Towards understanding the climate of Venus from the perspective of an Earthling

- A modeling approach -

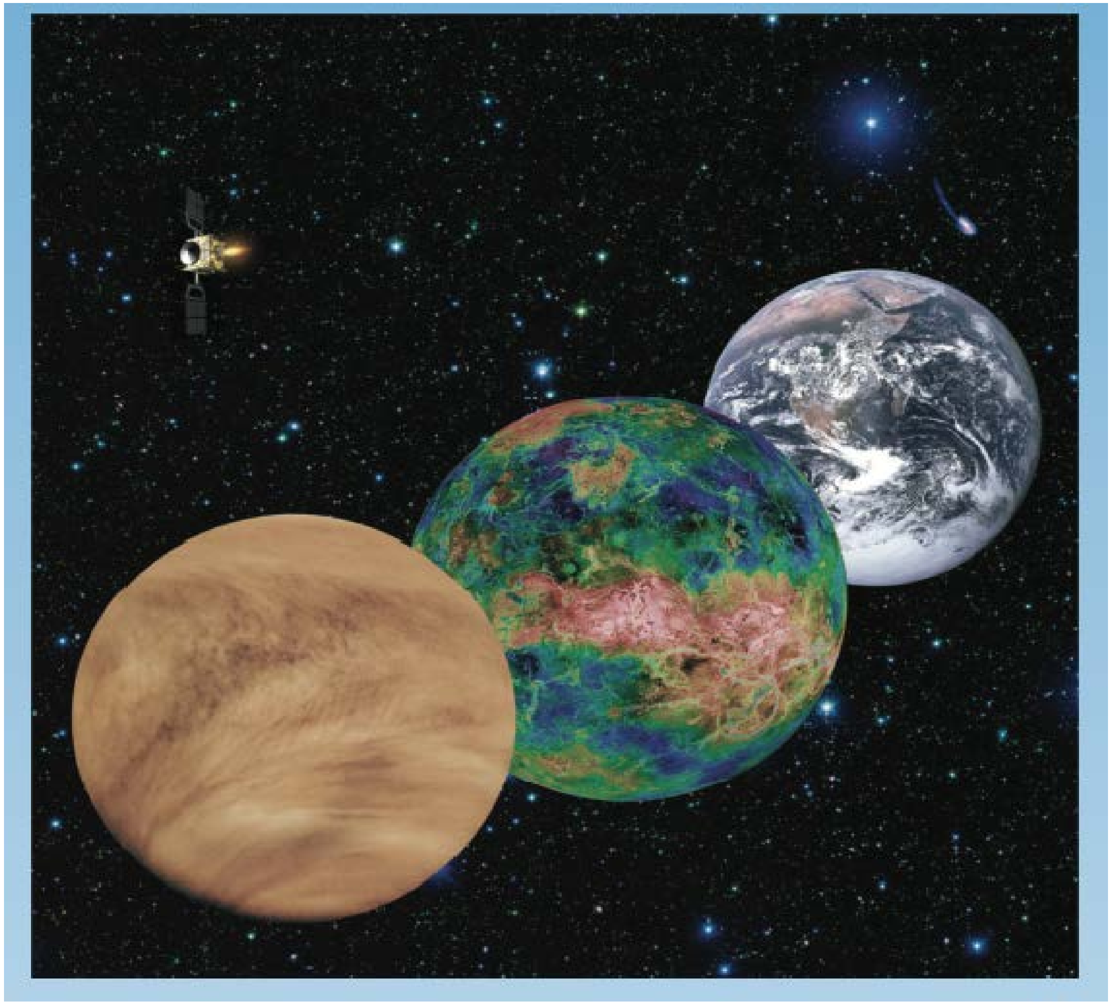
Lennart Bengtsson

ISSI, Bern

University of Reading and Uppsala

Member of the Royal Swedish Academy of Sciences

Application of Terrestrial Models to Our Sister Planet



Credits to the ISSI Venus Working Group

- R-M Bonner, ISSI, France
- D Grinspoon, US
- S Koumoutsaris, ISSI, UK
- S Lebonnois, France
- S Lewis, UK
- S Limaye, US
- P Read UK
- H Schmidt, Germany
- H Svedhem, ESA

D Titov*, ESA

M Yamamoto, Japan

and ISSI staff

* Special thanks to Dima Titov for some impressive figures

How can modeling contribute towards a better understanding of the climate of Venus?

-
- Introduction and background/ my motivation
-
- Modeling the Earth atmosphere and climate system
- Modeling the Venus atmosphere – fundamental challenges in observations and theory
- Modeling the Venus atmosphere – historical overview
- How far have we come in modeling and understanding?
- Concluding remarks - comments on a future strategy

Scientific rationale (from 2007) from my presentation to the ISSU Science Board

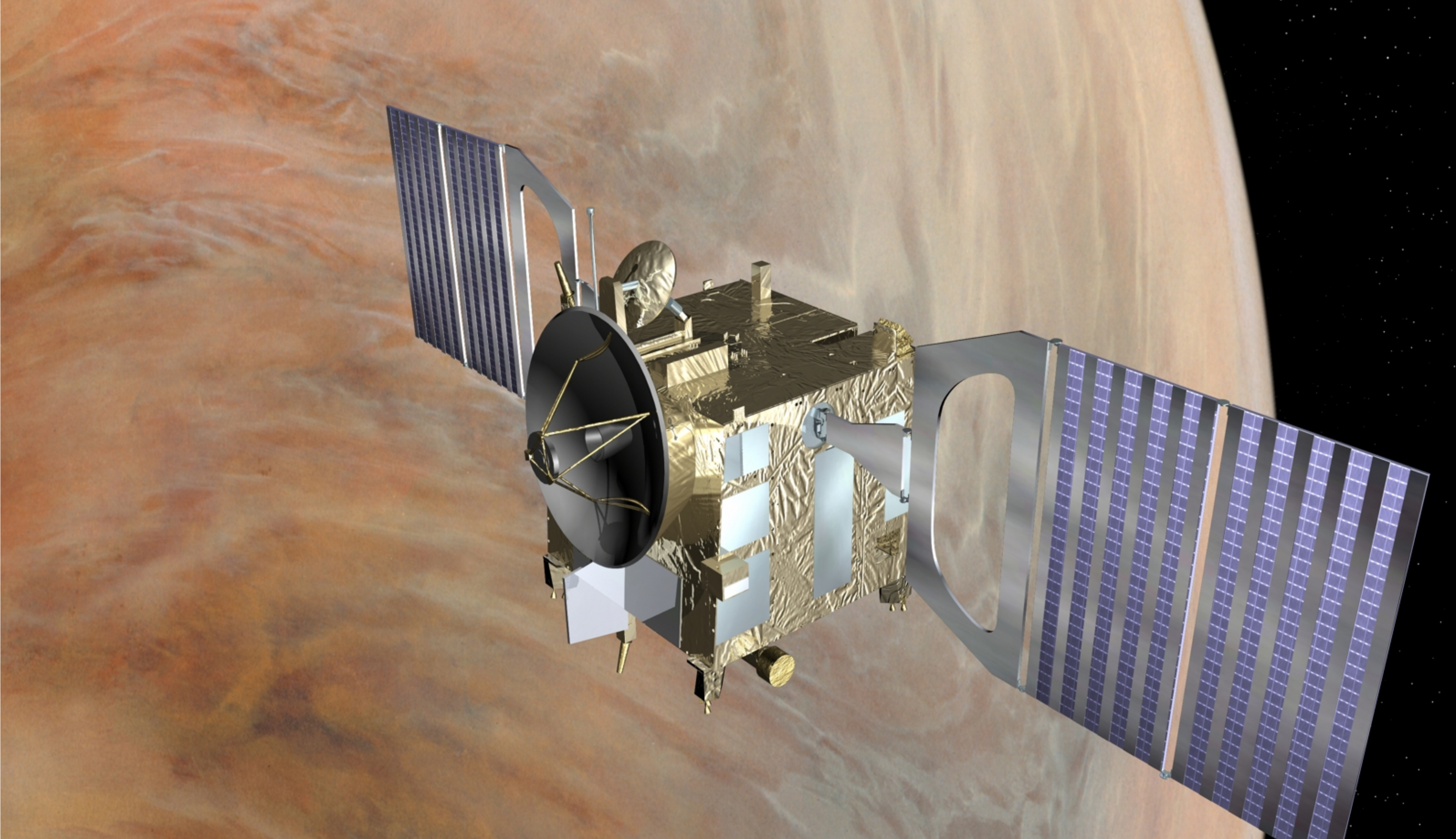
- We need to better understand the atmosphere of Venus to demonstrate the generalities of models of planetary atmospheres presently mainly tested for the Earth. New observations from ESA Venus Express and soon from the Planet-C by Japan is setting a suitable time schedule.

- Venus is here a primary candidate as there are both similarities and considerable differences to the Earth.

- We may be able to obtain further insight in the evolution of the Venus atmosphere. Has there been a greenhouse run-away effect on Venus?

- We may obtain further insight into the long-term future of the Earth if being exposed to massive greenhouse gases in the future.

Here comes Venus Express



Planetary parameters for Venus and Earth

Properties	**Venus**	**Earth**
Distance to sun	0.72 AU	1 AU
Solar constant	2.622 W/m^2	1.364 W/m^2
Albedo	0.76	0.29
Eq. Temperature	- 41° C	- 18° C
Surf. Temperature	+ 460° C	+ 15° C
Atmos. mass	92	1
CO2 (%)	96.5	0.0397
GHG Forcing	157 - 163 W/m^2	16000 W/m^2
GHG Temp.	+33 – +34 K	+ 500 K
Rotation rate (Eq)	1.8 m/s	463 m/s
Coriolis force (45)	$4x10^{-7}$ s^{-1}	10^{-4} s^{-1}

Modeling the Earth atmosphere and climate system- ongoing development

- First experiments started in the 1950s (US)
- *Jules Charney, Norman Phillips, Syukuro Manabe*

- Related to modeling work in numerical weather prediction

- Driven by super-computer development and space observations

- Global weather prediction at high resolution including tropical cyclones

- Climate simulations with coupled ocean/atmosphere/land models including vegetation and bio/geo/chemical processes

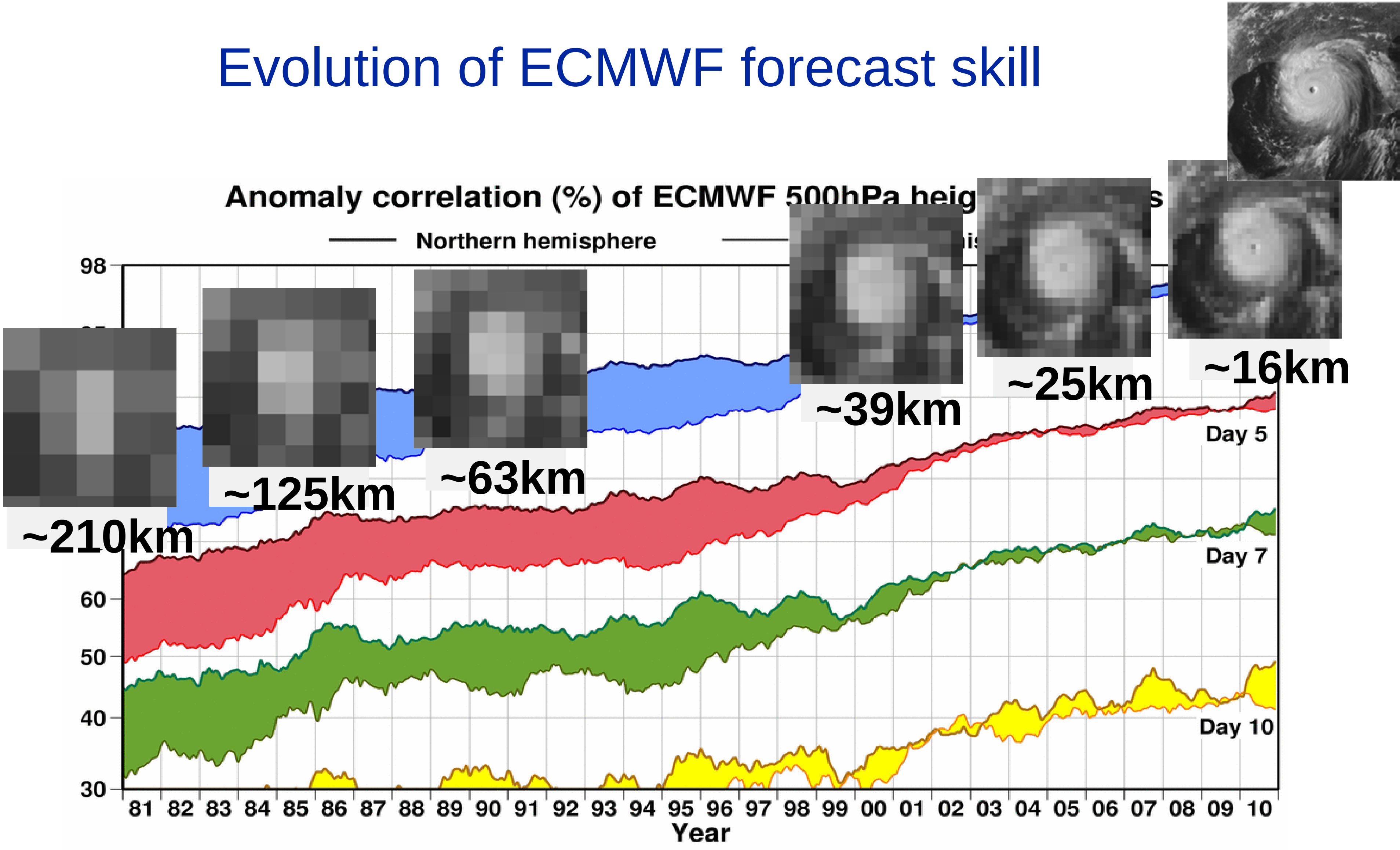
The climate and weather observing system

