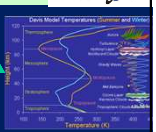
SPECATMOS : "Spectroscopy and Atmosphere: Measurements and Modelling" International Summer School

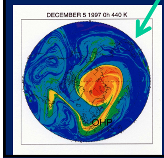
15-20 May 2022 Fréjus (France)

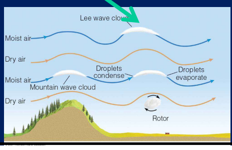
Middle atmosphere dynamics and dynamita models for chemical measurements interpretation

Alain Hauchecorne, LATMOS, CNRS, UVSQ

- Atmospheric structure and circulation
- Atmospheric waves
- High resolution modeling of constituent transport



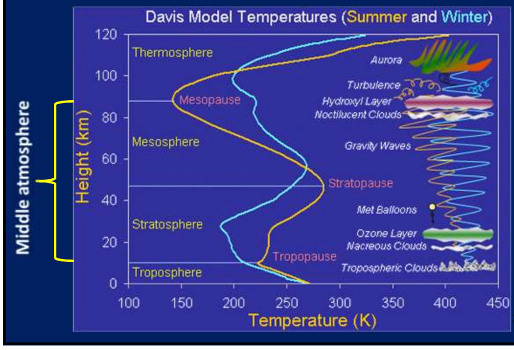




1

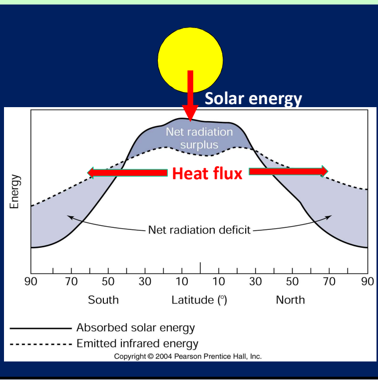
The middle atmosphere

Middle atmosphere = stratosphere + mesosphere, 12 to 90 km



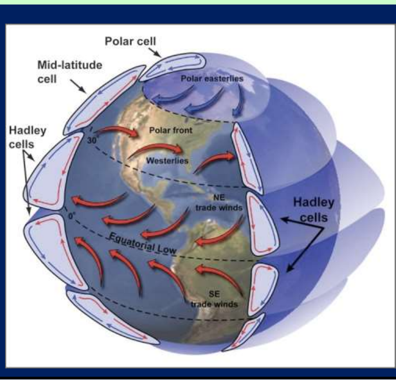
2

Net radiation vs Latitude



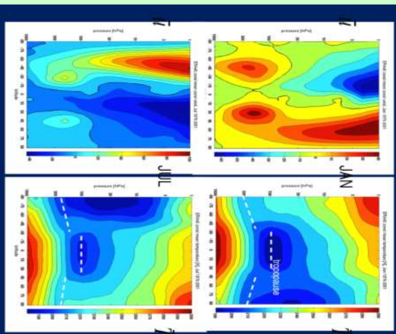
3

Tropospheric circulation



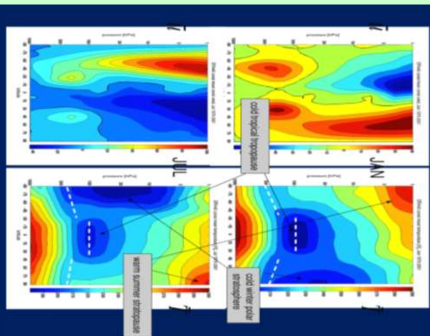
4

Observed zonal averaged temperature and winds



5

Observed zonal averaged temperature and winds

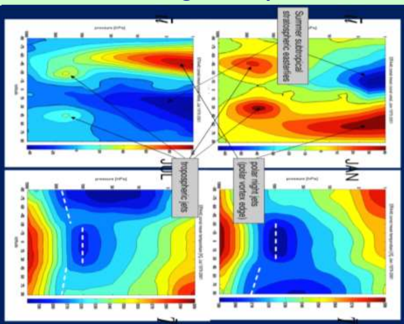


Zonal wind

Temperature

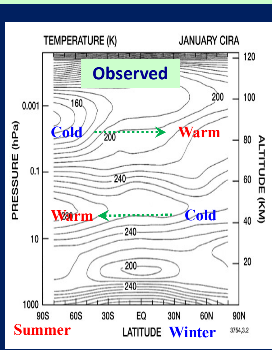
6

Observed zonal averaged temperature and winds



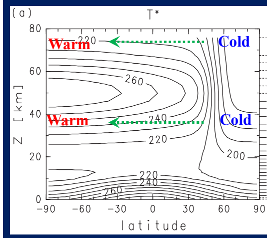
7

Observed temperature and radiative equilibrium



Brasseur and Solomon (2005)
based on Fleming et al., 1998

Radiative equilibrium



Nishizawa and Yoden (2004)

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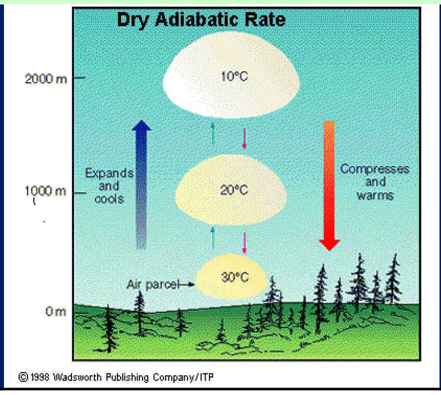
Adiabatic heating/cooling in the atmosphere



