Boundary Layers, Transport and Mixing - part 2

Lecture 4, Aarnout van Delden
a.j.vandelden@uu.nl

The role of eddies/waves in shaping the General Circulation, part 1

The three components of the General Circulation

Some animations of simulations with the 2D-GCM without the effect of the eddies (zonal asymmetries)

How do eddies and waves influence the zonal mean state?

The early history of general circulation modelling

"Planetary wave drag": the term which describes this interaction in a nutshell

Parametrisation of planetary wave drag in the 2D-GCM: **it works !!! But why ??? (Is** *"Planetary wave drag"* a true description of wave/eddy - zonal-mean flow interaction?

Next week (lecture 5): The eight ingredients of eddy – zonal-mean flow interaction **...**

Three Components of the General Circulation

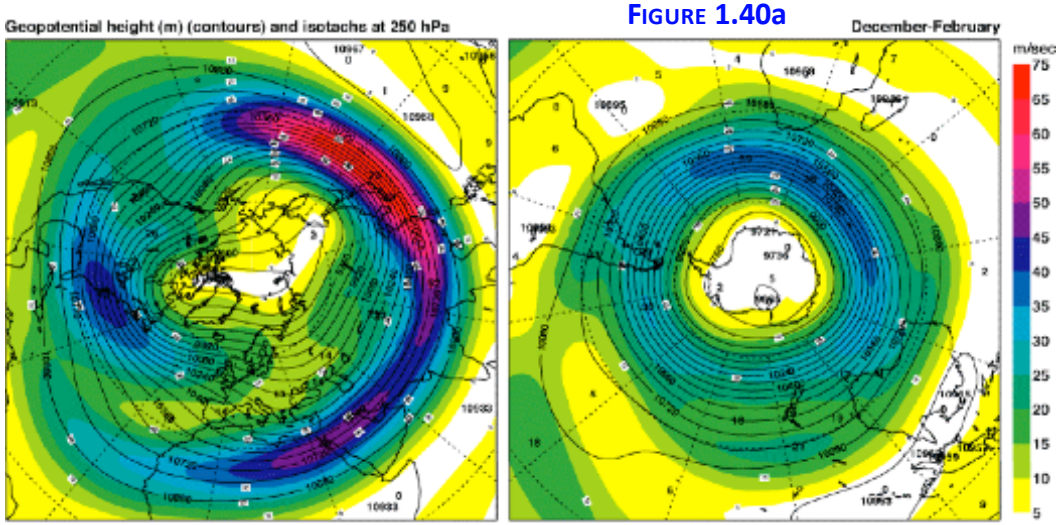


FIGURE 1.40a

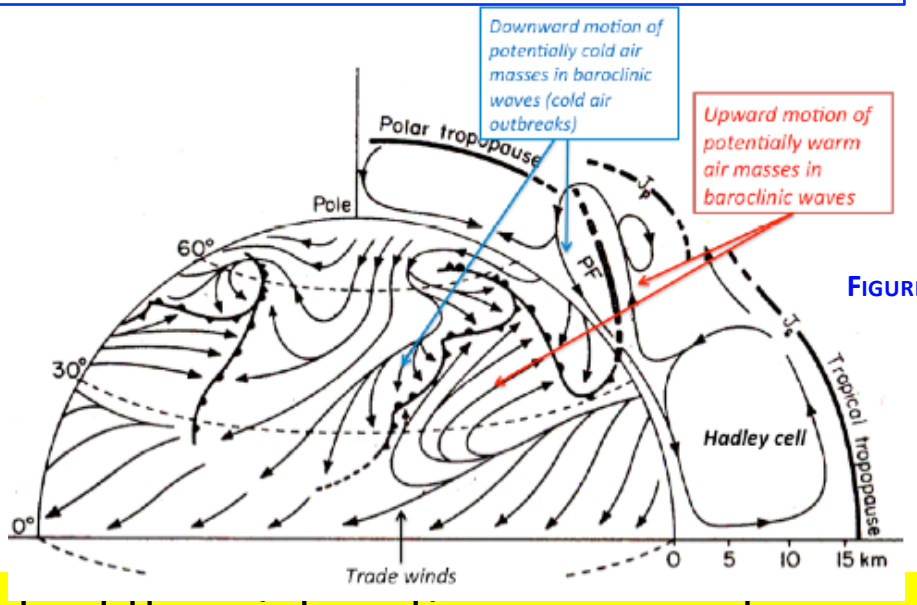


FIGURE 1.55

The general circulation of the atmosphere consists of three interacting components:

(1)The **"primary", zonally symmetric, circumpolar circulation**,

(2)The **"secondary" zonally symmetric meridional circulation**, (Hadley- & Ferrel-cells)

(3)Eddies and/or waves (zonal asymmetries).

Three Components of the General Circulation

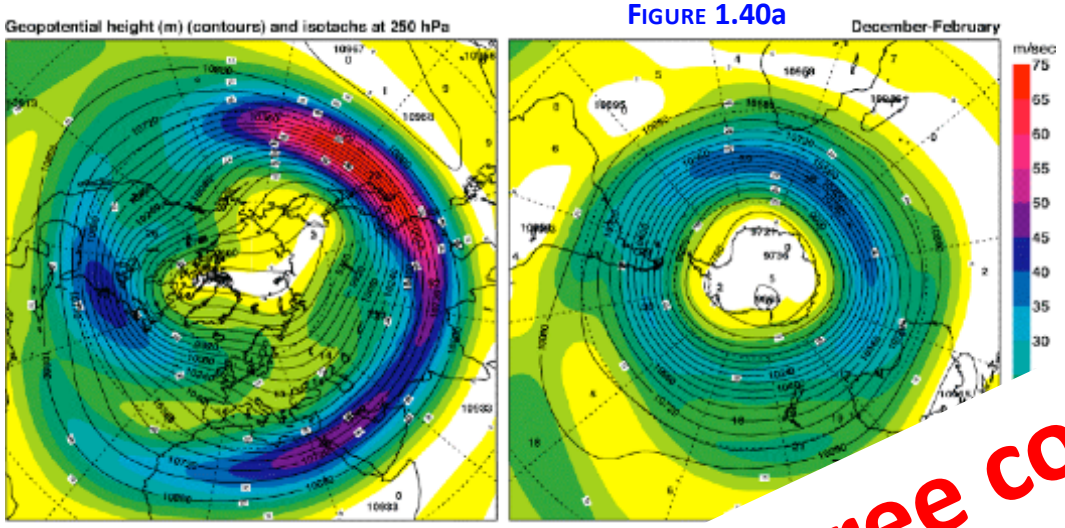


FIGURE 1.40a

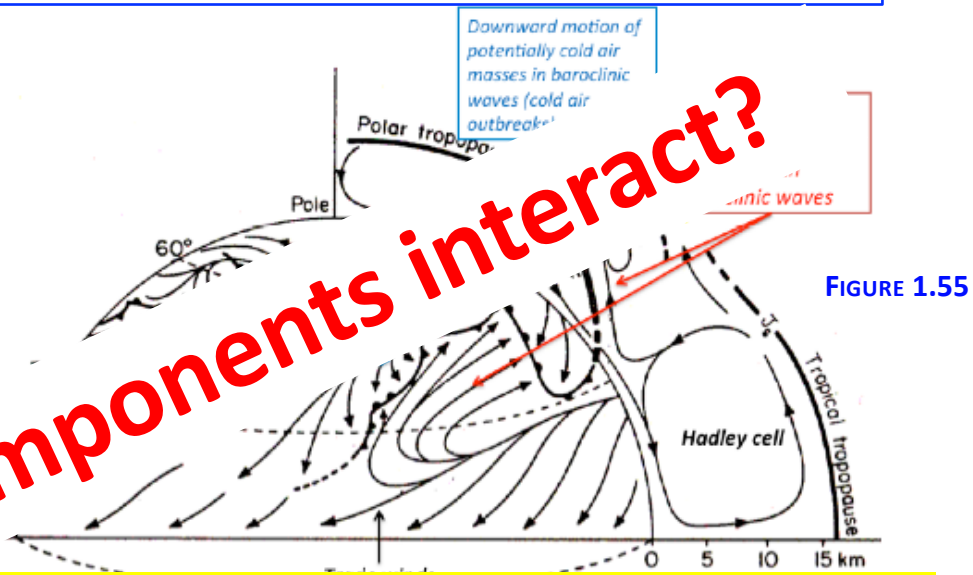


FIGURE 1.55

How do these three components interact?

The general circulation of t e consists of three interacting components:

(1)The **"prima ymmetric, circumpolar circulation**,

(2)Th **ary" zonally symmetric meridional circulation**, (Hadley- & Ferrel-cells)

(3)Eddies and/or waves (zonal asymmetries).

The 2D-GCM contains only components 1 and 2

Component 2 (**secondary circulation**) is needed to maintain
Component 1 (**primary circulation**) in thermal wind balance

$$\frac{\partial u}{\partial p} = \frac{R}{fp}\frac{\partial T}{\partial y}$$ (in pressure coordinates !!)

Today's questions:

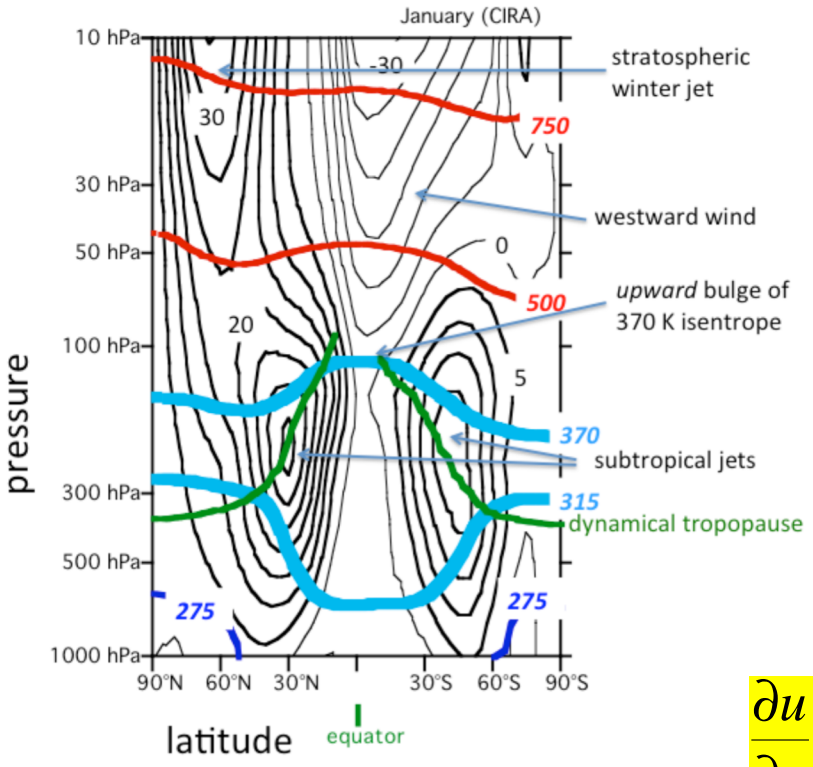
How important is **component 3** (waves & eddies)?

In which way and why does component 3 interact with the other 2 components?

What consequences does this have for component 1, in particular?

