What causes the subtropical jet?

A model study

By Roos de Wit

Supervision: Aarnout van Delden
What is the subtropical jet?
Introduction

• Interesting:
  – Weather phenomena
  – Fundamental question

• Stone (2008): zonal mean state of the atmosphere still not completely understood
Introduction

• Research question:
  – What processes are responsible for the establishment of the subtropical jet?

• Use relatively simple model to answer question
Outline

• Introduction
• The observed zonal state of the atmosphere
• The model
• Model experiments:
  – Basic model
  – Addition of latent heat release
  – Addition of wave drag
  – Wave drag without ozone, water vapor
• Conclusion
Observations: zonal wind DJF

ECMWF ERA-40
Observations: zonal wind MAM
Observations: zonal wind JJA
Observations: zonal wind SON
Observations

• Subtropical jet: westerly wind maximum in troposphere

• Stratospheric jet:
  – In summer hemisphere: easterly
  – All other seasons: westerly
Observations

• How can the zonal wind field be explained?
  – Thermal wind balance
  – Decrease temperature equator to pole →
    increase zonal wind with height
Observations: temperature JJA
Temperature $\rightarrow$ zonal wind

ECMWF ERA-40
The model: basics

• 2-D primitive equation model

• Basic model:
  – Absorption of SW radiation: water vapor + ozone
  – Absorption of LW radiation: CO$_2$ + water vapor
  – Friction in lowest part atmosphere
Results: basic model

CONTOURS
Potential temperature: blue; Interval: 25 K below 400 K and 50 K above 400 K; thick: 400 K and 750K
Zonal wind, u: red; Interval: 5 m/s; Thick: u>0; thin: u<0; thick-red: u=50 m/s or 0 m/s
Potential vorticity, PV: black; contours shown are ±2, ±20, ±100, ±1000, ±2000 PVU
Conclusion: basic model

- Only radiative processes: not possible to explain the observed zonal state of the atmosphere
The model: additional processes

• To investigate the establishment of subtropical jet addition of:
  – Latent heat release
  – Wave drag
Process: latent heat release (tropics)

- Hinssen *et al.*: latent heat release in tropics important?

Annual mean precipitation from NCEP
Results: latent heat release (tropics)
Conclusion: latent heat release (tropics)

• Addition of latent heat release over the tropics does not lead to the observed zonal state of the atmosphere
Process: wave drag

- Previous experiments: summer pole too cold, no cold pool over equator
- Wave drag could solve this!

Kim et al. (2003)
The model: wave drag

- Wave drag applied:
  - Centered around ± 45°
  - Approximately 17.5 km
  - Only if \( u > 0 \) m s\(^{-1}\)

Applied wave drag (m s\(^{-2}\)), NH summer
Results: wave drag

CONTOURS
Potential temperature: blue; Interval: 25 K below 400K and 50 K above 400 K; thick: 400 K and 750K
Zonal wind, u: red; Interval: 5 m/s; Thick: u>0; thin: u<0; thick-red: u=50 m/s or 0 m/s
Potential vorticity, PV: black; contours shown are ±2, ±20, ±100, ±1000, ±2000 PVU
Results: wave drag

July, NH summer
Effect drag on $\theta$, $u$

- To study the effect of wave drag on the potential temperature and the zonal wind field:

  $\rightarrow$ Situation with drag – situation without drag
Effect drag on $\theta$

- Situation with drag – situation without drag
  - If $\Delta \theta > 0$ temperatures increased due to drag
  - If $\Delta \theta < 0$ temperatures decreased due to drag
Effect wave drag on $\theta$

The effect of wave drag on the potential temperature (in K) for NH summer
Effect drag on $u$

- Situation with drag – situation without drag

→ In region with $u > 0$
  - If $\Delta u > 0$ wind speed increased due to drag
  - If $\Delta u < 0$ wind speed decreased due to drag
Effect wave drag on $u$

The effect of wave drag on the zonal wind (in m s$^{-1}$) for NH summer
Circulation without wave drag
Circulation with wave dag

July, NH summer
Conclusion: wave drag

• Addition of wave drag brings the model closer to the observations:
  – Reversal of stratospheric jet in summer hemisphere
  – Separation of subtropical jet and stratospheric jet
Importance of drag vs radiation

• Wave drag is needed in order to establish subtropical jet

• Importance of radiation?

• Remove ozone, water vapor from the atmosphere
  – Still subtropical jet?
The model: no ozone

- The model with wave drag: remove ozone from atmosphere
Results: no ozone

CONTOURS
Potential temperature: blue; Interval: 25 K below 400K and 50 K above 400 K; thick: 400 K and 750K
Zonal wind, u: red; Interval: 5 m/s; Thick: u>0; thin: u<0; thick-red: u=50 m/s or 0 m/s
Potential vorticity, PV: black; contours shown are ±2, ±20, ±100, ±1000, ±2000 PVU
Effect of removal ozone on $\theta$

The effect of removal of ozone on the potential temperature (in K) for NH summer.
Conclusion: ozone

- Removal of ozone does not lead to disappearance subtropical jet
- Before: radiative effect of ozone not strong enough to establish subtropical jet
The model: no water vapor

- The model with wave drag: remove water vapor from atmosphere

Precipitable water as function of latitude in July (NH summer)
Results: no water vapor

CONTOURS
Potential temperature: blue; Interval: 25 K below 400K and 50 K above 400 K; thick: 400 K and 750K
Zonal wind, u: red; interval: 5 m/s; Thick: u>0; thin: u<0; thick-red: u=50 m/s or 0 m/s
Potential vorticity, PV: black; contours shown are ±2, ±20, ±100, ±1000, ±2000 PVU
Effect removal water vapor on $\theta$

The effect of removal of water vapor on the potential temperature (in K) for NH summer
Effect removal water vapor on $u$

The effect of removal of water vapor on the zonal wind (in m s$^{-1}$) for NH summer
Conclusion: removal water vapor

• Removal of water vapor leads to disappearance of subtropical jet

• However: wave drag was included → both wave drag and radiative effect water vapor important!
Conclusion

• Radiation only:
  – cannot explain subtropical jet

• Addition of latent heat release:
  – cannot explain subtropical jet

• Addition of wave drag:
  – Separation subtropical/stratospheric jet
  – Reversal of stratospheric jet in summer
Conclusion

- Only wave drag: also not possible to establish subtropical jet $\rightarrow$ radiative processes important as well!
Questions?
Latent heat release

- Evaporation instantaneously balanced by precipitation
  - Evaporation coupled to sensible heat flux by the Bowen ratio: \( B = \frac{H}{L_v E} \)
- Sine function to determine vertical and horizontal extent of cloud
Wave drag

\[ D(\phi, z) = D_0 B(\phi) Z(z), \]
\[ B(\phi) = \sin 2\phi, \]
\[ Z(z) = \begin{cases} 
0, & z < 5000m \\
\sin\left(\pi \frac{z-5000}{25000}\right), & 5000 < z < 30000m \\
0, & z > 30000m 
\end{cases} \]

\[ D_0 = -5.0 \cdot 10^{-5} \text{ ms}^{-2}. \]
EP flux

NH summer

Vallis, 2005
Water vapor

- Water vapor concentration at surface related to surface temperature by prescribing RH and using ideal gas law

- Vertical distribution water vapor by exponential function:
  \[ \rho = \rho_s e^{\frac{-z}{H_v}} \]