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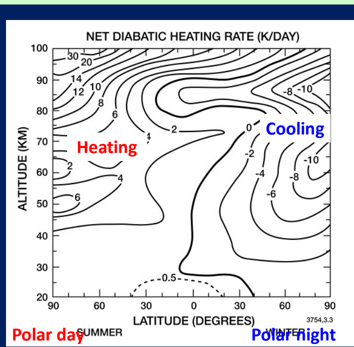
Net adiabatic heating rate (K/day)

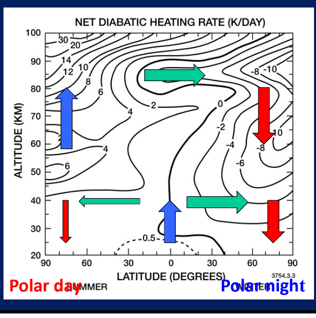


Brasseur and Solomon, 2005; from London, 1980

10

Residual circulation

Diabatic heating (cooling) → vertical ascent (descent) of air
Continuity equation → meridional wind



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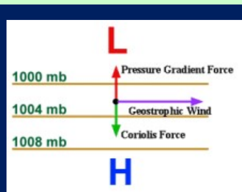
Zonal wind: the geostrophic approximation

Coriolis force equilibrates
Pressure gradient force



Coriolis force = 2 ω sin(latitude)
ω: Earth rotation rate

Wind blows around depression
- anticlockwise in Northern Hemisphere
- clockwise in Southern Hemisphere

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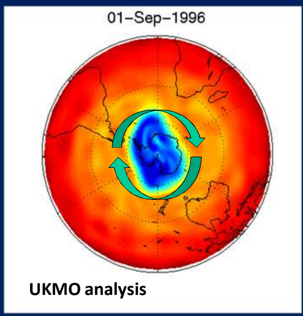
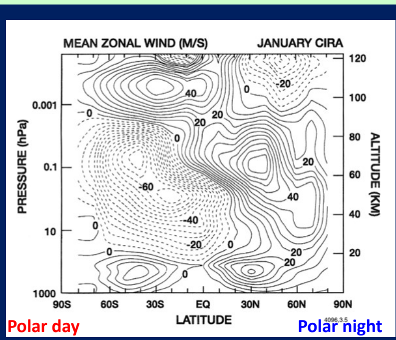
Antarctic polar vortex evolution 1996

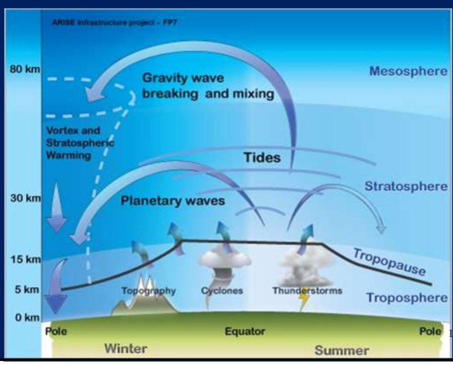


Zonal wind



Brasseur and Solomon, 2005; based on Fleming, 1988

Middle atmosphere radiative balance and general circulation



Atmospheric waves in the atmosphere

Transport energy, momentum flux and atmospheric constituants

Different kinds of waves:

- planetary waves: global scale
- gravity waves: local scale
- atmospheric tides: global scale, diurnal period, solar heating of stratospheric ozone and tropospheric water vapour

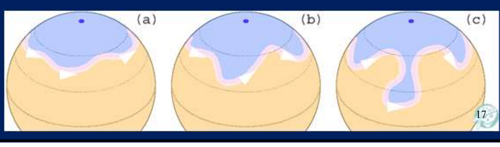
Planetary Rossby waves

Meridional gradient of Coriolis force

Hemispheric extension

Upward propagation possible only if zonal wind > 0 (winter conditions in the stratosphere)

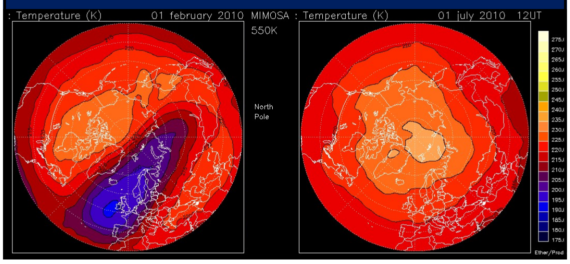
Interaction with zonal wind: stratospheric warming



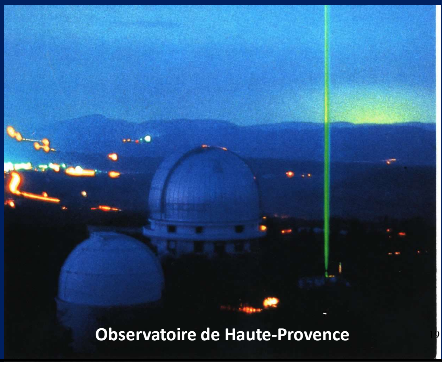
Temperature maps at 22 km

Winter 01/02/2010
Non zonal structure
Planetary waves

Summer 07/01/2010
Zonal structure



Rayleigh lidar observations



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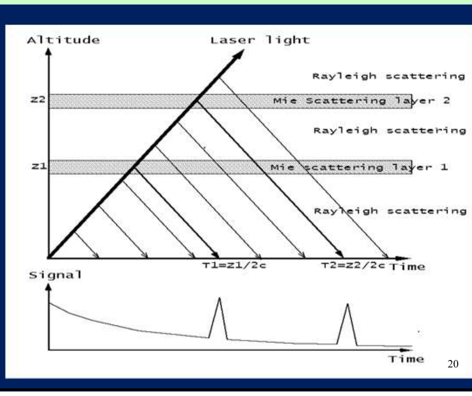
Backscatter lidar principle



