AGE OF AIR IN ERA-INTERIM AND HEATING RATES

Bernard Legras and Stefan Füglistaler
Laboratoire de Météorologie Dynamique, ENS and CNRS, Paris, France
(legras@lmd.ens.fr, S.Fueglistaler@damtp.cam.ac.uk)

The age of air, that is the residence time of an air parcel in the stratosphere , is a measure of the Brewer-Dobson circulation. The ability of GCM or analysed winds to reproduce this quantity is a pre-requisite for the representation of transport and distribution of long-lived species in the stratosphere.

Data used in this study

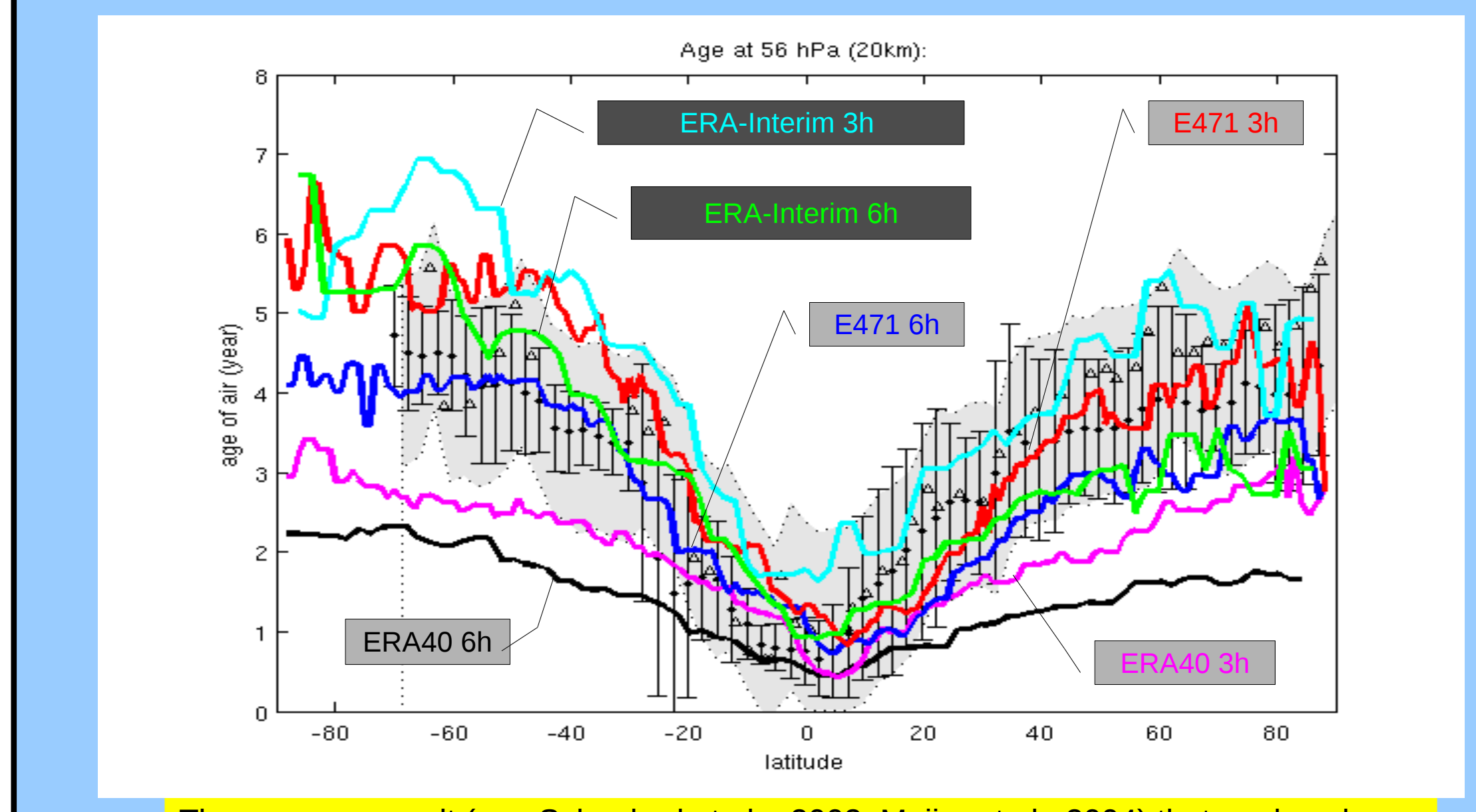
ERA-40 reanalysis from ECMWF (Uppala et al., 2005) over the period 1997-2001: cycle 23 of IFS model, 3D-Var assimilation, static bias correction, T159, 60 levels for winds and temperature, 240x480x61 Gaussian grid for heating rates.
Intermediate reanalysis (Exp471) for 2000: cycle 29 of IFS model, 4D-Var assimilation, VarBC, same resolution as ERA-40. Also used by Monge-Sanz et al., 2007
ERA Interim reanalysis from ECMWF over the period 1996-1998: cycle 31 of IFS model, 4-D Var assimilation, VarBC, T255, 60 levels (see ECMWF newsletters 110 & 115)

Wind and temperature are retrieved every 6h from analysis. 3h forecasts for ERA40, 3h and 9h forecasts for IRA, are used to generate 3-hourly datasets.
Vertical velocity is calculated from integration of mass conservation equation (FLEXPART procedure).
Heating rates are retrieved every 3h from short range forecasts

Age of air estimated from backward Lagrangian trajectories.

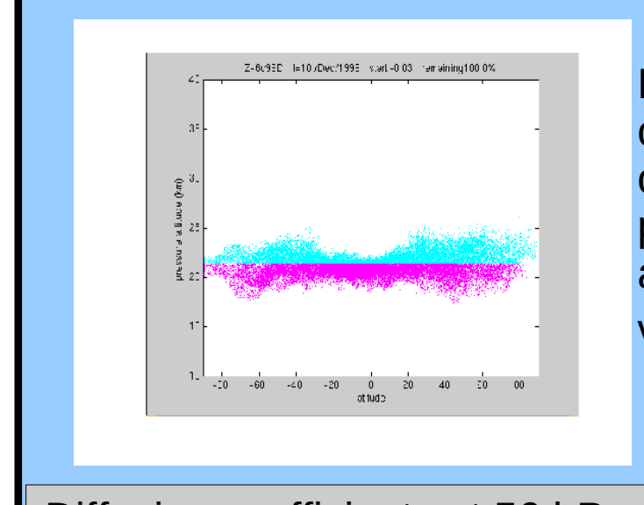
Observed ages mainly from SF6 and CO2 data (Boering et al., 1996; Elkins et al., 1996, Harnisch et al., 1996; Andrews et al., 2001; Waugh et al., 2002; Monge-Sanz et al., 2007).

Age of air calculated with 2000 perpetuals* using diabatic heating rates corrected to cancel the mean vertical mass flux and horizontal isentropic mass divergence modified to balance the heating rates .



