

ransX framework

Theory Guide

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June 9, 2019

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1 Introduction

We present a statistical analysis of turbulent convection in stars within our Reynolds-Averaged Navier Stokes (RANS) framework in spherical geometry which we derived from first principles (see Sect.17 and further sections for details). The analysed data include **core convection during oxygen burning in a 15 M_⊙ supernova progenitor, envelope convection in a 5 M_⊙ red giant and core convection during core helium flash and hydrogen injection flash of a 1.25 M_⊙ star**. These simulations have been partially already described by [Meakin and Arnett \[2007\]](#), [Arnett et al. \[2010\]](#), [Viallet et al. \[2013\]](#) and [Mocák et al. \[2009, 2011\]](#).

We obtain our 1D RANS equations by introducing two types of averaging: statistical averaging and horizontal averaging [[Besnard et al., 1992](#), [Viallet et al., 2013](#)]. In practice, statistical averages are computed by performing a time average (the ergodic hypothesis). Therefore, the combined average of a quantity q is defined as

$$\bar{q}(r, t) = \frac{1}{T\Delta\Omega} \int_{t-T/2}^{t+T/2} q(r, \theta, \phi, t') d\Omega dt' \quad (1)$$

where $d\Omega = \sin\theta d\theta d\phi$ is the solid angle in spherical coordinates, T is the averaging time period, and $\Delta\Omega$ is total solid angle being averaged over.

The flow variables are then decomposed into mean and fluctuation $q = \bar{q} + q'$, noting that $\bar{q}' = 0$ by construction. Similarly, we introduce Favre (or density weighted) averaged quantities by

$$\tilde{q} = \frac{\bar{\rho}q}{\bar{\rho}} \quad (2)$$

which defines a complimentary decomposition of the flow into mean and fluctuations according to $q = \tilde{q} + q''$. Here, q'' is the Favrian fluctuation and its mean is zero when Favre averaged $\tilde{q}'' = 0$. For a more complete elaboration on the algebra of these averaging procedures we refer the reader to [Chassaing et al. \[2010\]](#). All calculated mean fields shown for a given equation in next sections were additionally multiplied by $4\pi r^2$. It gives us advantage to reflect changing volume of our computational domain as a function of radius and visualize better volume integral budgets of the individual mean fields, which are then equivalent to the area below corresponding mean field profile. We explore not only general properties of mean fields but also their resolution dependency, wedge-size dependency, convection zone depth dependency, position of driving source dependency and validity of few turbulence models.

2 Summary of Reynolds-averaged Navier Stokes equations in spherical geometry

2.1 Various mean fields equations (first-order moments)

$$\tilde{D}_t \bar{\rho} = -\bar{\rho} \tilde{d} + \mathcal{N}_\rho \quad (3)$$

$$\bar{\rho} \tilde{D}_t \tilde{u}_r = -\nabla_r \tilde{R}_{rr} - \overline{G_r^M} - \partial_r \bar{P} + \bar{\rho} \tilde{g}_r + \mathcal{N}_{ur} \quad (4)$$

$$\bar{\rho} \tilde{D}_t \tilde{u}_\theta = -\nabla_r \tilde{R}_{\theta r} - \overline{G_\theta^M} - (1/r) \bar{\partial}_\theta \bar{P} + \mathcal{N}_{u\theta} \quad (5)$$

$$\bar{\rho} \tilde{D}_t \tilde{u}_\phi = -\nabla_r \tilde{R}_{\phi r} - \overline{G_\phi^M} + \mathcal{N}_{u\phi} \quad (6)$$

$$\bar{\rho} \tilde{D}_t \tilde{c}_I = -\nabla_r (f_I + f_T) - \bar{P} \bar{d} - W_P + \mathcal{S} + \mathcal{N}_{\epsilon I} \quad (7)$$

$$\bar{\rho} \tilde{D}_t \tilde{c}_k = -\nabla_r (f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + W_P + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) + \mathcal{N}_{\epsilon k} \quad (8)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_t = -\nabla_r (f_I + f_T + f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i - \bar{P} \bar{d} + W_b + \mathcal{S} + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) + \mathcal{N}_{\epsilon t} \quad (9)$$

$$\bar{\rho} \tilde{D}_t \tilde{h} = -\nabla_r f_h - \Gamma_1 \bar{P} \bar{d} - \Gamma_1 W_P + \Gamma_3 \mathcal{S} + \Gamma_3 \nabla_r f_T + \mathcal{N}_h \quad (10)$$

$$\bar{\rho} \tilde{D}_t \tilde{s} = -\nabla_r f_s + \overline{(\nabla \cdot F_T) / T} + \overline{S / T} + \mathcal{N}_s \quad (11)$$

$$\overline{D}_t \bar{P} = -\nabla_r f_P - \Gamma_1 \bar{P} \bar{d} + (1 - \Gamma_1) W_P + (\Gamma_3 - 1) \mathcal{S} + (\Gamma_3 - 1) \nabla_r f_T + \mathcal{N}_P \quad (12)$$

$$\overline{D}_t \bar{T} = -\nabla_r f_T + (1 - \Gamma_3) \bar{T} \bar{d} + (2 - \Gamma_3) \bar{T}' \bar{d}' + \overline{(\nabla \cdot F_T) / \rho c_v} + \overline{(\tau_{ij} \partial_i u_j) / \rho c_v} + \overline{\epsilon_{\text{nuc}} / c_v} + \mathcal{N}_T \quad (13)$$

$$\bar{\rho} \tilde{D}_t \tilde{X}_\alpha = -\nabla_r f_\alpha + \bar{\rho} \tilde{X}_\alpha^{\text{nuc}} + \mathcal{N}_\alpha \quad (14)$$

$$\bar{\rho} \tilde{D}_t \tilde{A} = -\nabla_r f_A - \overline{\rho A^2 \Sigma_\alpha (\dot{X}_\alpha^{\text{nuc}} / A_\alpha)} + \mathcal{N}_A \quad (15)$$

$$\bar{\rho} \tilde{D}_t \tilde{Z} = -\nabla_r f_Z - \overline{\rho Z A \Sigma_\alpha (\dot{X}_\alpha^{\text{nuc}} / A_\alpha)} + \overline{\rho A \Sigma_\alpha (Z_\alpha \dot{X}_\alpha^{\text{nuc}} / A_\alpha)} + \mathcal{N}_Z \quad (16)$$

$$\bar{\rho} \tilde{D}_t \tilde{j}_z = -\nabla_r f_{jz} + \mathcal{N}_{jz} \quad (17)$$

2.2 Mean turbulent mass flux and mean density-specific volume covariance equation (second-order moments)

$$\bar{\rho} \tilde{D}_t \overline{u'_r u''_r} = -(\bar{\rho}' \overline{u'_r u'_r} / \bar{\rho}) \partial_r \bar{\rho} + (\tilde{R}_{rr} / \bar{\rho}) / \partial_r \bar{\rho} - \bar{\rho} \nabla_r (\overline{u''_r u''_r}) + \nabla_r \overline{\rho' u'_r u'_r} - \bar{\rho} \overline{u''_r} \nabla_r \bar{u}_r + \bar{\rho} \overline{u'_r d''} - b \partial_r \bar{P} + \overline{\rho' v \partial_r P'} + \mathcal{G}_a + \mathcal{N}_a \quad (18)$$

$$\overline{D}_t b = +\bar{v} \nabla_r \bar{\rho} \overline{u''_r} - \bar{\rho} \nabla_r (\overline{u'_r v'}) + 2 \bar{\rho} \overline{v' d'} + \mathcal{N}_b \quad (19)$$

2.3 Mean Reynolds stress equations (second-order moments)

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{rr}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{rrr}^R + f_p^r + f_p^r + f_{\tau}^{rr} + f_{\tau}^{rr}) + \overline{u''_r} \partial_r \bar{P} + \overline{u''_r} \partial_r \bar{P} - \tilde{R}_{rr} \partial_r \tilde{u}_r + \overline{P' \nabla_r u''_r} + \overline{P' \nabla_r u''_r} - \overline{u''_r G_r^M} - \overline{u''_r G_r^M} - \overline{G_{rr}^R} - \varepsilon_{\tau}^{rr} - \varepsilon_{\tau}^{rr} \quad (20)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{r\theta}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{r\theta r}^R + f_p^{\theta} + f_{\tau}^{r\theta} + f_{\tau}^{\theta r}) - \overline{u''_r} \partial_r \bar{P} - \tilde{R}_{rr} \partial_r \tilde{u}_\theta - \tilde{R}_{\theta r} \partial_r \tilde{u}_r + \overline{P' \nabla_r u''_\theta} + \overline{P' \nabla_\theta u''_r} - \overline{u''_r G_\theta^M} - \overline{u''_\theta G_r^M} - \overline{G_{r\theta}^R} - \varepsilon_{\tau}^{r\theta} - \varepsilon_{\tau}^{\theta r} \quad (21)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{r\phi}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{r\phi r}^R + f_p^{\phi} + f_{\tau}^{r\phi} + f_{\tau}^{\phi r}) - \overline{u''_\phi} \partial_r \bar{P} - \tilde{R}_{rr} \partial_r \tilde{u}_\phi - \tilde{R}_{\phi r} \partial_r \tilde{u}_r + \overline{P' \nabla_r u''_\phi} + \overline{P' \nabla_\phi u''_r} - \overline{u''_r G_\phi^M} - \overline{u''_\phi G_r^M} - \overline{G_{r\phi}^R} - \varepsilon_{\tau}^{r\phi} - \varepsilon_{\tau}^{\phi r} \quad (22)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\theta r}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{\theta rr}^R + f_p^{\theta} + f_{\tau}^{\theta r} + f_{\tau}^{r\theta}) - \overline{u''_\theta} \partial_r \bar{P} - \tilde{R}_{\theta r} \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{u}_\theta + \overline{P' \nabla_\theta u''_r} + \overline{P' \nabla_r u''_\theta} - \overline{u''_\theta G_r^M} - \overline{u''_r G_\theta^M} - \overline{G_{\theta r}^R} - \varepsilon_{\tau}^{\theta r} - \varepsilon_{\tau}^{r\theta} \quad (23)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\theta\theta}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{\theta\theta r}^R + f_{\tau}^{\theta\theta} + f_{\tau}^{\theta\theta}) - \overline{u''_\theta} \partial_r \bar{P} - \tilde{R}_{\theta r} \partial_r \tilde{u}_\theta - \tilde{R}_{\theta r} \partial_r \tilde{u}_\theta + \overline{P' \nabla_\theta u''_\theta} + \overline{P' \nabla_\theta u''_\theta} - \overline{u''_\theta G_\theta^M} - \overline{u''_\theta G_\theta^M} - \overline{G_{\theta\theta}^R} - \varepsilon_{\tau}^{\theta\theta} - \varepsilon_{\tau}^{\theta\theta} \quad (24)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\theta\phi}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{\theta\phi r}^R + f_{\tau}^{\theta\phi} + f_{\tau}^{\phi\theta}) - \overline{u''_\phi} \partial_r \bar{P} - \tilde{R}_{\theta r} \partial_r \tilde{u}_\phi - \tilde{R}_{\phi r} \partial_r \tilde{u}_\theta + \overline{P' \nabla_\theta u''_\phi} + \overline{P' \nabla_\phi u''_\theta} - \overline{u''_\phi G_\phi^M} - \overline{u''_\phi G_\theta^M} - \overline{G_{\theta\phi}^R} - \varepsilon_{\tau}^{\theta\phi} - \varepsilon_{\tau}^{\phi\theta} \quad (25)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\phi r}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{\phi rr}^R + f_p^\phi + f_{\tau}^{\phi r} + f_{\tau}^{r\phi}) - \overline{u''_\phi} \partial_r \bar{P} - \tilde{R}_{\phi r} \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{u}_\phi + \overline{P' \nabla_\phi u''_r} + \overline{P' \nabla_r u''_\phi} - \overline{u''_\phi G_r^M} - \overline{u''_r G_\phi^M} - \overline{G_{\phi r}^R} - \varepsilon_{\tau}^{\phi r} - \varepsilon_{\tau}^{r\phi} \quad (26)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\phi\theta}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{\phi\theta r}^R + f_{\tau}^{\phi\theta} + f_{\tau}^{\theta\phi}) - \overline{u''_\theta} \partial_r \bar{P} - \tilde{R}_{\phi r} \partial_r \tilde{u}_\theta - \tilde{R}_{\theta r} \partial_r \tilde{u}_\phi + \overline{P' \nabla_\phi u''_\theta} + \overline{P' \nabla_\theta u''_\phi} - \overline{u''_\theta G_\theta^M} - \overline{u''_\phi G_\theta^M} - \overline{G_{\phi\theta}^R} - \varepsilon_{\tau}^{\phi\theta} - \varepsilon_{\tau}^{\theta\phi} \quad (27)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\phi\phi}/\bar{\rho} \right) = -\nabla_r (\tilde{F}_{\phi\phi r}^R + f_{\tau}^{\phi\phi} + f_{\tau}^{\phi\phi}) - \overline{u''_\phi} \partial_r \bar{P} - \tilde{R}_{\phi r} \partial_r \tilde{u}_\phi - \tilde{R}_{\phi r} \partial_r \tilde{u}_\phi + \overline{P' \nabla_\phi u''_\phi} + \overline{P' \nabla_\phi u''_\phi} - \overline{u''_\phi G_\phi^M} - \overline{u''_\phi G_\phi^M} - \overline{G_{\phi\phi}^R} - \varepsilon_{\tau}^{\phi\phi} - \varepsilon_{\tau}^{\phi\phi} \quad (28)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{rr}/\bar{\rho} \right) = -\nabla_r (2f_k^r + 2f_P) + 2W_b - 2\tilde{R}_{rr} \partial_r \tilde{u}_r + 2\overline{P' \nabla_r u''_r} + 2\mathcal{G}_k^r + \mathcal{N}_{Rrr} \quad (29)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\theta\theta}/\bar{\rho} \right) = -\nabla_r (2f_k^{\theta}) - 2\tilde{R}_{\theta r} \partial_r \tilde{u}_\theta + 2\overline{P' \nabla_\theta u''_\theta} + 2\mathcal{G}_k^{\theta} + \mathcal{N}_{R\theta\theta} \quad (30)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\phi\phi}/\bar{\rho} \right) = -\nabla_r (2f_k^{\phi}) - 2\tilde{R}_{\phi r} \partial_r \tilde{u}_\phi + 2\overline{P' \nabla_\phi u''_\phi} + 2\mathcal{G}_k^{\phi} + \mathcal{N}_{R\phi\phi} \quad (31)$$

2.4 Mean turbulent kinetic energy equations (second-order moments)

$$\bar{\rho} \tilde{D}_t \tilde{k} = -\nabla_r (f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + W_P + \mathcal{N}_k \quad (32)$$

$$\bar{\rho} \tilde{D}_t \tilde{k}^r = -\nabla_r (f_k^r + f_P) - \tilde{R}_{rr} \partial_r \tilde{u}_r + W_b + \overline{P' \nabla_r u''_r} + \mathcal{G}_k^r + \mathcal{N}_{kr} \quad (33)$$

$$\bar{\rho} \tilde{D}_t \tilde{k}^h = -\nabla_r f_k^h - (\tilde{R}_{\theta r} \partial_r \tilde{u}_\theta + \tilde{R}_{\phi r} \partial_r \tilde{u}_\phi) + (\overline{P' \nabla_\theta u''_\theta} + \overline{P' \nabla_\phi u''_\phi}) + \mathcal{G}_k^h + \mathcal{N}_{kh} \quad (34)$$

$$(35)$$

2.5 Mean flux equations (second-order moments)

$$\bar{\rho}\tilde{D}_t(f_I/\bar{\rho}) = -\nabla_r f_I^r - f_I \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{\epsilon}_I - \overline{\epsilon''_I \partial_r \bar{P}} - \overline{u''_r (Pd)} + \overline{u''_r (\mathcal{S} + \nabla \cdot F_T)} + \mathcal{G}_I + \mathcal{N}_{fI} \quad (36)$$

$$\bar{\rho}\tilde{D}_t(f_h/\bar{\rho}) = -\nabla_r f_h^r - f_h \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{h} - \overline{h'' \partial_r \bar{P}} - \overline{h'' \partial_r \bar{P'}} - \Gamma_1 \overline{u''_r (Pd)} + \Gamma_3 \overline{u''_r (\mathcal{S} + \nabla \cdot F_T)} + \mathcal{G}_h + \mathcal{N}_h \quad (37)$$

$$\bar{\rho}\tilde{D}_t(f_s/\bar{\rho}) = -\nabla_r f_s^r - f_s \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{s} - \overline{s'' \partial_r \bar{P}} - \overline{s'' \partial_r \bar{P'}} + \overline{u''_r (\mathcal{S} + \nabla \cdot F_T)/T} + \mathcal{G}_s + \mathcal{N}_{fs} \quad (38)$$

$$\bar{\rho}\tilde{D}_t(f_{\alpha r}/\bar{\rho}) = -\nabla_r f_{\alpha r}^r - f_{\alpha r} \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_{\alpha} - \overline{X''_{\alpha} \partial_r \bar{P}} - \overline{X''_{\alpha} \partial_r \bar{P'}} + \overline{u''_r \rho \dot{X}_{\alpha}^{\text{nuc}}} + \mathcal{G}_{\alpha} + \mathcal{N}_{f\alpha} \quad (39)$$

$$\bar{\rho}\tilde{D}_t(f_{\alpha\theta}/\bar{\rho}) = -\nabla_r f_{\alpha\theta}^{\theta} - f_{\alpha r} \partial_r \tilde{u}_{\theta} - \tilde{R}_{\theta r} \partial_r \tilde{X}_{\alpha} + \overline{u''_{\theta} \rho \dot{X}_{\alpha}^{\text{nuc}}} + \mathcal{G}_{\alpha\theta} + \mathcal{N}_{f\alpha\theta} \quad (40)$$

$$\bar{\rho}\tilde{D}_t(f_{\alpha\phi}/\bar{\rho}) = -\nabla_r f_{\alpha\phi}^{\phi} - f_{\alpha r} \partial_r \tilde{u}_{\phi} - \tilde{R}_{\phi r} \partial_r \tilde{X}_{\alpha} + \overline{u''_{\phi} \rho \dot{X}_{\alpha}^{\text{nuc}}} + \mathcal{G}_{\alpha\phi} + \mathcal{N}_{f\alpha\phi} \quad (41)$$

$$\bar{\rho}\tilde{D}_t(f_A/\bar{\rho}) = -\nabla_r f_A^r - f_A \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{A} - \overline{A'' \partial_r \bar{P}} - \overline{A'' \partial_r \bar{P'}} - \overline{u''_r \rho A^2 \Sigma_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}/A_{\alpha}} + \mathcal{G}_A + \mathcal{N}_{fA} \quad (42)$$

$$\bar{\rho}\tilde{D}_t(f_Z/\bar{\rho}) = -\nabla_r f_Z^r - f_Z \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{Z} - \overline{Z'' \partial_r \bar{P}} - \overline{Z'' \partial_r \bar{P'}} - \overline{u''_r \rho Z A \Sigma_{\alpha} (\dot{X}_{\alpha}^{\text{nuc}}/A_{\alpha})} - \overline{u''_r \rho A \Sigma_{\alpha} (Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}/A_{\alpha})} + \mathcal{G}_Z + \mathcal{N}_{fZ} \quad (43)$$

$$\bar{\rho}\tilde{D}_t(f_{jz}/\rho) = -\nabla_r f_{jz}^r - f_{jz} \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{j}_z - \overline{j_z'' \partial_r \bar{P}} - \overline{j_z'' \partial_r \bar{P'}} + \mathcal{G}_{jz} + \mathcal{N}_{jz} \quad (44)$$

$$\tilde{D}_t f_T = -\nabla_r f_T^r - f_T \partial_r \bar{u}_r - \overline{u'_r u''_r \partial_r \bar{T}} - \overline{T' \partial_r P/\rho} - (\Gamma_3 - 1) (\overline{T} \overline{u'_r d''} + \overline{d} \overline{u'_r T'} + \overline{u'_r T' d''}) + \overline{T' u'_r d''} + \overline{u'_r \epsilon_{\text{nuc}}/c_v} + \overline{u'_r \nabla \cdot F_T/\rho c_v} + \mathcal{G}_T + \mathcal{N}_{fT} \quad (45)$$

$$\bar{\rho}\tilde{D}_t(f_k/\bar{\rho}) = -\nabla_r (2f_k^r + f_P^r) - (1/2) (\nabla_r \overline{u''_i u''_i P'} + \nabla_r 2k \partial_r \tilde{u}_r - \overline{u''_i u''_i \nabla_r \tilde{R}_{rr}} - 2k \partial_r \bar{P} + \overline{u''_i u''_i \partial_r \bar{P}} - \overline{P' \nabla_r u''_i u''_i}) - \quad (46)$$

$$-(k^r_i \partial_r \tilde{u}_i - \overline{u''_i u''_i \nabla_r u''_i u''_i} - 2k^r \partial_r \bar{P} + \overline{u''_i u''_i \partial_r \bar{P}} - \overline{P' \nabla_i u''_i u''_i}) + \mathcal{G}_{fk} + \mathcal{N}_{fk} \quad (47)$$

$$\tilde{D}_t f_{pr} = -\nabla_r f_p^r - f_{pr} \partial_r \bar{u}_r + \overline{u'_r u''_r \partial_r \bar{P}} + \Gamma_1 \overline{u'_r Pd} + (\Gamma_3 - 1) \overline{u'_r \rho \varepsilon_{\text{nuc}}} + \overline{P' u''_r d''} - \overline{P' G_r^M/\rho} - \overline{P' \partial_r P/\rho} + \mathcal{N}_{fpr} \quad (48)$$

$$\tilde{D}_t f_{p\theta} = -\nabla_r f_p^{\theta} - f_{pr} \partial_r \bar{u}_{\theta} + \overline{u'_{\theta} u''_r \partial_r \bar{P}} + \Gamma_1 \overline{u'_{\theta} Pd} + (\Gamma_3 - 1) \overline{u'_{\theta} \rho \varepsilon_{\text{nuc}}} + \overline{P' u''_{\theta} d''} - \overline{P' G_{\theta}^M/\rho} - \overline{P' \partial_{\theta} P/\rho r} + \mathcal{N}_{fp\theta} \quad (49)$$

$$\tilde{D}_t f_{p\phi} = -\nabla_r f_p^{\phi} - f_{pr} \partial_r \bar{u}_{\phi} + \overline{u'_{\phi} u''_r \partial_r \bar{P}} + \Gamma_1 \overline{u'_{\phi} Pd} + (\Gamma_3 - 1) \overline{u'_{\phi} \rho \varepsilon_{\text{nuc}}} + \overline{P' u''_{\phi} d''} - \overline{P' G_{\phi}^M/\rho} - \overline{P' \partial_{\phi} P/\rho r \sin \theta} + \mathcal{N}_{fp\phi} \quad (50)$$

2.6 Mean variance equations (second-order moments)

$$\tilde{D}_t \sigma_{\rho} = -\nabla_r (\overline{\rho' \rho' u''_r}) - 2\bar{\rho} \overline{\rho' d''} - 2\overline{\rho' u''_r} \partial_r \bar{\rho} - 2\tilde{d} \sigma_{\rho} - \overline{\rho' \rho' d''} + \mathcal{N}_{\sigma_{\rho}} \quad (51)$$

$$\tilde{D}_t \sigma_P = -\nabla_r (\overline{P' P' u''_r}) - 2\Gamma_1 \overline{P} W_P - 2f_P \partial_r \bar{P} - 2\Gamma_1 \tilde{d} \sigma_P - (2\Gamma_1 - 1) \overline{P' P' d''} + 2(\Gamma_3 - 1) \overline{P' S} + \mathcal{N}_{\sigma_P} \quad (52)$$

$$\tilde{D}_t \sigma_T = -\nabla_r (\overline{T' T' u''_r}) - 2(\Gamma_3 - 1) \overline{T} \overline{T' d''} - 2\overline{T' u''_r} \partial_r \bar{T} - 2(\Gamma_3 - 1) \tilde{d} \sigma_T + (3 - 2\Gamma_3) \overline{T' T' d''} + \overline{2T' \nabla \cdot F_T/\rho c_v} + \overline{2T' \epsilon_{\text{nuc}}/c_v} + \mathcal{N}_{\sigma_T} \quad (53)$$

$$\bar{\rho}\tilde{D}_t \sigma_{ur} = -\nabla_r (\overline{\rho u''_r u''_r u''_r}) + 2\nabla_r f_P + 2W_b - 2\tilde{R}_{rr} \partial_r \tilde{u}_r + 2\overline{P' \nabla_r u''_r} + \mathcal{G}_{\sigma_{ur}} + \mathcal{N}_{\sigma_{ur}} \quad (54)$$

$$\tilde{D}_t \sigma_T = -\nabla_r (\overline{T' T' u''_r}) - 2(\Gamma_3 - 1) \overline{T} \overline{T' d''} - 2\overline{T' u''_r} \partial_r \overline{T} - 2(\Gamma_3 - 1) \tilde{d} \sigma_T + (3 - 2\Gamma_3) \overline{T' T' d''} + \overline{2T' \nabla \cdot F_T / \rho c_v} + \overline{2T' \epsilon_{\text{nuc}} / c_v} + \mathcal{N}_{\sigma T} \quad (55)$$

$$\bar{\rho} \tilde{D}_t \sigma_{ur} = -\nabla_r (\overline{\rho u''_r u''_r u''_r}) + 2\nabla_r f_P + 2W_b - 2\tilde{R}_{rr} \partial_r \tilde{u}_r + 2\overline{P' \nabla_r u''_r} + \mathcal{G}_{\sigma_{ur}} + \mathcal{N}_{\sigma_{ur}} \quad (56)$$

$$\bar{\rho} \tilde{D}_t \sigma_{\epsilon I} = -\nabla_r (\overline{\rho \epsilon''_I \epsilon''_I u''_r}) - 2f_I \partial_r \tilde{\epsilon}_I - 2\overline{\epsilon''_I P} \tilde{d} - 2\overline{P} \overline{\epsilon''_I d''} - 2\tilde{d} \overline{\epsilon''_I P'} - 2\overline{\epsilon''_I P' d''} + 2\overline{\epsilon''_I S} + \mathcal{N}_{\sigma_{\epsilon I}} \quad (57)$$

$$\bar{\rho} \tilde{D}_t \sigma_h = -\nabla_r (\overline{\rho h'' h'' u''_r}) - 2f_h \partial_r \tilde{h} - 2\Gamma_1 \overline{h'' P d} + 2\Gamma_3 \overline{h'' \rho S} + \mathcal{N}_{\sigma_h} \quad (58)$$

$$\bar{\rho} \tilde{D}_t \sigma_s = -\nabla_r (\overline{\rho s'' s'' u''_r}) - 2f_s \partial_r \tilde{s} - 2\overline{s'' \nabla \cdot F_T / T} + 2\overline{s'' S / T} + \mathcal{N}_{\sigma_s} \quad (59)$$

$$\bar{\rho} \tilde{D}_t \sigma_\alpha = -\nabla_r (\overline{\rho X''_\alpha X''_\alpha u''_r}) - 2f_\alpha \partial_r \tilde{X}_\alpha + 2\overline{X''_\alpha \rho \dot{X}_\alpha^{\text{nuc}}} + \mathcal{N}_{\sigma_\alpha} \quad (60)$$

Table 1: Definitions:

ρ	density	g_r	radial gravitational acceleration
T	temperature	$\mathcal{S} = \rho\epsilon_{\text{nuc}}(q)$	nuclear energy production (cooling function)
P	pressure	$\tau_{ij} = 2\mu S_{ij}$	viscous stress tensor (μ kinematic viscosity)
u_r, u_θ, u_ϕ	velocity components	$S_{ij} = (1/2)(\partial_i u_j + \partial_j u_i)$	strain rate
$\mathbf{u} = (u_r, u_\theta, u_\phi)$	velocity	$\tilde{R}_{ij} = \bar{\rho}\widetilde{u''_i u''_j}$	Reynolds stress tensor
$j_z = r \sin \theta u_\phi$	specific angular momentum	$F_T = \chi \partial_r T$	heat flux
$d = \nabla \cdot \mathbf{u}$	dilatation	$\Gamma_1 = (d \ln P / d \ln \rho) _s$	
ϵ_I	specific internal energy	$\Gamma_2 / (\Gamma_2 - 1) = (d \ln P / d \ln T) _s$	
h	specific enthalpy	$\Gamma_3 - 1 = (d \ln T / d \ln \rho) _s$	
$k = (1/2)\widetilde{u''_i u''_i}$	turbulent kinetic energy	$\tilde{k}^r = (1/2)\widetilde{u''_r u''_r} = (1/2)\widetilde{\bar{R}_{rr}}/\bar{\rho}$	radial turbulent kinetic energy
ϵ_k	specific kinetic energy	$\tilde{k}^\theta = (1/2)\widetilde{u''_\theta u''_\theta} = (1/2)\widetilde{\bar{R}_{\theta\theta}}/\bar{\rho}$	angular turbulent kinetic energy
ϵ_t	specific total energy	$\tilde{k}^\phi = (1/2)\widetilde{u''_\phi u''_\phi} = (1/2)\widetilde{\bar{R}_{\phi\phi}}/\bar{\rho}$	angular turbulent kinetic energy
s	specific entropy	$\tilde{k}^h = \tilde{k}^\theta + \tilde{k}^\phi$	horizontal turbulent kinetic energy
$v = 1/\rho$	specific volume	$f_k = (1/2)\bar{\rho}\widetilde{u''_i u''_i u''_r}$	turbulent kinetic energy flux
X_α	mass fraction of isotope α	$f_k^r = (1/2)\bar{\rho}\widetilde{u''_r u''_r u''_r}$	radial turbulent kinetic energy flux
$\dot{X}_\alpha^{\text{nuc}}$	rate of change of X_α	$f_k^\theta = (1/2)\bar{\rho}\widetilde{u''_\theta u''_\theta u''_r}$	angular turbulent kinetic energy flux
A_α	number of nucleons in isotope α	$f_k^\phi = (1/2)\bar{\rho}\widetilde{u''_\phi u''_\phi u''_r}$	angular turbulent kinetic energy flux
Z_α	charge of isotope α	$f_k^h = f_k^\theta + f_k^\phi$	horizontal turbulent kinetic energy flux
A	mean number of nucleons per isotope	$W_p = \overline{P' d'}$	turbulent pressure dilatation
Z	mean charge per isotope	$W_b = \bar{\rho}\widetilde{u''_r g_r}$	buoyancy
$f_P = \overline{P' u'_r}$	acoustic flux	$f_T = -\overline{T' u'_r}$	heat flux (χ thermal conductivity)

Table 2: Definitions (continued):

$f_I = \widetilde{\rho c_f'' u_r''}$	internal energy flux	$f_\alpha = \widetilde{\rho X_\alpha'' u_r''}$	X_α flux
$f_s = \widetilde{\rho s'' u_r''}$	entropy flux	$f_{jz} = \widetilde{\rho j_z'' u_r''}$	angular momentum flux
$f_T = \overline{u_r' T'}$	turbulent heat flux	$f_A = \widetilde{\rho A'' u_r''}$	A (mean number of nucleons per isotope) flux
$f_h = \widetilde{\rho h'' u_r''}$	enthalpy flux	$f_Z = \widetilde{\rho Z'' u_r''}$	Z (mean charge per isotope) flux
$b = \overline{v' \rho'}$	density-specific volume covariance	$\mathcal{N}_\rho, \mathcal{N}_{ur}, \mathcal{N}_{u\theta}, \mathcal{N}_{u\phi}, \mathcal{N}_{jz}, \mathcal{N}_\alpha, \mathcal{N}_A, \mathcal{N}_Z$	numerical effect
$f_\tau = f_\tau^r + f_\tau^\theta + f_\tau^\phi$	viscous flux	$\mathcal{N}_{\epsilon I} = -\nabla_r f_\tau + \varepsilon_k$	numerical effect
$f_\tau^r = -\overline{\tau_{rr}' u_r'}$	viscous flux	$\mathcal{N}_{\epsilon k} = -\varepsilon_k$	numerical effect
$f_\tau^\theta = -\overline{\tau_{\theta r}' u_\theta'}$	viscous flux	$\mathcal{N}_{\epsilon t} = -\nabla_r f_\tau$	numerical effect
$f_\tau^\phi = -\overline{\tau_{\phi r}' u_\phi'}$	viscous flux	$\mathcal{N}_s = \overline{-\varepsilon_k/T}$	numerical effect
$f_\tau^h = f_\tau^\theta + f_\tau^\phi$	viscous flux	$\mathcal{N}_h = -\nabla_r f_\tau + (\Gamma_3 - 1)\varepsilon_k$	numerical effect
$f_I^r = \overline{\rho \epsilon_I'' u_r'' u_r''}$	radial flux of f_I	$\mathcal{N}_P = +(\Gamma_3 - 1)\varepsilon_k$	numerical effect
$f_s^r = \overline{\rho s'' u_r'' u_r''}$	radial flux of f_s	$\mathcal{N}_T = +(\overline{\tau_{ij} \partial_j u_i}) / (\overline{c_v \rho})$	numerical effect
$f_h^r = \overline{\rho h'' u_r'' u_r''}$	radial flux of f_h	$\mathcal{N}_{Rrr} = -2\nabla_r f_\tau^r - 2\varepsilon_k^r$	numerical effect
$f_T^r = \overline{T' u_r' u_r'}$	radial flux of f_T	$\mathcal{N}_{R\theta\theta} = -2\nabla_r f_\tau^\theta - 2\varepsilon_k^\theta$	numerical effect
$f_{jz}^r = \overline{\rho j_z'' u_r'' u_r''}$	radial flux of f_{jz}	$\mathcal{N}_{R\phi\phi} = -2\nabla_r f_\tau^\phi - 2\varepsilon_k^\phi$	numerical effect
$f_\alpha^r = \overline{\rho X_\alpha'' u_r'' u_r''}$	radial flux of f_α	$\mathcal{N}_k = -\nabla_r f_\tau - \varepsilon_k$	numerical effect
$f_A^r = \overline{\rho A'' u_r'' u_r''}$	radial flux of f_A	$\mathcal{N}_{kr} = -\nabla_r f_\tau^r - \varepsilon_k^r$	numerical effect
$f_Z^r = \overline{\rho Z'' u_r'' u_r''}$	radial flux of f_Z	$\mathcal{N}_{kh} = -\nabla_r f_\tau^h - \varepsilon_k^h$	numerical effect
$\mathcal{G}_k^r = -(1/2)\overline{G_{rr}^R} - \overline{u_r'' G_r^M}$		$\mathcal{N}_a = -\varepsilon_a$	numerical effect

Table 3: Definitions (continued):

$\mathcal{G}_k^\theta = -(1/2)\overline{G_{\theta\theta}^R} - \overline{u''_\theta G_\theta^M}$	\mathcal{N}_b numerical effect
$\mathcal{G}_k^\phi = -(1/2)\overline{G_{\phi\phi}^R} - \overline{u''_\phi G_\phi^M}$	$\mathcal{N}_{fI} = -\nabla_r(\overline{\epsilon_I'' \tau'_{rr}}) + \overline{u''_r \tau_{ij} \partial_i u_j} - \varepsilon_I$ numerical effect
$\mathcal{G}_k^h = +\mathcal{G}_k^\theta + \mathcal{G}_k^\phi$	$\mathcal{N}_{fh} = -\nabla_r(\overline{h'' \tau'_{rr}}) + \overline{u''_r (\Gamma_3 - 1) \tau_{ij} \partial_i u_j} - \overline{u''_r \nabla_i u_i \tau_{ji}} - \varepsilon_h$ numerical effect
$\mathcal{G}_a = +\overline{\rho' v G_r^M}$	$\mathcal{N}_{fs} = -\nabla_r(\overline{s'' \tau'_{rr}}) + \overline{u''_r \tau_{ij} \partial_i u_j / T} - \varepsilon_s$ numerical effect
$\mathcal{G}_I = -\overline{G_r^I} - \overline{\epsilon_I'' G_r^M}$	$\mathcal{N}_{fA} = -\nabla_r(\overline{A'' \tau'_{rr}}) - \varepsilon_A$ numerical effect
$\mathcal{G}_\alpha = -\overline{G_r^\alpha} - \overline{X_\alpha'' G_r^M}$	$\mathcal{N}_{fZ} = -\nabla_r(\overline{Z'' \tau'_{rr}}) - \varepsilon_Z$ numerical effect
$\mathcal{G}_A = -\overline{G_r^A} - \overline{A'' G_r^M}$	$\mathcal{N}_{f\alpha} = -\nabla_r(\overline{\alpha'' \tau'_{rr}}) - \varepsilon_\alpha$ numerical effect
$\mathcal{G}_Z = -\overline{G_r^Z} - \overline{Z'' G_r^M}$	$\mathcal{N}_{fjz} = -\nabla_r(\overline{j_z'' \tau'_{rr}}) - \varepsilon_{jz}$ numerical effect
$\mathcal{G}_h = -\overline{G_r^h} - \overline{h'' G_r^M}$	$\mathcal{N}_{fT} = +\overline{T' \partial_i \tau_{ri} / \rho} + \overline{u'_r \tau_{ij} \partial_i u_j / \rho c_v}$ numerical effect
$\mathcal{G}_T = -\overline{G_r^T} - \overline{T' G_r^M}$	
$\mathcal{G}_s = -\overline{G_r^s} - \overline{s'' G_r^M}$	
$\mathcal{G}_{jz} = -\overline{G_r^{jz}} - \overline{j_z'' G_r^M}$	
$\sigma_\rho = \overline{\rho' \rho'}$	$\mathcal{N}_{\sigma_\rho}$ numerical effect
$\sigma_P = \overline{P' P'}$	$\mathcal{N}_{\sigma_P} = +2(\Gamma_3 - 1) \overline{P' \tau_{ij} \partial_i u_j}$ numerical effect
$\sigma_T = \overline{T' T'}$	$\mathcal{N}_{\sigma_T} = +2\overline{T' \tau_{ij} \partial_i u_j / \rho c_v}$ numerical effect
$\sigma_{ur} = \widetilde{u''_r u''_r}$	$\mathcal{N}_{\sigma_{ur}} = +2\nabla_r f_\tau^r - 2\varepsilon_k^r$ numerical effect
$\sigma_s = \widetilde{s'' s''}$	$\mathcal{N}_{\sigma_s} = +2\overline{s'' \tau_{ij} \partial_j u_i / T}$ numerical effect
$\sigma_\alpha = \widetilde{X_\alpha'' X_\alpha''}$	$\mathcal{N}_{\sigma_\alpha}$ numerical effect numerical effect
$\sigma_{\epsilon I} = \widetilde{\epsilon_I'' \epsilon_I''}$	$\mathcal{N}_{\sigma_{\epsilon I}} = +2\overline{\epsilon_I'' \tau_{ij} \partial_j u_i}$ numerical effect

Table 4: Definitions (continued):

$$\begin{aligned}
 \varepsilon_k^r &= \overline{\tau'_{rr} \partial_r u''_r} + \overline{\tau'_{r\theta}(1/r) \partial_\theta u''_r} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi u''_r} \\
 \varepsilon_k^\theta &= \overline{\tau'_{\theta r} \partial_r u''_\theta} + \overline{\tau'_{\theta\theta}(1/r) \partial_\theta u''_\theta} + \overline{\tau'_{\theta\phi}(1/r \sin \theta) \partial_\phi u''_\theta} \\
 \varepsilon_k^\phi &= \overline{\tau'_{\phi r} \partial_r u''_\phi} + \overline{\tau'_{\phi\theta}(1/r) \partial_\theta u''_\phi} + \overline{\tau'_{\phi\phi}(1/r \sin \theta) \partial_\phi u''_\phi} \\
 \varepsilon_k &= \varepsilon_k^r + \varepsilon_k^\theta + \varepsilon_k^\phi \\
 \varepsilon_k^h &= \varepsilon_k^\theta + \varepsilon_k^\phi \\
 \varepsilon_a &= \overline{\rho' v \nabla_r \tau'_{rr}} \\
 \varepsilon_I &= \overline{\tau'_{rr} \partial_r \epsilon''_I} + \overline{\tau'_{r\theta}(1/r) \partial_\theta \epsilon''_I} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi \epsilon''_I} \\
 \varepsilon_s &= \overline{\tau'_{rr} \partial_r s''} + \overline{\tau'_{r\theta}(1/r) \partial_\theta s''} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi s''} \\
 \varepsilon_\alpha &= \overline{\tau'_{rr} \partial_r X''_\alpha} + \overline{\tau'_{r\theta}(1/r) \partial_\theta X''_\alpha} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi X''_\alpha} \\
 \varepsilon_A &= \overline{\tau'_{rr} \partial_r A''} + \overline{\tau'_{r\theta}(1/r) \partial_\theta A''} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi A''} \\
 \varepsilon_Z &= \overline{\tau'_{rr} \partial_r Z''} + \overline{\tau'_{r\theta}(1/r) \partial_\theta Z''} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi Z''} \\
 \varepsilon_h &= \overline{\tau'_{rr} \partial_r h''} + \overline{\tau'_{r\theta}(1/r) \partial_\theta h''} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi h''} \\
 \varepsilon_{jz} &= \overline{\tau'_{rr} \partial_r j''_z} + \overline{\tau'_{r\theta}(1/r) \partial_\theta j''_z} + \overline{\tau'_{r\phi}(1/r \sin \theta) \partial_\phi j''_z}
 \end{aligned}$$

$$\begin{aligned}
 \overline{G_r^M} &= -\overline{\rho u_\theta u_\theta / r} - \overline{\rho u_\phi u_\phi / r} \\
 \overline{G_\theta^M} &= +\overline{\rho u_\theta u_r / r} - \overline{\rho u_\phi u_\phi / (r \tan \theta)} \\
 \overline{G_\phi^M} &= +\overline{\rho u_\phi u_r / r} + \overline{\rho u_\phi u_\theta / (r \tan \theta)} \\
 \overline{G_{rr}^R} &= -\overline{\rho u_\theta'' u_\theta'' u_r'' / r} - \overline{\rho u_\theta'' u_r'' u_\theta'' / r} - \overline{\rho u_\phi'' u_\phi'' u_r'' / r} - \overline{\rho u_\phi'' u_r'' u_\phi'' / r} \\
 \overline{G_{\theta\theta}^R} &= +\overline{\rho u_\theta'' u_r'' u_\theta'' / r} + \overline{\rho u_\theta'' u_\theta'' u_r'' / r} - \overline{\rho u_\phi'' u_\phi'' u_\theta'' / (r \tan \theta)} - \overline{u_\phi'' u_\theta'' u_\phi'' / (r \tan \theta)} \\
 \overline{G_{\phi\phi}^R} &= +\overline{\rho u_\phi'' u_r'' u_\phi'' / r} + \overline{\rho u_\phi'' u_\theta'' u_\phi'' / (r \tan \theta)} + \overline{\rho u_\phi'' u_\phi'' u_r'' / r} + \overline{\rho u_\phi'' u_\theta'' u_\theta'' / (r \tan \theta)} \\
 \overline{G_r^I} &= -\overline{\rho \epsilon''_I u_\theta'' u_\theta'' / r} - \overline{\rho \epsilon''_I u_\phi'' u_\phi'' / r} \\
 \overline{G_r^s} &= -\overline{\rho s'' u_\theta'' u_\theta'' / r} - \overline{\rho s'' u_\phi'' u_\phi'' / r} \\
 \overline{G_r^\alpha} &= -\overline{\rho X''_\alpha u_\theta'' u_\theta'' / r} - \overline{\rho X''_\alpha u_\phi'' u_\phi'' / r} \\
 \overline{G_r^A} &= -\overline{\rho A'' u_\theta'' u_\theta'' / r} - \overline{\rho A'' u_\phi'' u_\phi'' / r} \\
 \overline{G_r^Z} &= -\overline{\rho Z'' u_\theta'' u_\theta'' / r} - \overline{\rho Z'' u_\phi'' u_\phi'' / r} \\
 \overline{G_r^h} &= -\overline{\rho h'' u_\theta'' u_\theta'' / r} - \overline{\rho h'' u_\phi'' u_\phi'' / r} \\
 \overline{G_r^T} &= -\overline{\rho T' u_\theta' u_\theta' / r} - \overline{\rho T' u_\phi' u_\phi' / r} \\
 \overline{G_r^{jz}} &= -\overline{\rho j_z'' u_\theta'' u_\theta'' / r} - \overline{\rho j_z'' u_\phi'' u_\phi'' / r}
 \end{aligned}$$

Table 5: Definitions (continued):

$$\begin{aligned}
 \tilde{F}_{ijk}^R &= \bar{\rho} u_i'' \widetilde{u_j''} u_k'' \text{ Reynolds stress flux} \\
 f_\tau^{ij} &= \overline{u_i'' \tau_{jr}} \text{ viscous flux} \\
 \varepsilon_\tau^{ij} &= \overline{\tau'_{ir} \partial_r u_i''} + \overline{\tau'_{i\theta} (1/r) \partial_\theta u_j''} + \overline{\tau'_{i\phi} (1/r \sin \theta) \partial_\phi u_j''} \text{ viscous dissipation} \\
 G_r^M &= -(\rho u_\theta^2 - \tau_{\theta\theta})/r - (\rho u_\phi^2 - \tau_{\phi\phi})/r \\
 G_\theta^M &= +(\rho u_\theta u_r - \tau_{\theta r})/r - (\rho u_\phi^2 - \tau_{\phi\phi}) \cos \theta / (r \sin \theta) \\
 G_\phi^M &= +(\rho u_\phi u_r - \tau_{\phi r})/r + (\rho u_\phi u_\theta - \tau_{\phi\theta}) \cos \theta / (r \sin \theta)
 \end{aligned}$$

Below are non-vanishing terms of space-time average over $\nabla \cdot F_{ijk}$ (F_{ijk} is 3rd order tensor)

$$\begin{aligned}
 \overline{G_{rr}^R} &= -\overline{F_{\theta\theta r}^R/r} - \overline{F_{\theta r\theta}^R/r} - \overline{F_{\phi\phi r}^R/r} - \overline{F_{\phi r\phi}^R/r} \\
 \overline{G_{r\theta}^R} &= -\overline{F_{\theta\theta\theta}^R/r} + \overline{F_{\theta rr}^R/r} - \overline{F_{\phi\phi\theta}^R/r} - \overline{F_{\phi r\phi}^R \cos \theta / (r \sin \theta)} \\
 \overline{G_{r\phi}^R} &= +\overline{F_{\theta\theta\phi}^R/r} - \overline{F_{\phi\phi\phi}^R} + \overline{F_{\phi r\phi}^R \cos \theta / (r \sin \theta)} \\
 \overline{G_{\theta r}^R} &= +\overline{F_{\theta rr}^R/r} - \overline{F_{\theta\theta\theta}^R/r} - \overline{F_{\phi\phi r}^R \cos \theta / (r \sin \theta)} - \overline{F_{\phi\theta\phi}^R/r} \\
 \overline{G_{\theta\theta}^R} &= +\overline{F_{\theta r\theta}^R/r} + \overline{F_{\theta\theta r}^R/r} - \overline{F_{\phi\phi\theta}^R \cos \theta / (r \sin \theta)} - \overline{F_{\phi\theta\phi}^R \cos \theta / (r \sin \theta)} \\
 \overline{G_{\theta\phi}^R} &= +\overline{F_{\theta r\phi}^R/r} + \overline{F_{\phi\theta r}^R/r} + \overline{F_{\phi\theta\theta}^R \cos \theta / (r \sin \theta)} \\
 \overline{G_{\phi r}^R} &= -\overline{F_{\theta\phi\theta}^R/r} + \overline{F_{\phi rr}^R/r} + \overline{F_{\phi\phi r}^R \cos \theta / (r \sin \theta)} - \overline{F_{\phi\phi\phi}^R/r} \\
 \overline{G_{\phi\theta}^R} &= +\overline{F_{\theta\phi r}^R/r} + \overline{F_{\phi rr}^R/r} + \overline{F_{\phi\theta\theta}^R \cos \theta / (r \sin \theta)} - \overline{F_{\phi\theta\phi}^R \cos \theta / (r \sin \theta)} \\
 \overline{G_{\phi\phi}^R} &= +\overline{F_{\phi r\phi}^R/r} + \overline{F_{\phi\theta\phi}^R \cos \theta / (r \sin \theta)} + \overline{F_{\phi\phi r}^R/r} + \overline{F_{\phi\phi\theta}^R \cos \theta / (r \sin \theta)}
 \end{aligned} \tag{61}$$

$$\nabla(.) = \nabla_r(.) + \nabla_\theta(.) + \nabla_\phi(.) = \frac{1}{r^2} \partial_r(r^2 .) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta .) + \frac{1}{r \sin \theta} \partial_\phi(.)$$

3 Properties of our oxygen shell burning and red giant data

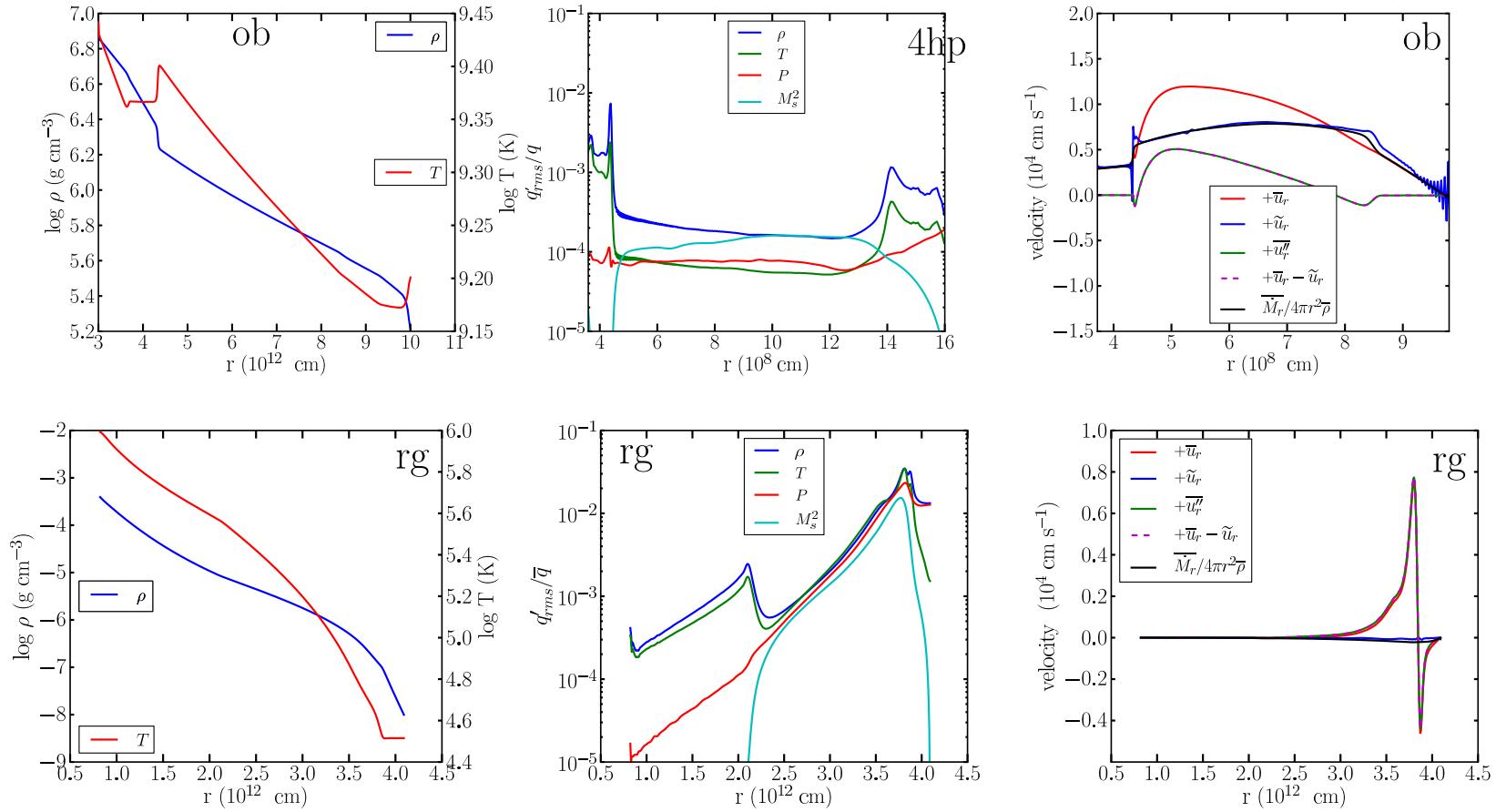


Figure 1: Properties of our data. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

3.1 Snapshots of turbulent kinetic energy in a meridional plane

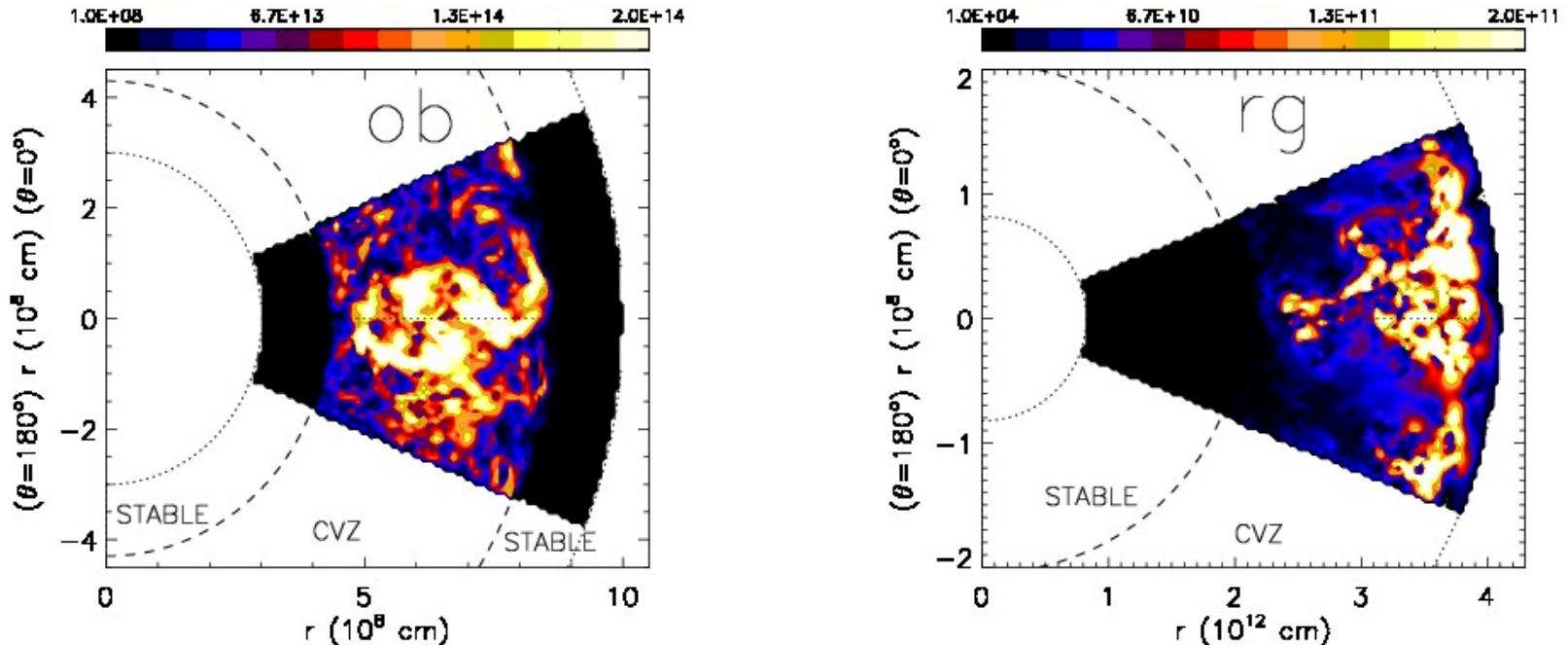


Figure 2: Snapshots of turbulent kinetic energy (in erg g^{-1}) in a meridional plane of 3D oxygen burning shell model ob.3D.mr (left) and red giant envelope convection model rg.3D.mr (right). Convectively unstable (CVZ) and stable layers (STABLE) are separated by dashed lines.

3.2 Summary of the Oxygen Burning Simulations and their properties

Parameter	ob.3D.lr	ob.3D.mr	ob.3D.hr	ob.3D.1hp	ob.3D.2hp	ob.3D.4hp	ob.3d.1hp.vc	ob.3d.1hp.vh
Grid zoning	192×128^2	384×256^2	786×512^2	200×50^2	400×100^2	320×50^2	200×50^2	400×100^2
$r_{\text{in}}, r_{\text{out}}$ (10^9 cm)	0.3, 1.0	0.3, 1.0	0.3, 1.0	0.3, 0.9	0.3, 1.0	0.3, 1.6	0.3, 0.9	0.3, 0.9
$r_{\text{b}}^c, r_{\text{t}}^c$ (10^9 cm)	0.43, 0.85	0.43, 0.85	0.43, 0.84	0.43, 0.68	0.43, 0.84	0.42, 1.4	0.43, 0.65	0.43, 0.68
$\Delta\theta, \Delta\phi$	45°	45°	45°	27.5°	27.5°	27.5°	27.5°	27.5°
CZ stratification (H_P)	1.9	1.9	1.9	1.2	1.9	4.1	1.1	1.2
Δt_{av} (s)	230	230	165	900	230	500	300	300
v_{rms} (10^6 cm/s)	10.7	10.9	10.9	5.28	9.15	4.88	4.66	4.97
τ_{conv} (s)	78.2	77.1	75.6	94.7	89.2	403.	94.6	95.6
$P_{\text{turb}}/P_{\text{gas}}(10^{-4})$	3.88	4.05	4.03	0.96	3.01	1.73	0.79	0.96
L (10^{46} erg/s)	2.74	2.63	2.58	0.44	2.86	0.26	0.40	-0.42
L_d (10^{46} erg/s)	0.29	0.28	0.26	0.04	0.31	0.08	0.03	0.03
l_d (10^8 cm)	7.39	7.92	8.73	3.87	4.15	5.1	2.85	4.1
τ_d (s)	34.48	36.47	39.98	36.72	22.64	52.04	30.56	41.1
τ_{dr} (s)	38.06	39.27	-	75.65	46.59	130.73	90.20	90.8
τ_{dh} (s)	30.77	32.14	-	22.91	14.21	28.42	18.4	25.24

Table 6: boundaries of computational domain $r_{\text{in}}, r_{\text{out}}$; boundaries of convection zone at bottom and top $r_{\text{b}}^c, r_{\text{t}}^c$; angular size of computational domain $\Delta\theta, \Delta\phi$; depth of convection zone “CZ stratification” in pressure scale height H_P ; averaging timescale of mean fields analysis Δt_{av} ; global rms velocity v_{rms} ; convective turnover timescale τ_{conv} ; average ratio of turbulent ram pressure and gas pressure $p_{\text{turb}}/p_{\text{gas}}$; total luminosity of the hydrodynamic model L ; total rate of kinetic energy dissipation L_d ; dissipation length-scale l_d ; turbulent kinetic energy dissipation time-scale τ_d ; radial turbulent kinetic energy dissipation time-scale τ_{dr} ; horizontal turbulent kinetic energy dissipation time-scale τ_{dh} . The numerical values may vary in time up to 20% due to limited amount of data for averaging out the time dependence.