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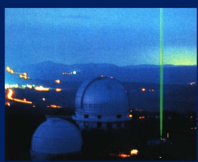
Temperature measurements using Rayleigh Lidar

- Required pure molecular scattering
- Density and pressure are relative measurements
- Temperature is absolute

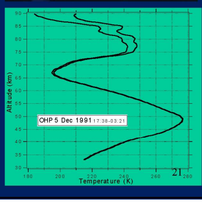


$$\rho(z) = f(N(z))$$

$$dP(z) = -g(z)\rho(z)dz$$

$$T(z) = \frac{MP(z)}{R\rho(z)}$$

$$T(z) = \frac{M}{R}\frac{\sum_{0}^{z} g\rho(z')dz'}{\rho(z)} = \frac{Mg(z)}{R}\frac{\sum_{z}^{top} N(z')dz'}{N(z)}$$



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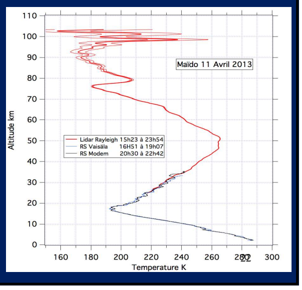
Temperature lidar profile At Maïdo Observatory, Reunion Island



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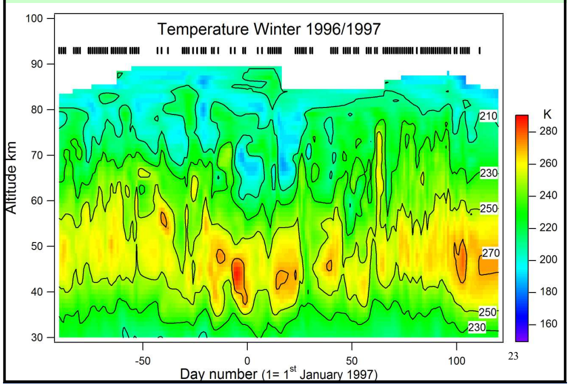
OHP temperature evolution in winter 1996/97



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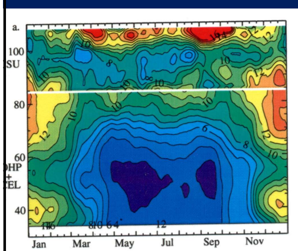
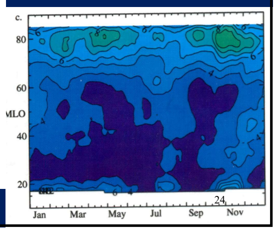
Temperature variability

Middle latitude (44° N)



Leblanc et al.

Tropics 21° N



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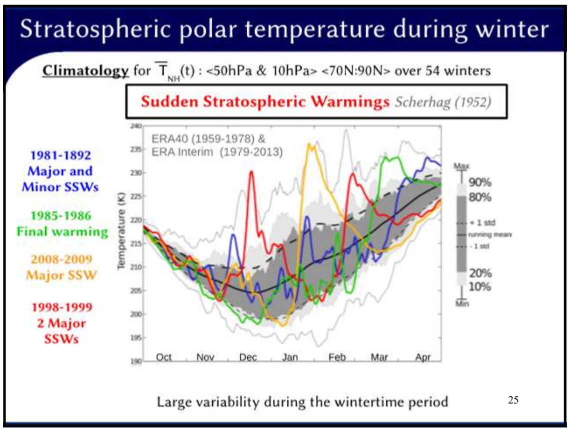
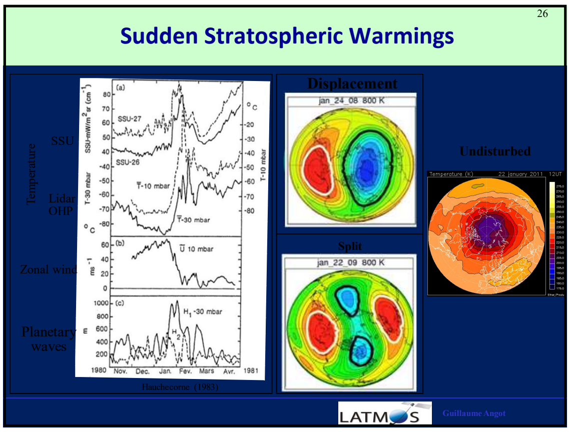

