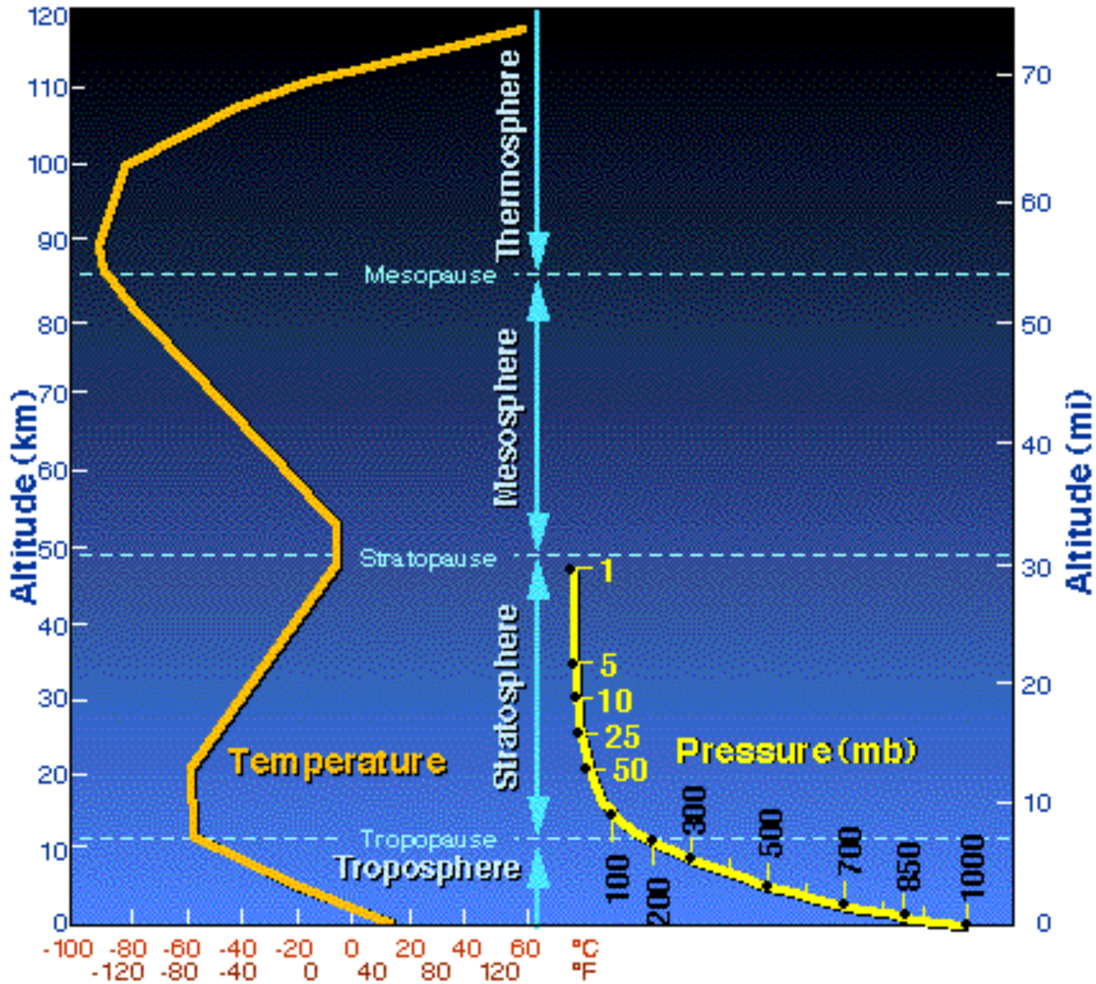
Lecture 2
Internal gravity waves in the atmosphere

- Main sources of internal gravity waves
- Amplification processes of internal gravity waves
- Wave-wind interaction at a critical level
- Examples of the impact of internal gravity waves in the stratosphere:

  the quasi-biennal oscillation (QBO) and the Brewer-Dobson circulation.

The vertical structure of the temperature in the atmosphere



The vertical structure of the temperature in the atmosphere

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Troposphere

- 85% mass of the atmosphere, all the water vapor
- temperature decreases due to air rarefaction ($dT/dz \simeq -6$ K/km)
- this is where clouds form

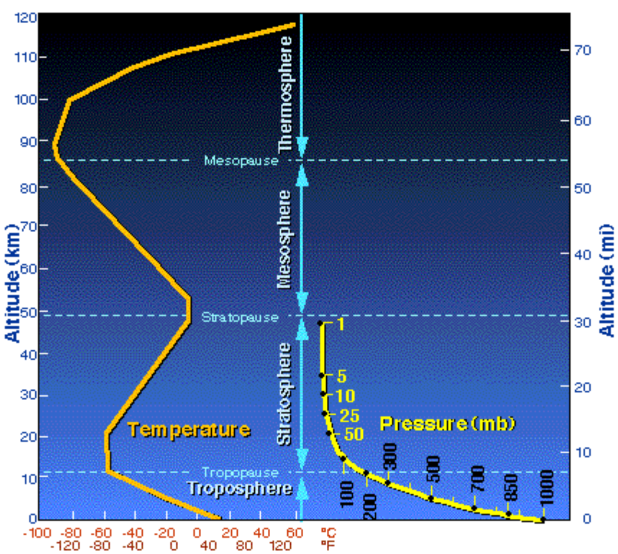
Stratosphere

- contains 80% of atmospheric ozone
- temperature increases due to solar radiation (absorption of UV by ozone)
- very weakly mixed because of stable stratification (→ long residence times ; internal gravity waves)

Tropopause (8-15 km)
dT/dz changes sign
(ajustement between convection and radiation)

Stratopause (70 km)

- dT/dz changes sign ;
- 1/1000 of the mass of the atmosphere located above



Mesosphere

- as in the stratosphere, motions are dominated by internal gravity waves, now of very large amplitude
- temperature decreases again (but still stably-stratified)

Mesopause (85 km): dT/dz changes sign.