3.3 Summary of Red Giant Simulations and their properties

Parameter	rg.3D.lr	rg.3D.mr	rg.3D.4hp
Grid zoning	216×128^2	432×256^2	176×128^2
$r_{\text{in}}, r_{\text{out}}$ (10^{12} cm)	0.82, 4.09	0.82, 4.09	0.82, 0.34
$r_{\text{in}}^c, r_{\text{out}}^c$ (10^{12} cm)	2.05, 3.86	2.07, 3.88	2.16, 3.33
$\Delta\theta, \Delta\phi$	45°	45°	45°
CZ stratification (H_p)	7.0	7.2	3.5
Δt_{av} (days)	800	800	800
v_{rms} (10^5 cm/s)	2.59	2.66	2.01
τ_{conv} (days)	161.	158.	134.
$P_{\text{turb}}/P_{\text{gas}}(10^{-3})$	4.68	4.98	0.98
L_{cool} (10^{36} erg/s)	-8.57	-7.13	-9.2
L_d (10^{36} erg/s)	7.26	7.24	2.27
l_d (10^{11} cm)	9.95	10.4	11.6
τ_d (days)	22.2	22.7	33.3
τ_{dr} (days)	36.7	44.7	53.0
τ_{dh} (days)	18.3	17.9	28.2

Table 7: boundaries of computational domain $r_{\text{in}}, r_{\text{out}}$; boundaries of convection zone at bottom and top r_b^c, r_t^c ; angular size of computational domain $\Delta\theta, \Delta\phi$; depth of convection zone “CZ stratification” in pressure scale height H_P ; averaging timescale of mean fields analysis Δt_{av} ; global rms velocity v_{rms} ; convective turnover timescale τ_{conv} ; average ratio of turbulent ram pressure and gas pressure $p_{\text{turb}}/p_{\text{gas}}$; total luminosity of the hydrodynamic model L ; total rate of kinetic energy dissipation L_d ; dissipation length-scale l_d ; turbulent kinetic energy dissipation time-scale τ_d ; radial turbulent kinetic energy dissipation time-scale τ_{dr} ; horizontal turbulent kinetic energy dissipation time-scale τ_{dh} . The numerical values may vary in time up to 20% due to limited amount of data for averaging out the time dependence.

4 Profiles and intergral budgets of mean fields equations

4.1 Mean continuity equation

$$\tilde{D}_t \bar{\rho} = -\bar{\rho} \tilde{d} + \mathcal{N}_\rho \quad (62)$$

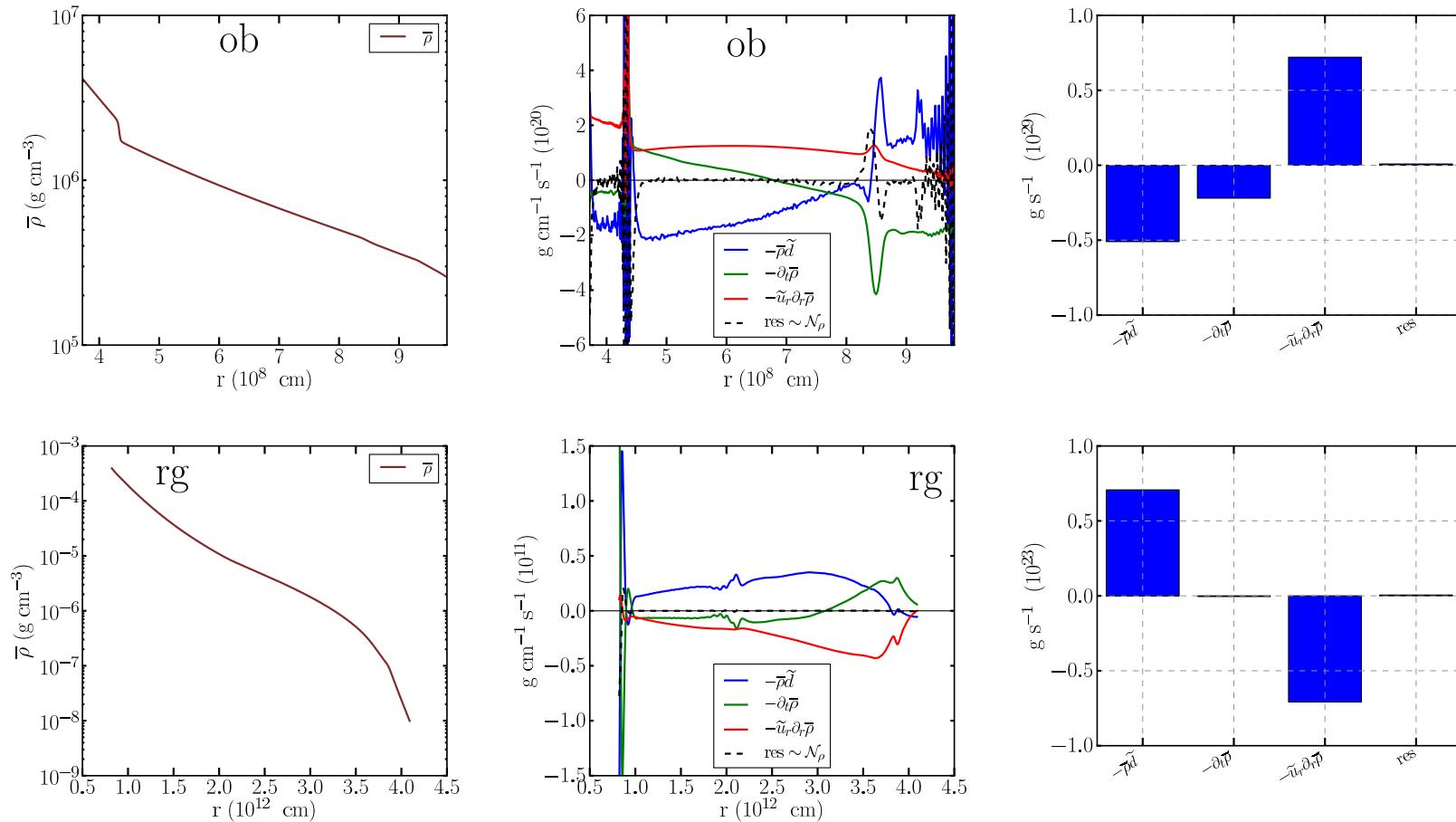


Figure 3: Mean continuity equation. Model **ob.3D_mr** (upper panels) and model **rg.3D_mr** (lower panels).

4.2 Mean radial momentum equation

$$\bar{\rho} \tilde{D}_t \tilde{u}_r = -\nabla_r \tilde{R}_{rr} - \overline{G_r^M} - \partial_r \overline{P} + \bar{\rho} \tilde{g}_r + \mathcal{N}_{ur} \quad (63)$$

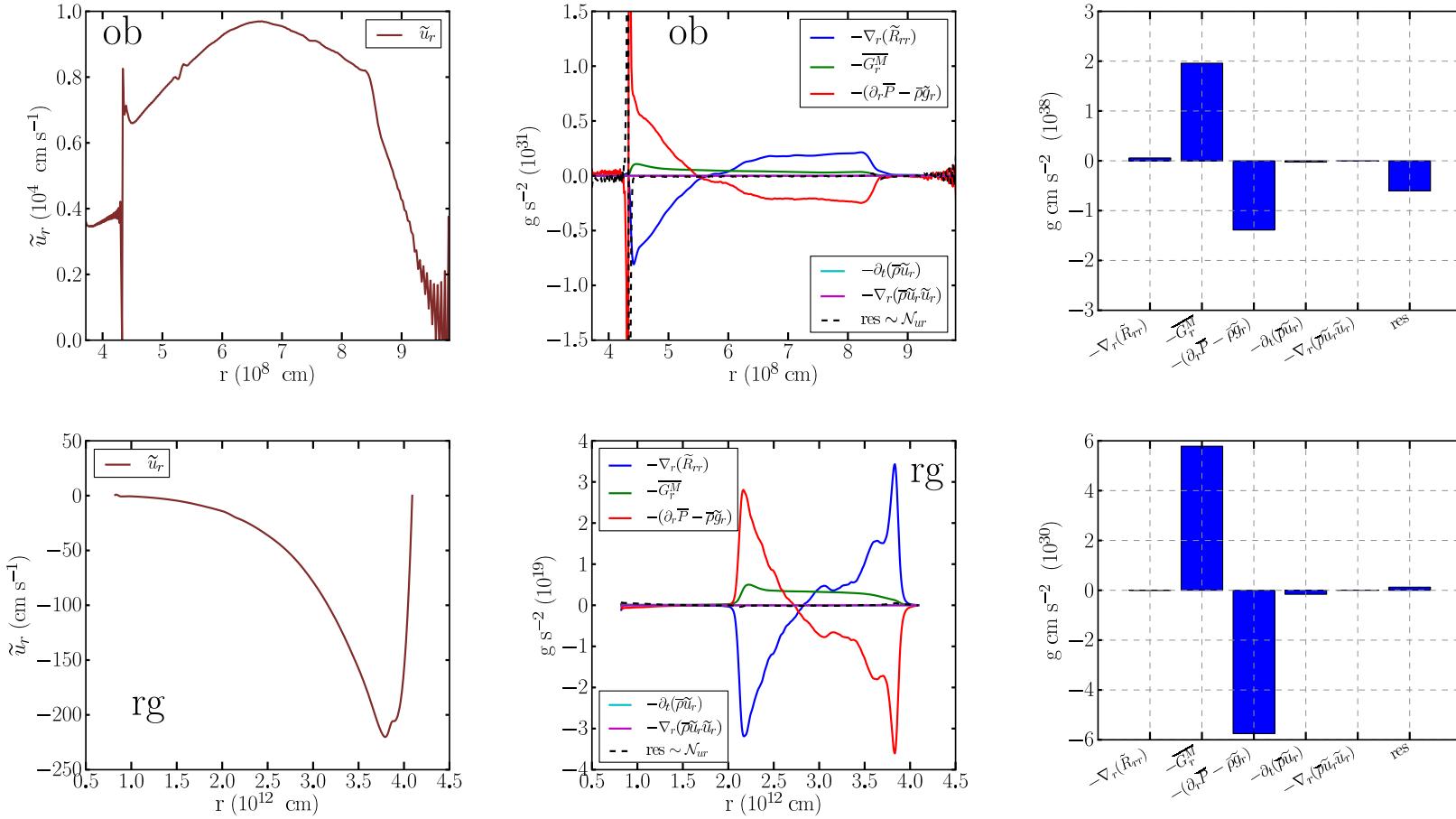


Figure 4: Mean radial momentum equation. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

4.3 Mean azimuthal momentum equation

$$\bar{\rho} \tilde{D}_t \tilde{u}_\theta = -\nabla_r \tilde{R}_{\theta r} - \overline{G_\theta^M} - (1/r) \overline{\partial_\theta P} + \mathcal{N}_{u\theta} \quad (64)$$

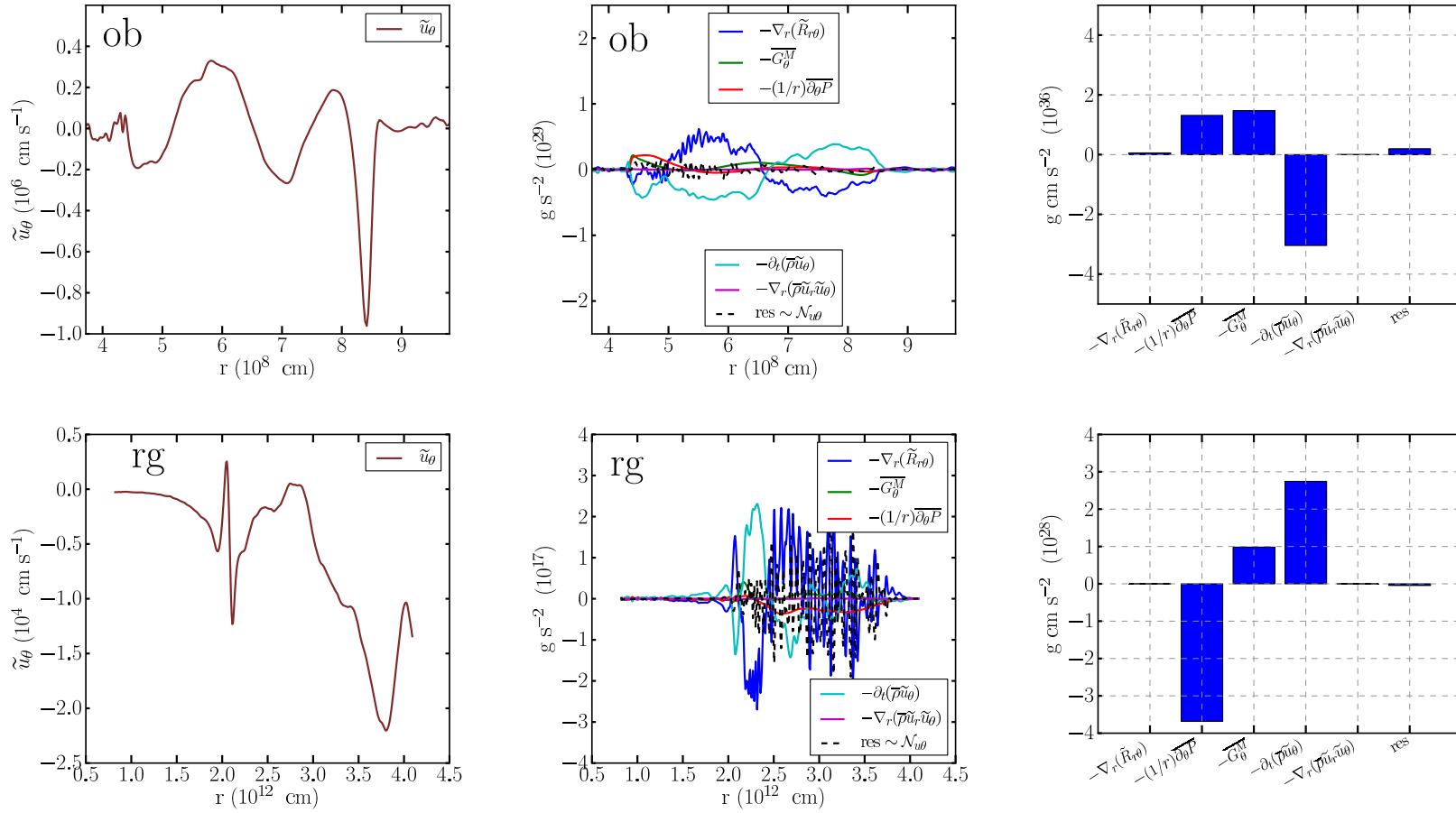


Figure 5: Mean azimuthal momentum equation. Model ob.3D.mr (upper panels) and model rg.3D.mr (lower panels).

4.4 Mean polar momentum equation

$$\bar{\rho} \tilde{D}_t \tilde{u}_\phi = -\nabla_r \tilde{R}_{\phi r} - \overline{G_\phi^M} + \mathcal{N}_{u\phi} \quad (65)$$

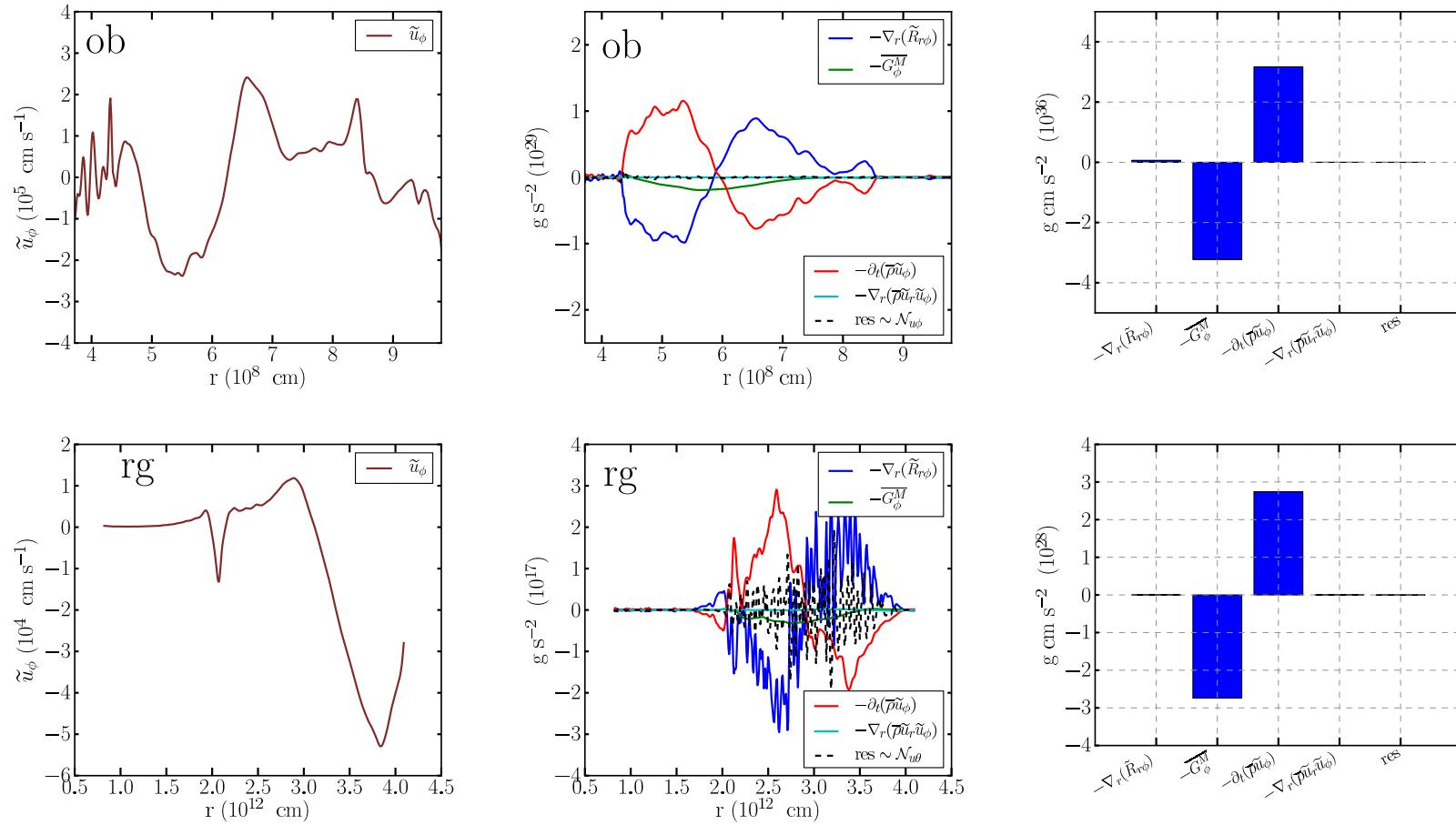


Figure 6: Mean polar omentum equation. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

4.5 Mean internal energy equation

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_I = -\nabla_r(f_I + f_T) - \bar{P} \bar{d} - W_P + S + \mathcal{N}_{\epsilon I} \quad (66)$$

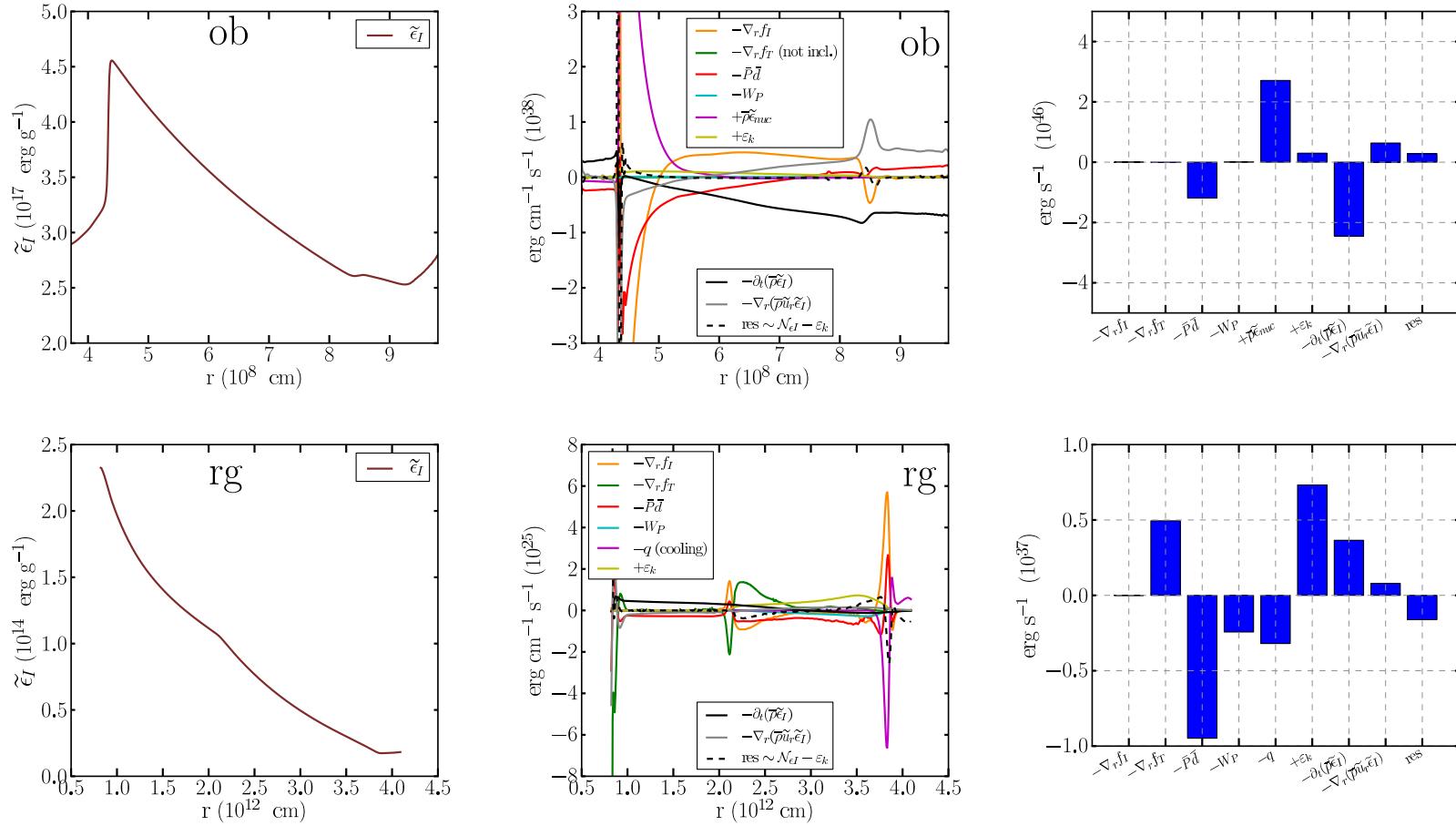


Figure 7: Mean internal energy equation. Model ob.3D.mr (upper panels) and model rg.3D.mr (lower panels).

4.6 Mean kinetic energy equation

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_k = -\nabla_r(f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + W_P + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) + \mathcal{N}_{ek} \quad (67)$$

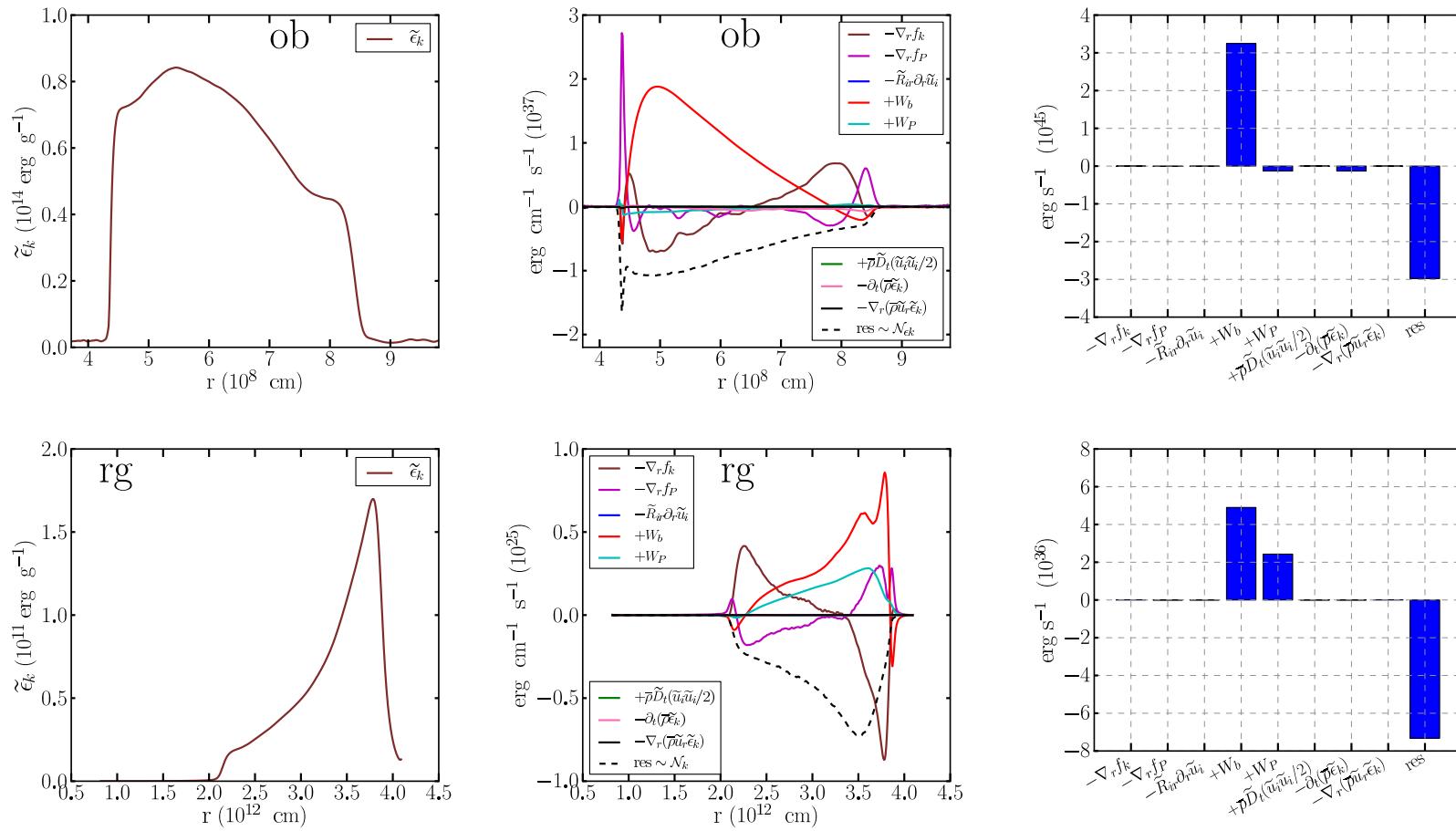


Figure 8: Mean kinetic energy equation. Model ob.3D.mr (upper panels) and model rg.3D.mr (lower panels).

4.7 Mean total energy equation

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_t = -\nabla_r(f_I + f_T + f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i - \bar{P} \bar{d} + W_b + \mathcal{S} + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) + \mathcal{N}_{et} \quad (68)$$

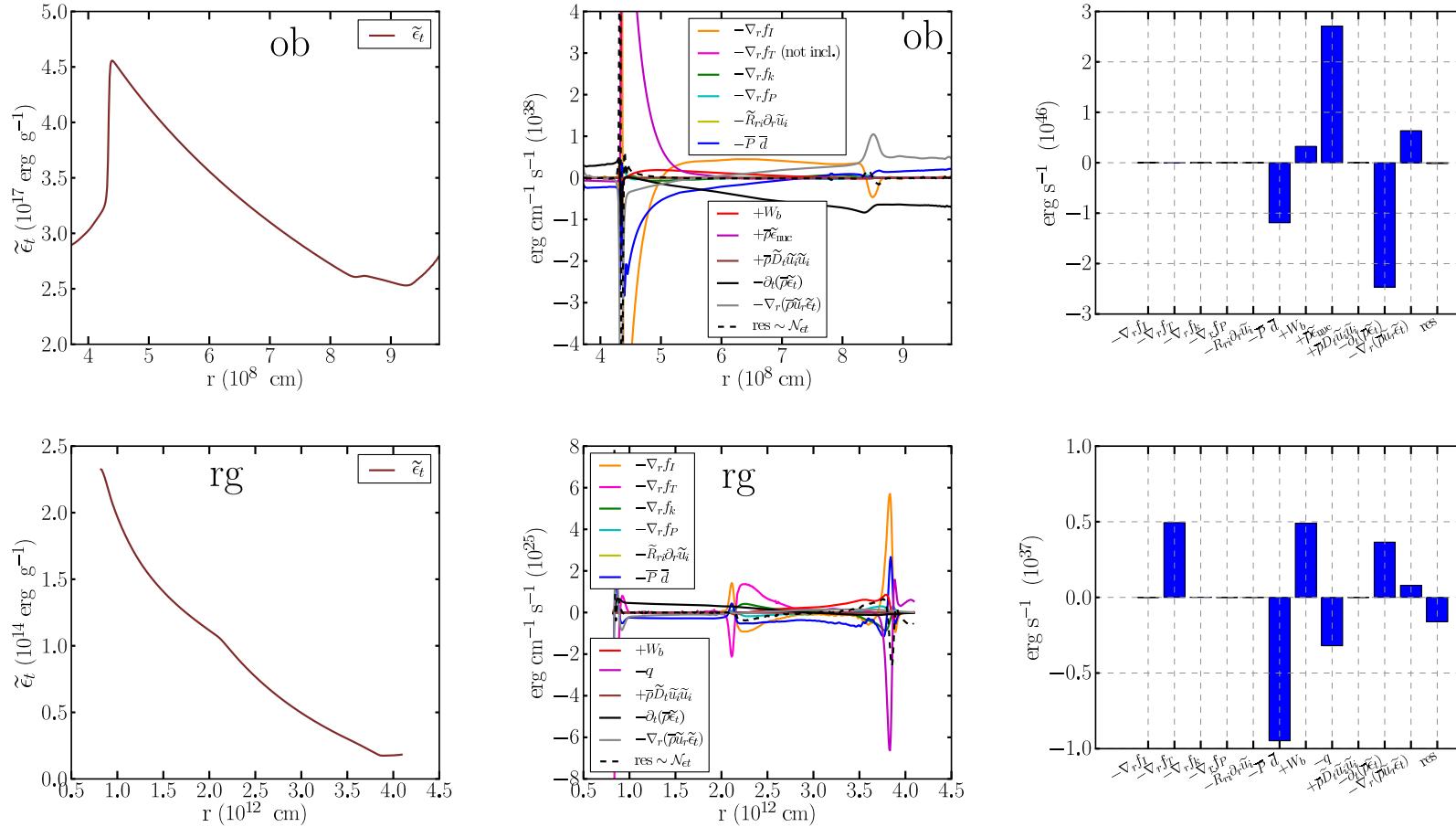


Figure 9: Mean total energy equation. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

4.8 Mean entropy equation

$$\bar{\rho} \tilde{D}_t \tilde{s} = -\nabla_r f_s - (\nabla \cdot F_T)/T + \bar{\mathcal{S}}/T + \mathcal{N}_s \quad (69)$$

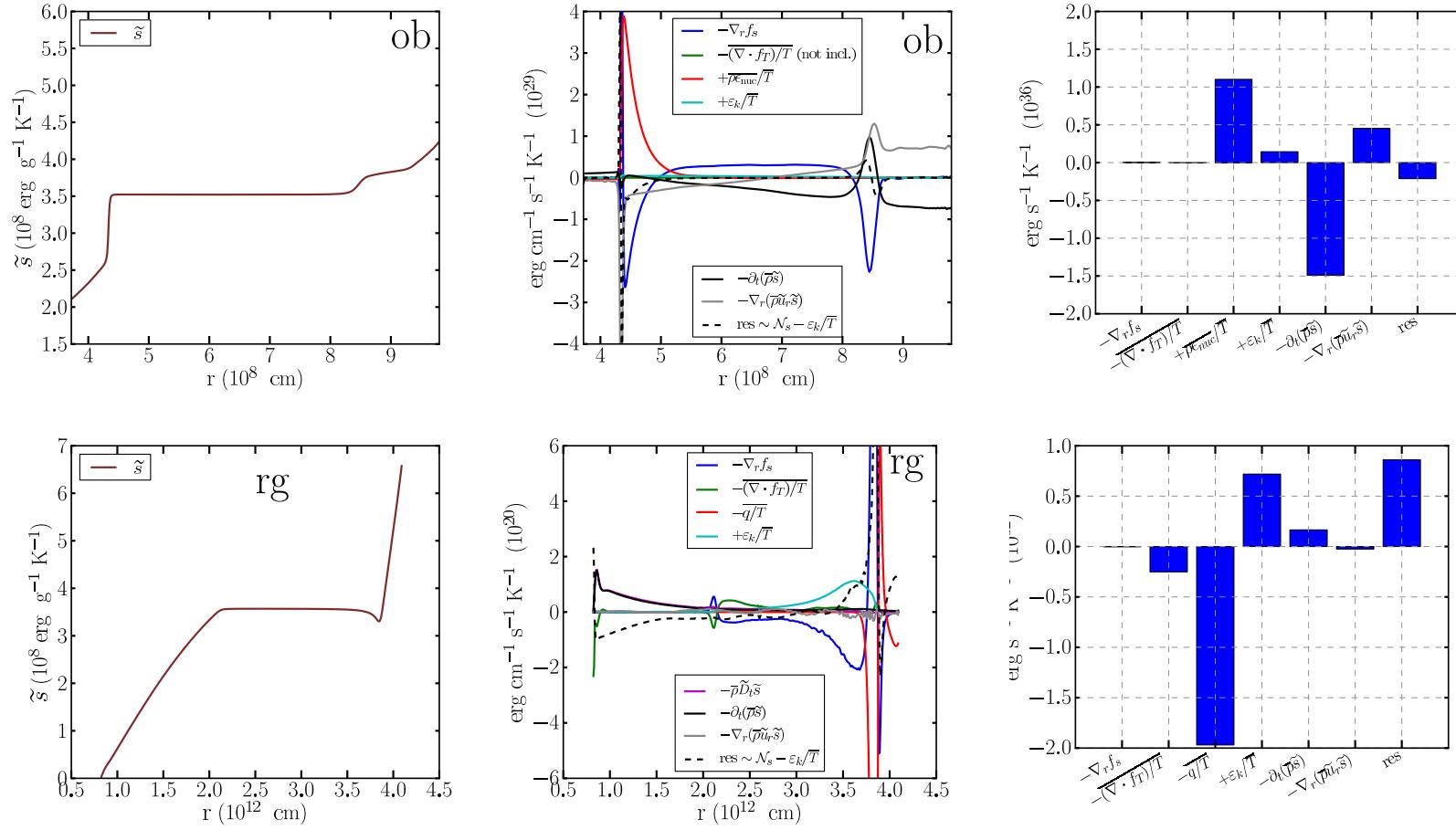


Figure 10: Mean entropy equation. Model ob.3D.2hp (upper panels) and model rg.3D.mr (lower panels).

4.9 Mean pressure equation

$$\bar{D}_t \bar{P} = -\nabla_r f_P - \Gamma_1 \bar{P} \bar{d} + (1 - \Gamma_1) W_P + (\Gamma_3 - 1) \mathcal{S} + (\Gamma_3 - 1) \nabla_r f_T + \mathcal{N}_P \quad (70)$$

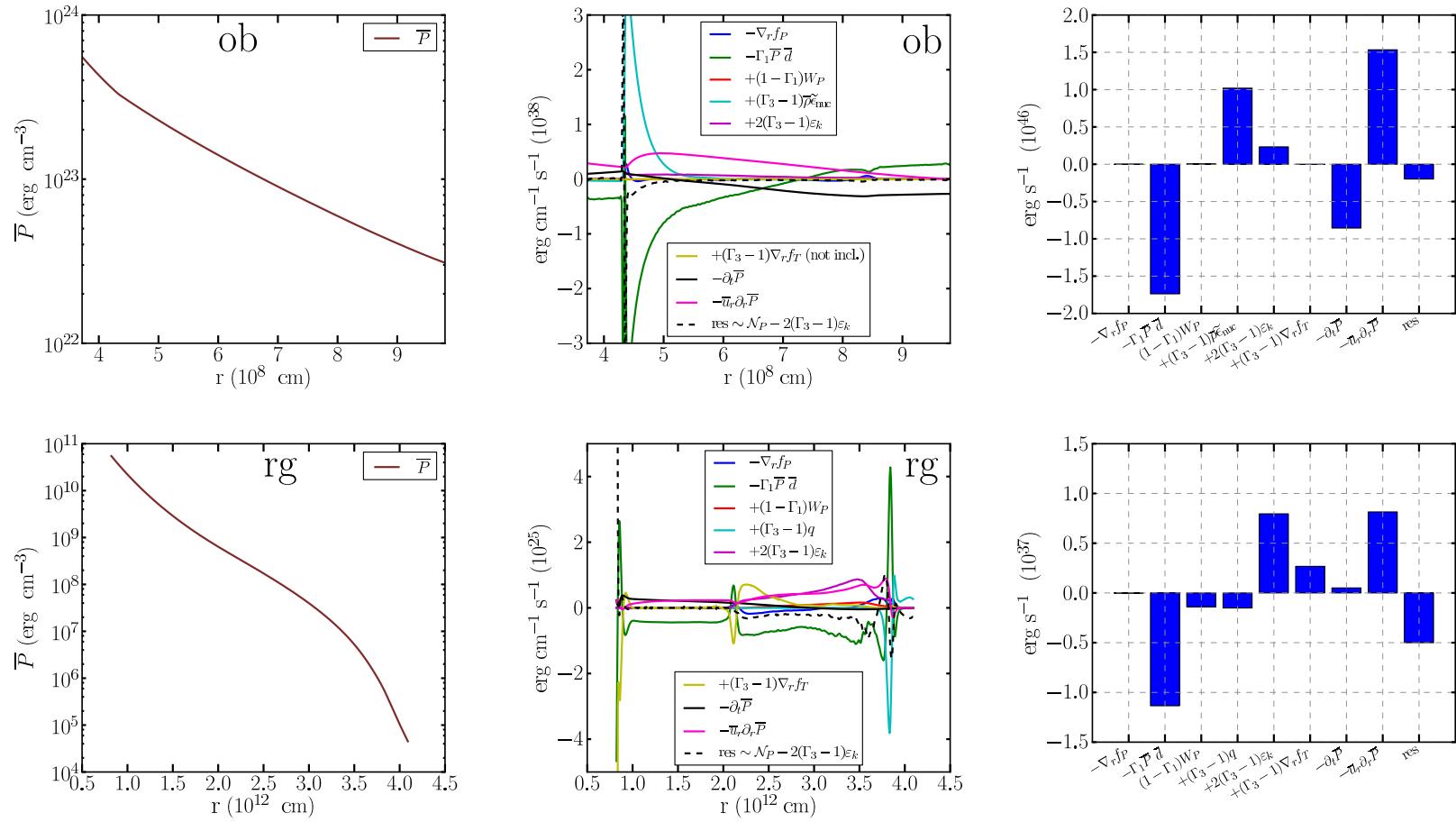


Figure 11: Mean pressure equation. Model ob.3D.mr (upper panels) and model rg.3D.mr (lower panels).

4.10 Mean enthalpy equation

$$\bar{\rho} \tilde{D}_t \tilde{h} = -\nabla_r f_h - \Gamma_1 \bar{P} \bar{d} - \Gamma_1 W_P + \Gamma_3 \mathcal{S} + \Gamma_3 \nabla_r f_T + \mathcal{N}_h \quad (71)$$

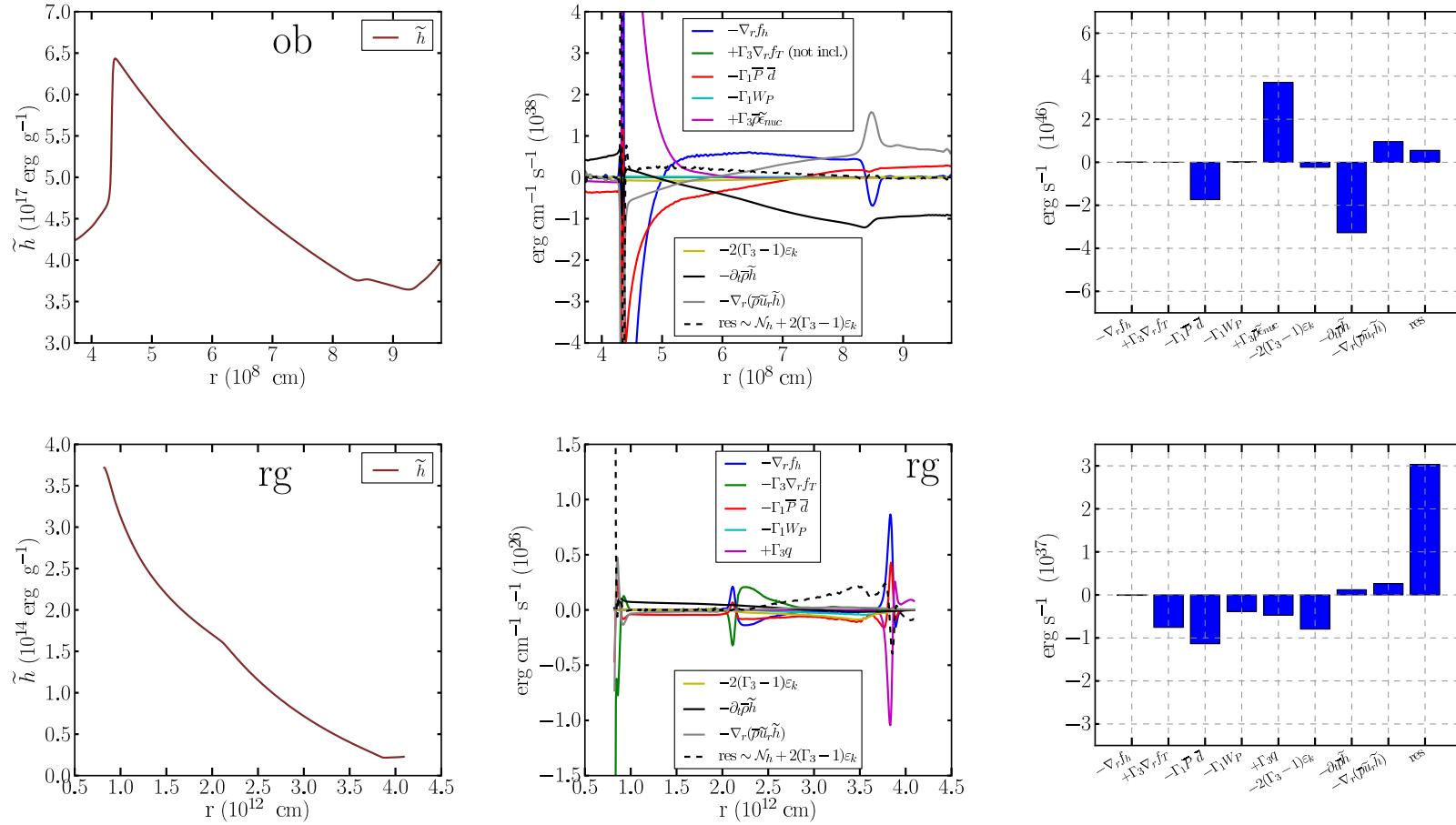


Figure 12: Mean enthalpy equation. Model ob.3D.mr (upper panels) and model rg.3D.mr (lower panels).

4.11 Mean angular momentum equation (z-component)

$$\bar{\rho} \tilde{D}_t \tilde{j}_z = -\nabla_r f_{jz} + \mathcal{N}_{jz} \quad (72)$$

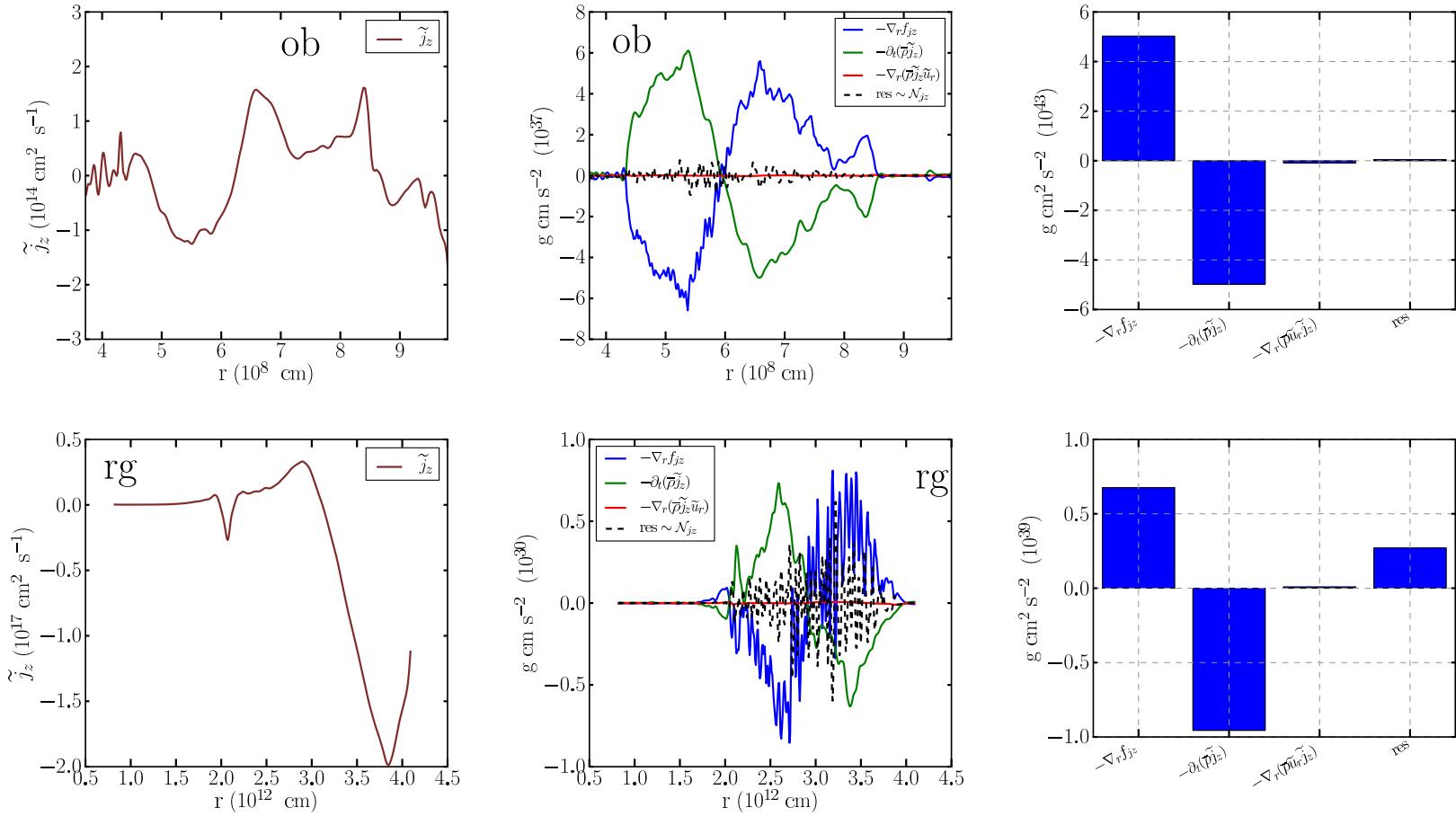


Figure 13: Mean angular momentum equation. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

4.12 Mean composition equation

$$\bar{\rho} \tilde{D}_t \tilde{X}_\alpha = -\nabla_r f_\alpha + \bar{\rho} \tilde{X}_\alpha^{\text{nuc}} + \mathcal{N}_\alpha \quad \bar{\rho} \tilde{D}_t \tilde{A} = -\nabla_r f_A - \overline{\rho A^2 \Sigma_\alpha (\dot{X}_\alpha^{\text{nuc}} / A_\alpha)} + \mathcal{N}_A \quad (73)$$

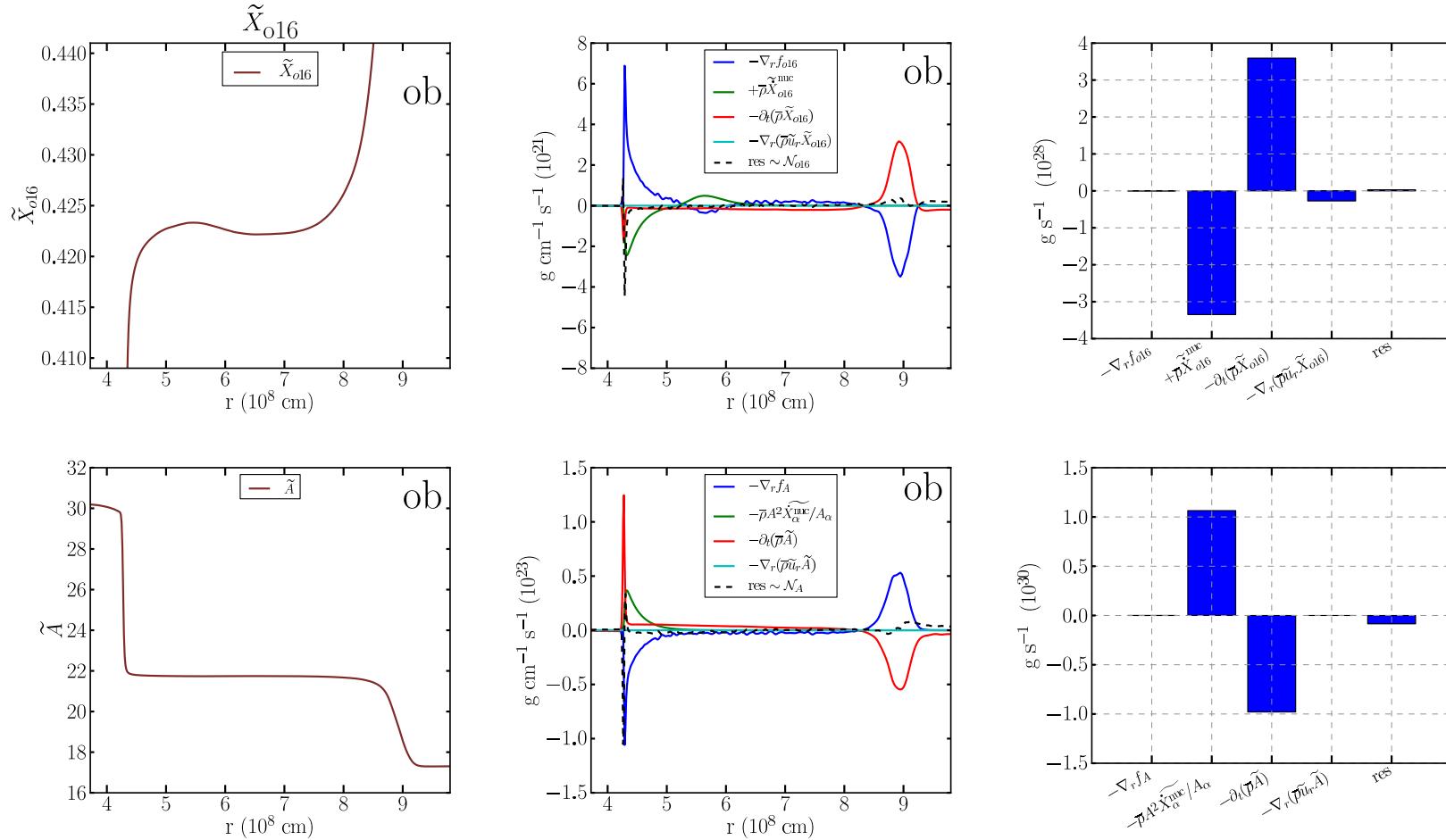


Figure 14: Mean composition equation for O^{16} and equation for mean number of nucleons per isotope. Model ob.3D.2hp.

4.13 Mean turbulent kinetic energy equation

$$\bar{\rho} \tilde{D}_t \tilde{k} = -\nabla_r(f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + W_P + \mathcal{N}_k \quad (74)$$

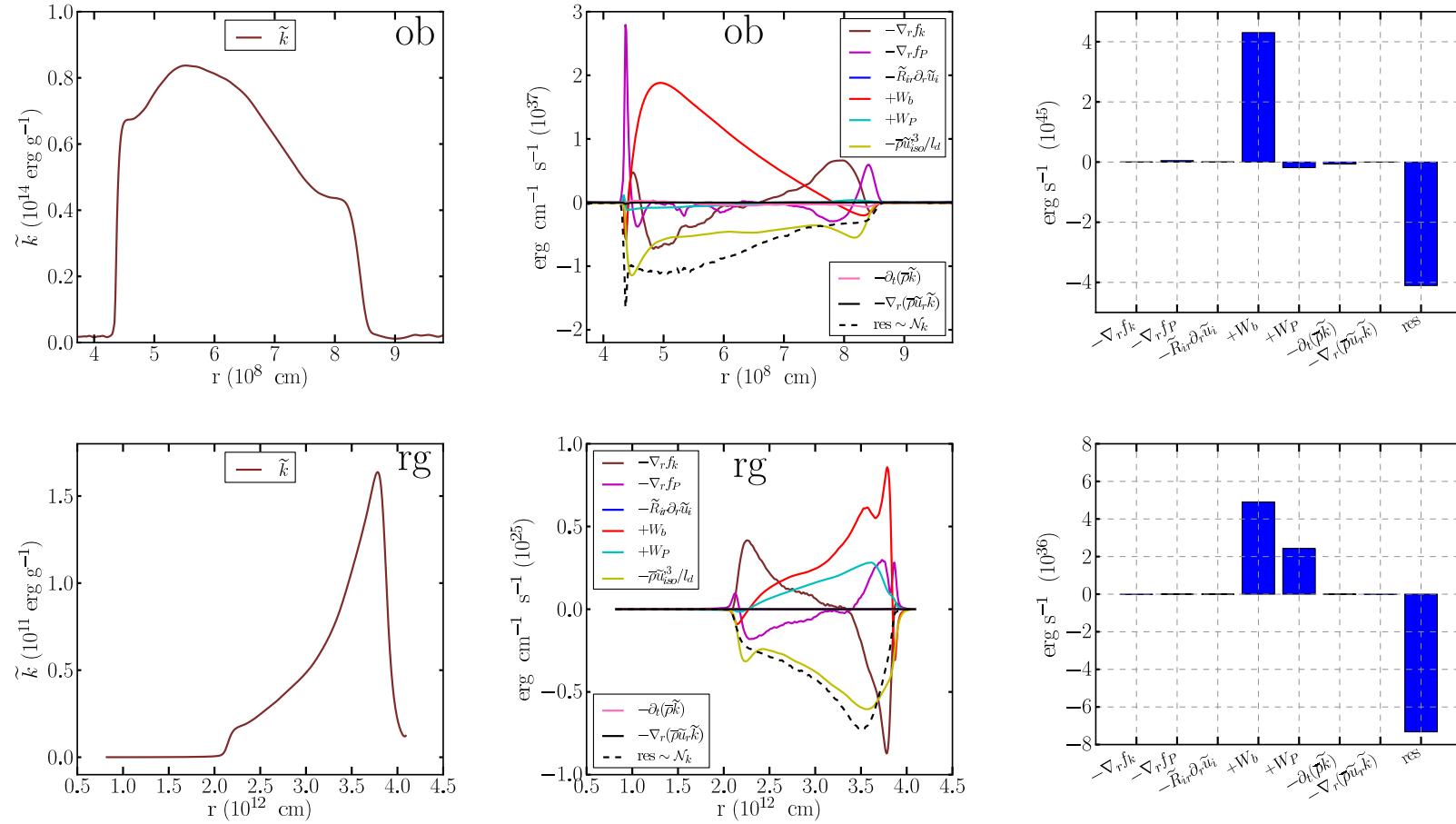


Figure 15: Turbulent kinetic energy equation. Model `ob.3D.mr` (upper panels) and model `rg.3D.mr` (lower panels).