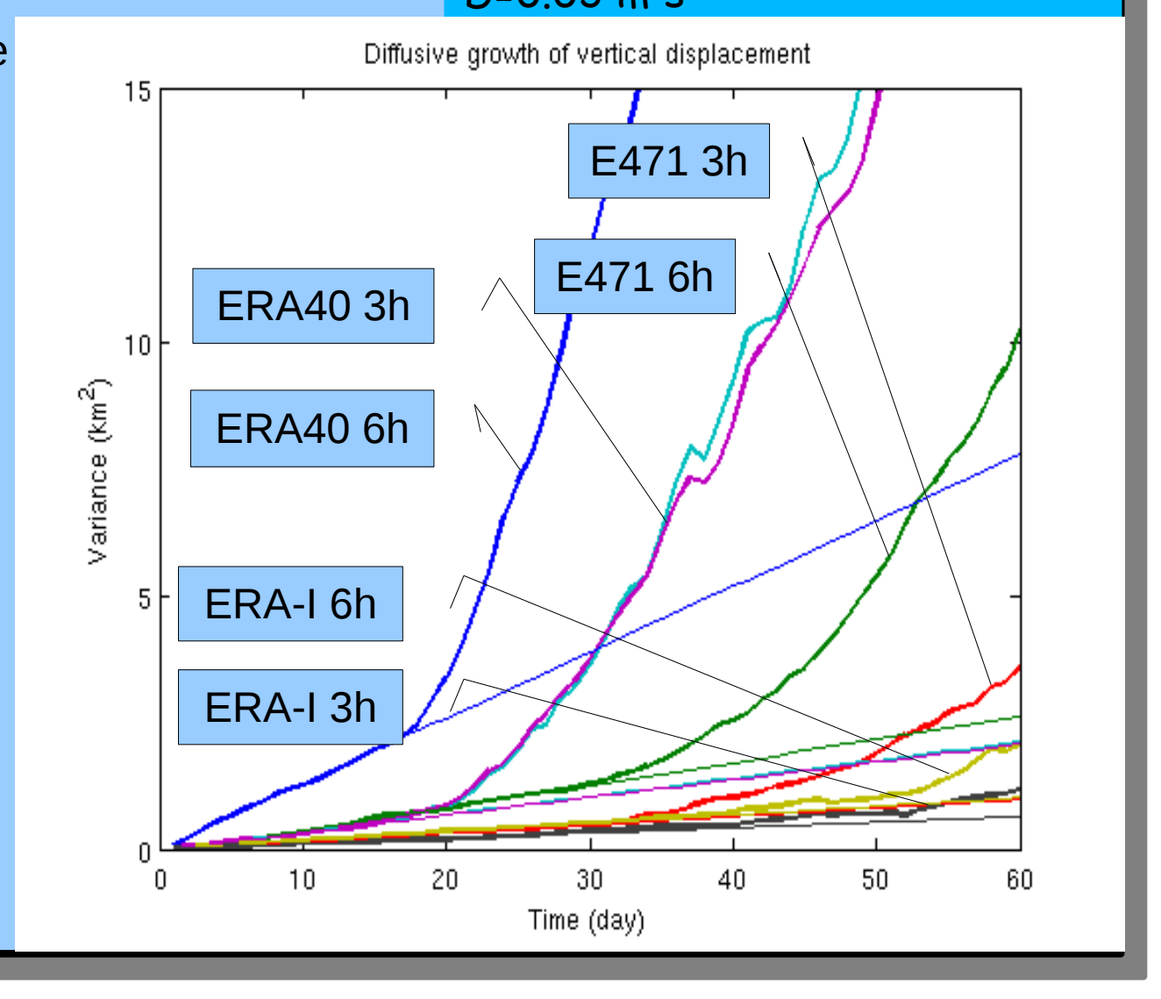
The common result (e.g. Schoeberl et al., 2003, Meijer et al., 2004) that analysed velocities provide too young ages of air is challenged by recent developments in weather forecast models and assimilation.
However, using 3-hourly winds instead of 6-hourly winds is highly recommended.

* actually 15 years and extrapolation of ages done as in Scheele et al., 2005



Random motion of a large number of independent particles average as diffusion variance ≈ 2 D t

Diffusive coefficients from ERA-Interim heating rates in 15S-15N
$(\delta \log \theta)^2 = 1.15\ 10^{-5}\ t(\text{days})$
$D = 0.03\ m^2 s^{-1}$



Diffusive coefficients at 56 hPa 15S-15N

ERA40 6h	$D=0.75\ m^2s^{-1}$
ERA40 3h	$D=0.20\ m^2s^{-1}$
E471 6h	$D=0.26\ m^2s^{-1}$
E471 3h	$D=0.097\ m^2s^{-1}$
ERA-I 6h	$D=0.098\ m^2s^{-1}$
ERA-I 3h	$D=0.062\ m^2s^{-1}$

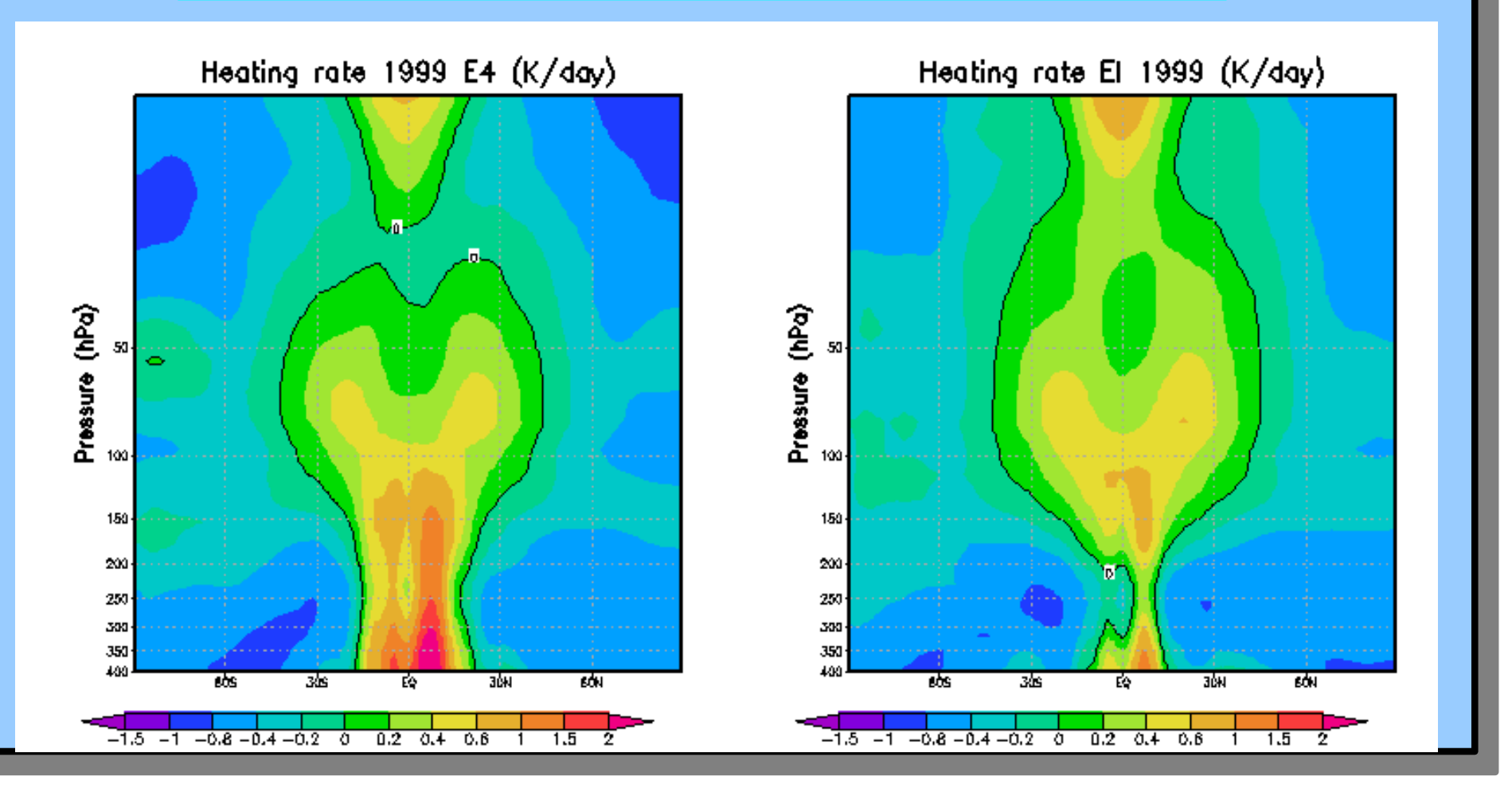
Heating rates in the ECMWF model

$$\frac{DT}{Dt}=\frac{\partial T}{\partial t}+\boldsymbol{u}\cdot\nabla_{h}T+\omega\frac{\partial T}{\partial p}=\frac{K T_v \omega}{(1+(\delta-1)q)p}+H_v$$

where H_v includes radiative, convective and diffusive contributions.
In terms of potential temperature