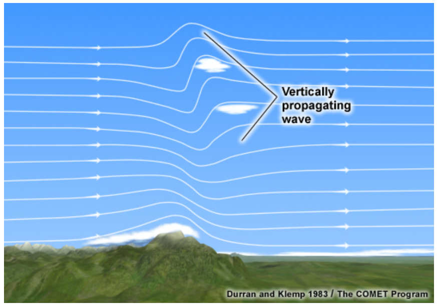
From tropopause to $\sim$100 km : « **middle atmosphere** »

The main sources of internal waves in the atmosphere

- **Orographic (or lee) waves**

  Interaction of the wind with topography

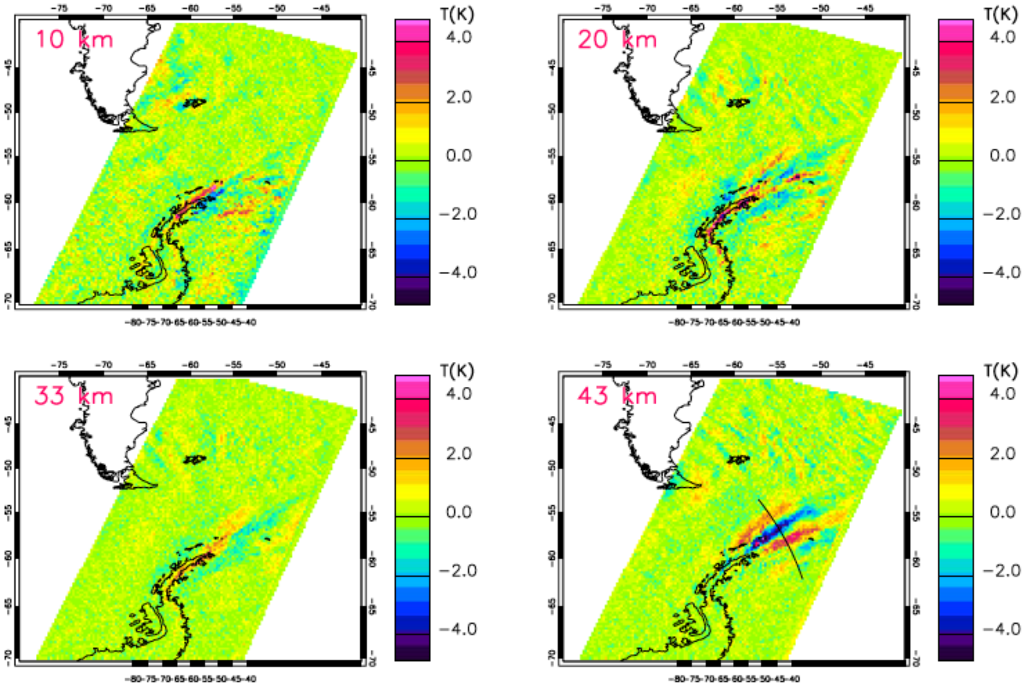
  Steady with respect to the mountain



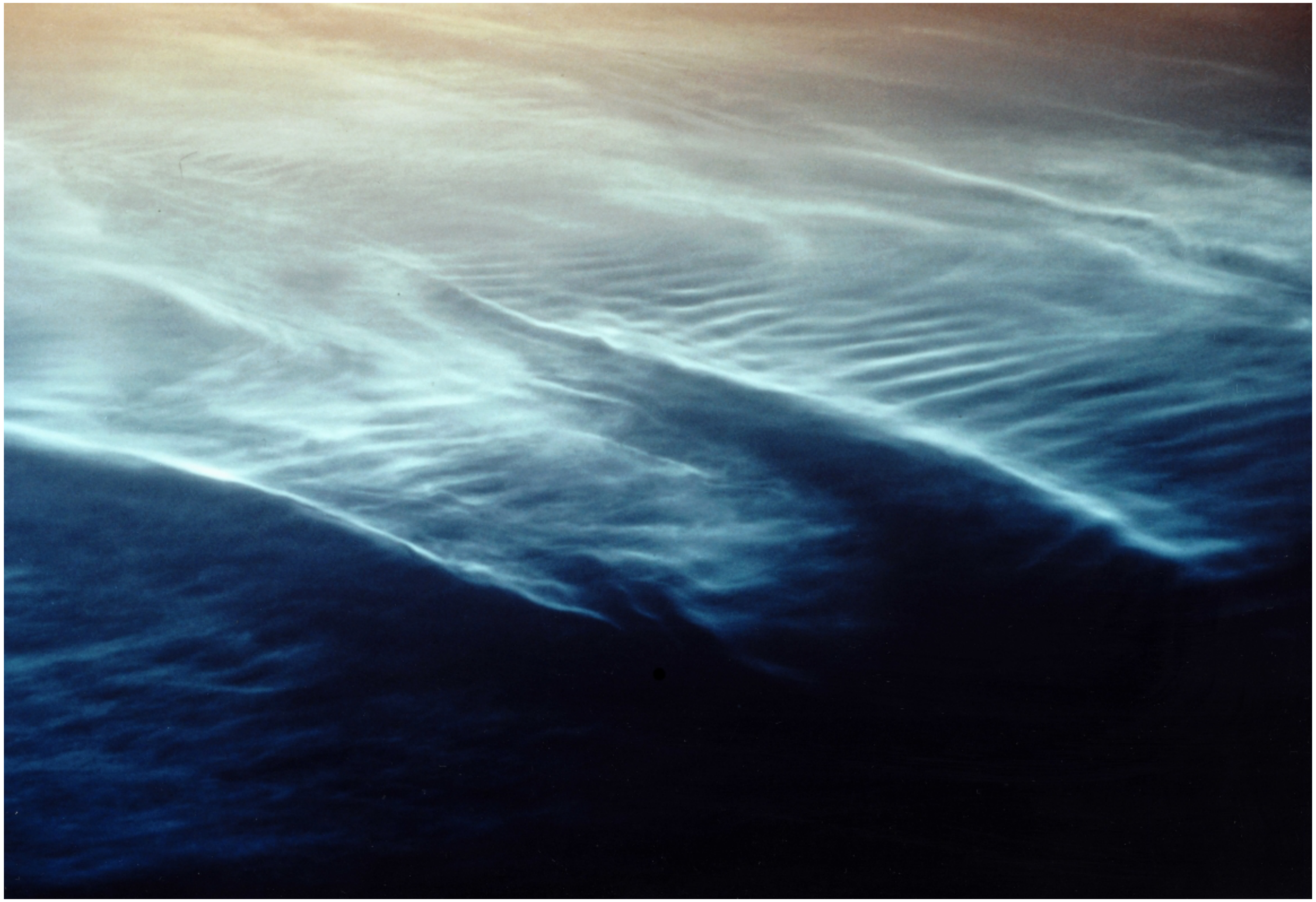
Durran, 2003

Evidence of lee waves over the Antarctic peninsula measured by Atmospheric Infrared Sounder embarked on a satellite

Alexander and Teitelbaum, J. Geophys. Res., 2007



The main sources of internal waves in the atmosphere

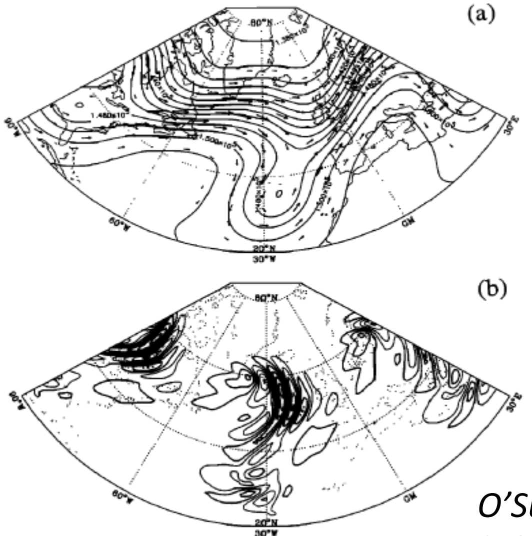


View of noctilucent clouds from Kustavi, Finland (61°N, 21°E) on 22 July 1989 showing characteristic bands and streak structures. In this case, bands are separated by ≈50km and streaks by ≈3 to 5 km (from Fritts et al., Geophys. Res. Lett. 1993; photograph by Pakka Parviainen).