4.14 Mean turbulent kinetic energy equation (radial part)

$$\bar{\rho} \tilde{D}_t \tilde{k}^r = -\nabla_r(f_k^r + f_P) - \tilde{R}_{rr} \partial_r \tilde{u}_r + W_b + \overline{P' \nabla_r u''_r} + \mathcal{G}_k^r + \mathcal{N}_{kr} \quad (75)$$

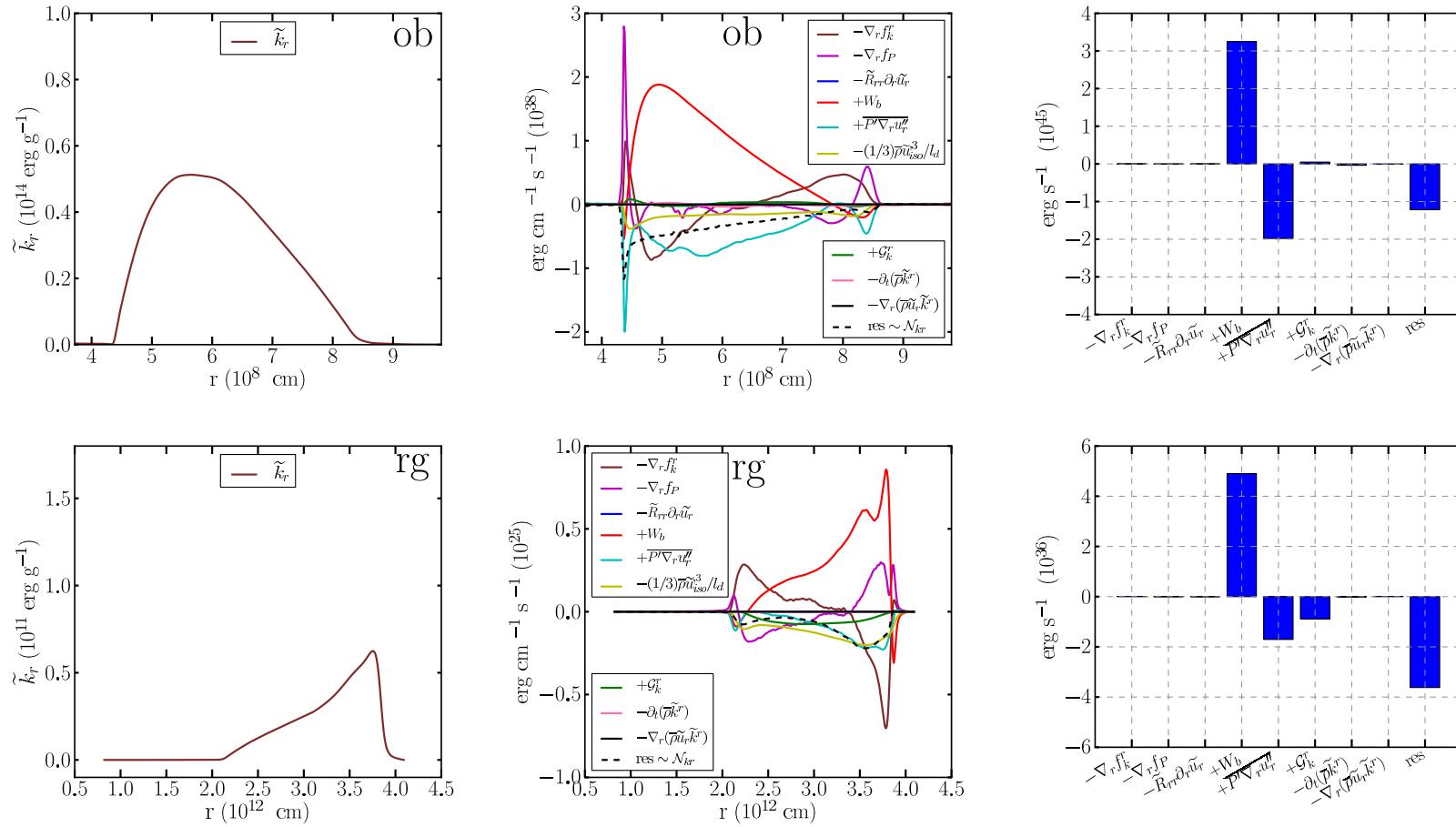


Figure 16: Turbulent radial kinetic energy equation. Model ob.3D.mr (upper panels) and model rg.3D.mr (lower panels).

4.15 Mean turbulent kinetic energy equation (horizontal part)

$$\bar{\rho} \tilde{D}_t \tilde{k}^h = -\nabla_r f_k^h - (\tilde{R}_{\theta r} \partial_r \tilde{u}_\theta + \tilde{R}_{\phi r} \partial_r \tilde{u}_\phi) + (\overline{P' \nabla_\theta u'_\theta} + \overline{P' \nabla_\phi u'_\phi}) + \mathcal{G}_k^h + \mathcal{N}_{kh} \quad (76)$$

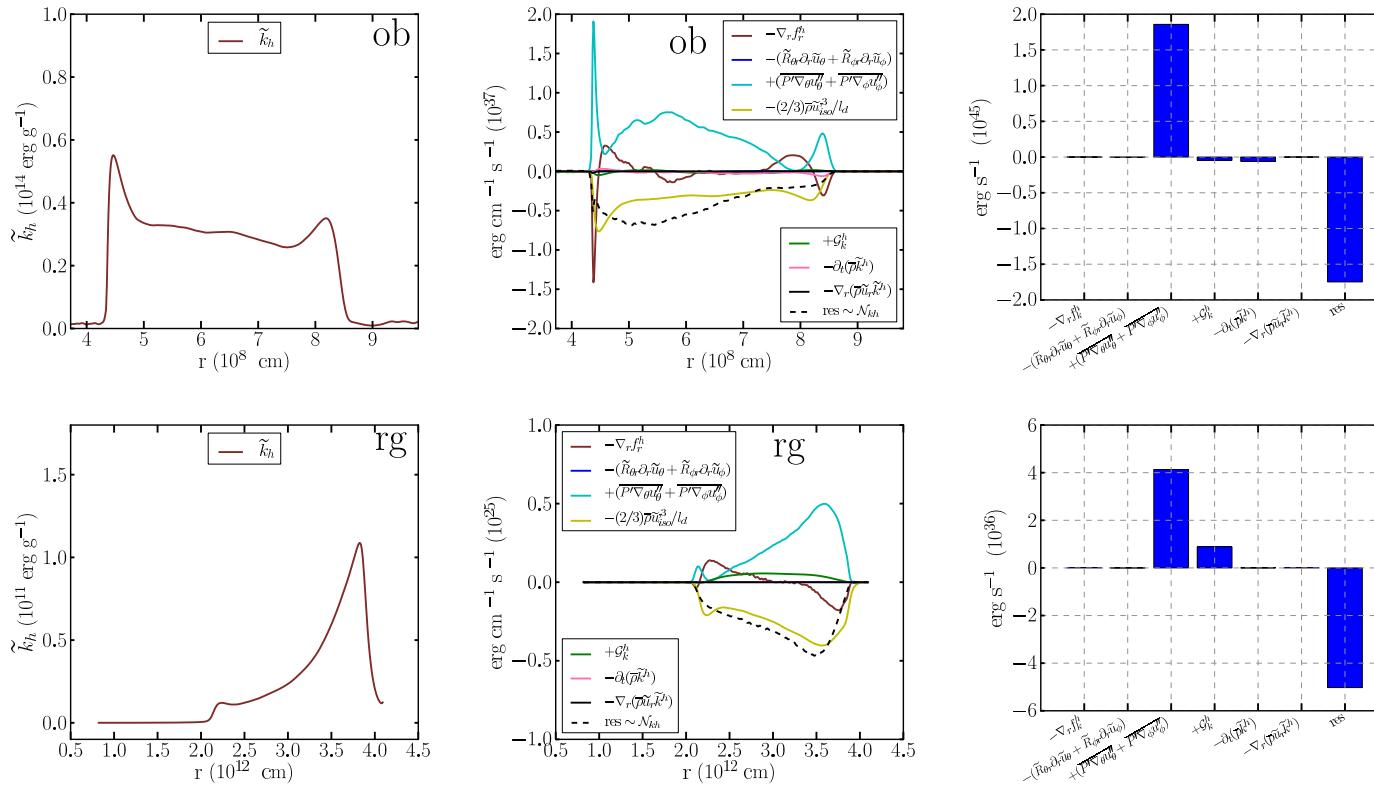


Figure 17: Turbulent horizontal kinetic energy equation. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

4.16 Mean turbulent mass flux equation

$$\bar{\rho} \tilde{D}_t \bar{u}_r'' = -(\bar{\rho}' u_r' u_r' / \bar{\rho}) \partial_r \bar{\rho} + (\tilde{R}_{rr} / \bar{\rho}) / \partial_r \bar{\rho} - \bar{\rho} \nabla_r (\bar{u}_r'' \bar{u}_r'') + \nabla_r \bar{\rho}' u_r' u_r' - \bar{\rho} u_r'' \nabla_r \bar{u}_r + \bar{\rho} u_r' d'' - b \partial_r \bar{P} + \bar{\rho}' v \partial_r \bar{P}' + \mathcal{G}_a + \mathcal{N}_a \quad (77)$$

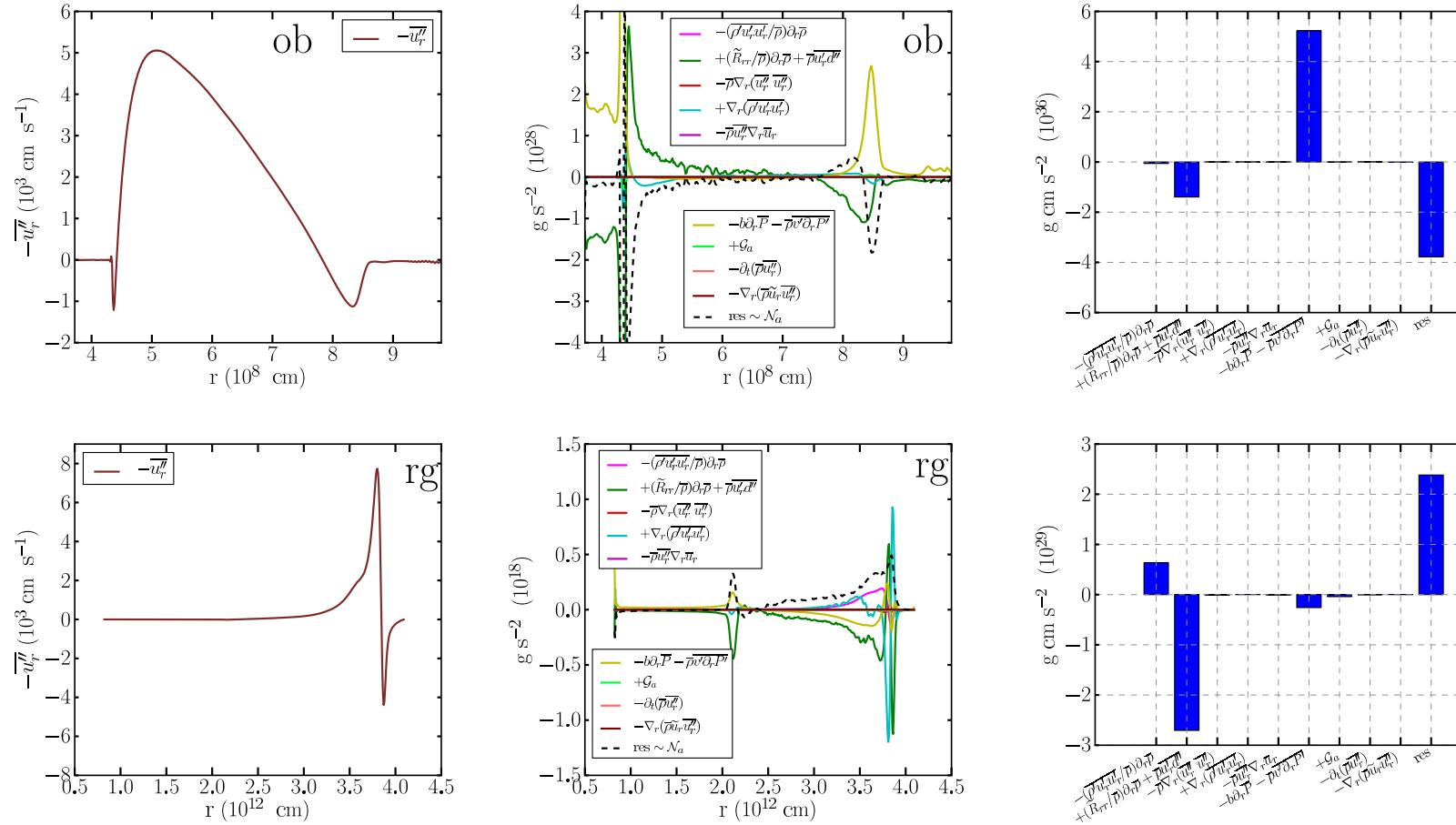


Figure 18: Turbulent mass flux equation. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

4.17 Mean density-specific volume covariance equation

$$\bar{D}_t b = +\bar{v} \nabla_r \bar{\rho} \bar{u}_r'' - \bar{\rho} \nabla_r (\bar{u}_r' \bar{v}') + 2\bar{\rho} \bar{v}' \bar{d}' + \mathcal{N}_b \quad (78)$$

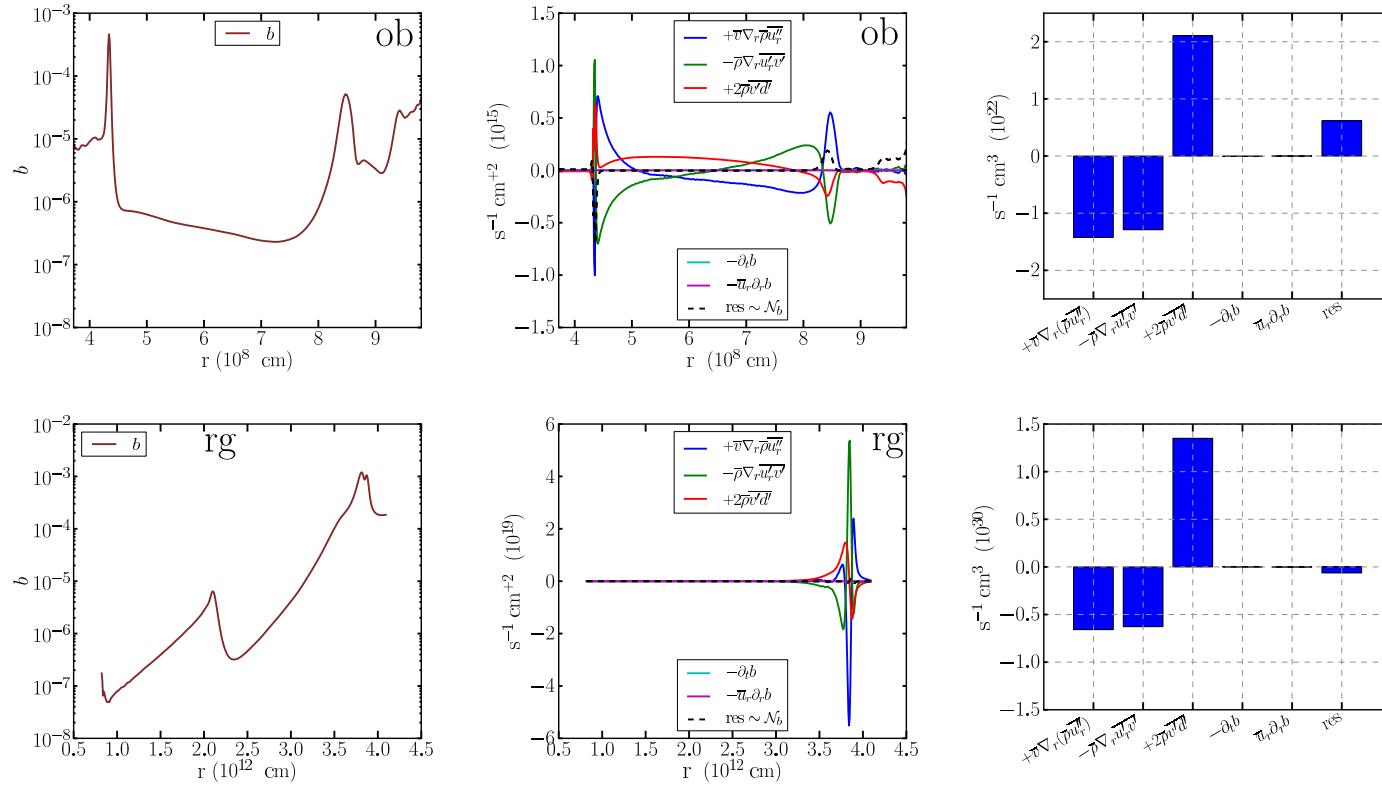


Figure 19: Density-specific volume covariance equation. Model ob.3D.mr (upper panels) and model rg.3D.mr (lower panels).

4.18 Mean internal energy flux equation

$$\bar{\rho} \tilde{D}_t(f_I/\bar{\rho}) = \mathcal{N}_{fI} - \nabla_r f_I^r - f_I \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{\epsilon}_I - \overline{\epsilon_I''} \partial_r \overline{P} - \overline{\epsilon_I''} \partial_r \overline{P'} - \overline{u_r''} (Pd) + \overline{u_r''} (\mathcal{S} + \nabla \cdot f_T) + \mathcal{G}_I + \mathcal{N}_{fI} \quad (79)$$

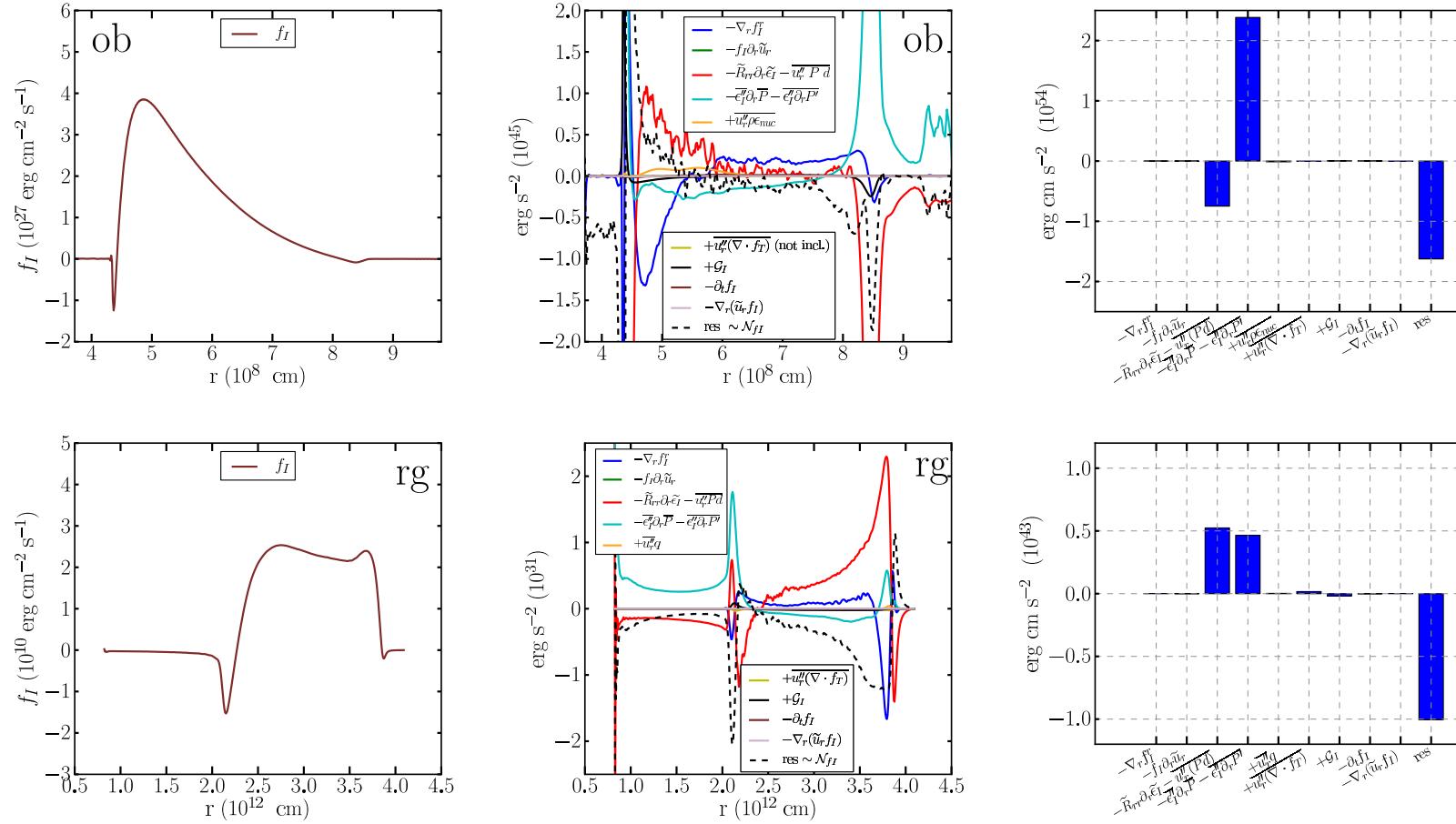


Figure 20: Mean internal energy flux equation. Model **ob.3D.mr** (upper panels) and model **rg.3D.mr** (lower panels).

4.19 Mean entropy flux equation

$$\bar{\rho} \tilde{D}_t(f_s/\bar{\rho}) = -\nabla_r f_s^r - f_s \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{s} - \bar{s}'' \partial_r \bar{P} - \bar{s}'' \partial_r \bar{P}' + \bar{u}_r'' (\mathcal{S} + \nabla \cdot \mathbf{F}_T) / \bar{T} + \mathcal{G}_s + \mathcal{N}_{fs} \quad (80)$$

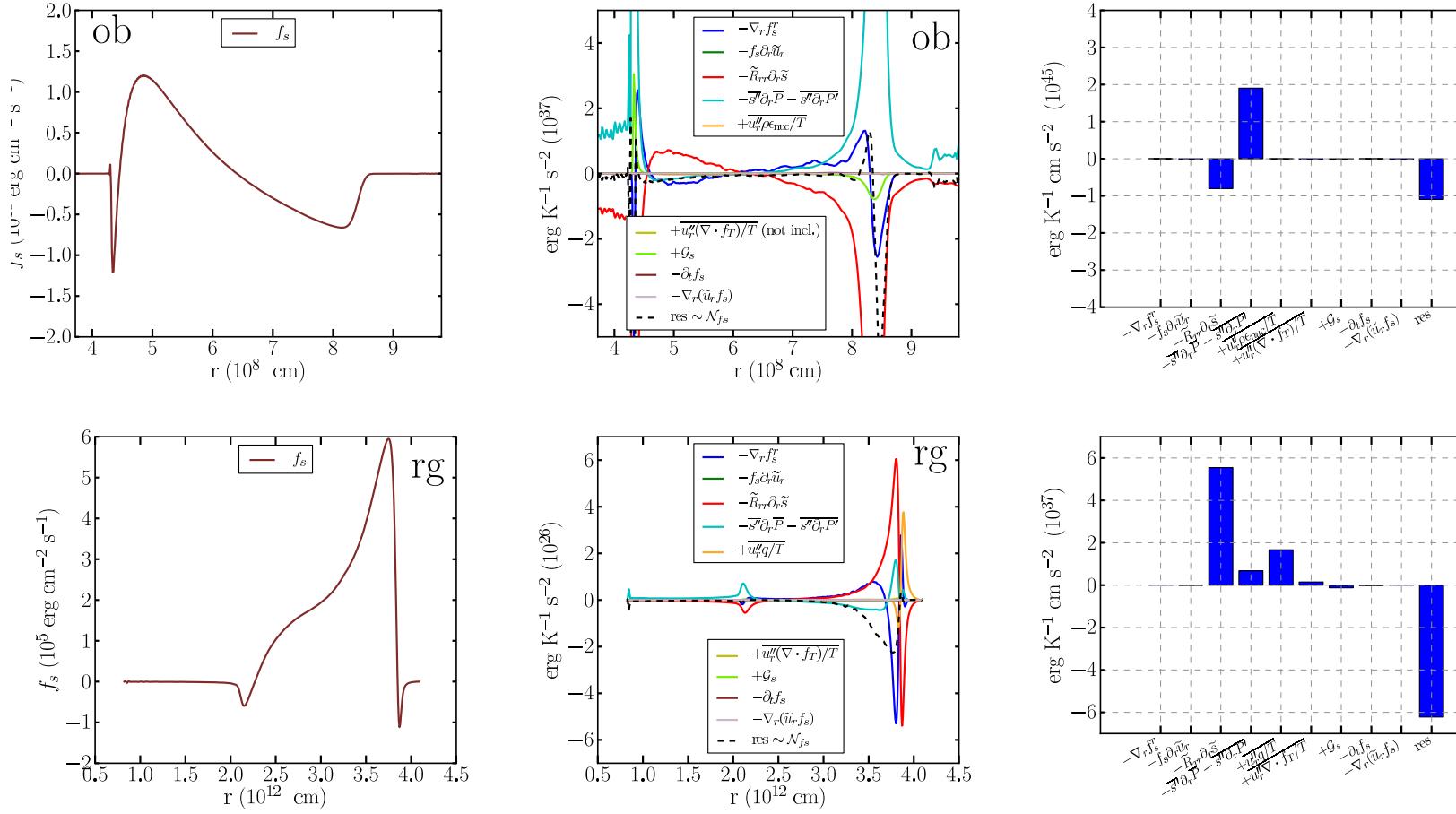


Figure 21: Mean entropy flux equation. Model ob.3D.2hp (upper panels) and model rg.3D.mr (lower panels).

4.20 Mean composition flux equation and mean A and Z flux equations

$$\bar{\rho} \tilde{D}_t(f_\alpha/\bar{\rho}) = -\nabla_r f_\alpha^r - f_\alpha \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_\alpha - \overline{X''_\alpha \partial_r \bar{P}} - \overline{X''_\alpha \partial_r \bar{P'}} + \overline{u''_r \rho \dot{X}_\alpha^{\text{nuc}}} + \mathcal{G}_\alpha + \mathcal{N}_{f_\alpha} \quad (81)$$

$$\bar{\rho} \tilde{D}_t(f_A/\bar{\rho}) = \mathcal{N}_{fA} - \nabla_r f_A^r - f_A \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{A} - \overline{A'' \partial_r \bar{P}} - \overline{A'' \partial_r \bar{P'}} - \overline{u''_r \rho A^2 \Sigma_\alpha \dot{X}_\alpha^{\text{nuc}} / A_\alpha} + \mathcal{G}_A \quad (82)$$

$$\begin{aligned} \bar{\rho} \tilde{D}_t(f_Z/\bar{\rho}) = & \mathcal{N}_{fZ} - \nabla_r f_Z^r - f_Z \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{Z} - \overline{Z'' \partial_r \bar{P}} - \overline{Z'' \partial_r \bar{P'}} - u''_r \rho Z A \Sigma_\alpha (\dot{X}_\alpha^{\text{nuc}} / A_\alpha) - \\ & - u''_r \rho A \Sigma_\alpha (Z_\alpha \dot{X}_\alpha^{\text{nuc}} / A_\alpha) + \mathcal{G}_Z \end{aligned} \quad (83)$$

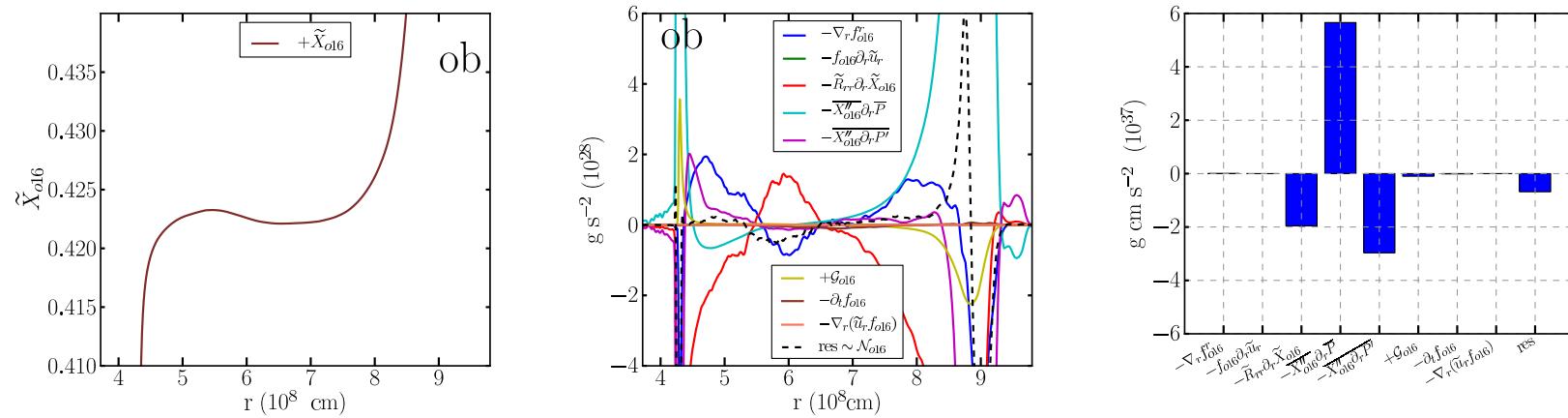


Figure 22: Mean composition flux equation. Model **ob.3D.2hp**.

4.21 Mean A and Z flux equations

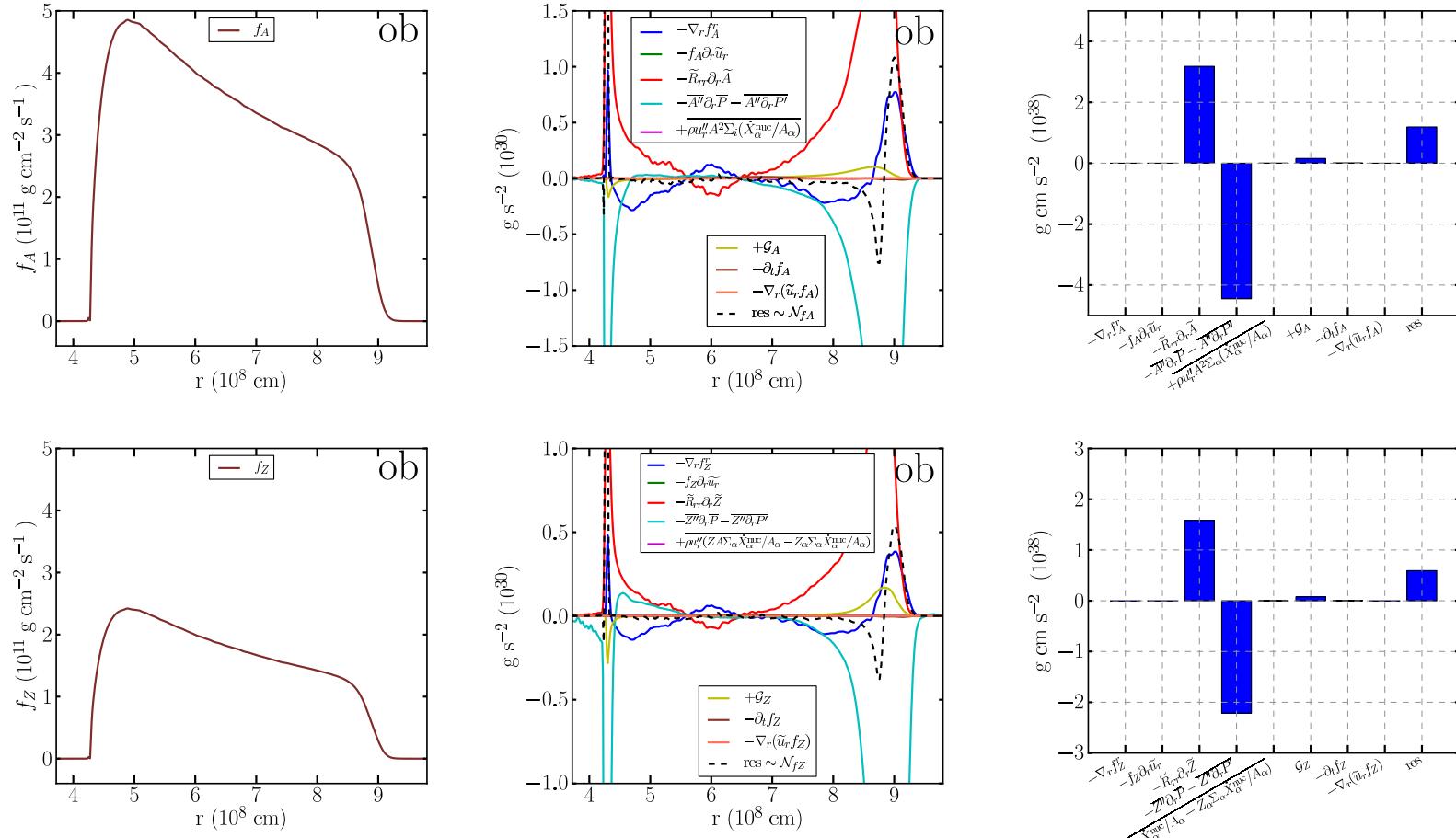


Figure 23: Mean A and Z flux equation. Model ob.3D.2hp.

5 Mean composition equations (for all elements in oxygen burning model ob.3D.2hp)

5.1 Mean C¹² and O¹⁶ equation

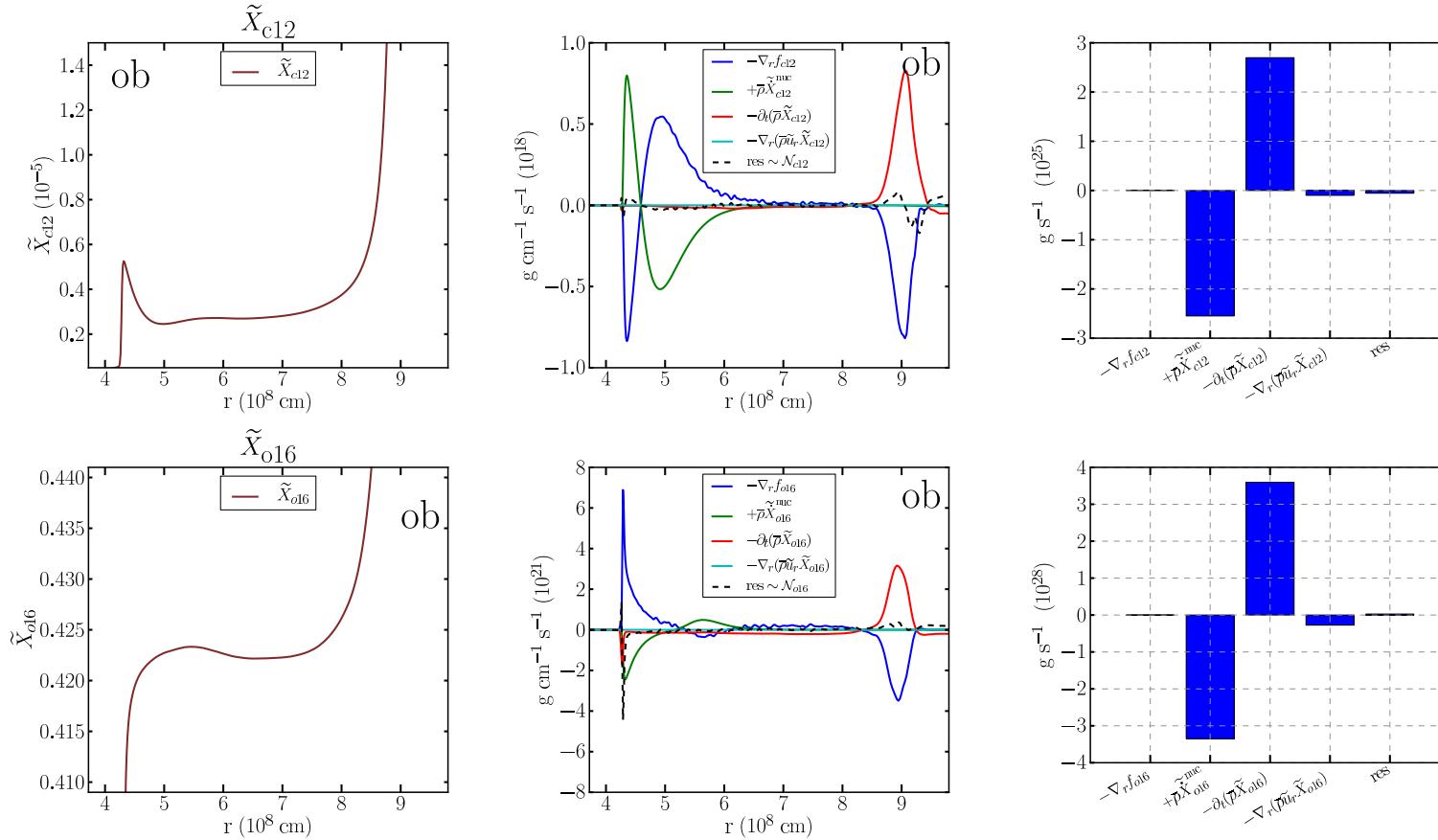


Figure 24: Mean composition equations. Model ob.3D.2hp.

5.2 Mean Ne²⁰ and Na²³ equation

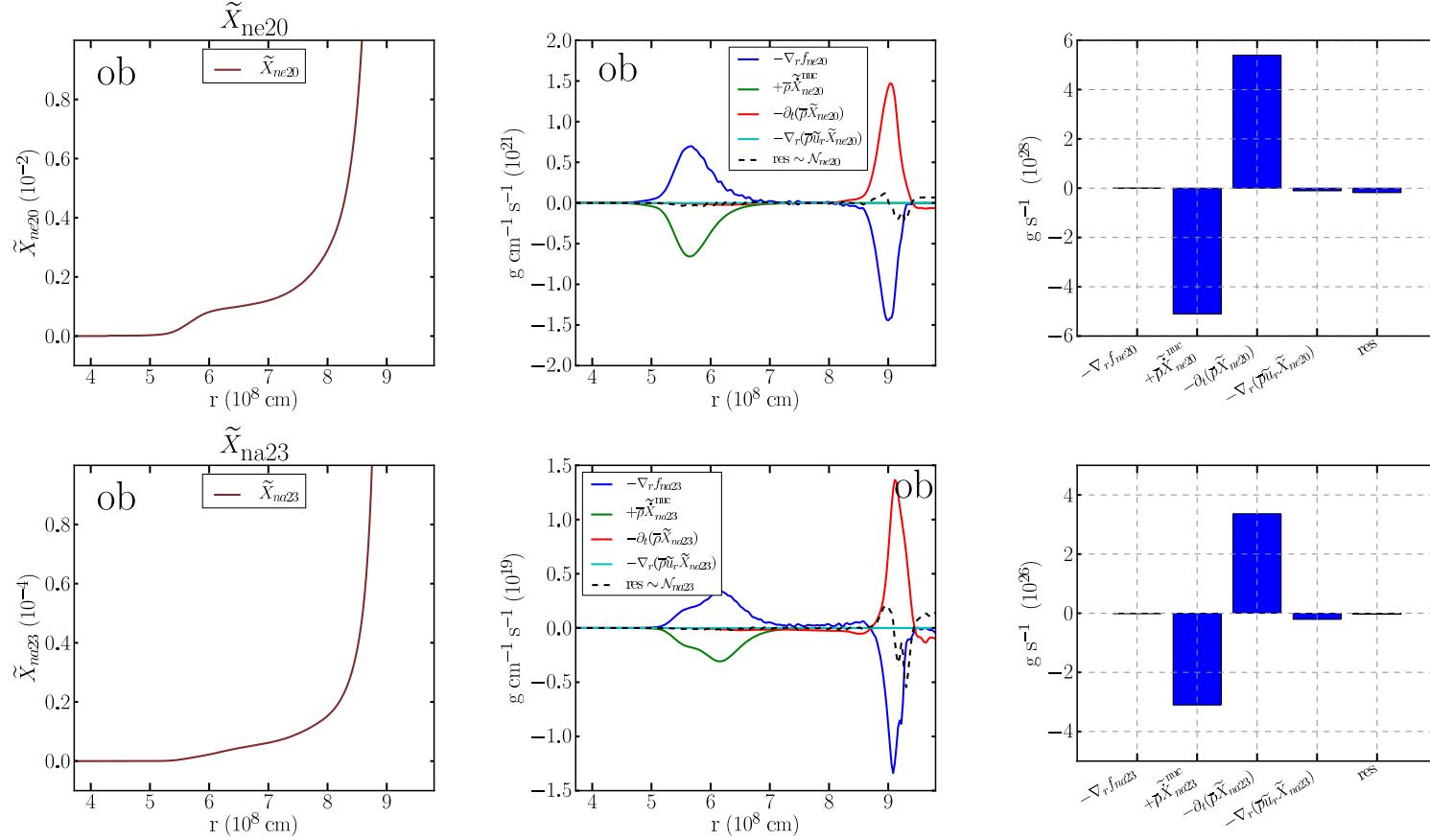


Figure 25: Mean composition equations. Model ob.3D.2hp.

5.3 Mean Mg²⁴ and Si²⁸ equation

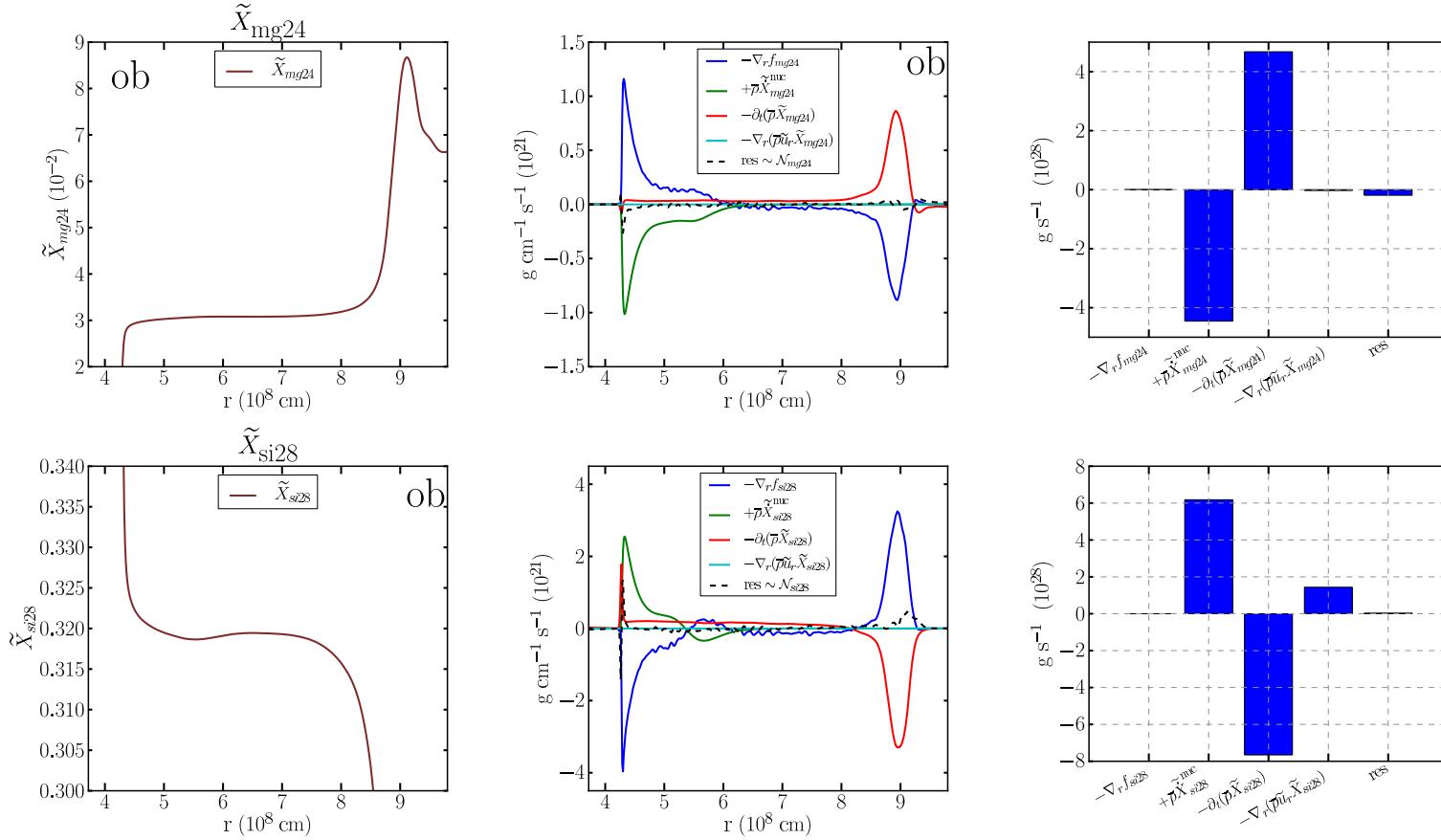


Figure 26: Mean composition equations. Model ob.3D.2hp.

5.4 Mean P³¹ and S³² equation

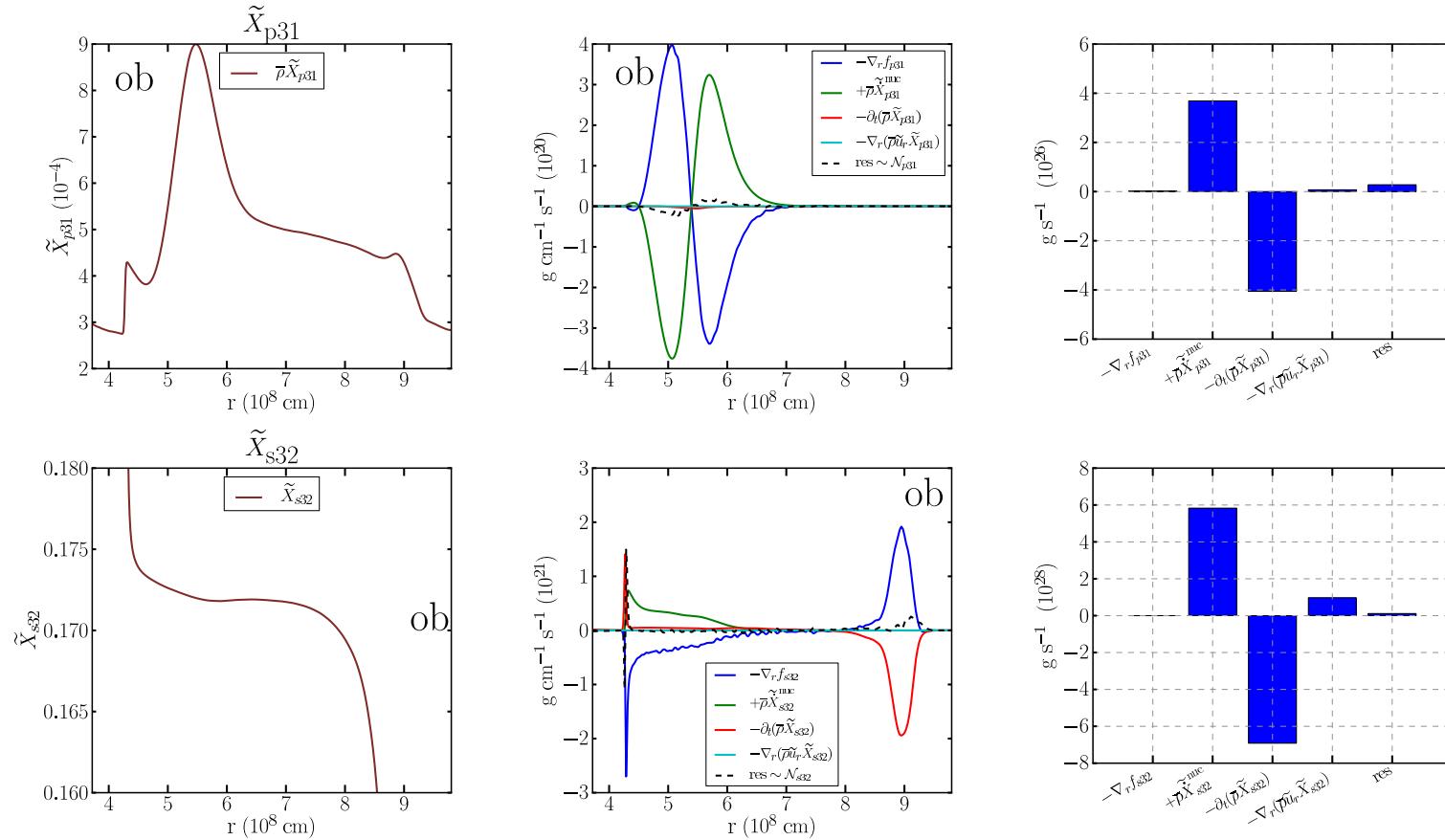


Figure 27: Mean composition equations. Model ob.3D.2hp.

5.5 Mean S³⁴ and Cl³⁵ equation

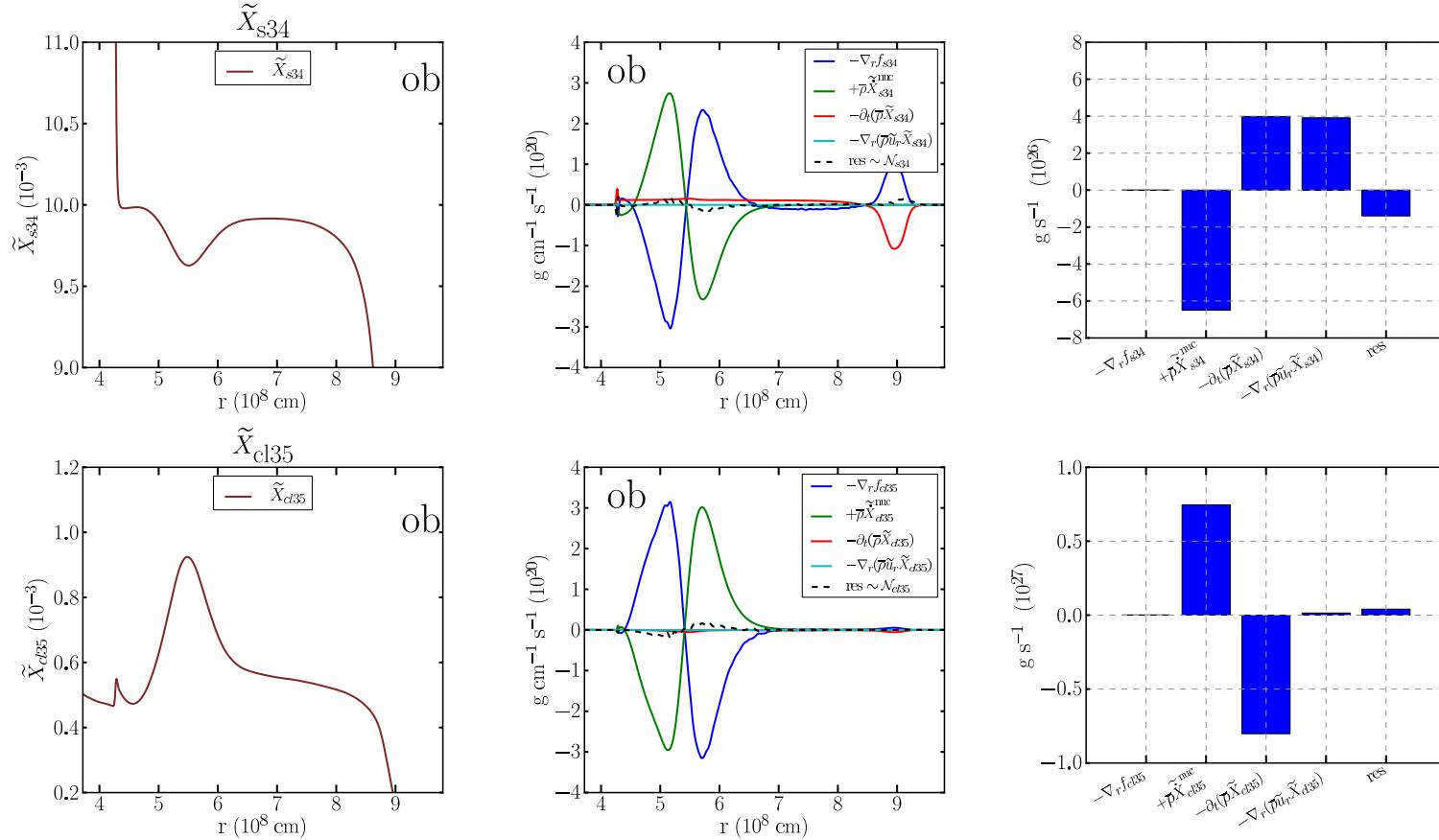


Figure 28: Mean composition equations. Model ob.3D.2hp.

5.6 Mean Ar³⁶ and Ar³⁸ equation

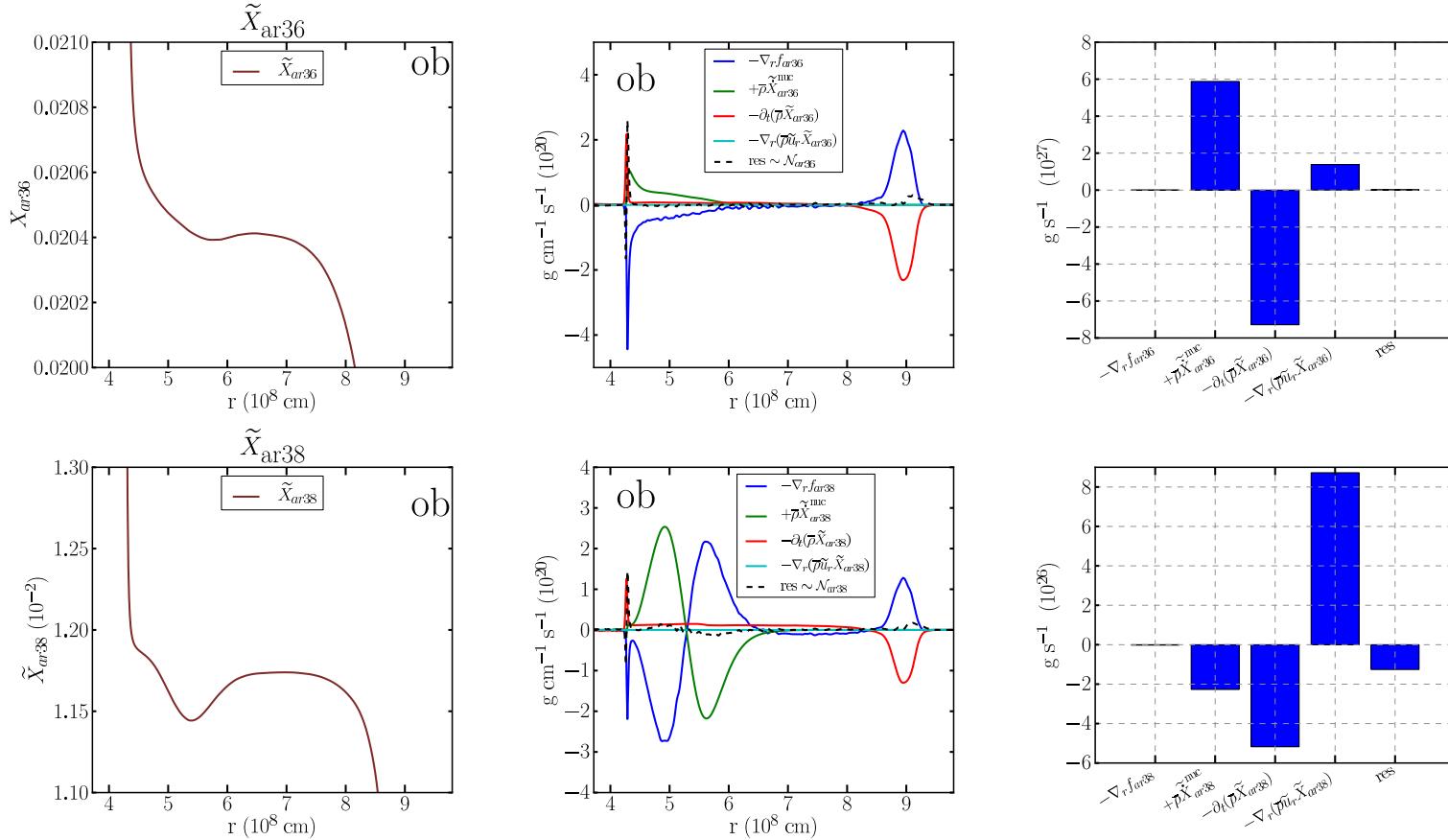


Figure 29: Mean composition equations. Model ob.3D.2hp.

5.7 Mean K³⁹ and Ca⁴⁰ equation

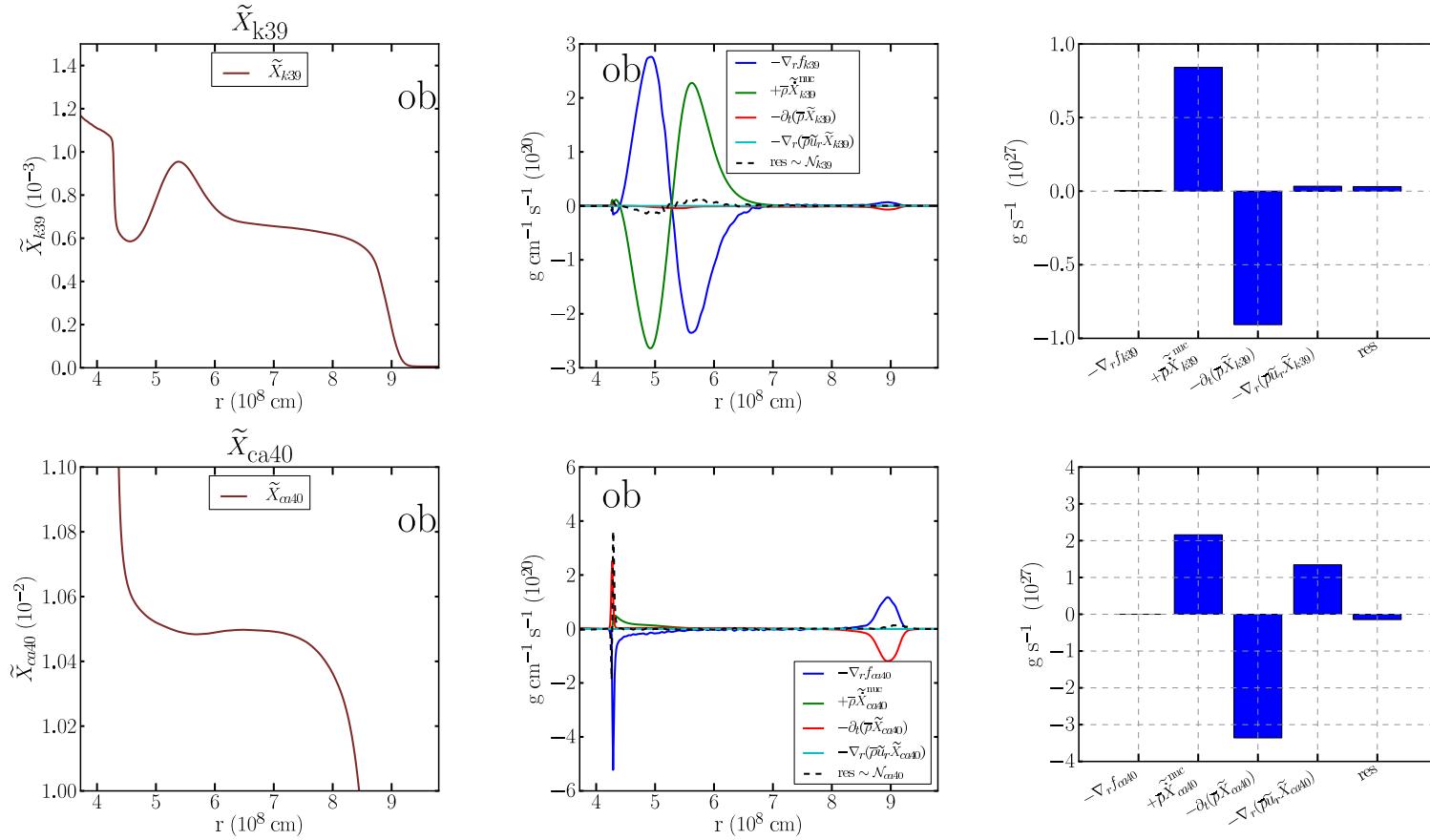


Figure 30: Mean composition equations. Model ob.3D.2hp.