Stratospheric polar temperature during winter
Climatology for $\overline{T}_{NH}(t)$: <50hPa & 10hPa> <70N:90N> over 54 winters
Sudden Stratospheric Warmings Scherhag (1952)
1981-1892 Major and Minor SSWs
1985-1986 Final warming
2008-2009 Major SSW
1998-1999 2 Major SSWs
ERA40 (1959-1978) & ERA Interim (1979-2013)
Temperature (K)
Oct Nov Dec Jan Feb Mar Apr
Max 90% 80% 20% 10% Min
Large variability during the wintertime period
25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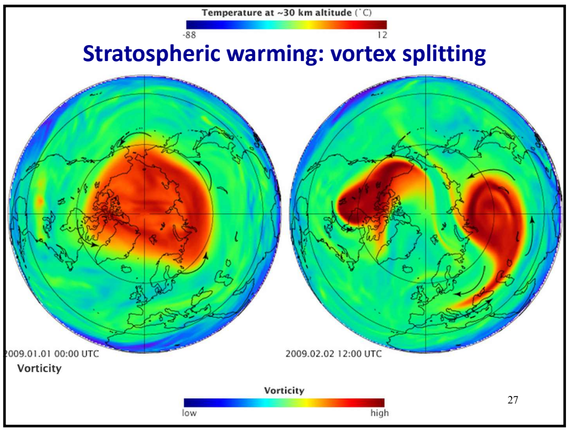
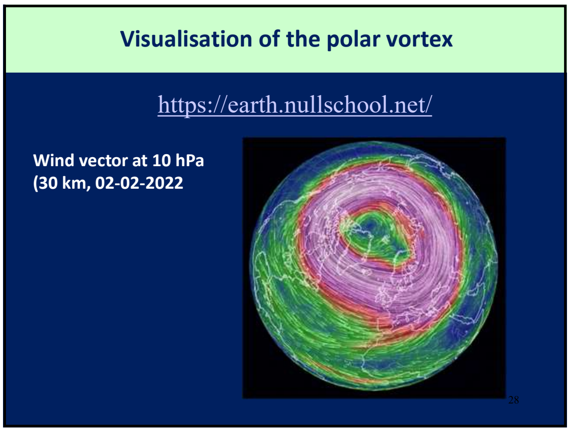
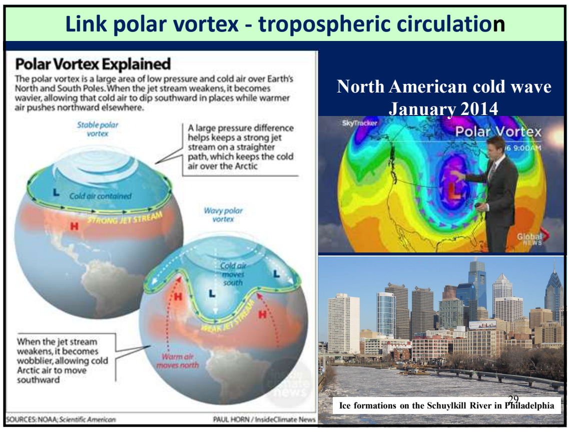
Sudden Stratospheric Warmings
Displacement
Undisturbed
Split
Temperature
SSU
Lidar OHP
Zonal wind
Planetary waves
LATMOS
Guillaume Angot


Temperature at ~30 km altitude (°C)
Stratospheric warming: vortex splitting
2009.01.01 00:00 UTC
2009.02.02 12:00 UTC
Vorticity
low high
27


Visualisation of the polar vortex
https://earth.nullschool.net/
Wind vector at 10 hPa
(30 km, 02-02-2022
28


Link polar vortex - tropospheric circulation
Polar Vortex Explained
The polar vortex is a large area of low pressure and cold air over Earth's North and South Poles. When the jet stream weakens, it becomes wavier, allowing that cold air to dip southward in places while warmer air pushes northward elsewhere.
Stable polar vortex
A large pressure difference helps keeps a strong jet stream on a straighter path, which keeps the cold air over the Arctic
Wavy polar vortex
When the jet stream weakens, it becomes wobblier, allowing cold Arctic air to move southward
SOURCES: NOAA; Scientific American
PAUL HORN / InsideClimate News
North American cold wave
January 2014
Polar Vortex
Ice formations on the Schuylkill River in Philadelphia
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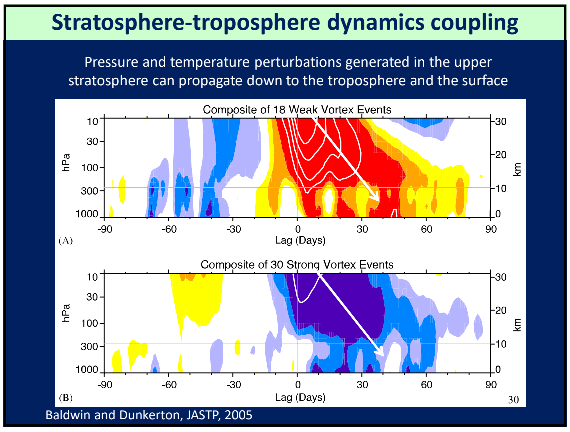
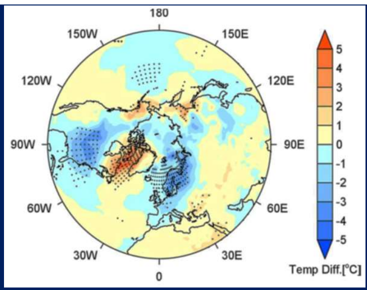

Stratosphere-troposphere dynamics coupling
Pressure and temperature perturbations generated in the upper stratosphere can propagate down to the troposphere and the surface
Composite of 18 Weak Vortex Events
Composite of 30 Strong Vortex Events
hPa
km
Lag (Days)
Baldwin and Dunkerton, JASTP, 2005
30

Impact of SSW on medium range weather forecast

Surface temperature 15 to 30 days after a Strat Warm event
Averaged over 15 SSWs



Charlton Perez et al., 2015

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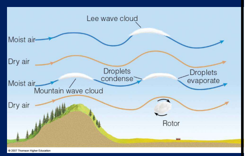
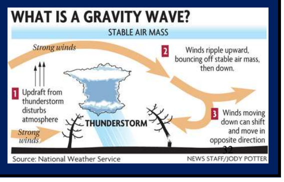
Gravity waves