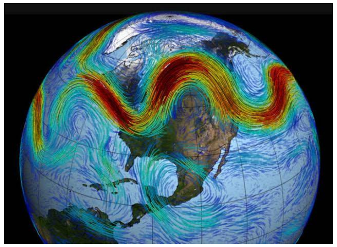
The main sources of internal waves in the atmosphere

Non-orographic waves

- Emission of inertia-gravity waves by jets
  and fronts
  - Coriolis force matters
  - Horizontal wavelength = a few hundreds kms
  - Vertical wavelength: a few kms (→ « small »)
  - Frequency : between f and 2f (≈ 10 h)



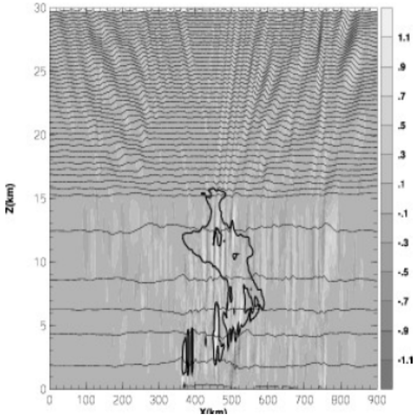
O'Sullivan & Dunkerton, J. Atmos. Sci., 1995



NASA

- Equatorial convection*

→ emission of internal gravity waves at the tropopause
  - « Short » wavelengths (λ_h<100 km)
  - Key role on winds in the stratosphere
    (f.i. QBO, discussed later)



Alexander and Holton, J. Atmos. Sci, 1997

* This is THE source of IGW in the Sun, from the bulk of the convective zone, see D. Lecoanet and T. Rogers' talks)

Amplification processes of internal gravity waves in the atmos.

Breaking implies that the wave amplitude increases.

How can the wave amplitude increase in the atmosphere? This can be due to:

1. **the decrease of density with altitude**:
   - Because of decrease of pressure with altitude + compressibility of air
   - Conservation of energy flux ($\sim \rho A^2$) → wave amplitude A increases

Amplification processes of internal gravity waves in the atmos.

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Breaking implies that the wave amplitude increases.

How can the wave amplitude increase in the atmosphere? This can be due to:

1. **the decrease of density with altitude**
2. **a local accumulation of the wave-induced energy** (as a « side-effect » of a critical level, see the experiments of Koop and McGee (1986) on next slides)

Amplification processes of internal gravity waves in the atmos.

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How can the wave amplitude increase in the atmosphere? This can be due to:

1. **the decrease of density with altitude**
2. **a local accumulation of the wave-induced energy**
3. **a process**, different from an instability, **which results in an extraction of energy from a source** (such as reflection on an unstable shear flow, see f.i., Jones, J. Fluid Mech., 1968)

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3. **a process**, different from an instability, **which results in an extraction of energy from a source**
4. **the growth of an instability** (such as parametric-subharmonic instability −PSI)

The growth of PSI requires a relative steadiness of the wave over many periods (the growth rate of PSI being proportional to the wave amplitude)

→ On an ice shelf in winter, a very cold layer forms over the surface in which internal gravity waves are trapped. PSI may occur there

→ PSI may also occur in lee waves if the wind and stratification conditions remain quasi-steady (over the time of growth of the perturbation by PSI) − see J.-M. Chomaz' work.

Apart from these specific conditions, PSI is unlikely to occur in the atmosphere because of

-upward propagation (which increases the wave amplitude) and

-ambient winds which may change the wave frequency.

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→ Once of large « enough » amplitude (steepness > 1), the wave breaks by Kelvin-Helmholtz instability or by convective instability, thereby depositing the momentum it transports.

→ In the atmosphere, the major effect of waves on the ambient medium is via **momentum deposition.** Momentum deposition occurs

- when the **wave dissipates** (due to momentum conservation) or
- by **interaction with the wind** (which results in the acceleration or decceleration of the wind).

Wave-wind interaction at a critical level

Critical level?

We assume that a monochromatic wave (**k**,ω) propagates in a shear flow U(z).

Before entering the shear flow, the wave frequency is ω_0.

When the wave enters and propagates into the shear flow:
- the properties of the medium **do not vary in time** → the **frequency ω_0 does not change**; ω_0 is the absolute frequency of the wave.
-the properties of the medium **do not vary in x** → **k_x** does not change.

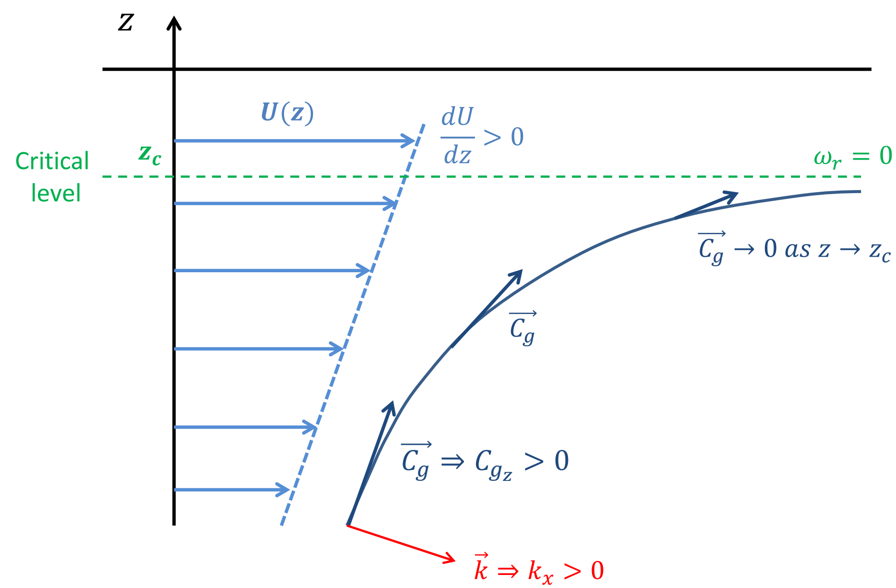
But:

-the properties of the medium **change along the z-direction → k_z changes**.