Credit: ECMWF

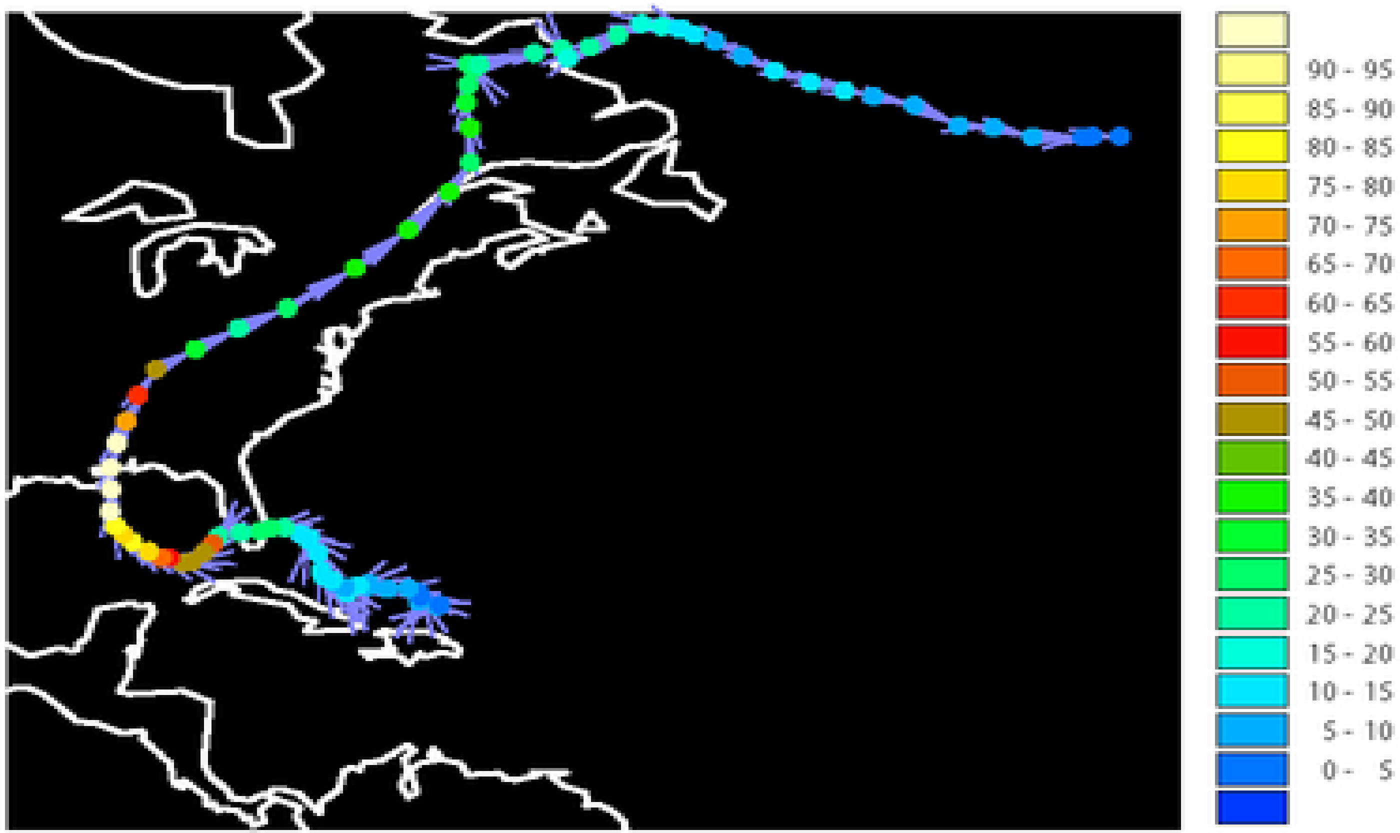
Development of spectral transform models at ECMWF 1983-2012

Triangular truncation	Number of vertical levels	Pressure at top most level in hPa	Grid distance (approx) in km
T63	17	25	325
T106	19	10	190
T213	31	10	95
T319	60	0.1	65
T 511	60	0.1	40
T 799	91	0.01	25
T 1279	91	0.01 (80 km)	16 **(ca 800M var.)**

Evolution of ECMWF forecast skill



Hurricane Katrina August 2005
ECMWF operational analyses, 850 hPa vorticity

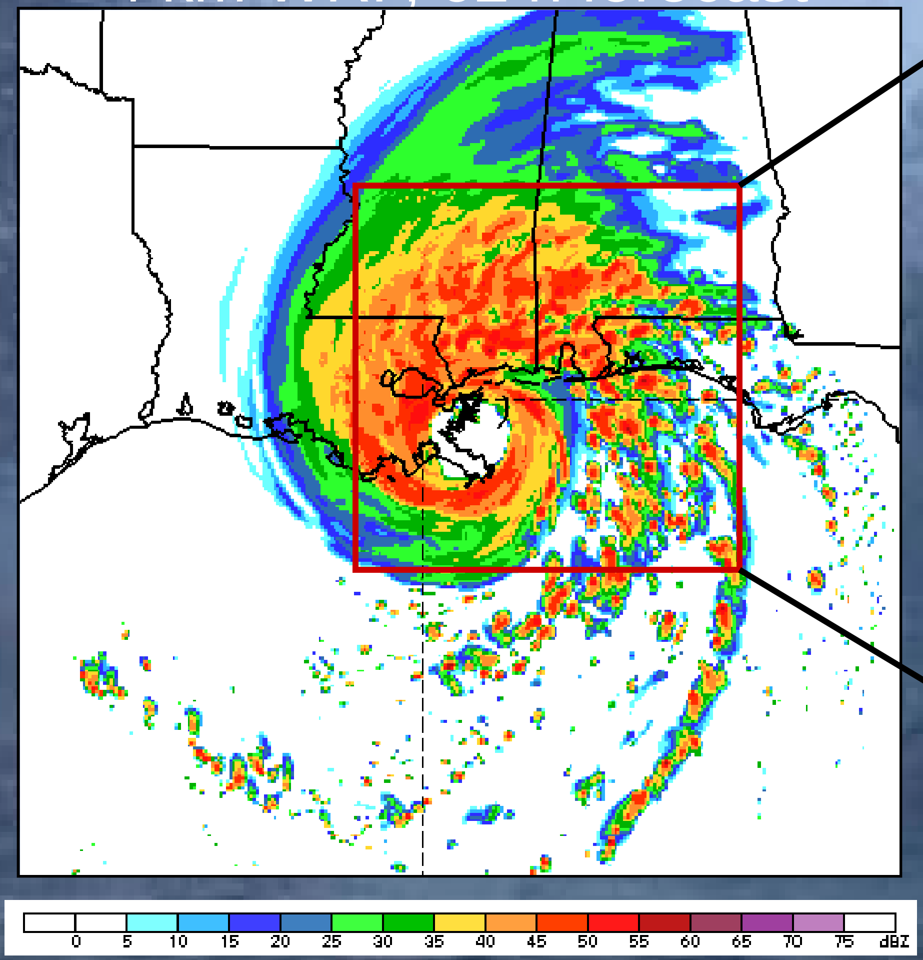


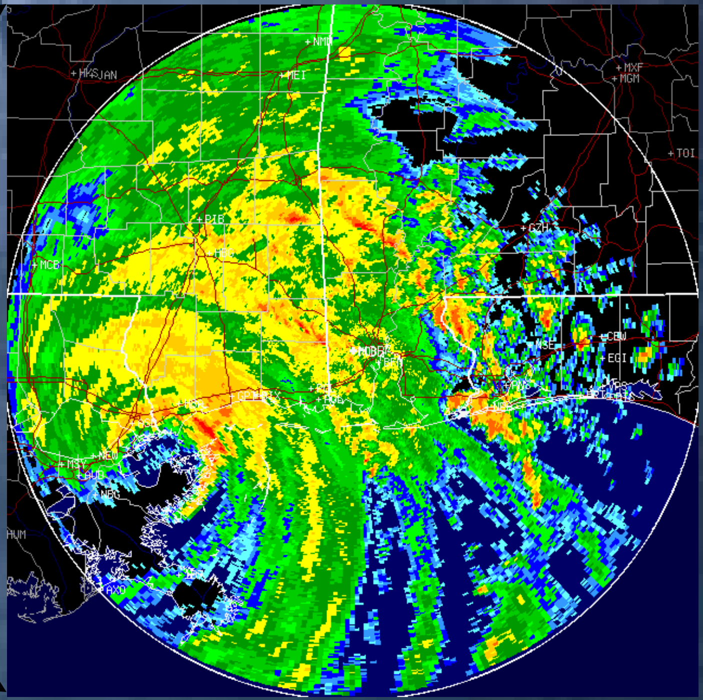
(c)

