence of mass

Convergence of mass

Divergence of mass

$\sigma\dot{\theta}[315]$

Because $\sigma[315] >> \sigma[370]$ $\quad |\sigma\dot{\theta}[315]| >> |\sigma\dot{\theta}[370]|$

Mass converges into the isentropic layer if there is diabatic heating, while it diverges out of the isentropic layer if there is diabatic cooling

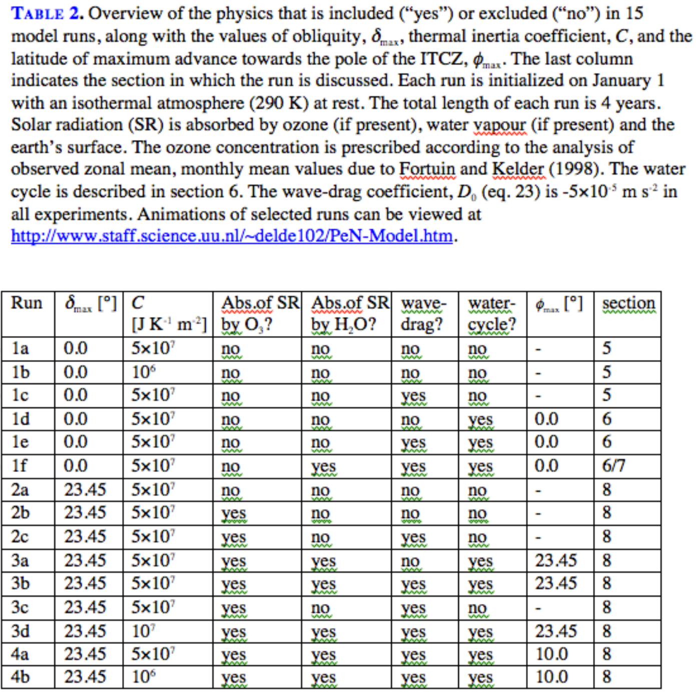


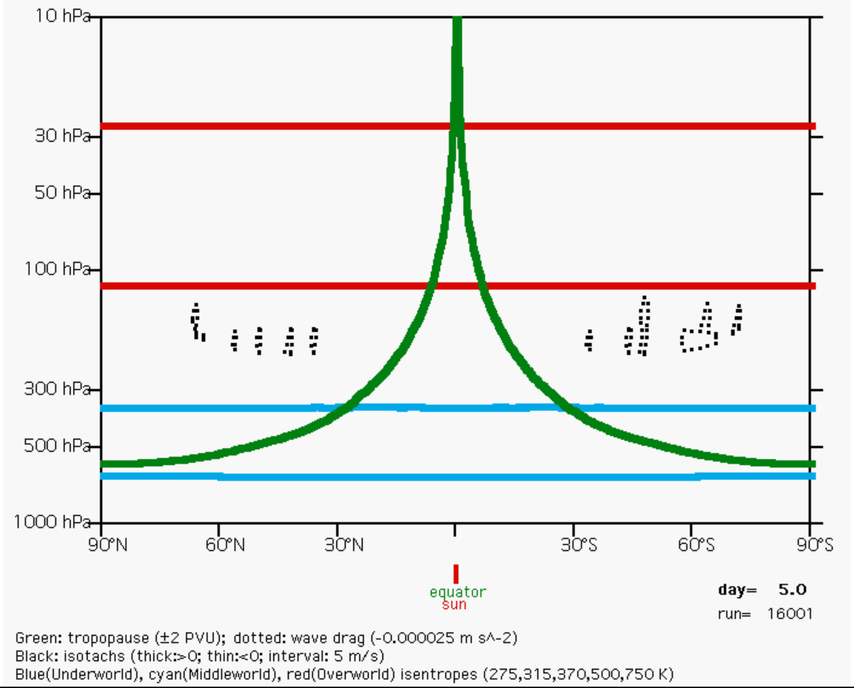
Table 2. Overview of the physics that is included ("yes") or excluded ("no") in 15 model runs, along with the values of obliquity, δ_{max}, thermal inertia coefficient, C, and the latitude of maximum advance towards the pole of the ITCZ, ϕ_{max}. The last column indicates the section in which the run is discussed. Each run is initialized on January 1 with an isothermal atmosphere (290 K) at rest. The total length of each run is 4 years. Solar radiation (SR) is absorbed by ozone (if present), water vapour (if present) and the earth's surface. The ozone concentration is prescribed according to the analysis of observed zonal mean, monthly mean values due to Fortuin and Kelder (1998). The water cycle is described in section 6. The wave-drag coefficient, D_0 (eq. 23) is -5×10^{-5} m s^{-2} in all experiments. Animations of selected runs can be viewed at http://www.staff.science.uu.nl/~delde102/PeN-Model.htm.

