Simulations of the Structure and Dynamics of the Solar Atmosphere using the GS98 and AGS05 abundance mixtures

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ABSTRACT

We present a comparison between two three-dimensional radiative hydrodynamical (3D RHD) simulations of the solar outer layers which we have performed for the Grevesse & Sauval (1998; GS98) and the Asplund, Grevesse & Sauval (2005; AGS05) abundance mixtures, respectively. Both our simulations are performed using a 3D RHD code (that of Robinson et al. 2003) that includes a physically realistic treatment of radiation. Both simulations use identical opacity tables and use the same equation of state.

Our principal aim is to **test the internal consistency of the AGS05 approach** of deriving a new solar mixture based on the structure and dynamics of a solar 3D RHD simulation due to Stein & Nordlund (1989, 1998), constructed with the GS98 mixture.

Our 3D simulations show that chemical abundances make a difference to the structure and dynamics of the outer layers where radiative transfer dominates and where convective overshoot takes place. When deriving the solar abundances, one must "close the loop", and iterate the chemical composition in the 3D simulation on which the model atmosphere is based.

The issue of solar abundances

❖ Standard solar models had shown a remarkable agreement with the Sun.

BUT

❖ The new, lowered, solar abundances spoil the agreement.

Older abundances : Grevesse & Sauval (1998), Z/X=0.0229 (GS98)

New abundances: Asplund et al. (2005), Z/X=0.0165 (AGS)

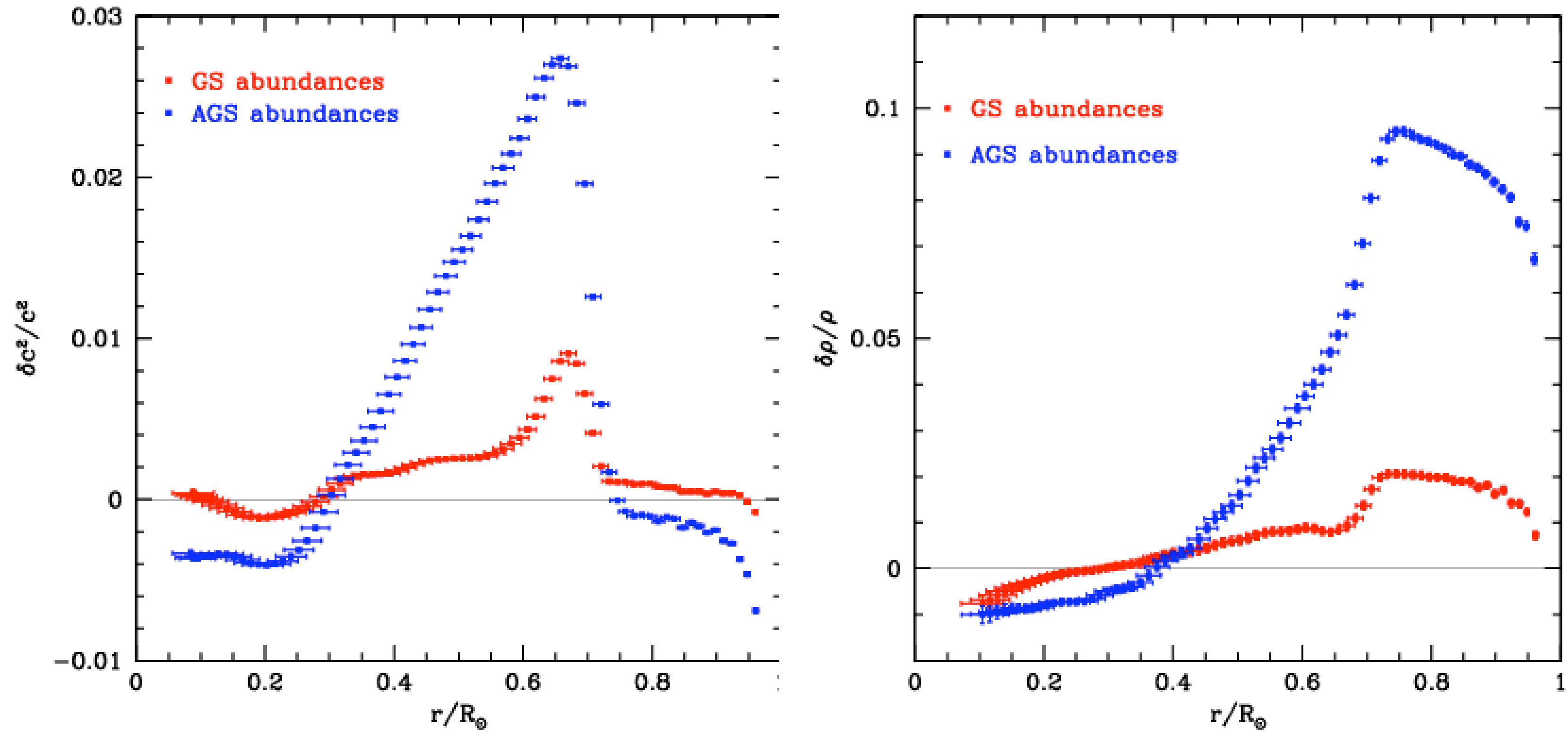
Solar abundances [units of $\log(N_i/N_H)+12$]