Gravity force

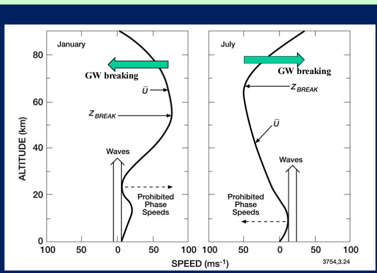
Local extension (10 à 1000 km)

Main sources
- Orography (Lee waves)
- Deep convection
- Jet stream (geostrophic adjustment)





Gravity wave propagation and breaking



Brasseur and Solomon, 2005; from Lindzen, 1981

Gravity wave breaking → wind deceleration → Vertical and meridional wind
→ summer mesosphere cooling and winter mesosphere warming

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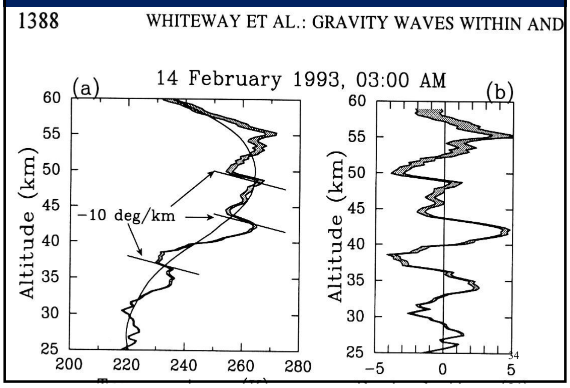

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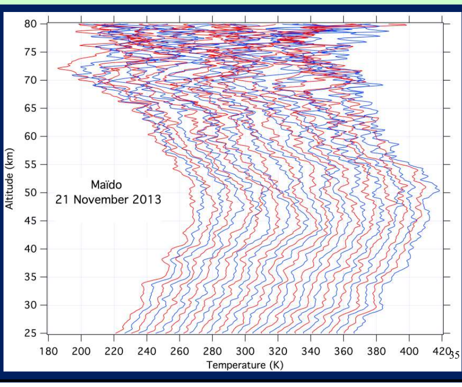
Temperature profile evolution during one night



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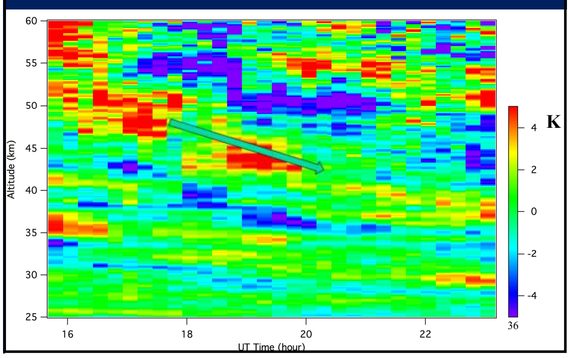
Temperature anomaly: gravity wave propagation



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GW characterization

NDACC Rayleigh Temperature lidars: from the variance of lidar signal fluctuations at OHP

COSMIC-GPS radio-occultation: from the fluctuations in temperature profiles in a 10° longitude by 5° latitude box around OHP

Radiosoundings: from the fluctuations in temperature profiles at Nîmes (100 km from OHP)

GW potential energy per unit of mass $E_p = \frac{1}{2}\left(\frac{g^2}{N^2}\right)\left(\frac{T'}{T}\right)^2$

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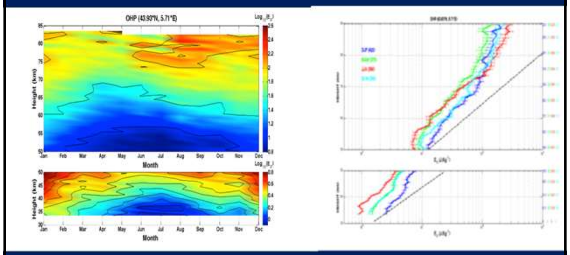
Climatology of GW potential energy from OHP lidar data



Mze et al., JGR, 2014

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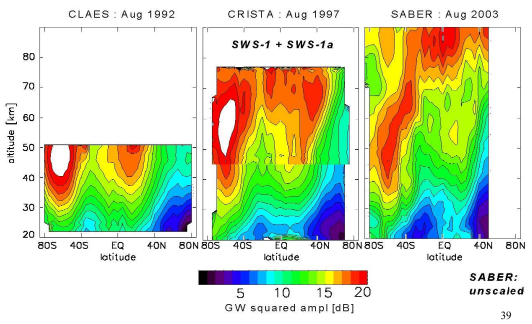
Gravity waves observed from space



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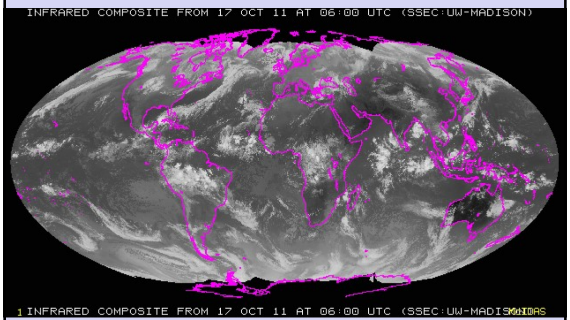
Preusse, 2006