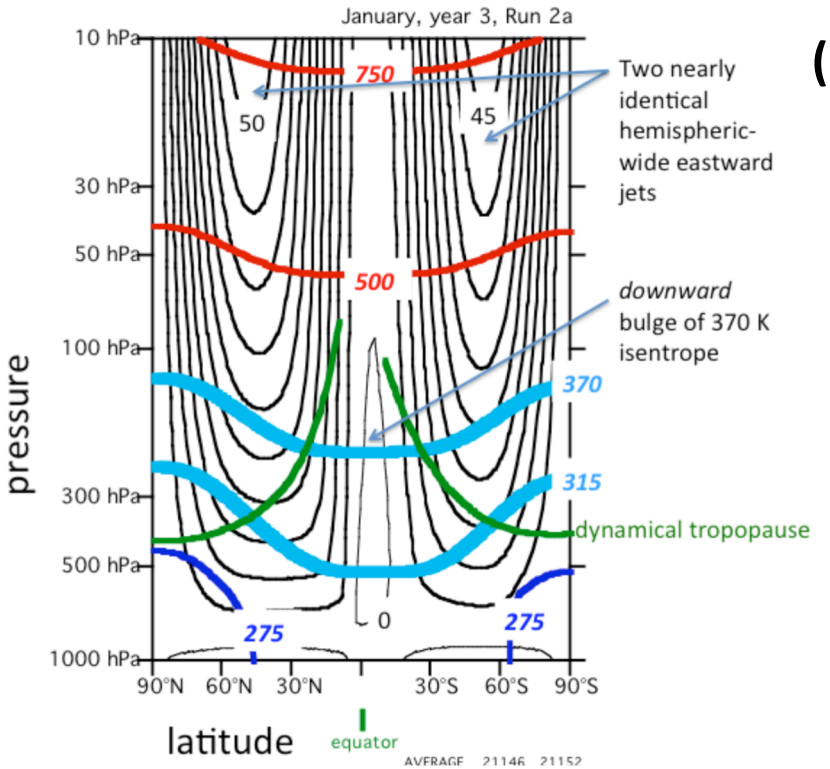
2D-General Circulation Model: **components 1 & 2**

Observed zonal mean state



Modelled zonal mean state (**no eddies/waves**)

(run 2a)



$$\frac{\partial u}{\partial p} = \frac{R}{fp}\frac{\partial T}{\partial y}$$

Thermal wind balance is fulfilled qualitatively

Overview of runs, performed in 2014 (Tellus publication)

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 [eq. (15)], and the latitude of maximum advance toward the pole of the ITCZ, ϕ_{max}

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

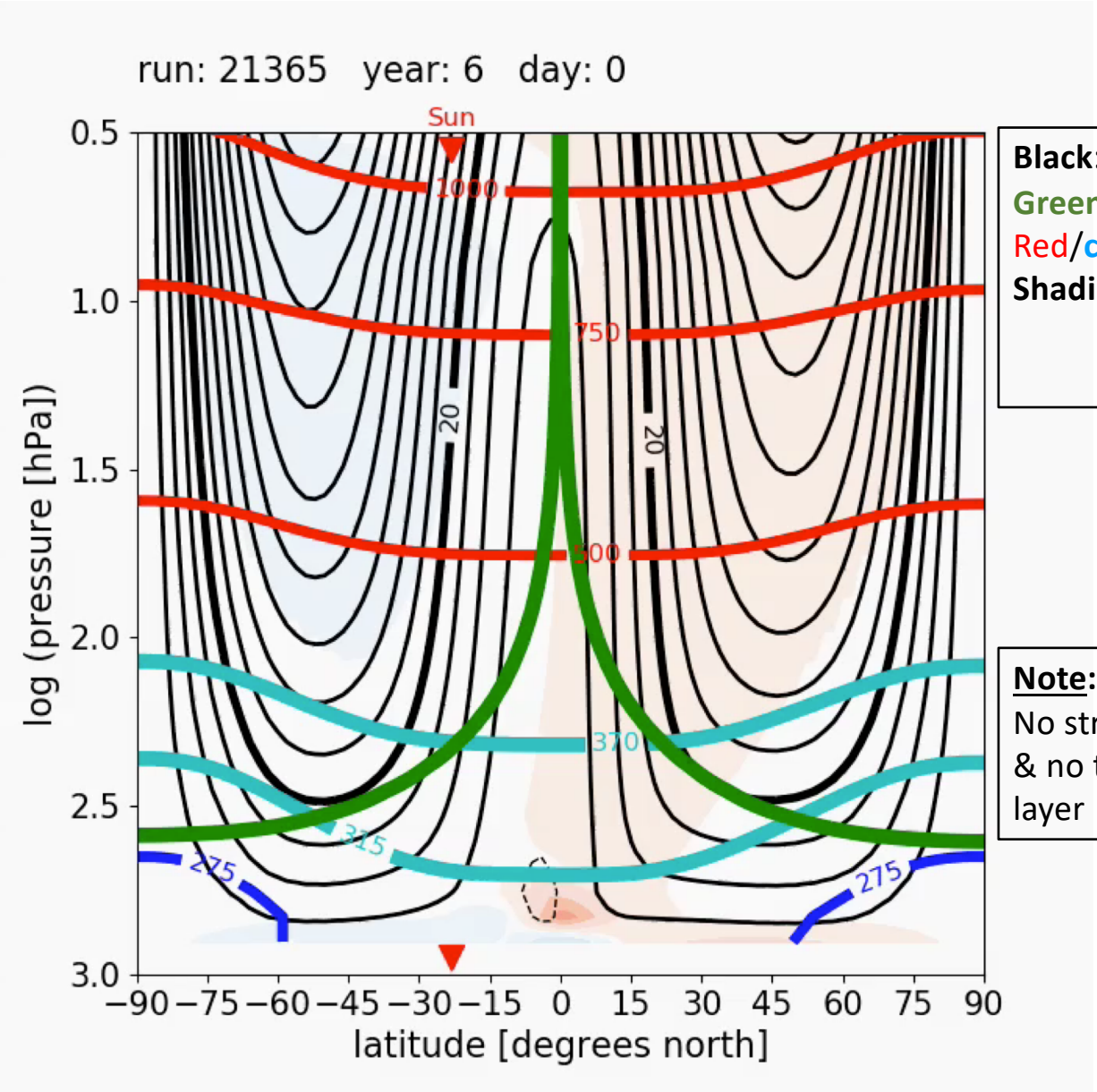
The last column indicates the section in which the run is discussed. Each run is initialised on January 1 with an isothermal atmosphere (290 K) at rest. The total length of each run is 4 yr. Solar radiation (SR) is absorbed by ozone (if present), water vapour (if present) and the earth's surface. The 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. (25)] is -5×10^{-5} m s^{-2} in all experiments. Furthermore, $z_0 = 10$ km and $z_1 = 25$ km. Animations of selected runs can be viewed in the supplementary files.

Animation

(year 6)

Run 2a

Water cycle: no
Ozone: no



Black: [*u*] (interval=5 m/s)
Green: dynamical tropopause
Red/**cyan**/**blue**: isentropes [K]
Shading: [*v*]
red: northward
blue: southward

Note:
No stratospheric wind reversals & no tropical tropopause cold layer

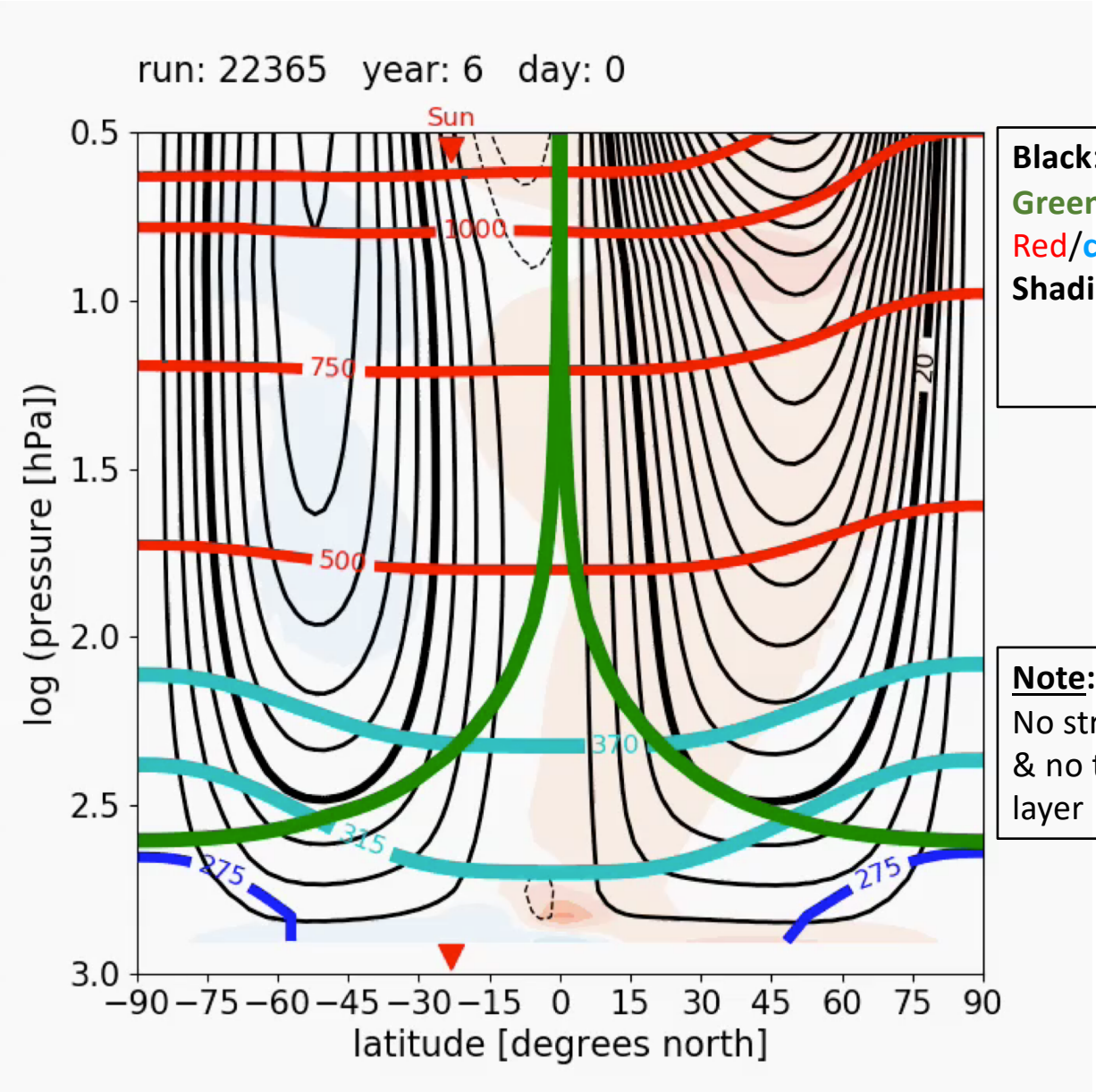
$$\frac{\partial u}{\partial p} = \frac{R}{fp}\frac{\partial T}{\partial y}$$

Animation

(year 6)

Run 2b

Water cycle: no
Ozone: **yes**



Black: [*u*] (interval=5 m/s)
Green: dynamical tropopause
Red/**cyan**/**blue**: isentropes [K]
Shading: [*v*]
red: northward
blue: southward