5.8 Mean Ca^{42} and Ti^{44} equation

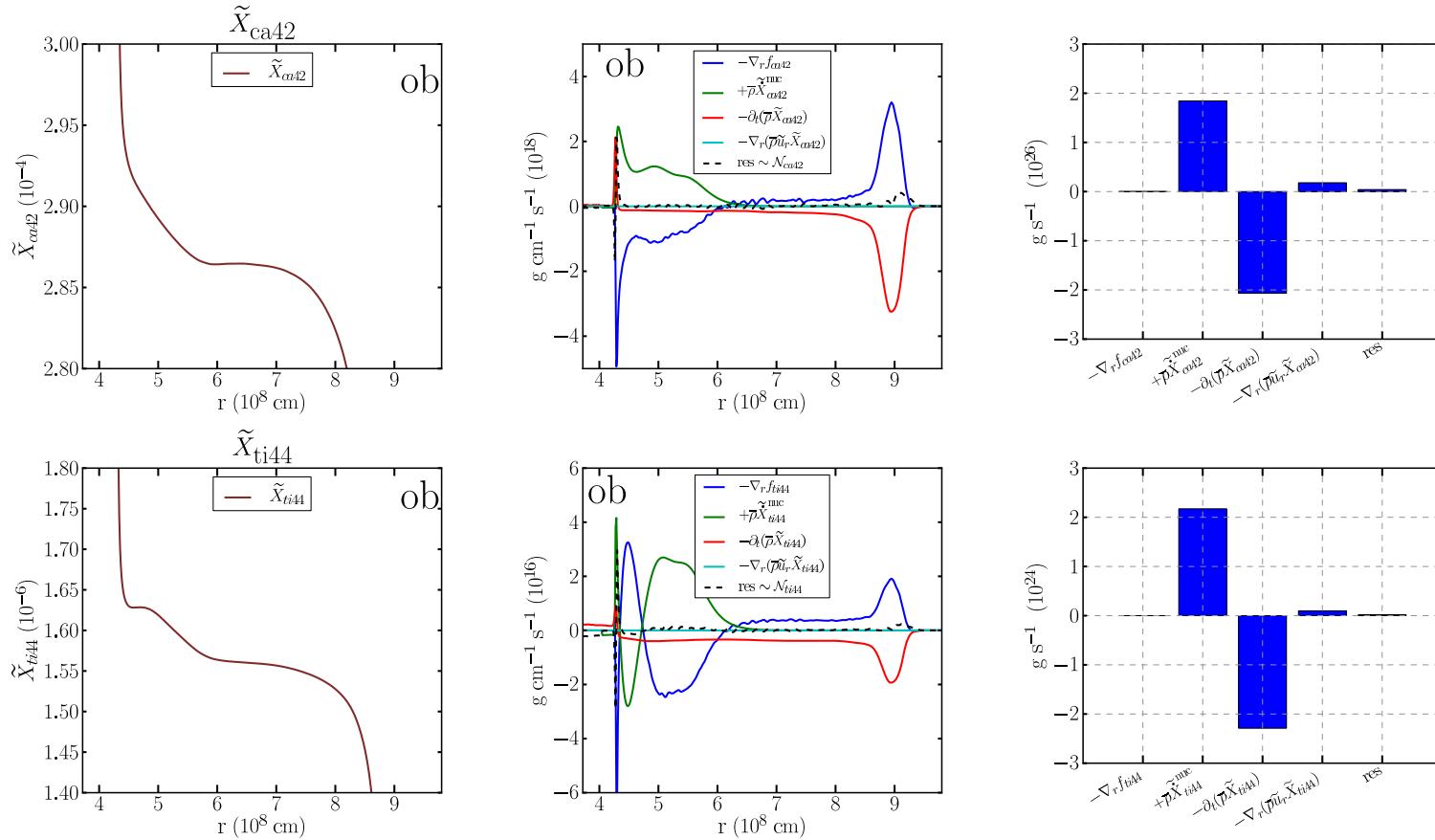


Figure 31: Mean composition equations. Model ob.3D.2hp.

5.9 Mean Ti^{46} and Cr^{48} equation

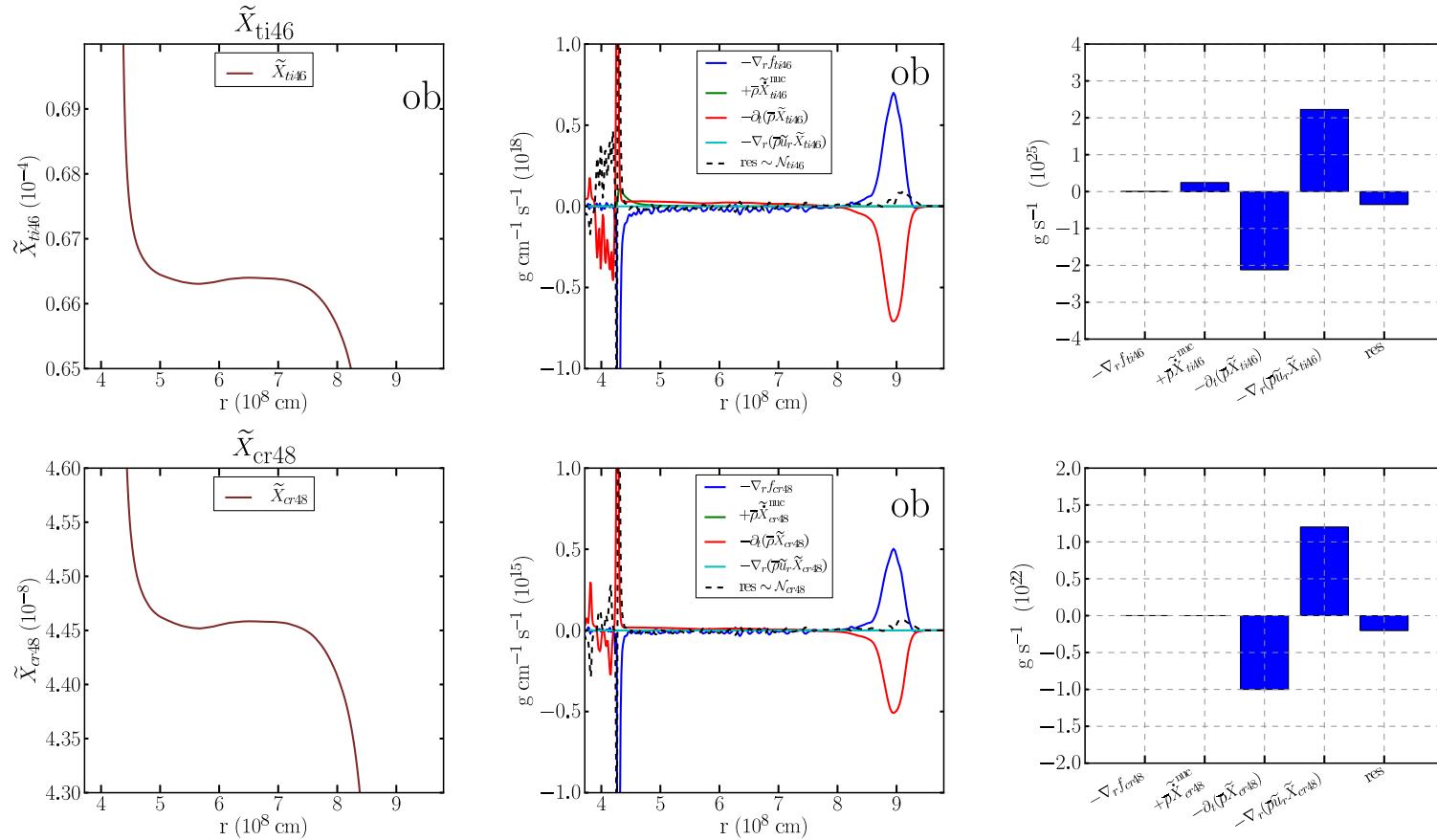


Figure 32: Mean composition equations. Model ob.3D.2hp.

5.10 Mean Cr⁵⁰ and Fe⁵² equation

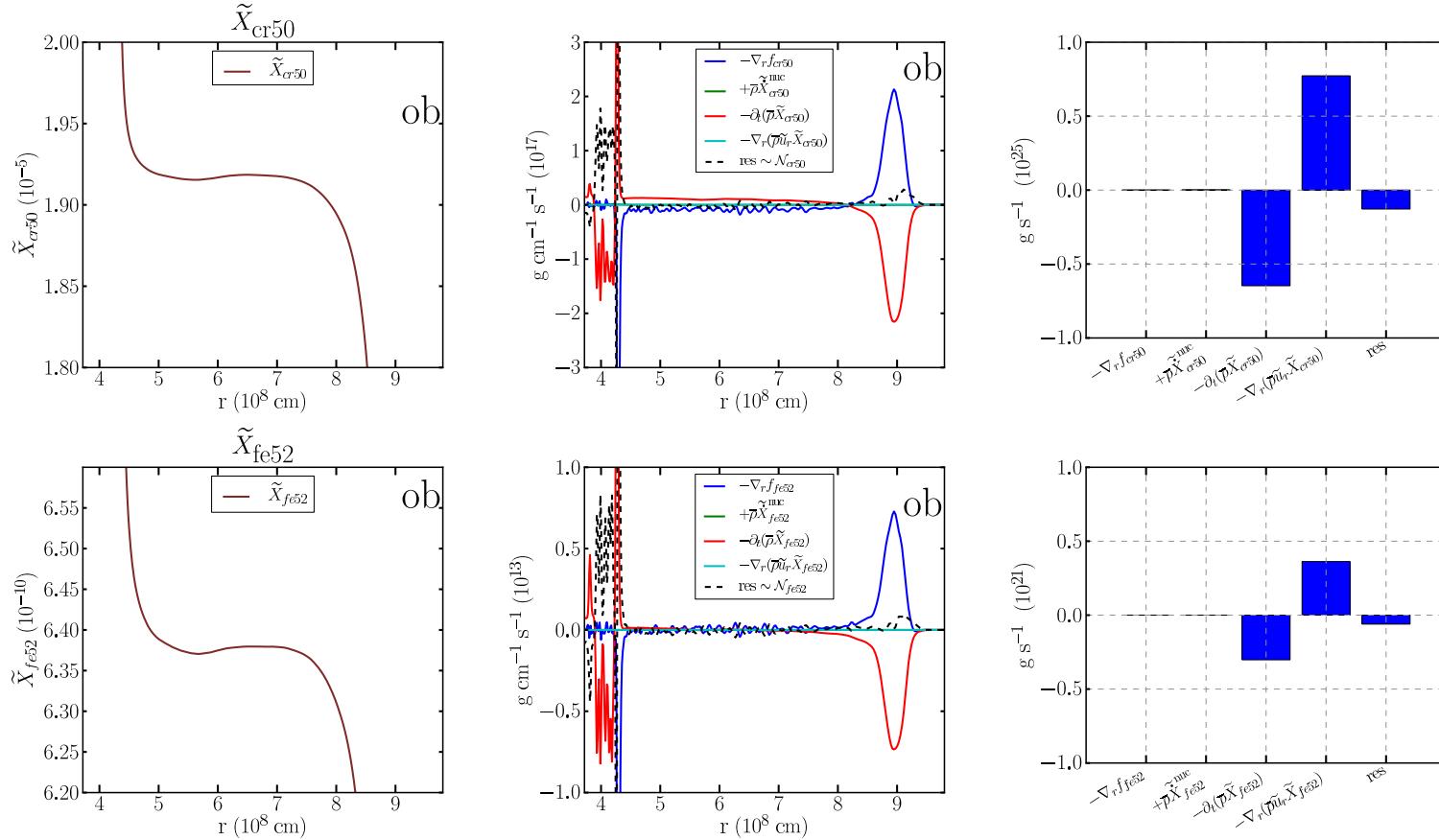


Figure 33: Mean composition equations. Model ob.3D.2hp.

5.11 Mean Fe⁵⁴ and Ni⁵⁶ equation

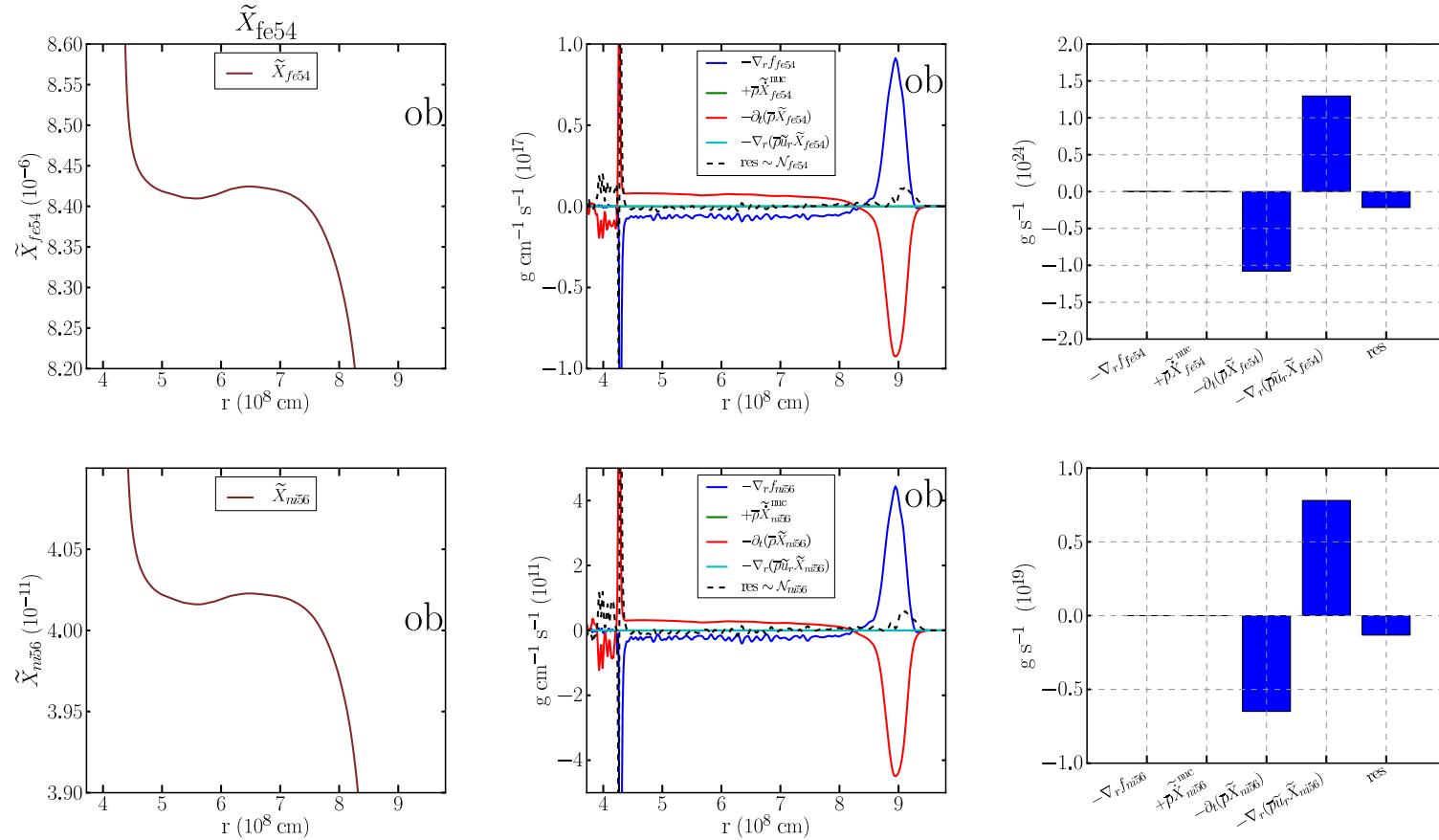


Figure 34: Mean composition equations. Model ob.3D.2hp.

6 Resolution effects

6.1 Oxygen burning shell models

Mean continuity equation and mean radial momentum equation

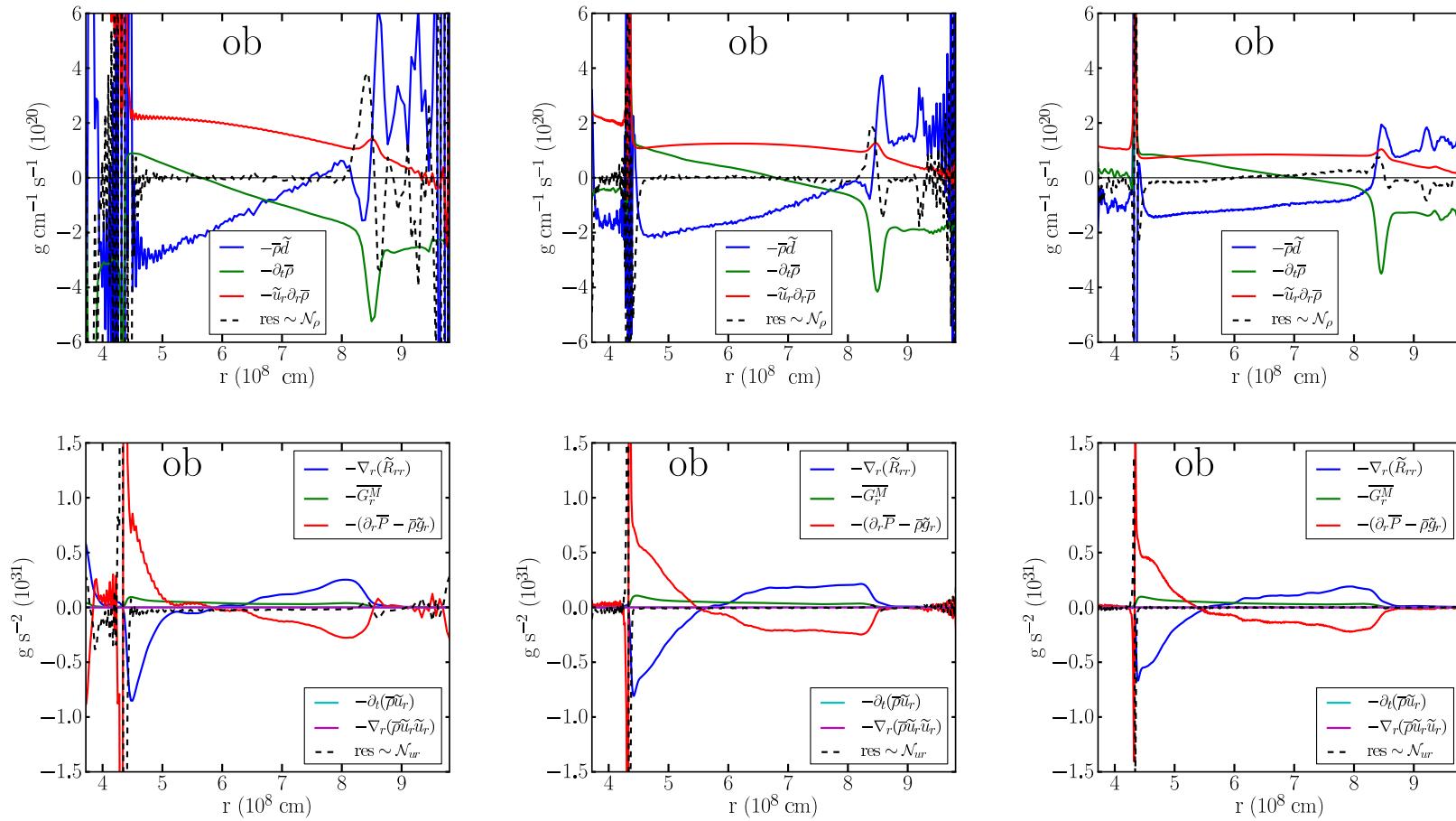


Figure 35: Mean continuity equation (upper panels) and radial momentum equation (lower panels). Model ob.3D.lr (left), ob.3D.mr (middle), ob.3D.hr (right)

Mean azimuthal and polar momentum equations

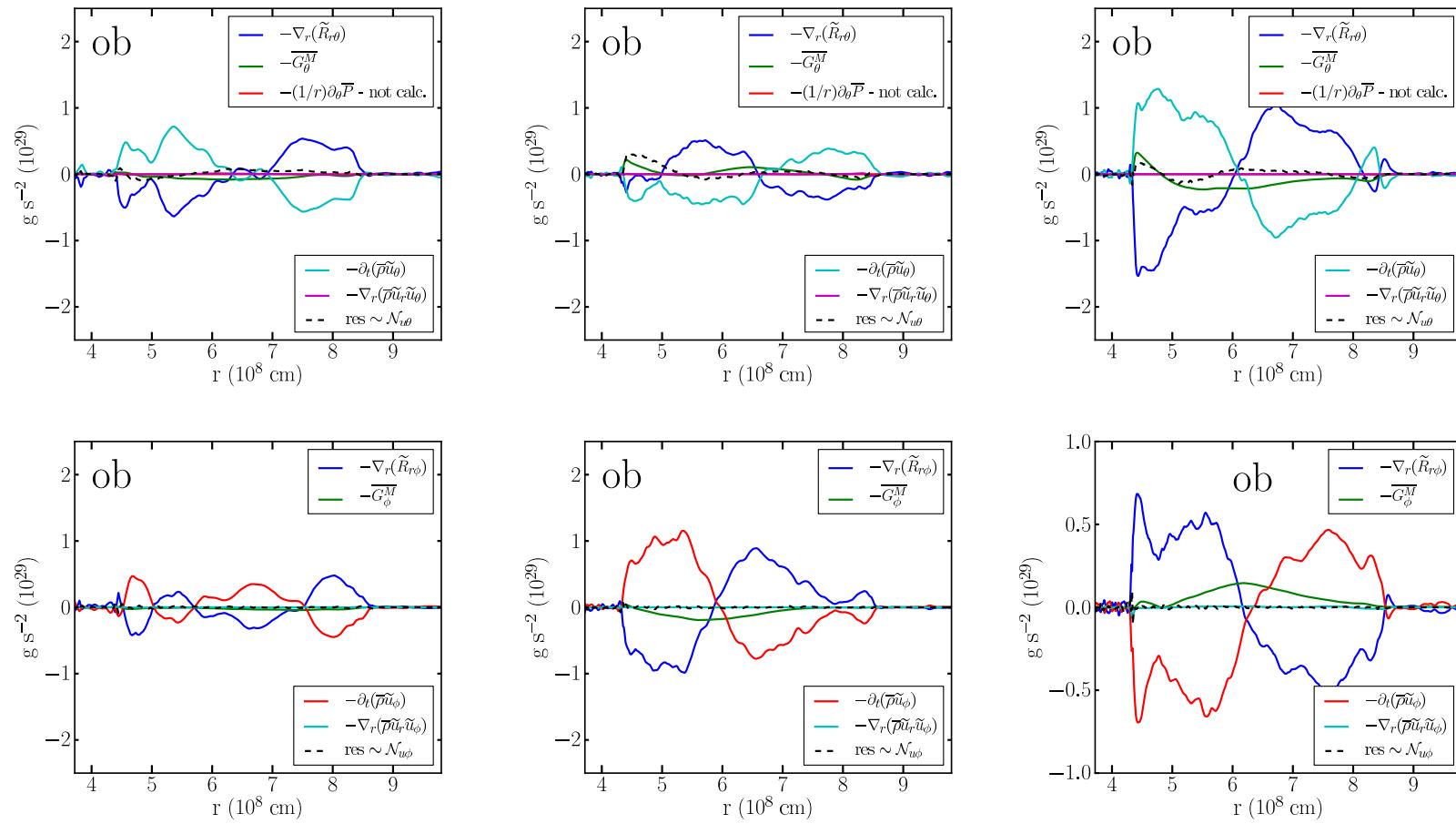


Figure 36: Mean azimuthal momentum equation (upper panels) and polar momentum equation (lower panels). Model **ob.3D.lr** (left), **ob.3D.mr** (middle), **ob.3D.hr** (right)

Mean internal and kinetic energy equation

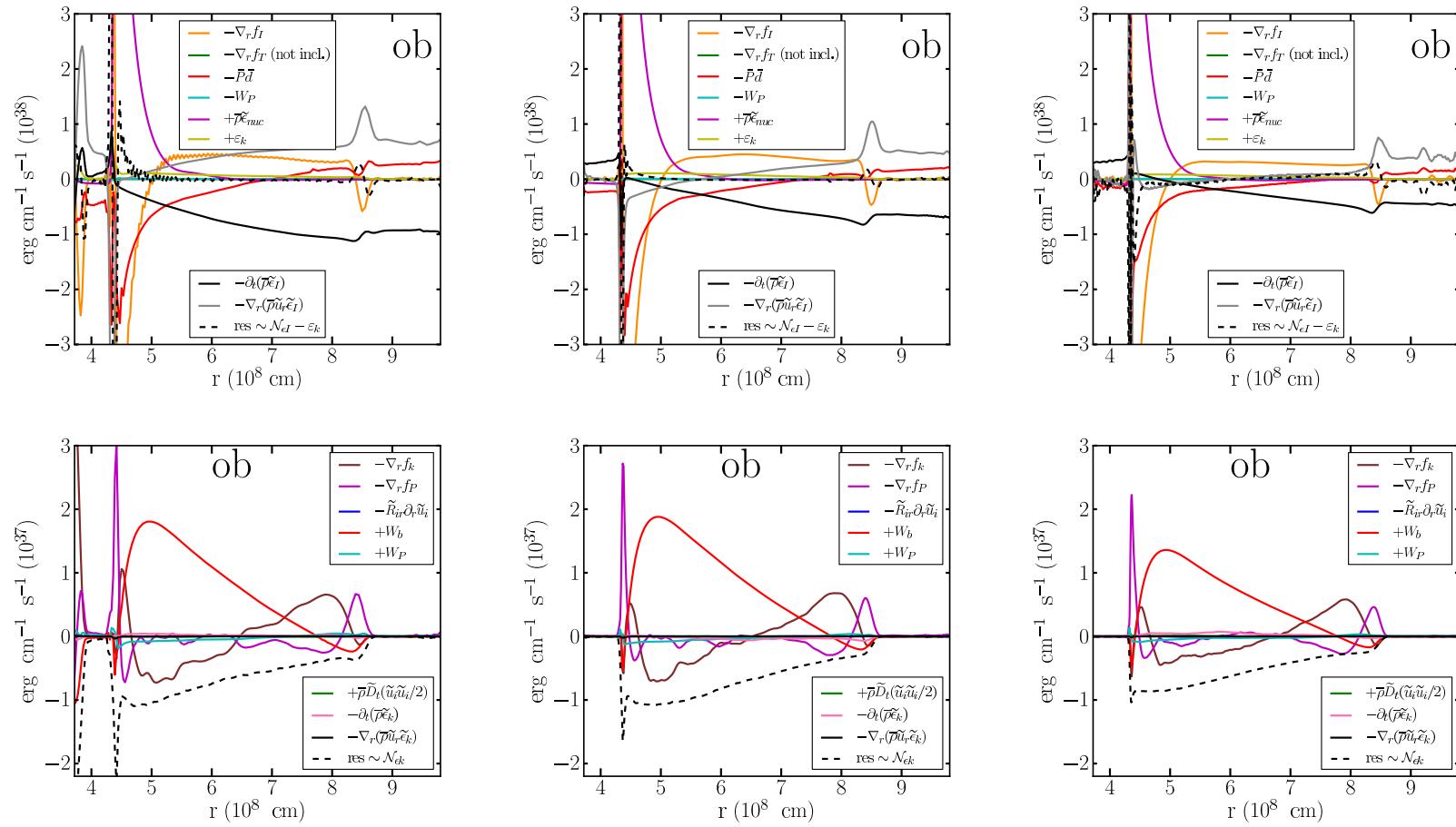


Figure 37: Mean internal energy equation (upper panels) and kinetic energy equation (lower panels). Model ob.3D.lr (left), ob.3D.mr (middle), ob.3D.hr (right)

Mean total energy and entropy equation

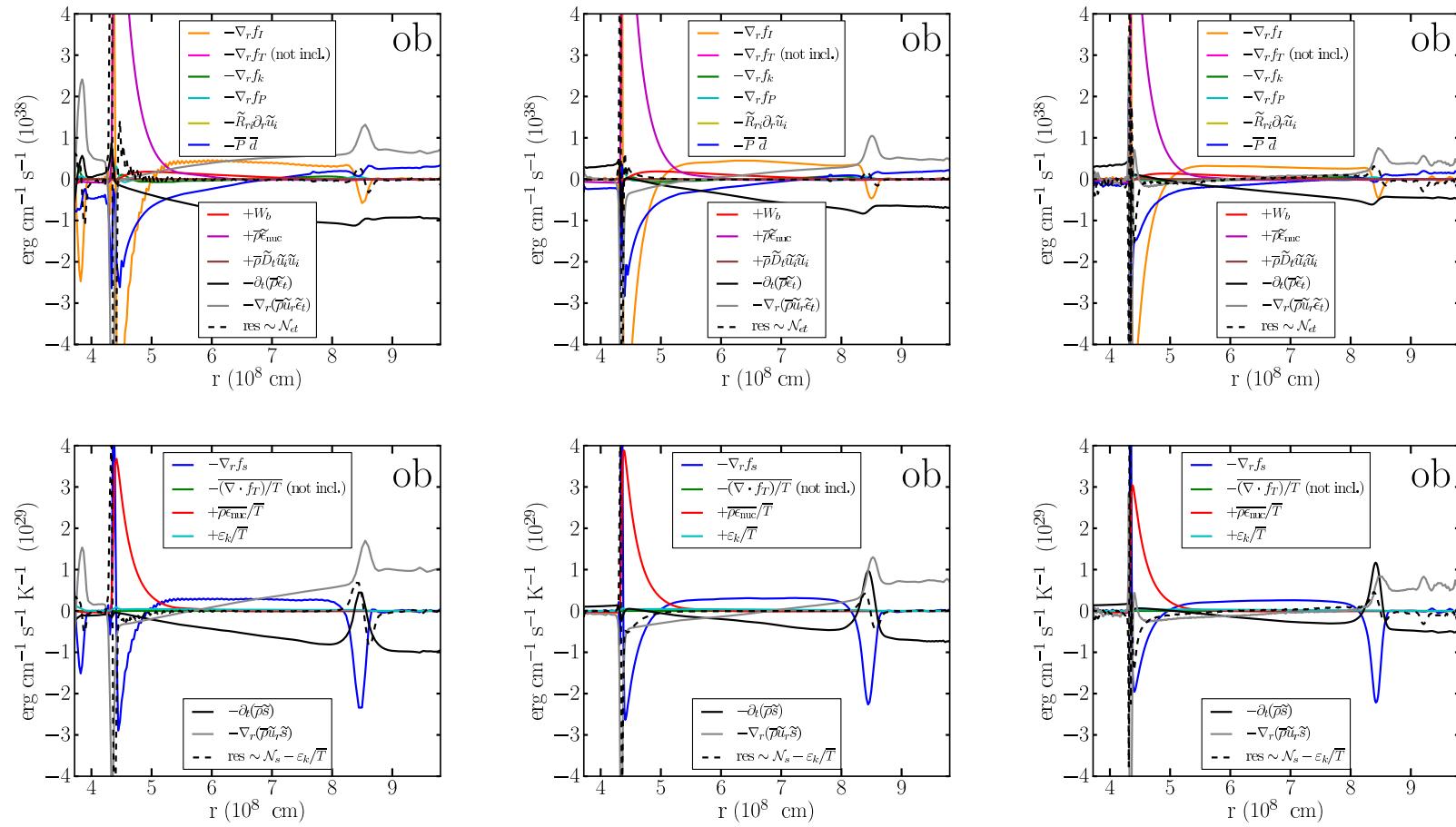


Figure 38: Mean total energy equation (upper panels) and mean entropy equation (lower panels). Model **ob.3D.lr** (left), **ob.3D.mr** (middle), **ob.3D.hr** (right)

Mean density-specific volume covariance equation and mean number of nucleons per isotope equation

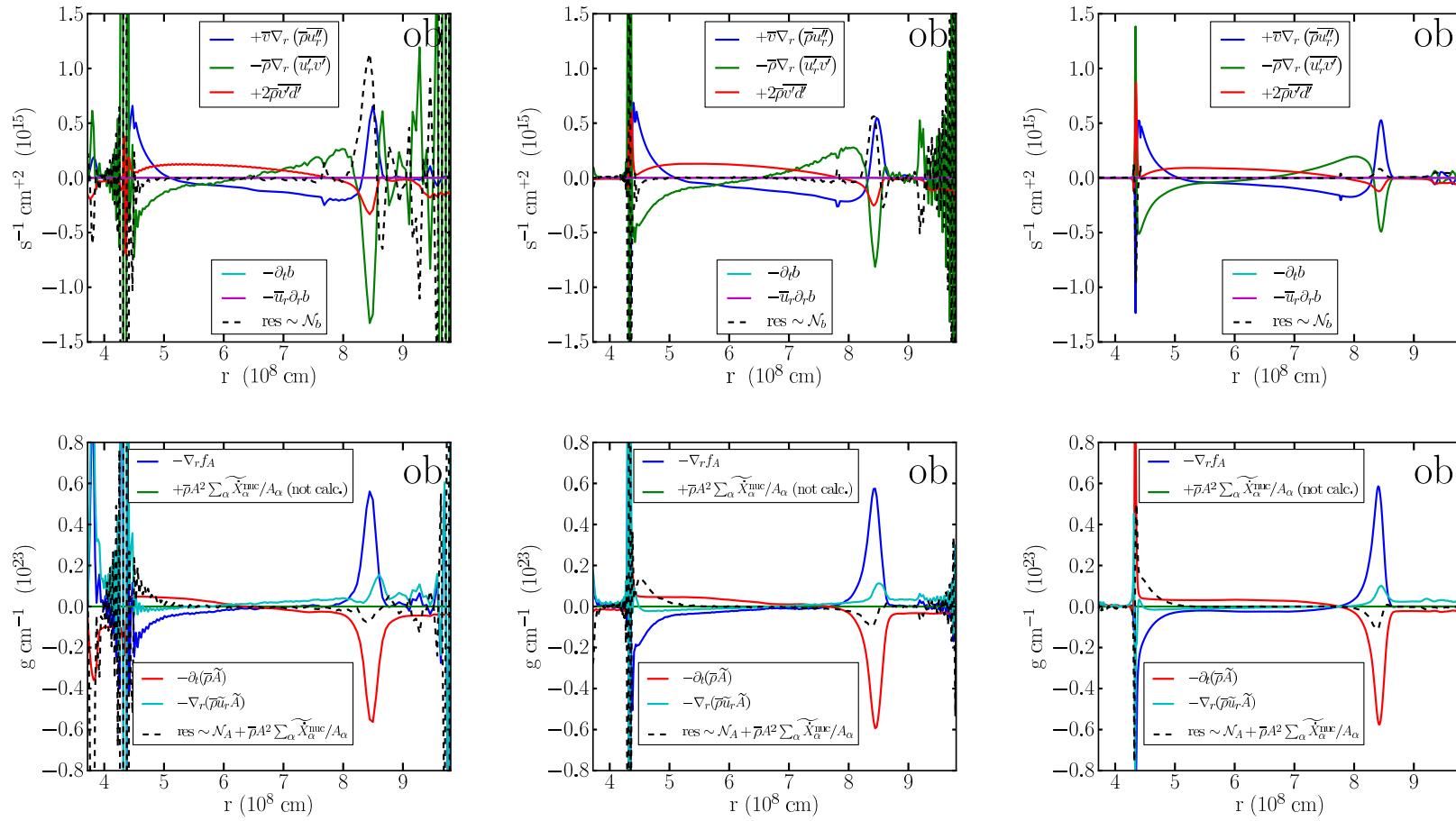


Figure 39: Mean density-specific volume covariance equation (upper panels) and mean number of nucleons per isotope equation (lower panels). Model ob.3D.lr (left), ob.3D.mr (middle), ob.3D.hr (right)

Mean turbulent kinetic energy equation and mean velocities

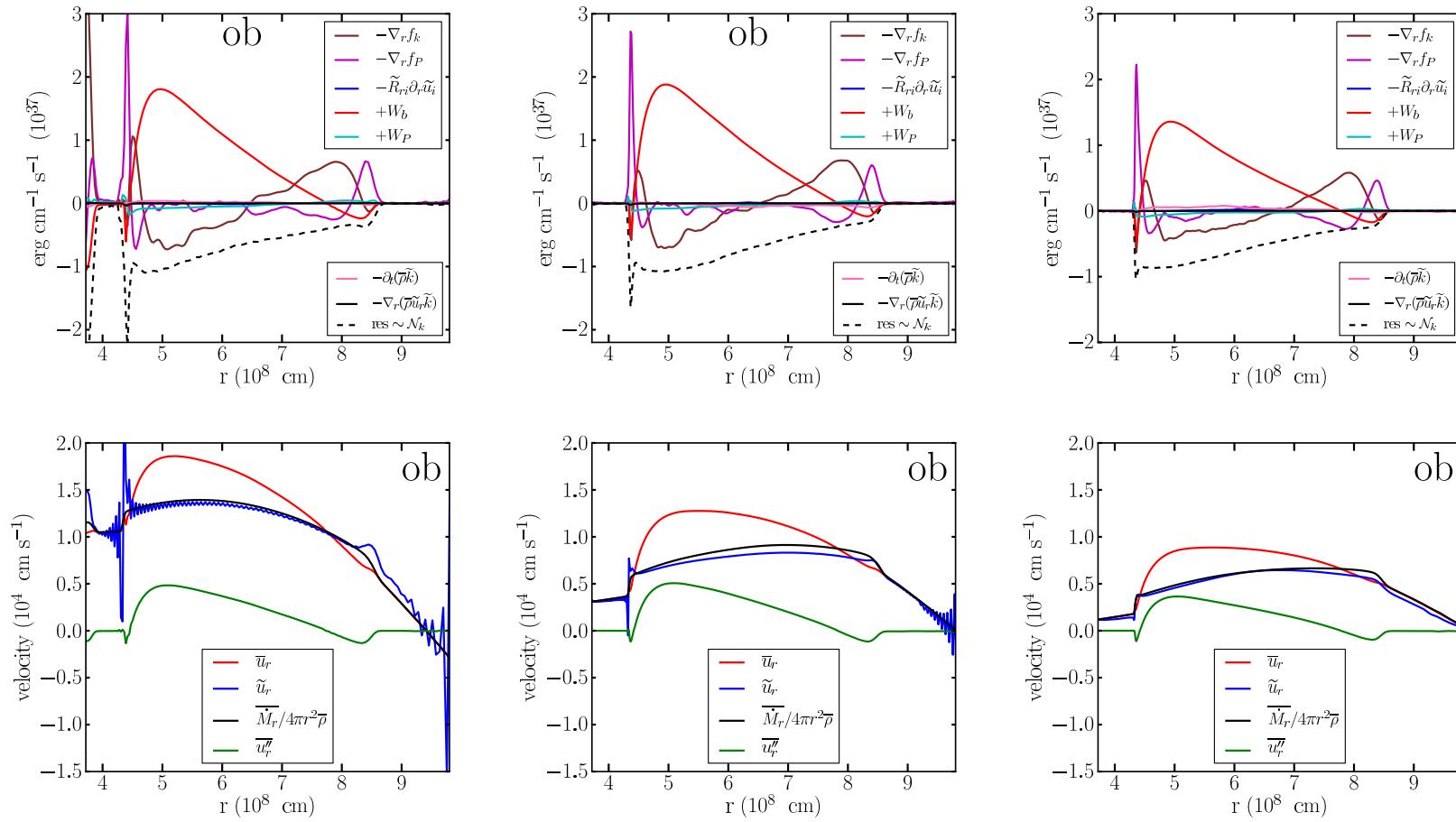


Figure 40: Mean turbulent kinetic energy equation (upper panels) and mean velocities (lower panels). Model **ob.3D.lr** (left), **ob.3D.mr** (middle), **ob.3D.hr** (right)

6.2 Red giant envelope convection

Mean continuity equation and mean radial momentum equation

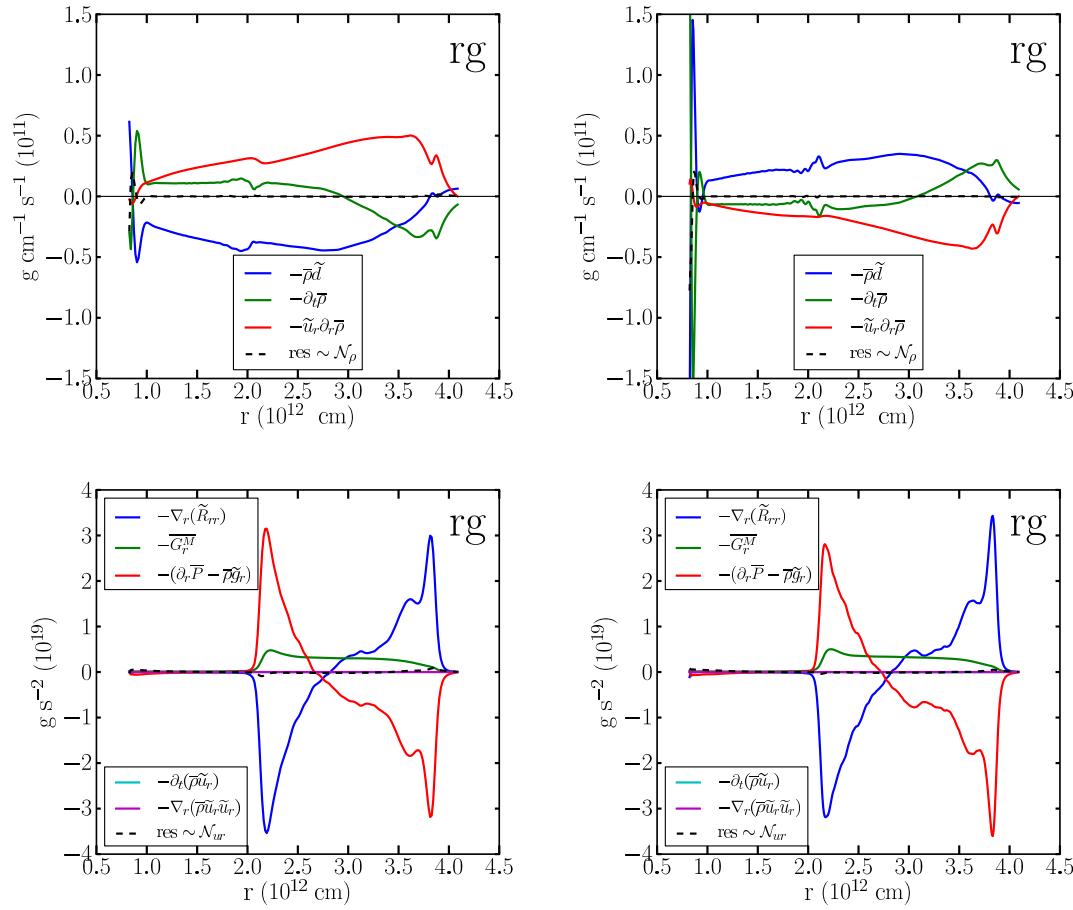


Figure 41: Mean continuity equation (upper panels) and radial momentum equation (lower panels). Model `rg.3D.lr` (left) and `rg.3D.mr` (right)

Mean azimuthal and polar momentum equation

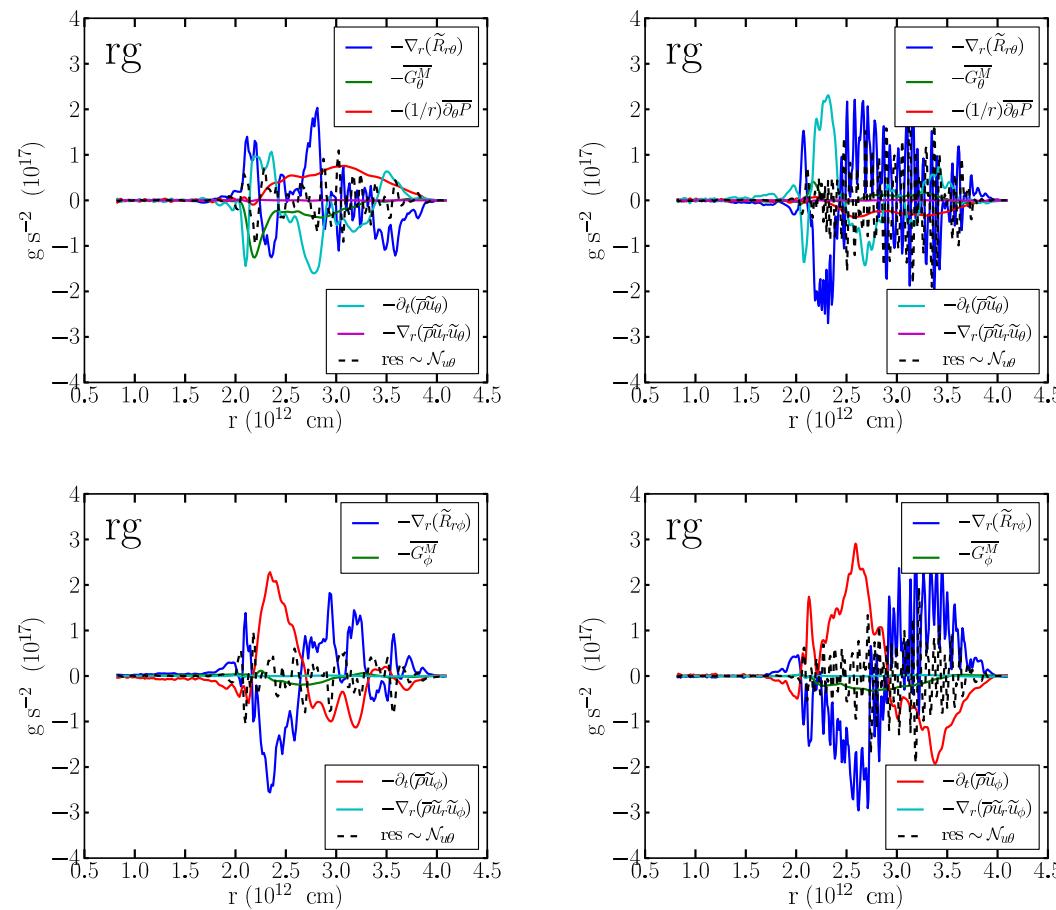


Figure 42: Mean azimuthal momentum (upper panels) and polar momentum equation (lower panels). Model rg.3D.lr (left) and rg.3D.mr (right)

Mean internal and kinetic energy equation

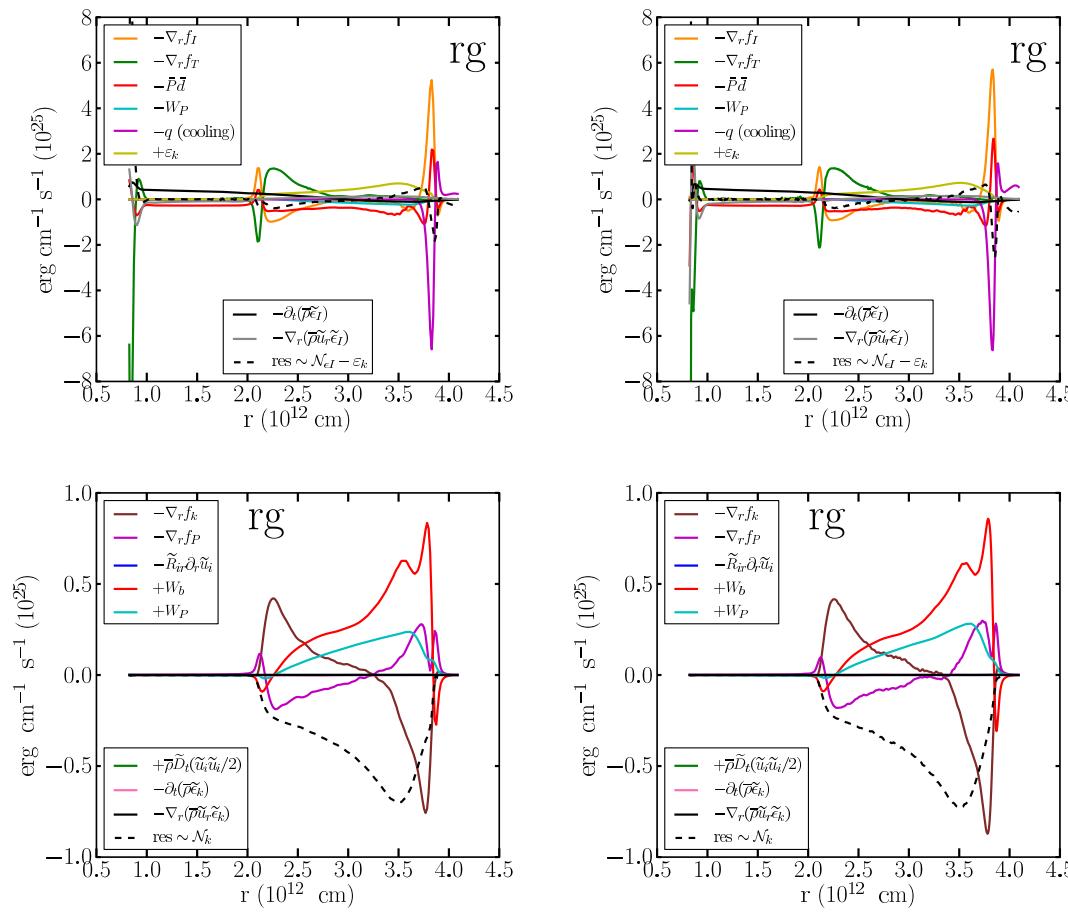


Figure 43: Mean internal energy equation (upper panels) and kinetic energy equation (lower panels). Model rg.3D.lr (left) and rg.3D.mr (right)

Mean total energy equation and mean entropy equation

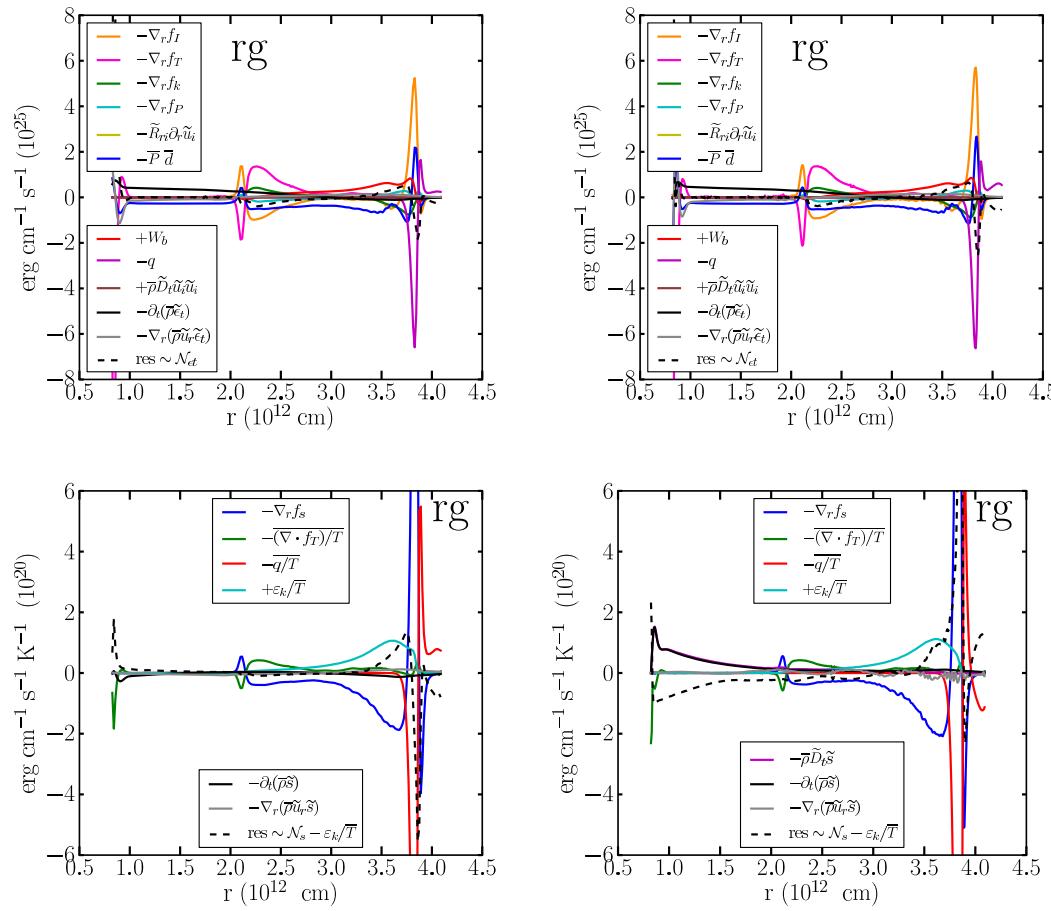


Figure 44: Mean total energy equation (upper panels) and mean entropy equation (lower panels). Model rg.3D.lr (left) and rg.3D.mr (right)

Mean density-specific volume covariance and entropy flux equation

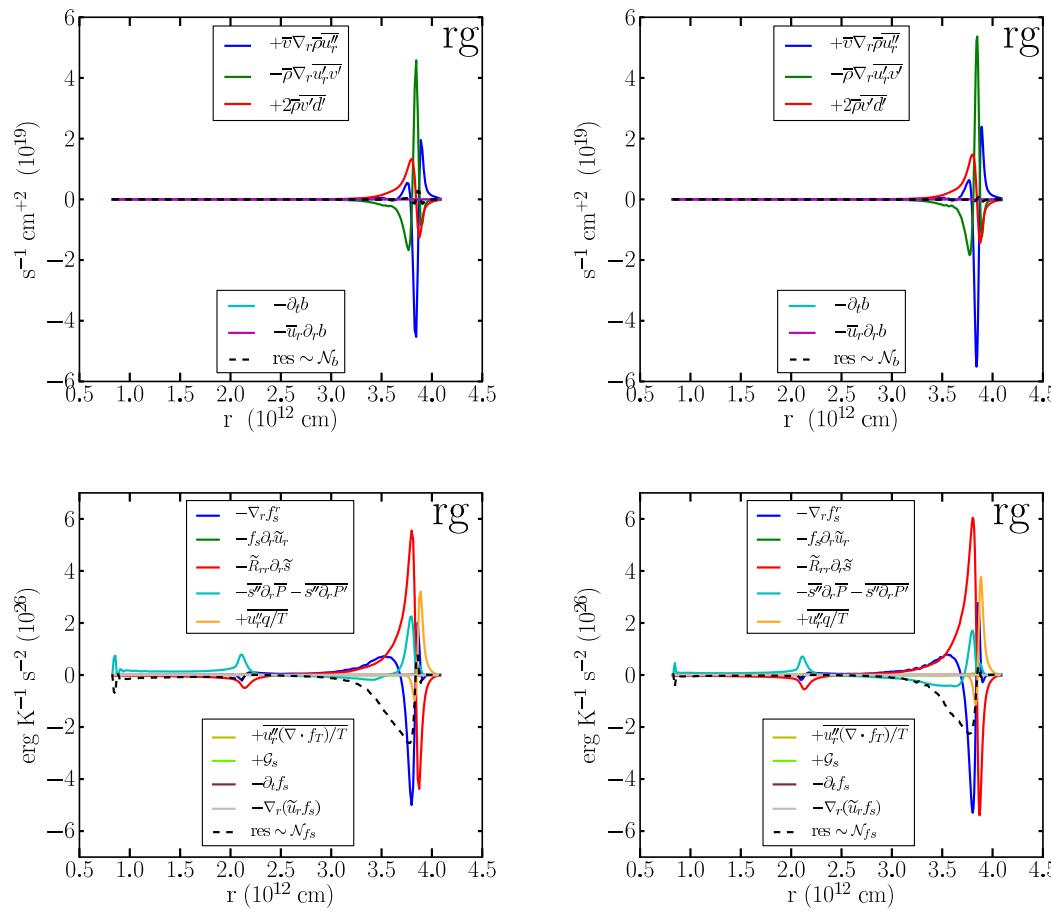


Figure 45: Mean density-specific volume covariance equation (upper panels) and entropy flux equation (lower panels). Model rg.3D.lr (left) and rg.3D.mr (right)

Mean turbulent kinetic energy equation and mean turbulent mass flux equation

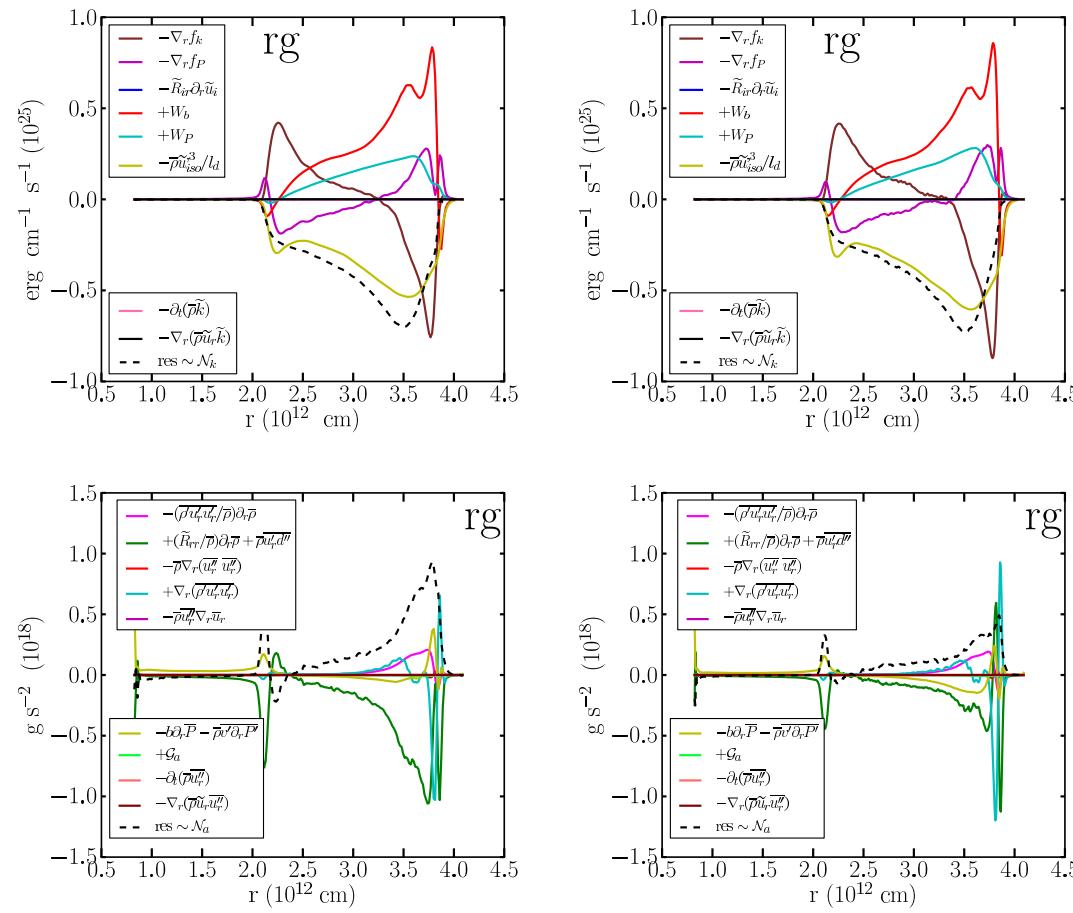


Figure 46: Mean turbulent kinetic energy equation (upper panels) and mean turbulent mass flux equation (lower panels). Model rg.3D.lr (left) and rg.3D.mr (right)

7 Wedge-size effects

7.1 Oxygen burning shell models

Mean continuity equation and mean radial momentum equation

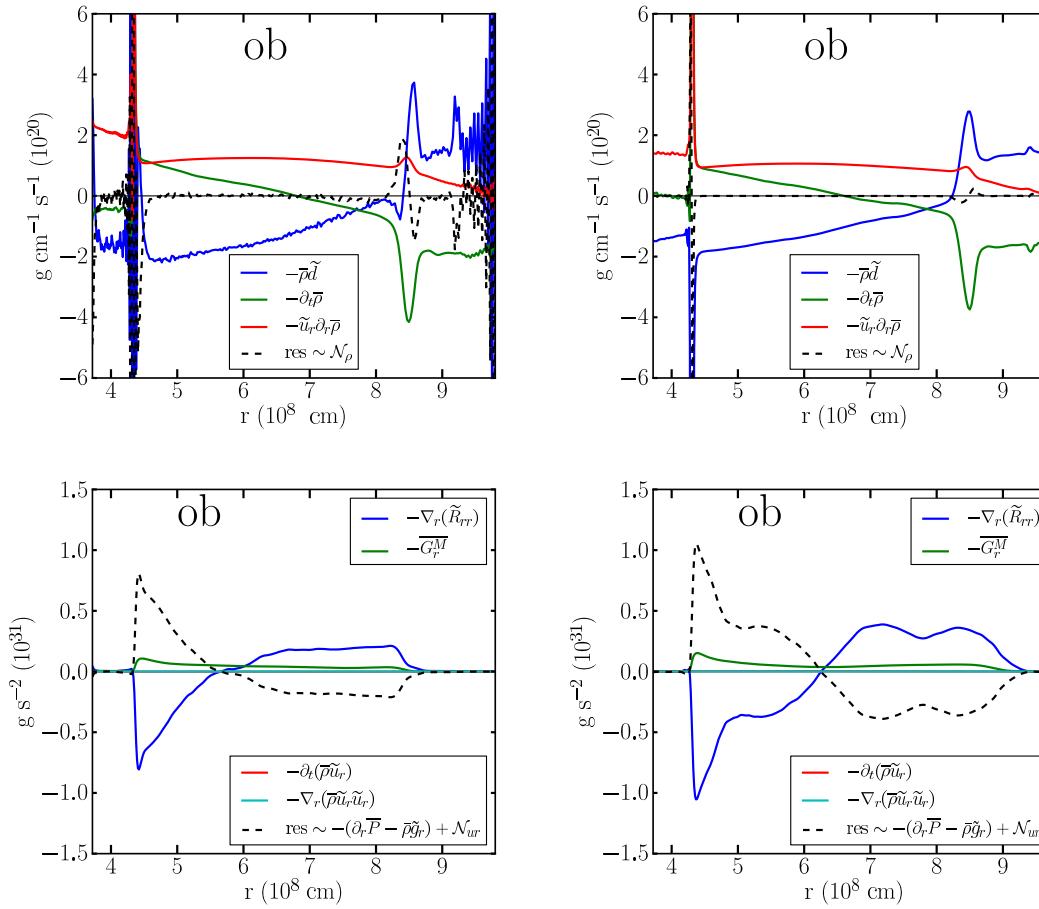


Figure 47: Continuity equation (upper panels) and radial momentum equation (lower panels). Model ob.3D.mr (45° wedge - left) and ob.3D.2hp (27.5° wedge - right).