Infrared composite from geostationary satellites



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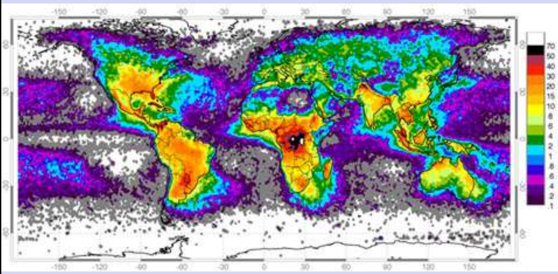
Lightning activity, NASA TRMM satellite 11 year average



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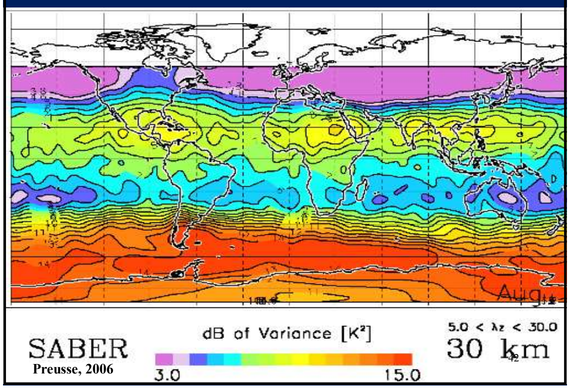

Preusse, 2006

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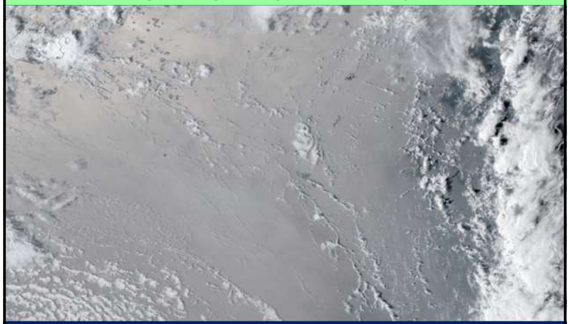
Hunga Tonga eruption, 15 July 2022



Credit: NASA Worldview/NOAA/NESDIS/STAR

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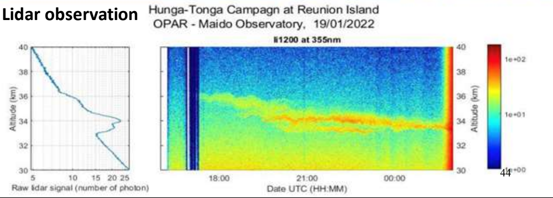
Hunga Tonga stratospheric injection

Credit Valentin Duflot
Reunion University

Lidar observation



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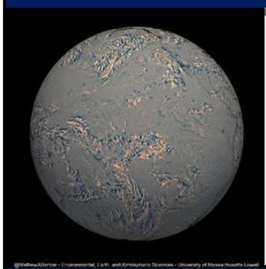
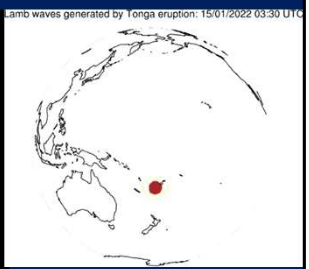
Hunga Tong Lamb waves





Satellite IR observation
Credit Mathew Barow

Lamb waves simulation
Credit Nedjeljka Žagar

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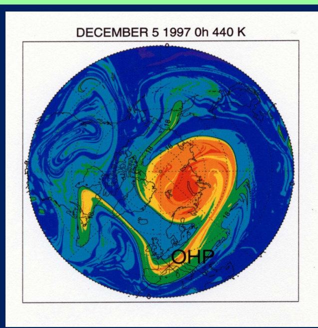
High resolution modeling of constituent transport : MIMOSA model



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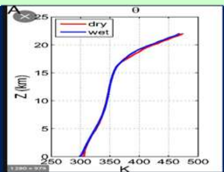
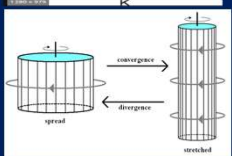
Potential temperature (Θ) and potential vorticity (PV)

$$\theta = T\left(\frac{1000}{P}\right)^{\frac{R_d}{C_p}}$$



$$PV = g\left\{\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)_\theta + f\right\}\left|\frac{\partial \theta}{\partial p}\right|$$



In absence of diabatic effects, an air mass is moving along isentropic surfaces (constant Θ) and its PV is conserved

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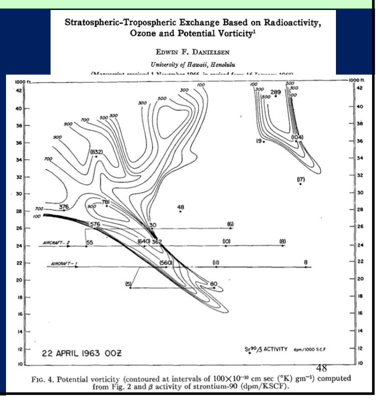
Relation tracer-PV

Danielsen (1968)

First evidence :
Increase of ozone and radioactivity in a tropopause folitation



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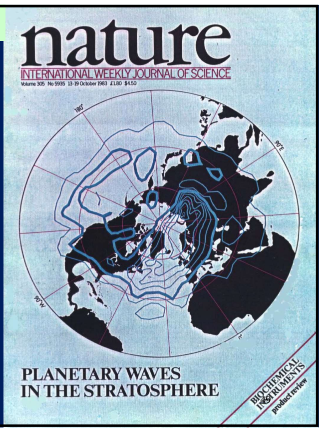
PV and polar vortex