Hurricane Katrina Intensity at Landfall

29 Aug 2005 14 Z

4 km WRF, 62 h forecast





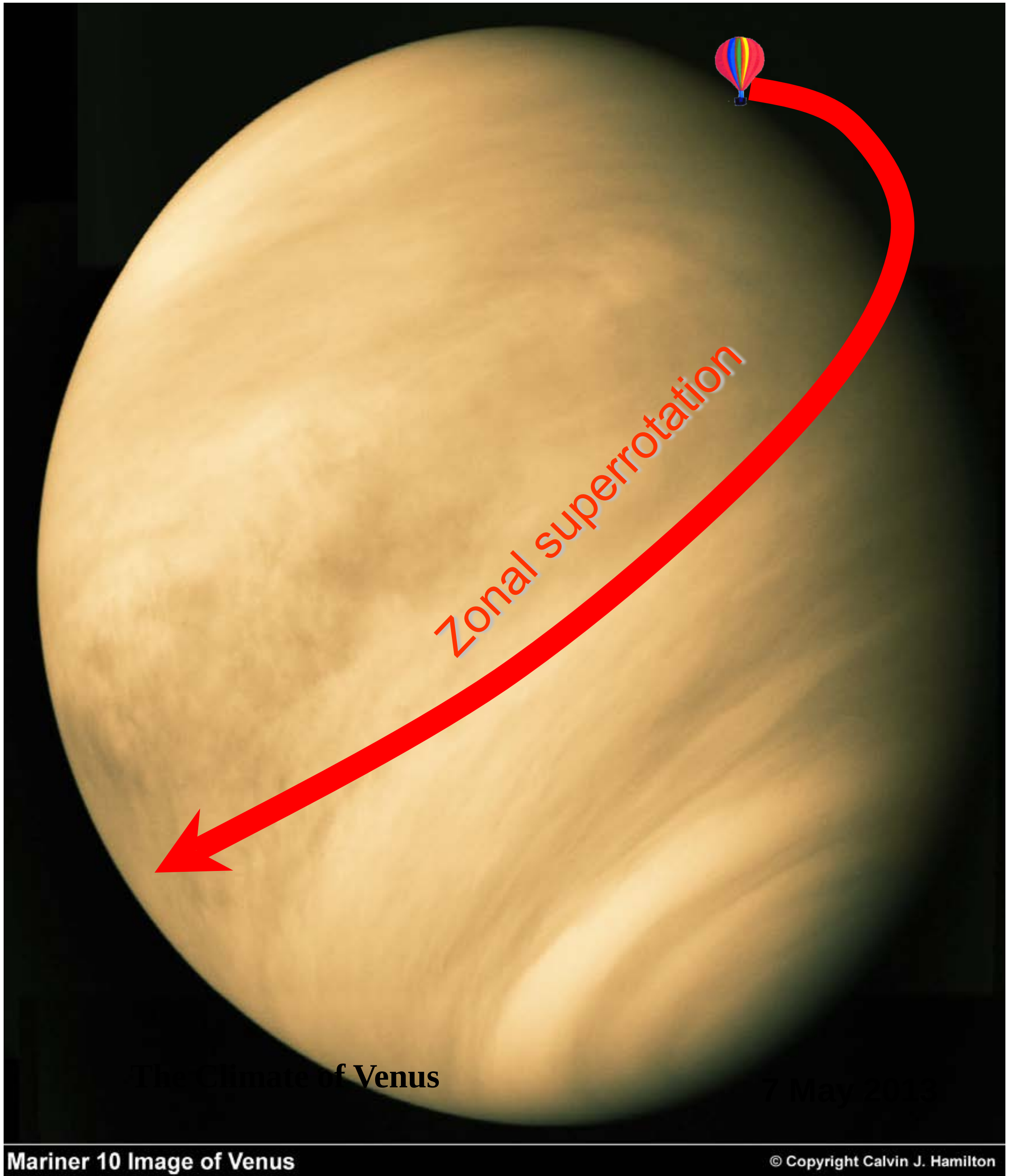
Mobile Radar

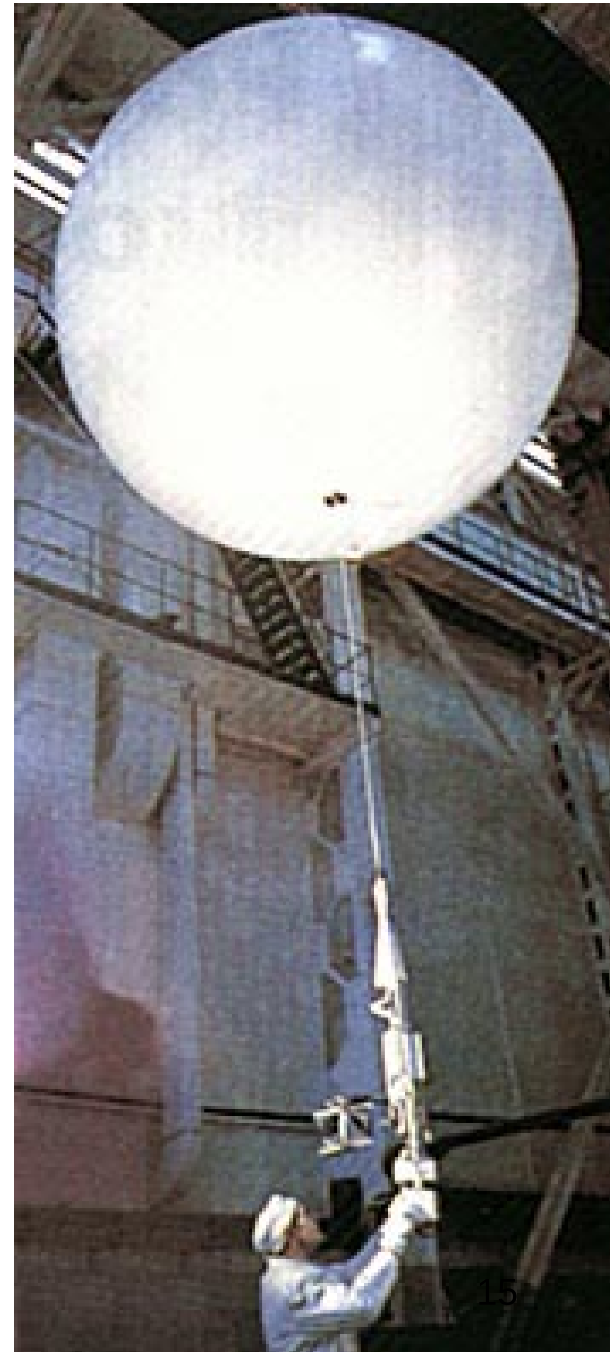
Courtesy of P. Fox (NCAR)

Modeling the Venus atmosphere – fundamental challenges in observations and theory

- Incomplete understanding of atmospheric composition
- The very slow rotation with insignificant balance between mass field and wind field
- Physical processes must be parameterized that requires detailed 3-dimensional measurements with high resolution in time.
- Computationally very demanding high resolution as well as very long integrations
- What can we learn from the Earth's system models?

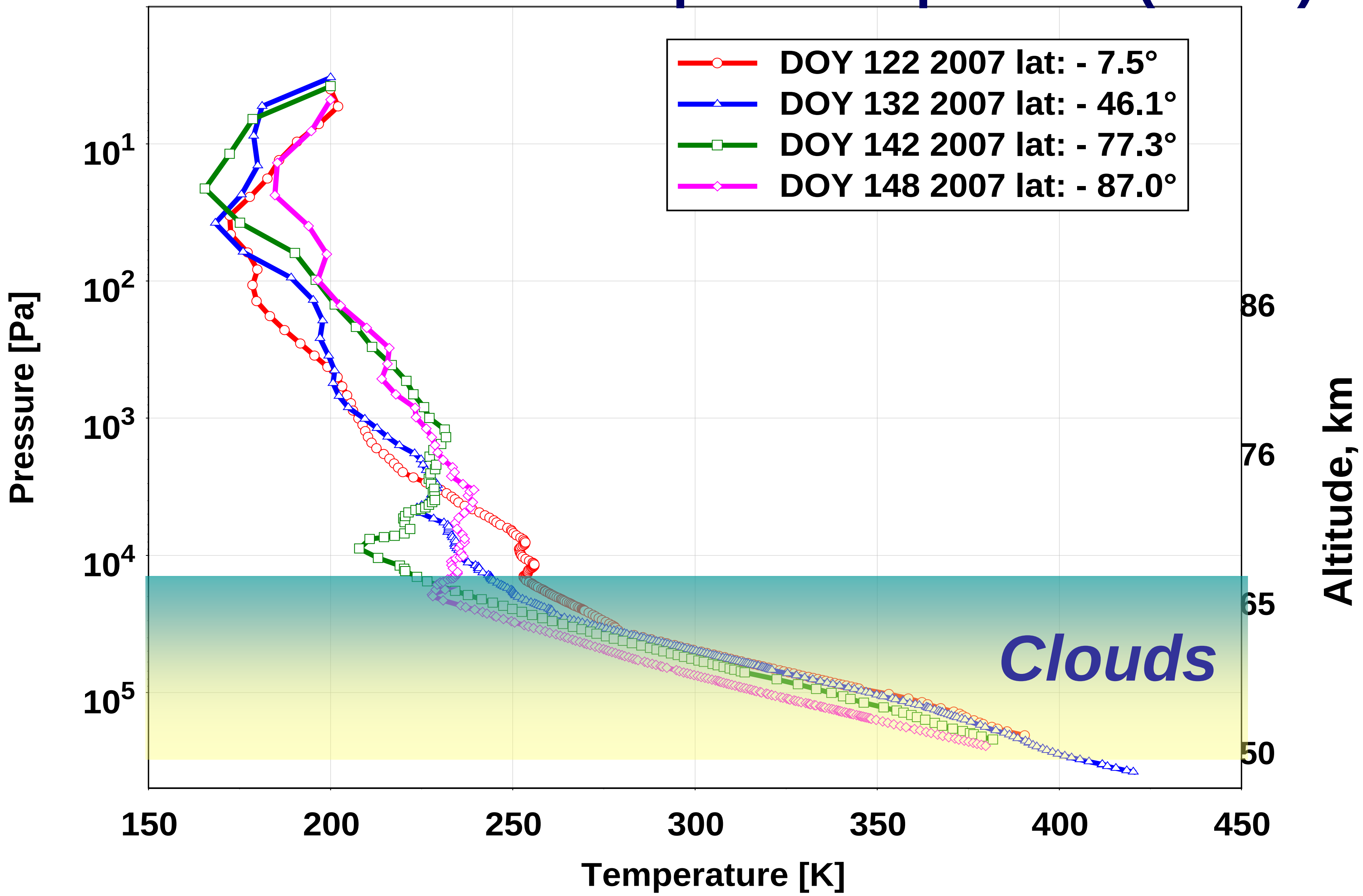
VEGA Balloons (1984)



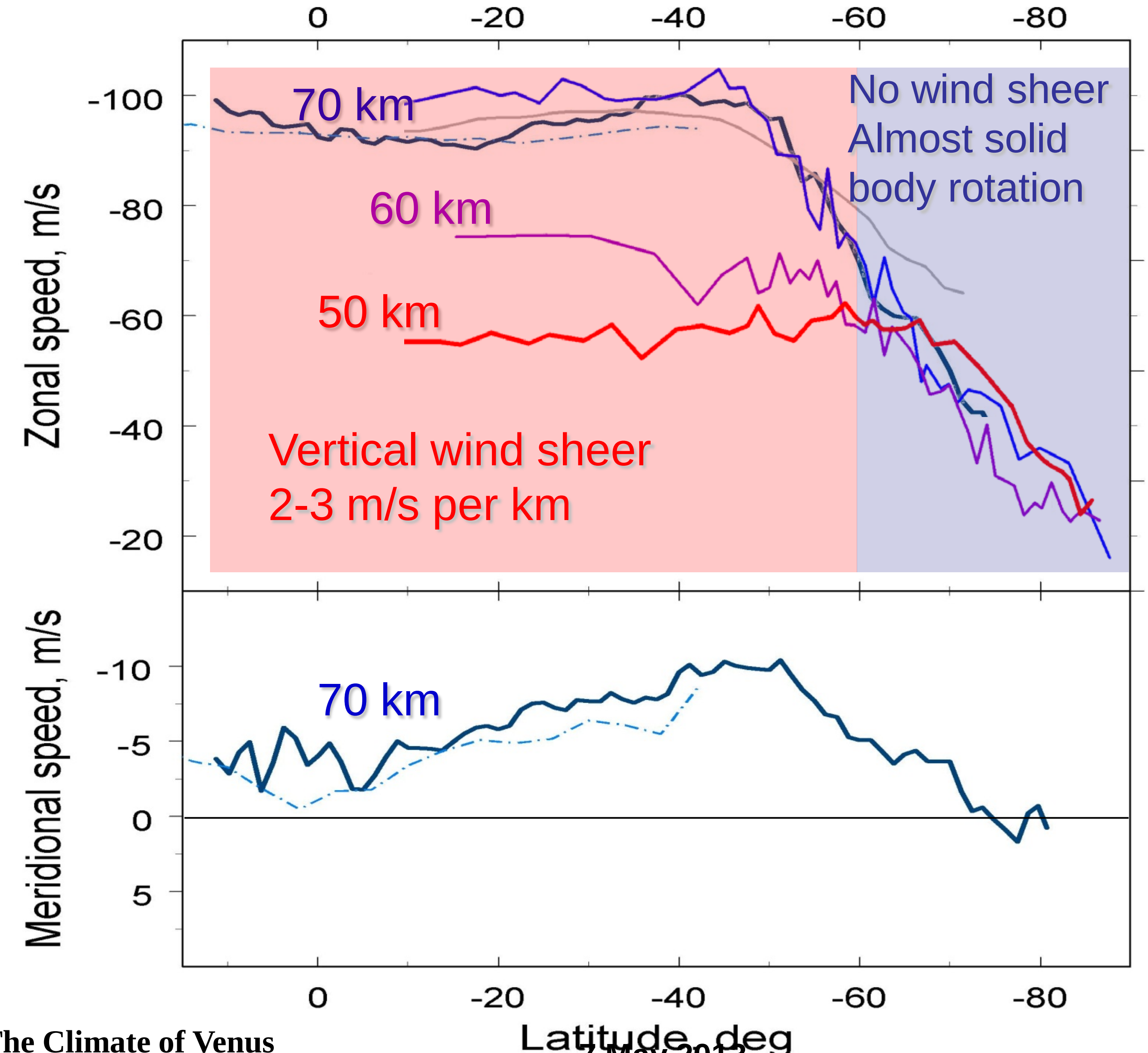


Mesospheric sounding in solar occultation

Radio-occultation temperature profiles (VeRa)



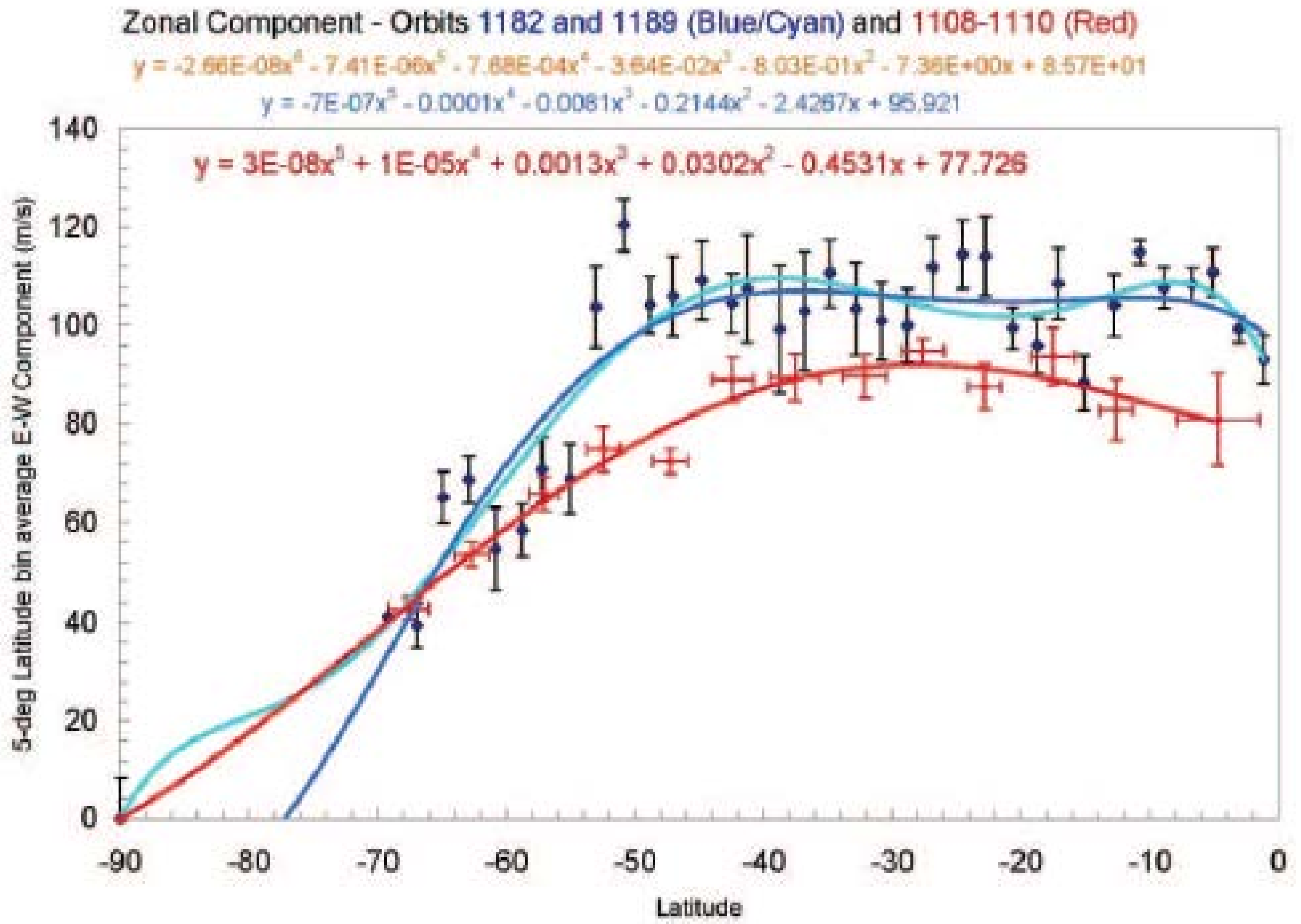
Winds at the cloud level



Khatuntsev et al., Sanches-Lavega et al.