-the intrinsic frequency of the wave ω_r is Doppler-shifted:

$$\omega_0 = \omega_r + \mathbf{k.U} = \omega_r + k_x U$$

(with ω_r satisfying the dispersion relation).



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Critical level?

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Before entering the shear flow, the wave frequency is ω_0.

During propagation in the shear flow:

- Unchanged: ω_0, k_x
- Change: $\omega_r = \omega_0 - k_x U$ (with ω_r satisfying the dispersion relation) and k_z

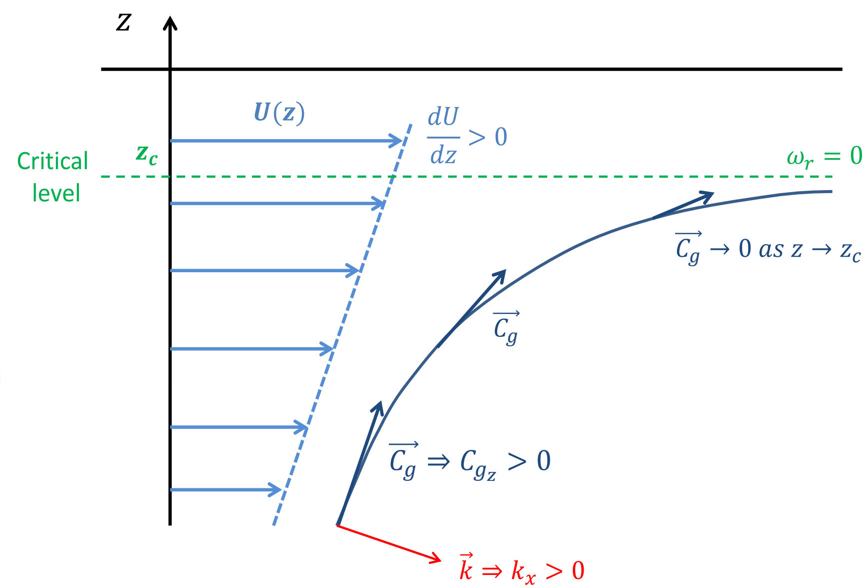
If $k_x U$ increases as the wave propagates, then ω_r decreases.

The z-level for which ω_r = 0 is a critical level.

At that level: * $\omega_0 = k_x U(z_c) \Rightarrow c_0 = U(z_c)$

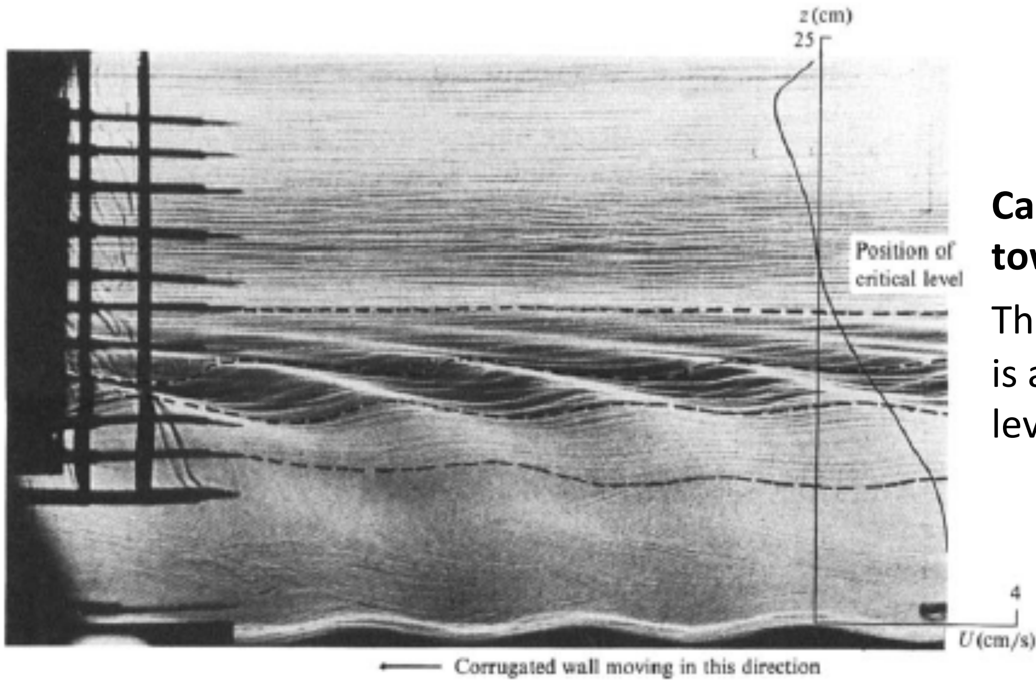
* $k_z \to +\infty$ (from dispersion relation)

* the wave transfers the momentum it transports to the wind → the wind is accelerated at a critical level.



Wave-wind interaction at a critical level

Koop & McGee, J. Fluid Mech., 1986

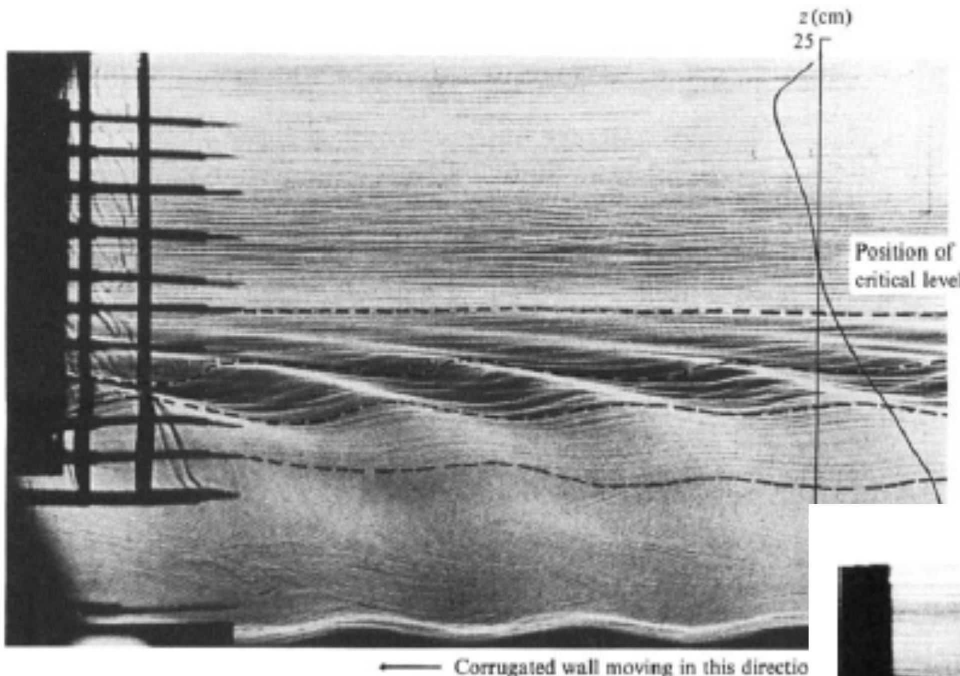


Case 1. λ=7.6cm, h=0.24 cm corrugated wall towed at 2.5 cm/s.