First use of PV conservation to study the polar vortex dynamicspolaire

McIntyre and Palmer, Nature, 1983

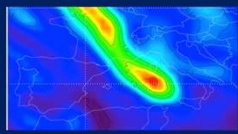


Motivation to use MIMOSA for transport studies of stratospheric species

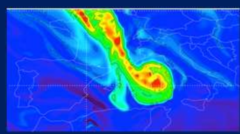
Better representation of filamentary structures than ECMWF PV (horizontal resolution and continuity of structures)

Advected PV more correlated with atmospheric species (O3, N2O, CH4, ..) than ECMWF dynamical PV (dynamical dissipation)

MIMOSA maps easy to use on AERIS/ESPRI for non-dynamicists



25/09/2006 18UTC , PV 315K ECMWF 1.125



25/09/2006 18UTC , PV 315K MIMOSA 1.125 Claud et al., 2007

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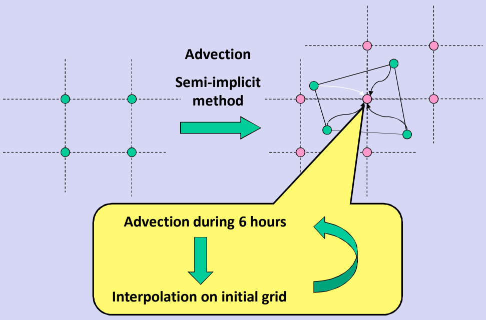
Advection and regridding



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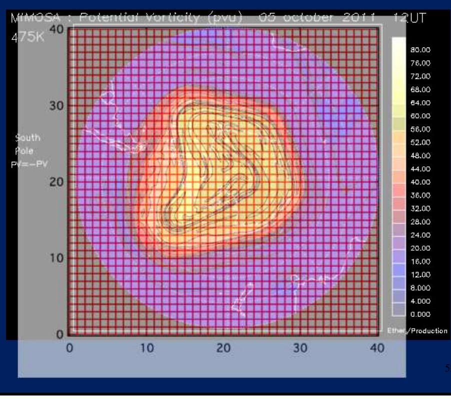

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MIMOSA model principle

Advection of potential vorticity at high horizontal resolution

Potential vorticity (PV) considered as quasi-passive tracer on isentropic surfaces in the stratosphere during 1 to 3 weeks

→Indicator of transport, good correlation with long lived species (i.e. ozone in the lower stratosphere)

In MIMOSA PV transported by Winds from meteorological analyses (ECMWF)

Relaxation toward ECMWF PV at large scale, time constant10 days (to take into account diabatic effects)

Hauchecorne et al., J. Geophys. Res., 107(D20), 8289, 2001

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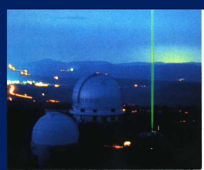
Projet EC-FP5 METRO-THESEO 1999-2000

Objective: to study the meridional transport of ozone in the lower and middle stratosphere (vortex filamentation, tropical intrusions)

Tools:
Lidar ozone ALTO on board French Falcon IGN-INSU
Lidar ozone at Observatoire de Haute-Provence
Need to have a isentropic transport model for the planning of aircraft flights and the interpretation



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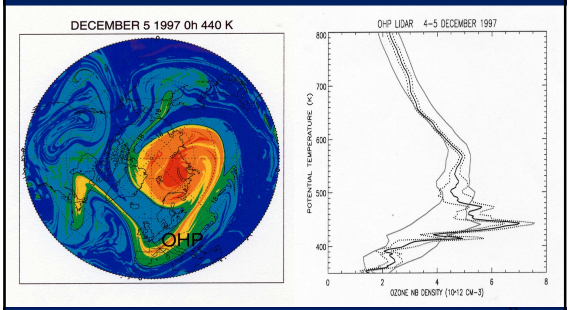
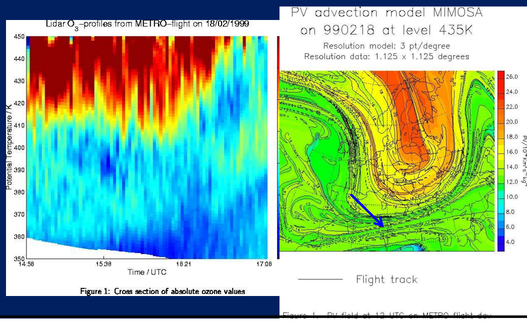
Polar filament seen by the OHP ozone lidar