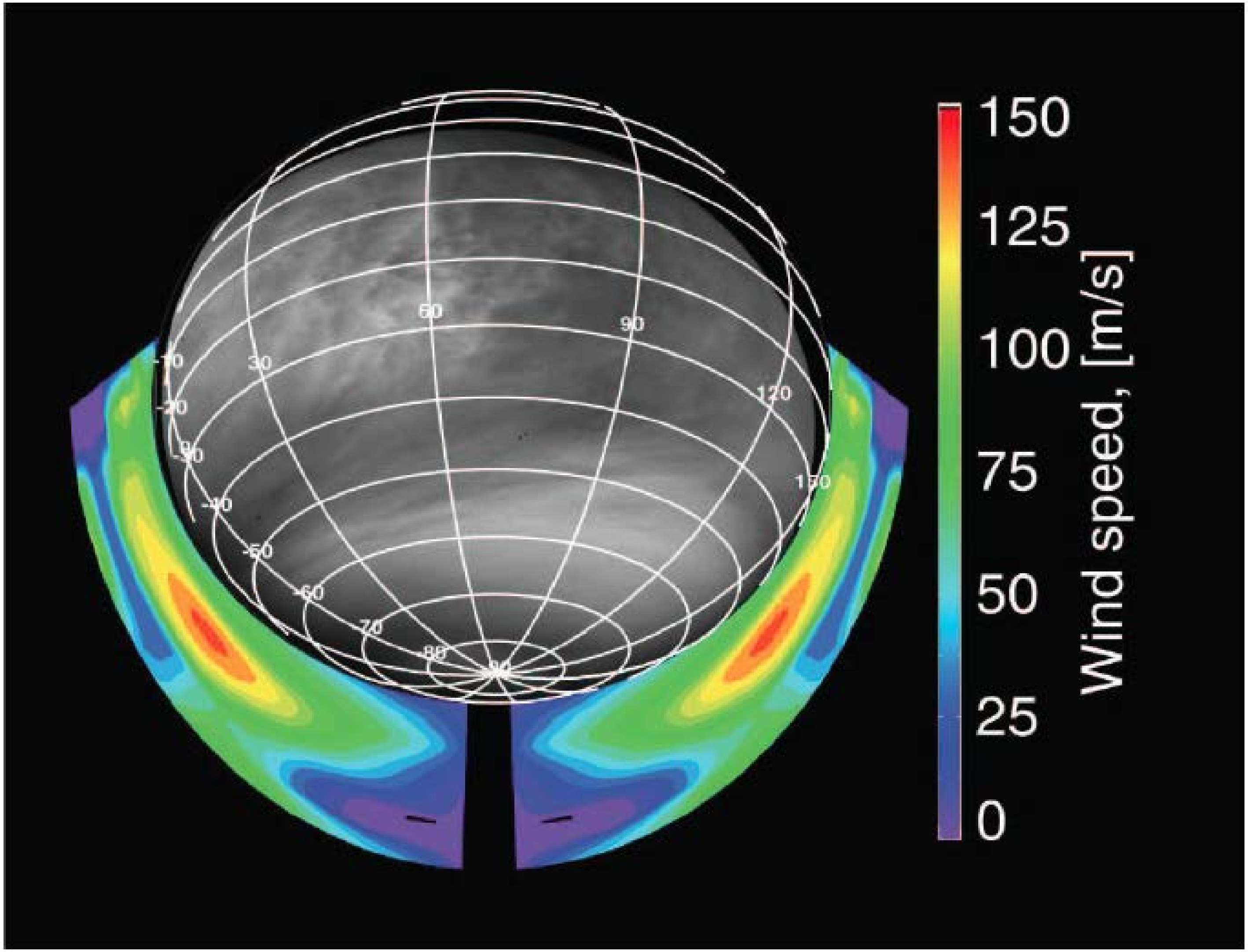
Digital cloud tracking from VMC data

Credit: *Limaye*, Uni Wisconsin

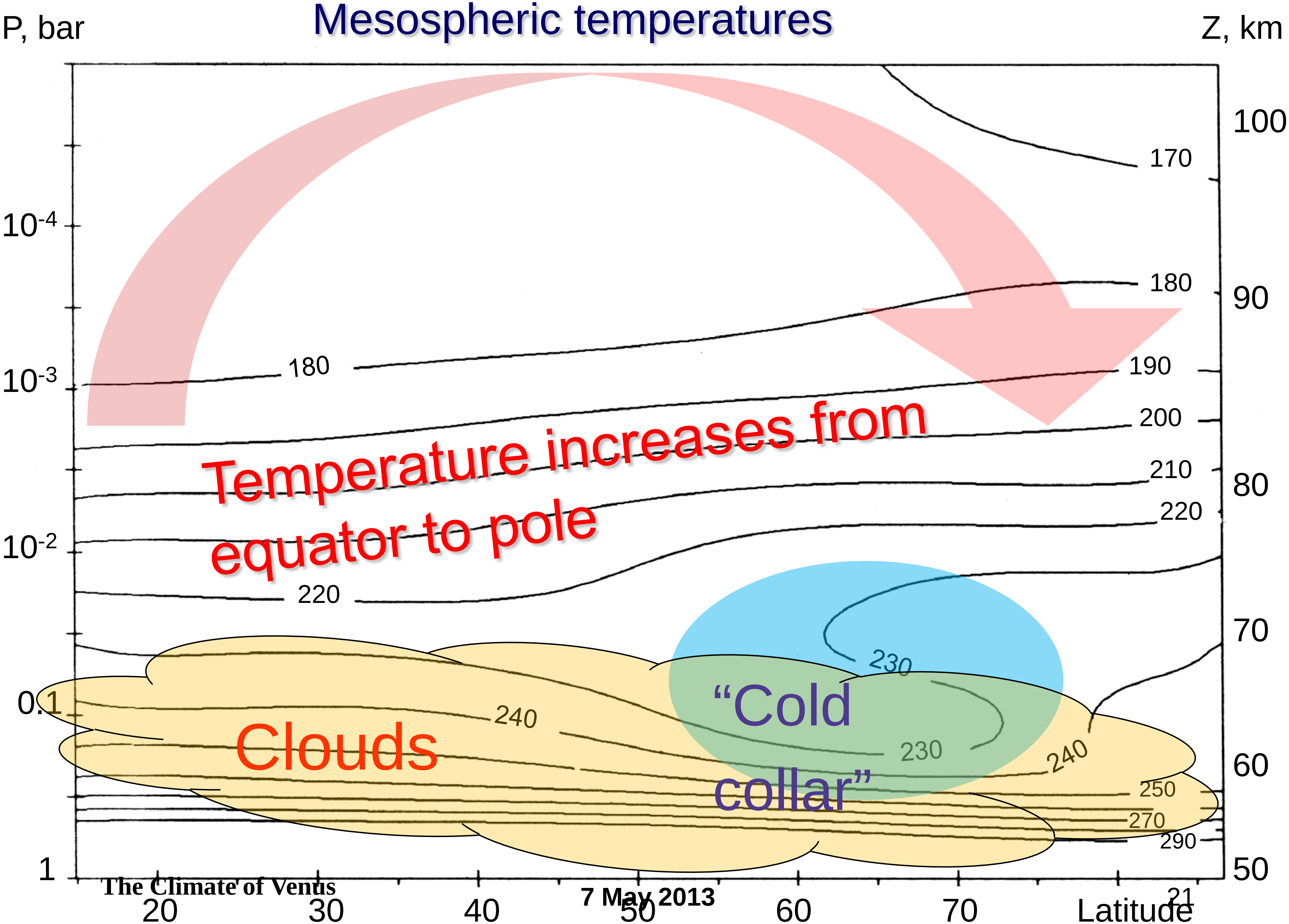


Zonal cyclostrophic winds from temperature soundings

(Piccialli et al 2012)

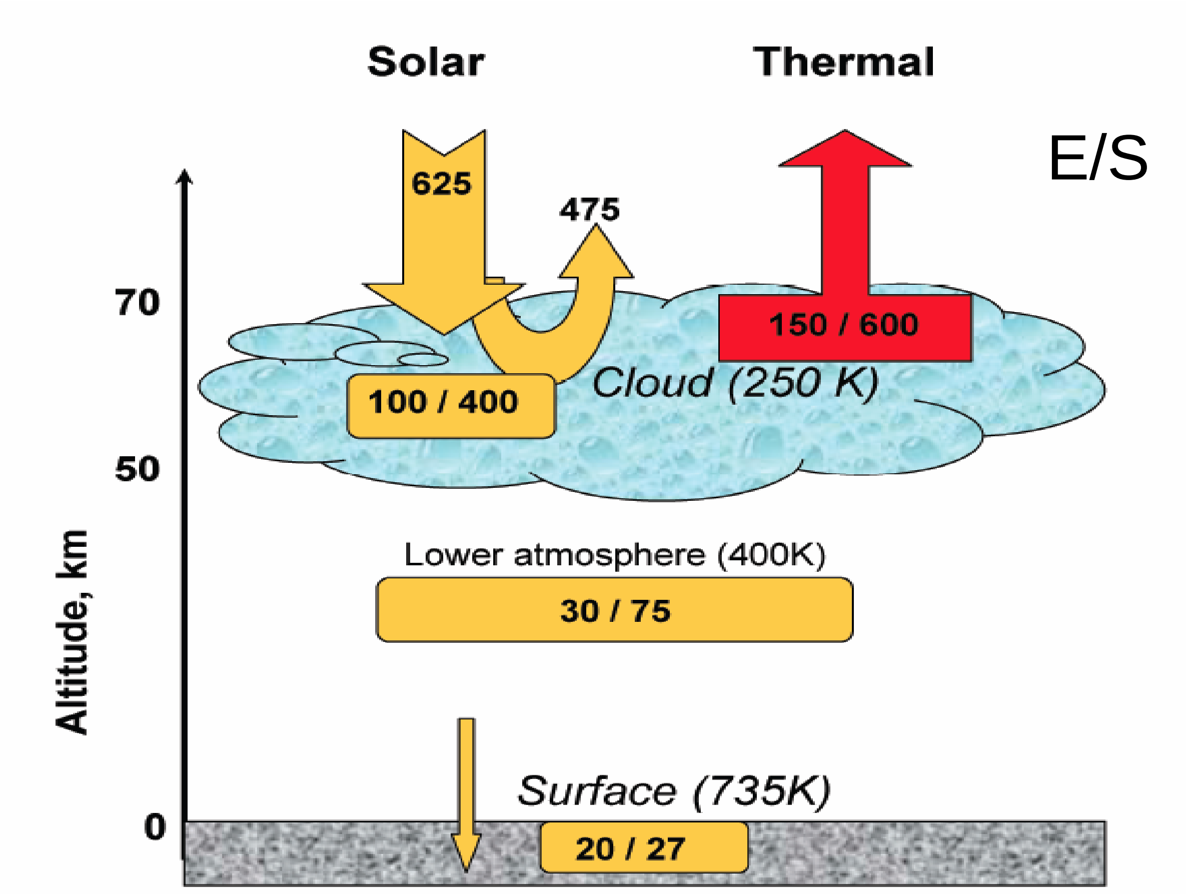


Mesospheric temperatures



Global budget of energy E and Entropy S (S = E/T) on Venus. Unit for energy W/m^2 and for entropy $mW/m^2/K$