Element (1)	GS98 (2)	AGS05 (3)
C	8.52	8.39
N	7.92	7.78
O	8.83	8.66
Ne	8.08	7.84
Na	6.32	6.27
Mg	7.58	7.53
Al	6.49	6.43
Si	7.56	7.51
S	7.20	7.16
Ar	6.40	6.18
Ca	6.35	6.29
Cr	5.69	5.63
Mn	5.53	5.47
Fe	7.50	7.45
Ni	6.25	6.19

- For GS98 abundances
  $Z/X=0.0229$
  $Z=0.018$

- For AGS abundances
  $Z/X=0.0165$
  $Z=0.012$

Sound speed and density differences between the Sun and two solar models, one with GS98 and the other with AGS05 abundances



Models from Bahcall, Basu & Serenelli (2005)

Solar properties: Y_{CZ}= **0.2485±0.0034** (Basu & Antia 1995,2004)
R_{CZ}=**0.713±0.001**R_0 (Basu & Antia 1997, 2004)

GS98 model: Y_{CZ}= **0.243**, R_{CZ}=**0.715** *AGS05* model: Y_{CZ}= **0.230**, R_{CZ}=**0.729**

How could the new abundance-determinations go wrong?

Line profile-calculations were done using an underlying 3D simulation of solar convection as the model atmosphere

Assumptions under which radiative transfer is calculated in AGS05:

- Most of the energy exchange takes place at those wavelengths where monochromatic optical depth is close to unity at that geometrical depth.
- At each time step, the integral over wavelengths can be represented by a sum over 4 wavelength bins, the bin membership of a wavelength is decided by the opacity $\kappa_\lambda(\rho,T)$, at the point in the 1D atmosphere where the monochromatic τ reaches unity.
- 4 opacity bins are sufficient, they correspond to continuum, weak lines, intermediate strong lines and strong lines.
- The equation of radiative transfer was solved for 8 rays (2 μ angles, and 2 ϕ angles).

Some possible sources of error in AGS05

(1) The radiative transfer calculations:

(a) Are four opacity bins enough?
(b) Are eight rays enough?

(2) The equation of state:

The simulations use the Mihalas, Hummer & Däppen (MHD) equation of state. Will use of OPAL give a different result? The EOS causes slight changes to the temperature structure.

(3) The abundances!

The simulations on which the new abundances are based themselves had the old abundances. The abundances have not been re-derived with simulations with the new abundances. Will we get back the same result if that is done?

<u>Our Aim:</u> Test assumption (3) by running two simulations, one with GS98 and one with AGS05 abundances

Run two simulations, identical in every way apart from abundances, which are either AGS05 or GS98.

Examine the relative differences in the photosphere between AGS05 and GS98 3D simulations, in both structure and dynamics.

Note that the helium content adopted for the AGS05 simulation is that of the AGS05 SSM (i.e. Y_{CZ}=0.230). As pointed out earlier, this model the values of Y_{CZ} and R_{CZ} for the Sun that differ from with those derived by Basu & Antia by seismic means, i.e. 0.2485 ± 0.0034 and 0.713±0.001 respectively.

Realistic solar surface convection (local models)

- Standard Solar model, 1D Yale Stellar Evolution model (Guenther & Demarque 1997) used to compute initial stratification.
- Realistic Physics. Ferguson et al. (2005) low temperature opacities, OPAL opacities and OPAL 2005 Equation of State. Hydrogen and Helium ionizations zones included.
- LES of full Navier-Stokes equations in a small box located in the vicinity of the photosphere (Kim & Chan 1998). Use same opacities and equation of state as in 1D stellar model.
- Radiative energy transport modeled by diffusion approximation in deep layers and 3D Eddington approximation in shallow regions (we assume a gray atmosphere)
- Vertical walls periodic. Horizontal walls free slip and impenetrable (closed box).