The momentum transported by the wave is absorbed by the mean flow at the critical level.

Wave-wind interaction at a critical level

Koop & McGee, J. Fluid Mech., 1986



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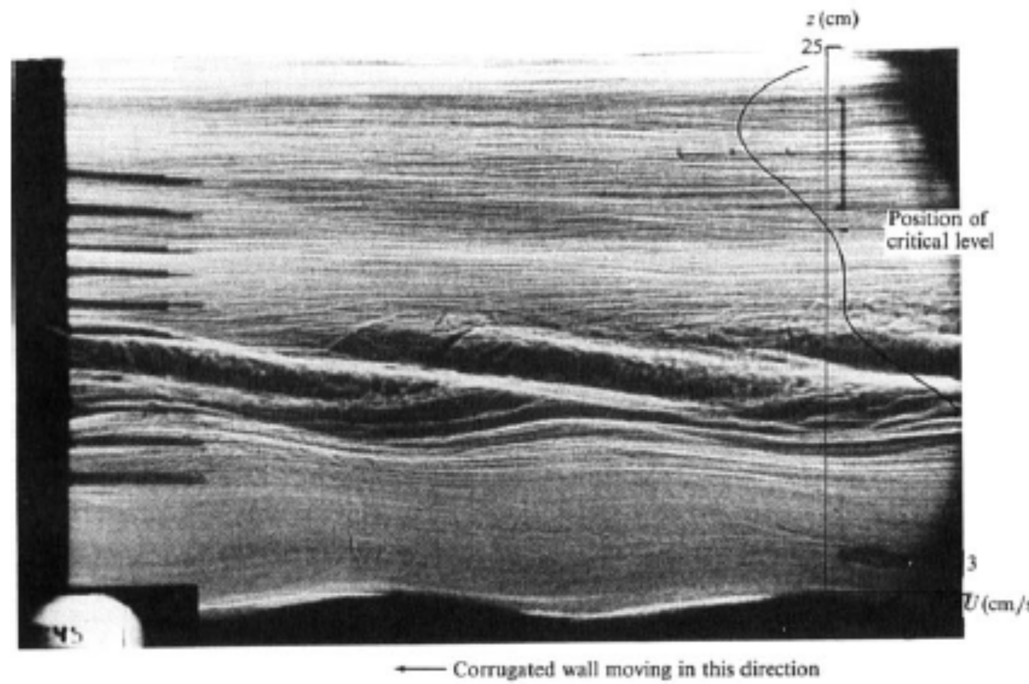


Case 2. λ=15 cm, h=0.48 cm corrugated wall towed at 3.88 cm/s → wave energy flux x 4

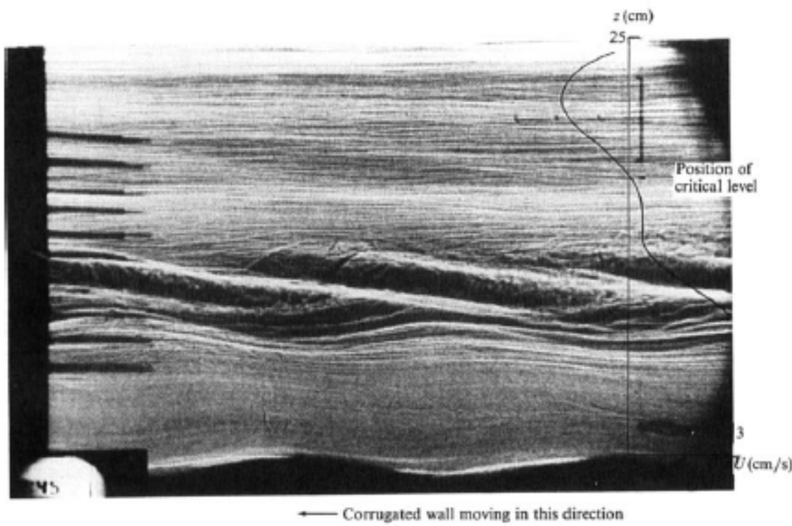
Only part of the momentum transported by the wave is absorbed at the critical level but no transmission occurs beyond that level
→ the wave amplitude increases below the critical level and breaking occurs.

Wave-wind interaction at a critical level

Wave breaking at a critical level

Winters & D'Asaro, J. Fluid Mech., 1994 (3D numerical work)

Results below are those of Winters and D'Asaro (1994)



When a wave packet interacts with a critical level:

-first effect (in time) of the wave upon the fluid is the transfer of momentum to the mean flow (Ri =0.5 at the critical level).

-largest energy sink …

- … which decreases as the initial wave amplitude increases (50% of the incident energy is transferred for weak amplitude, 35% for large amplitude waves).

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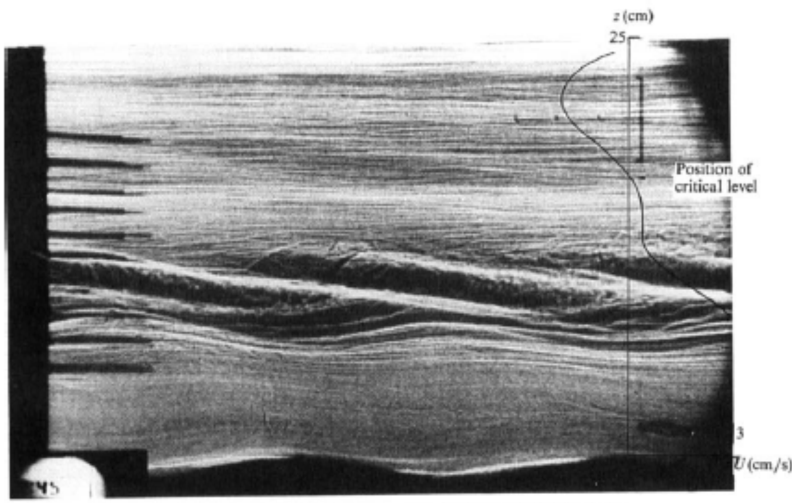

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- … which decreases as the initial wave amplitude increases (50% of the incident energy is transferred for weak amplitude, 35% for large amplitude waves).