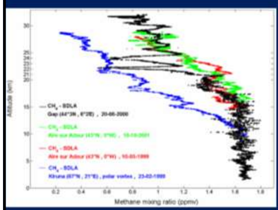


EU-METRO campaign airborne lidar ozone ALTO
Heese et al., JGR 2001

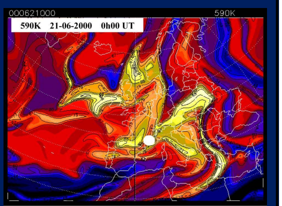


Evidence of polar air fragments in middle latitude summer stratosphere

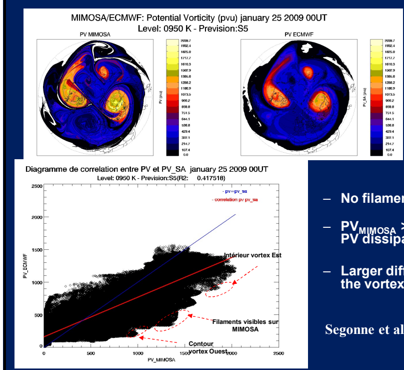
SDLA CH_4 balloon profiles



MIMOSA map at 590K



Durry and Hauchecorne, ACP, 2005

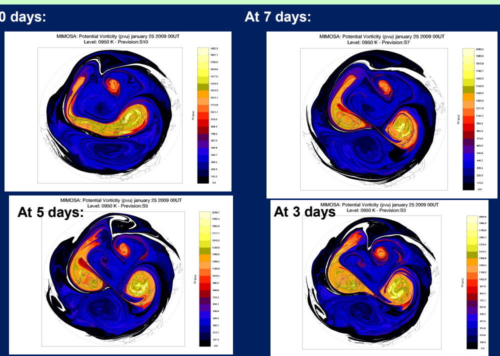


- No filaments visible on PV_{ECMWF}
- $PV_{MIMOSA} > PV_{ECMWF}$ (dynamical PV dissipation during SSW)
- Larger differences at the edge of the vortex and in filaments

Segonne et al., MIMOSA-VAE project

MIMOSA use in forecast mode

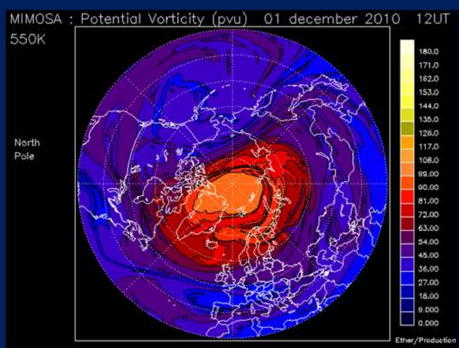
At 10 days: At 7 days:



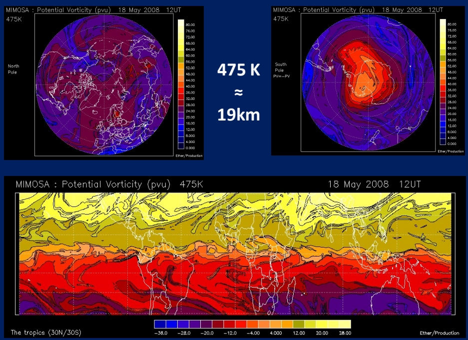
- Vortex split forecasted up to 7 days in advance

Segonne et al., MIMOSA-VAE project

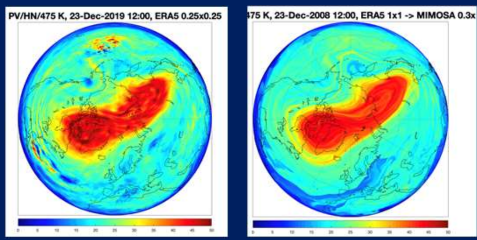
Polar vortex evolution



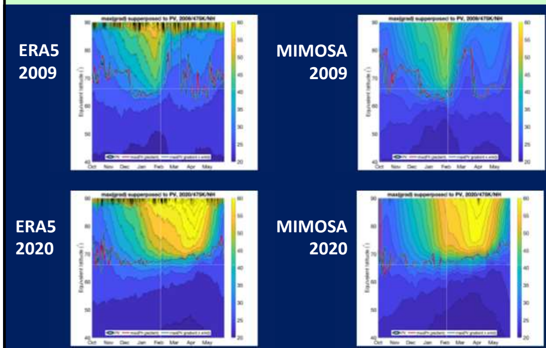
MIMOSA on AERIS/ESPRI database



Vortex edge determination



Evolution of vortex edge



Lecouffe et aal., 2022

MIMOSA service on AERIS/ESPRI

Daily production of PV and Temperature maps from High Resolution Transport Model MIMOSA

Archive access

- MAPS :
- 2011
- 2009 - 2010
- 2007 - 2008
- 2005 - 2006

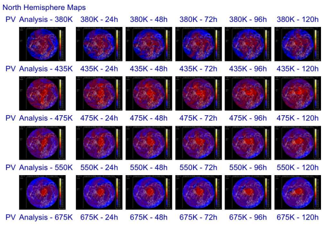
- DATA :
- Data 2011
- Data 2010
- Data 2009
- Data 2008
- Data 2007
- Data 2006
- Data 2005

- MIMOSA high/low resolution

MIMOSA (Modélisation Isentrope du transport Méso-échelle de l'Ozone Stratosphérique par Advection) high resolution advection model of potential vorticity (PV) has been developed at Service d'Aéronomie in the frame of the European Union project METRO (MEridional TRansport of Ozone in the lower stratosphere) which was part of THESEO (Third European Stratospheric Experiment on Ozone) 2000 campaigns. A full description of MIMOSA is given in Hauchecorne et al. [2001].
The model runs on an isentropic surface, starting on an orthogonal grid in an azimuthal equidistant projection centered at North or South Pole (parallels are represented as concentric equidistant circles). It covers latitudes between 90°S and 90°N in the present version. The size of an elementary grid cell 37*37 km (3 grid points/degree of latitude).

- Potential vorticity and temperature forecasts from 19 October (J) to day J+5

North Hemisphere Maps



Scientific coordinator: Alain Hauchecorne (LATMOS)
Technical coordinator: Cathy Boonne (IPSL)