HOW OUR CODE COMPARES WITH THOSE OF OTHERS

AVERAGE TEMPERATURE

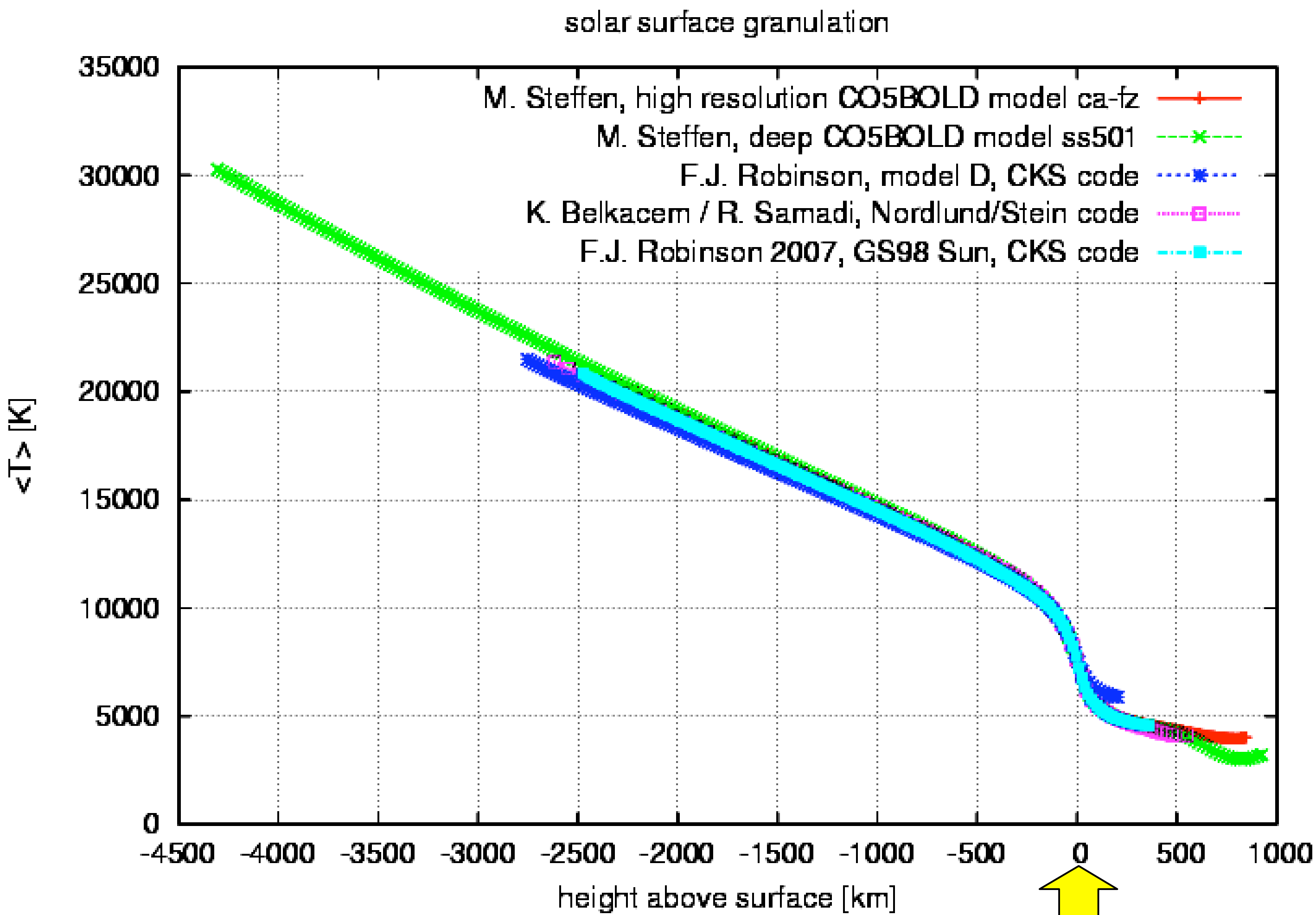


Figure courtesy of F. Kupka