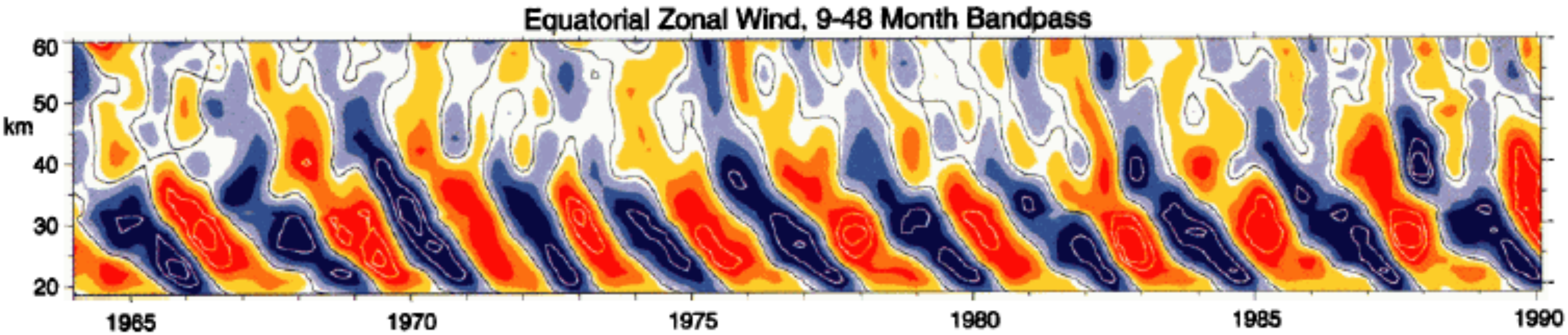
The second most important energetic process is wave reflection, which increases with the wave amplitude (about 35-40%).

The transmitted component remains smaller than a few percents of the initial wave energy, whatever the wave amplitude.

As a consequence, little energy (about 20-25%) is left for energy dissipation, for mixing, and for the production of potential vorticity.

Wave-wind interaction at a critical level: the Quasi-Biennal Oscil.

Quasi-biennal oscillation (QBO): periodic reversal of the wind in the equatorial stratosphere (period: 22 to 34 months, with an average of 28 months).



Time-height diagram of the equatorial wind from 1964 to 1990, as inferred from radio-sounding measurements. Red/blue colour : wind blowing from the west/east. Contour interval is 6 m/s (from Gray et al., Quart. J. Royal Met. Soc., 2001).

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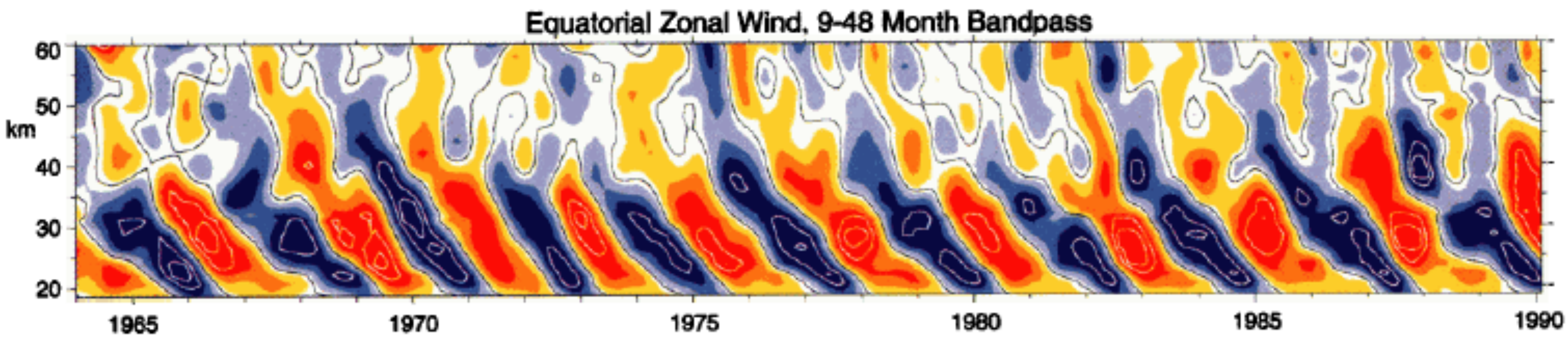


Time-height diagram of the equatorial wind from 1981 to 1991, as inferred from radio-sounding measurements. Red/blue colour : wind blowing from the west/east. Contour interval is 6 m/s (from Gray et al., Quart. J. Royal Met. Soc., 2001)

QBO explained by Lindzen and Holton (J. Atmos. Sci., 1968, 1972):