Mean azimuthal momentum and polar momentum equation

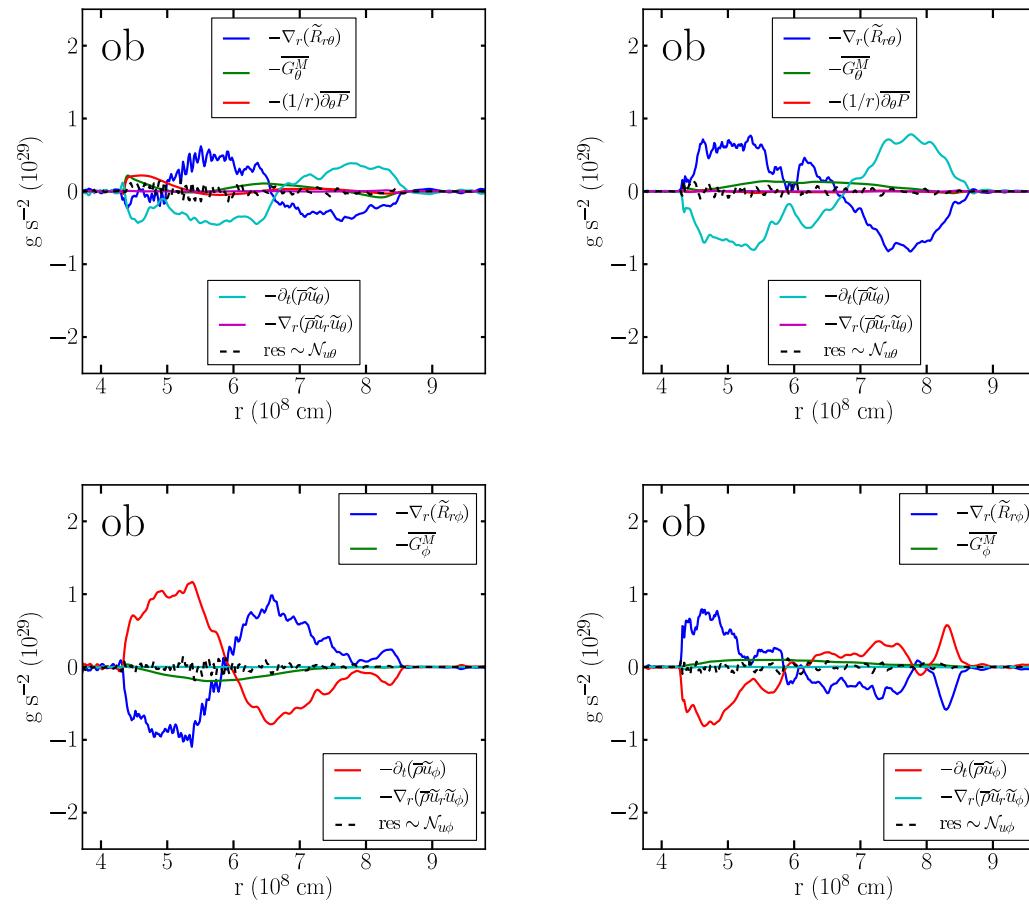


Figure 48: Mean azimuthal momentum (upper panels) and polar momentum equation (lower panels). Model ob.3D.mr (45° wedge - left) and ob.3D.2hp (27.5° wedge - right).

Mean internal energy equation and total energy equation

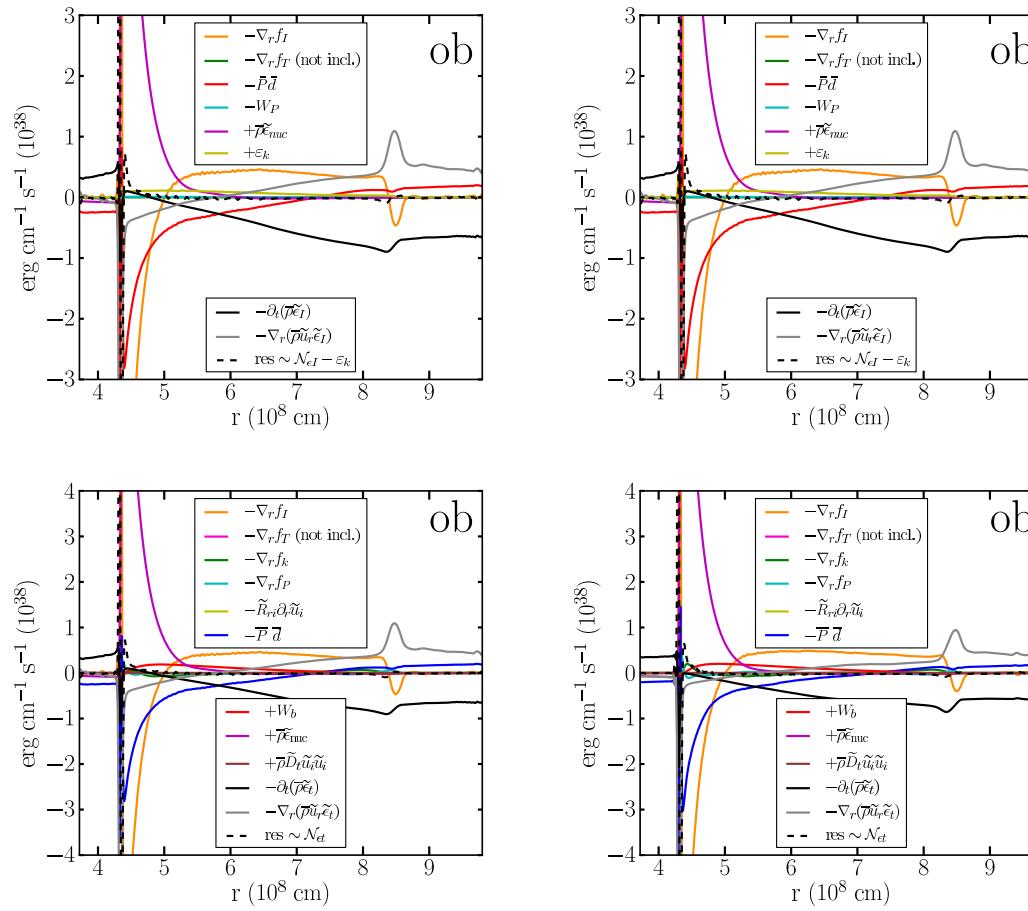
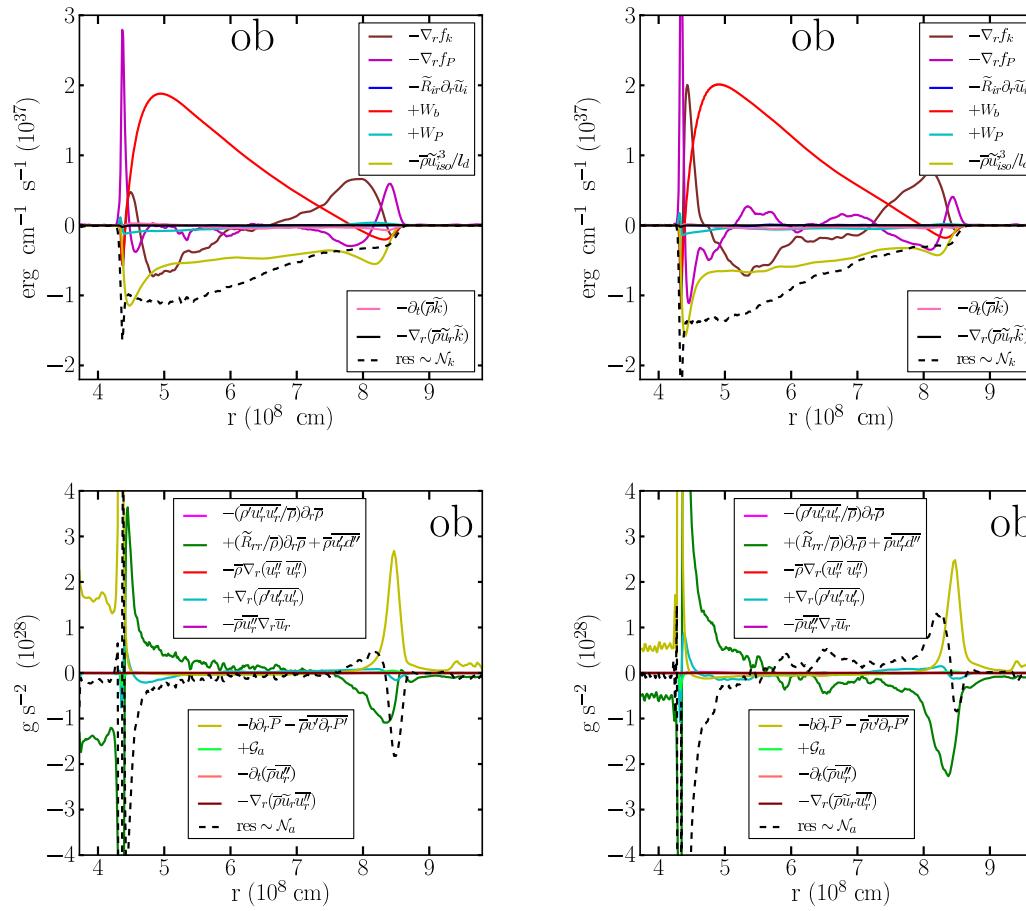


Figure 49: Mean internal energy (upper panels) equations and mean total energy equation (lower panels). Model ob.3D.mr (45° wedge - left) and ob.3D.2hp (27.5° wedge - right).

Mean turbulent kinetic energy equation and turbulent mass flux equation

Figure 50: Mean turbulent kinetic energy equation and turbulent mass flux equation. Model **ob.3D.mr** (45° wedge - left) and **ob.3D.2hp** (27.5° wedge - right).

Mean density-specific volume covariance and internal energy flux equation

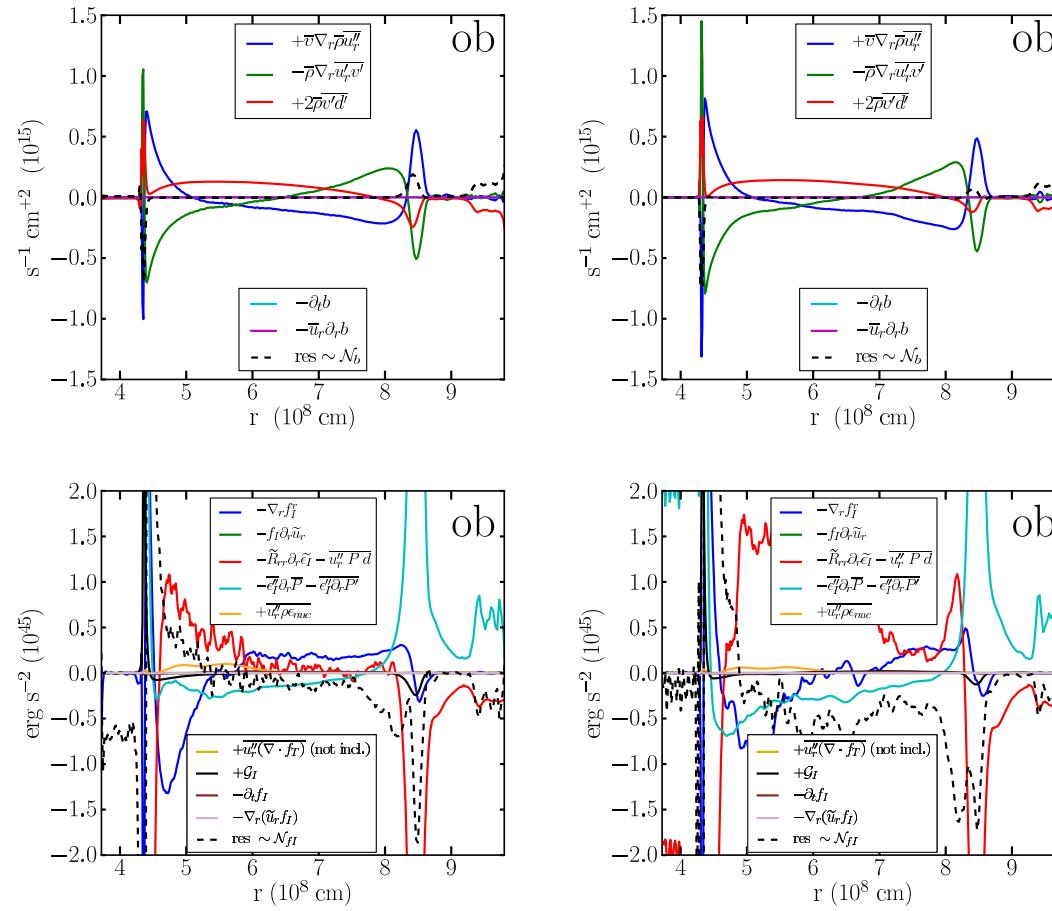


Figure 51: Mean density-specific volume covariance equation (upper panels) and mean internal energy flux equation (lower panels). Model **ob.3D.mr** (45° wedge - left) and **ob.3D.2hp** (27.5° wedge - right).

Mean kinetic energy equation and mean velocities

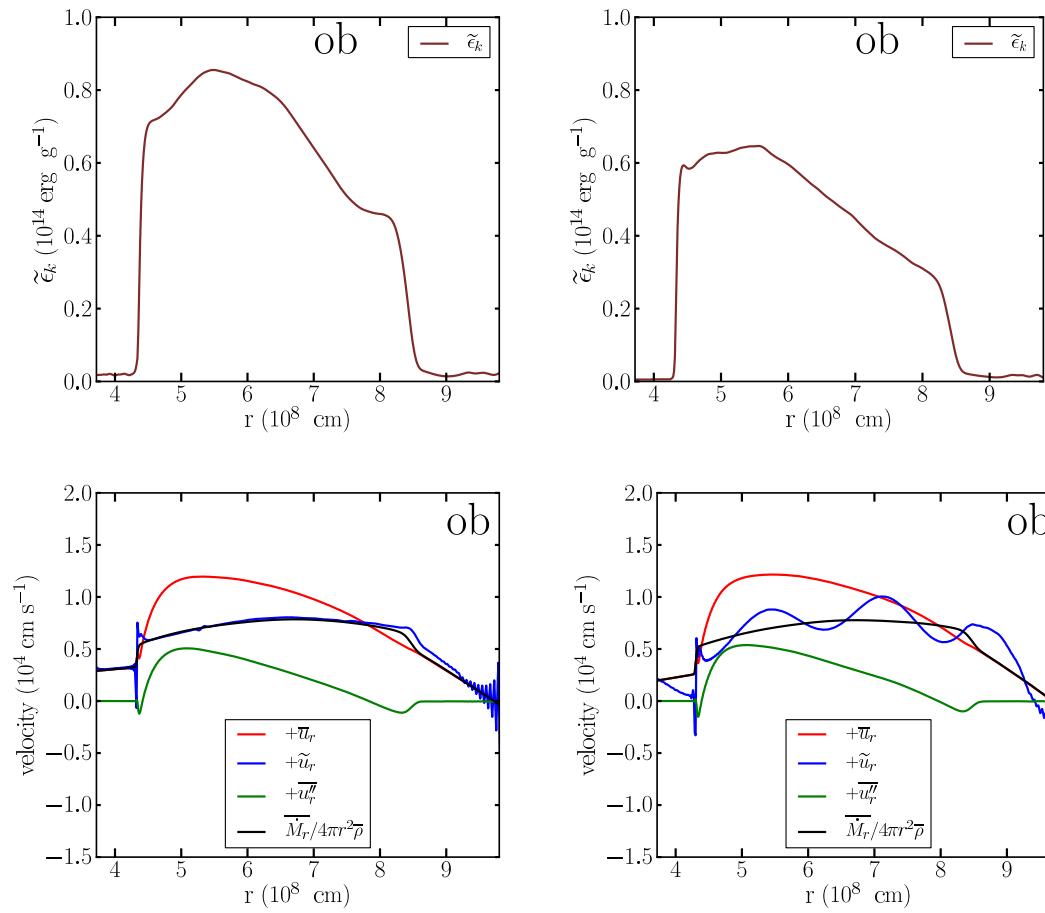


Figure 52: Mean kinetic energy equation (upper panels) mean velocities (lower panels). Model ob.3D.mr (45° wedge - left) and ob.3D.2hp (27.5° wedge - right).

8 Sensitivity to averaging window

8.1 Oxygen burning shell model

Mean continuity equation and mean radial momentum equation

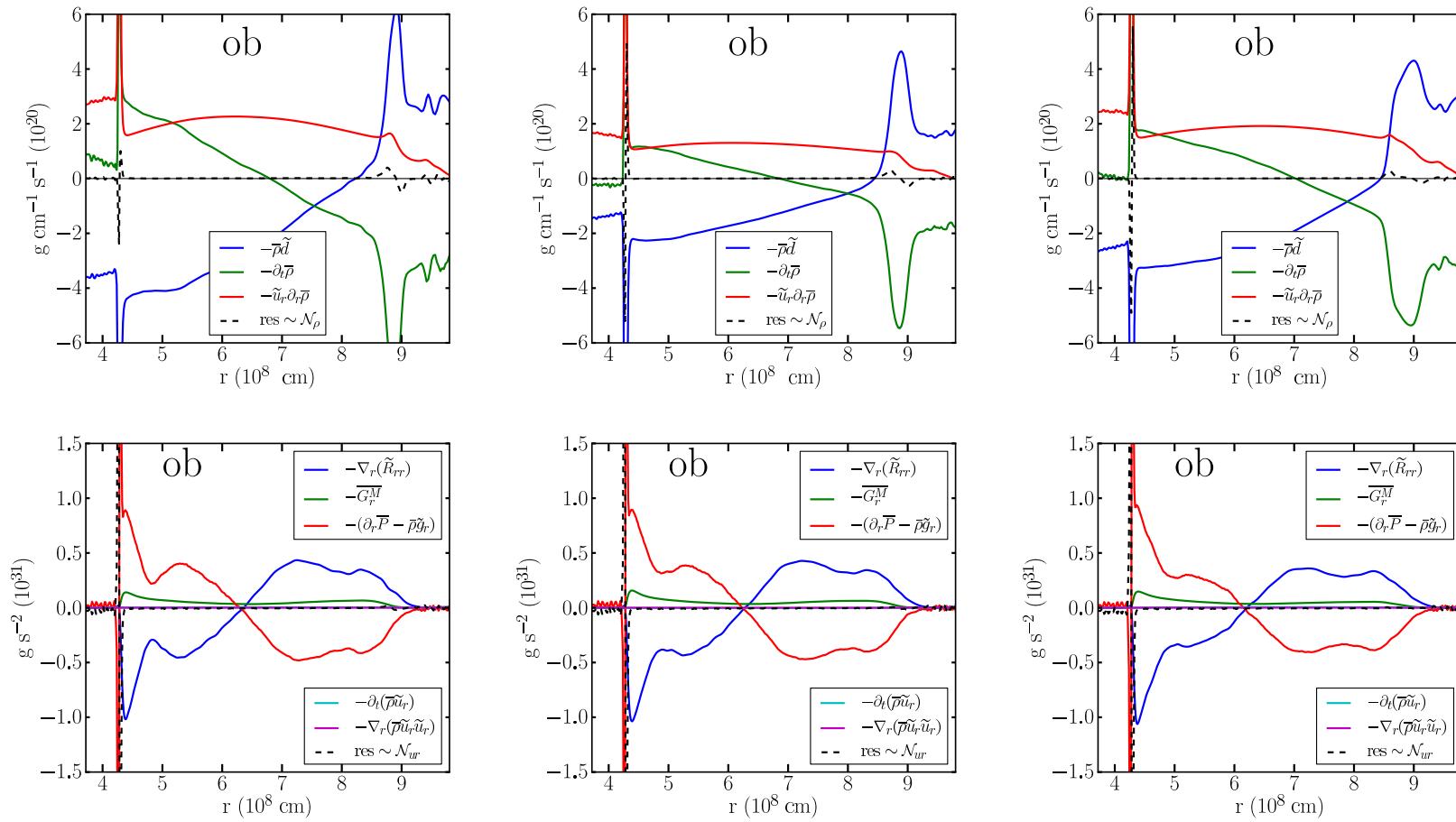


Figure 53: Mean continuity equation (upper panels) and radial momentum equation (lower panels) from model **ob.3D.2hp**. Averaging window over roughly 2 convective turnover timescales 150 s (left), 3 convective turnover timescales 230 s (middle) and 4 convective turnover timescales 460 s (right).

Mean azimuthal and polar momentum equations

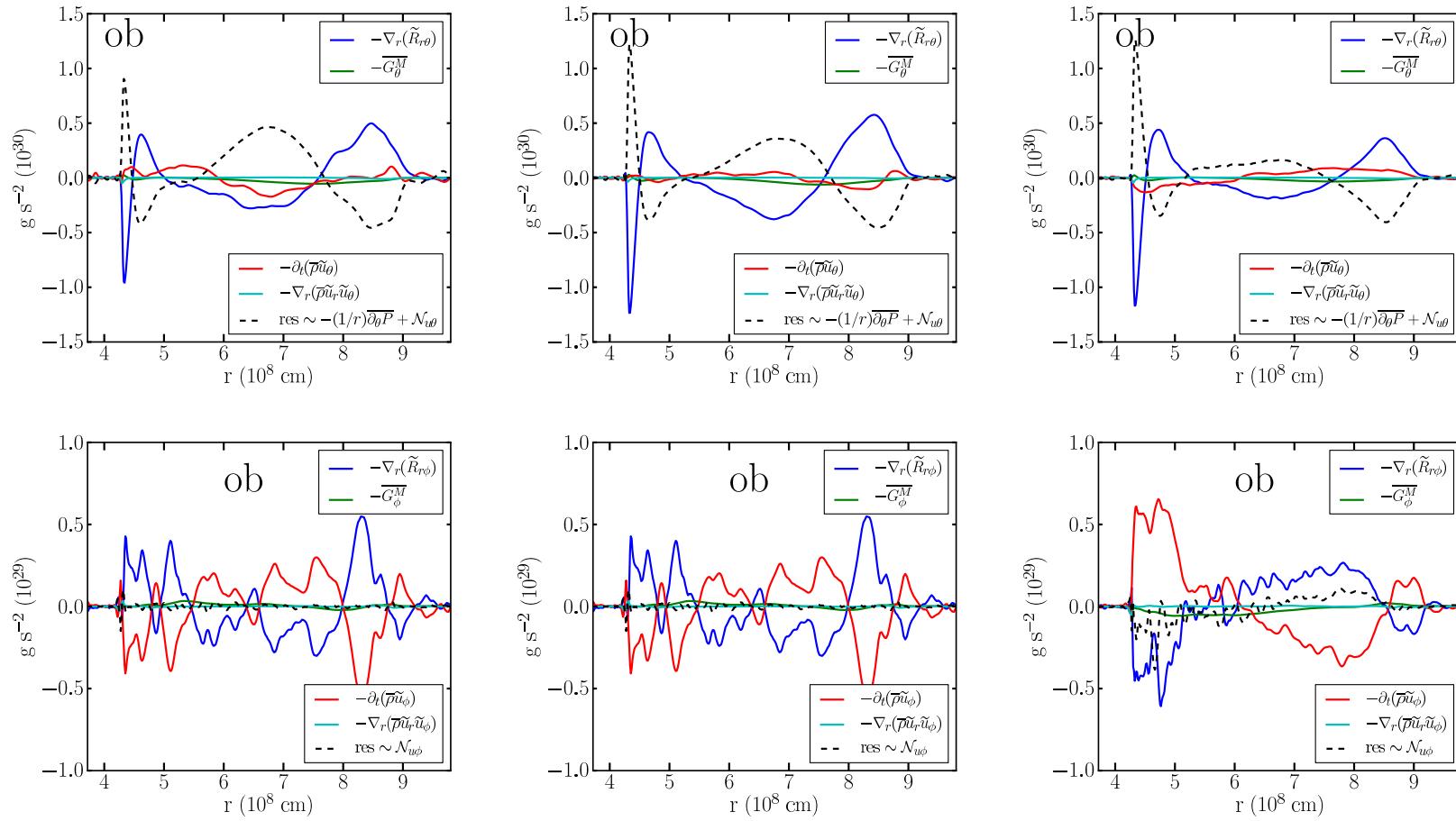


Figure 54: Mean azimuthal equation (upper panels) and mean polar momentum equation (lower panels) from model ob.3D.2hp. Averaging window over roughly 2 convective turnover timescales 150 s (left), 3 convective turnover timescales 230 s (middle) and 4 convective turnover timescales 460 s (right).

Mean total energy equation and mean turbulent kinetic energy equation

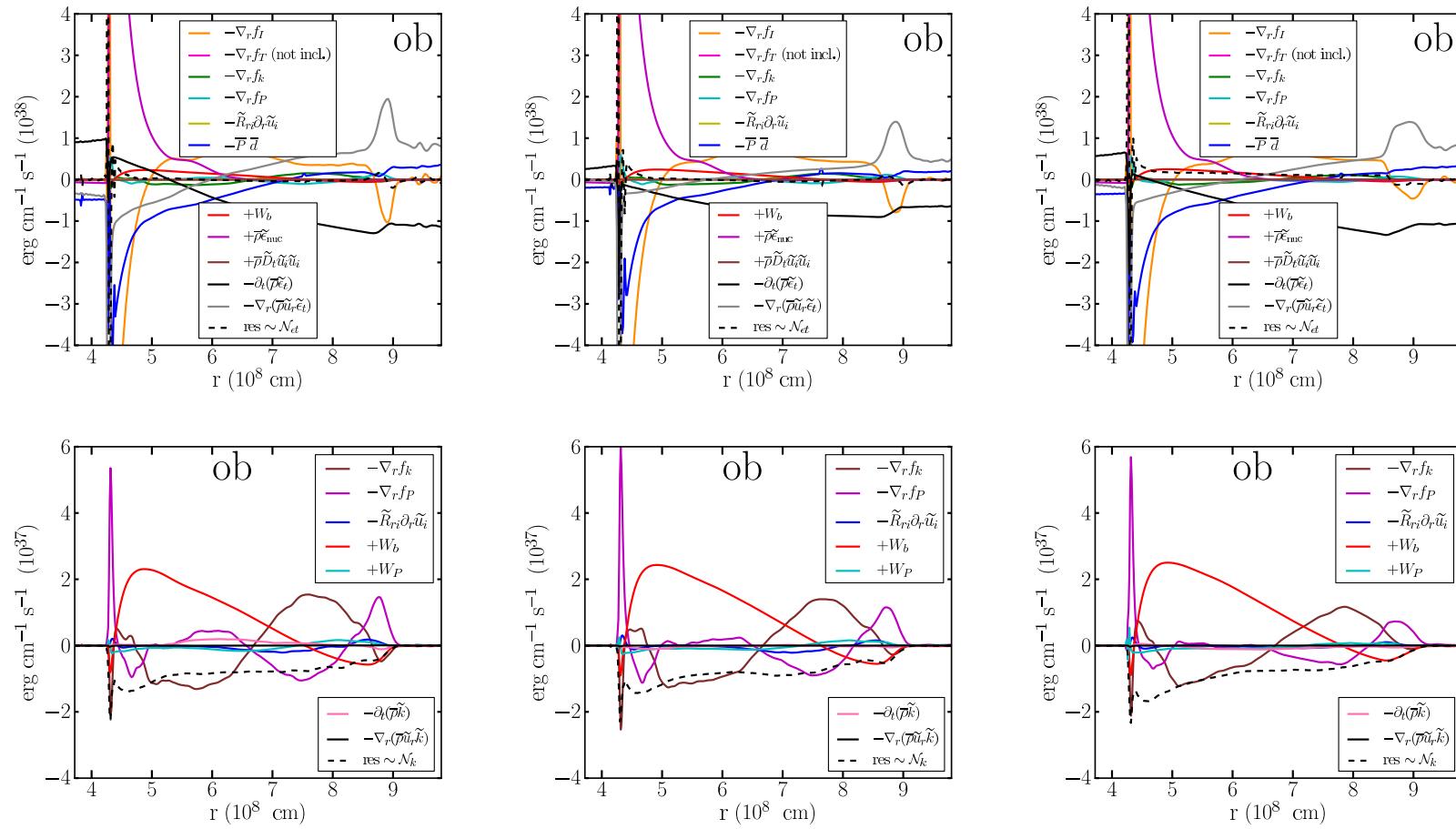


Figure 55: Mean total energy equation (upper panels) and mean turbulent kinetic energy equation (lower panels) from model ob.3D.2hp. Averaging window over roughly 2 convective turnover timescales 150 s (left), 3 convective turnover timescales 230 s (middle) and 4 convective turnover timescales 460 s (right).

Mean entropy equation and mean number of nucleons per isotope equation

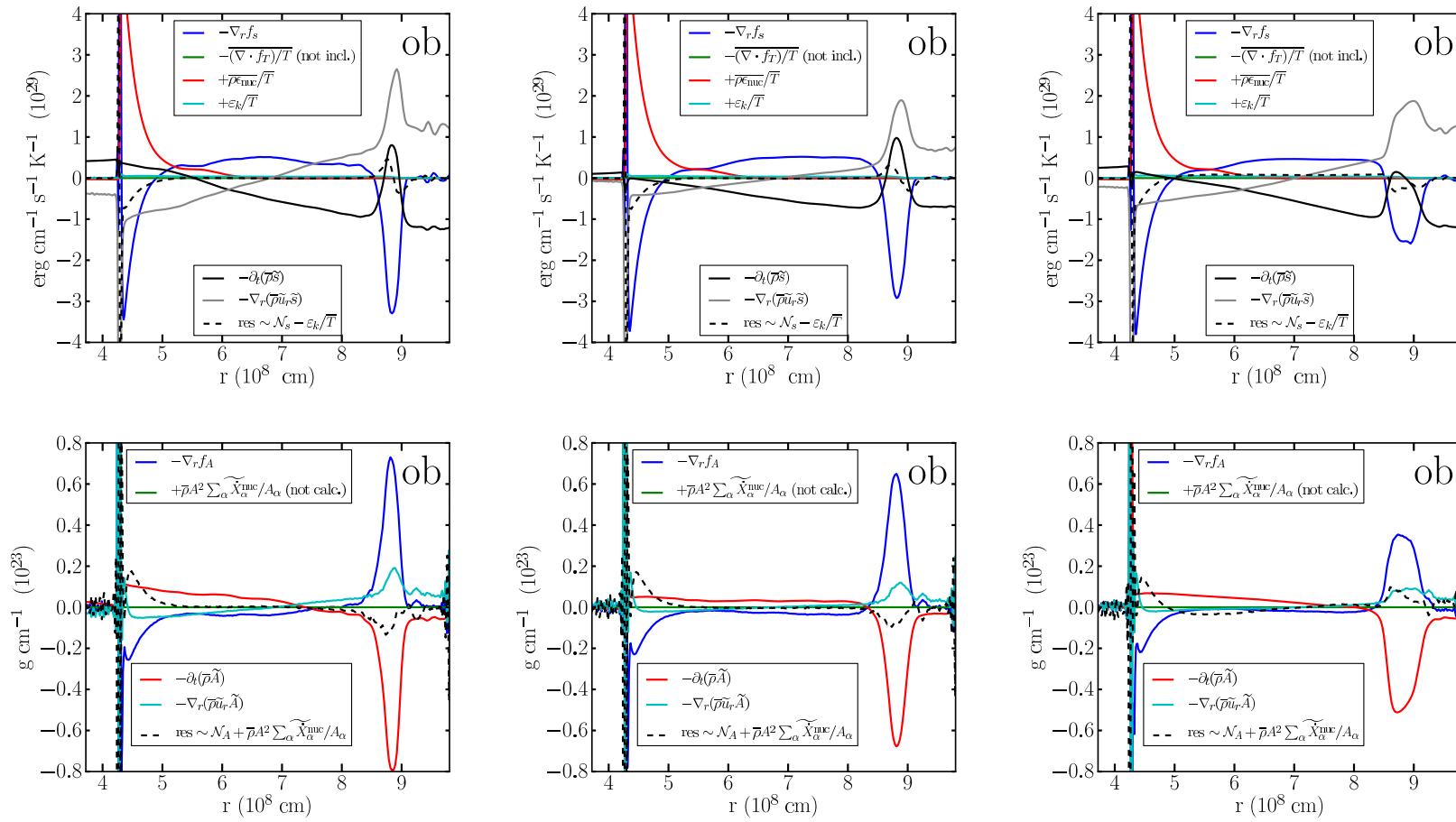


Figure 56: Mean entropy equation (upper panels) and mean number of nucleons per isotope (upper panels) from model ob.3D.2hp. Averaging window over roughly 2 convective turnover timescales 150 s (left), 3 convective turnover timescales 230 s (middle) and 4 convective turnover timescales 460 s (right).

Mean turbulent kinetic energy and mean velocities

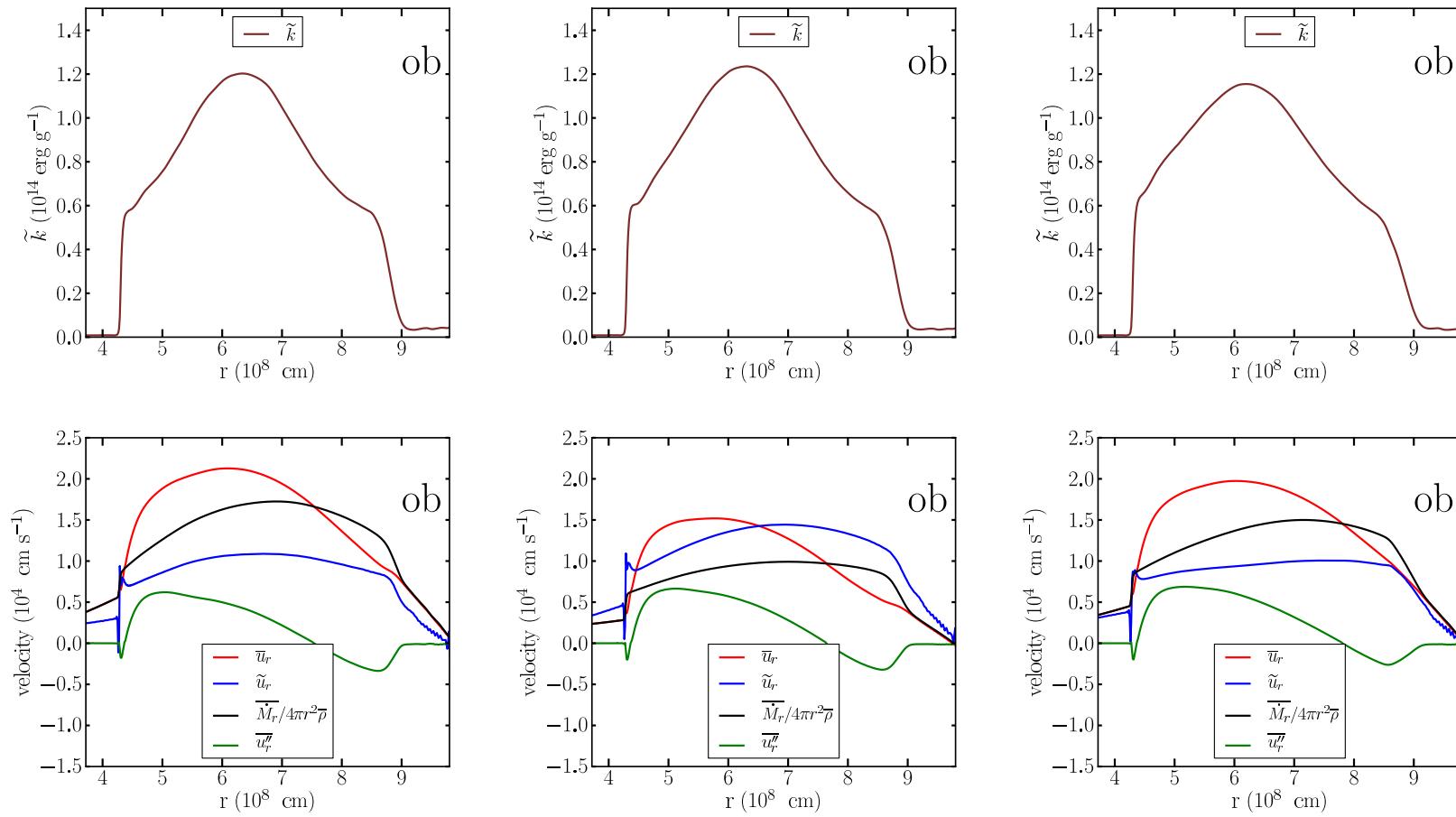


Figure 57: Mean turbulent kinetic energy equation (upper panels) and mean velocities from model ob.3D.2hp. Averaging window over roughly 2 convective turnover timescales 150 s (left), 3 convective turnover timescales 230 s (middle) and 4 convective turnover timescales 460 s (right).

9 Depth dependence

9.1 Oxygen burning shell model

Mean continuity equation and mean radial momentum equation

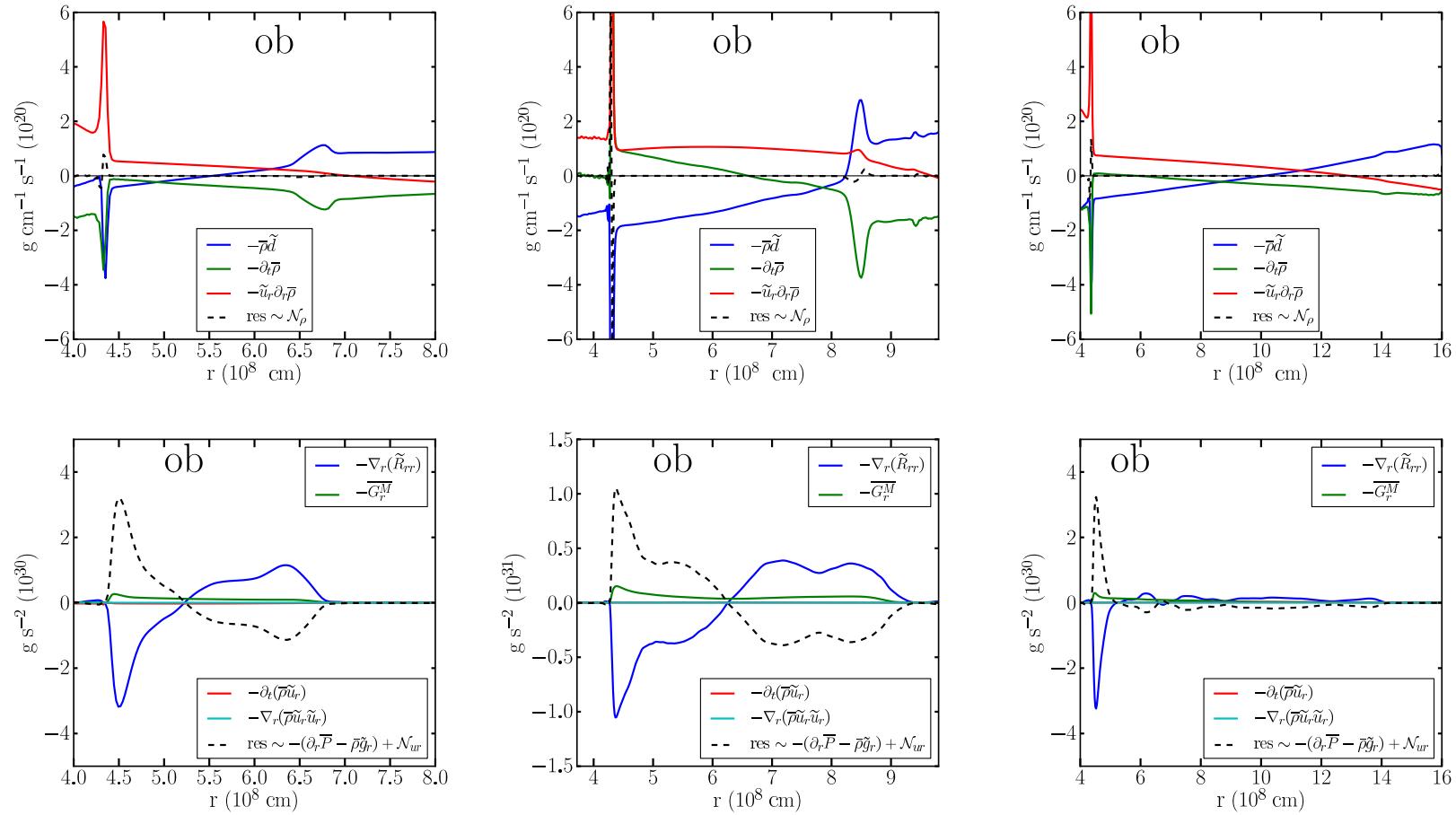


Figure 58: Mean continuity equation (upper panels) and radial momentum equation (lower panels). 1 Hp model ob.3D.1hp (left), 2 Hp model ob.3D.2hp (middle) and 4 Hp model ob.3D.4hp (right)

Mean azimuthal and polar momentum equation

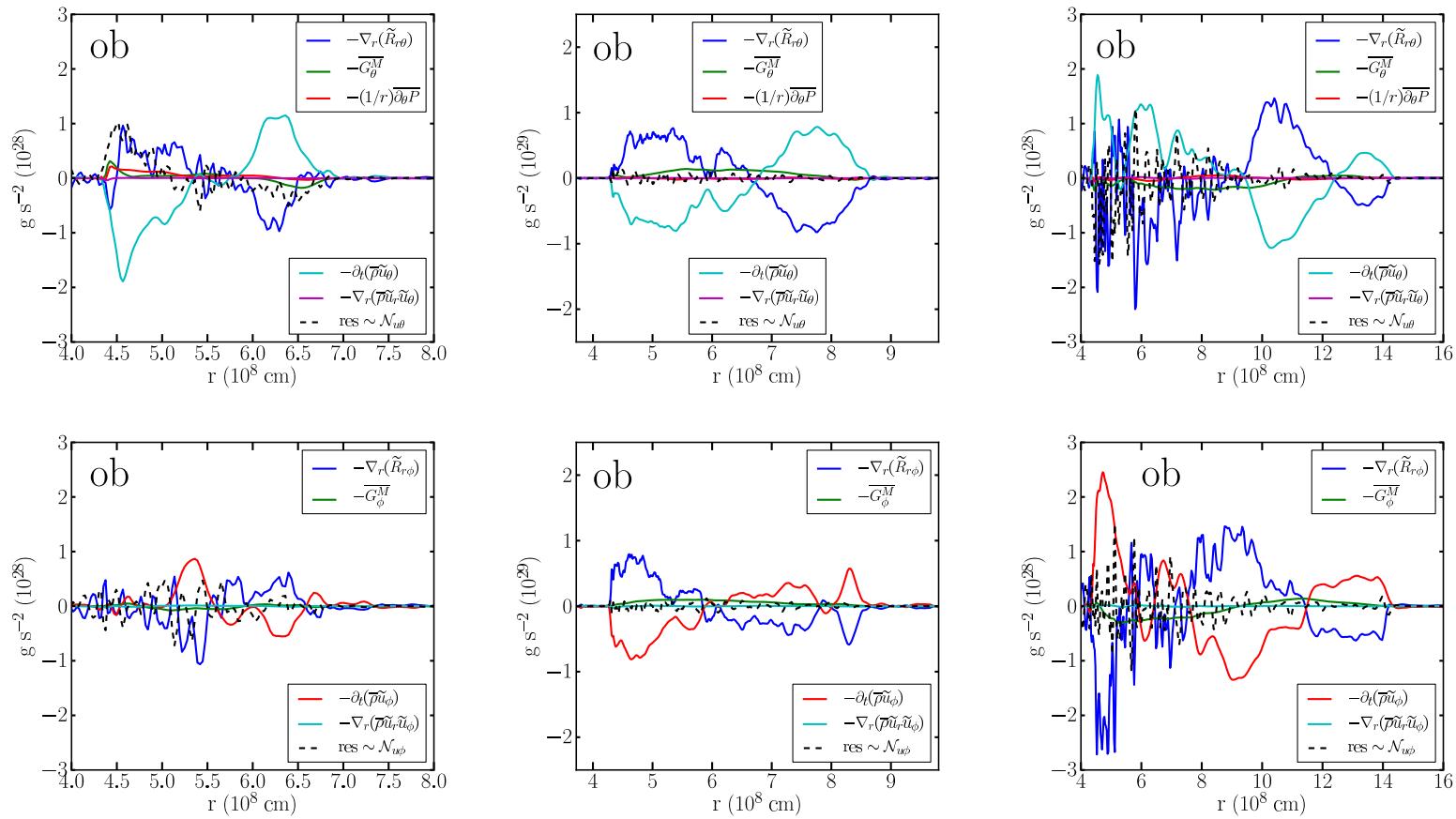


Figure 59: Mean azimuthal equation (upper panels) and mean polar momentum equation (lower panels). 1 Hp model **ob.3D.1hp** (left), 2 Hp model **ob.3D.2hp** (middle) and 4 Hp model **ob.3D.4hp** (right).

Mean total energy equation and turbulent kinetic energy equation

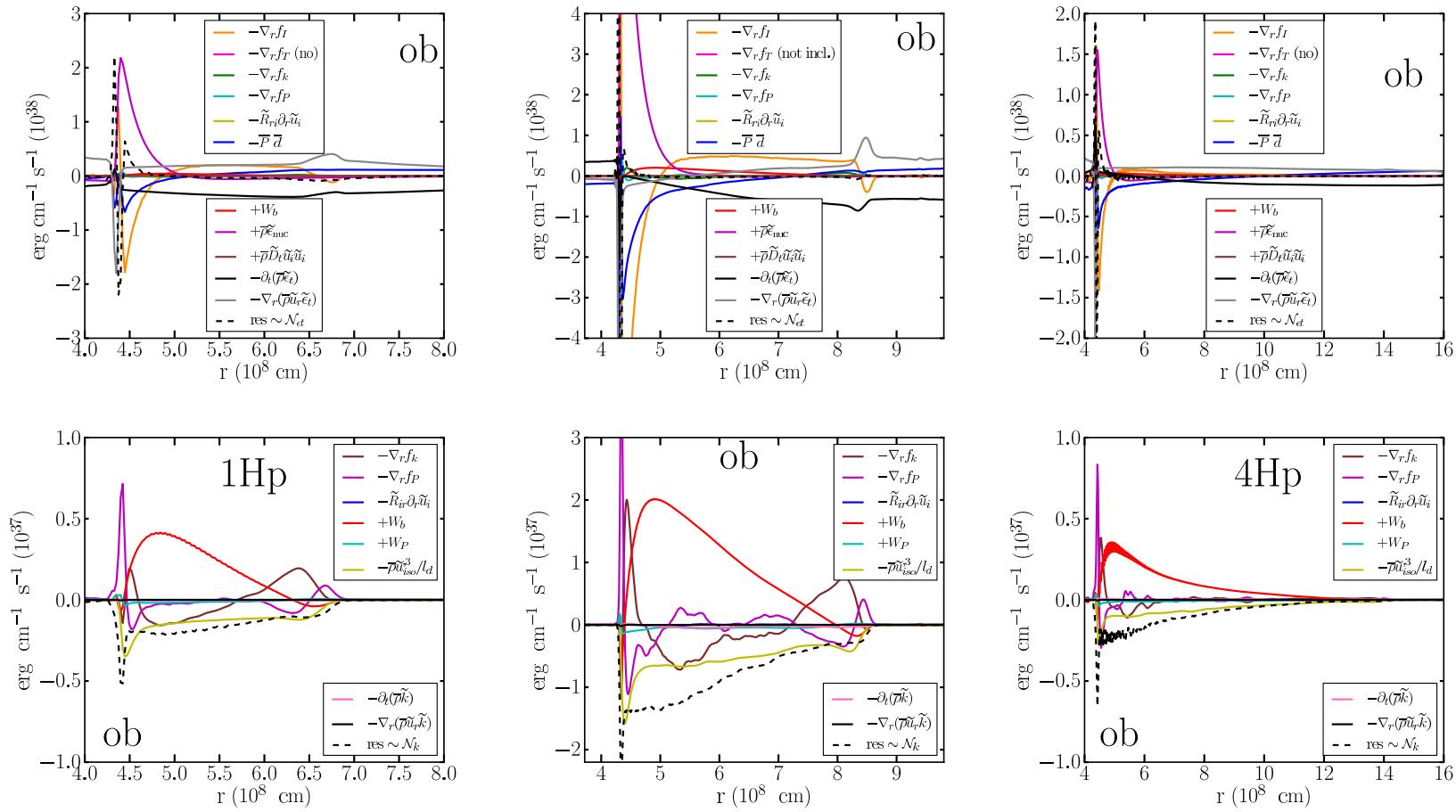


Figure 60: Mean total energy equation (upper panels) and mean turbulent kinetic energy equation (lower panels). 1 Hp model **ob.3D.1hp** (left), 2 Hp model **ob.3D.2hp** (middle) and 4 Hp model **ob.3D.4hp** (right).

Mean turbulent kinetic energy equation (radial + horizontal part)

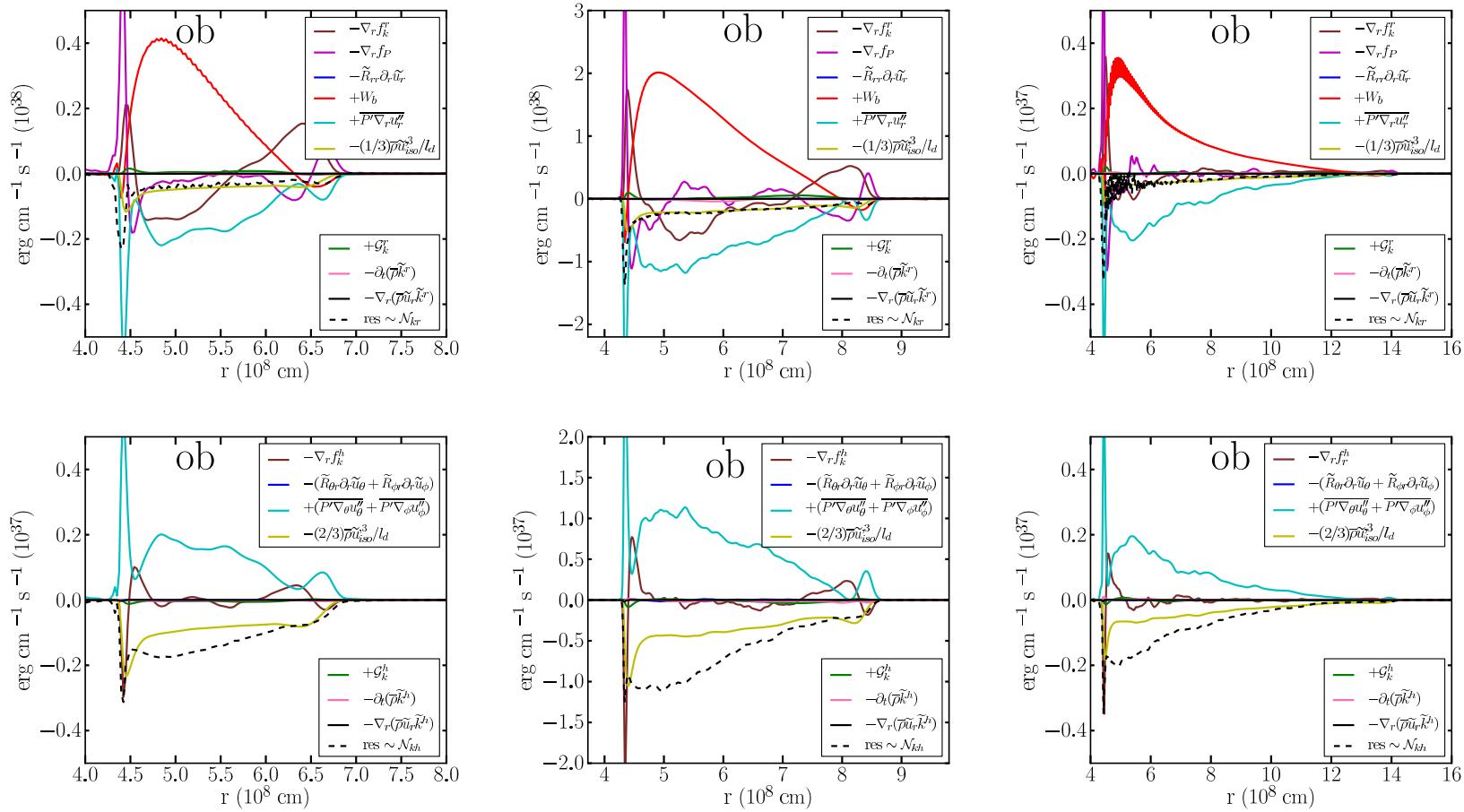


Figure 61: Radial (upper panels) and horizontal (lower panels) part of the mean turbulent kinetic energy equation. 1 Hp model **ob.3D.1hp** (left), 2 Hp model **ob.3D.2hp** (middle) and 4 Hp model **ob.3D.4hp** (right).