$$\frac{D\theta}{Dt}=Q_v=\left(\frac{p}{p_0}\right)^{\kappa}H_v$$

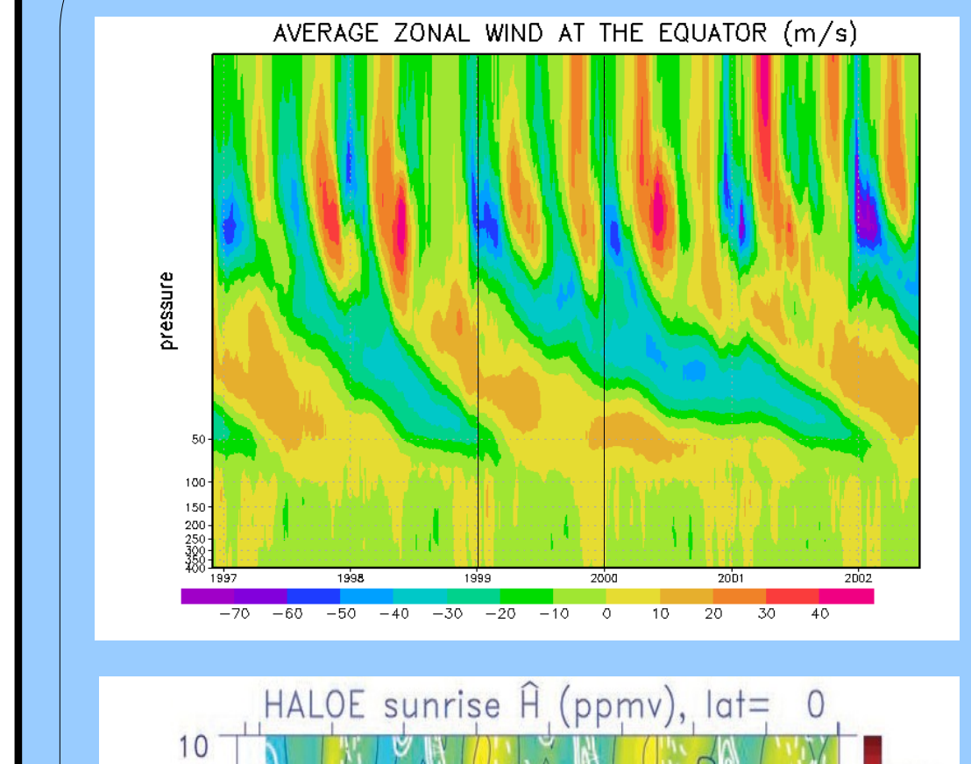
Annual zonally average heating rate H_v in 1999
↙ ERA-40 ERA -Interim ↘

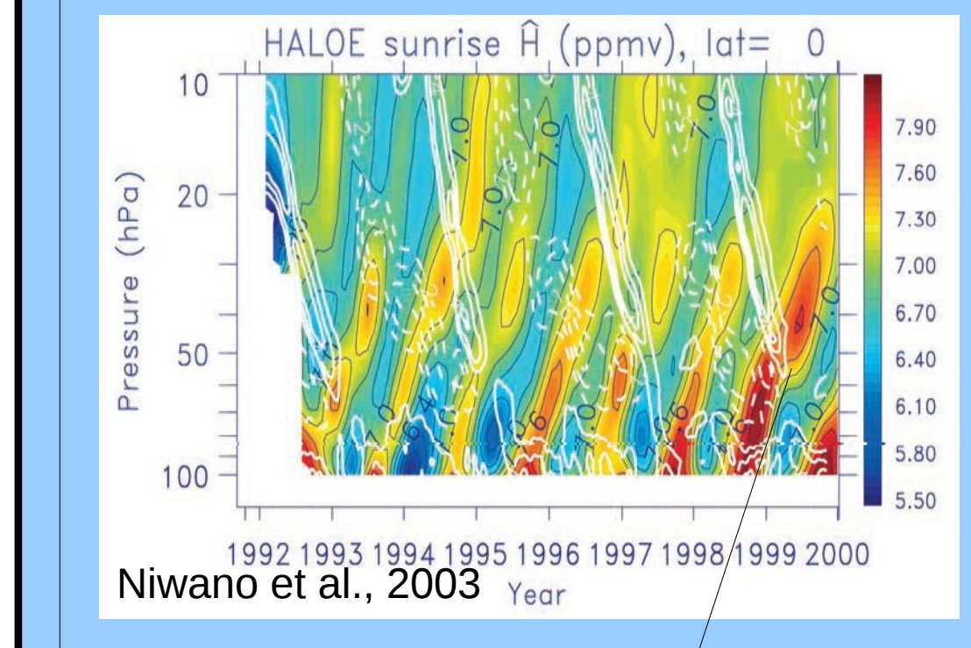


ERA-40 equatorial total heating rate exhibits a mimima near 30 hPa which can be negative over extended periods (depending on the phase of the QBO)
⇒ blocking of the Brewer-Dobson circulation