Note:
No stratospheric wind reversals & no tropical tropopause cold layer

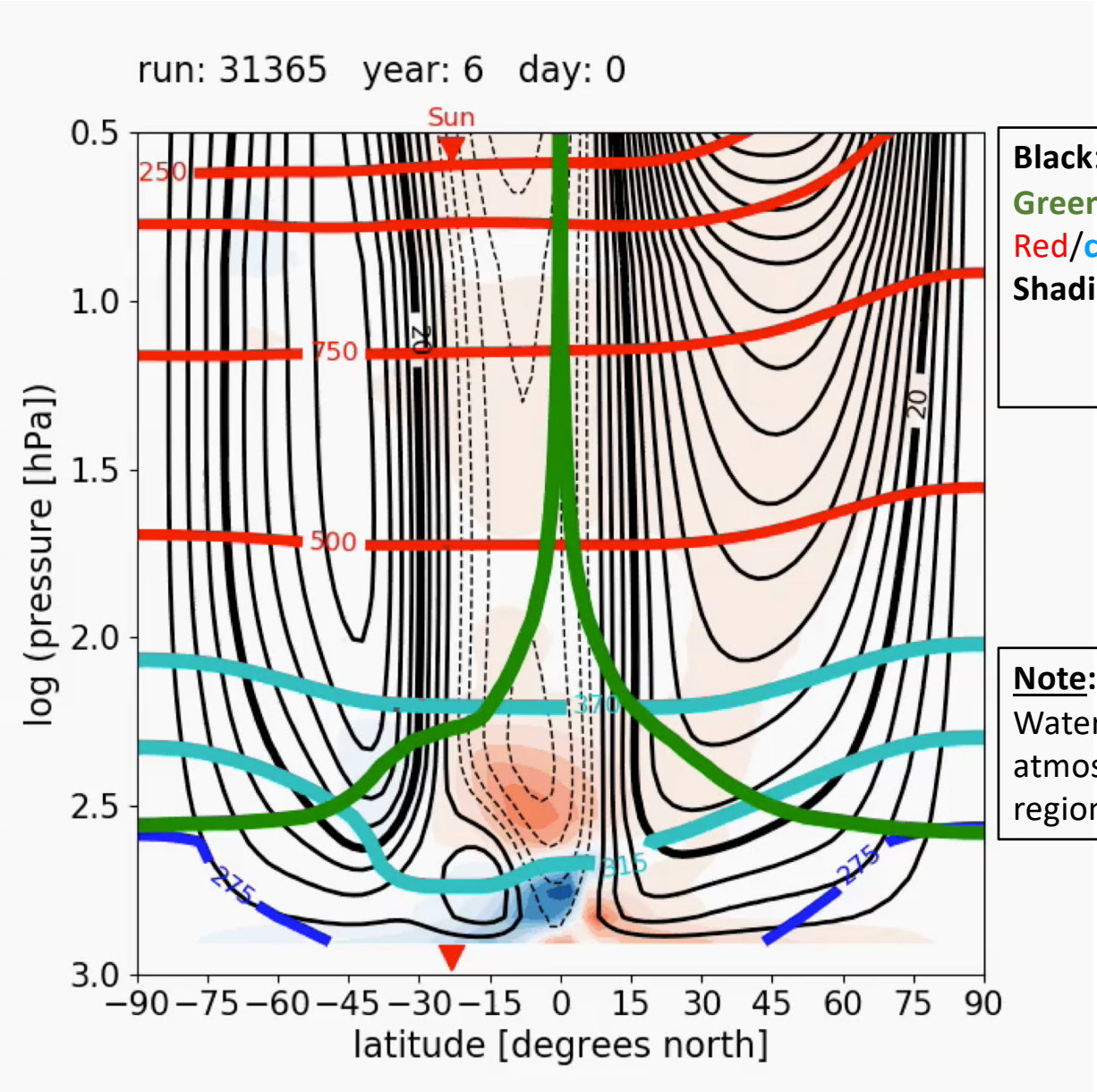
Animation

(year 6)

Run 3a

Water cycle: **yes**
Ozone: **yes**

ITCZ follows the overhead sun



Black: [*u*] (interval=5 m/s)
Green: dynamical tropopause
Red/**cyan**/**blue**: isentropes [K]
Shading: [*v*]
red: northward
blue: southward

Note:
Water cycle cools the atmosphere, except in the region of the ITCZ

Conclusion from these numerical experiments

A model with radiation, ozone , water cycle and the circulation, excluding zonal asymmetries does not work

Zonal-mean zonal wind velocity and temperature are not realistic

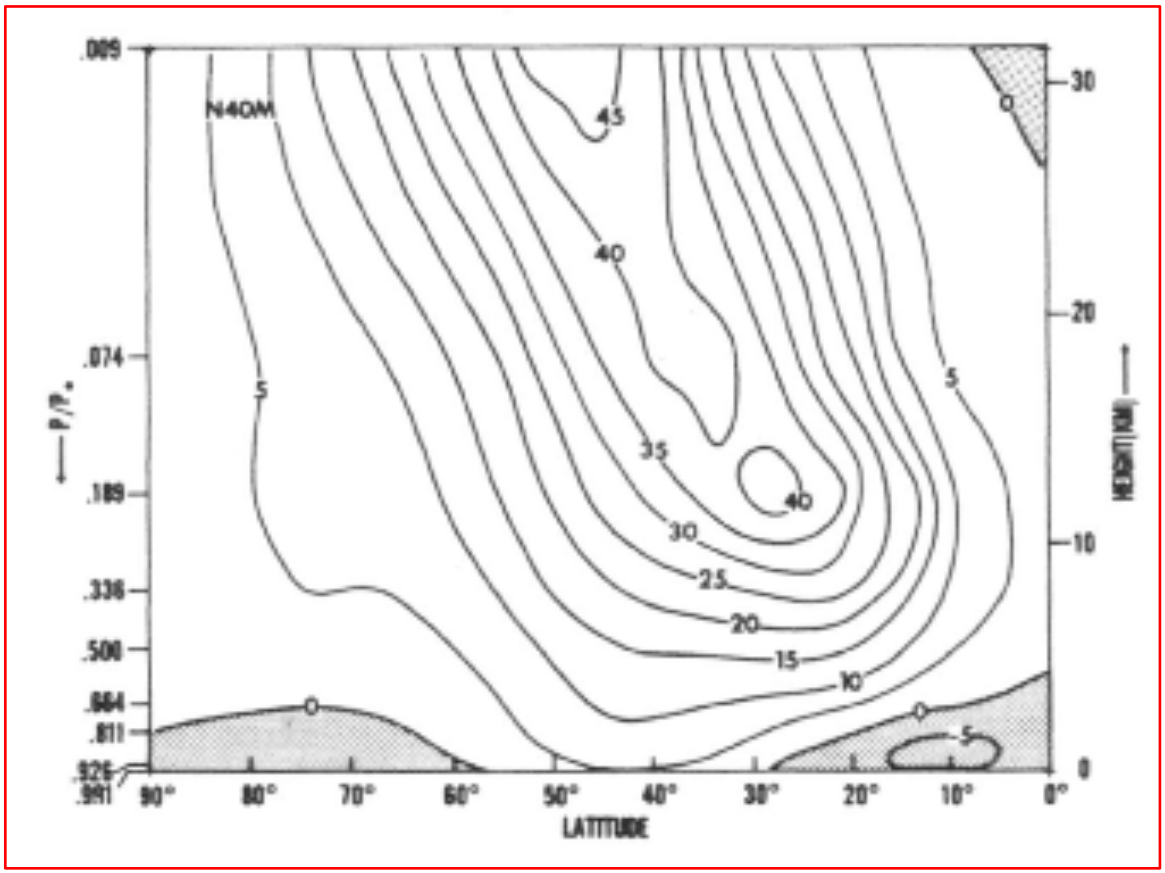
Early GCM simulations had similar problems….

The history of general circulation modelling

Permanent January simulation, Northern Hemisphere (section 12.12)

1970 - GFDL 3D-GCM

Quasi-equilibrium zonal mean zonal wind speed in the northern hemisphere as a function of latitude and non-dimensional pressure, p/p_s, in an early simulation of the General Circulation with a three dimensional primitive equation model with fixed insolation and a grid-size of 160 km at the equator and 270 km at 40°N.



Manabe, S., J. Smagorinsky, J. L. Holloway, H.M. Stone, 1970: Simulated climatology of a general circulation model with a hydrologic cycle, part 3. **Mon.Wea.Rev., 98**, 175-212.

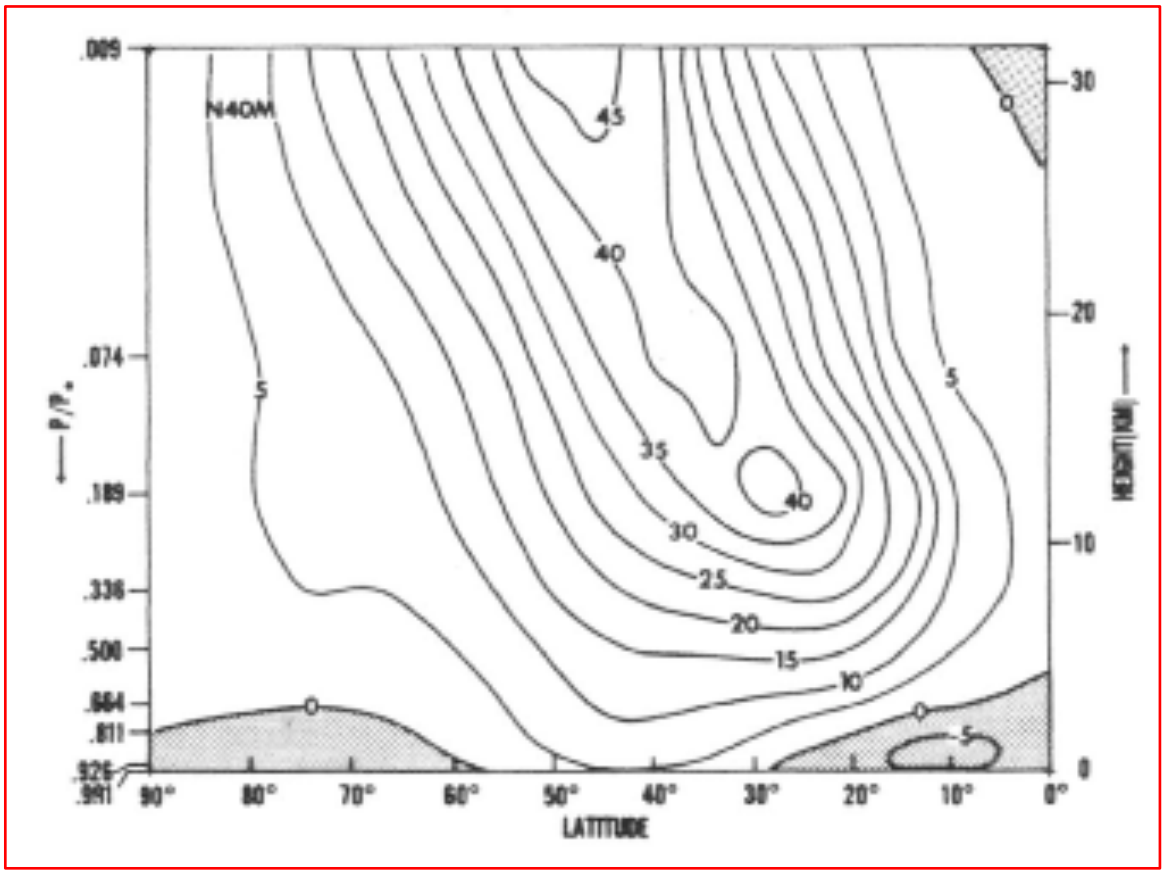
The history of general circulation modelling

Permanent January simulation, Northern Hemisphere (section 12.12)

1970 - GFDL 3D-GCM

Subtropical jet is not clearly separated from the stratospheric jet.

There are two likely reasons for this:
(1) insufficient resolution to resolve all waves and eddies and
(2) very little or no stationary wave activity due to the absence of mountains.



Manabe, S., J. Smagorinsky, J. L. Holloway, H.M. Stone, 1970: Simulated climatology of a general circulation model with a hydrologic cycle, part 3. **Mon.Wea.Rev., 98**, 175-212.