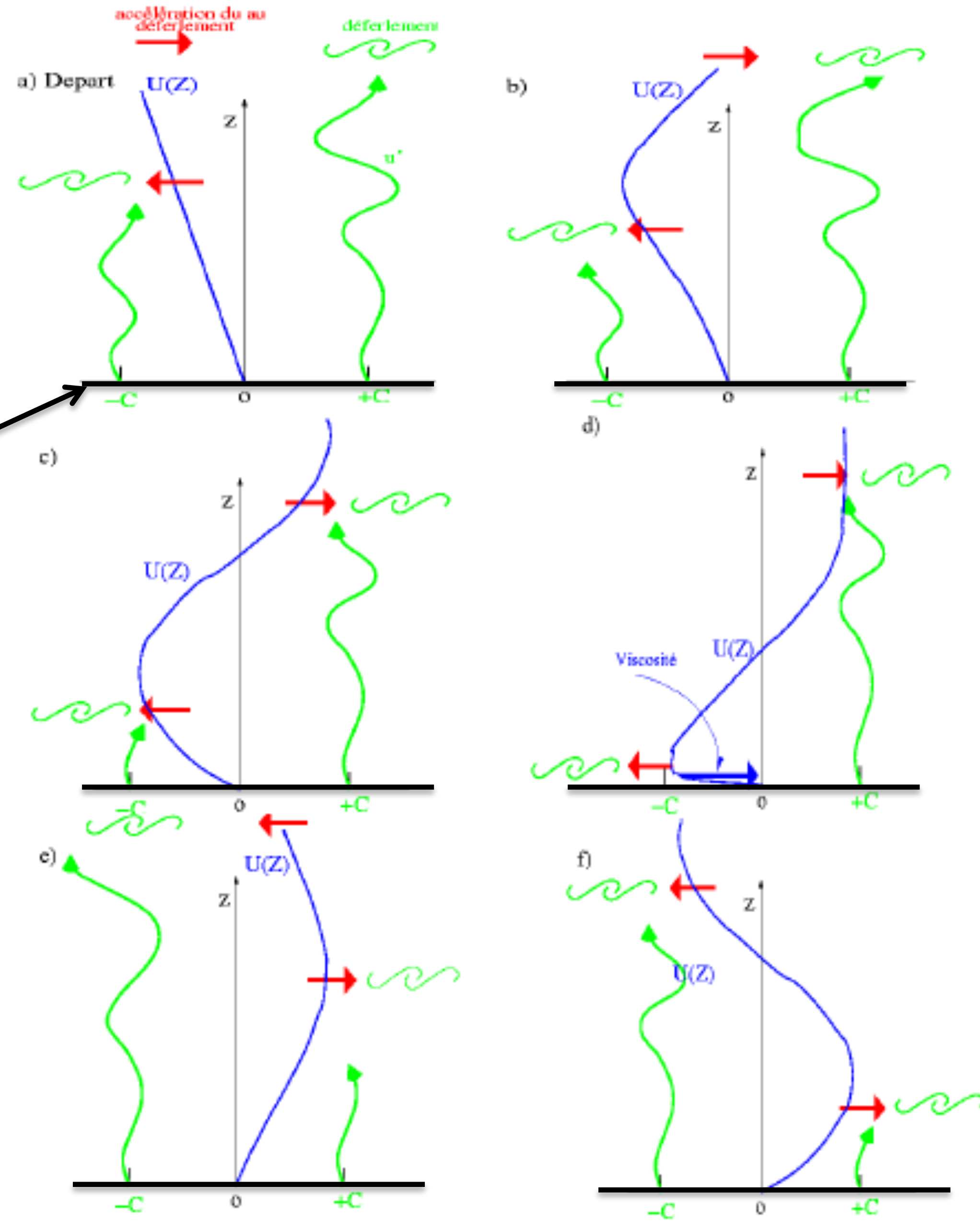
- Emission of internal gravity waves by convective clouds at the equator close to the tropopause.
- These waves propagate upwards in the stratosphere both westward and eastward.
- The deposition of their momentum (at critical levels and by breaking) results in alternating (in time) westward and eastward zonal flows, named the « Quasi-Biennal Oscillation » (QBO)

Sketch of the Quasi-Biennal Oscillation (from Lott 2010)

Internal gravity waves emitted by convection at the propopause:

-c: propagating toward the west
+c: propagating toward the east

Equatorial tropopause (about 15 km altitude)



For reviews on the QBO, see
-- Lindzen, Bull. Amer. Met. Soc., 1987
-- Baldwin et al, J. Geophys. Res., 2001

Momentum deposition by waves : the Brewer-Dobson circulation

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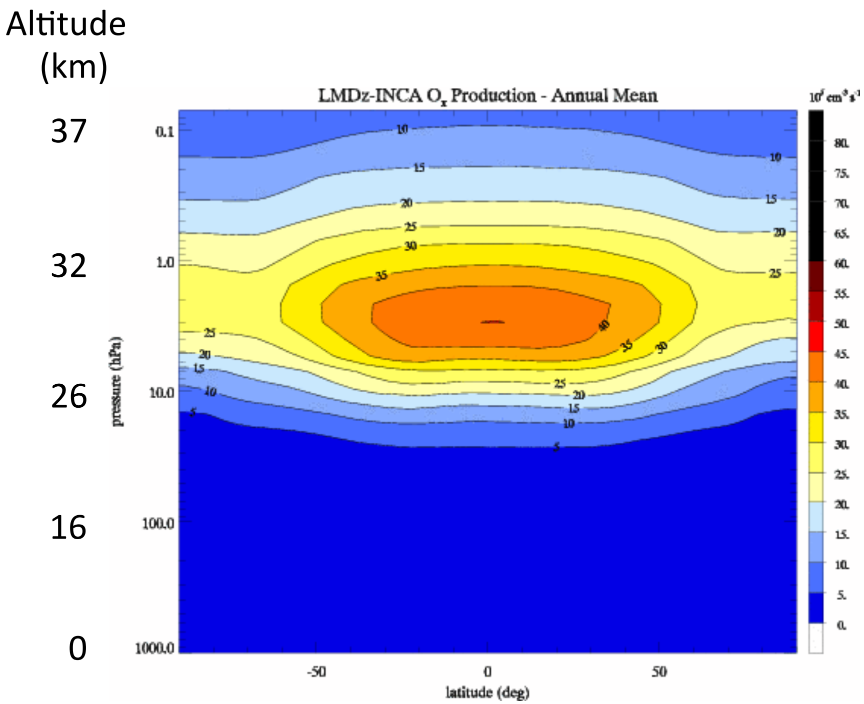
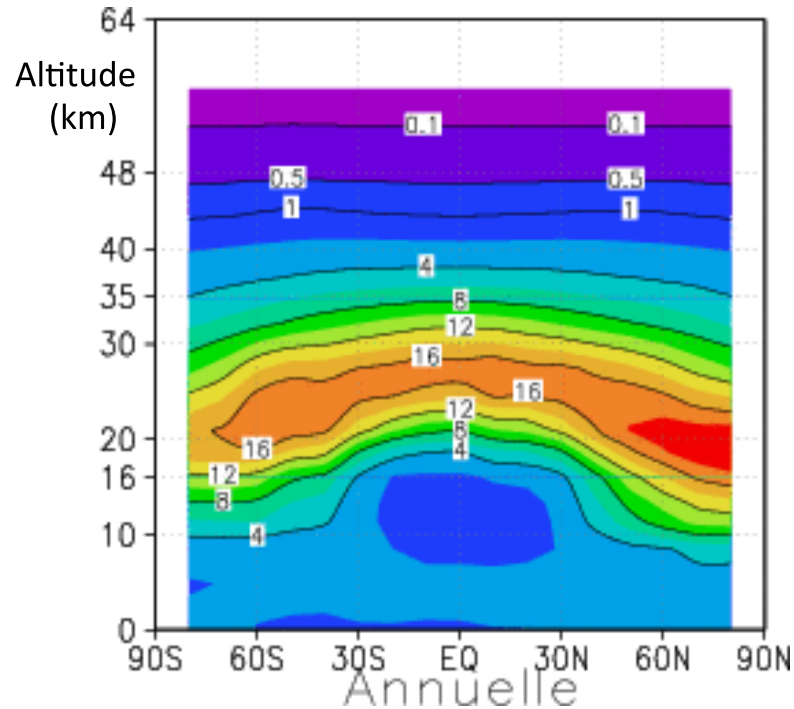
The problem : ozone is mainly produced in the equatorial statosphere but accumulates at much higher latitudes.