Mean turbulent mass flux equation and mean density-specific volume covariance equation

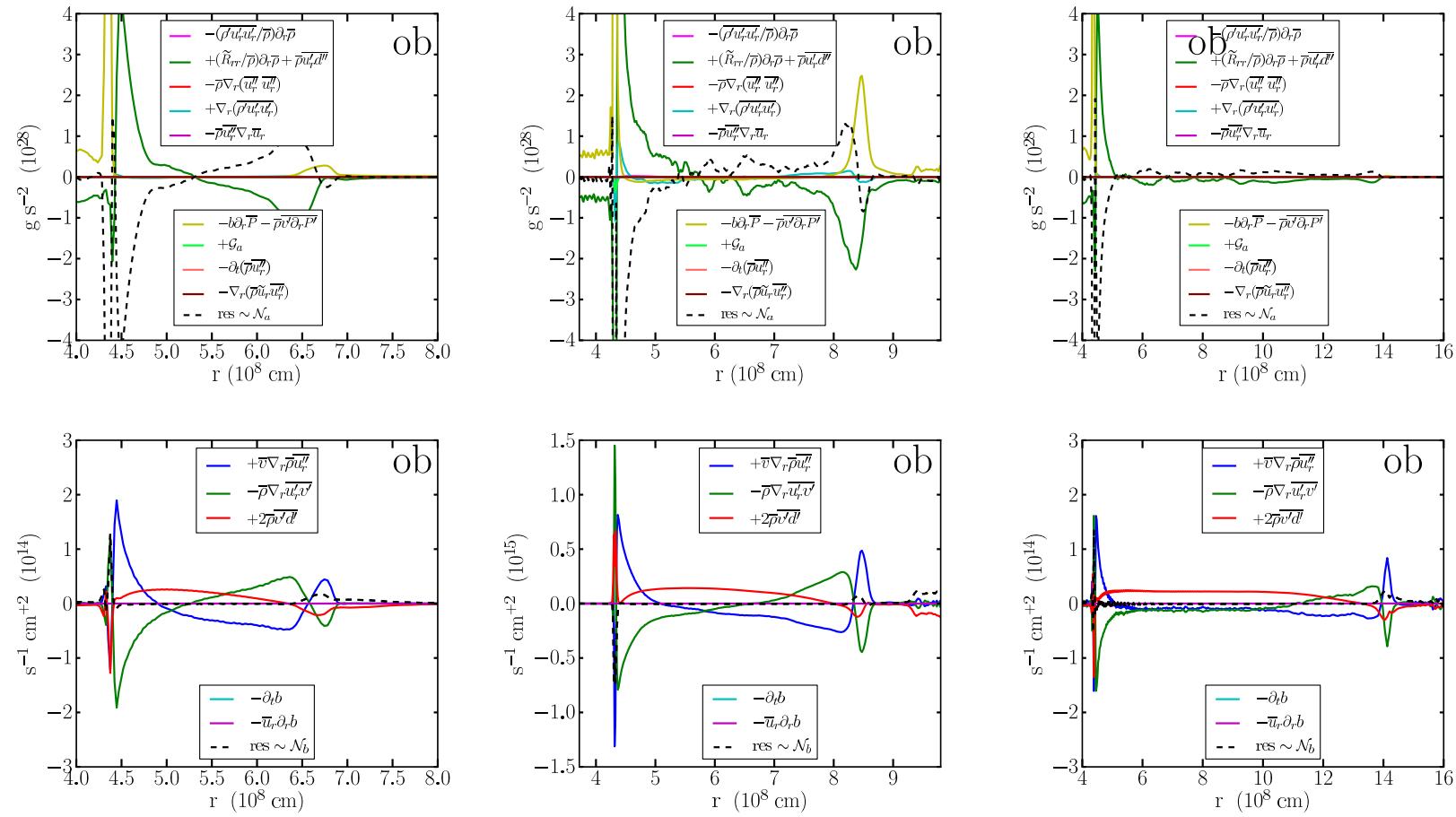


Figure 62: Mean turbulent mass flux equation (upper panels) and density-specific volume covariance equation (lower panels). 1 Hp model ob.3D.1hp (left), 2 Hp model ob.3D.2hp (middle) and 4 Hp model ob.3D.4hp (right).

Mean specific angular momentum equation and internal energy flux equation

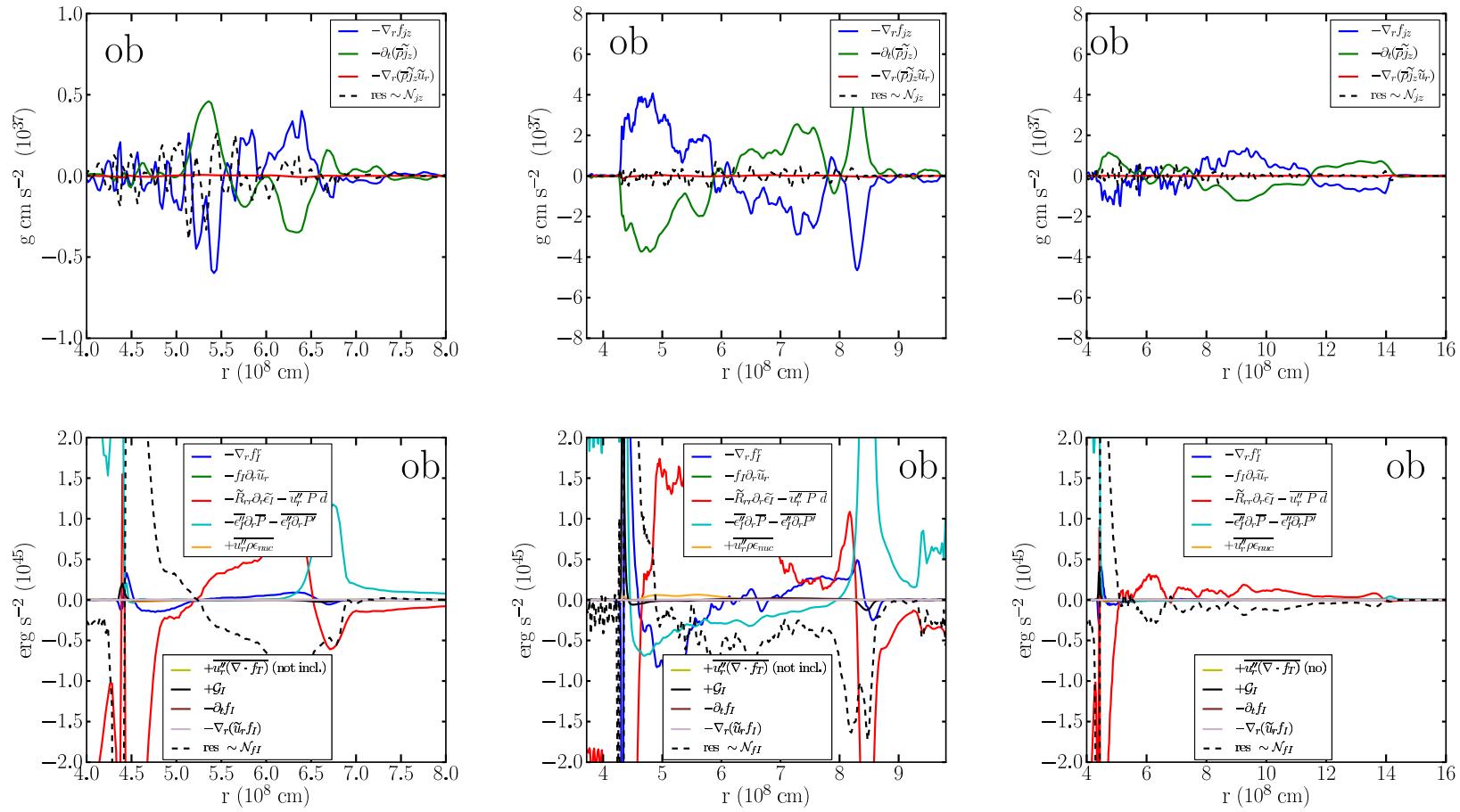


Figure 63: Mean specific angular momentum equation (upper panels) and mean turbulent internal energy flux equation (lower panels). 1 Hp model **ob.3D.1hp** (left), 2 Hp model **ob.3D.2hp** (middle) and 4 Hp model **ob.3D.4hp** (right).

Mean entropy equation and mean entropy flux equation

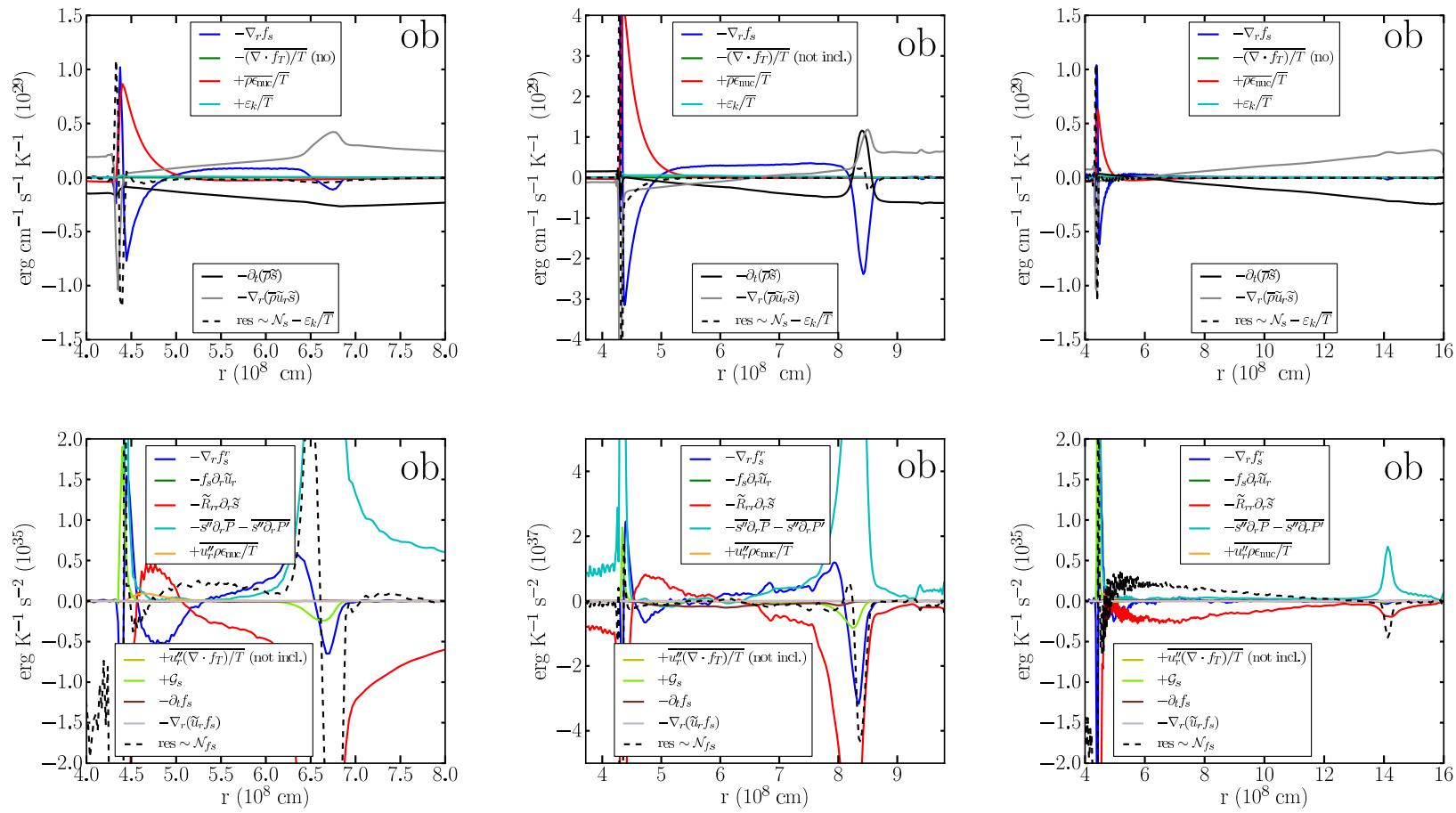


Figure 64: Mean entropy equation (upper panels) and mean entropy flux equation (lower panels). 1 Hp model ob.3D.1hp (left), 2 Hp model ob.3D.2hp (middle) and 4 Hp model ob.3D.4hp (right).

Mean turbulent kinetic energy and mean velocities

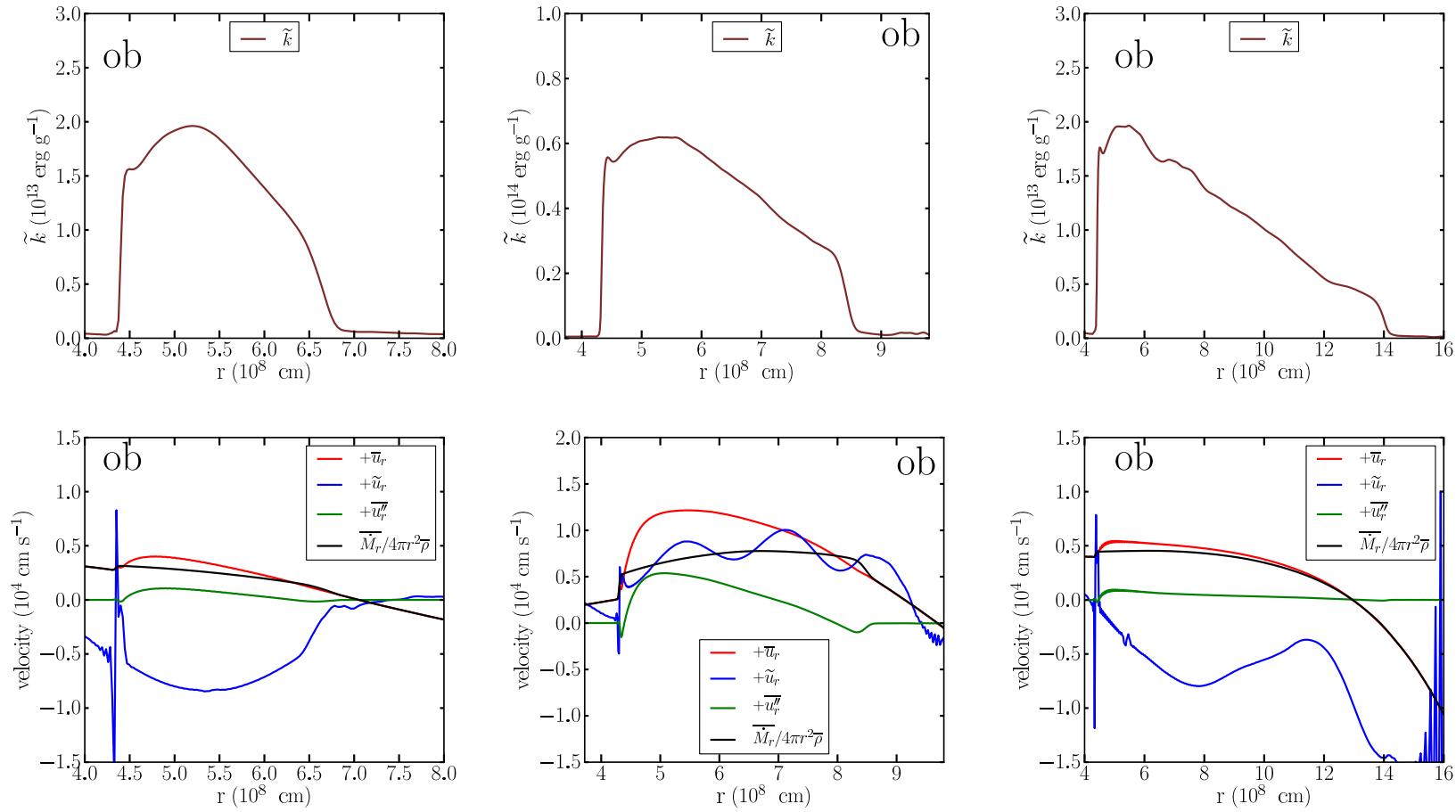


Figure 65: Mean turbulent kinetic energy (upper panels) and mean velocities (lower panels). 1 Hp model ob.3D.1hp (left), 2 Hp model ob.3D.2hp (middle) and 4 Hp model ob.3D.4hp (right).

9.2 Red giant convection envelope model

Mean continuity equation and mean radial momentum equation

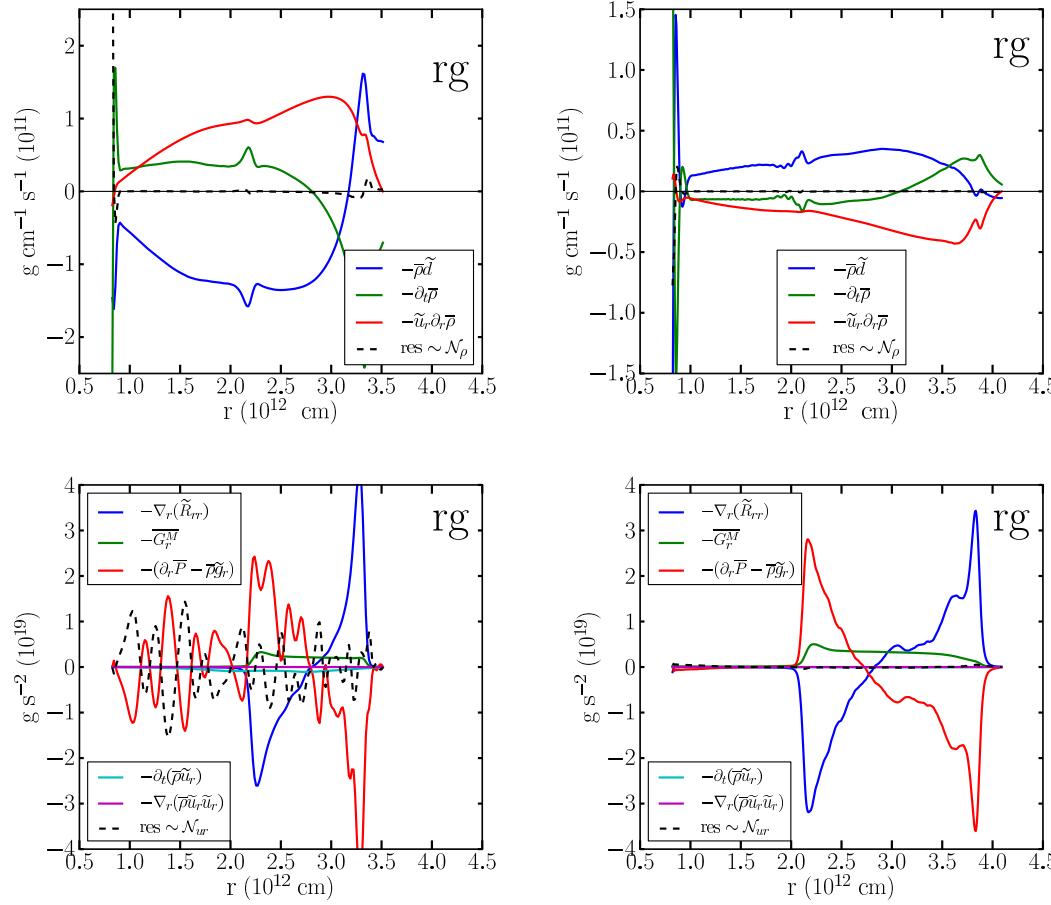


Figure 66: Mean continuity equation (upper panels) and radial momentum equation (lower panels). 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

Mean azimuthal and polar momentum equation

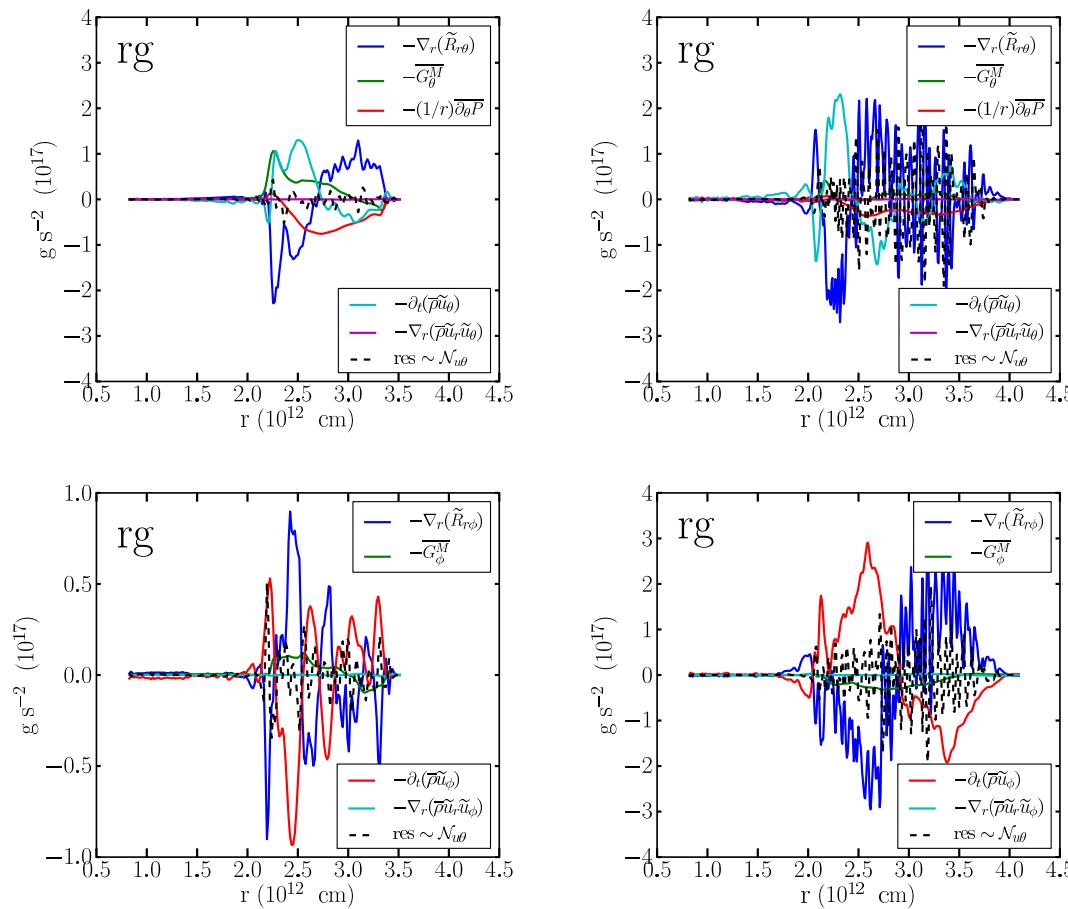


Figure 67: Mean azimuthal equation (upper panels) and mean polar momentum equation (lower panels). 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

Mean total energy equation and mean turbulent kinetic energy equation

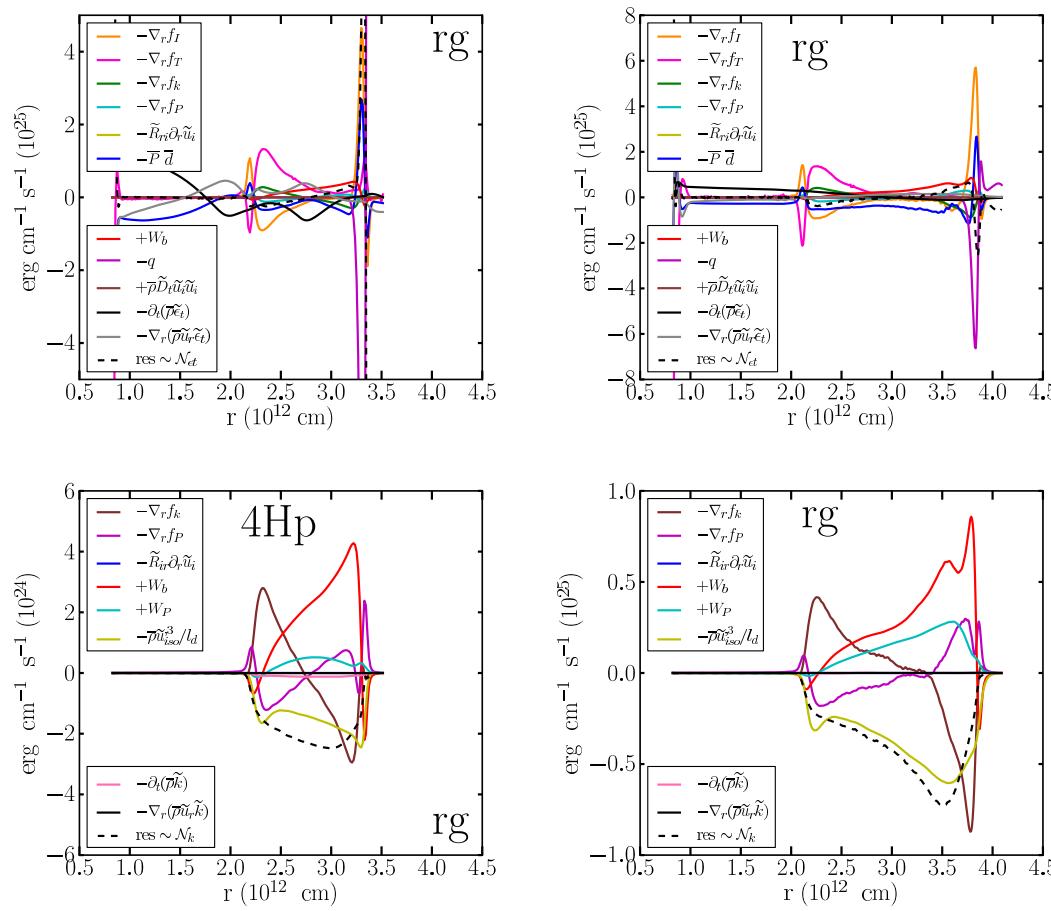


Figure 68: Mean total energy equation (upper panels) and mean turbulent kinetic energy equation (lower panels). 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

Mean turbulent kinetic energy equation (radial + horizontal part)

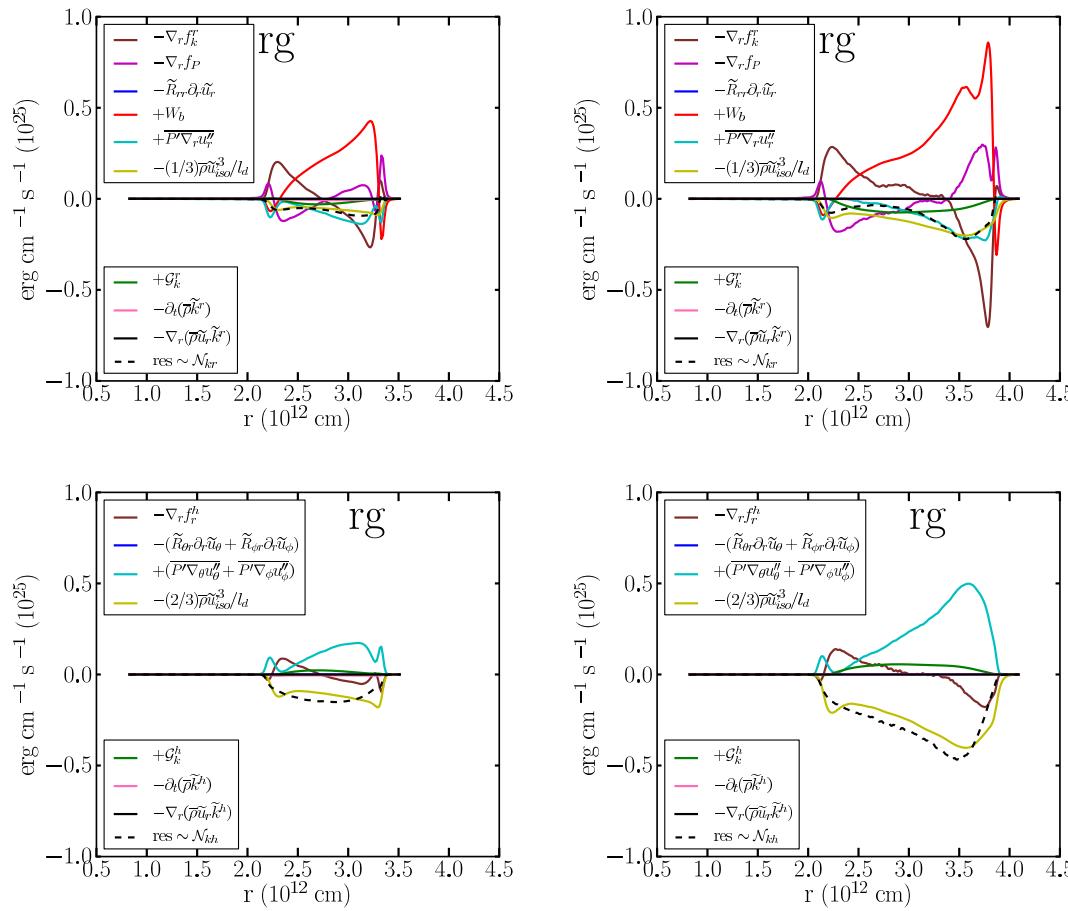


Figure 69: Radial (upper panels) and horizontal (lower panels) part of the mean turbulent kinetic energy equation. 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

Mean turbulent mass flux and mean density-specific volume covariance equation

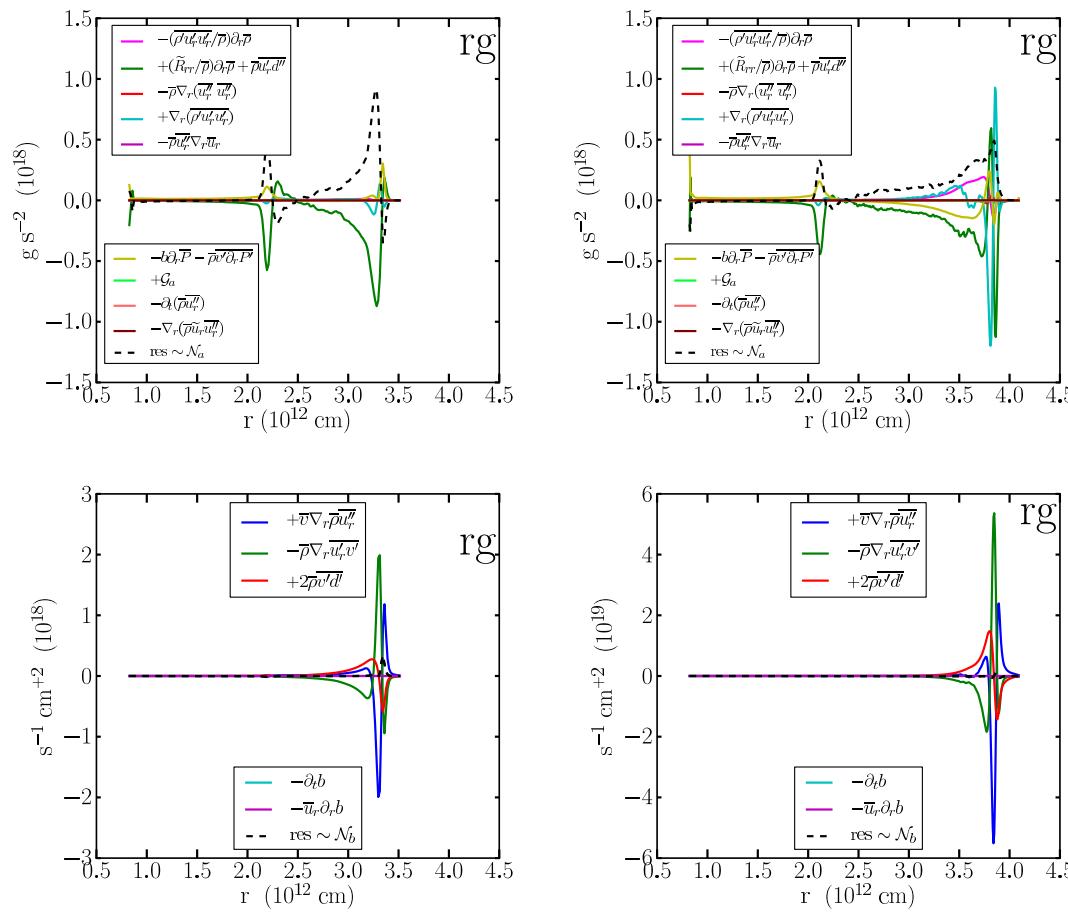


Figure 70: Mean turbulent mass flux equation (upper panels) and density-specific volume covariance equation (lower panels). 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

Mean specific angular momentum equation and internal energy flux equation

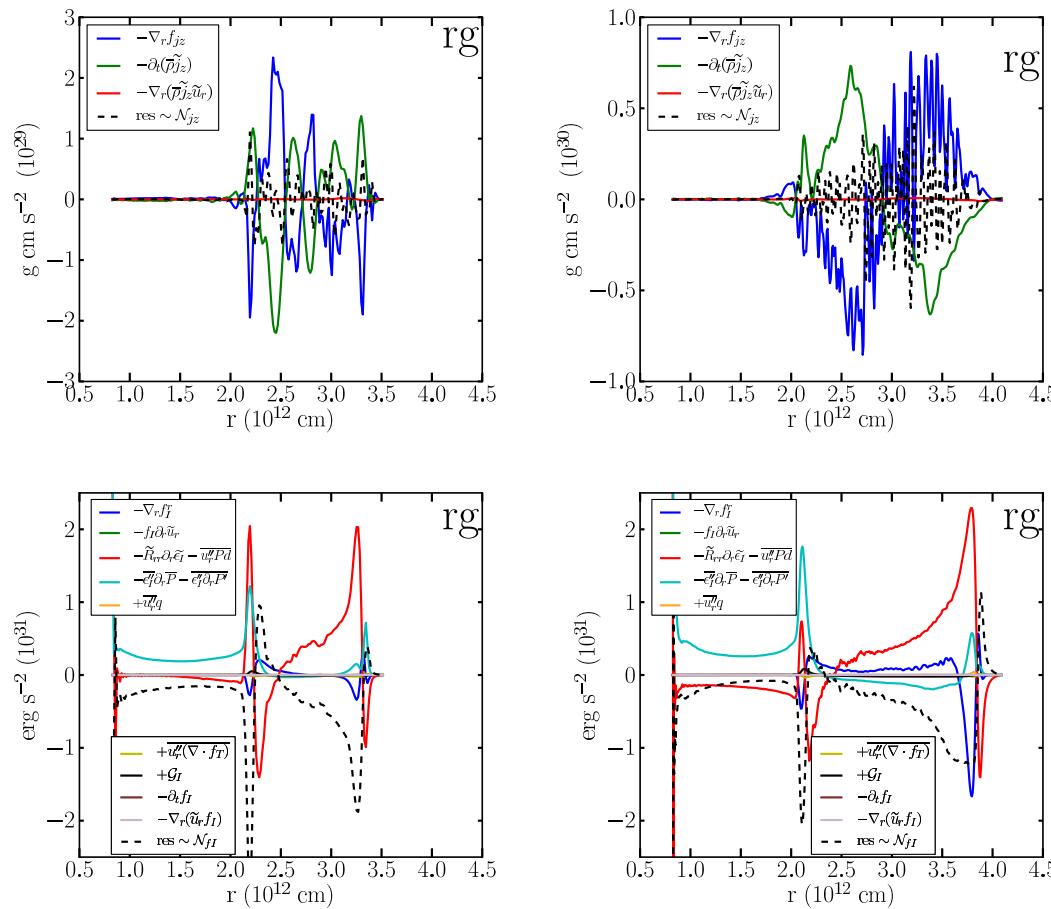


Figure 71: Mean specific angular momentum equation (upper panels) and mean turbulent internal energy flux equation (lower panels). 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

Mean entropy equation and mean entropy flux equation

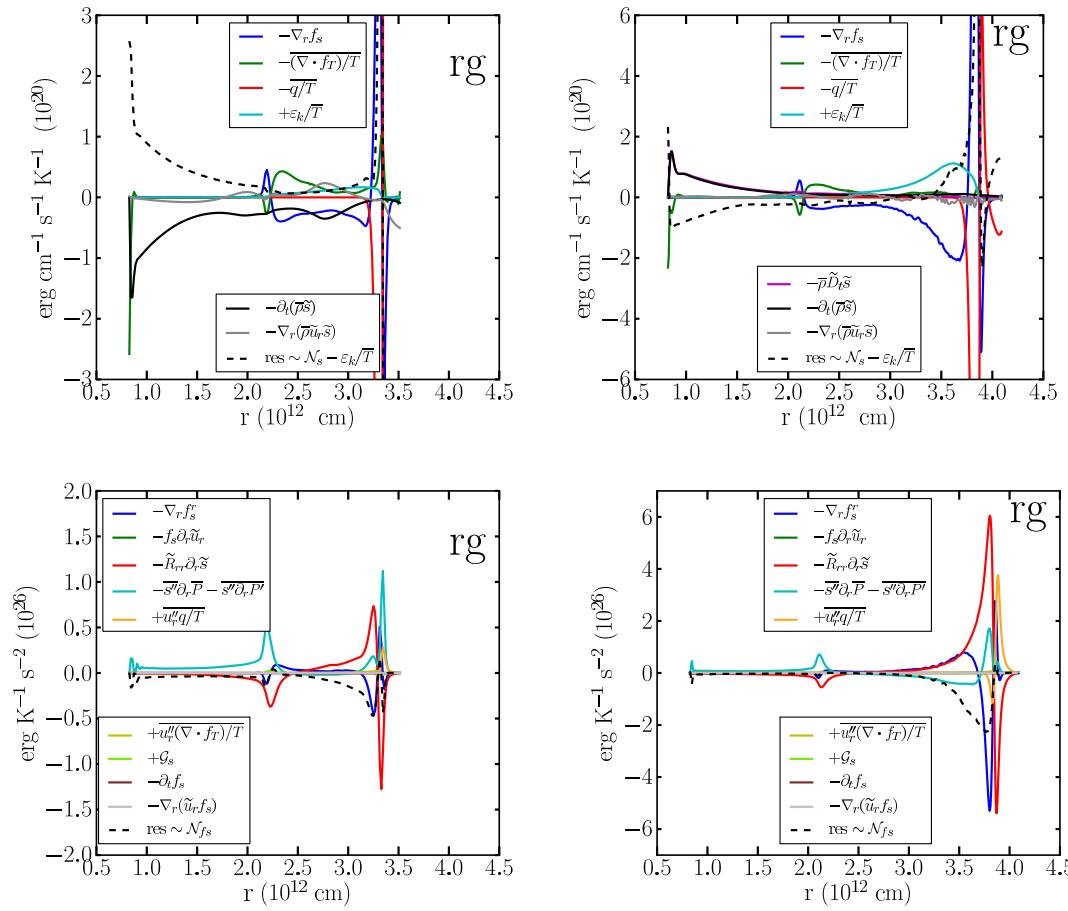


Figure 72: Mean entropy equation (upper panels) and mean entropy flux equation (lower panels). 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

Mean turbulent kinetic energy and mean velocities

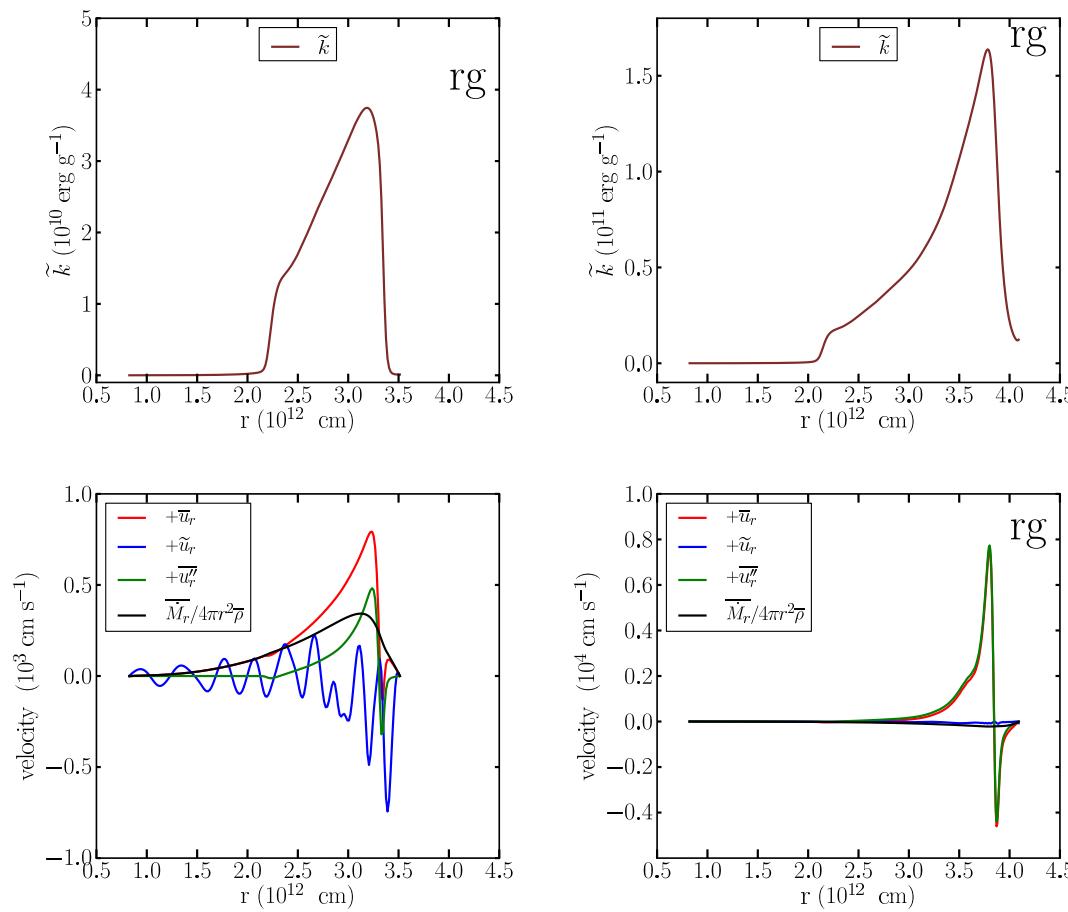


Figure 73: Mean turbulent kinetic energy (upper panels) and mean velocities (lower panels). 4 Hp model rg.3D.4hp (left) and 7 Hp model rg.3D.mrez (right).

10 Position of convection driving source

10.1 Oxygen burning shell models

Mean continuity equation and mean radial momentum equation

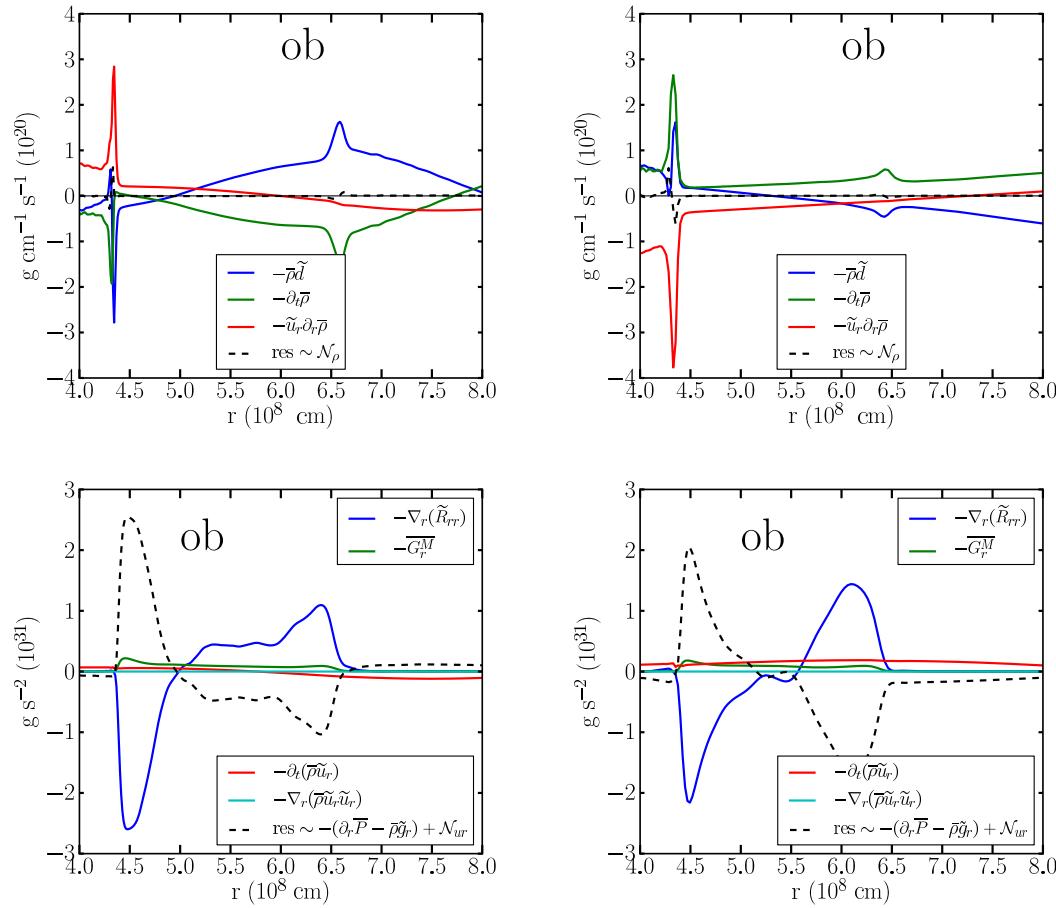


Figure 74: Mean continuity equation (upper panels) and radial momentum equation (lower panels). Model with volumetric heating at the bottom of convection zone ob.3D.1hp.vh (left) and model with volumetric cooling at the top of convection zone ob.3D.1hp.vc (right).

Mean azimuthal and polar momentum equation

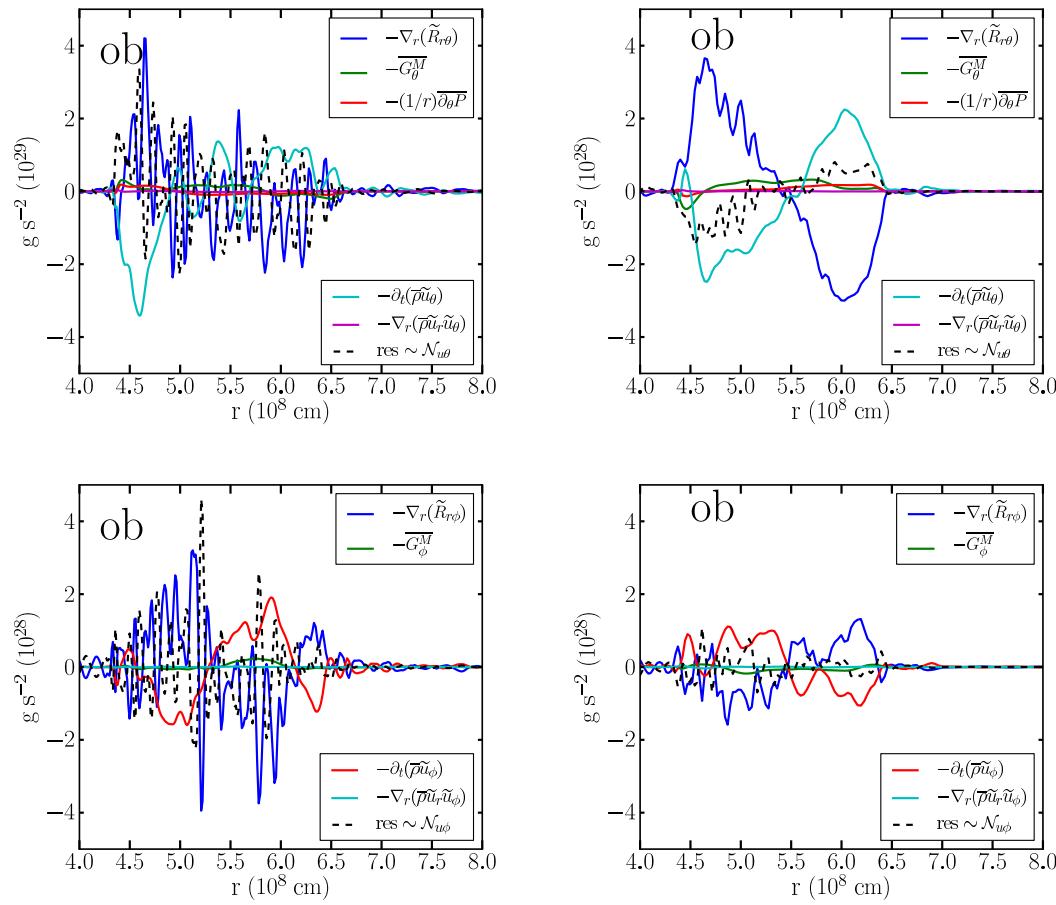


Figure 75: Mean azimuthal equation (upper panels) and mean polar momentum equation (lower panels). Model with volumetric heating at the bottom of convection zone `ob.3D.1hp.vh` (left) and model with volumetric cooling at the top of convection zone `ob.3D.1hp.vc` (right).

Mean total energy equation and mean turbulent kinetic energy equation

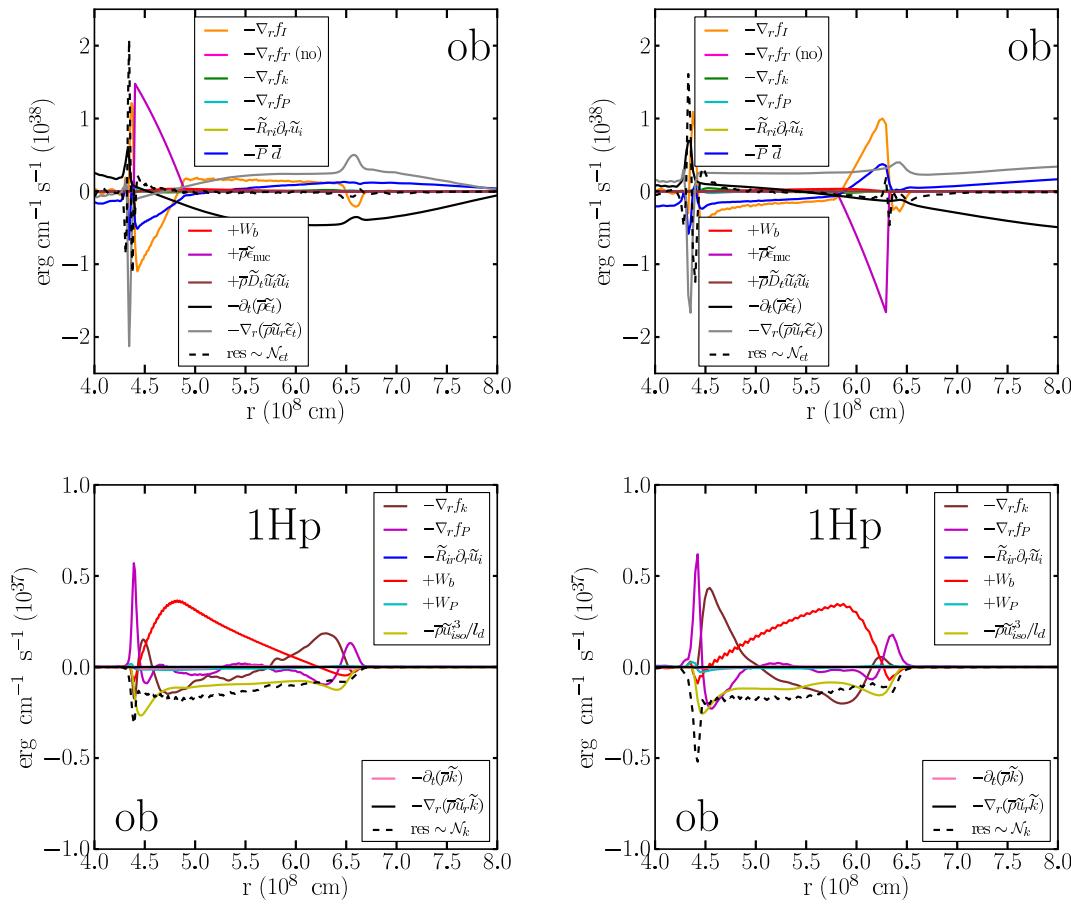


Figure 76: Mean total energy equation (upper panels) and mean turbulent kinetic energy equation (lower panels). Model with volumetric heating at the bottom of convection zone **ob.3D.1hp.vh** (left) and model with volumetric cooling at the top of convection zone **ob.3D.1hp.vc** (right).

Mean turbulent kinetic energy equations (radial + horizontal part)

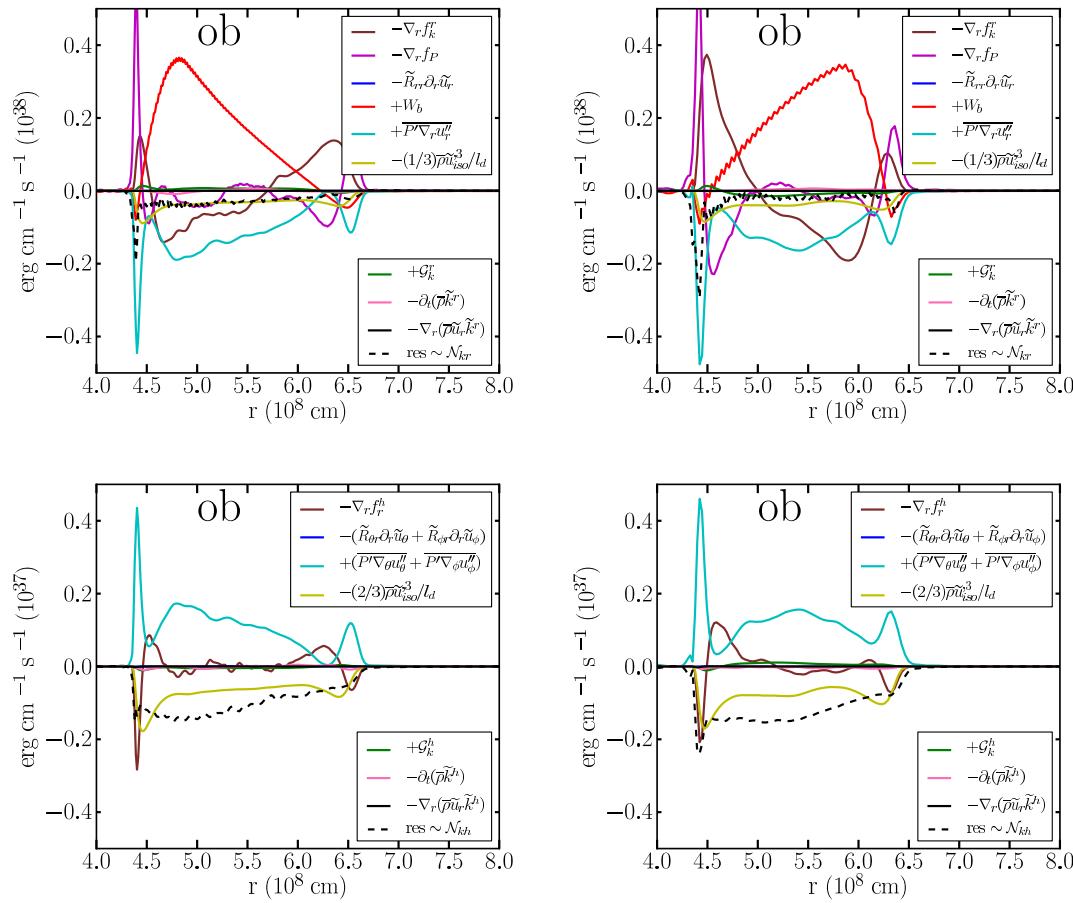


Figure 77: Radial (upper panels) and horizontal (lower panels) part of the mean turbulent kinetic energy equation. Model with volumetric heating at the bottom of convection zone ob.3D.1hp.vh (left) and model with volumetric cooling at the top of convection zone ob.3D.1hp.vc (right).