The history of general circulation modelling
First simulation of the seasonal zonal wind reversal in the stratosphere

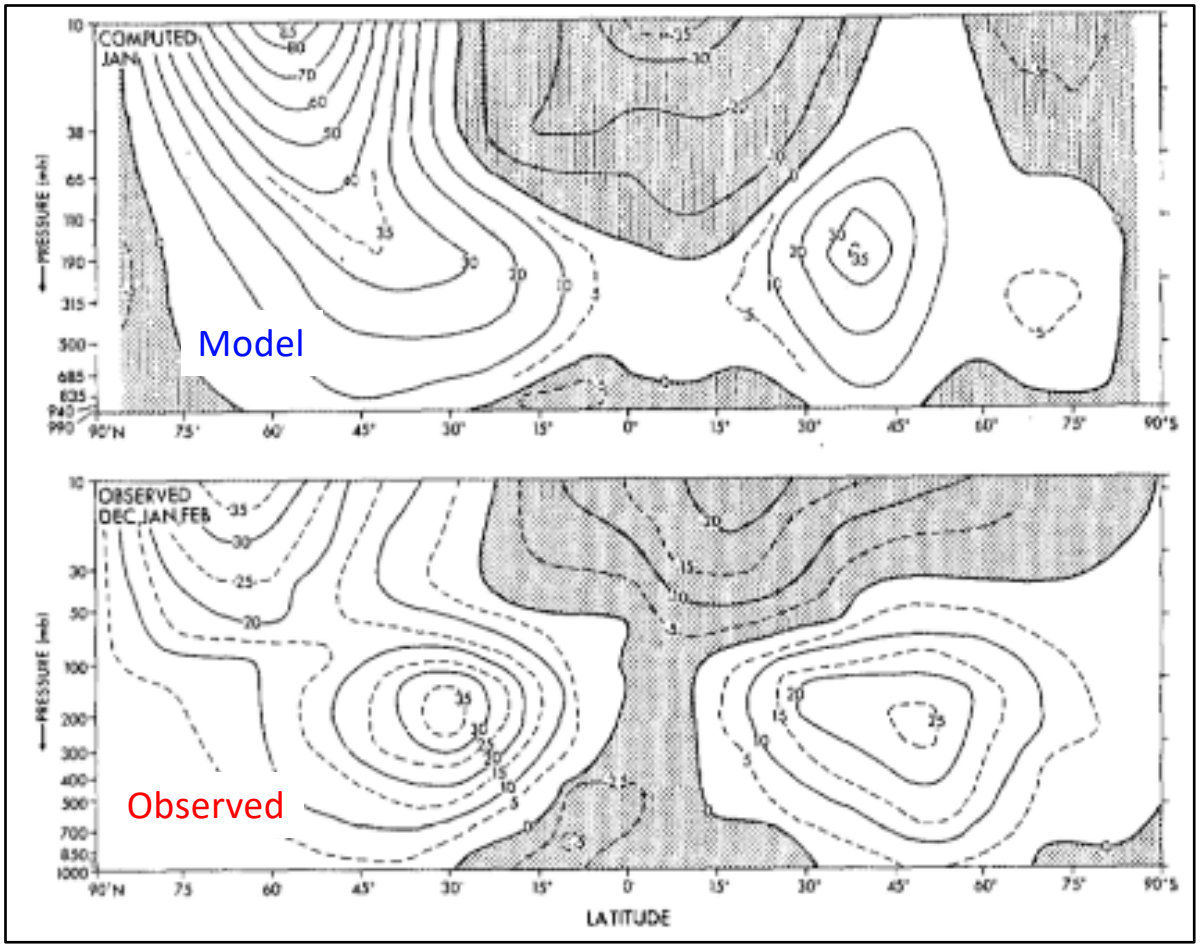
1976 - GFDL 3D-GCM with a uniform horizontal grid distance is about 265 km and 11 layers, including the stratosphere.

Stratospheric jet is much too strong!
Because of the low resolution?
(waves and eddies in the troposphere are not well resolved).

Computed zonal mean zonal wind (**upper panel**) and observed zonal mean zonal wind (lower panel) in January according to Manabe and Mahlman (1976). Labels in units of m//s. Grey shading indicates regions where [*u*]<0.

Manabe, S. and J.D. Mahlman, 1976: Simulation of seasonal and interhemispheric variations in the stratospheric circulation. **J.Atmos.Sci., 33**, 2185-2217.

FIGURE 12.47



The history of general circulation modelling
First simulation of the seasonal zonal wind reversal in the stratosphere

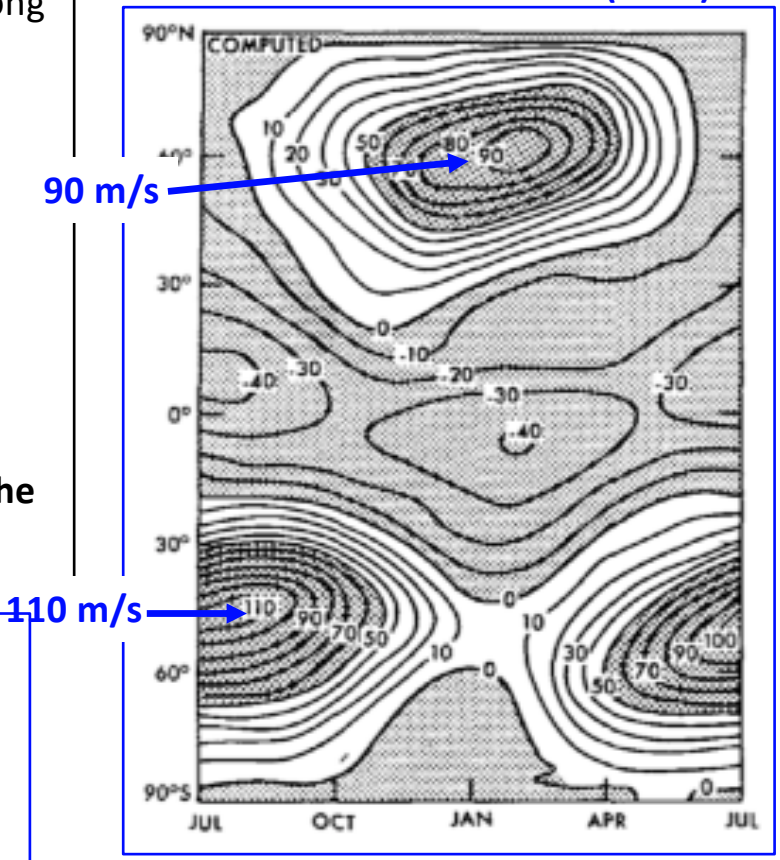
Zonal-mean zonal wind much too strong in the simulation due to Manabe and Mahlman!

Is this due to less wave activity in low resolution model?

Difference in strength of the stratospheric jets in Southern and Northern Hemispheres is usually attributed to more wave-activity in the Northern Hemisphere.

Left panel: Seasonal cycle of the zonal mean zonal wind at 10 hPa in the first GCM simulation that produced seasonal zonal mean zonal wind reversals in the stratosphere according to Manabe and Mahlman (1976). Labels in m s^{-1}.

Manabe and Mahlman (1976)



ERA5 1979-2020 (42 years)

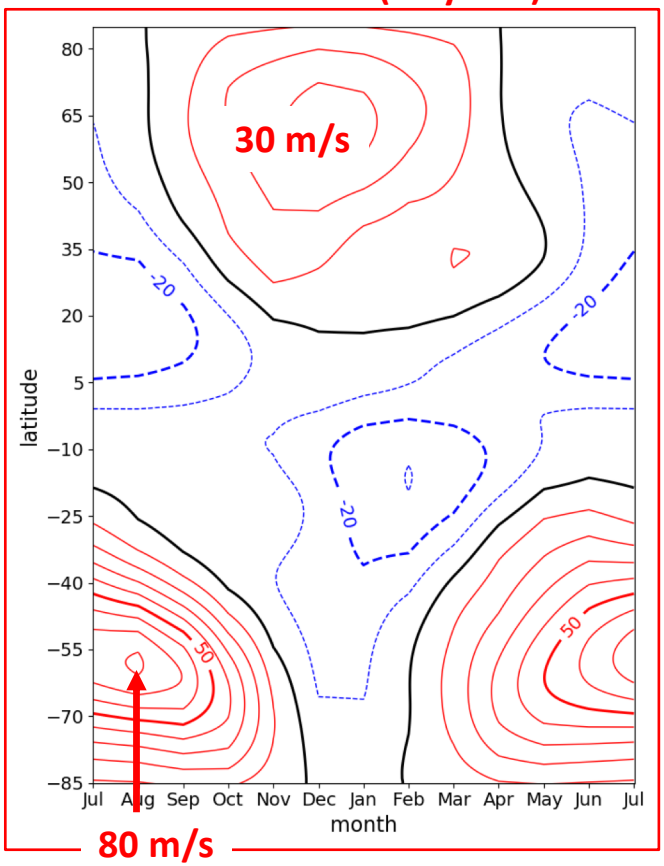


FIGURE 12.48

The history of general circulation modelling

1997 - Canadian 3D-GCM

Previous slide:

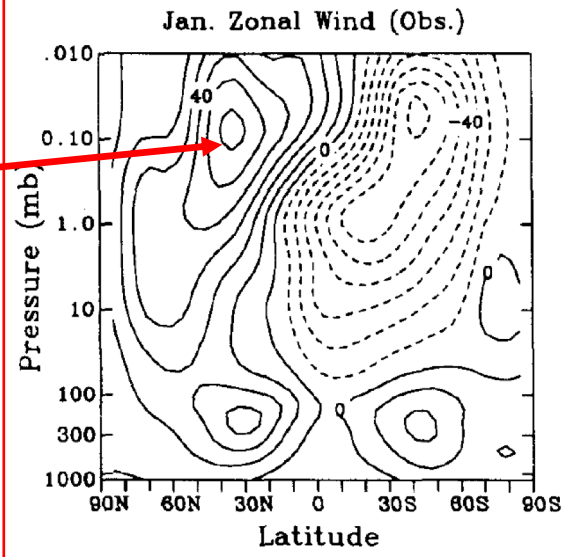
Difference in strength of the stratospheric jets in Southern and Northern Hemispheres is attributed to more wave-activity in the Northern Hemisphere. Why?

Beagley et al. 1997 (p.295):

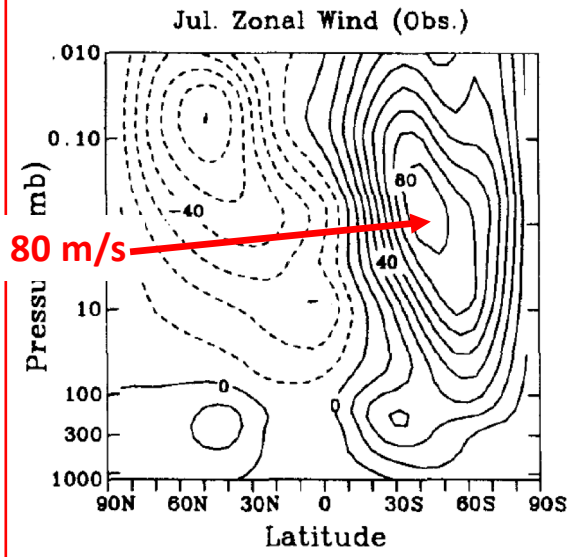
> Simulation of the radiative-dynamical climate of the middle atmosphere requires an accurate representation of three main physical processes: (i) radiation; (ii) meridional circulation, including symmetric (inertial) overturning in the tropics; and (iii) dynamical forcing from the troposphere. An accurate representation of the first two processes should be possible from first principles. (The radiation is normally parametrized, but can be validated against accurate line-by-line calculations.) The dynamical forcing, however, is another matter. Drag exerted by breaking and dissipating planetary waves is a major driver of the stratospheric Brewer-Dobson circulation, and this process should be explicitly resolvable. Large-scale tropical waves

S.R. Beagley , J. de Grandpré , J.N. Koshyk , N.A. McFarlane & T.G. Shepherd, 1997: Radiative-dynamical climatology of the first-generation Canadian middle atmosphere model, **Atmosphere-Ocean, 35:3**, 293-331, DOI: 10.1080/07055900.1997.9649595