T=T eff

RMS VERTICAL VELOCITIES

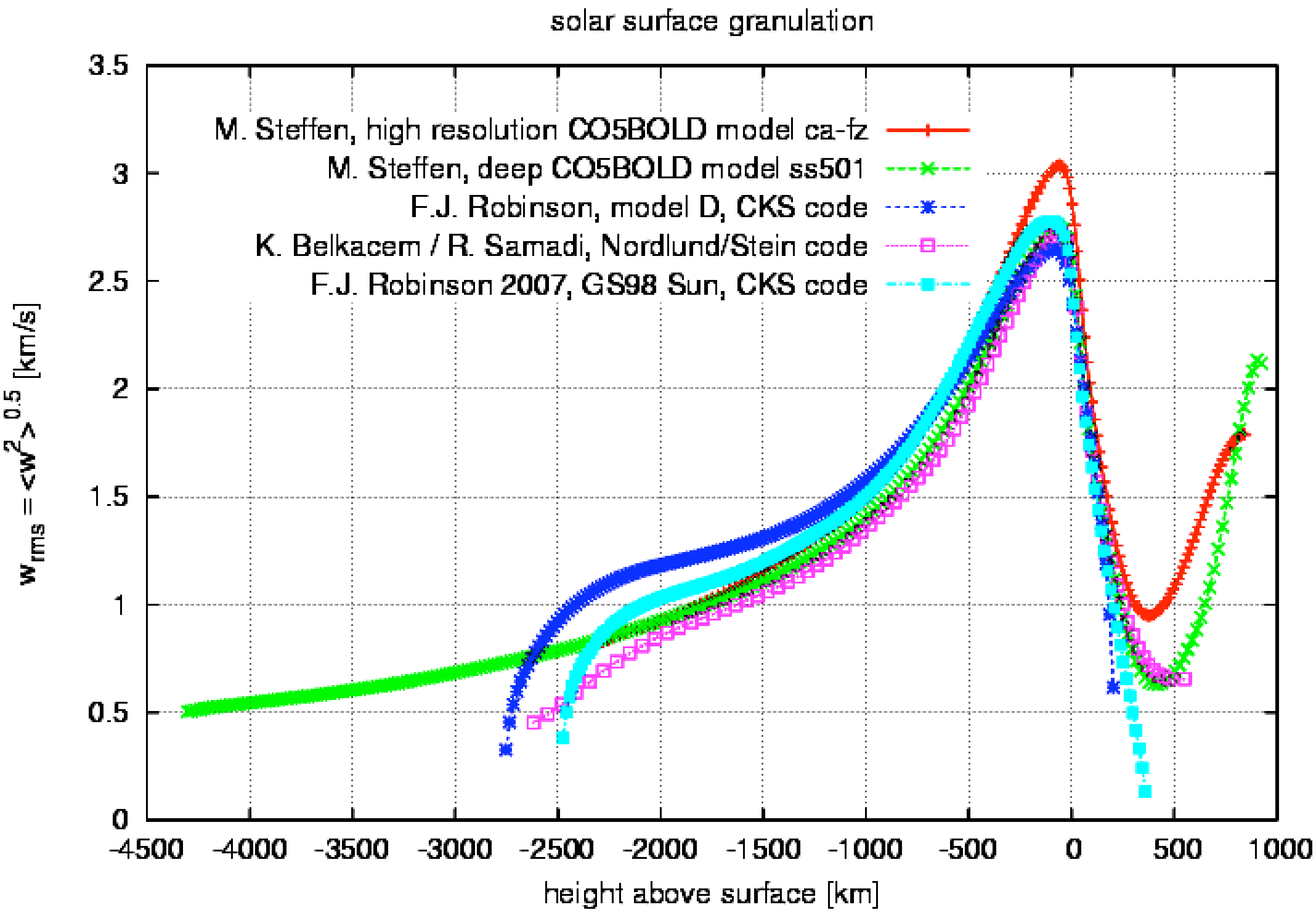
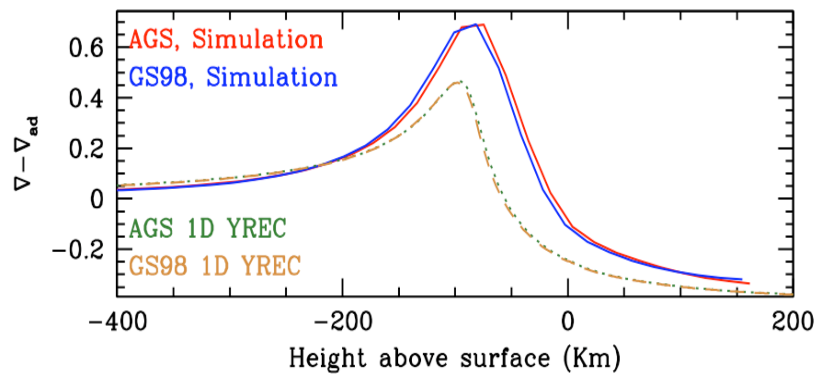