Mean turbulent mass flux and mean density-specific volume covariance equations

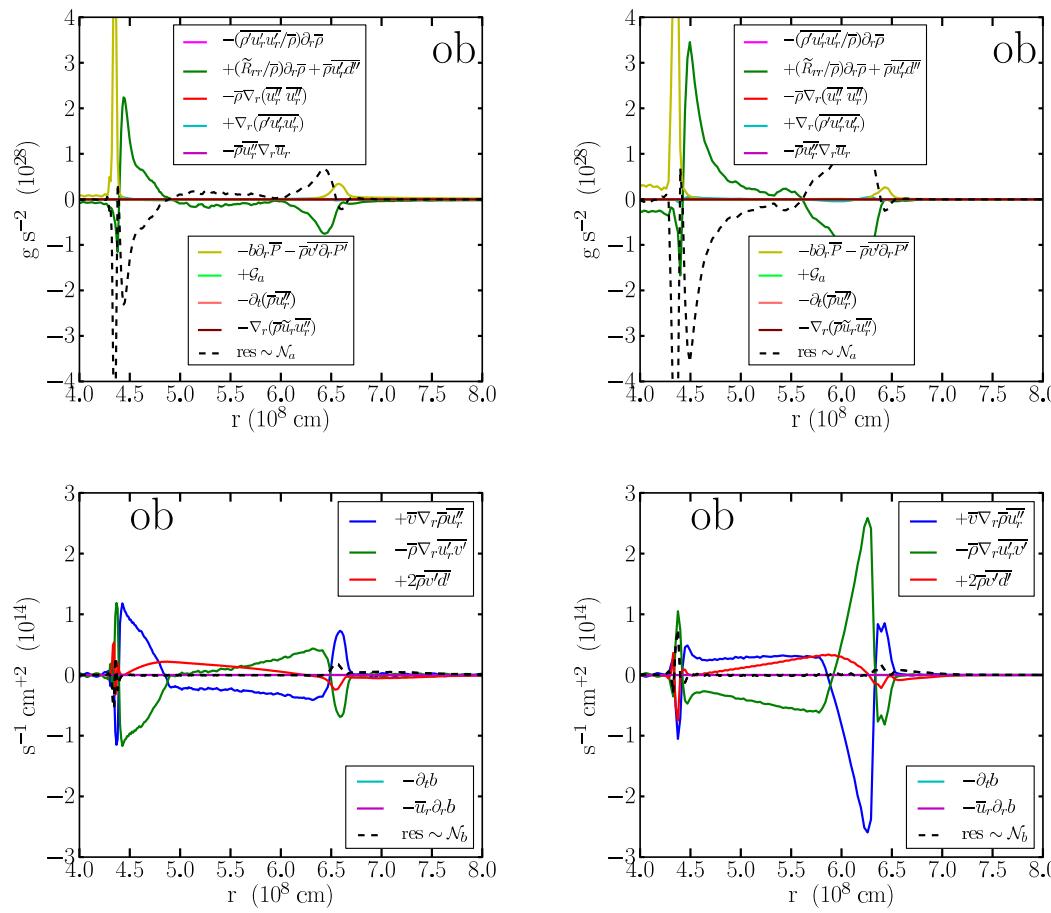


Figure 78: Mean turbulent mass flux equation (upper panels) and density-specific volume covariance equation (lower panels). Model with volumetric heating at the bottom of convection zone ob.3D.1hp.vh (left) and model with volumetric cooling at the top of convection zone ob.3D.1hp.vc (right).

Mean specific angular momentum equation and mean internal energy flux equation

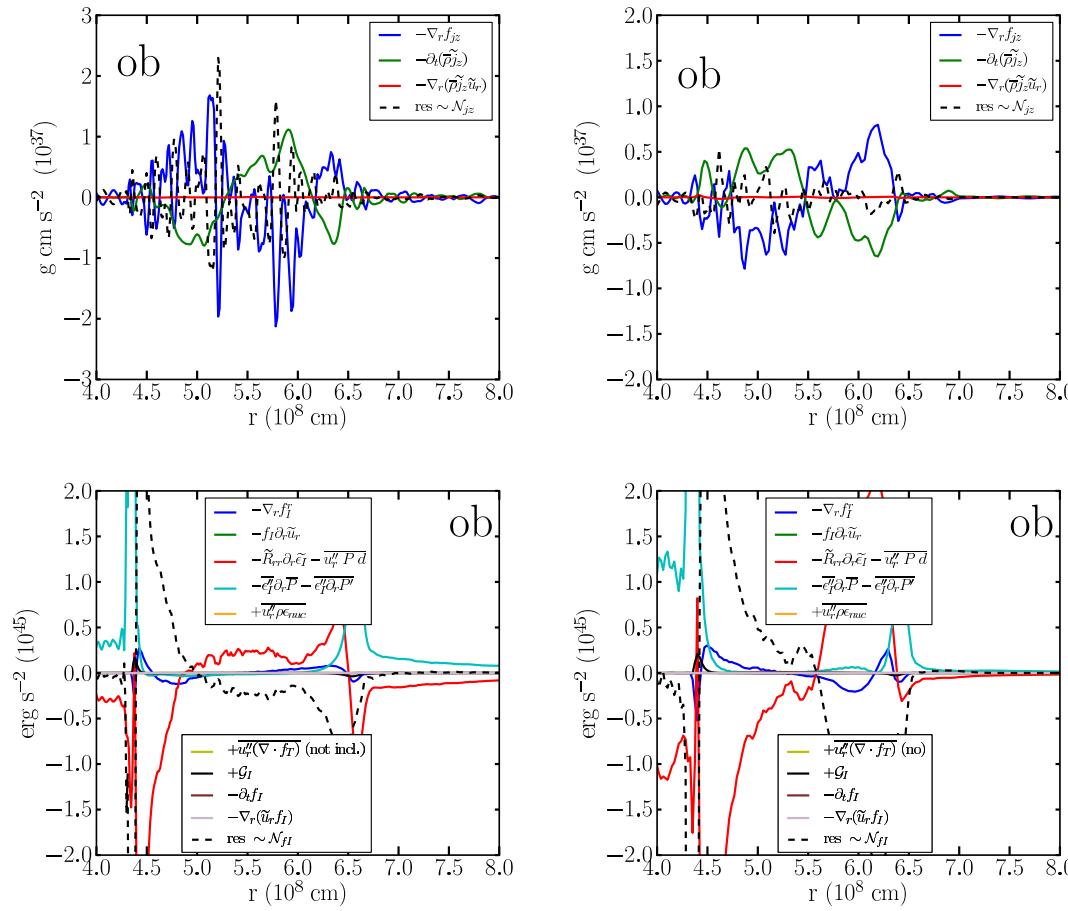


Figure 79: Mean specific angular momentum equation (upper panels) and mean turbulent internal energy flux equation (lower panels). Model with volumetric heating at the bottom of convection zone **ob.3D.1hp.vh** (left) and model with volumetric cooling at the top of convection zone **ob.3D.1hp.vc** (right).

Mean turbulent kinetic energy and mean velocities

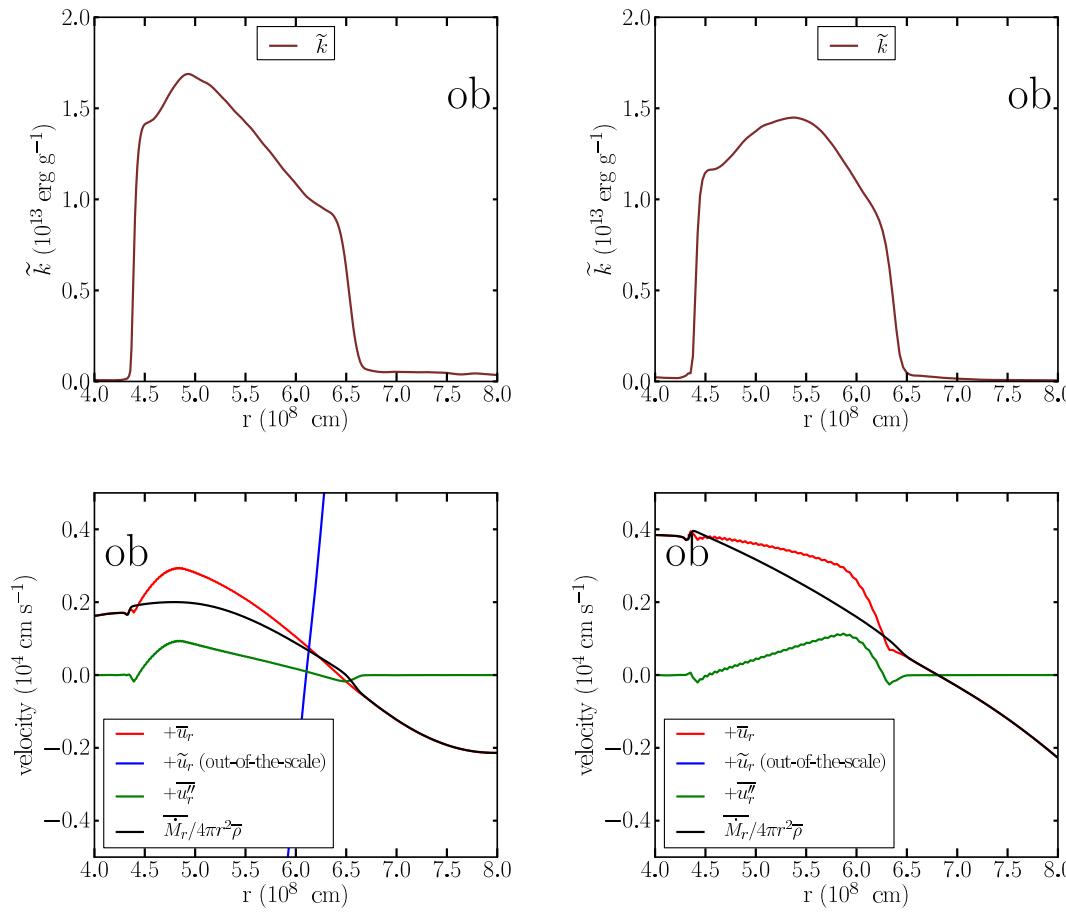


Figure 80: Mean turbulent kinetic energy (upper panels) and mean background velocities (lower panels). Model with volumetric heating at the bottom of convection zone **ob.3D.1hp.vh** (left) and model with volumetric cooling at the top of convection zone **ob.3D.1hp.vc** (right).

11 Analysis of some turbulence one-point closure models

11.1 Downgradient approximation theory background

$$\tilde{F}_i^q \sim -\Gamma_t \frac{\partial \tilde{q}}{\partial x_i} \quad (\Gamma_t \text{ is turbulence diffusivity and } \tilde{F}_i^q = \overline{\rho q'' u_i''} \text{ is a flux of } q)$$

- can be derived from a transport equation of a diffusive passive scalar (Harlow & Hirt, 1969; Daly & Harlow, 1970):

$$\partial_t \tilde{F}_i^q - \overline{u_i'' q'' \partial_t \rho} - \tilde{R}_{in} \partial_n \tilde{q} + \tilde{u}_n \overline{\rho \partial_n u_i'' q''} + \tilde{F}_n^q \partial_n \tilde{u}_i + \partial_n \overline{\rho u_n'' u_i'' q''} - \overline{u_i'' q'' \partial_n \rho u_n''} = -\overline{q'' \partial_i P} - \overline{q'' \partial_i P'} + \partial_n (\overline{\lambda \rho u_i'' \partial_n q''}) + f \tilde{F}_i^q$$

where q is the passive scalar governed by a diffusion equation $D_t q = \lambda \nabla^2 q$.

It implies, that the downgradient approximation holds only for:

- a transport of a diffusive passive scalar
- a flow in steady state ($\partial_t \tilde{F}_i^q = 0$)
- an incompressible flow ($\partial_t \rho = 0$)
- a flow with no background velocities ($\tilde{u}_i = 0$)
- a flow with no pressure-scalar correlations ($\overline{q'' \partial_i P} = \overline{q'' \partial_i P'} = 0$)
- a homogeneous flow ($\partial_n \overline{\rho u_n'' u_i'' q''} = 0$)
- an isotropic flow (decay-rate assumption: $\overline{\partial_n q'' \partial_n \rho u_i''} \sim f \tilde{F}_i^q$)

But, stellar turbulent convection is:

- stratified (not homogeneous)
- anisotropic
- compressible on expanding/contracting background

– **downgradient approximation is not suitable for modelling stellar processes**

11.2 Downgradient approximations

$$f_k = (C \rho \sqrt{\tilde{k}} l_d) \partial_r \tilde{k} \quad f_I = (C \rho \sqrt{\tilde{k}} l_d) \partial_r \tilde{\epsilon}_I \quad f_I = (C \rho \tilde{k}^2 / \varepsilon_k) \partial_r \tilde{\epsilon}_I \quad (84)$$

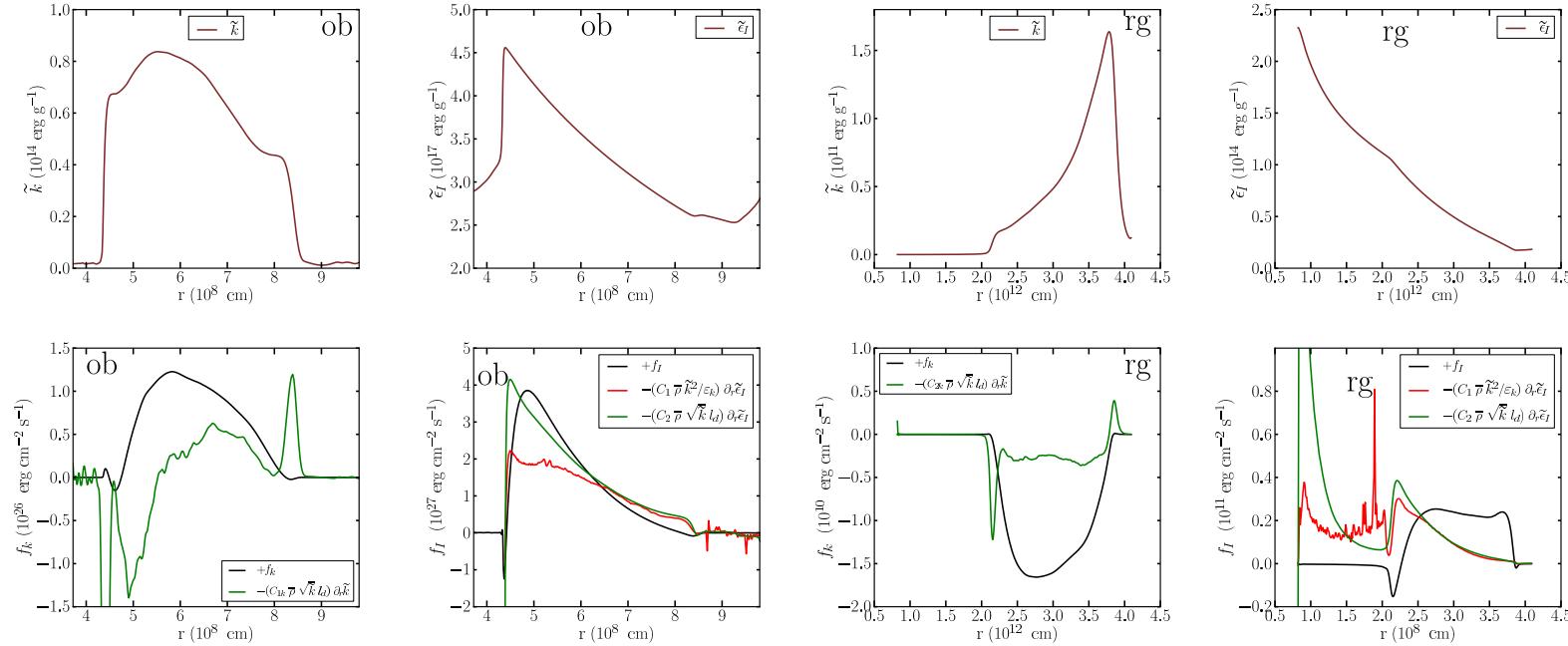


Figure 81: Profiles of mean turbulent kinetic energy and mean internal energy (upper panels) and various downgradient approximations to turbulent kinetic energy flux and internal energy flux (lower panels) derived from oxygen burning shell model ob.3D.mr (ob) and red giant envelope convection rg.3D.mr (rg). l_d is dissipation length scale and C is model constant.

11.3 Various approximations taken from Besnard-Harlow-Rauenzahn (BHR) model

$$\rho' u'_r u'_r = C_{1a} \frac{l_d}{\sqrt{k}} \tilde{R}_{rr} \partial_r \bar{u''}_r \quad v' \partial_r P' = -C_{2a} \frac{\sqrt{k}}{l_d} \bar{u''}_r \quad v' u'_r = -C_{1b} \frac{l_d}{\sqrt{k}} \frac{\tilde{R}_{rr}}{\bar{\rho}} \frac{\partial}{\partial r} \left(\frac{1+b}{\bar{\rho}} \right) \quad v' d' = -C_{2b} \frac{\sqrt{k}}{l_d} \frac{b}{\bar{\rho}}$$

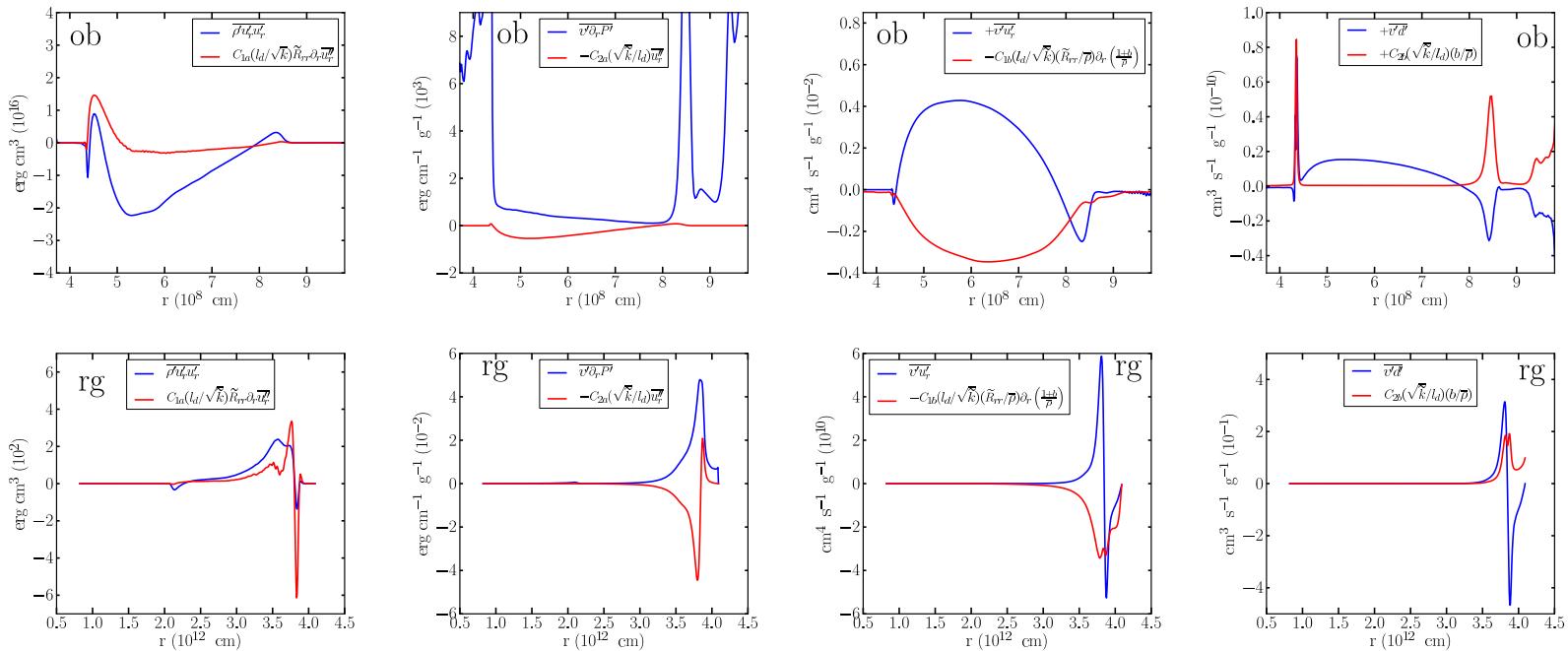


Figure 82: Various approximations taken from Besnard-Harlow-Rauenzahn (BHR) model derived from oxygen burning shell model `ob.3D.mr` (ob) and red giant envelope convection `rg.3D.mr` (rg). l_d is dissipation length scale and C is model constant.

11.4 Quasi-normal approximation and decay-rate assumption model

$$\begin{aligned} \overline{a'b'c'd'} &= \overline{a'b'} \overline{c'd'} + \overline{a'c'} \overline{b'd'} + \overline{a'd'} \overline{b'c'} \\ a''\widetilde{b''c''d''} &= \widetilde{a''b''} \widetilde{c''d''} + \widetilde{a''c''} \widetilde{b''d''} + \widetilde{a''d''} \widetilde{b''c''} \end{aligned}$$

$$\overline{a'b'} = (l_d^2/\Delta) \overline{\partial_k a' \partial_k b'} \quad (\text{original formulations}) \quad (85)$$

$$\widetilde{a''b''} = (l_d^2/\Delta) \overline{\partial_k a'' \partial_k b''} \quad (\text{assumed Favre equivalents}) \quad (86)$$

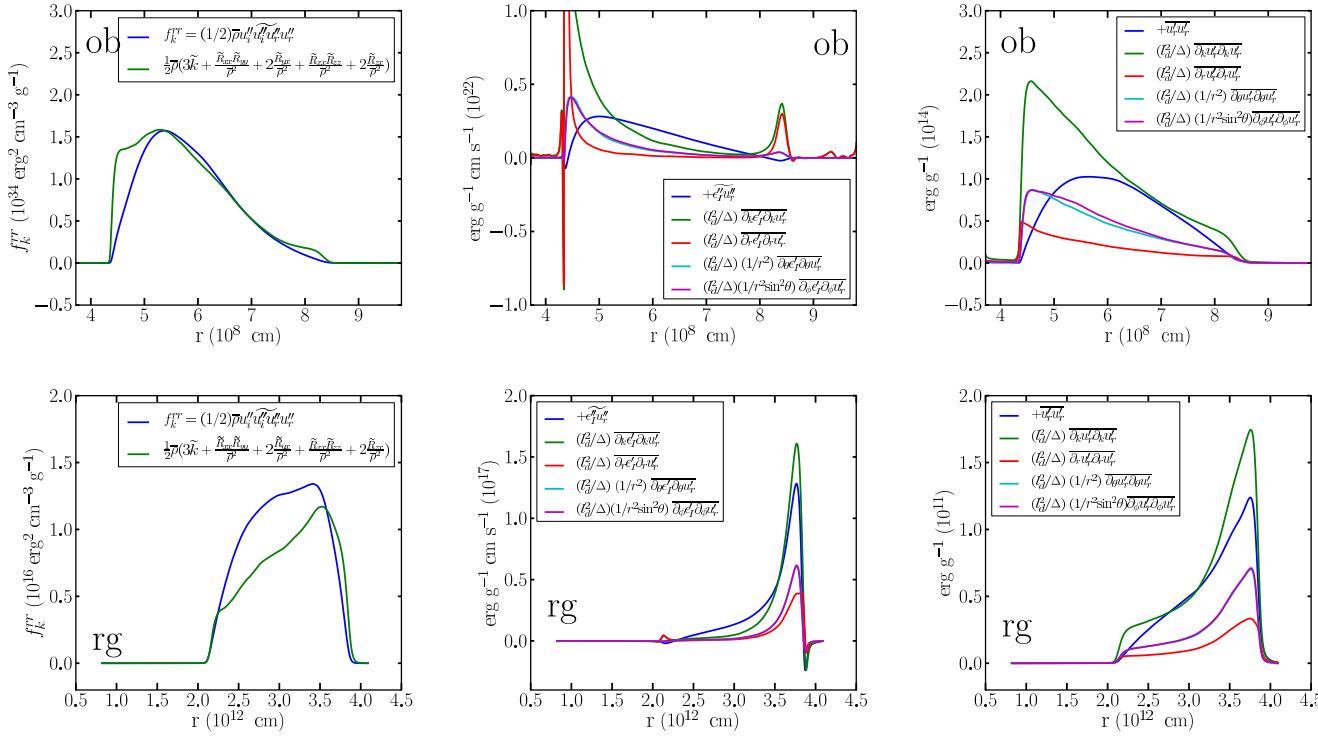


Figure 83: Quasi-normal approximations (left panels) and decay-rate assumption models (middle, right panels) derived from oxygen burning shell model ob.3D.mr (ob) and red giant envelope convection rg.3D.mr (rg).

11.5 Integral models

$$f_I = \int (\epsilon_{\text{nuc}} + \varepsilon_k/\bar{\rho} - \bar{P} \bar{d}/\bar{\rho} - W_P/\bar{\rho} - T \dot{\bar{s}}) dr \quad f_k = \int (-(f_I(\Gamma_3 - 1) - f_P)) / ((\Gamma_3 - \Gamma_1 - 1) H_P) - \varepsilon_k - \nabla_r f_P + W_P dr$$

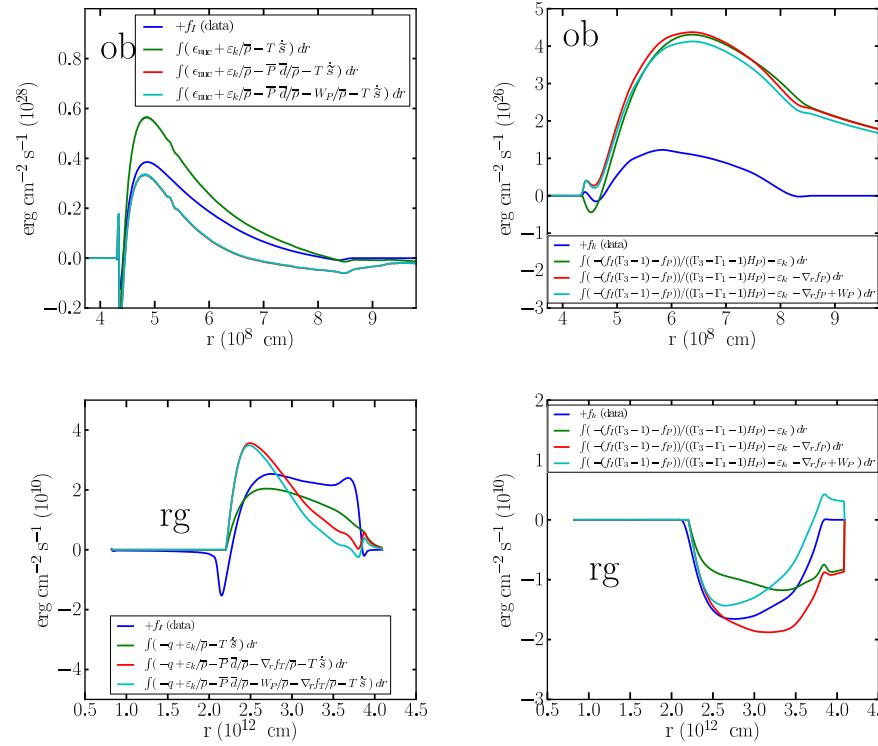


Figure 84: Integral models for internal energy flux f_I (left) and turbulent kinetic energy flux (right) derived from oxygen burning shell model ob.3D.mr (ob) and red giant envelope convection rg.3D.mr (rg).

12 Fourier scale analysis

We perform scale analysis on fluctuation correlations containing two constituents by using Fourier analysis and taking advantage of Parceval's theorem. If $a''(r, \theta, \phi)\delta(r')$ and $b''(r, \theta, \phi)\delta(r')$ are real-valued functions (in our case fluctuations in a two dimensional plane at radius r') and their Fourier transforms are $\widehat{a''}$ and $\widehat{b''}$ then “energy” contribution from large and small scales to horizontally averaged correlation $a''b''$ can be calculated as:

$$\begin{aligned} E(k) &= \frac{1}{\Delta\Omega} \int_{\Omega} a''b'' d\Omega = \int_k \widehat{a''}(k) \widehat{b''}^*(k) dk = \\ &= \underbrace{\int_{k \leq k_T} \widehat{a''}(k) \widehat{b''}^*(k) dk}_{\text{large scales}} + \underbrace{\int_{k > k_T} \widehat{a''}(k) \widehat{b''}^*(k) dk}_{\text{small scales}} \end{aligned} \quad (87)$$

where this integral is evaluated by summing the integrand over spherical shells of constant radius $k = \sqrt{(k_\theta^2 + k_\phi^2)}$ and unit wavenumber. k_T is a threshold wave number which separates large and small scales. Ω is our two-dimensional cut domain.

The angular size of a structure in a horizontal plane can be at a given radius and wave number k expressed as $l \sim N/k$, where N is the angular size of simulated wedge. It means that in a 45° wedge simulation will structures at wave number $k = 10$ have approximately size 4.5° .

For a separation of contribution from large and small scales to a given correlation field, we choose a length scale equivalent to $1 H_P$. This number is close to average vertical correlation length scales for u'_r, ρ', P' in middle of convection zones calculated by [Viallet et al. \[2013\]](#). It is about 1.5×10^8 cm in the $2 H_P$ oxygen burning models and 3×10^{11} cm in $7 H_P$ red giant models. Corresponding separation wave numbers k_T are 4 for the oxygen case and 11 for the red giant case. These separation scales should be considered as a lower limit for a size of actual large scales, as we know that they are elongated in radial direction [[Meakin and Arnett, 2007](#)]. Here, we Fourier transform our data in two dimensional horizontal planes and essentially looking only at horizontal scales.

We present our scale analysis in a form of the cumulative Fourier spectra, which are calculated according the formula:

$$\overline{E}_c(k) = \sum_{i \leq k} \overline{E(i)/E_t} \quad (88)$$

where i is a wave number and $E(i)$ defined by Eq. 87. E_t is total energy of a correlation field or in other words a horizontally averaged value of the correlation field. The over bar represent time averaging of instantaneous values. Such a spectrum shows how big energy contribution to a field comes from first k Fourier modes.

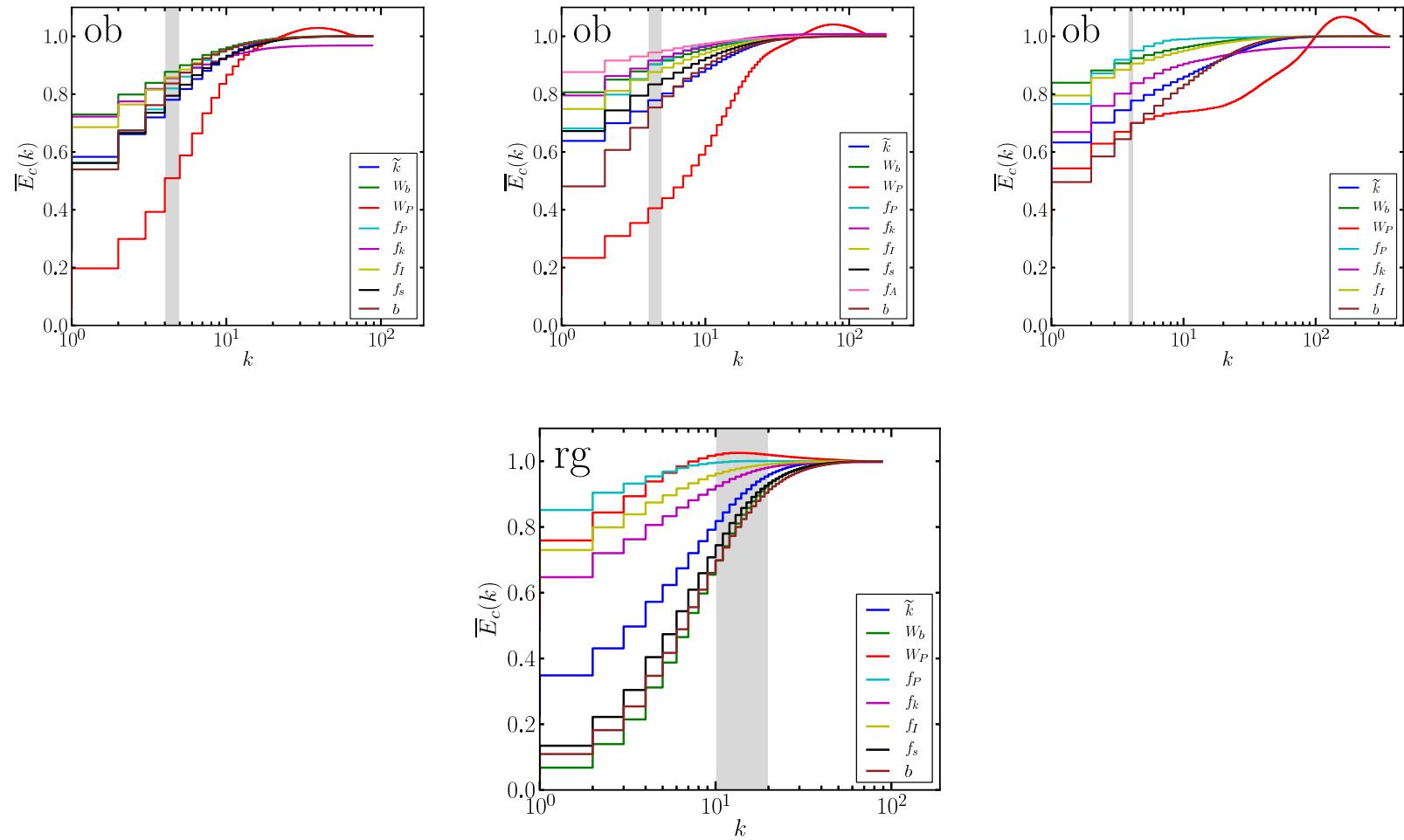


Figure 85: Cumulative Fourier spectra of relevant mean fields derived from oxygen burning shell models (upper panels) ob.3D.lr (left), ob.3D.mr (middle) and ob.3D.hr (right) derived at radius where corresponding mean field has a maximum value. The same is done for red giant convection model (lower panel) rg.3D.lr. The shaded vertical lines separates cumulative contributions from large and small scales.

13 Properties of our hydrogen injection flash and core helium flash data

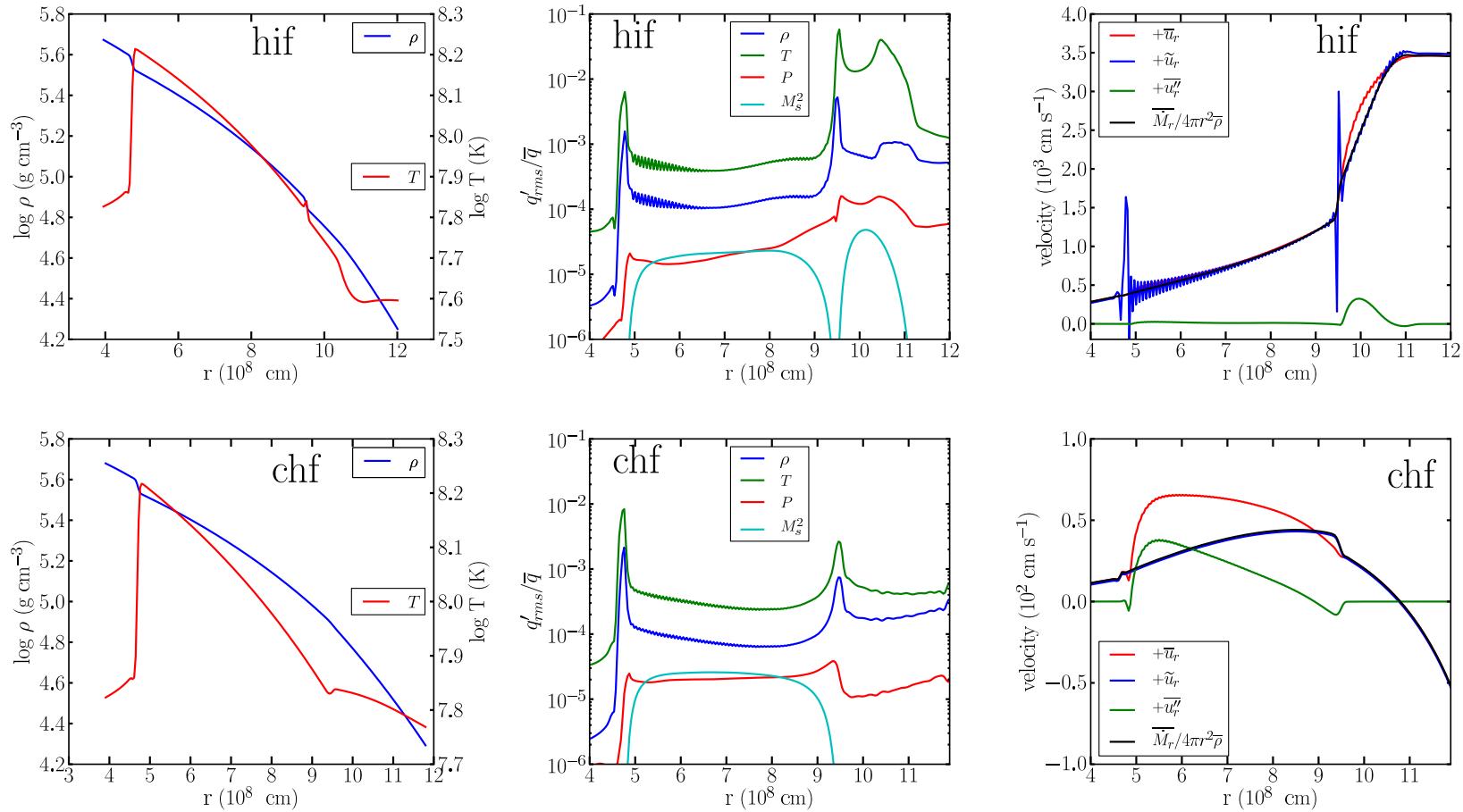


Figure 86: Properties of our data. Model hif.3D (upper panels) and model chf.3D (lower panels).

13.1 Snapshots of turbulent kinetic energy in a meridional plane

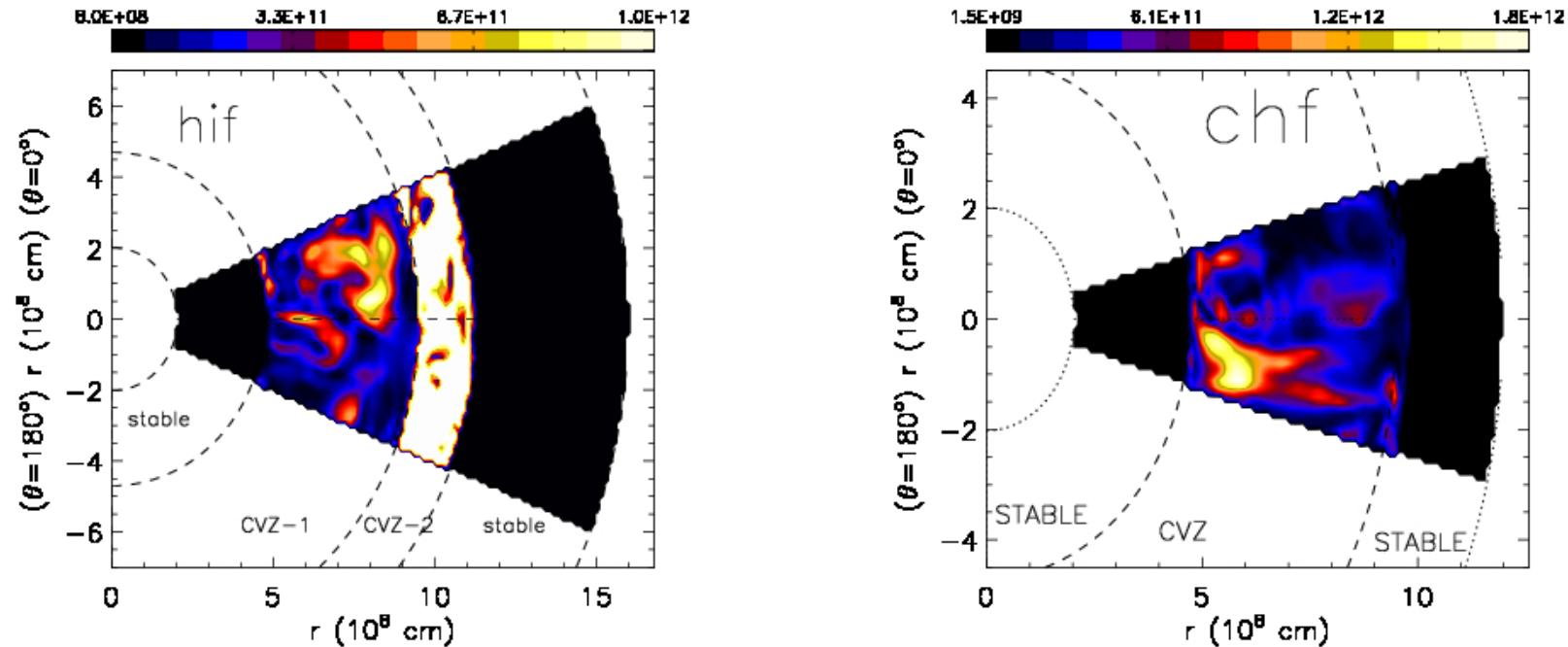


Figure 87: Snapshots of turbulent kinetic energy (in erg g^{-1}) in a meridional plane.

13.2 Summary of the hydrogen injection flash and core helium flash simulations and their properties

Parameter	hif.3D	hif.3D	chf.3D
Grid zoning	375×45^2	375×45^2	270×30^2
$r_{\text{in}}, r_{\text{out}}$ (10^8 cm)	2., 16.	2., 16.	2., 12.
$\Delta\theta, \Delta\phi$	45°		30°
Convection zone	He-burning (CVZ-1)	CNO-burning (CVZ-2)	He-burning (CVZ)
$r_{\text{in}}^c, r_{\text{out}}^c$ (10^8 cm)	4.7, 9.55	9.55, 11.3	4.7, 9.4
CZ stratification (H_p)	2.4	1.3	2.3
Δt_{av} (s)	4000	4000	18000
v_{rms} (10^5 cm/s)	8.2	11.8	8.5
τ_{conv} (s)	1180	290	1100
$P_{\text{turb}}/P_{\text{gas}}$ (10^{-5})	2.6	3.7	3.3
L_{heat} (10^{43} erg/s)	1.2	1.8	1.2
L_d (10^{41} erg/s)	5.3	6.1	6.
l_d (10^8 cm)	5.6	2.9	4.8
τ_d (s)	337.4	123.6	281.9
τ_{dr} (s)	719.7	175.8	659.7
τ_{dh} (s)	211.2	116.1	142.5

Table 8: boundaries of computational domain $r_{\text{in}}, r_{\text{out}}$; boundaries of convection zone at bottom and top r_b^c, r_t^c ; angular size of computational domain $\Delta\theta, \Delta\phi$; depth of convection zone “CZ stratification” in pressure scale height H_P ; averaging timescale of mean fields analysis Δt_{av} ; global rms velocity v_{rms} ; convective turnover timescale τ_{conv} ; average ratio of turbulent ram pressure and gas pressure $p_{\text{turb}}/p_{\text{gas}}$; total luminosity of the hydrodynamic model L ; total rate of kinetic energy dissipation L_d ; dissipation length-scale l_d ; turbulent kinetic energy dissipation time-scale τ_d ; radial turbulent kinetic energy dissipation time-scale τ_{dr} ; horizontal turbulent kinetic energy dissipation time-scale τ_{dh} . The numerical values may vary in time up to 20% due to limited amount of data for averaging out the time dependence.

14 Profiles and integral budgets of mean fields equations

14.1 Mean continuity equation

$$\tilde{D}_t \bar{\rho} = -\bar{\rho} \tilde{d} + \mathcal{N}_\rho \quad (89)$$

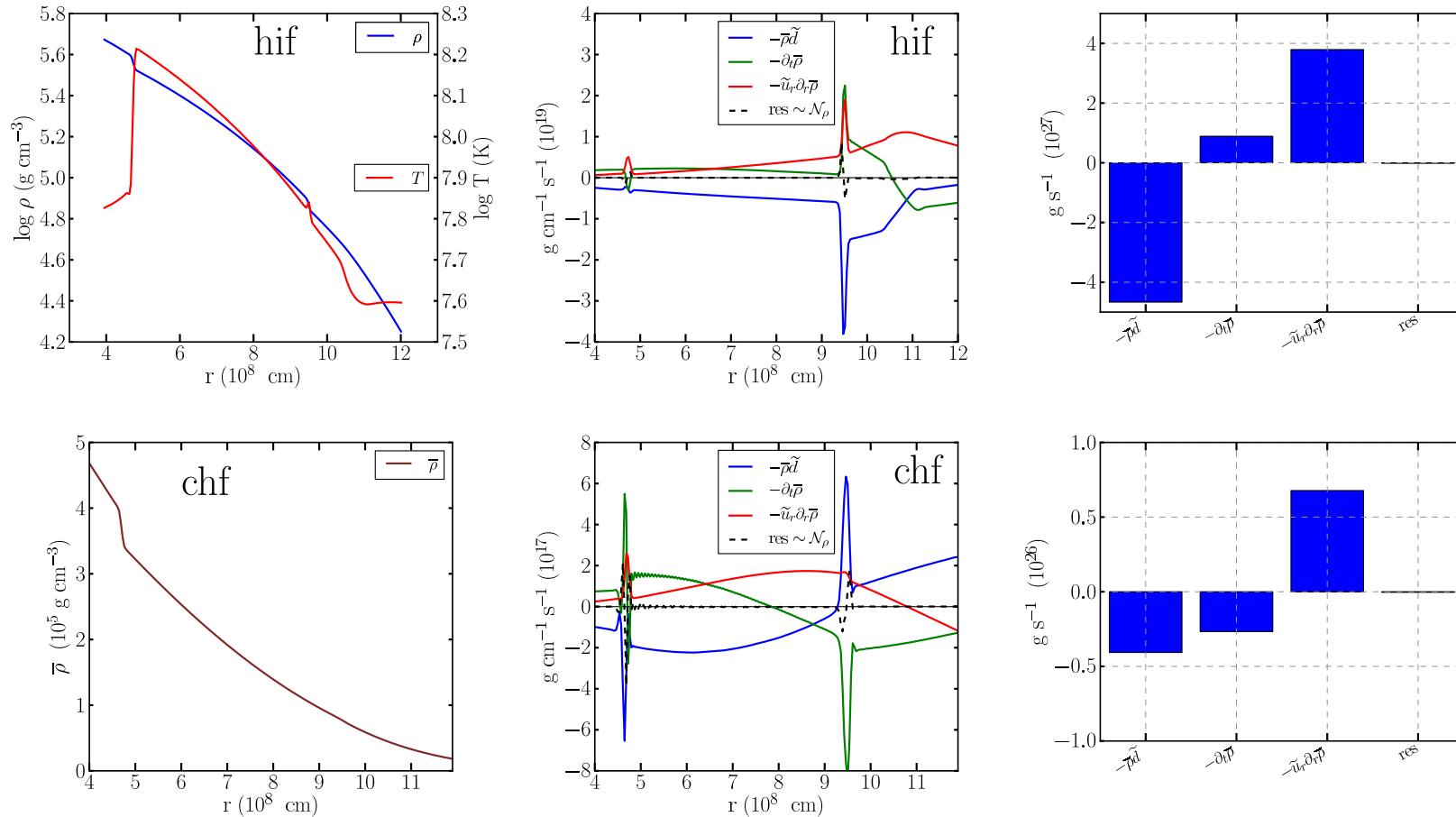


Figure 88: Mean continuity equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.2 Mean radial momentum equation

$$\bar{\rho} \tilde{D}_t \tilde{u}_r = -\nabla_r \tilde{R}_{rr} - \overline{G_r^M} - \partial_r \overline{P} + \bar{\rho} \tilde{g}_r + \mathcal{N}_{ur} \quad (90)$$

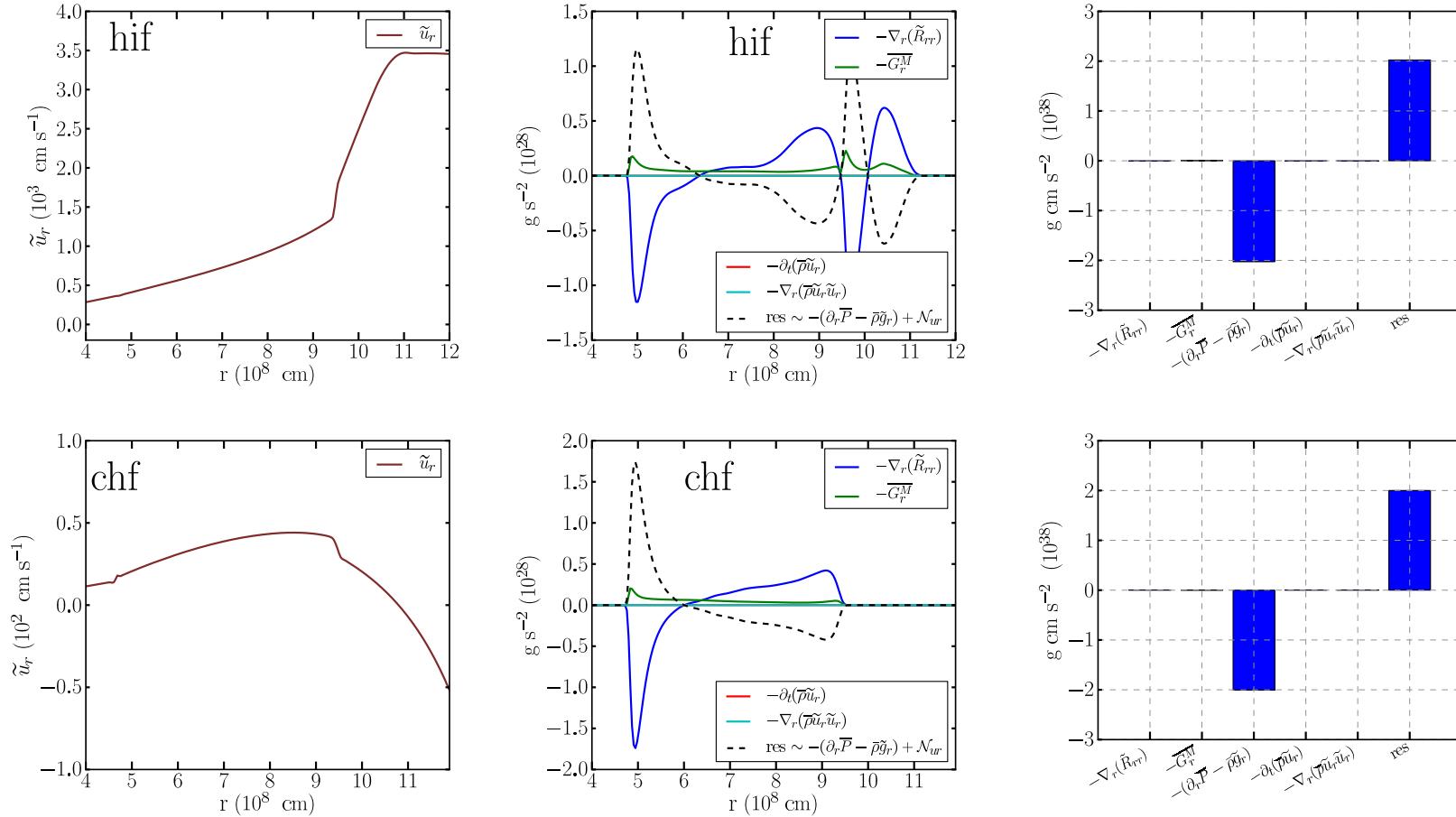


Figure 89: Mean radial momentum equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.3 Mean azimuthal momentum equation

$$\bar{\rho} \tilde{D}_t \tilde{u}_\theta = -\nabla_r \tilde{R}_{\theta r} - \overline{G_\theta^M} - (1/r) \overline{\partial_\theta P} + \mathcal{N}_{u\theta} \quad (91)$$

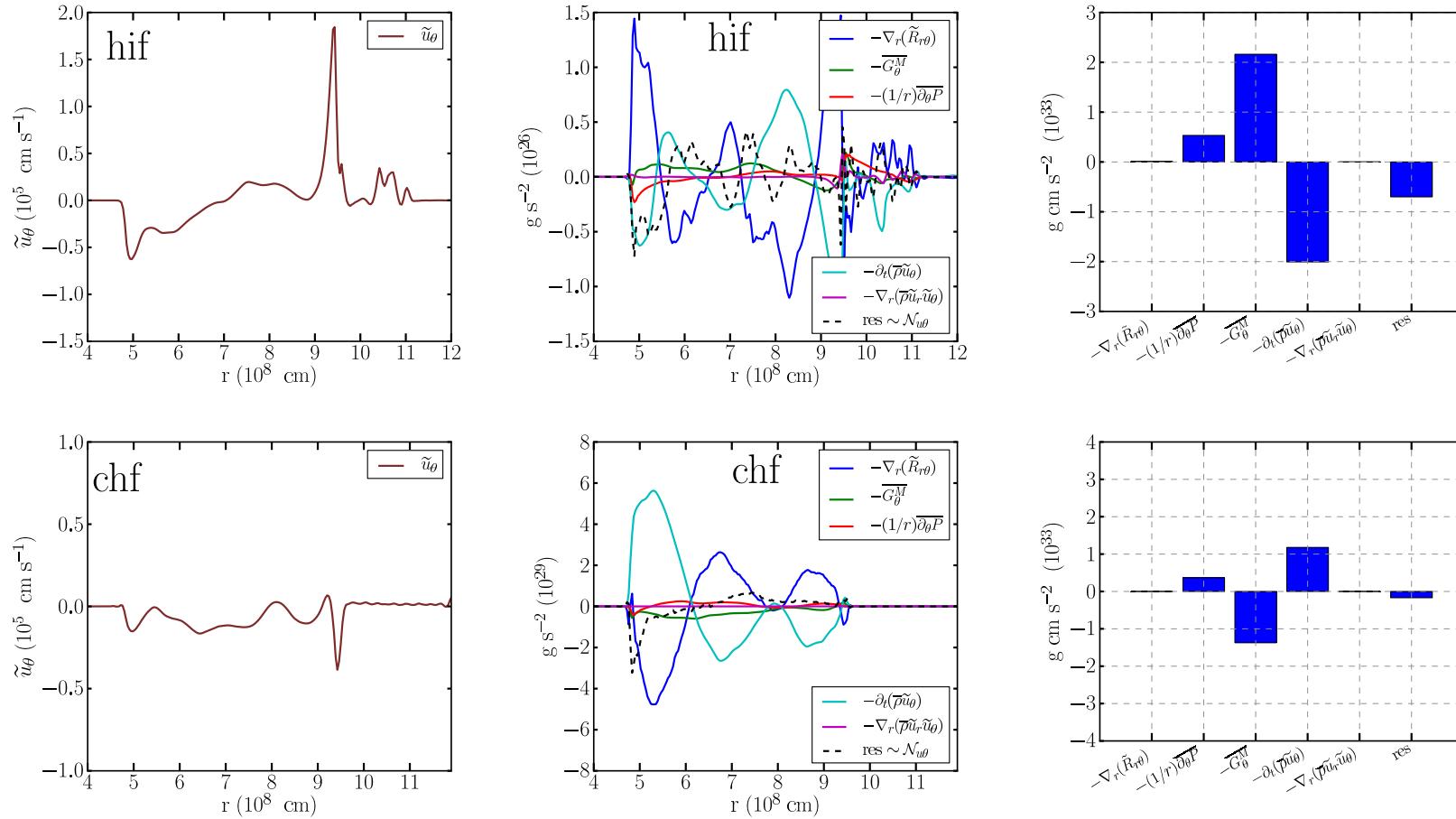


Figure 90: Mean azimuthal momentum equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.4 Mean polar momentum equation

$$\bar{\rho} \tilde{D}_t \tilde{u}_\phi = -\nabla_r \tilde{R}_{\phi r} - \overline{G_\phi^M} + \mathcal{N}_{u\phi} \quad (92)$$

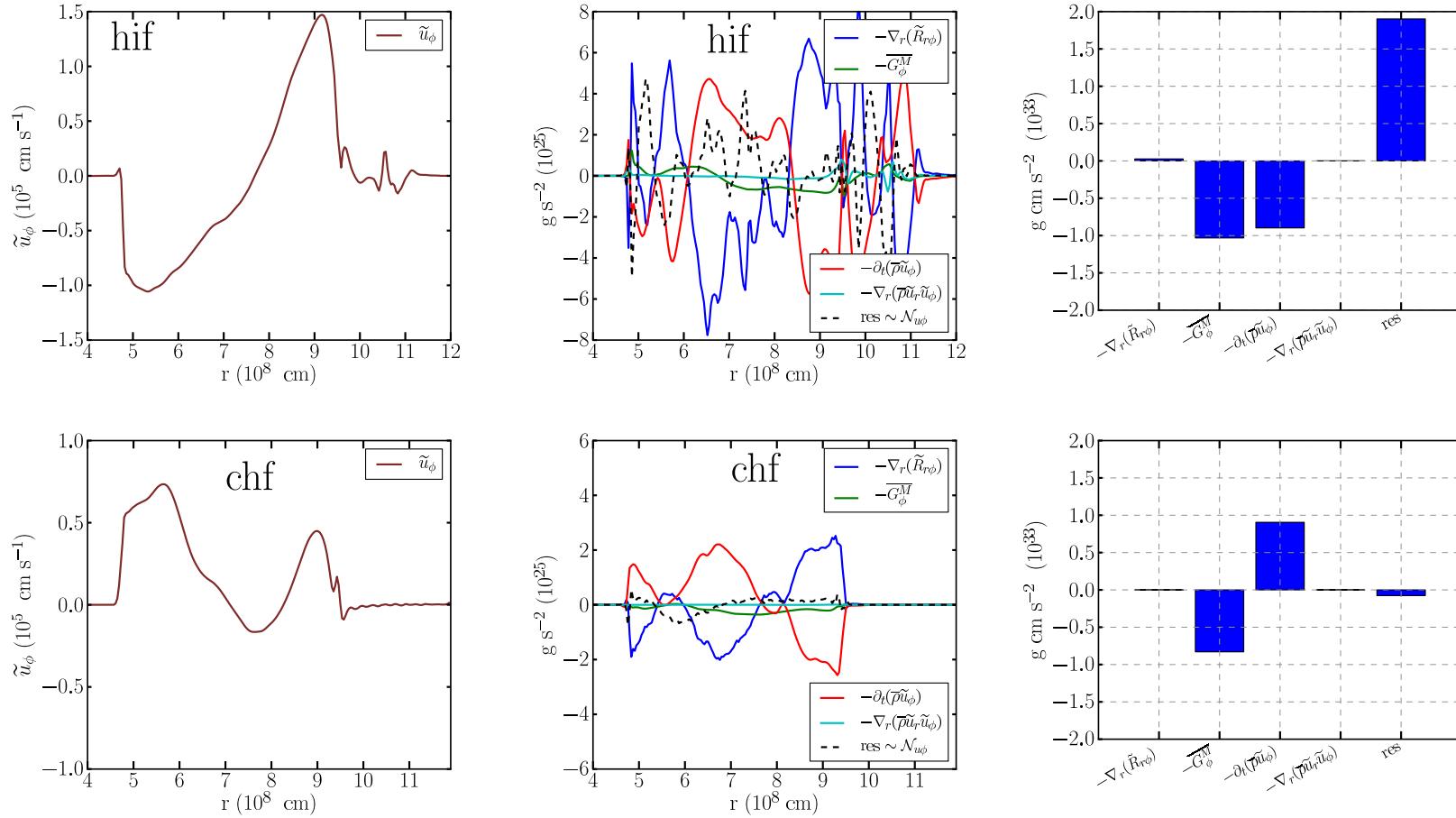


Figure 91: Mean polar momentum equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.5 Mean internal energy equation