Observations 50 m/s



80 m/s



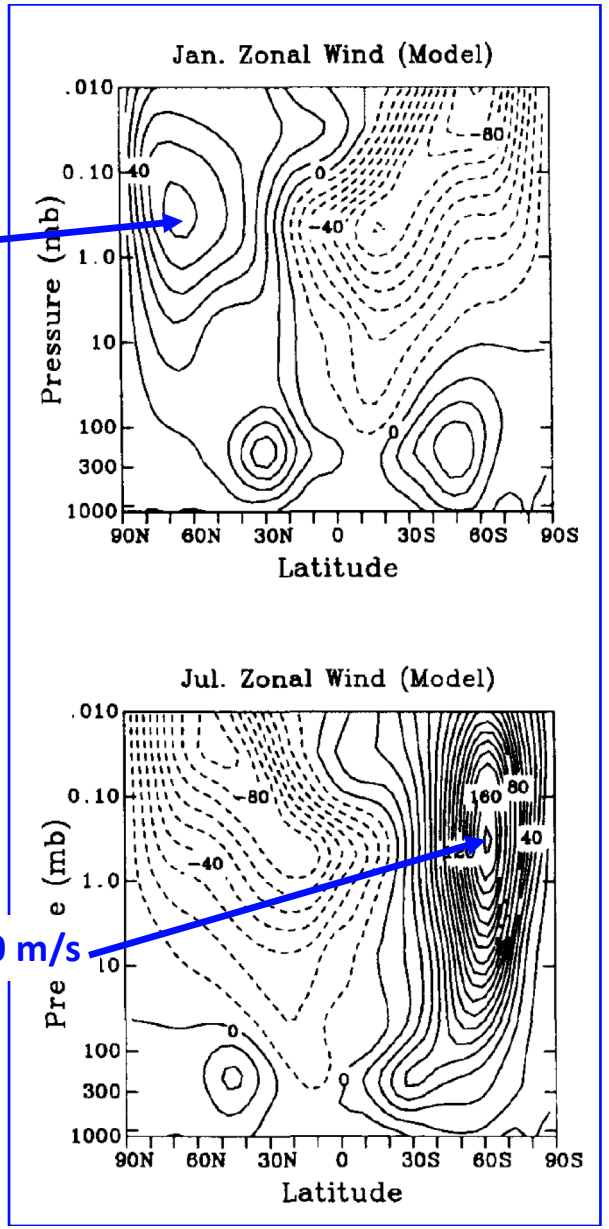
The history of general circulation modelling

1997 - Canadian 3D-GCM

Beagley et al. 1997 (p.302):

Fig. 4. (There is no need for difference fields in this case!) The agreement between the model and the observations can be said to be at best qualitative, though it should be noted that since the zonal wind is roughly the vertical integral of the temperature gradient, it tends to magnify the biases seen in the temperature. The southern hemisphere cold bias in wintertime polar temperatures translates into an enormous westerly bias, with maximum zonal winds in the polar vortex reaching 180 m/s in July — more than a factor of two stronger than observations. This westerly bias is also present in both equinoctal seasons. Although the magnitudes

(p. 302)



S.R. Beagley , J. de Grandpré , J.N. Koshyk , N.A. McFarlane & T.G. Shepherd, 1997: Radiative-dynamical climatology of the first-generation Canadian middle atmosphere model, **Atmosphere-Ocean, 35:3**, 293-331, DOI: 10.1080/07055900.1997.9649595

The history of general circulation modelling

1997 - Canadian 3D-GCM

Beagley et al. 1997 (p.295):

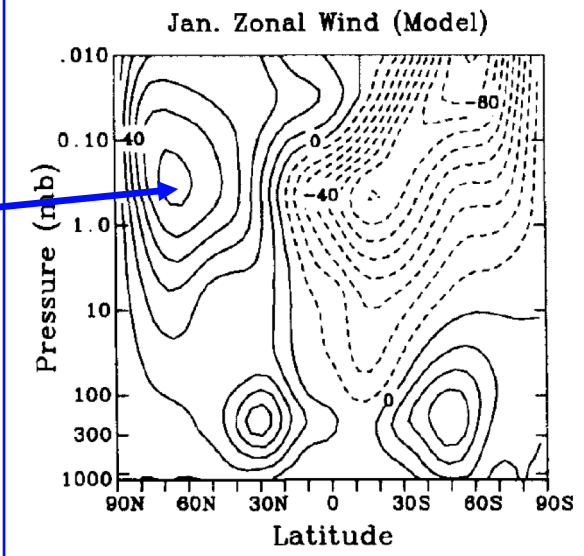
> Simulation of the radiative-dynamical climate of the middle atmosphere requires an accurate representation of three main physical processes: (i) radiation; (ii) meridional circulation, including symmetric (inertial) overturning in the tropics; and (iii) dynamical forcing from the troposphere. An accurate representation of the first two processes should be possible from first principles. (The radiation is normally parametrized, but can be validated against accurate line-by-line calculations.) The dynamical forcing, however, is another matter. Drag exerted by breaking and dissipating planetary waves is a major driver of the stratospheric Brewer-Dobson circulation, and this process should be explicitly resolvable. Large-scale tropical waves

Beagley et al. 1997 (p.304):

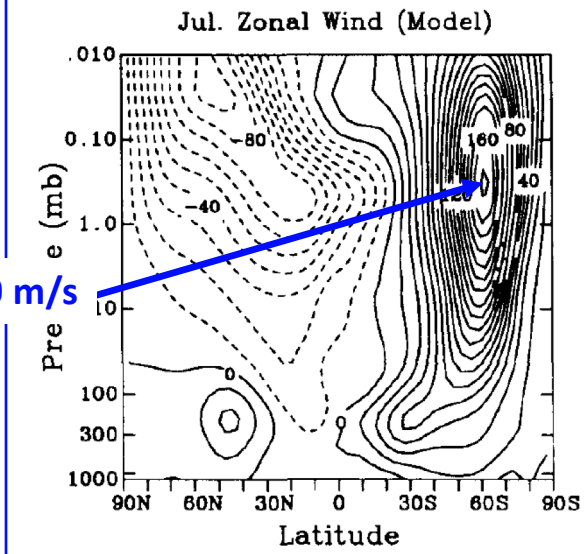
> Since the middle atmosphere is driven significantly by the drag exerted by planetary waves emanating from the troposphere, a prerequisite for a reasonable middle atmosphere climate is the representation of a reasonable tropospheric climate —

"drag exerted by planetary waves"

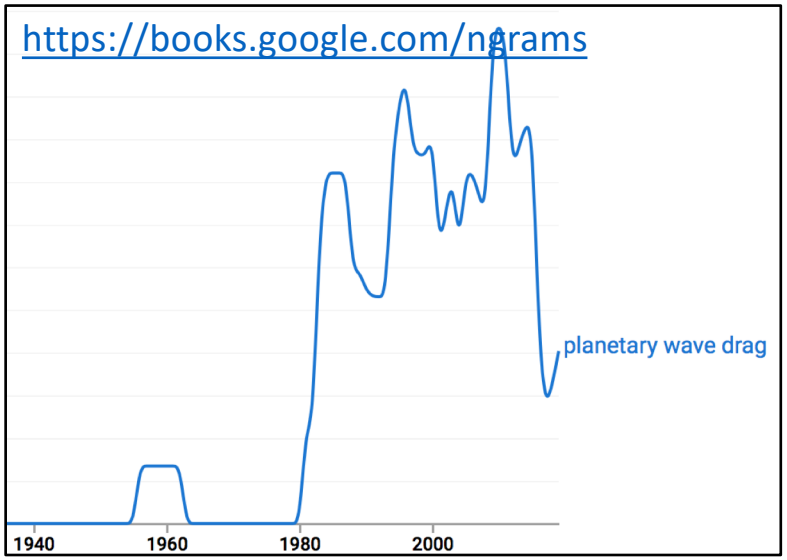
50 m/s

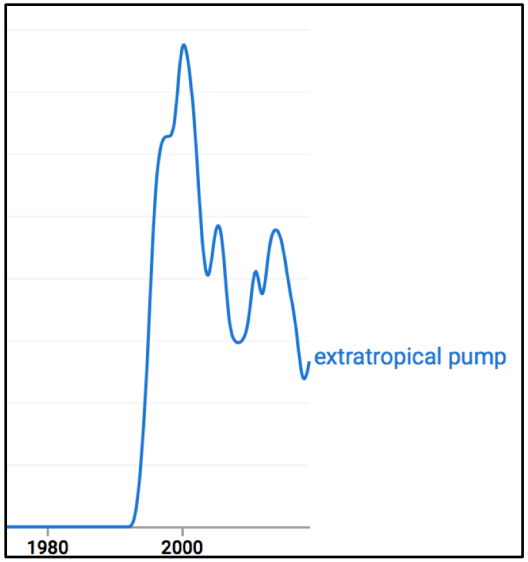


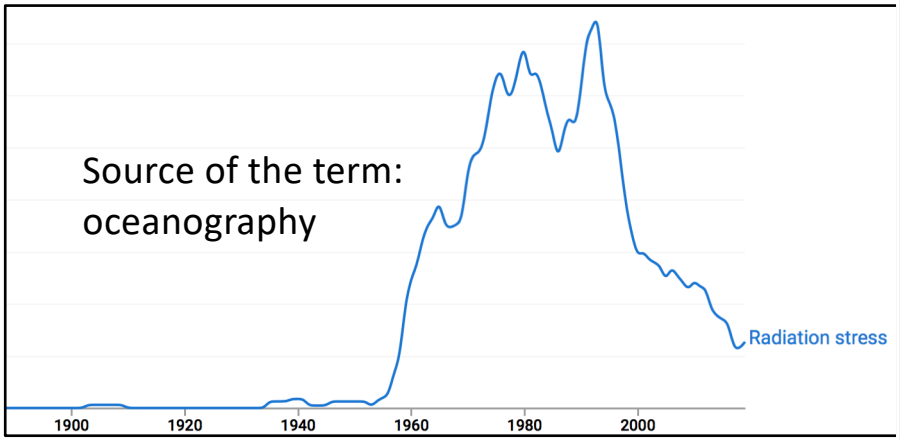
180 m/s



The terms, “**planetary wave radiation stress**”, “**Rossby- wave drag**”, “**Rossby-wave pump**”, “**extratropical pump**” and “**surf zone**” slowly (over the past 40-50 years) enter into the vocabulary of the (atmospheric) scientist

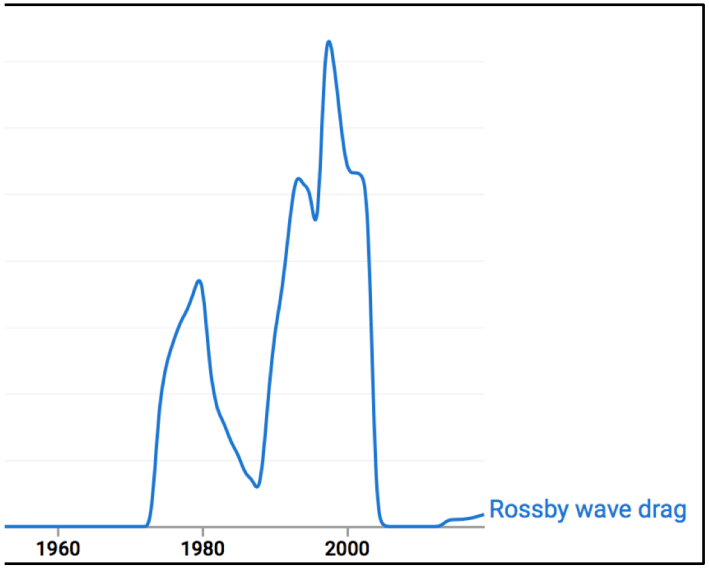








Breaking waves on beaches induce variations in radiation stress, driving longshore currents. The resulting longshore sediment transport shapes the beaches, and may result in beach erosion or accretion.