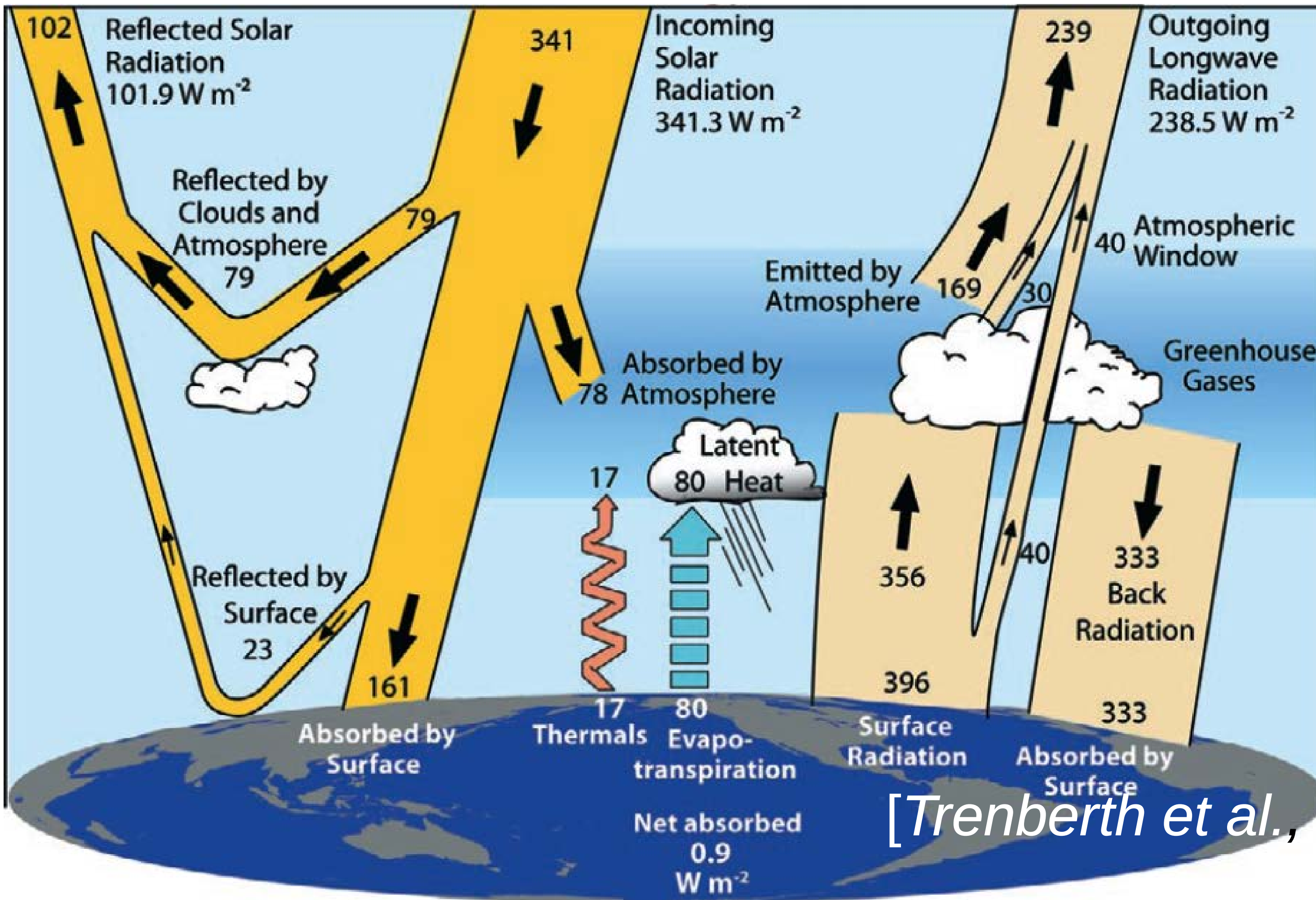
Credit: *Titov et al (2007)*



The radiation budget of the Earth

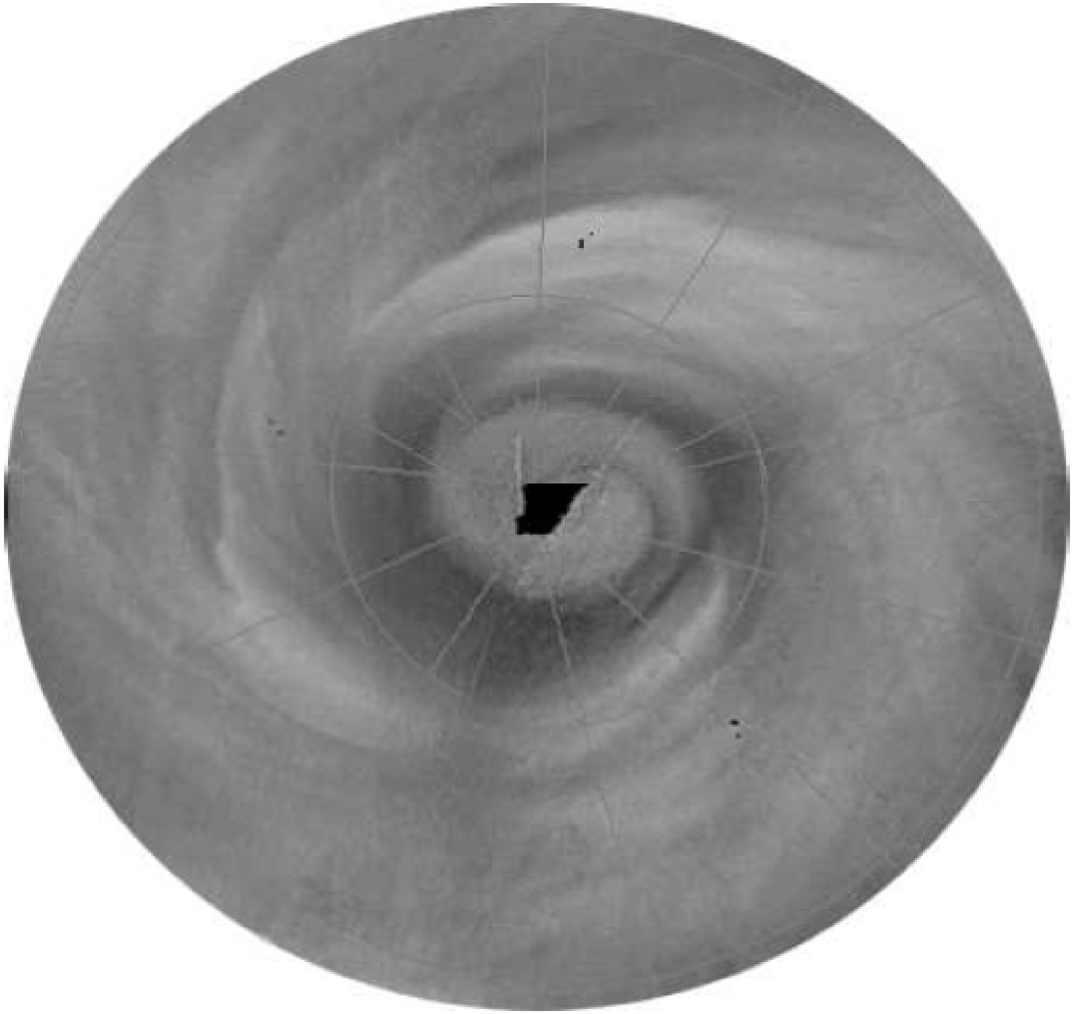
$$E_{in} = E_{out} \Leftrightarrow \tfrac{1}{4} \mathbf{S_0} \mathbf{(1 - \alpha)} = \boldsymbol{\varepsilon} \boldsymbol{\sigma} \mathbf{T_s^4}$$

Annual averages of global energy flows W m^{-2}



[*Trenberth et al.*, 2009]

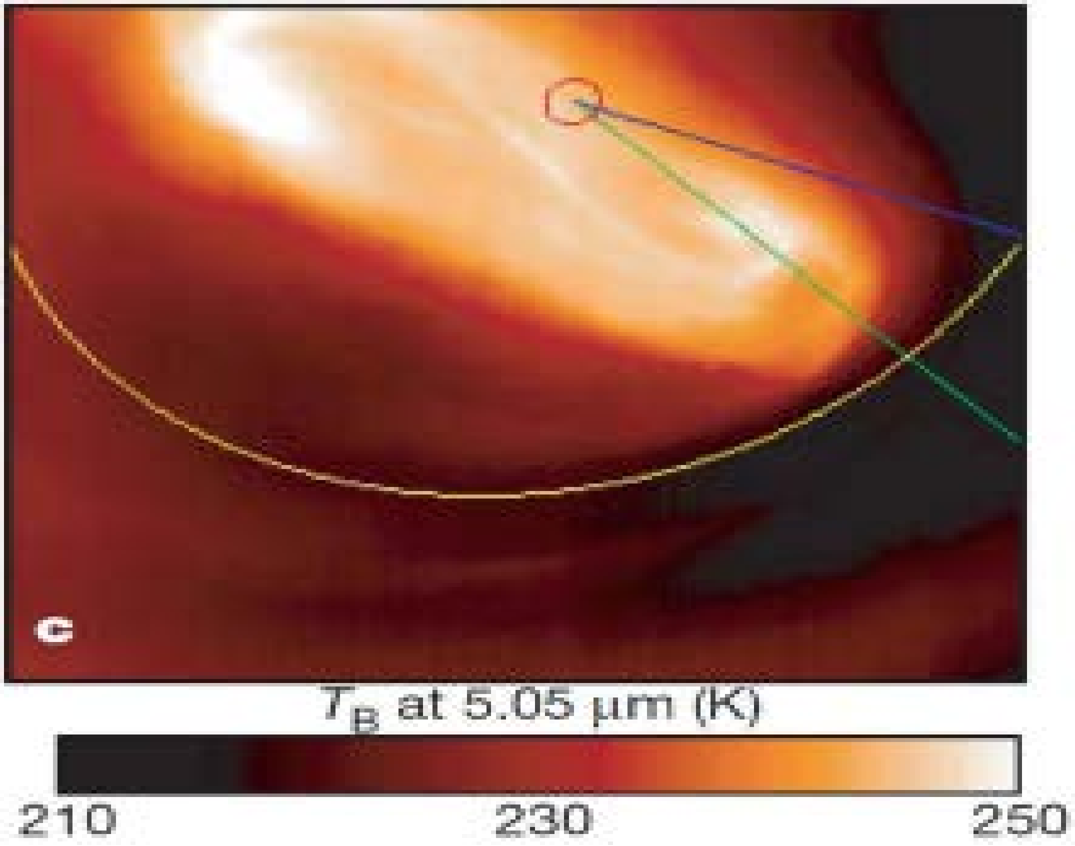
Space-time composite views of the Southern Hemisphere of Venus from UV images. *Credit:ESA*



False color image at wavelength 5.05 mm of the Venus south polar vortex by VIRTIS at Venus Express.