Permanent equinox runs:

Run	δ_{max} [°]	C [J K^{-1} m^{-2}]	Abs.of SR by O_3?	Abs.of SR by H_2O?	wave-drag?	water-cycle?	ϕ_{max} [°]	section
1a	0.0	5×10^7	no	no	no	no	-	5
1b	0.0	10^6	no	no	no	no	-	5
1c	0.0	5×10^7	no	no	yes	no	-	5
1d	0.0	5×10^7	no	no	no	yes	0.0	6
1e	0.0	5×10^7	no	no	yes	yes	0.0	6
1f	0.0	5×10^7	no	yes	yes	yes	0.0	6/7
2a	23.45	5×10^7	no	no	no	no	-	8
2b	23.45	5×10^7	yes	no	no	no	-	8
2c	23.45	5×10^7	yes	no	yes	no	-	8
3a	23.45	5×10^7	yes	yes	no	yes	23.45	8
3b	23.45	5×10^7	yes	yes	yes	yes	23.45	8
3c	23.45	5×10^7	yes	no	yes	no	-	8
3d	23.45	10^7	yes	yes	yes	yes	23.45	8
4a	23.45	5×10^7	yes	yes	yes	yes	10.0	8
4b	23.45	10^6	yes	yes	yes	yes	10.0	8

Run 1f

http://www.staff.science.uu.nl/~delde102/Wind&Tropopause_Run1f.mov



Green: tropopause (±2 PVU); dotted: wave drag (-0.000025 m s^-2)
Black: isotachs (thick:>0; thin:<0; interval: 5 m/s)
Blue(Underworld), cyan(Middleworld), red(Overworld) isentropes (275,315,370,500,750 K)

Permanent equinox runs: equilibrium state (without water cycle)

FIGURE 9 (next slide). *Permanent equinox equilibrium state* without (run 1a, left panel) and with (run 1c, right panel) wave-drag, in an atmosphere lacking water (**table 2**). Isentropes are labelled in units of K (blue: Underworld; cyan: Middleworld; red: Overworld), zonal wind (u) (black; labelled in units of m s^{-1}; contour interval is 5 m s^{-1}), wave-drag, D (eq. 23) (the dotted line corresponds to D=-2.5×10^{-5} m s^{-2}) and the dynamical tropopause, (green line, labelled in PVU), as a function of latitude and pressure. Due to symmetry around the equator, only the northern hemisphere is shown.

Note that drag pulls isentropes upward in the tropics and pushes these isentropes downward in the extratropics

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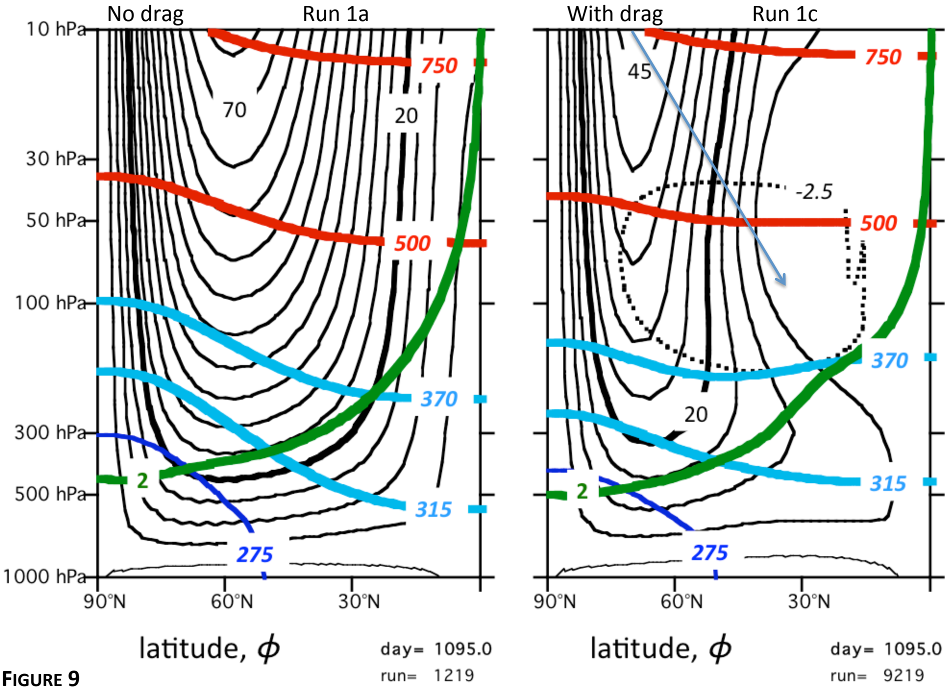