The terms, “**planetary wave radiation stress**”, “**Rossby- wave drag**”, “**Rossby-wave pump**”, “**extratropical pump**” and “**surf zone**” slowly (over the past 40-50 years) enter into the vocabulary of the atmospheric scientist

Adv. Geosci., 15, 47–56, 2008
www.adv-geosci.net/15/47/2008/
© Author(s) 2008. This work is distributed under
the Creative Commons Attribution 3.0 License.

Advances in Geosciences

Potential-vorticity inversion and the wave-turbulence jigsaw: some recent clarifications

(p. 54)

M. E. McIntyre

Centre for Atmospheric Science at the Department of Applied Mathematics and Theoretical Physics, Wilberforce Road, Cambridge CB3 0WA, UK

The terrestrial winter stratosphere illustrates all these points in great detail. It efficiently mixes PV over vast areas, mostly in the midlatitude Rossby-wave surf zone. The well-observed stratospheric global-scale (Brewer-Dobson) circulation is persistently poleward. It is poleward because of the radiation stress. In a zonally averaged description, the winter stratosphere feels a persistent retrograde force arising from the radiation-stress field of the breaking planetary-scale Rossby waves coming up from below, mostly in zonal wavenumbers 1 and 2. The abovementioned gyroscopic-

The terms, "**planetary wave radiation stress**", "**Rossby- wave drag**", "**Rossby-wave pump**", "**extratropical pump**" and "**surf zone**" slowly (over the past 40 years) enter into the vocabulary of the atmospheric scientist

Chem. Rev. **2003,** *103,* 4509–4531

Large-Scale Atmospheric Dynamics for Atmospheric Chemists

Theodore G. Shepherd*

Department of Physics, University of Toronto, 60 St. George Street, Toronto, M5S 1A7 Canada

From the insight of downward control, much follows.[21] In the extratropical stratosphere, wave drag comes dominantly from planetary-scale Rossby waves which propagate up from the troposphere and dissipate in the stratosphere. Rossby waves always exert a negative wave drag where they dissipate. Thus, Rossby-wave drag drives a poleward circulation within the stratosphere, and mass conservation then dictates descending motion in the extratropics and ascending motion in the tropics, as already inferred from Figure 9. This is the origin of the celebrated *Brewer–Dobson circulation*. To reiterate: the upward

(p. 4520)

Reviews of Geophysics

REVIEW ARTICLE
10.1002/2013RG000448

The Brewer-Dobson circulation

Neal Butchart[1]

[1]Met Office Hadley Centre, Exeter, Devon, UK

Key Points:

a CCM for the year 2000 (contours) and the simulated change in age from 2000 to 2080 (colors). Figure 2a from *Li et al.* [2012]. ©American Geophysical Union. Used with permission.

(p. 162)

4.1. Wave Driving and Gyroscopic Pumping

Qualitatively, the underlying mechanism for the persistent poleward mass flow in the middle and upper winter stratosphere is the "extratropical pump" [*Holton et al.*, 1995] or, perhaps, more appropriately the "Rossby-wave pump" [*Plumb*, 2002] since it is now known that even small wave forcing close to the Equator can be as significant as the extratropical wave driving [*Plumb and Eluszkiewicz*, 1999]. As discussed in *Holton et al.* [1995], the pumping is the nonlocal effect of the wave drag from dissipating upward propagating waves from the troposphere. Drag from the dominant planetary-scale Rossby waves can only be westward, and consequently, the pumping action is one way with the air driven poleward to conserve angular momentum. This, in turn, sucks up air in the Tropics and pushes it down in the middle and high latitudes, at least in the steady state limit. From simple kinematic considerations, the flow has to be upward in

Adv. Geosci., 15, 47–56, 2008
www.adv-geosci.net/15/47/2008/
© Author(s) 2008. This work is distributed under
the Creative Commons Attribution 3.0 License.

Advances in Geosciences

Potential-vorticity inversion and the wave-turbulence jigsaw: some recent clarifications

M. E. McIntyre

Centre for Atmospheric Science at the Department of Applied Mathematics and Theoretical Physics, Wilberforce Road, Cambridge CB3 0WA, UK

(p. 54)

try to turn the air poleward. This amounts to a mechanical pumping action, pushing air poleward and then mostly downward (Haynes et al., 1991) against infrared radiative relaxation. It is almost exactly the same thing as Ekman pumping apart from the different origin of the retrograde force. Both things can reasonably be described as cases of "gyroscopic pumping", flagging the crucial role of the strong Coriolis force. There are well known consequences for the distributions of ozone and other greenhouse gases.

Analogy to “Ekman pumping”

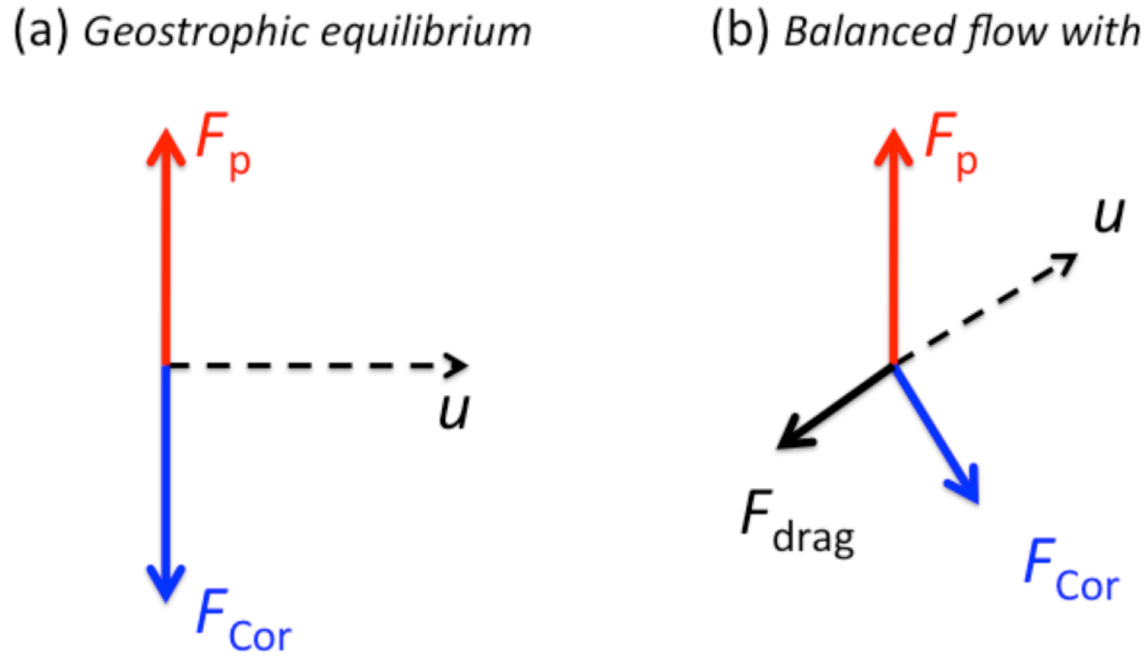


FIGURE 1.65. Force balance for a steady geostrophic mean wind during northern hemisphere winter in the absence of wave drag (a) and with wave drag (b), where the drag force F_{drag}, opposes the wind and the Coriolis force, F_{Cor}, is directed at right angles to the wind direction. The pressure gradient force, F_p, is directed towards the north pole.

The Brewer–Dobson Circulation: Dynamics of the Tropical Upwelling

R. ALAN PLUMB

Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts

JANUSZ ELUSZKIEWICZ

Atmospheric and Environmental Research, Inc., Cambridge, Massachusetts

(p. 869)

The primary driving for the midlatitude stratospheric circulation is wave drag associated with breaking Rossby waves in the winter hemisphere, together with contributions by synoptic waves in the very low stratosphere. Gravity wave drag, the primary forcing in the mesosphere, is thought to be of secondary importance in much of the stratosphere. The dominant contribution in the stratosphere, from large-scale Rossby waves, is concentrated within the "surf zone" (McIntyre and Palmer 1983) of the midlatitude winter hemisphere. The

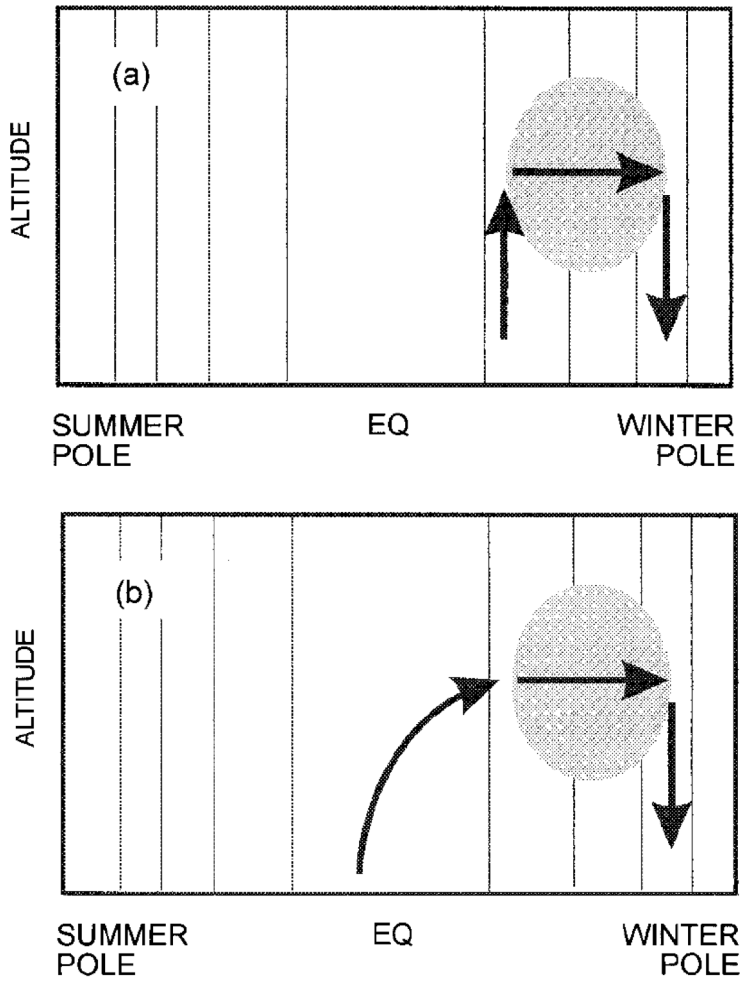
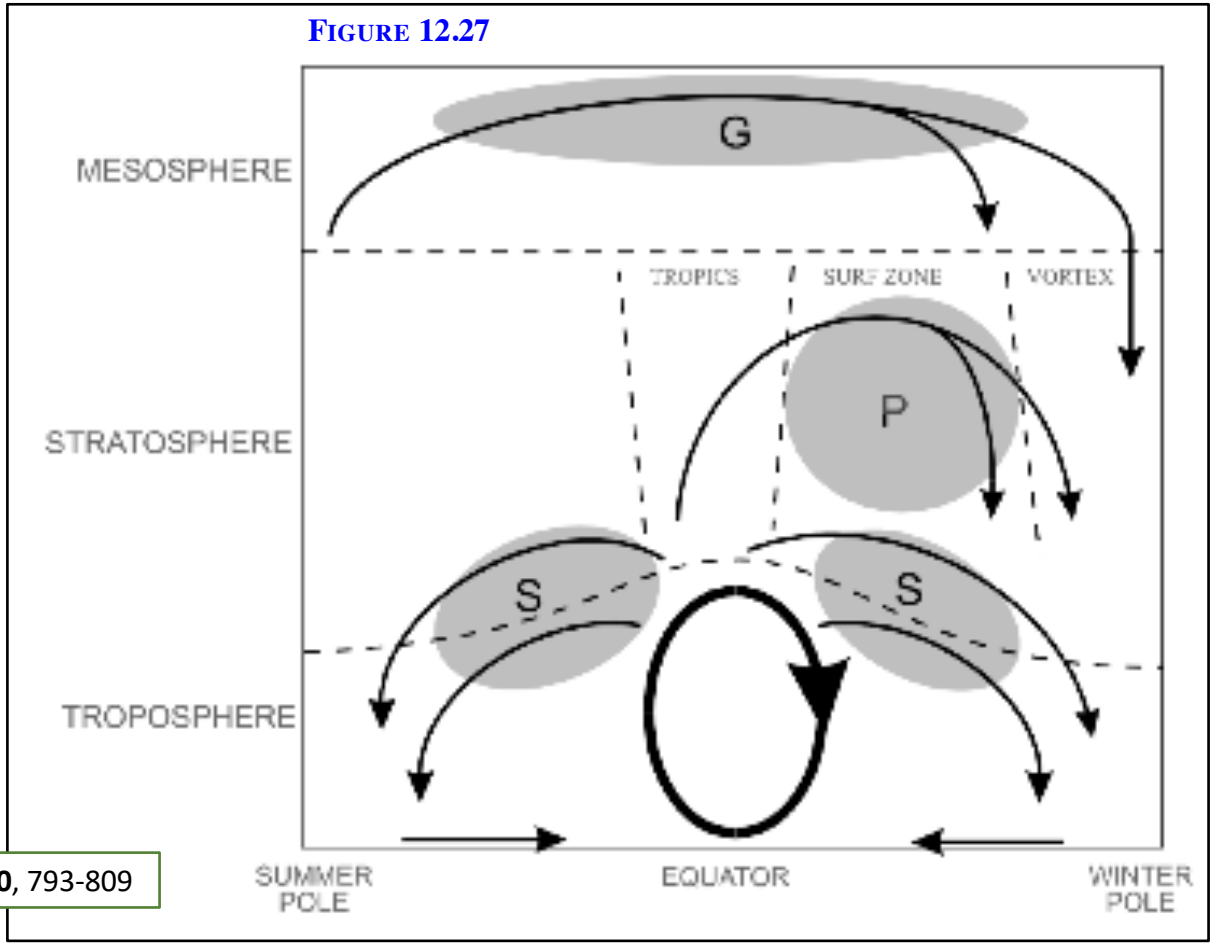