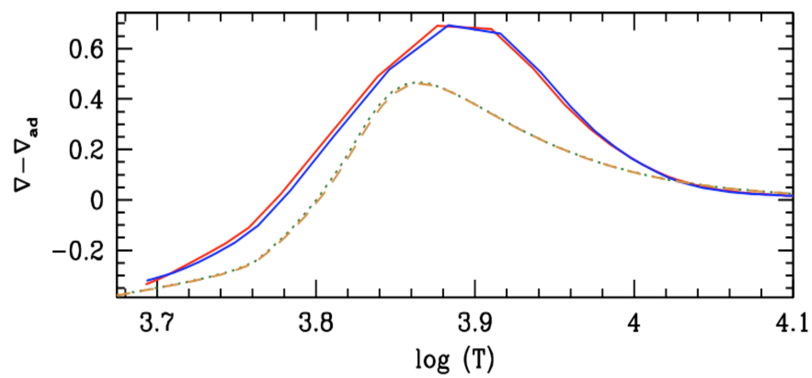
Figure courtesy of F. Kupka

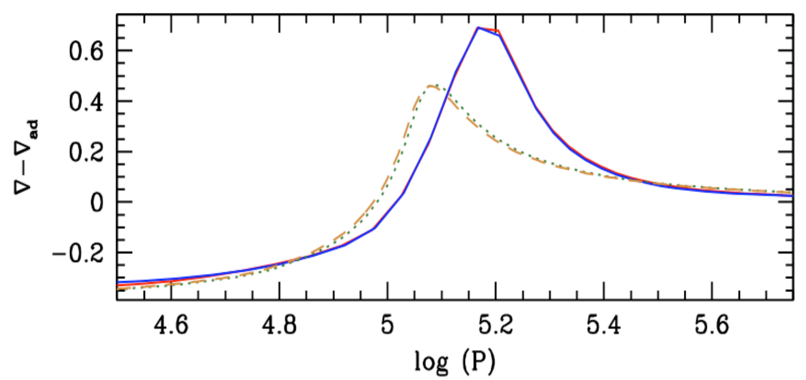
Results from our simulations

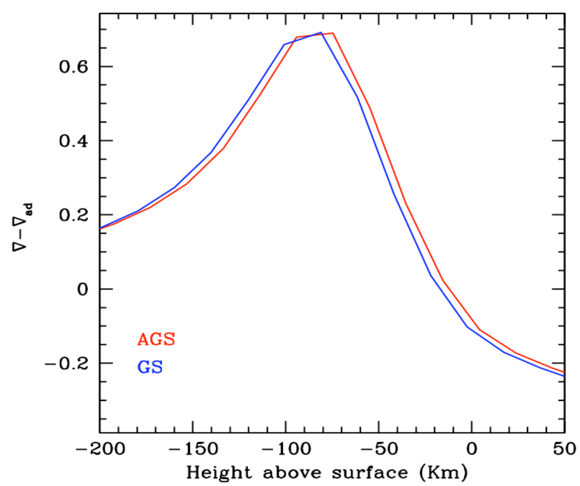
Comparison of the super-adiabatic layer (SAL)