No drag Run 1a

With drag Run 1c

FIGURE 9

Permanent equinox runs: equilibrium state (with water cycle)

FIGURE 11 (next slide). Permanent equinox equilibrium state in run 1f. This run takes wave drag and the water cycle into account (**table 2**). Left panel: potential temperature, pressure, zonal wind and wave drag as a function of latitude and pressure. Isentropes are labelled in units of K (blue: Underworld; cyan: Middleworld; red: Overworld), zonal wind (u) (black lines, labelled in units of m s^{-1}; contour interval is 5 m s^{-1}), wave-drag, D (eq. 23) (the dotted line corresponds to D=-2.5×10^{-5} m s^{-2}) and the dynamical tropopause, shown in green (labelled in PVU). Right panel: cross-isentropic flow (labelled in units of K day^{-1}; blue: downwelling; red: upwelling) and pressure (dotted lines labelled in units of hPa) as a function of latitude and potential temperature. Due to symmetry around the equator, only the northern hemisphere is shown.

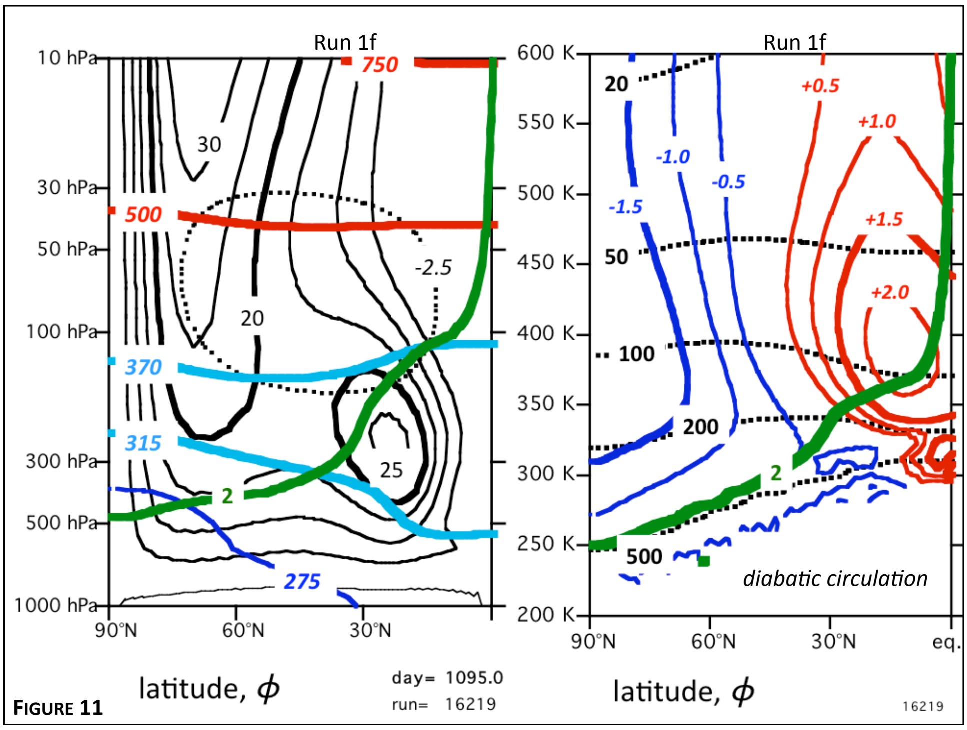
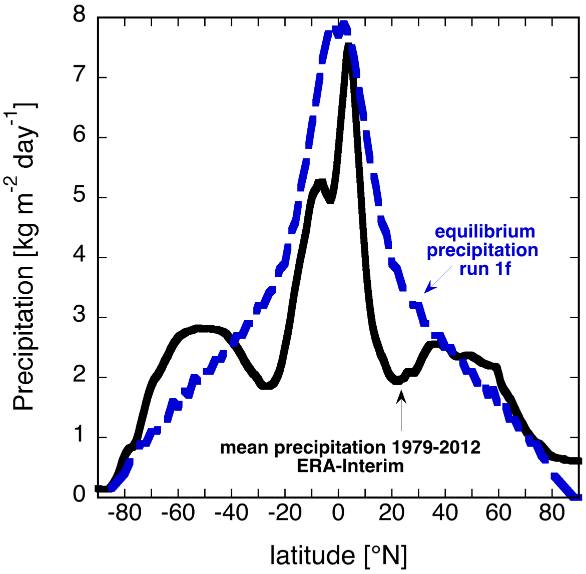