FIG. 1. Schematic of the steady meridional circulation produced by midlatitude wave drag (cf. Haynes et al. 1991). Wave drag is confined to the winter midlatitude surf zone, denoted by the shading. Light lines show contours of angular momentum, assumed here to be dominated by the planetary term. Arrows depict the circulation. See text for discussion of cases a and b.

Schematic picture of the residual mean meridional circulation in the atmosphere due to Alan Plumb

The heavy ellipse indicates the Hadley circulation of the troposphere. The shaded regions (labelled "S", "P", and "G") denote regions of breaking waves (synoptic- and planetary-scale waves, and gravity waves, respectively), responsible for driving branches of the stratospheric and mesospheric circulation. The surf zone is region of mixing of potential vorticity by planetary waves, which acts as a drag force on the mean zonal flow..



Plumb, R.A., 2002: Stratospheric Transport. **J.Meteorol.Soc.Japan, 80**, 793-809

Parametrisation of planetary wave drag in the 2D-GCM

See page 44 of AtmosphericDynamics[2021]Ch12.pdf

Drag from the dominant planetary-scale Rossby waves can only be westward. [16]

Here we adopt this attractive and simple, but admittedly naïve, idea (**sections 12.9-11**) by incorporating a body force into the 2D-GCM as a parametrisation of the effect of planetary waves on zonal mean flow. According to this parametrisation, following Plumb and Eluszkiewicz (1999), the term D in the model zonal wind equation (12.17) is specified by

$$D=D_0 B(\phi) Z(z), \tag{12.42}$$

where

$$\frac{\partial p_s u}{\partial t} = -\frac{\partial p_s uv}{\partial y} - \frac{\partial}{\partial \eta}\left(p_s u \frac{d\eta}{dt} \right) + \left(f + \frac{u \tan\phi}{a} \right) p_s v + p_s D + p_s F_x \; ; \tag{12.17}$$

$$B(\phi)=\sin(2|\phi|), \tag{12.43}$$

which means that wave drag is a maximum at 45° latitude. Furthermore

$$Z(z) = \sin\left[\pi \left(\frac{z - z_0}{z_1 - z_0} \right) \right] \text{ if } z_0 < z < z_1 \; ; \tag{12.44a}$$

$$Z(z) = 0 \text{ if } z \le z_0 \text{ or } z \ge z_1 \; . \tag{12.44b}$$

A refinement to the parametrisation of planetary wave drag

See page 45 of AtmosphericDynamics[2021]Ch12.pdf

This parametrisation of planetary wave drag has been adopted by many others in simplified two-dimensional models of the atmospheric General Circulation, with variations in the chosen values of D_0, z_0, z_1 and the function $B(\phi)$. Here we add an important refinement of this scheme, which takes into account the **presence of a wave guide**. This refinement is based on the theoretical idea, due to Charney and Drazin (**section 11.3**), that planetary waves do not propagate through regions with zonal mean westward winds, where $[u]<0$. This implies that wave drag is non-existent at all levels above a layer with a zonal mean westward wind. Another way of formulating this theoretical idea is that planetary waves can propagate only in a wave guide, which is characterised by a positive poleward PV-gradient. In an atmosphere in thermal wind balance a positive poleward PV-gradient is associated with westerly flow ($u>0$). This effect is incorporated by letting the value of the parameter D_0 depend on u, as follows.

$D_0=0$ if $u<0$ at any lower level in the atmosphere;
$D_0<0$ if $u\geq 0$ at all lower levels. (12.45)

After a series of sensitivity tests ("tuning" the model), we find that $D_0=-10^{-4}$ m s^{-2}=8.64 m s^{-1} day^{-1}, if $u\geq 0$ at all lower levels, produces a very realistic simulation including the appearance of a cold tropical layer at about 150 hPa (**figure 12.22**) and a spring zonal wind reversal (**figure 12.25**).

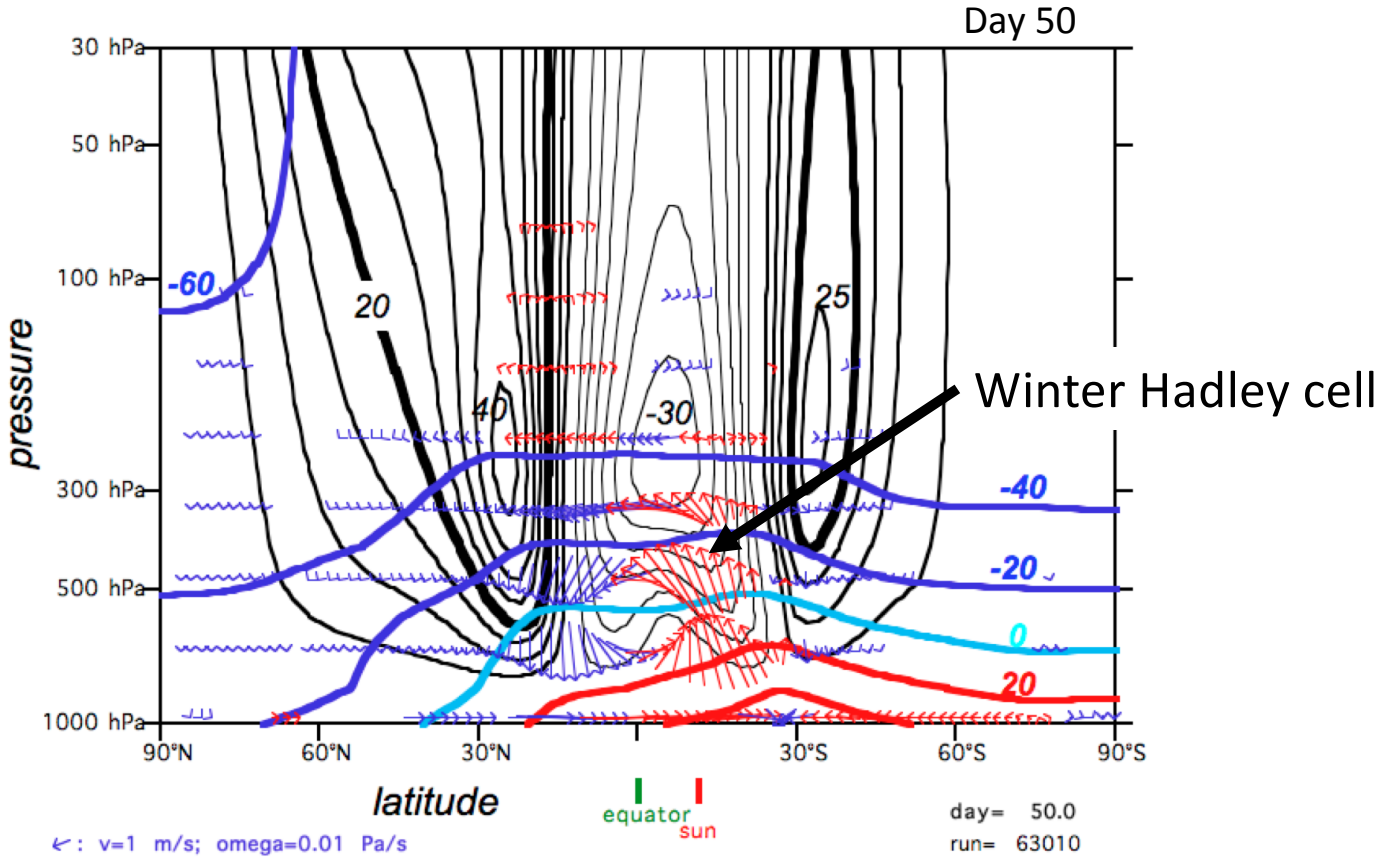
Lecture 3:

Model state after 50 days with water cycle

50 days after initialization on 1 January with an isothermal (290 K) atmosphere at rest

Tropical cold layer is missing!