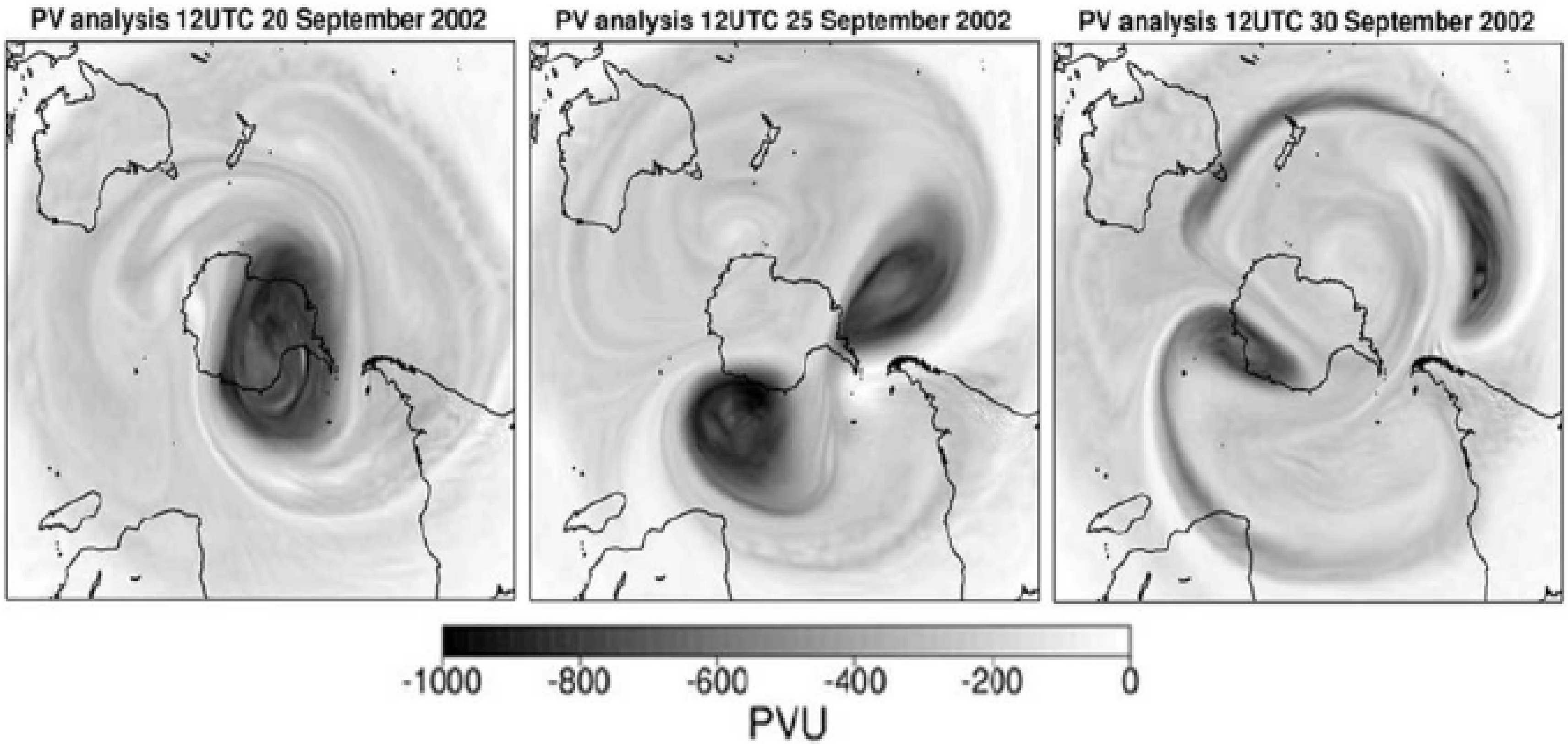
Credit: *Piccioni et al 2007*

South Pole is marked with a red circle

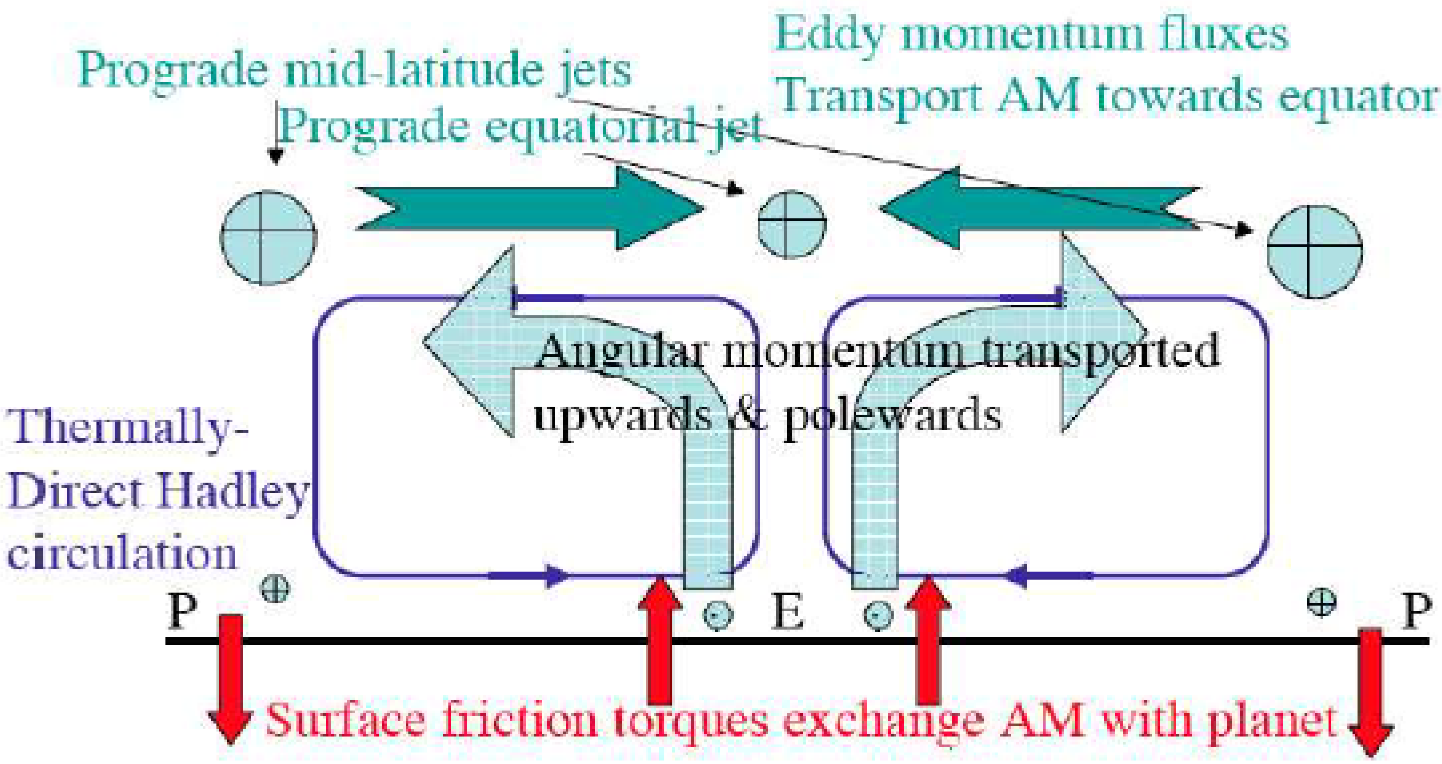


Evolution of the Earth potential vorticity at ca 30 km in September 2002 (SH). Adopted from *Simmons et al. 2005*

Credit H Schmidt



Main feature of the classical Gierasch-Rossow-Williams (GRW) mechanism



Modeling difficulties

- In the Earth's atmosphere the inertial terms in the equations of motions are generally much smaller than the Coriolis force and the pressure gradient force.

- A consequence is that we have a quasi-geostrophic balance with a small Rossby number $Ro = U/f_{\circ} L$

- Because of Venus slow rotation the inertial term (U^2/L) (acceleration term) is larger than the coriolis term ($f_{\circ} U$) and consequently there is a quasi-balance between the inertial term and the centrifugal term that we call cyclostrophic balance with the Rossby number being some 3 orders of magnitude larger.

Modeling the Venus atmosphere – historical overview

- Early studies , Kalnay ,1975, 2D-modeling

- Young and Pollack, 1977, 3D-modelling
- Rossow and Williams, 1979

(identified need for higher resolution due to inertial cascading)

- Gierasch (1975)
- *(mean meridional circulation)*
- Mayr and Harris(1983)
- Yamamoto and Takahashi (2003)

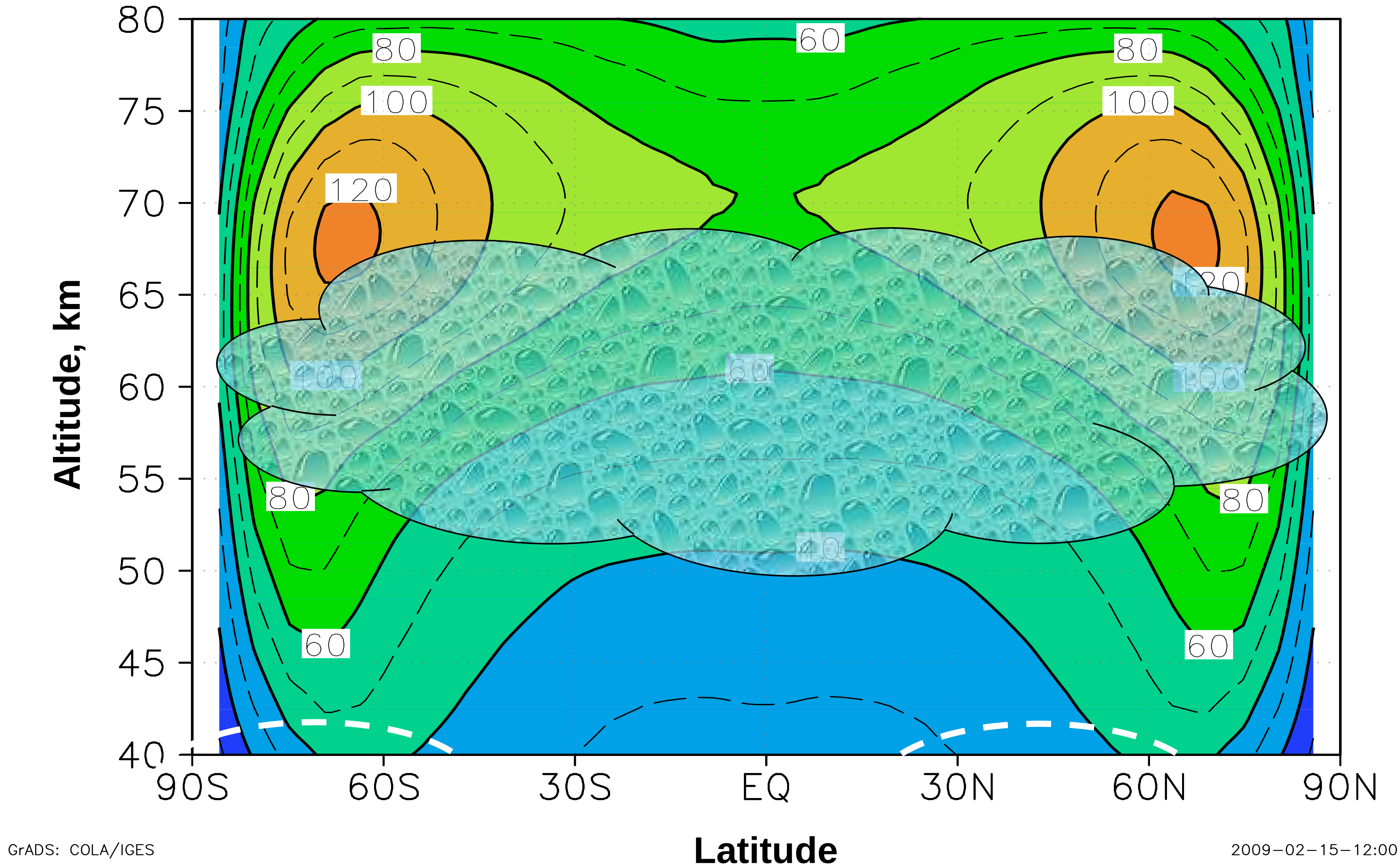
Modeling the Venus atmosphere – present situation

- More advanced models are under development
- Systematic model intercomparison and validation was part of the ISSI modeling project
- Experiment and validation with new data from Venus Express are carried out- leading to empirically based parameterization
- Better computer resources is a positive aspect but more staff resources are needed.

Modeling Inter-comparison at ISSI

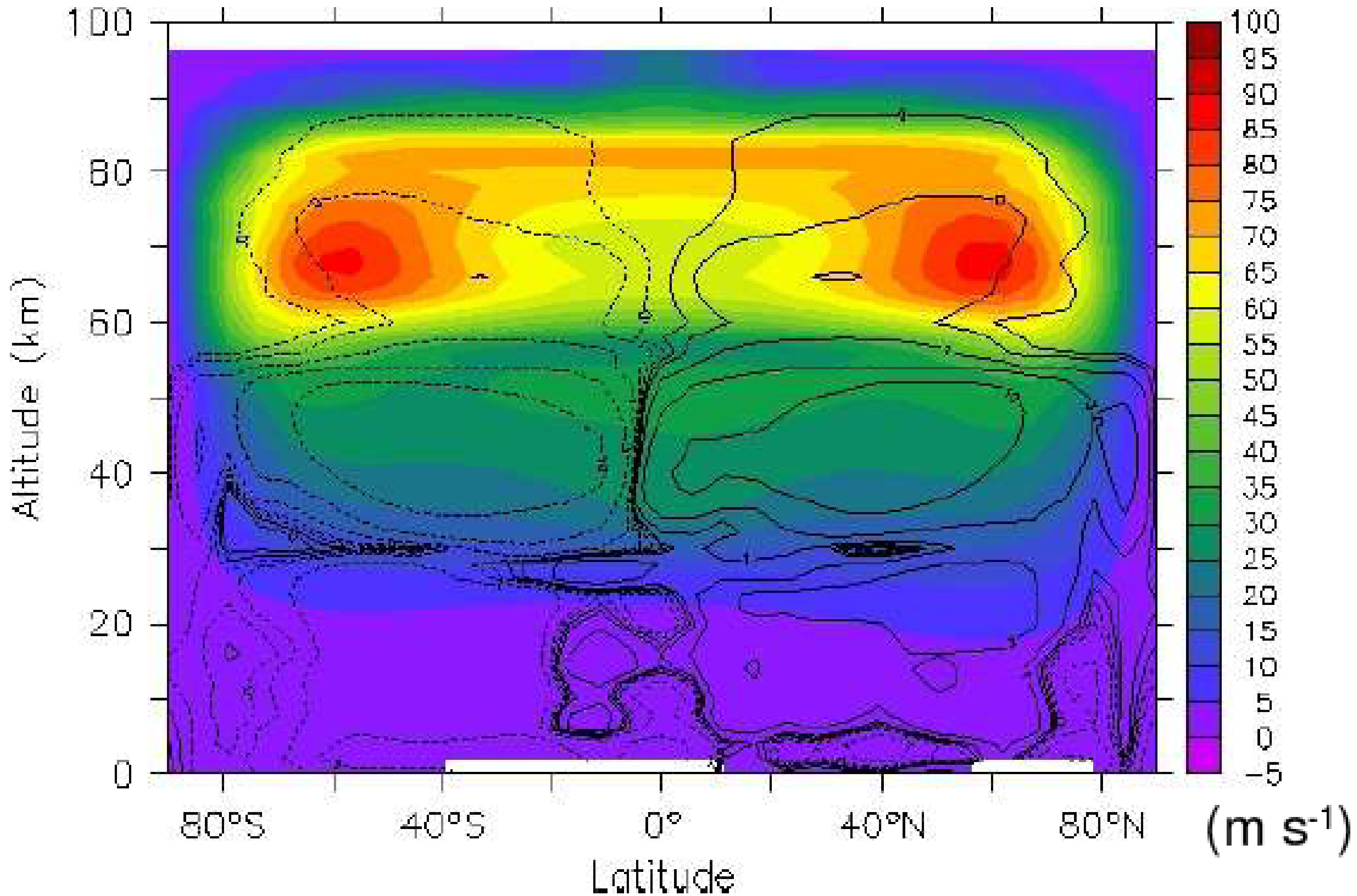
- CCSR, Kyushu/Tokio – Yamamoto, Takahashi
- LMD, Paris – Lebonnois
- OU, Open University, UK – Lewis, Dawson
- UCLA – Shubert, Covey
- OX, Oxford – Read, Mendonca, Lee
- LR10, GFDL – Lee and Richardson

General circulation modelling



Yamamoto & Takahashi

Super-rotation



Mean zonal wind and stream function after 250 Vdays
(Topography, Rayleigh friction at top boundary)

Lebonnois (2007)

Modeling results following NWP type of protocol

- Difficult to reproduce the same angular momentum (AM) and balance with different models
- Sensitive parameters are topography, planetary boundary layer scheme, vertical and horizontal resolution.
- Choice of vertical and horizontal resolution does affect the result noticeable.
- Further work should include AM budget, transport terms and budgets and the analysis of different kind of waves in the transport of AM.