Variability

QBO



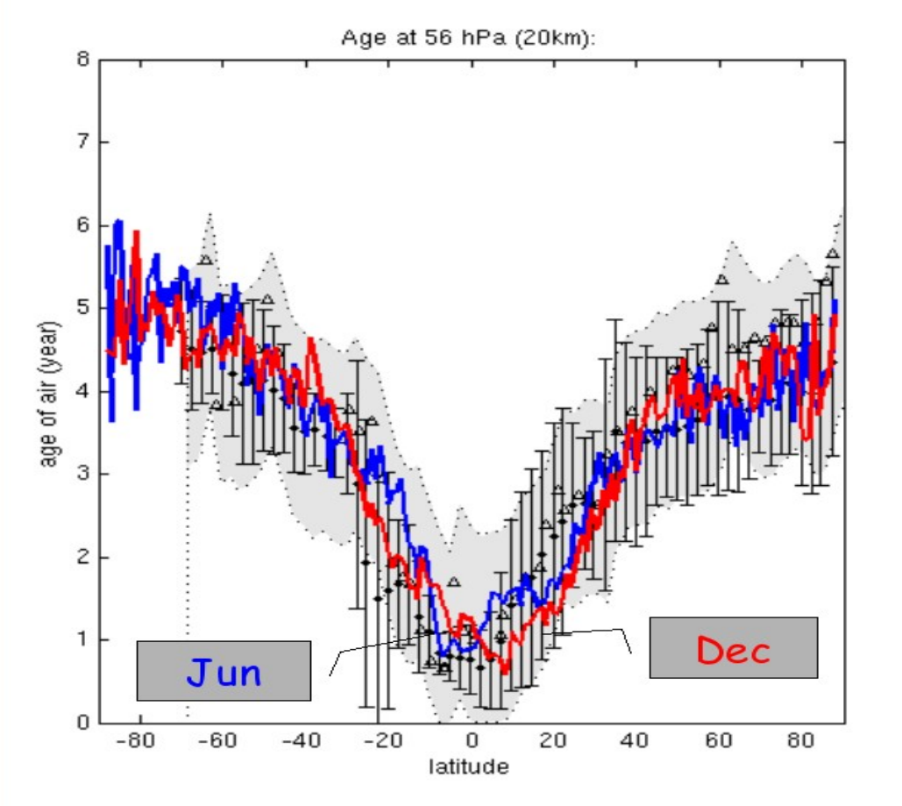


Niwano et al., 2003

1999: eastward shear positive T anomaly
⇒ cooling anomaly
⇒ slow ascent

Weakened ascent

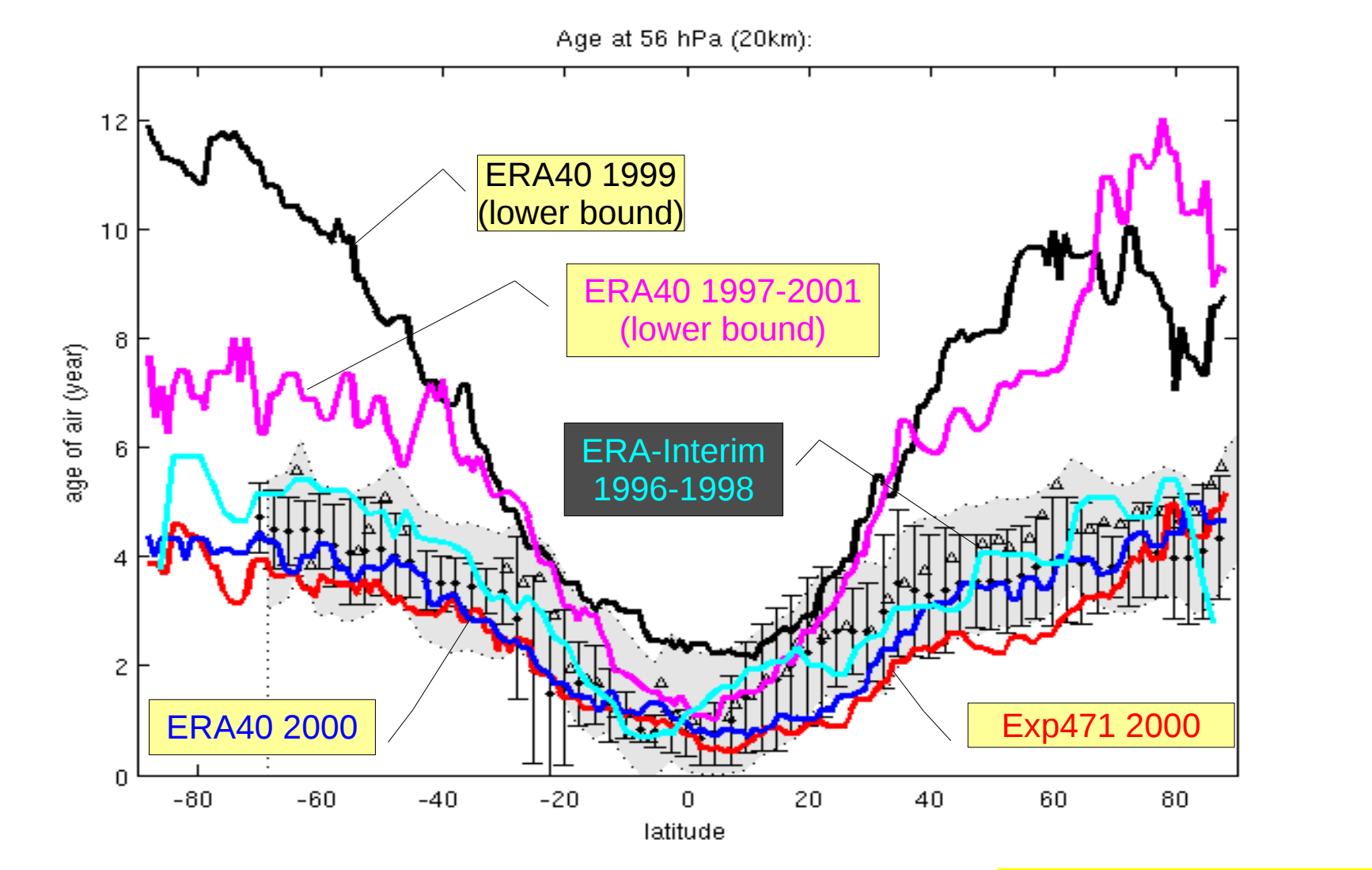
Seasonal



Comparing Exp 471 simulations using parcels initialised on 31 Dec and 30 June

Ascent at the tropopause is stronger in the summer hemisphere. There is a time-lag of about six months at 20 km which is consistent with the mean age of air near the equator.

Age of air calculated with raw diabatic rates as vertical velocities in isentropic coordinates



Diabatic ages at 20 km generally too long in ERA40 but in 2000. Slightly too young for Exp471 2000. Correct values for ERA-Interim

Continuity equation in isentropic coordinate

$$\frac{\partial\sigma}{\partial t}+\nabla_{\theta}(\sigma\boldsymbol{u})+\frac{\partial\left(\sigma\frac{D\theta}{Dt}\right)}{\partial\theta}=0 \qquad (1)$$

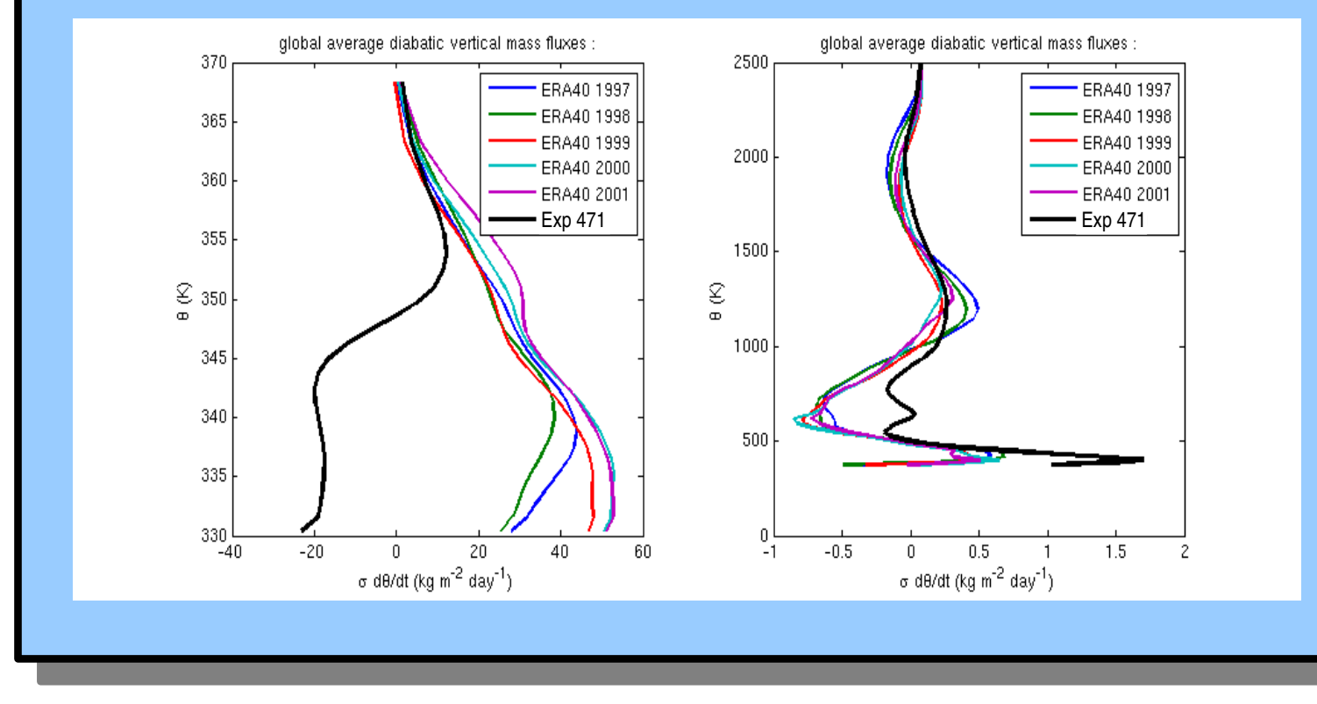
is not automatically satisfied. That is:

- mean vertical mass flux $\iiint \sigma\frac{D\theta}{Dt}dx\,dy\,dt\neq 0$
- the mass divergence of the horizontal wind does not satisfy (1)