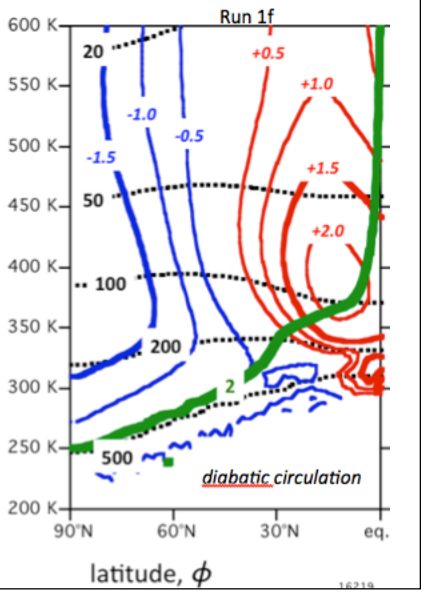
FIGURE 11

FIGURE 10. *<u>Zonal mean precipitation</u>*, averaged for the years 1979-2012, according to the ERA-Interim reanalysis (http://www.ecmwf.int/research/era/do/get/index), as a function of latitude (solid line), and the equilibrium precipitation in run 1f (dashed line).



Diabatic circulation is totally different from radiatively determined diabatic circulation! (see next slide)

FIGURE 6 (next slide). Radiatively determined cross-isentropic flow (labelled in units of K day^{-1}; contour interval is 0.25 K day^{-1}; zero contour not drawn) as a function of latitude and pressure for January 15 (in the fourth year), for two values of the thermal inertia coefficient, C: in the left panel C=10^6 J K^{-1} m^{-2}; in the right panel C=5×10^7 J K^{-1} m^{-2}. The atmosphere is assumed to be transparent to solar radiation and contains one well-mixed greenhouse gas (see the text below eq. 11).