- Note the difference between 1D and 3D



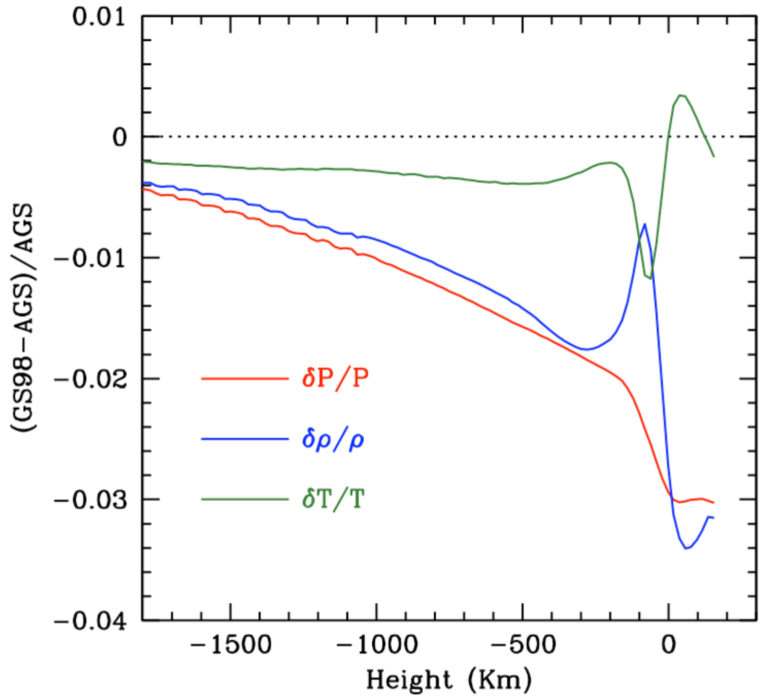


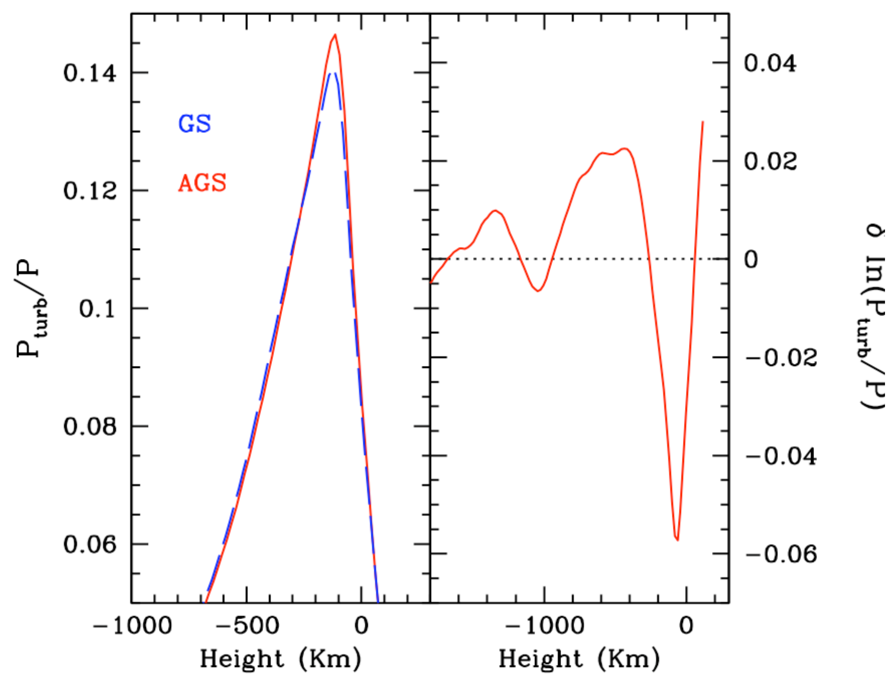




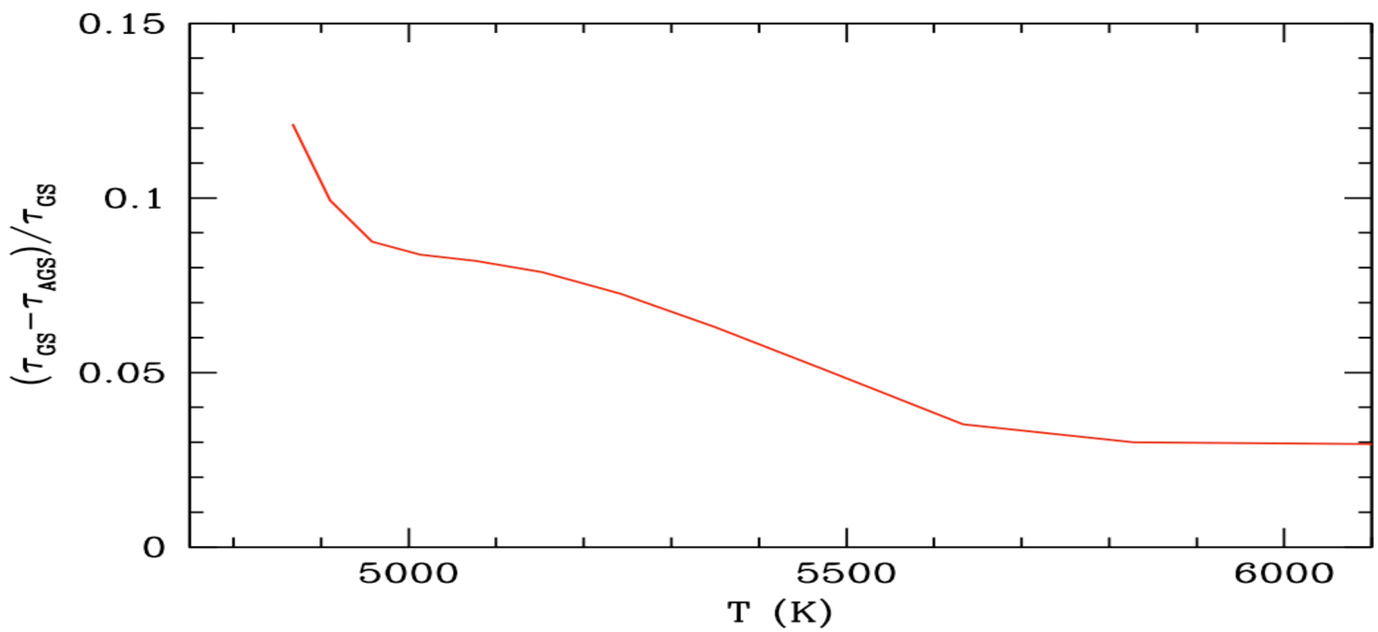
SAL close-up

Differences in structure



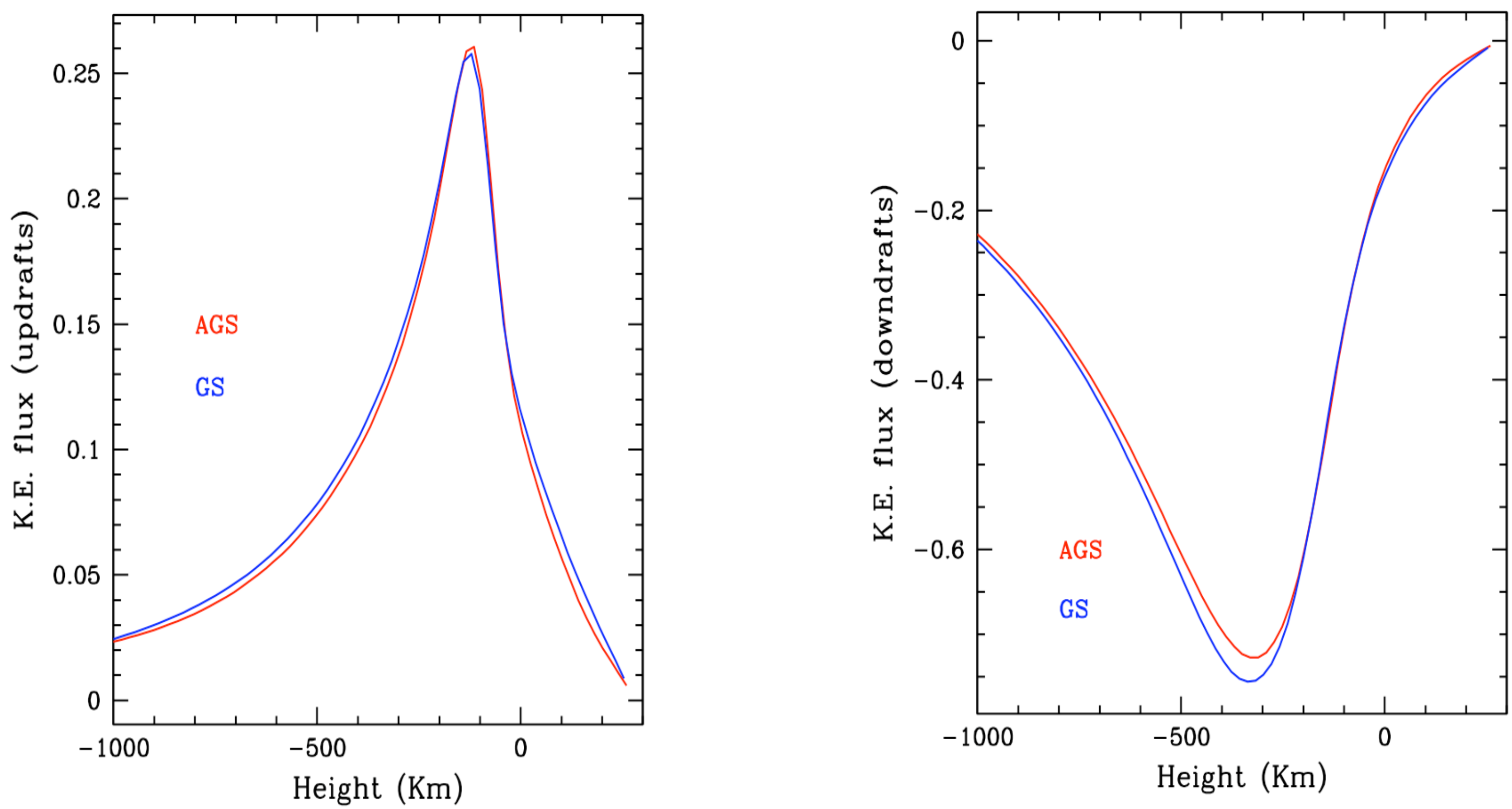


Effect on the T - τ relation



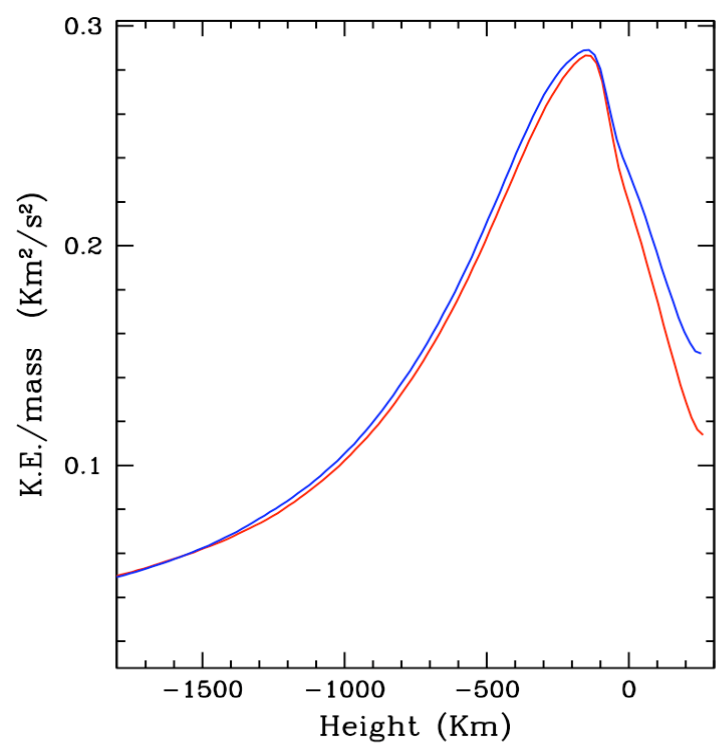
- Relative difference in T - τ relations. The main departure occurs at low temperatures where radiative transfer dominates

Effects of dynamics: Kinetic energy by upflows and downflows