CORRECTIVE STEPS

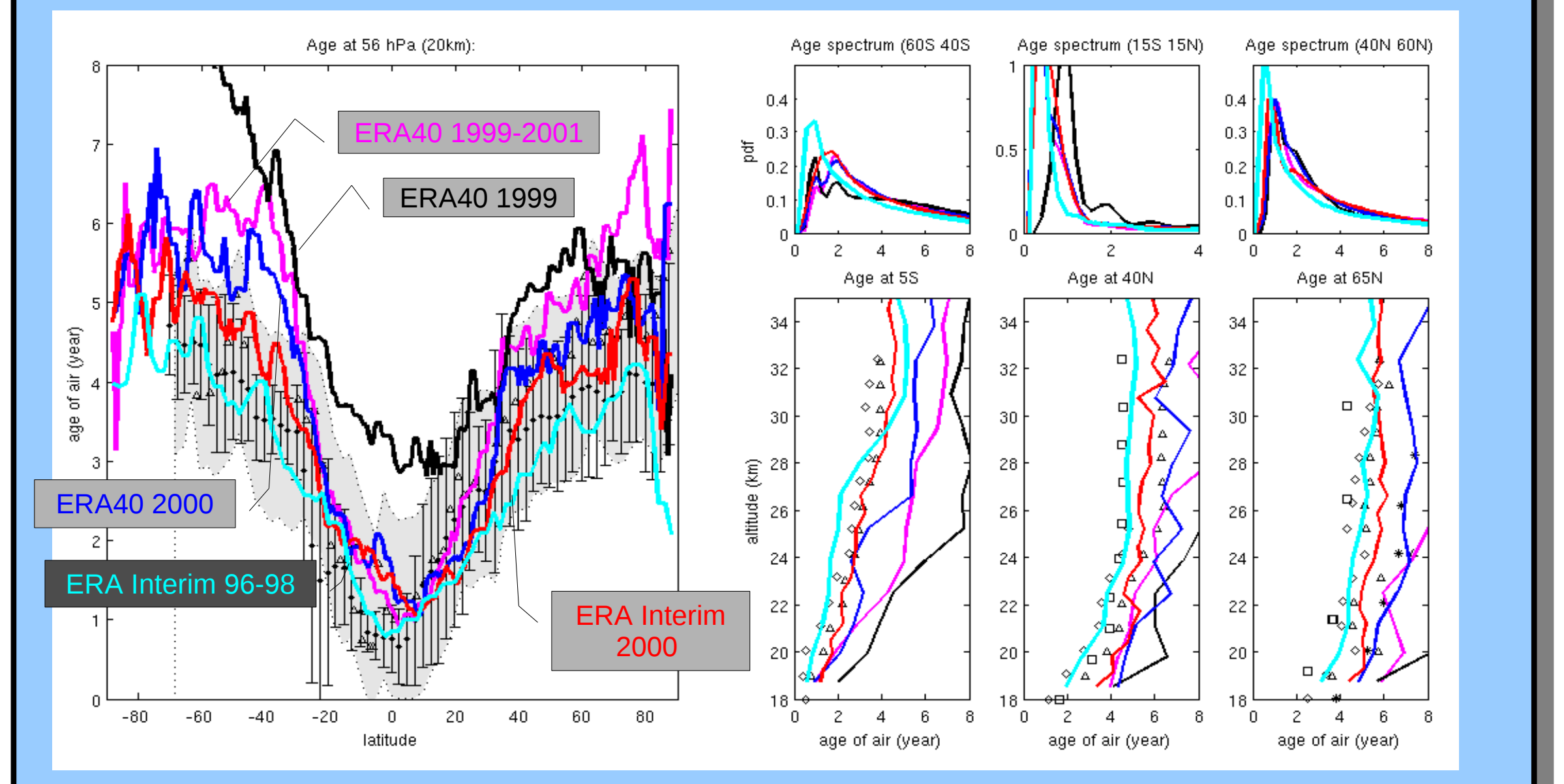
(a) Add a horizontally uniform correction to the mass flux

(b) Correct the horizontal wind by replacing the horizontal mass flux divergence with that calculated from (1)



Mean vertical mass flux, annual average.

Age of air calculated with diabatic heating rates corrected to cancel the mean vertical mass flux and with horizontal isentropic mass divergence modified to balance the heating rates .



Single year perpetual cycles perform best with ERA Interim
Large difference between ERA40 1999 and ERA40 2000
Improved results with 3-year .cycle 1996-1998
Larger discrepancies in the southern hemisphere

Discussion and conclusion

Simulations of the age of air, that is of the Brewer-Dobson circulation, from analysed wind are no longer in strong disagreement with observations. Some simulations are indeed in excellent agreement. The defaults mentioned in previous studies like excessive meridional exchanges have disappeared.

The combination of new model + 4D-Var + variational bias correction in the ERA_Interim performs particularly well while ERA-40 provides still too young or too old ages depending on the applied procedure (see also Monge-Sanz et al., 2007).

Discrepancies between observations and simulations are larger in the southern hemisphere.

If analysed vertical winds are used for vertical motion, it is highly recommended to use 3h sampling by interleaving forecasts with analysis usually available every 6h (see also Legras et al., 2005).

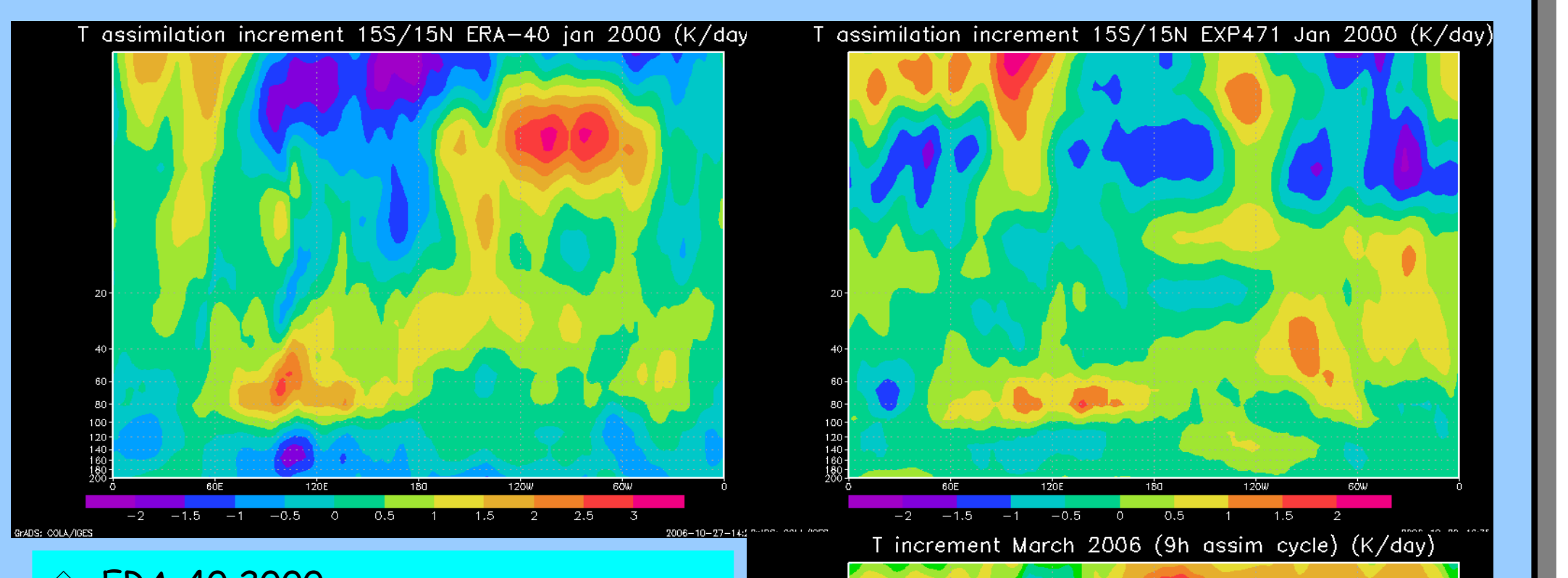
A measure of the consistency of the model and of its performance regarding the age of air appears to be the assimilation increment. A model with a small increment bias performs much better. In the ERA-40, the increment is of the same order as the heating calculated by the radiative code.