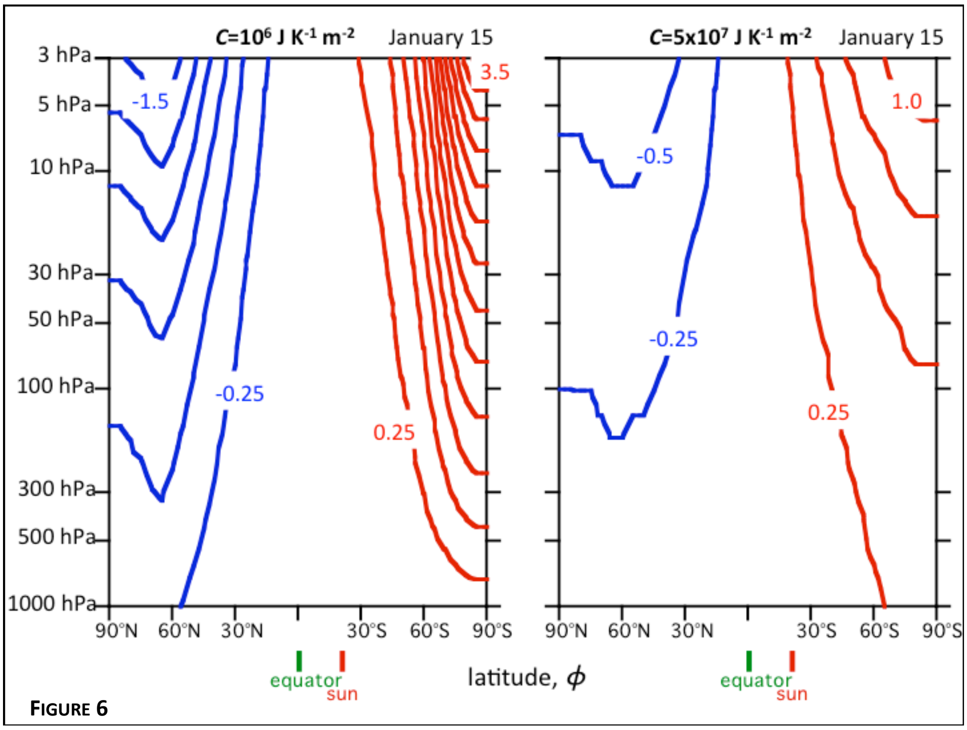


FIGURE 6

Diabatic convergence of mass in the Middleworld is determined by latent release in the tropics

FIGURE 13 (next slide). Steady state *diabatic mass flux convergence* per unit horizontal area into the Middleworld layer between θ=315 K and θ=370 K as a function of latitude, in the permanent equinox runs 1a, 1c and 1f (**table 2**), as well an estimate of the annual mean of this quantity in reality, based on the ERA-40 reanalysis (**figure 2)**.

<u>Diabatic mass flux convergence</u> per unit horizontal area into the Middleworld layer between θ=315 K and θ=370 K

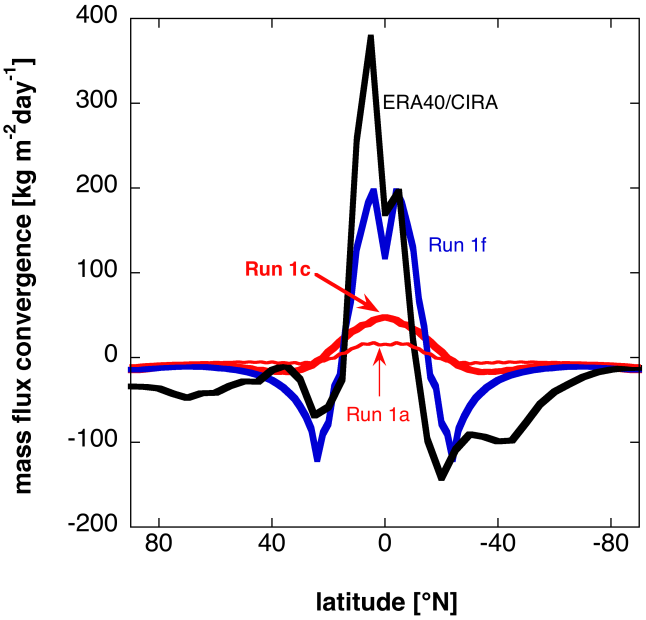
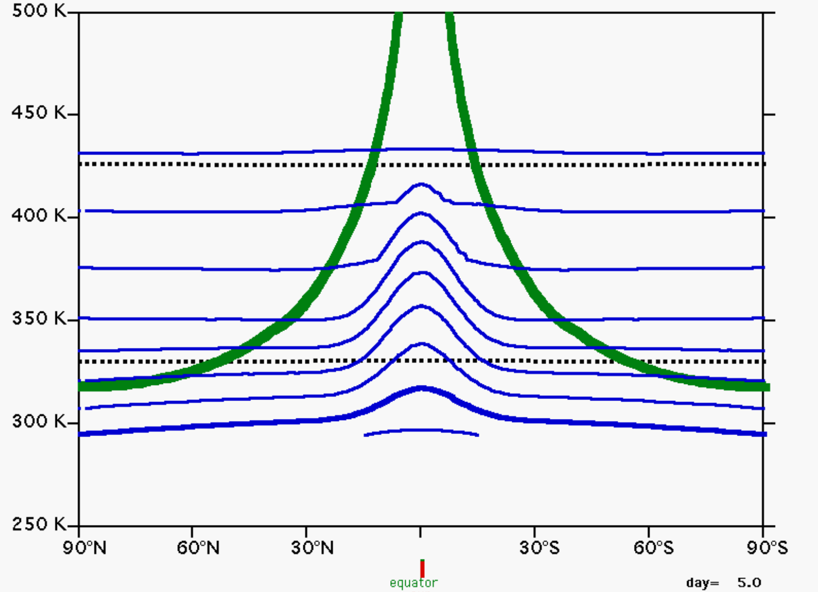