Future challenges – a possible strategy

- A future mission should include a modeling and data-assimilation component similar to what commenced during the global weather experiment in 1978/79
- This will include a more comprehensive sampling. This could have been accomplished with the planned Akatsuki mission
- The role of the clouds at Venus and their origin must be better understood
- And the fundamentally important question. Did Venus previously had a habitable climate?

Venus before the space era

- 20-th century – the birth of spectroscopy
- 1920s - cloud top temperature of ~ 240K
- 1930s - CO_2 , H_2O
- 1950s – radio investigations: planet rotation, hot surface
- Venus models: from Earth-like to hell-like

Venus according to S. Arrhenius

Concluding remarks

- I believe that the recent progress in extra-terrestrial planetary research has strongly contributed towards a more focused research on the planets in our solar system.
- I believe in an approach similar to what have been undertaken with Earth in the last three decades. This has been enormously successful.
- Like on Earth such an approach should be a combination of observational studies, modeling and data-assimilation.

Relevance for the Earth‘s climate in the longer perspective

- Is it a risk that there will be a run-away climate on the Earth?
- Probably not, as there are counteracting processes in the Earth’s atmosphere, such as clouds acting as a sort of thermostat and that heat is transported to higher latitudes where cooling is more efficient.
- But, we can not be sure as cloud distribution may change due to atmospheric circulation changes
- It can not be excluded that Venus has undergone a climate run away.

END

- Thanks for your attention

Earth and Venus

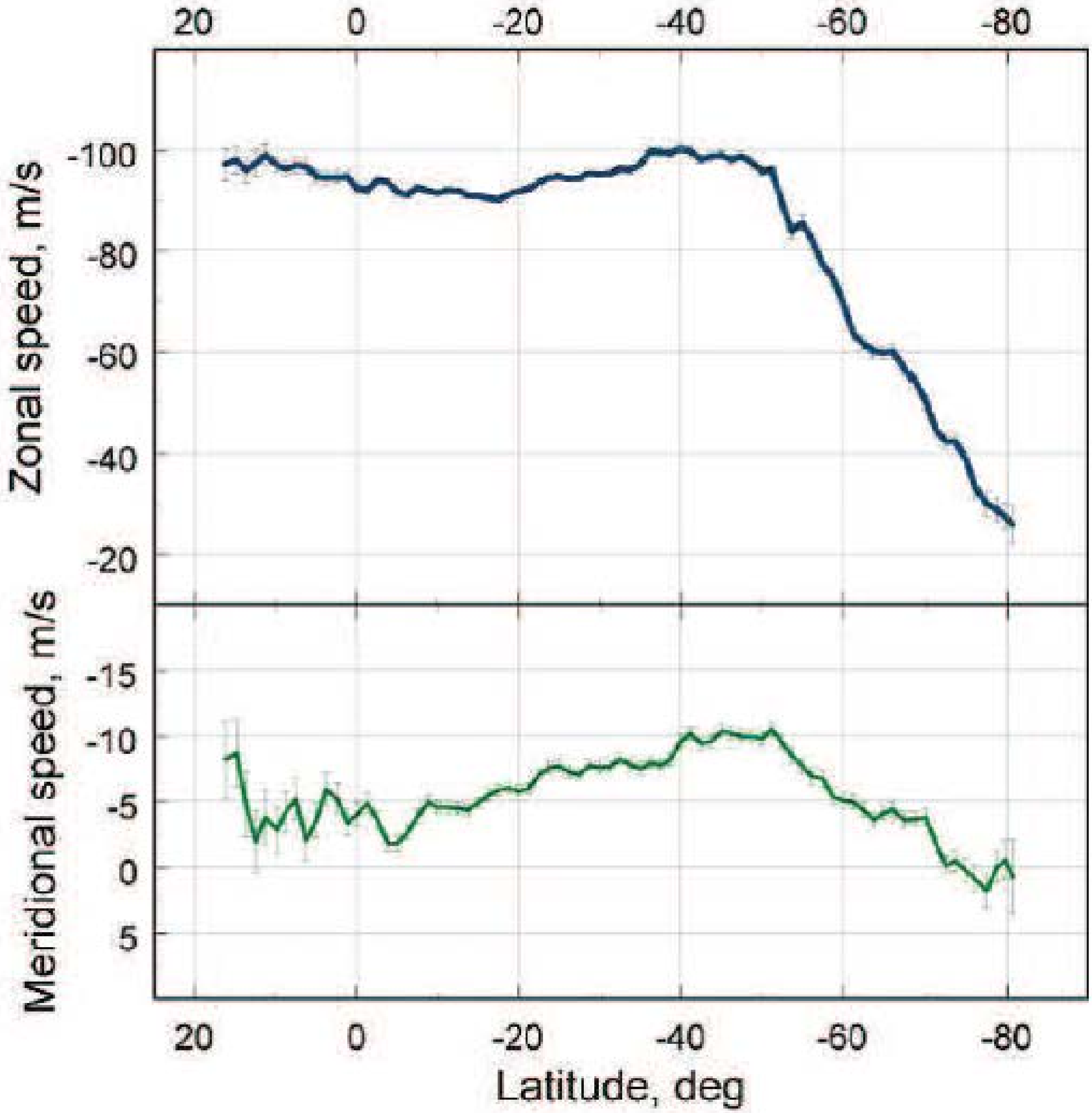
There may be more similarity between Earth and Venus than hitherto appreciated.

Earth's circulation is driven from below by solar heating variations. On Venus, solar heating is focused at cloud heights where T, p conditions are earthlike. The cloud level circulation on Venus might have some similar characteristics as circulation on Earth. Recent Venus GCM calculations suggest that
atmospheric circulation is driven largely from above, at cloud levels, where solar heating is concentrated, with the lower massive atmosphere playing a more passive role. Earthlike features include a cloud level Hadley cell and high latitude jets.

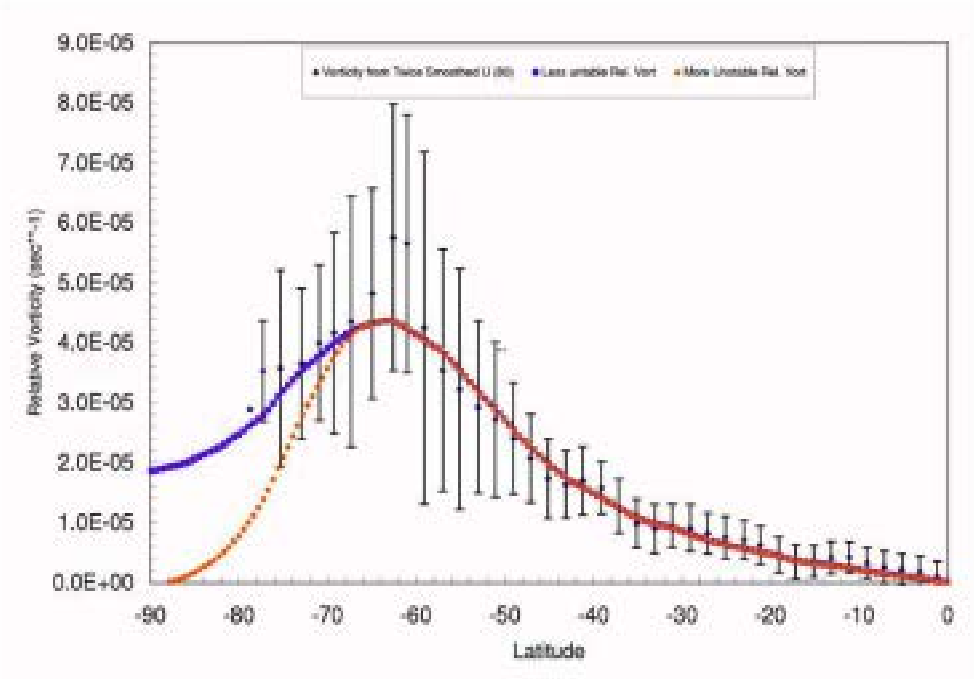
Sources and Sinks of the planetary entropy for Earth and Venus. *Units: mW/m^2/K*

	EARTH Goody (2000)	VENUS Titov et al.(2007)
Net radiative sink	- 70	- 100
Moist convection	+ 55	0
Mechanical dissipation	+12	1
Net balance	- 3	- 100

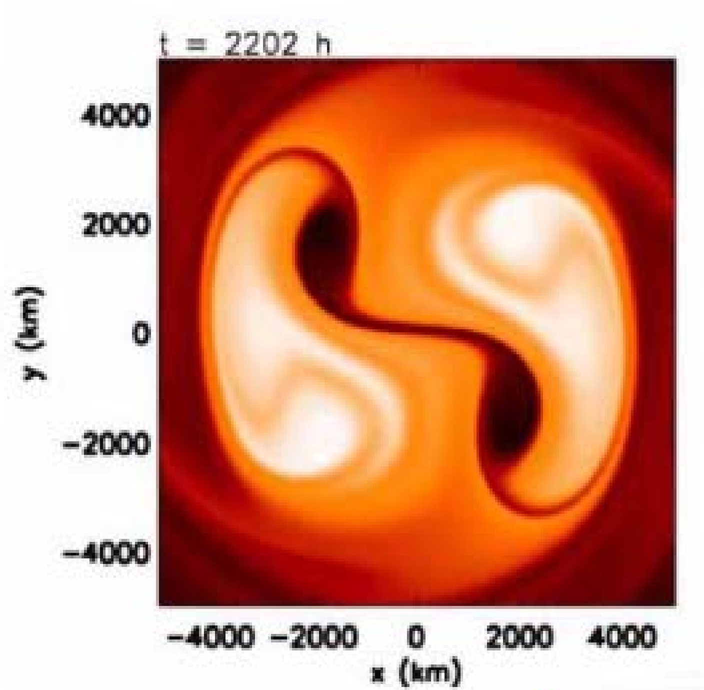
What do the dynamical regimes of Venus and Earth have in common?
What accounts for the differences in the atmospheric dynamics of these planets?
Why study Venus' atmospheric dynamics to understand the dynamics of Earth's atmosphere?


20
0
-20
-40
-60
-80
Zonal speed, m/s
-100
-80
-60
-40
-20
Meridional speed, m/s
-15
-10
-5
0
5
20
0
-20
-40
-60
-80
Latitude, deg

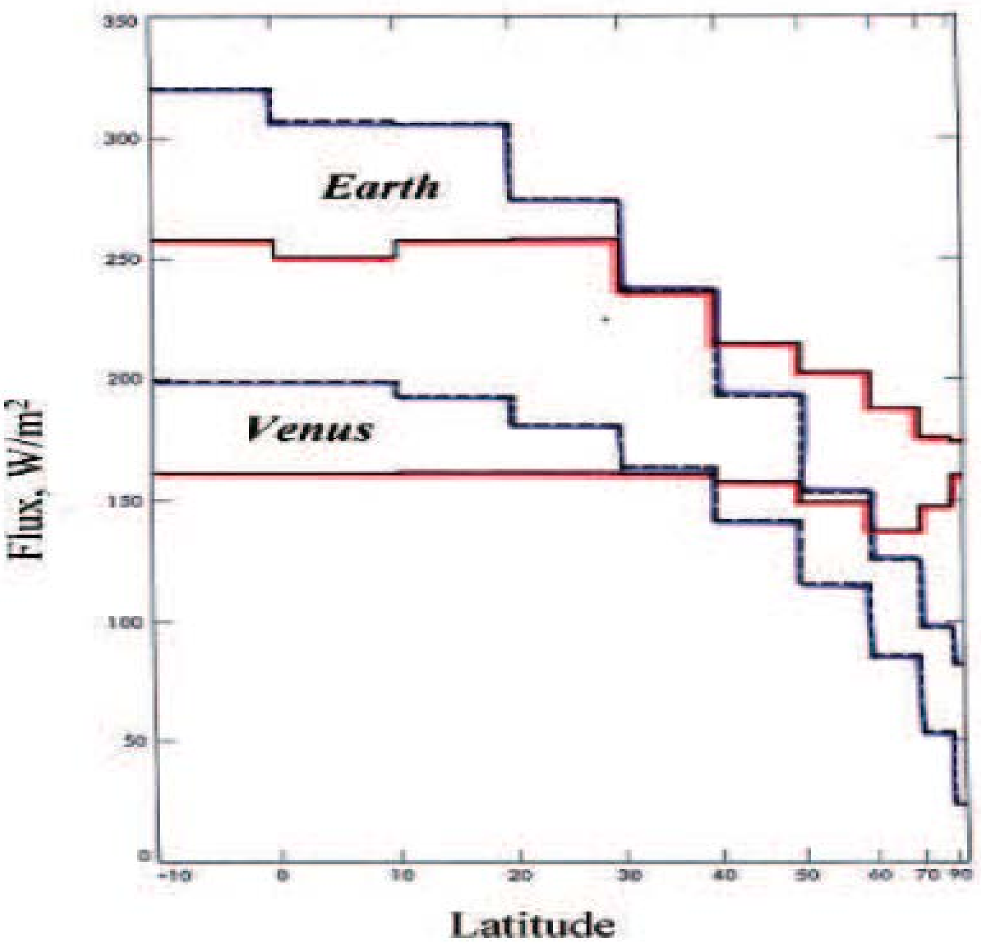
Latitudinal profile of relative vorticity close to the north polar vortex of Venus Credit: *Limaye et al 2009*