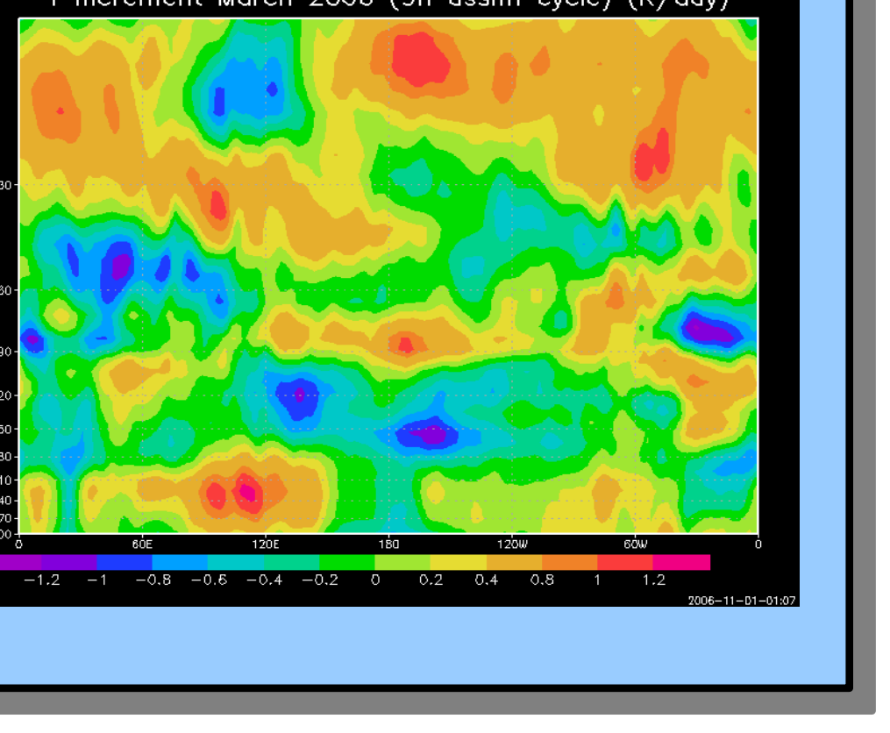
Raw heating rates, although much less diffusive than vertical velocities, require corrections to reproduce the age of air. This is related to inconsistencies in the model.

The Brewer-Dobson circulation is modulated by the QBO. Evaluation of the age of air should be done with multi-year ensembles including at least a full QBO cycle.

Assessing the quality of the simulations is now limited by the poverty and inaccuracy of available measurements of the age of air. More observations and/or better processing of available data are required.

Comparison of assimilation increments





⇧ ERA-40 2000
(T159L60, version 23, 3D-Var)

⇗ Exp471 2000
(T159L60, version 29, 4D-Var)

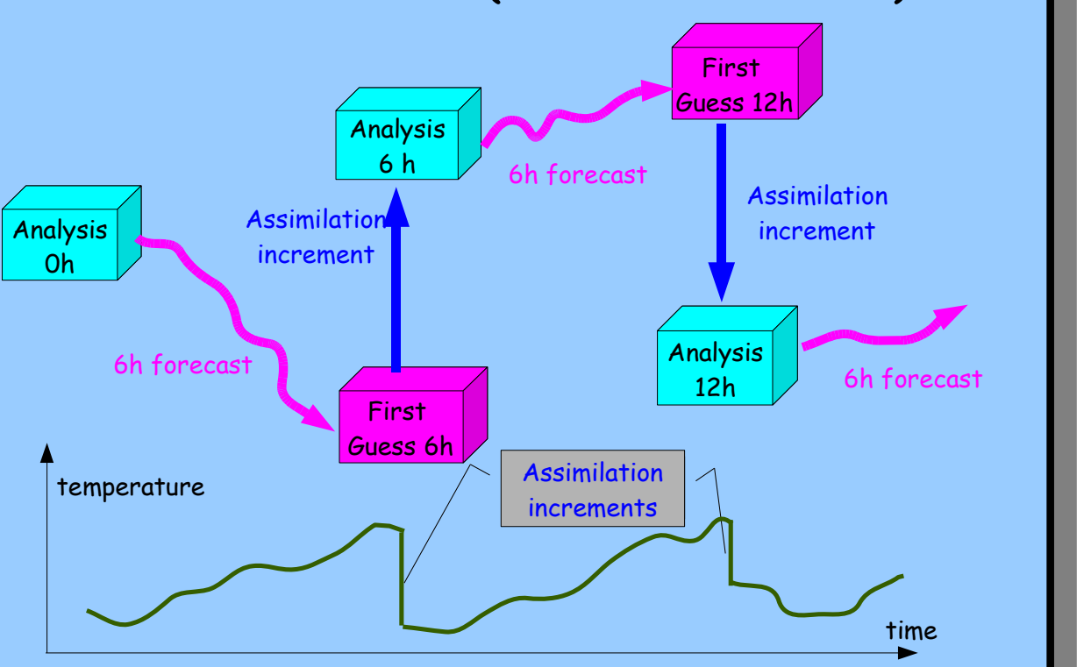
⇨ Operational model
(T799L90, version 30, 4D-Var)

15S/15N Jan 2000 average

The role of the assimilation increment

Each jump of temperature due to data assimilation should be considered as a contribution to the heating budget.

assimilation (ERA-40 / 3D-Var)

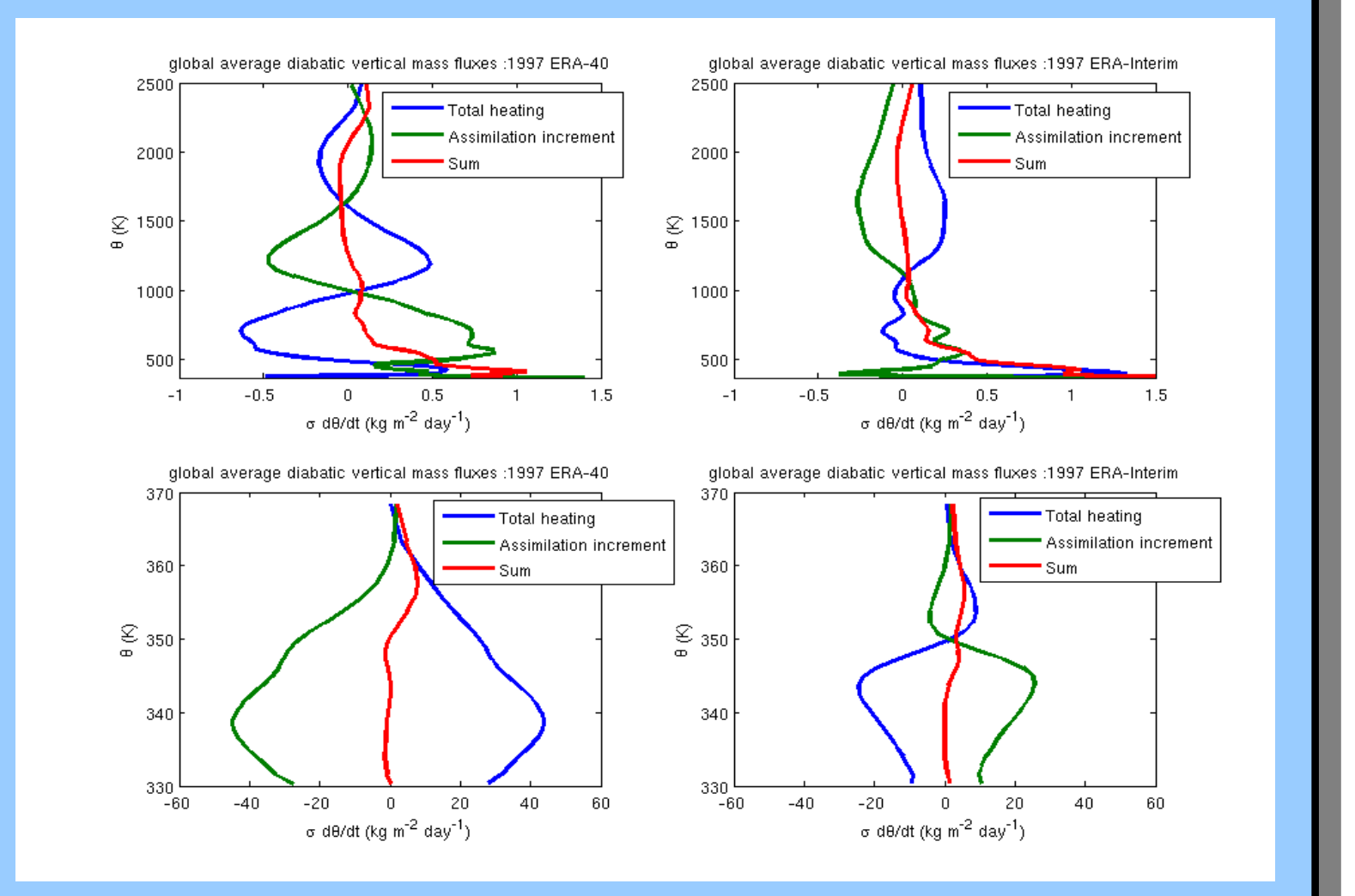


Assimilation temperature increments compensate for:

I) Errors that arise in the model itself (faulty radiation code or representation of convection, or non conservation of entropy by the dynamics)
II) Errors that arise due to incorrect representation of data fields other than wind
  IIa) Errors in off-line fields like ozone
  IIb) Errors in observations and/or assimilation inducing biases in temperature
III) Errors in the winds that induce spurious horizontal and vertical heat fluxes

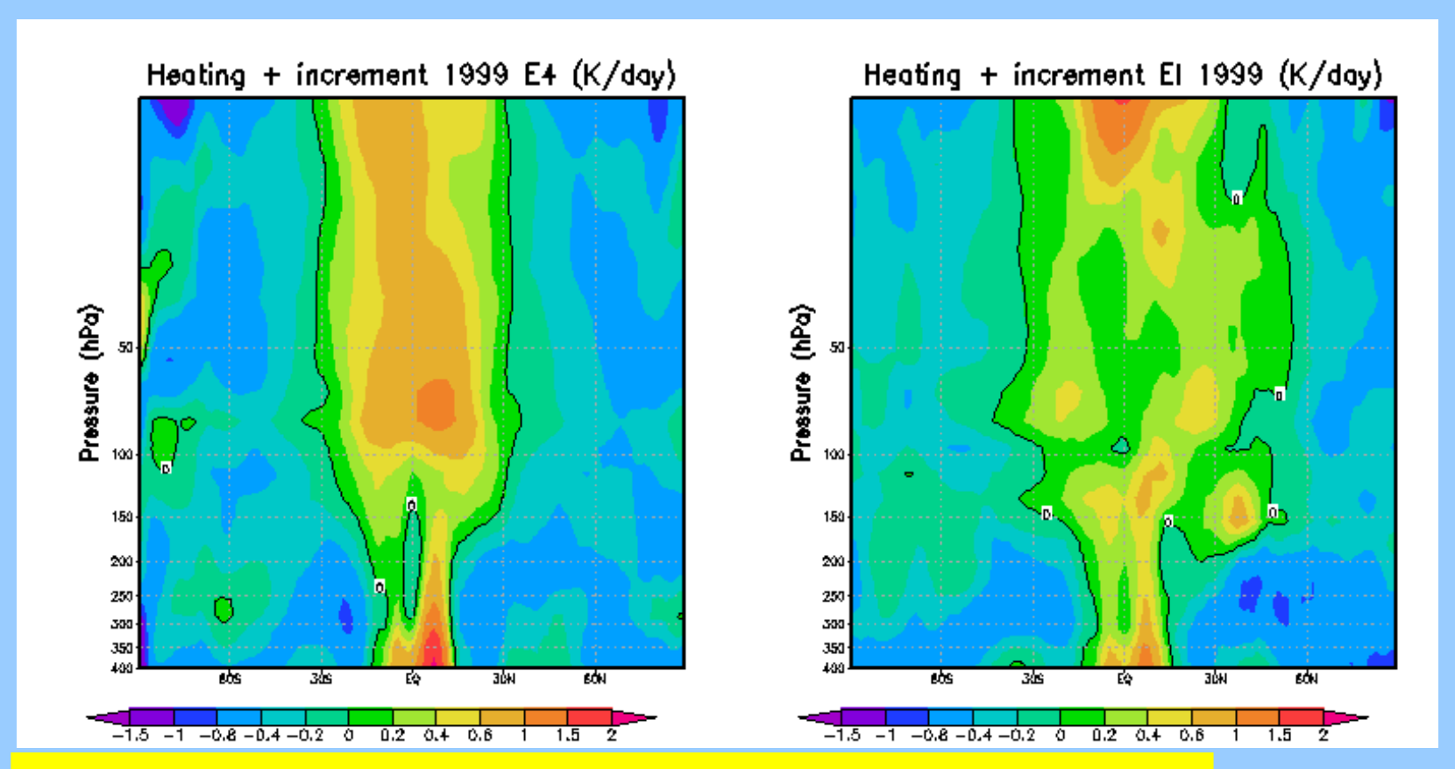
For cases I and II, the errors directly affects the calculation of the heating rate and the assimilation increment provides a correction towards the right value
For case III, the assimilation increment makes heating compatible with the spurious transport but does it by drifting away from the right heating
There is essentially no way to distinguish these error sources

Relation between the mean mass flux and the mean increment



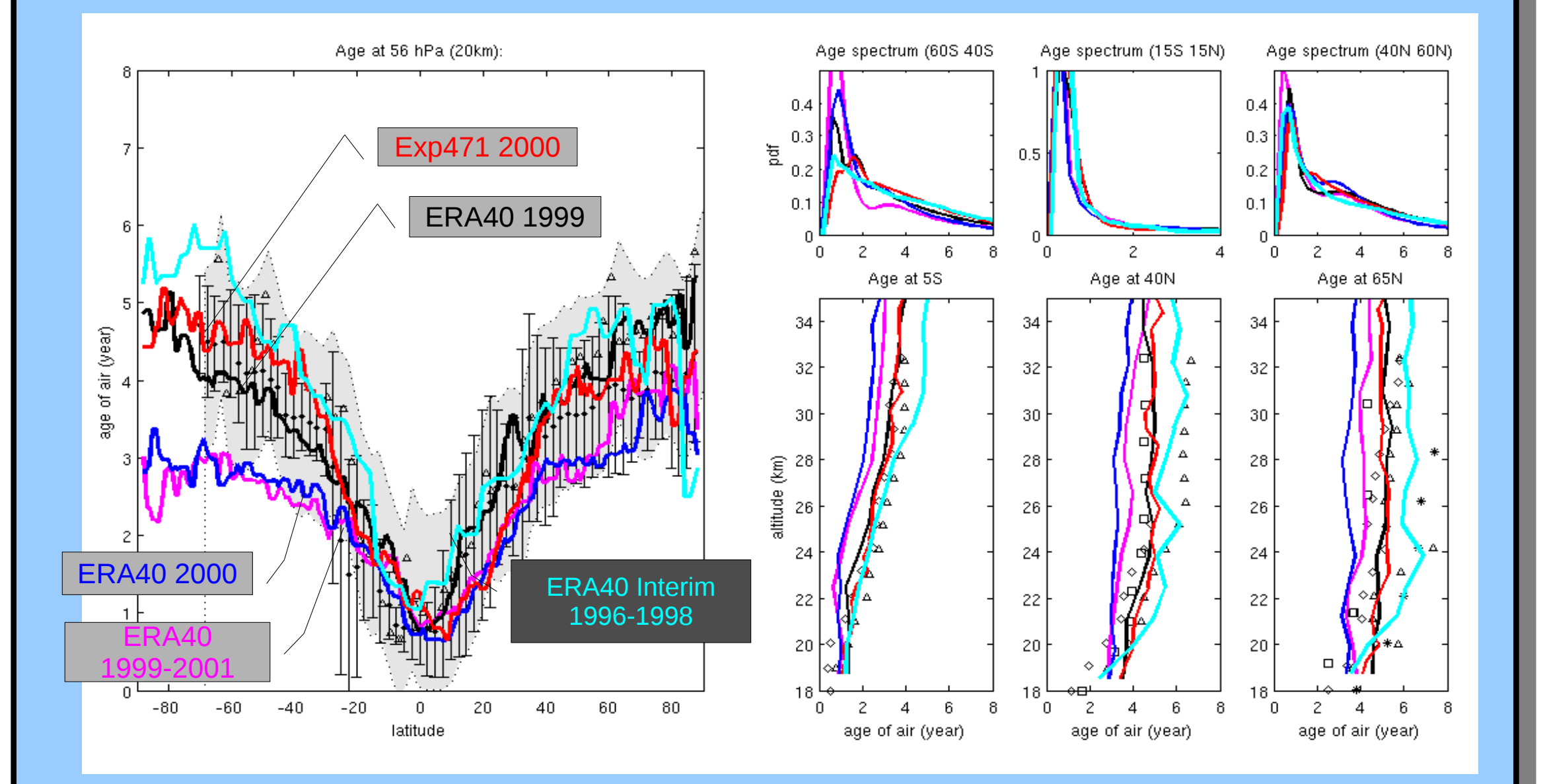
The residual imbalance can only be due to imperfect conservation of mass by the adiabatic part of the model.