Zonal wind distribution looks unrealistic: one jet in each hemisphere…



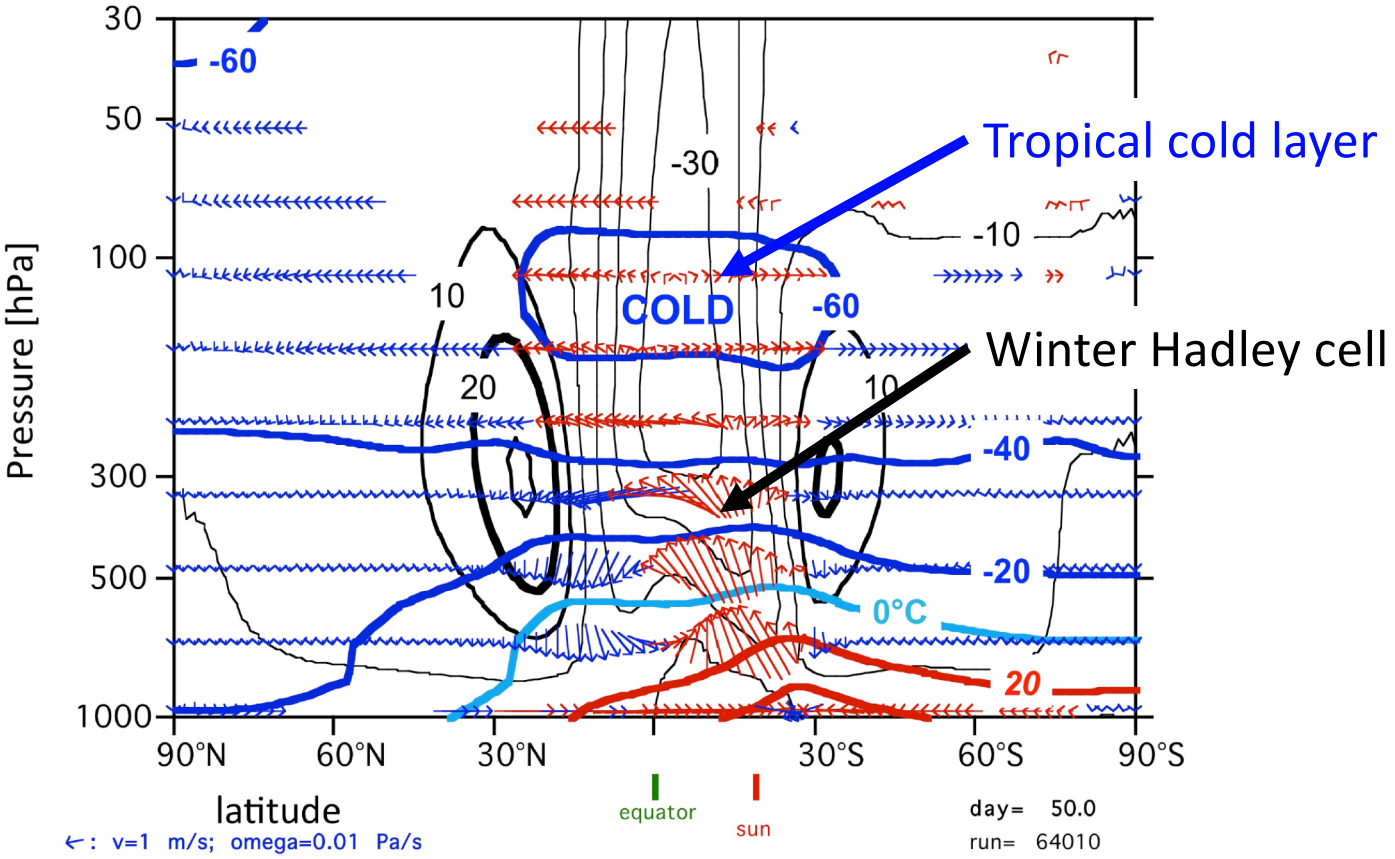
T [°C] and u [m s^{-1}]

Model state after 50 days with water cycle *and* wave drag

50 days after initialization on 1 January with an isothermal (290 K) atmosphere at rest

Tropical cold layer is there !

Zonal wind distribution looks more realistic: one subtropical jet in each hemisphere…



Model state after 530 days with water cycle *and* wave drag

Stippled contours: wave drag

in units of 10^{-6} m s^{-2}

Zonal wind is westward in the summer stratosphere

Zonal wind is eastward in the winter stratosphere

Subtropical jet is separated from the polar stratospheric jet

Upward bilge of the 370 K isentrope

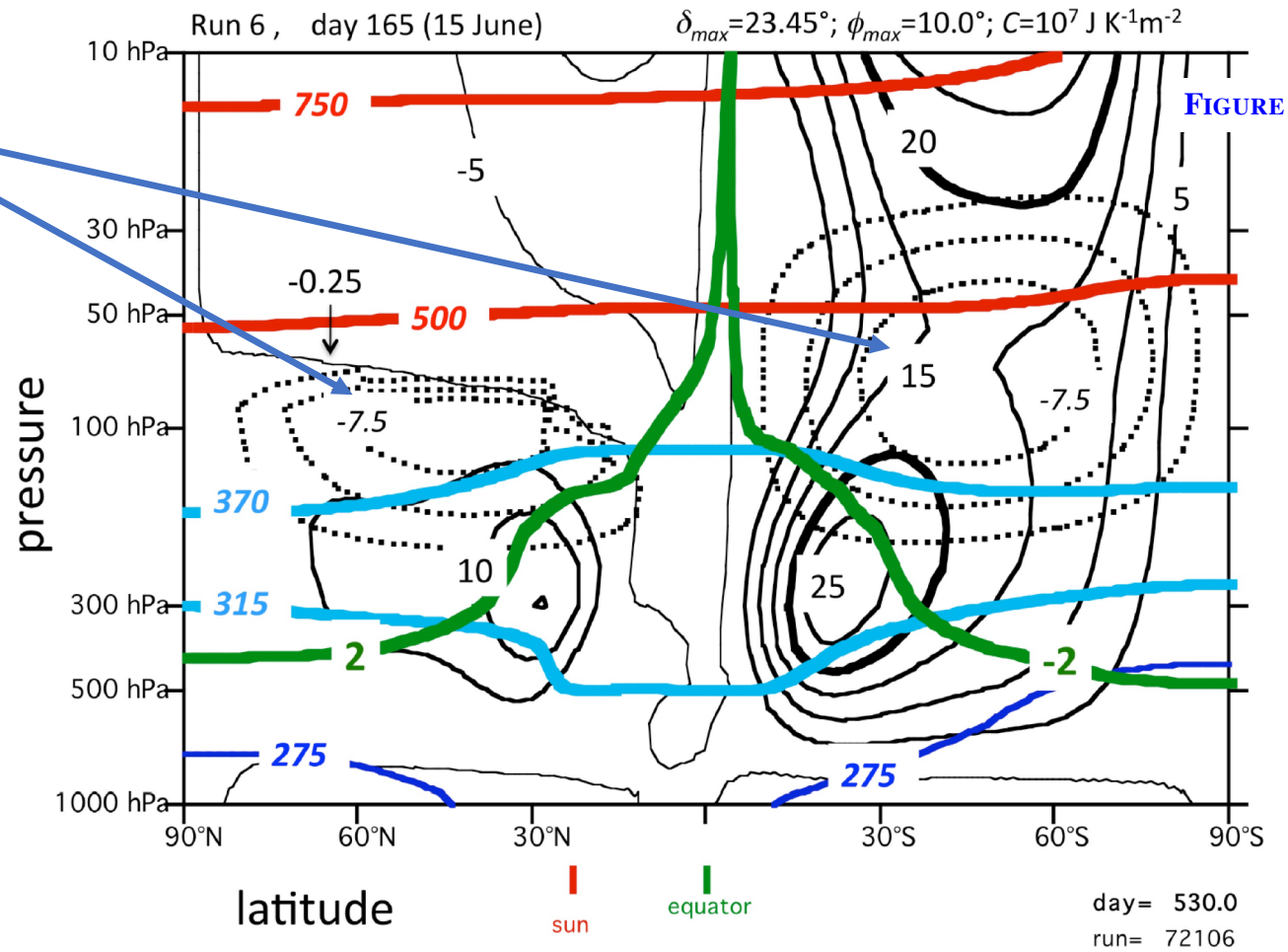


FIGURE 12.26

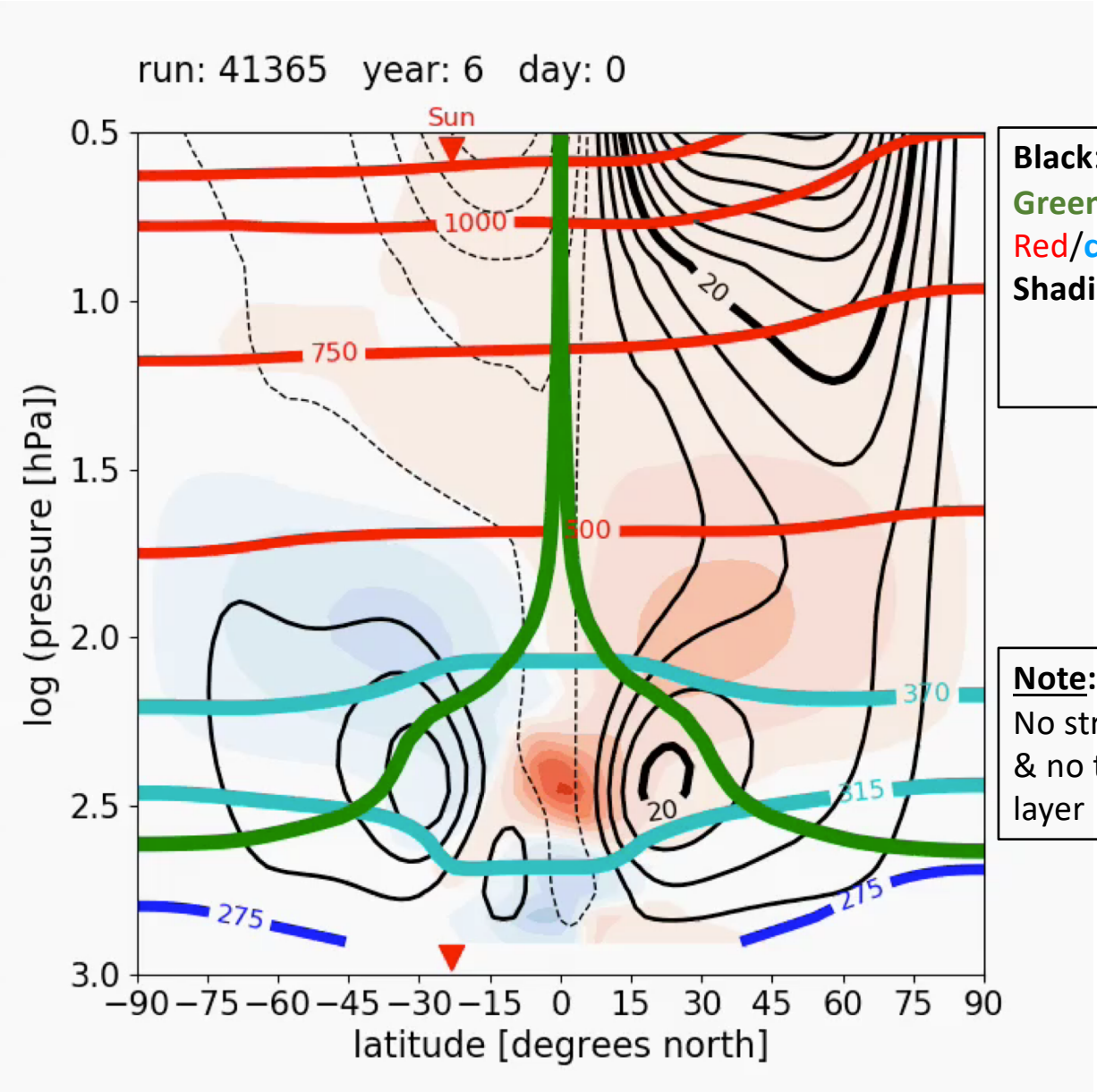
Animation

(year 6)

Run 4a

Water cycle: yes
Ozone: yes
Wave drag: yes

Latitude of the ITCZ between 10°S and 10°N



Black: [*u*] (interval=5 m/s)
Green: dynamical tropopause
Red/**cyan**/**blue**: isentropes
Shading: [*v*]
red: northward
blue: southward

Note:
No stratospheric wind- reversals & no tropical tropopause cold layer

Conclusions and questions left after lecture 4

As far is possible, the 2D-GCM reproduces all the important features of the dynamics of the zonal mean general circulation only if planetary wave drag is imposed!

Is this realistic?

Do waves and eddies act retard the zonal mean westerly flow?

Why and how does this work?

Next:

Lecture by Michiel van den Broeke:

Wednesday, 9 June, 2021, online

Lecture 5, BLT&M-2: 11 June, 10:00-11:45, BBG 061

What is planetary wave drag, really?

The eight ingredients of wave/eddy – zonal-mean flow interaction.

Understanding the General Circulation with PV-inversion.

Lecture 6, BLT&M-2: 25 June, 10:00-11:45, BBG 061

A recap of the first 5 lectures and conclusions remarks.

Feedback on what-if questions.