FIGURE 13

Run 1f

http://www.staff.science.uu.nl/~delde102/Cross-isentropicFlow_Run1f.mov

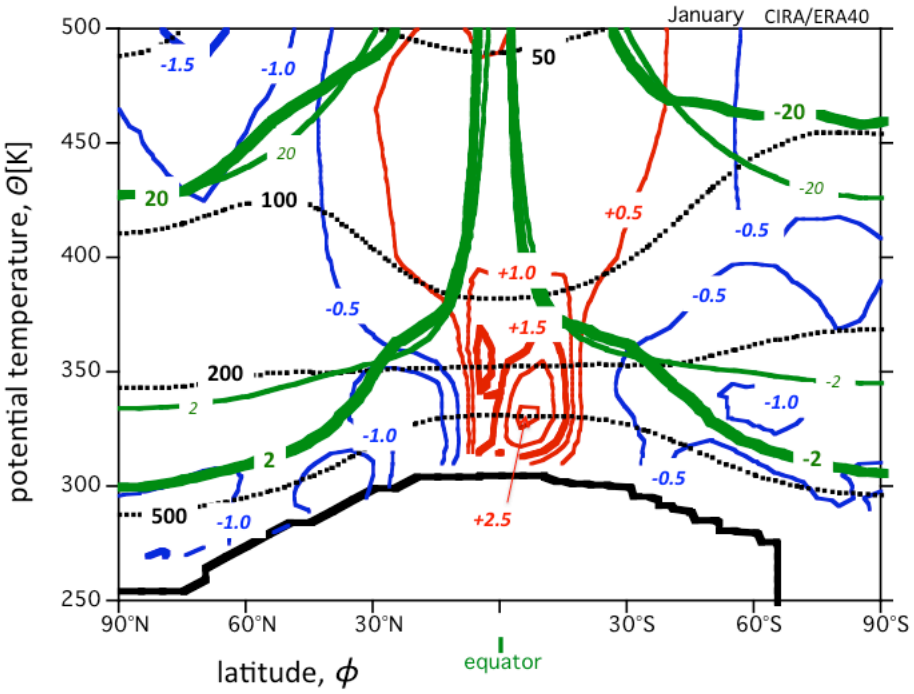


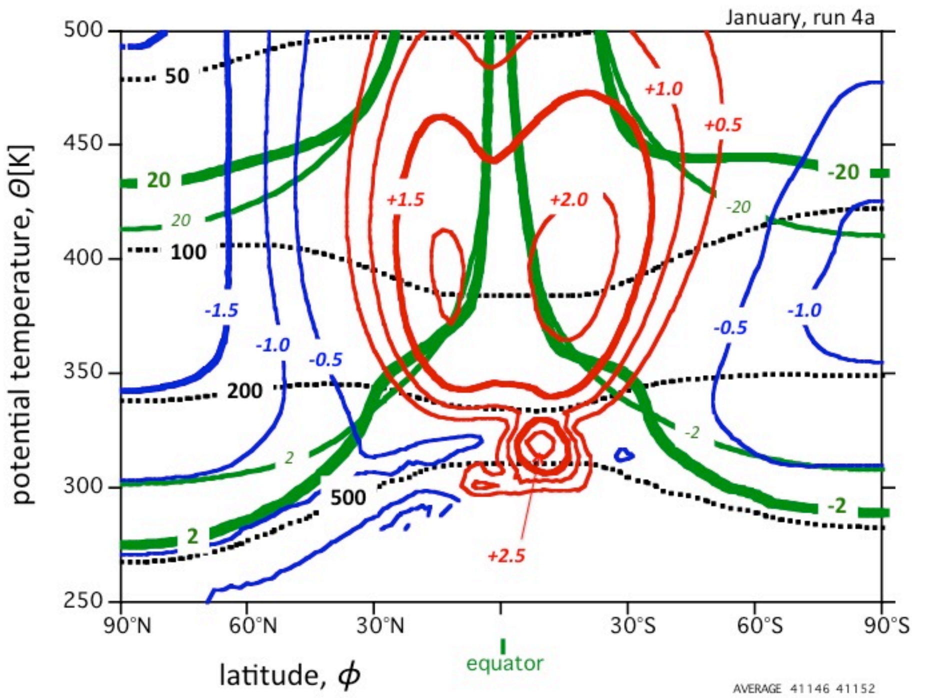
Green: PV (thick) PVref (thin); contours: ±2 & ±20 PVU
DOWNWELLING: first contour: -0.5 K/day; contour interval: 0.5 K/day
UPWELLING: first contour: +0.5 K/day; contour interval: 0.5 K/day
Black dotted lines are isobars: 500, 200, 100, 50 hPa
PVref is based on average poleward of ±10°lat. Equatorward of ±10°lat & below 650 hPa no contours are shown

The reviews

Reviews are very informative! Thank you very much!