How to explain this observation ?



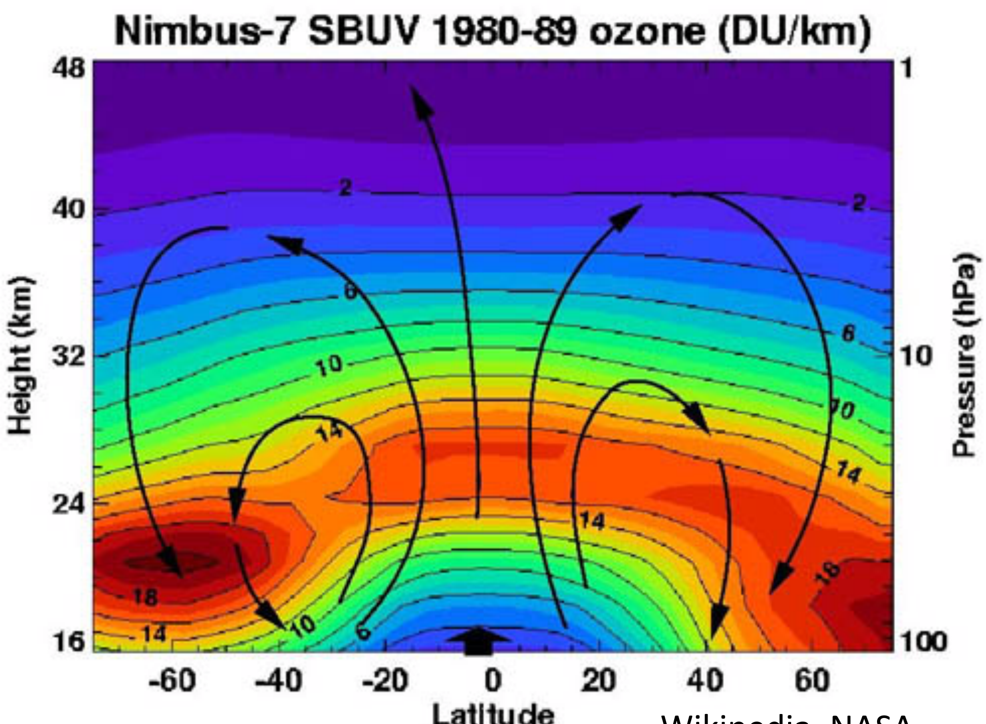
Annual mean production of Ox



Observation of O_3 (annual mean)

Momentum deposition by waves : the Brewer-Dobson circulation

Existence of a slow circulation (w ≈ 0.5 mm/s) conjectured by Dobson et al (Proc. Roy. Soc., 1929):
« the only way in which we could reconcile the observed high ozone concentration in the Arctic in spring and the low concentration in the Tropics, with the hypothesis that the ozone is formed by the action of sunlight, would be to **suppose a general slow poleward drift in the highest atmosphere with a slow descent of air near the Pole.** »



Wikipedia, NASA

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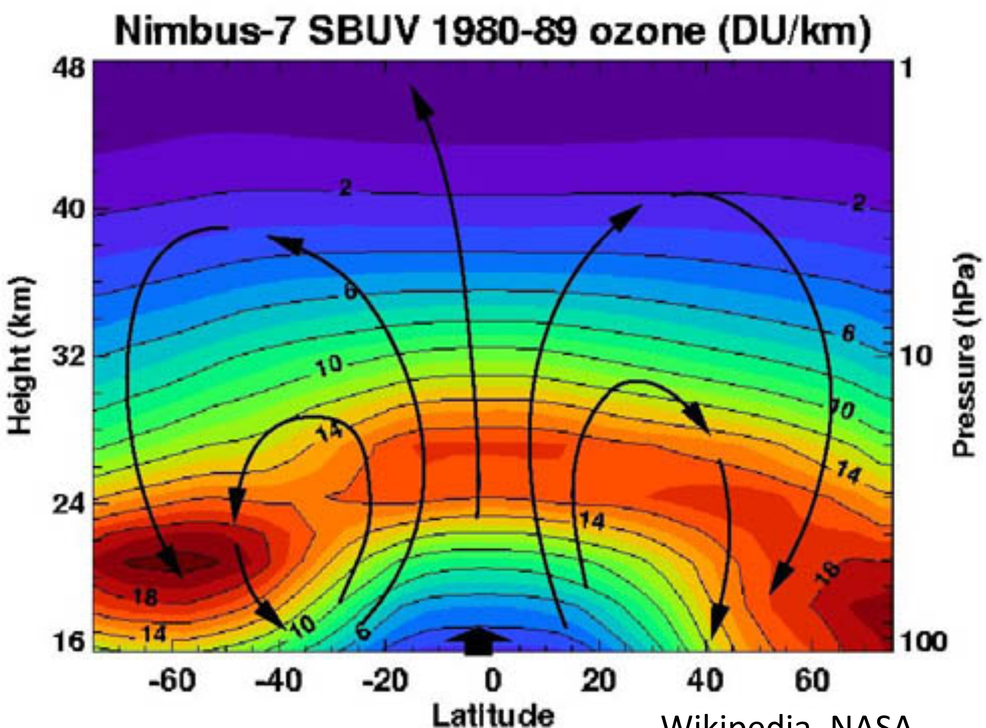

Wikipedia, NASA

Mechanism explained much later, by Andrews and McIntyre (J. Atmos. Sci., 1976) and Dunkerton (J. Atmos. Sci., 1978):
momentum deposition by Rossby waves and internal gravity waves.

For a review on the Brewer-Dobson circulation, see Butchart, Rev. Geophys. 2014

Internal gravity waves: atmosphere vs ocean

The importance of internal gravity waves lies in their impact on the fluid medium.

Internal gravity waves can
-mix the fluid (through breaking)
-deposit the momentum they transport (via dissipation or at a critical level)

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We summarize and point out the differences between atmosphere and ocean.

In the atmosphere, mixing by wave breaking is not very efficient because heat transfer is mainly controlled by radiative effect.
By contrast, **momentum deposition by internal gravity waves** plays a key role in large scale processes: the QBO and the Brewer-Dobson circulation are examples.

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In the ocean, the impact of the waves on the fluid is dominantly through **mixing** (via breaking).
However, momentum should be conserved during a breaking process
→ the waves also deposit the momentum they transport while breaking
→ this **momentum deposition generates a mean flow**.
This mean flow can be seen as the kinematic part of mixing.