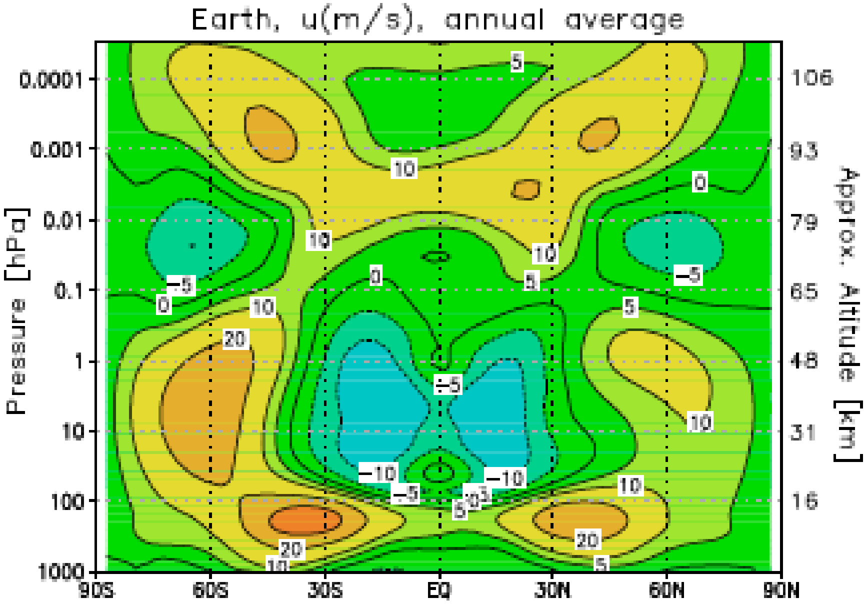


(a)

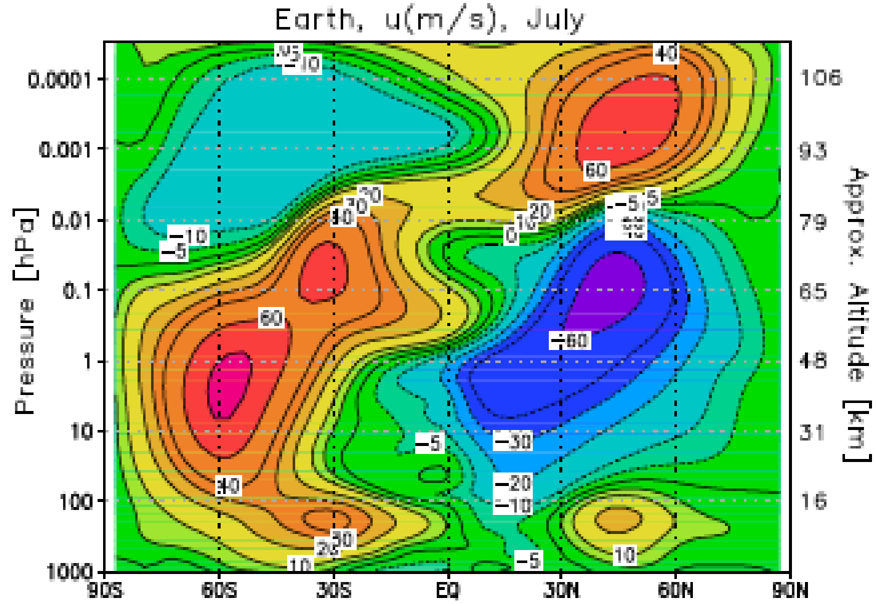


(b)


Earth
Venus
Flux, W/m²
Latitude
350
300
250
200
150
100
50
0
-10
0
10
20
30
40
50
60
70
90


Earth, u(m/s), annual average
Pressure [hPa]
Approx. Altitude [km]
0.0001
0.001
0.01
0.1
1
10
100
1000
106
93
79
65
48
31
16
90S
60S
30S
EQ
30N
60N
90N

(a)

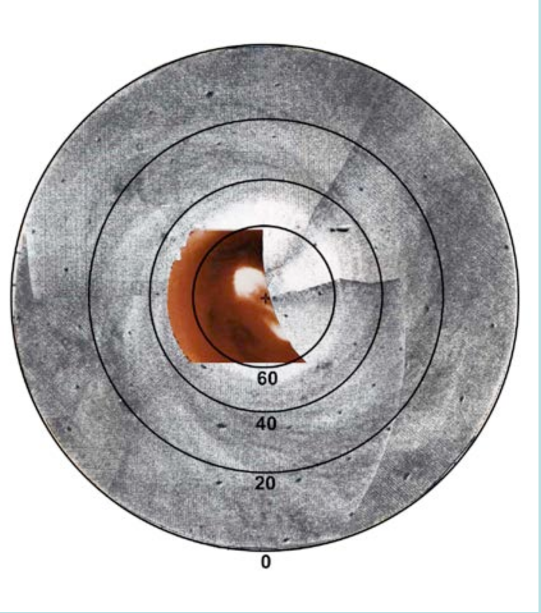

Earth, u(m/s), July
Pressure [hPa]
Approx. Altitude [km]
0.0001
0.001
0.01
0.1
1
10
100
1000
106
93
79
65
48
31
16
90S
60S
30S
EQ
30N
60N
90N

(b)

Earth and Venus

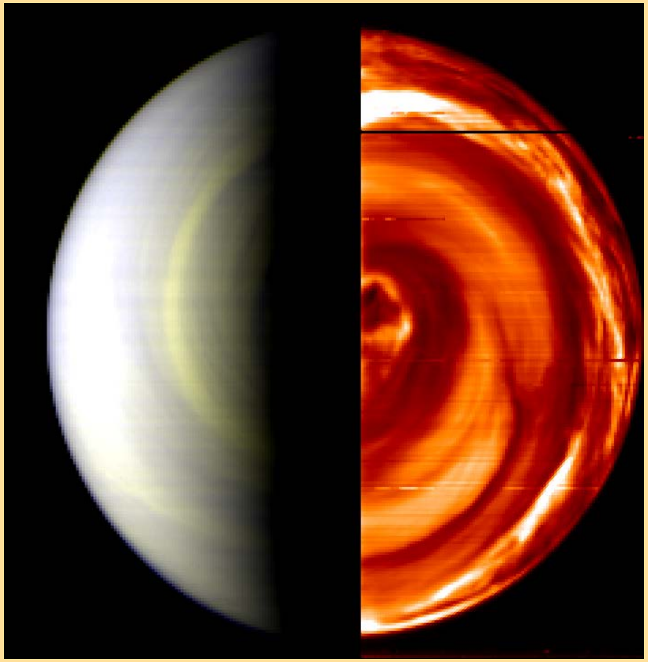
The polar vortex on Venus may have some dynamical similarities to Earth's hurricanes and stratospheric polar vortex.

Pioneer Venus OIR image (1980) superimposed on Mariner 10 UV images (1974)
Figure courtesy of Sanjay Limaye



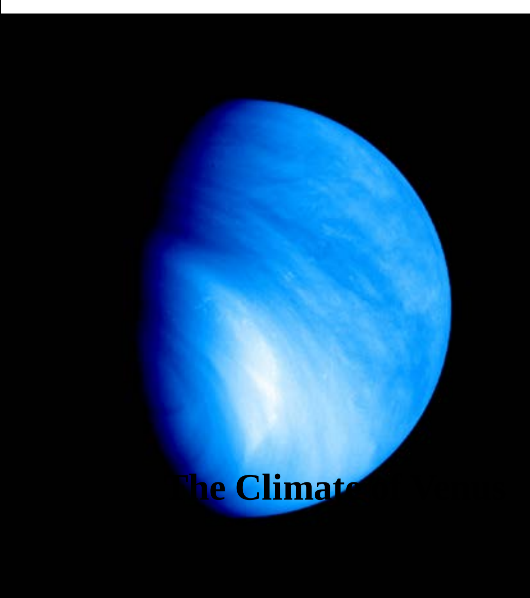
Venus Express VIRTIS UV and NIR images (2006)

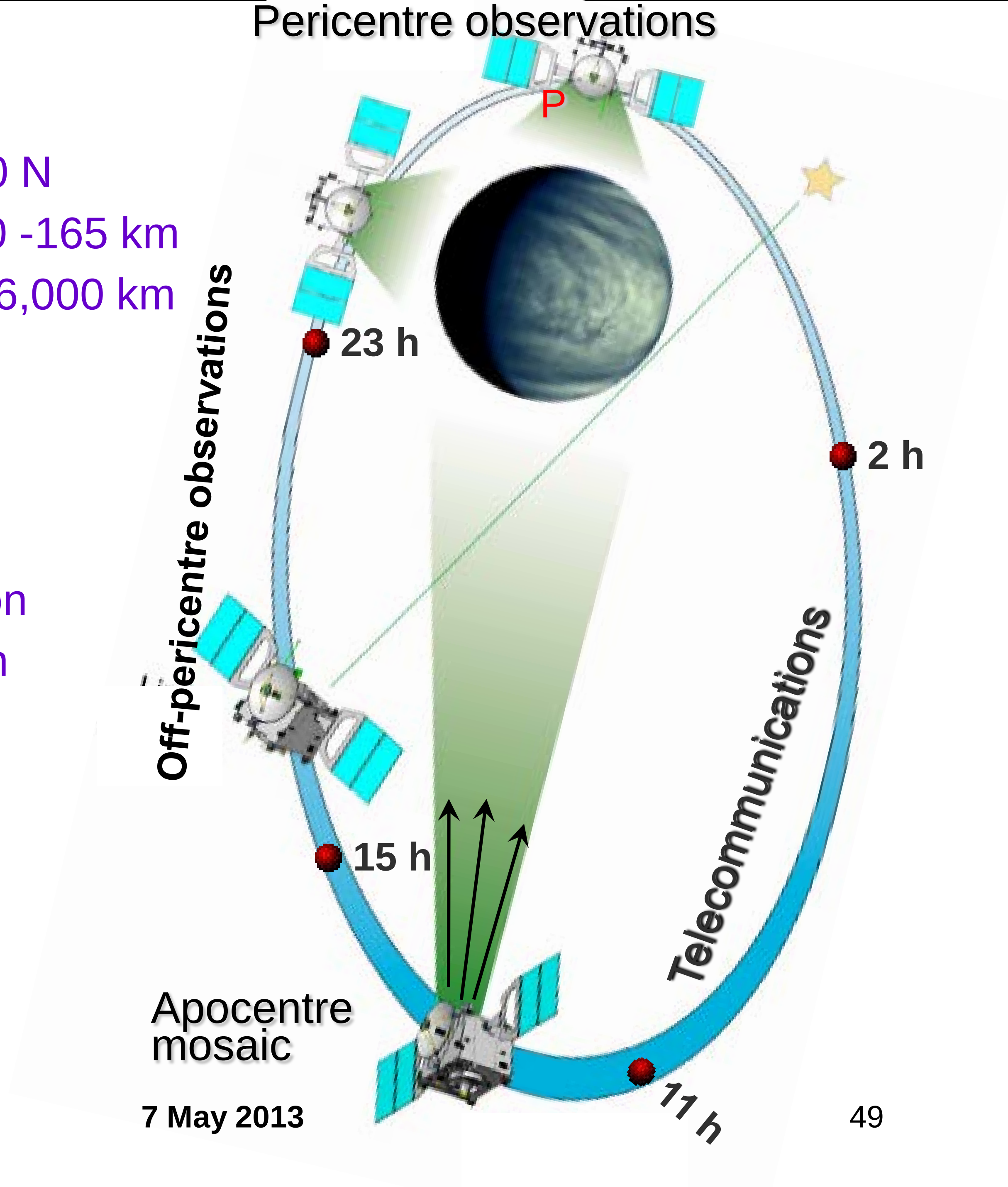
Downloaded from VEXP Web site



Orbit and operations

- Polar orbit
  - Pericentre latitude ~90 N
  - Pericentre altitude 280 -165 km
  - Apocentre altitude ~ 66,000 km
  - Period ~ 24h
- Observation modes
  - nadir
  - apocentre mosaic
  - solar/ stellar occultation
  - Earth radio-occultation





Alternative to the GRW mechanism for atmospheric superrotation(Credit: *P Read*)