Some points of Criticism:
Nothing much is said about formation of stratospheric PV-anomaly *
Justification of wave drag parametrization insufficient
Paper is too long (take away permanent equinox simulations)
Albedo=0.3 not realistic. Can easily make this more realistic….
Figure 16: wind reversal in the model is weak compared to reality *
Explanation Underworld, Middleworld, Overworld….
Influence thermal inertia on temperature not clear to everyone
Delay between declination angle of the Sun and position-ITCZ not taken into account
Effect of including ozone is not given much/enough attention
Choices made in wave drag parametrization are not clear to some
Figures somewhat messy (too much information)
Comparison figure 1 with figure 18 (too much optimism; see next 2 slides) *





Assignment 6

Problem 12.12. <u>Held and Hou's theory of the Hadley circulation</u>
In the light of insights gained in the present chapter, on the interaction between radiation and dynamics, and the role of the water cycle and the Earth's surface, evaluate or criticize (i.e. give your opinion on) the theory due to Held and Hou of the dynamics of the Hadley circulation, which is described in section 8.2.

*Hand-in on or before **18/6***

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

Presentations

Wednesday **18/6 & 25/6**, 2014, 13:15-15:00

Mariët+Marco 18 June ECHAM
Lars+Brenda 18 June EC-Earth
Stavros+Konstantinos 18 June GFDL
Robby+Erik 18 June Hadley
Maurits+Klaas 25 june MROC Japan

20 minutes each

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

Schedule of the C&HC-2

23 April: Introduction to radiative transfer; “grey gas”; radiative equilibrium
study sections 2.1-2.4 & boxes 2.1-2.4;
(1)** problem 12.1 (response time)* ***(0.5)
30 April: Radiatively determined state; Reanalyses
(2)** problem 12.2 (radiation at TOA; ERA-Interim)* ***(2.0)
7 May: Radiative-dynamical interaction in a dry atmosphere; GCM’s
***(3)** article for review (**yes/no**); Topic of presentation (GCM)*
14 May: Role of water cycle in the general circulation (the ITCZ)
(4)** problem 12.3 (check of model assumptions)* ***(2.5)
21 May: Role of wave drag in the general circulation
(5)** problem 12.5-12.9 (what-if? thought experiments)* ***(1.0)
4 June: The surf zone: further physical interpretation of wave drag
11 June: Hadley circulation, distribution of isentropic density
(6)** problem 12.12 (Hadley-circulation theory)* ***(1.5)
***(7)** hand in review*
18 June: Zonal mean mass- and potential vorticity budget (1)
***(8)** 4 presentations on GCM’s (**2.5**)*
***(6)** Hand in answer to problem 12.12*
25 June: Zonal mean mass- and potential vorticity budget (2)
***(8)** 1 presentation on GCM’s (**2.5**)*

23 June, 2014, 15:00-17:30: Brian Hoskins in Amsterdam!
https://www.knaw.nl/en/news/calendar/presentation-of-the-buys-ballot-medal

Sir Brian Hoskins, University of Reading and Grantham Institute for Climate Change at Imperial College London

Buys Ballot Medal lecture 2014
"Potential vorticity and the Hadley Cell"

Potential vorticity combines the dynamics and thermodynamics of the atmosphere in a variable that underlies much of our understanding of atmospheric motion. After a review of its properties, potential vorticity will be used as the basis for a new look at the Hadley Cell. The picture that emerges is very different from that in text books.

Maurits and Aarnout are going! Who else??

Next lecture

Wednesday **18/6 & 25/6**, 2014, 13:15-15:00

Potential vorticity budget

potential vorticity substance (PVS)

Impermeability theorem for PVS

Implications for PV-budget

Discussion of fifth assignment (problems 12.5-9)

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