Heating rates + assimilation increments averaged over 2000
↙ ERA40 ERA-Interim ↘



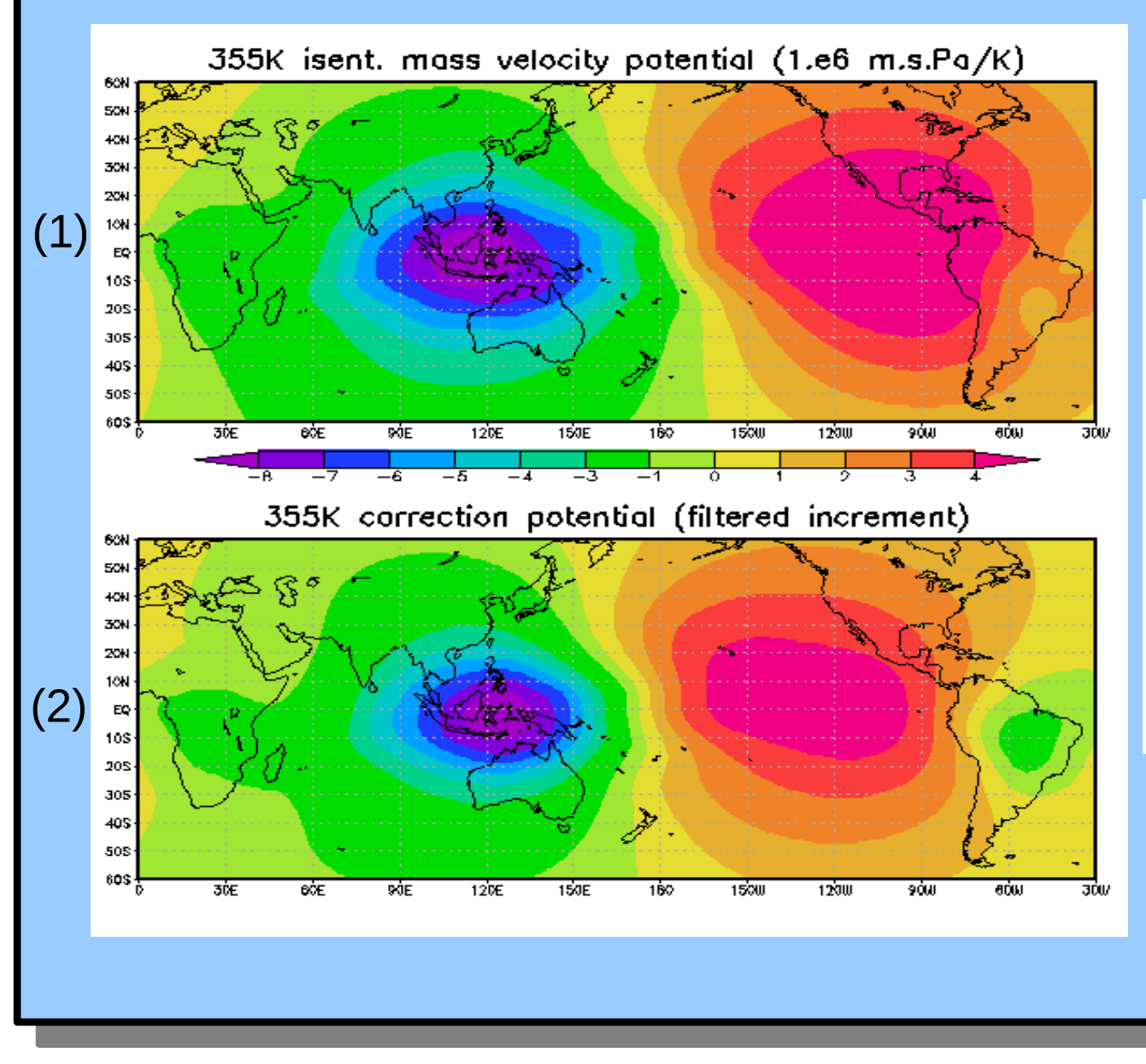
The sum of heating + assimilation increment for ERA40 is almost twice that for ERA-Interim in the lower stratosphere. This is consistent with a too strong negative upward heat flux in the ERA40 due to noisy vertical winds.

Age of air calculated with diabatic rates corrected by low-pass filtered assimilation increment and with recalculated mass divergence

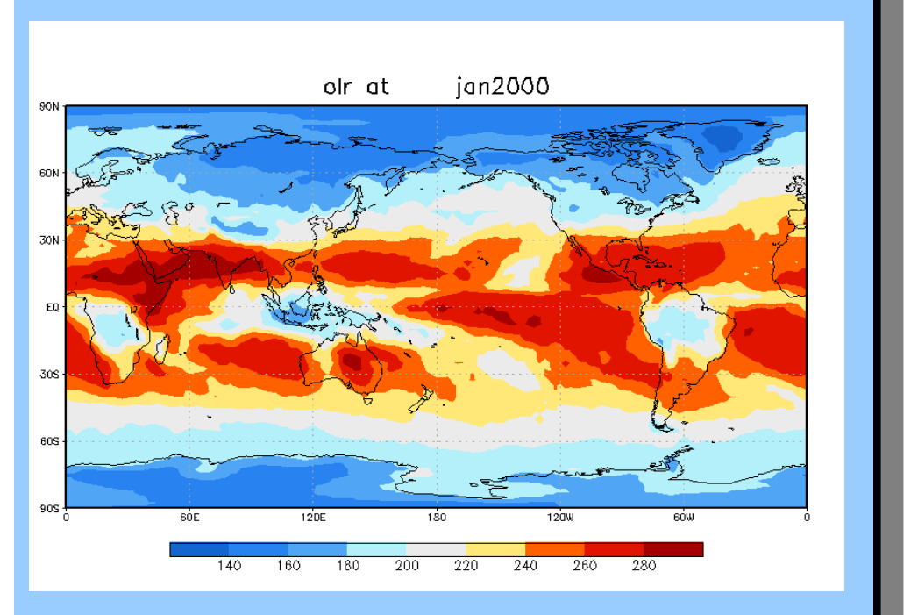


Single year perpetual for Exp-471 and ERA-Interim multi-year cycles provides ages in excellent agreement with observations.
More surprisingly, ERA40 1999 is as good
Again more discrepancies in the southern hemisphere

Comparison of isentropic mass velocity potential at 350K (200hPa) in Jan 2000 for ERA-Interim,
(1) directly from ECMWF winds and temperature and, (2) with divergence calculated from heating + assimilation increment



OLR for Jan 2000



Références
• Andrews et al., J. Geophys. Res., 106, 32,295-32,314 (2001).
• Boering et al., Science, 274, 1340-1343 (1996).
• Elkins et al., Geophys. Res. Lett., 23, 347-350 (1996).
• Harnisch et al., Geophys. Res. Lett., 23, 1099-1102 (1996).
• Legras, Pisso, Berthet & Lefèvre, Atmos. Chem. PhyS, 5, 1605-1622 (2005).
• Meijer, Bregman, Segers, & van Velthoven, Geophys. Res. Lett., 31, L32114, doi:10.1029/2004GL021158 (2004).
• Monge-Sanz, Chipperfield, Simmons & Uppala, Geophys. Res. Lett., 34, L04801, doi:10.1029/2006GL028515 (2007).
• Niwano, Yamasaki & Shiotani, J. Geophys. Res., 108, 4794, doi:10.1029/2003JD003871 (2003).
• Scheele, Stegmund & van Velthoven, Atmos. Chem. Phys., 5, 1-7 (2005).
• Schoeberl, Douglass, Zhu & Pawson, J. GeophyS. Res., 108, 4413, doi:10.1029/2002JD002652 (2003)
• Uppala et al., Quart. J. R. Met. Soc., 131, 2961-3012 (2005)..
• Waugh et Hall, Rev. Geophys., 40, 10.1029/2000RG000101 (2002).