Kinetic energy per unit mass

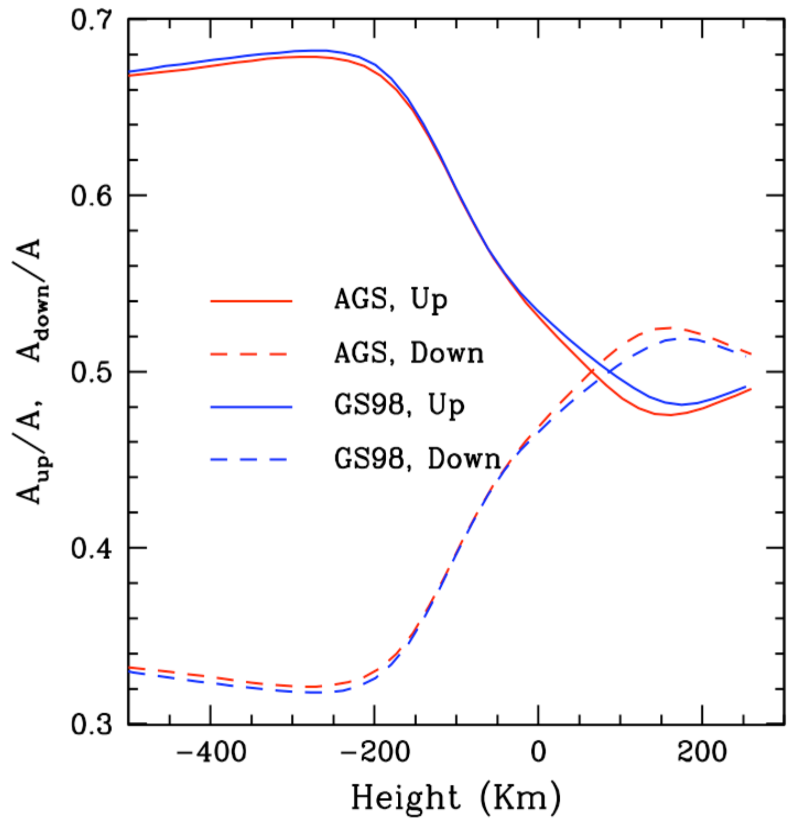
- The main difference ir turbulence is found in the atmospheric layers where radiative transport dominates
- The origin in height is set to $T = T_{eff}$



Granules in AGS05 and GS98

- Area 'filling factor', a signature of granules

- GS98 granules penetrate further out in the atmosphere due to stronger convection in the GS98 case



SUMMARY

- Both the structure and turbulent velocities due to overshoot in the outer solar atmosphere where radiative transfer dominate are affected by the adopted abundances.

- The T - τ relation yielded by AGS05 abundances differs by up to 12% from that of a simulation based on GS98 abundances.

- This is the region where absorption lines are formed.

THUS, TO DERIVE ABUNDANCES, WE NEED TO CLOSE THE LOOP AND ITERATE THE CHEMICAL COMPOSITION IN THE 3D SIMULATIONS ON WHICH THE MODEL ATMOSPHERE IS BASED

Acknowledgements

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