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_I = -\nabla_r(f_I + f_T) - \bar{P} \bar{d} - W_P + S + \mathcal{N}_{\epsilon I} \quad (93)$$

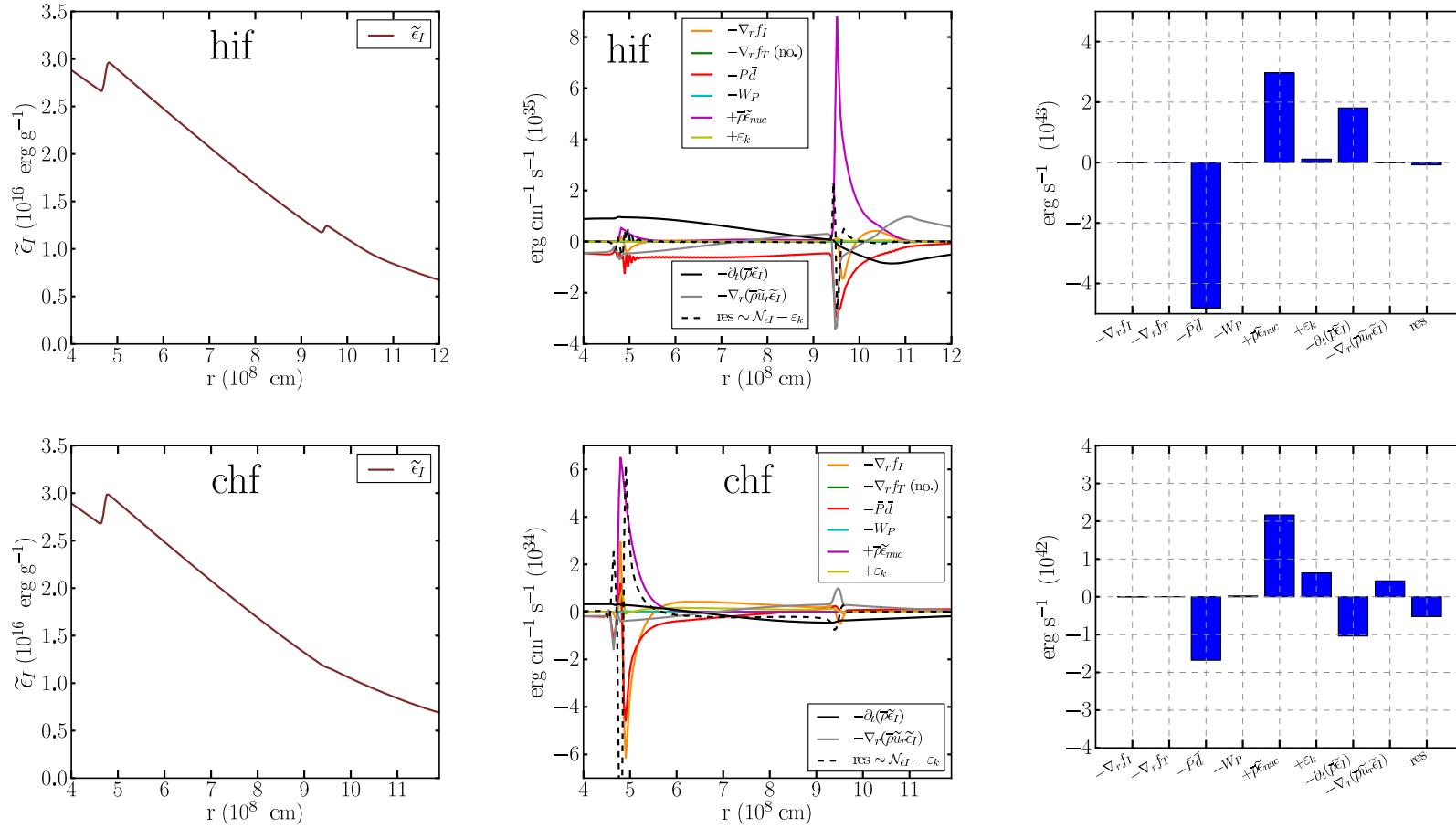


Figure 92: Mean internal energy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.6 Mean kinetic energy equation

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_k = -\nabla_r(f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + W_P + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) + \mathcal{N}_{ek} \quad (94)$$

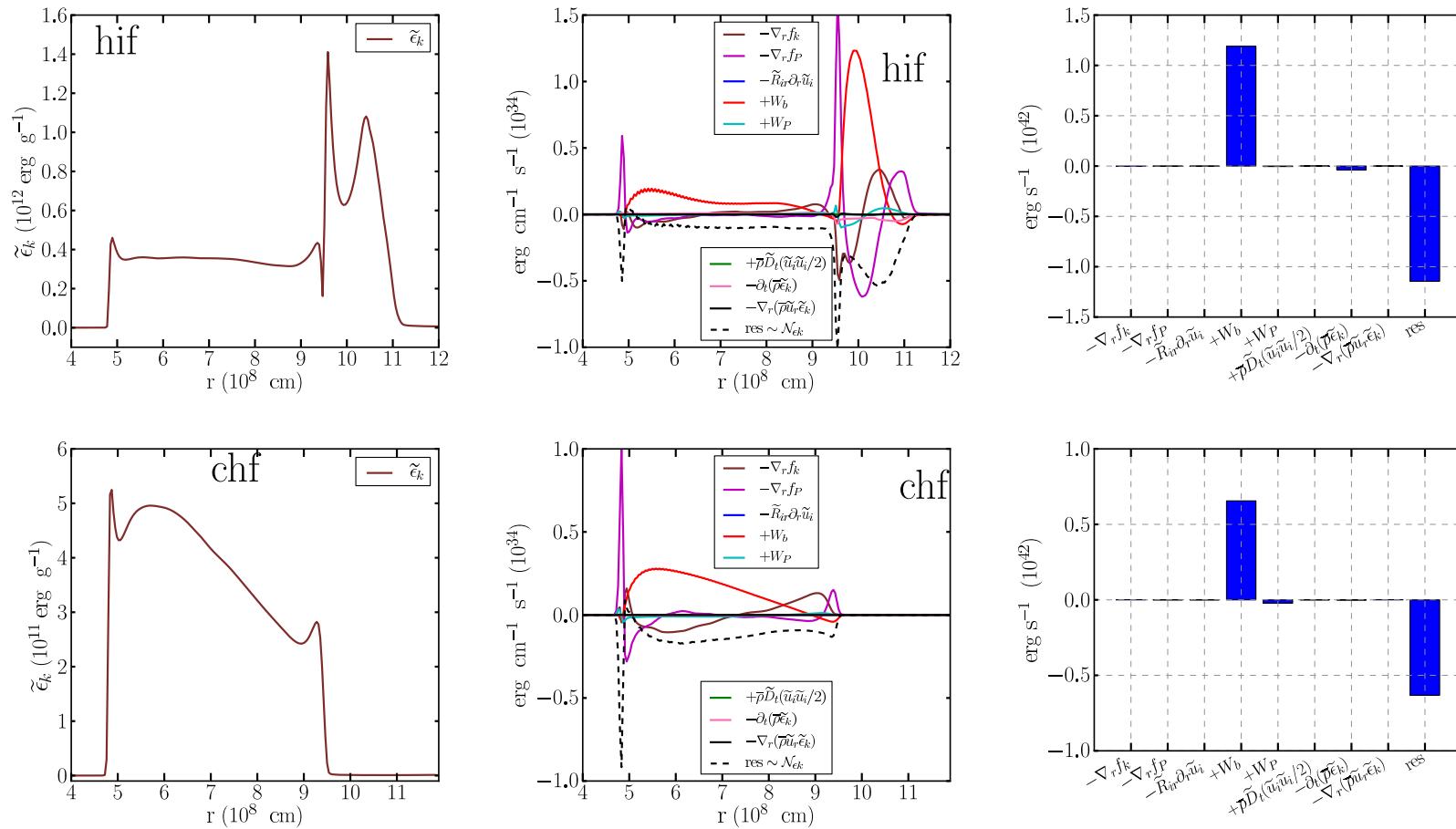


Figure 93: Mean kinetic energy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.7 Mean total energy equation

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_t = -\nabla_r(f_I + f_T + f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i - \bar{P} \bar{d} + W_b + \mathcal{S} + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) + \mathcal{N}_{et} \quad (95)$$

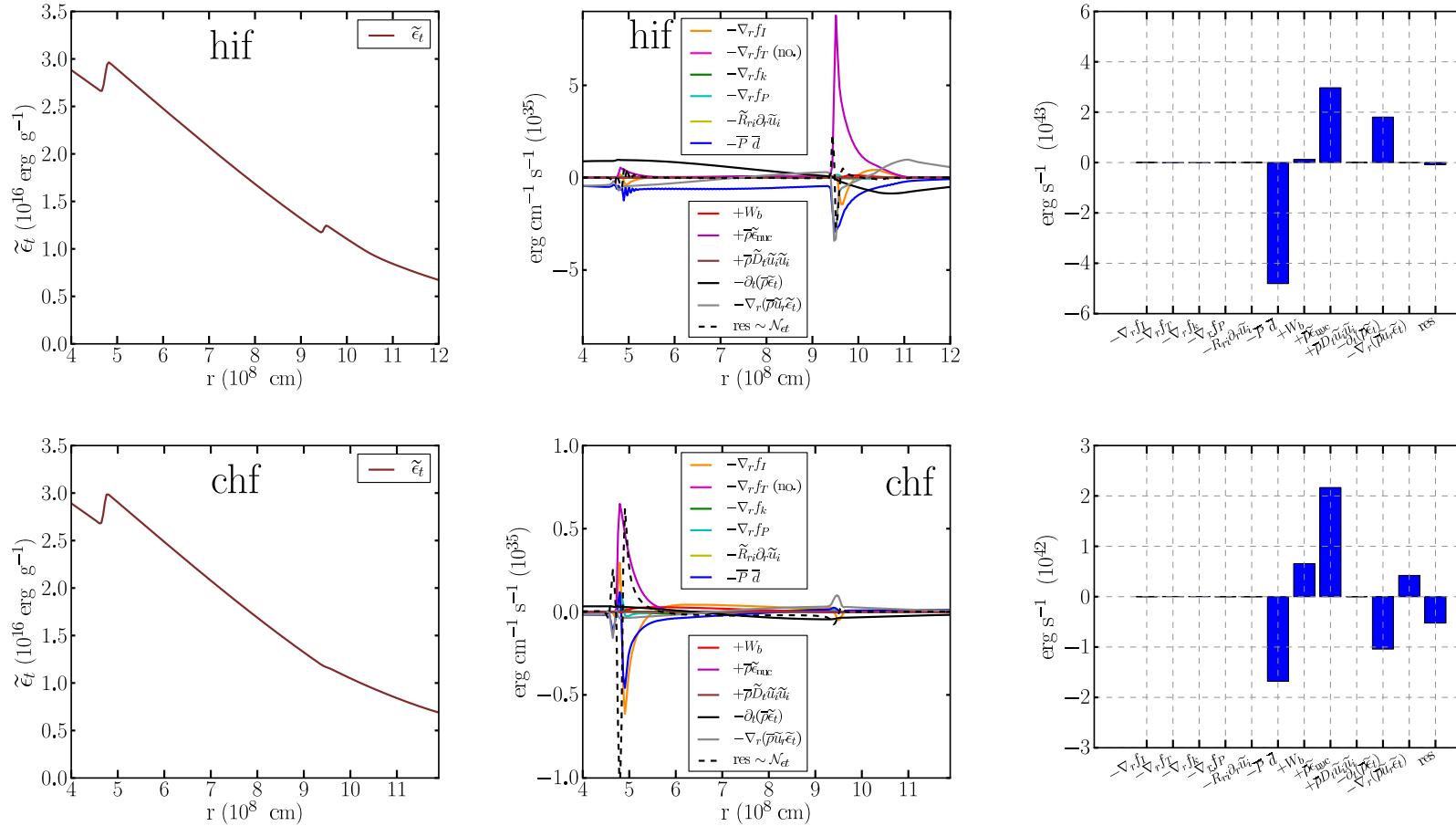


Figure 94: Mean total energy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.8 Mean entropy equation

$$\bar{\rho} \tilde{D}_t \tilde{s} = -\nabla_r f_s - (\nabla \cdot F_T)/\bar{T} + \bar{\mathcal{S}}/\bar{T} + \mathcal{N}_s \quad (96)$$

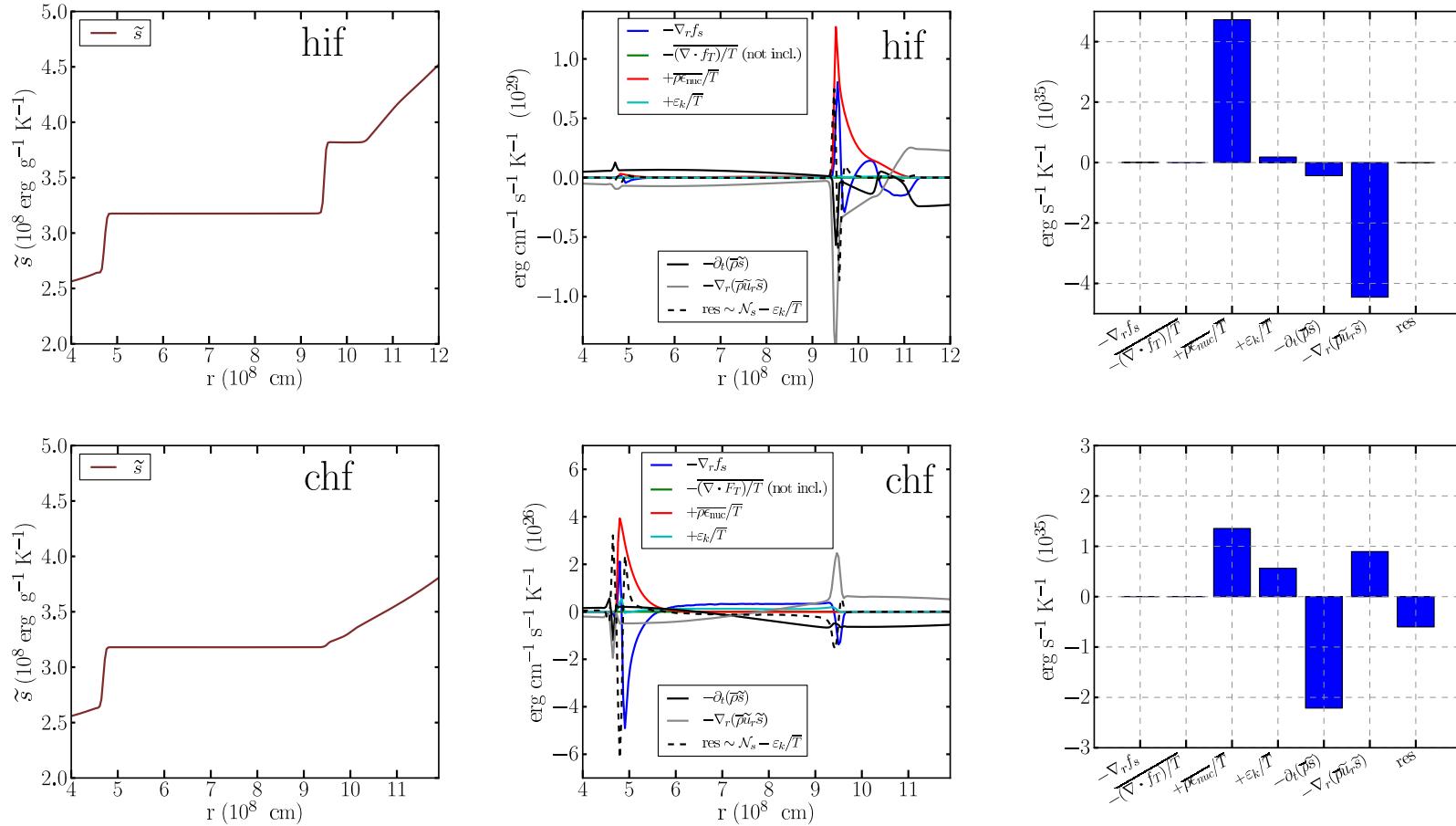


Figure 95: Mean entropy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.9 Mean pressure equation

$$\bar{D}_t \bar{P} = -\nabla_r f_P - \Gamma_1 \bar{P} \bar{d} + (1 - \Gamma_1) W_P + (\Gamma_3 - 1) \mathcal{S} + (\Gamma_3 - 1) \nabla_r f_T + \mathcal{N}_P \quad (97)$$

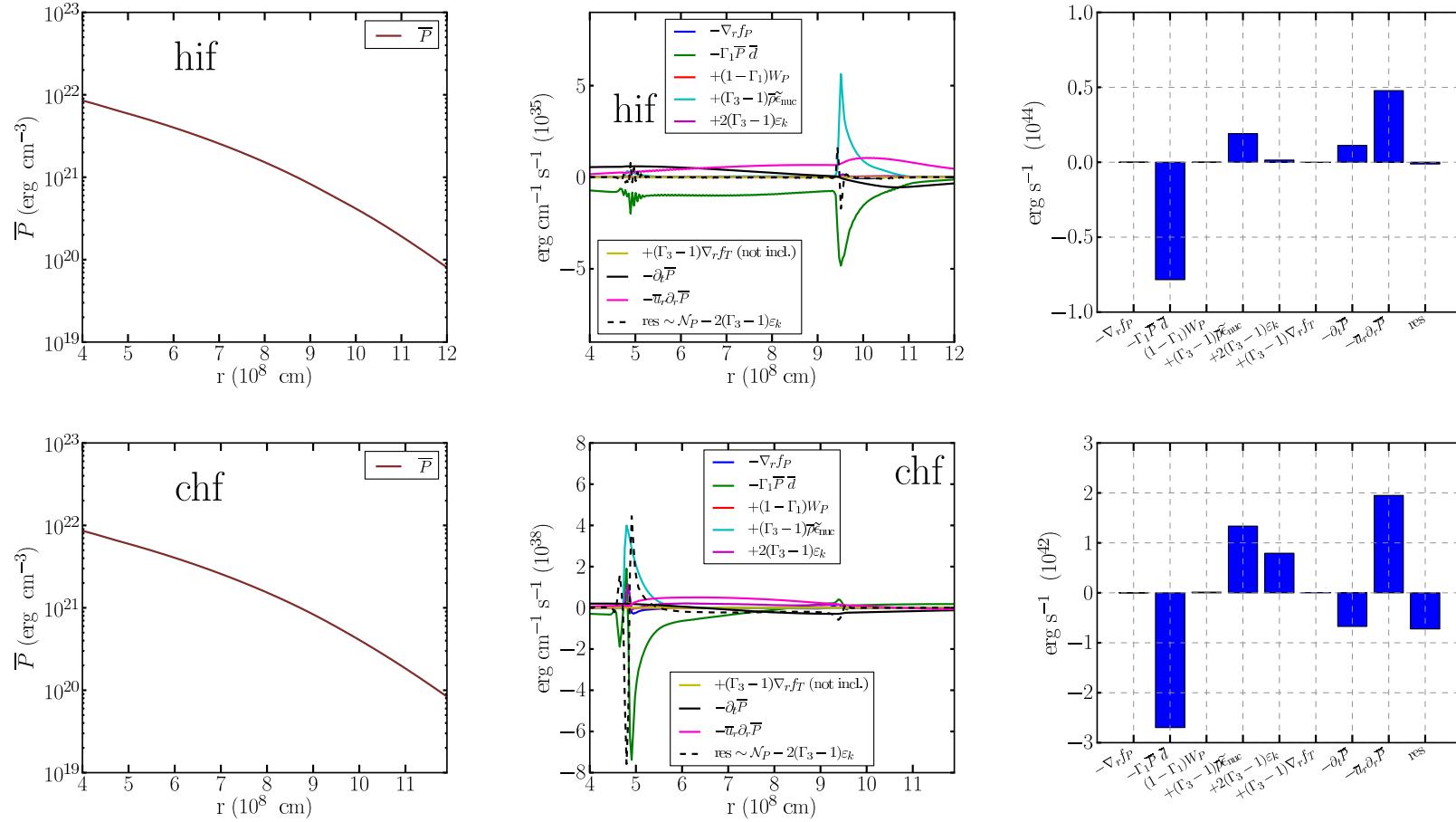


Figure 96: Mean pressure equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.10 Mean enthalpy equation

$$\bar{\rho} \tilde{D}_t \tilde{h} = -\nabla_r f_h - \Gamma_1 \bar{P} \bar{d} - \Gamma_1 W_P + \Gamma_3 \mathcal{S} + \Gamma_3 \nabla_r f_T + \mathcal{N}_h \quad (98)$$

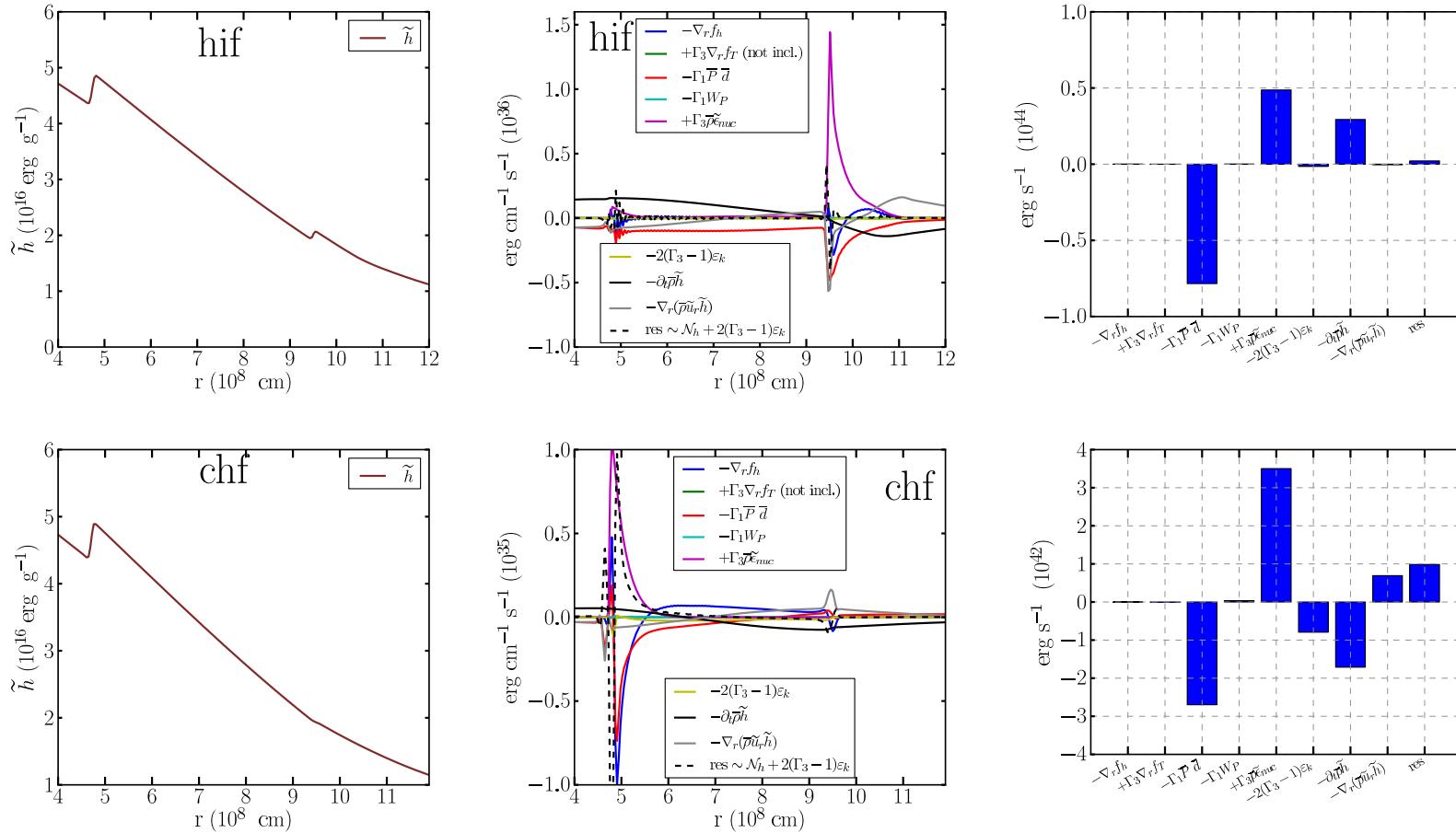


Figure 97: Mean enthalpy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.11 Mean angular momentum equation (z-component)

$$\bar{\rho} \tilde{D}_t \tilde{j}_z = -\nabla_r f_{jz} + \mathcal{N}_{jz} \quad (99)$$

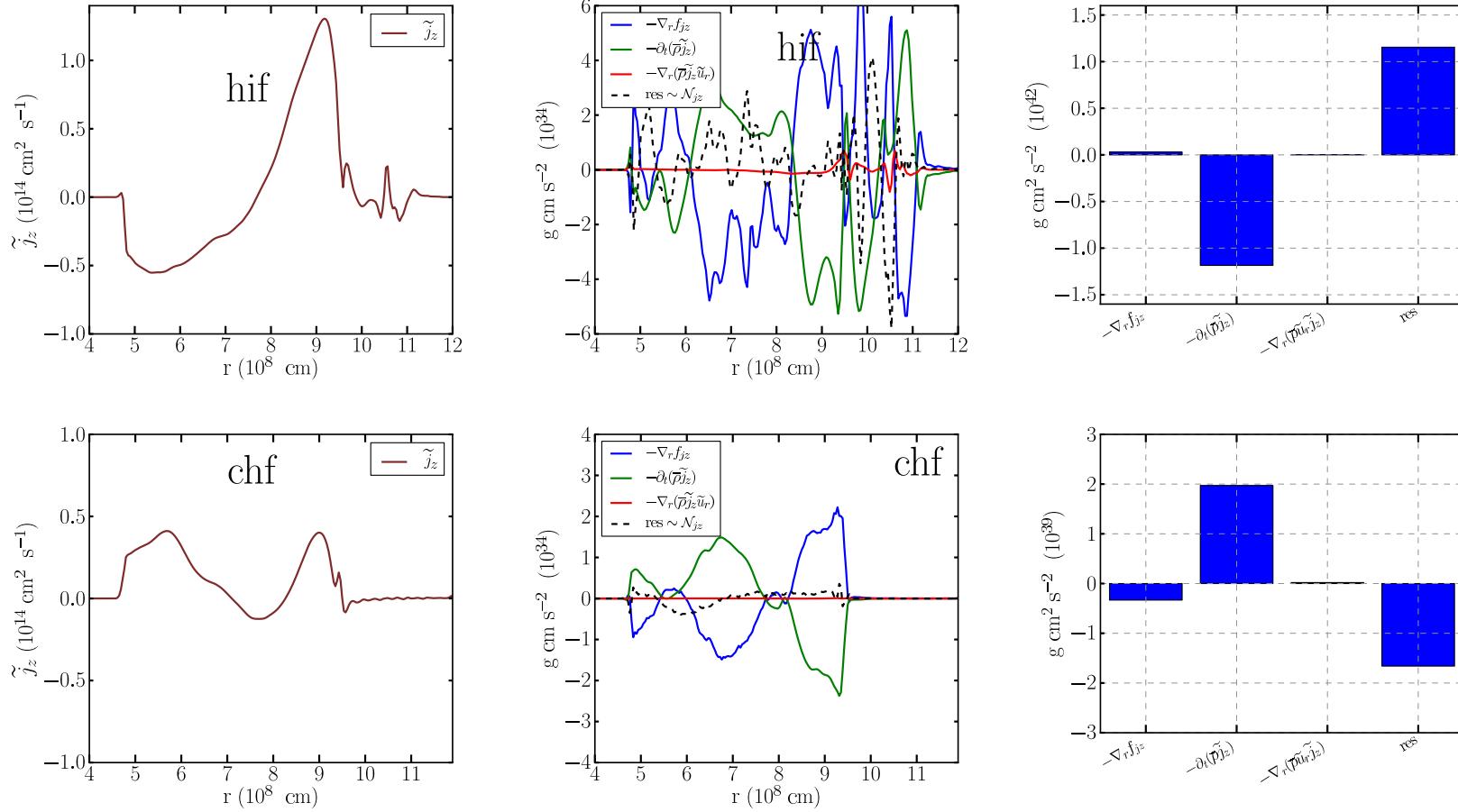


Figure 98: Mean angular momentum equation (z-component). Model hif.3D (upper panels) and model chf.3D (lower panels)

14.12 Mean composition equations

$$\bar{\rho} \tilde{D}_t \tilde{X}_\alpha = -\nabla_r f_\alpha + \bar{\rho} \tilde{X}_\alpha^{\text{nuc}} + \mathcal{N}_\alpha \quad (100)$$

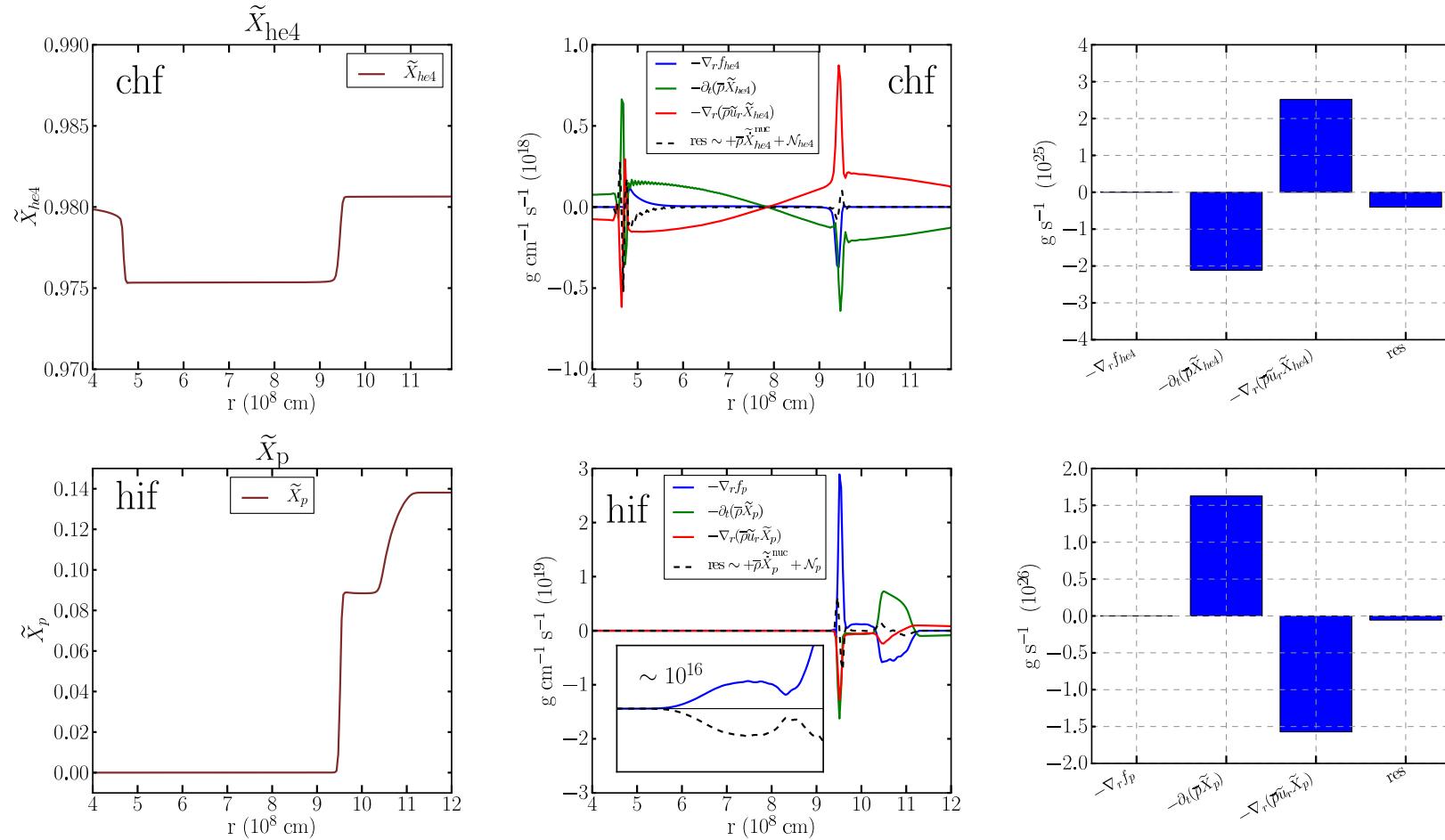


Figure 99: Mean composition equations. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.13 Mean turbulent kinetic energy equation

$$\bar{\rho} \tilde{D}_t \tilde{k} = -\nabla_r(f_k + f_P) - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + W_P + \mathcal{N}_k \quad (101)$$

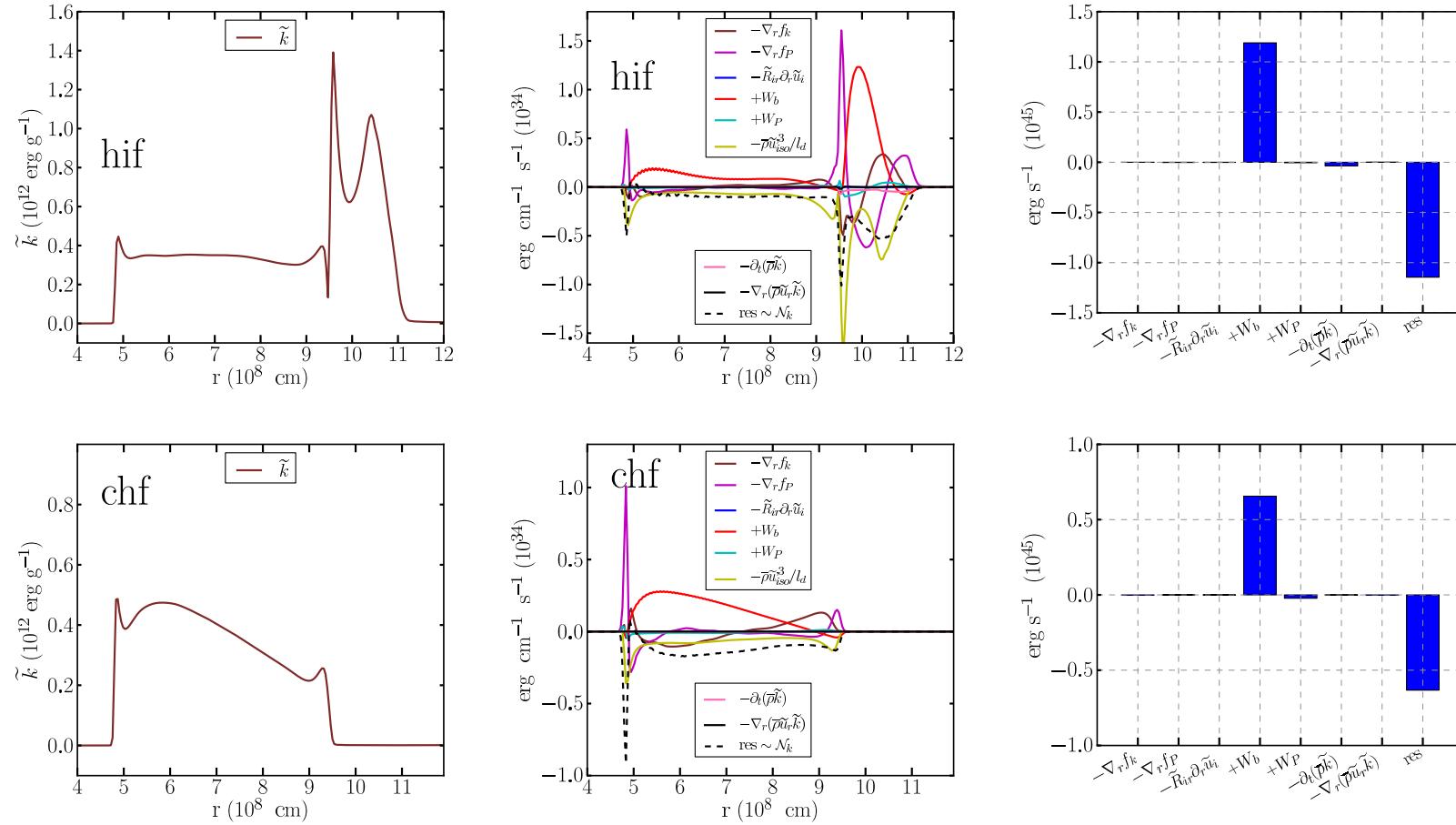


Figure 100: Mean turbulent kinetic energy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.14 Radial part of mean turbulent kinetic energy equation

$$\bar{\rho} \tilde{D}_t \tilde{k}^r = -\nabla_r(f_k^r + f_P) - \tilde{R}_{rr} \partial_r \tilde{u}_r + W_b + \overline{P' \nabla_r u_r''} + \mathcal{G}_k^r + \mathcal{N}_{kr} \quad (102)$$

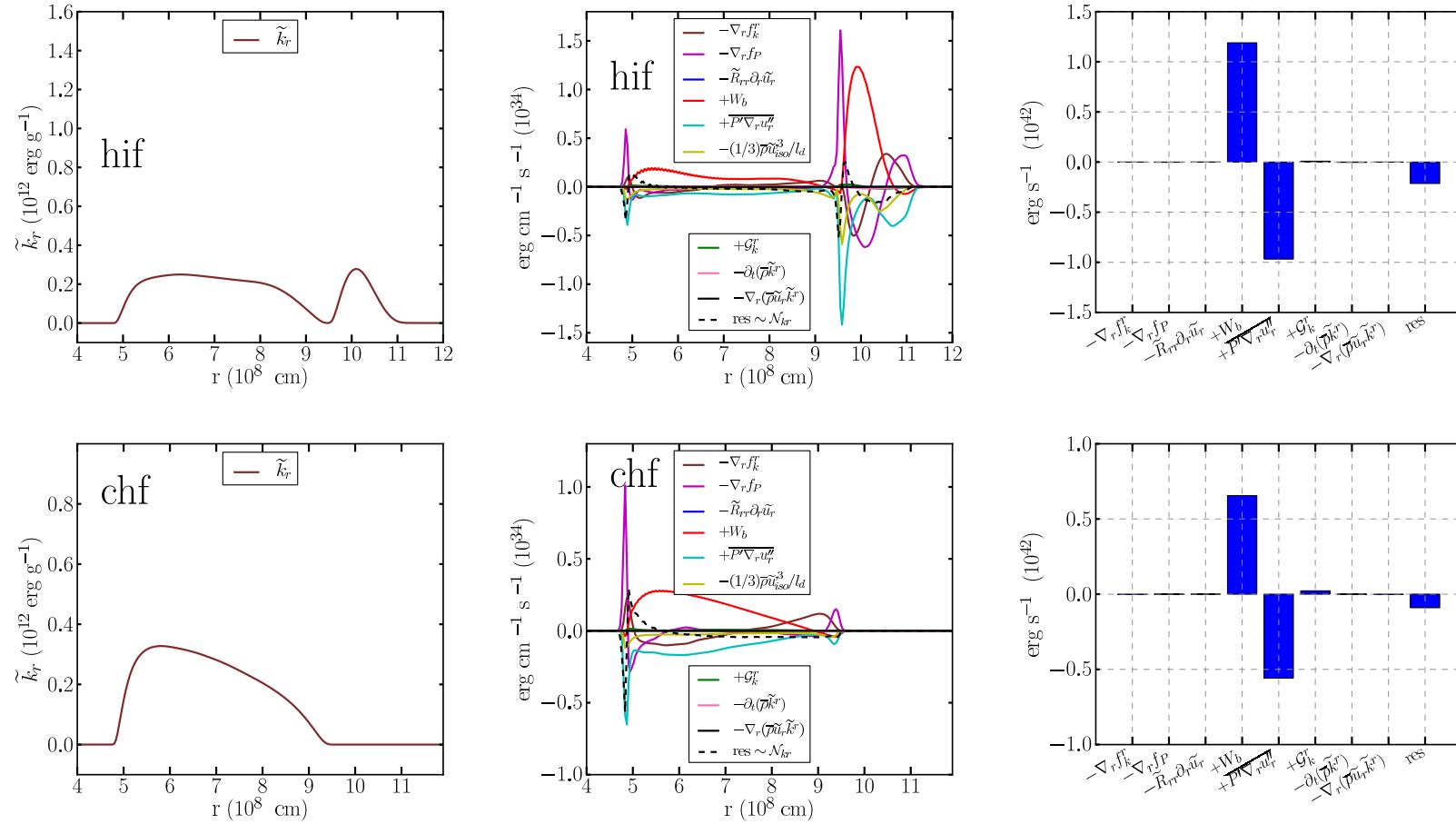


Figure 101: Radial turbulent kinetic energy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

14.15 Horizontal part of mean turbulent kinetic energy equation

$$\bar{\rho} \tilde{D}_t \tilde{k}^h = -\nabla_r f_k^h - (\tilde{R}_{\theta r} \partial_r \tilde{u}_\theta + \tilde{R}_{\phi r} \partial_r \tilde{u}_\phi) + (\bar{P}' \nabla_\theta \tilde{u}_\theta'' + \bar{P}' \nabla_\phi \tilde{u}_\phi'') + \mathcal{G}_k^h + \mathcal{N}_{kh} \quad (103)$$

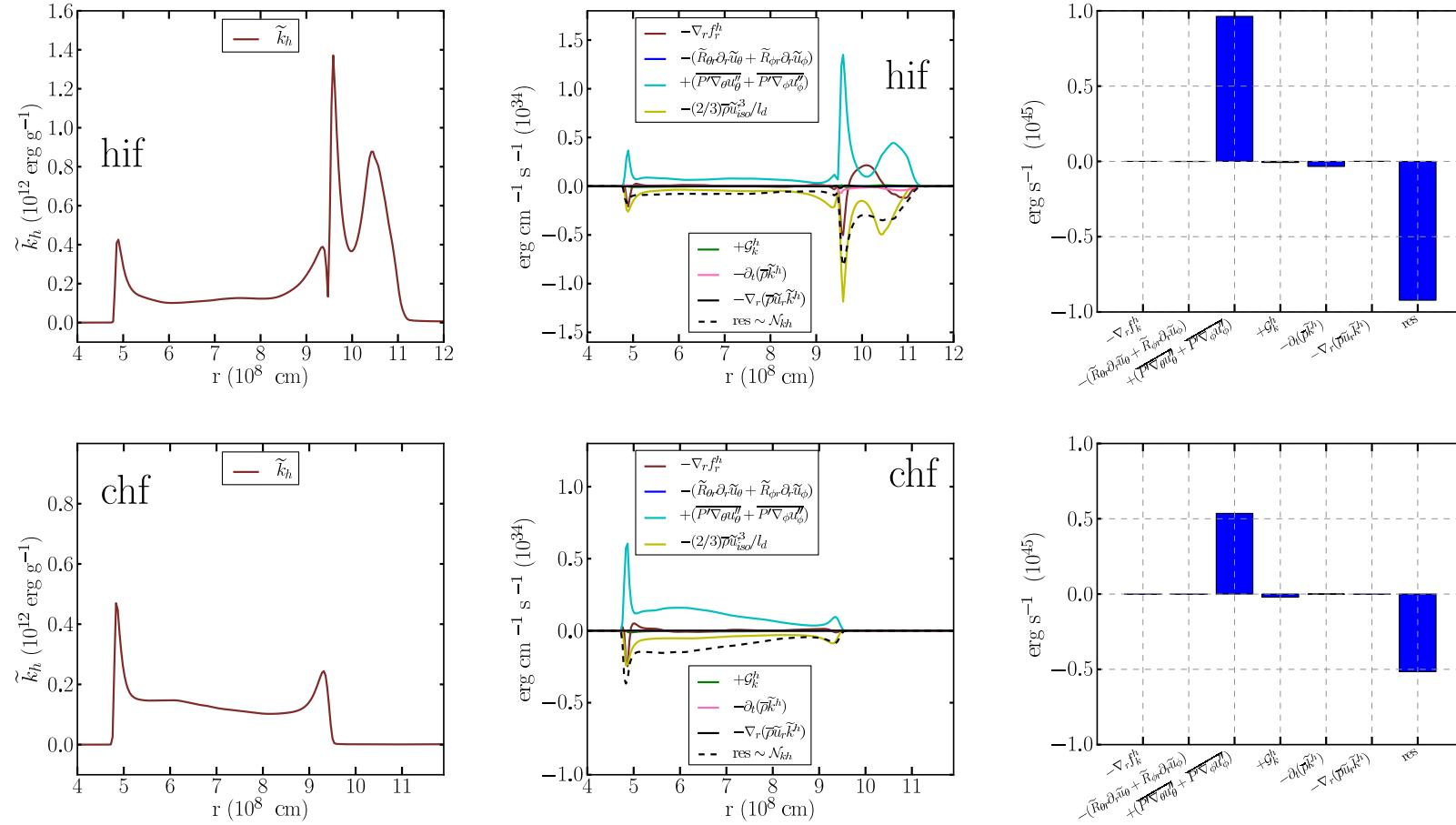


Figure 102: Horizontal turbulent kinetic energy equation. Model hif.3D (upper panels) and model chf.3D (lower panels)

15 Compositon equations derived from hydrogen injection flash data

15.1 Mean H¹ and He³ equation

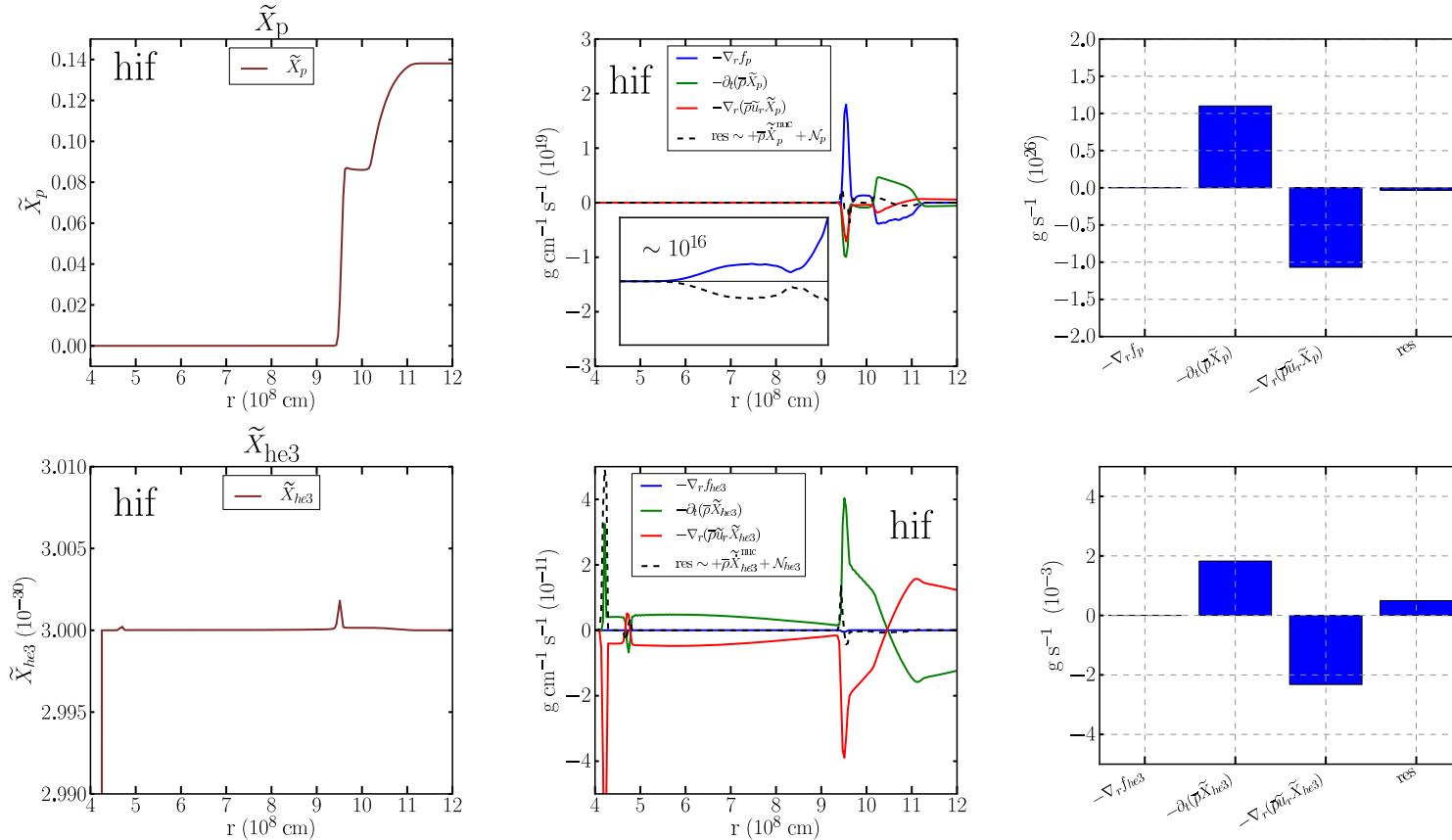


Figure 103: Mean composition equations derived from hif.3D.

15.2 Mean He⁴ and C¹² equation

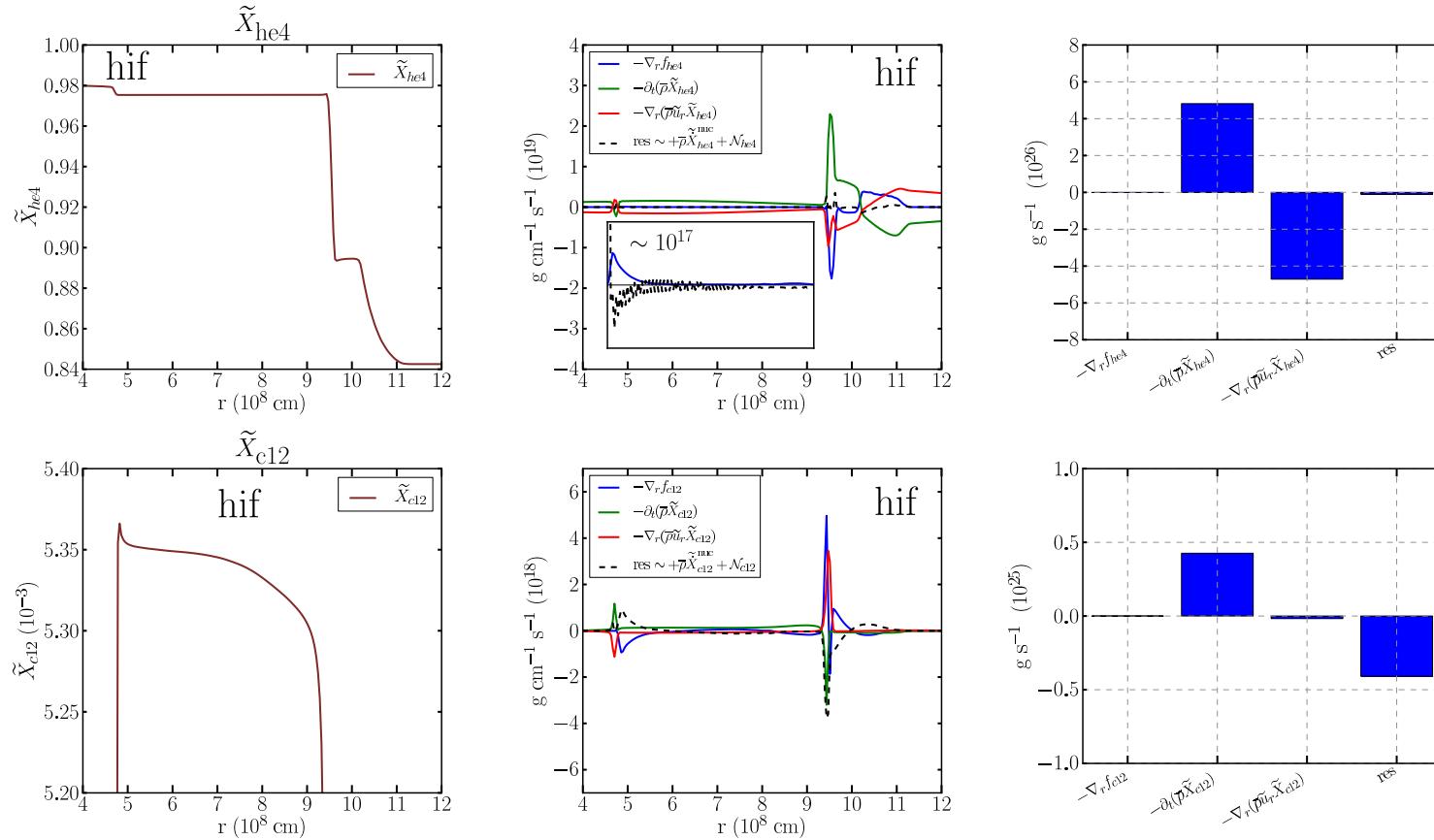


Figure 104: Mean composition equations derived from hif.3D.

15.3 Mean C¹³ and N¹³ equation

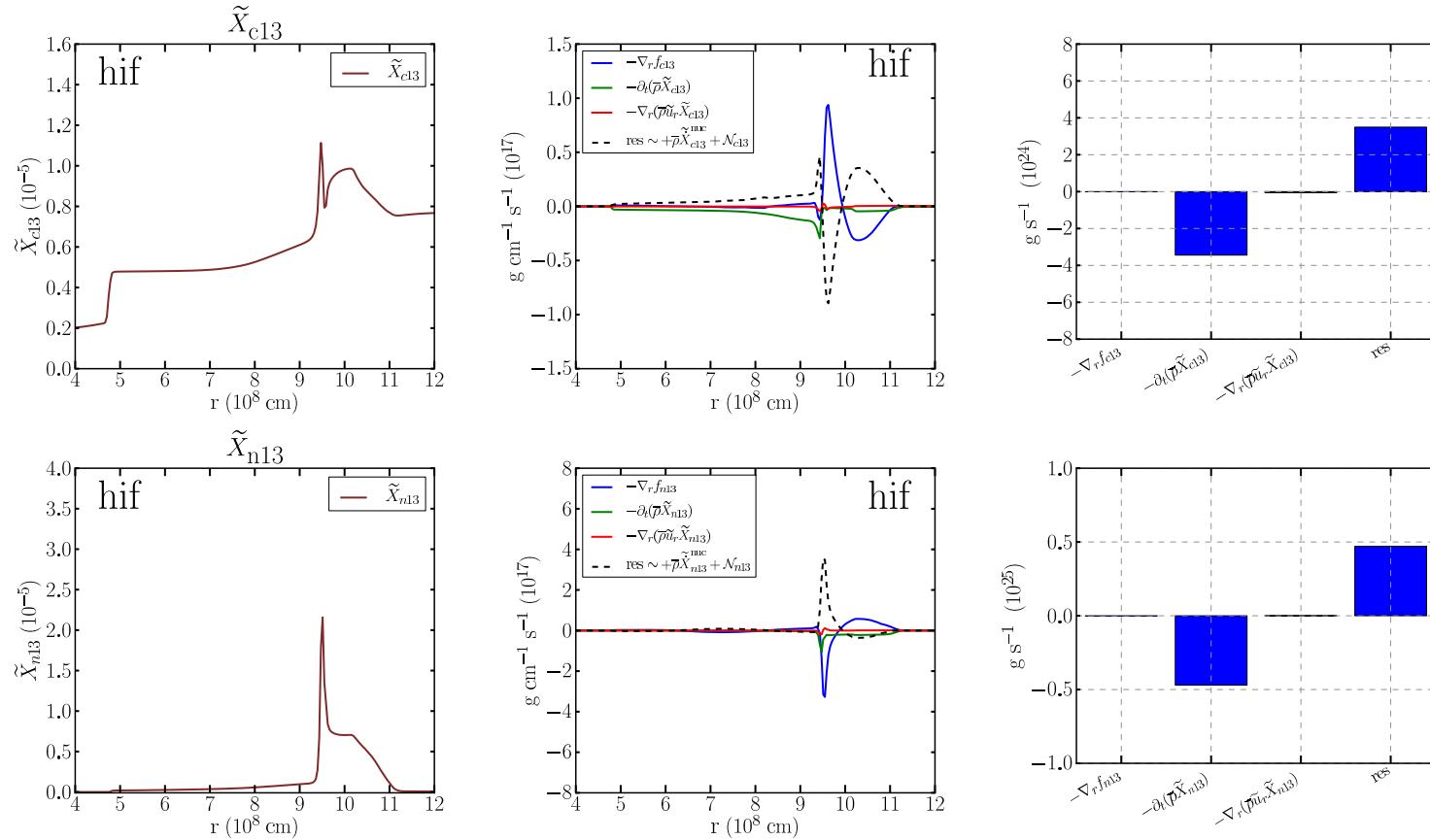


Figure 105: Mean composition equations derived from hif.3D.

15.4 Mean N^{14} and N^{15} equation

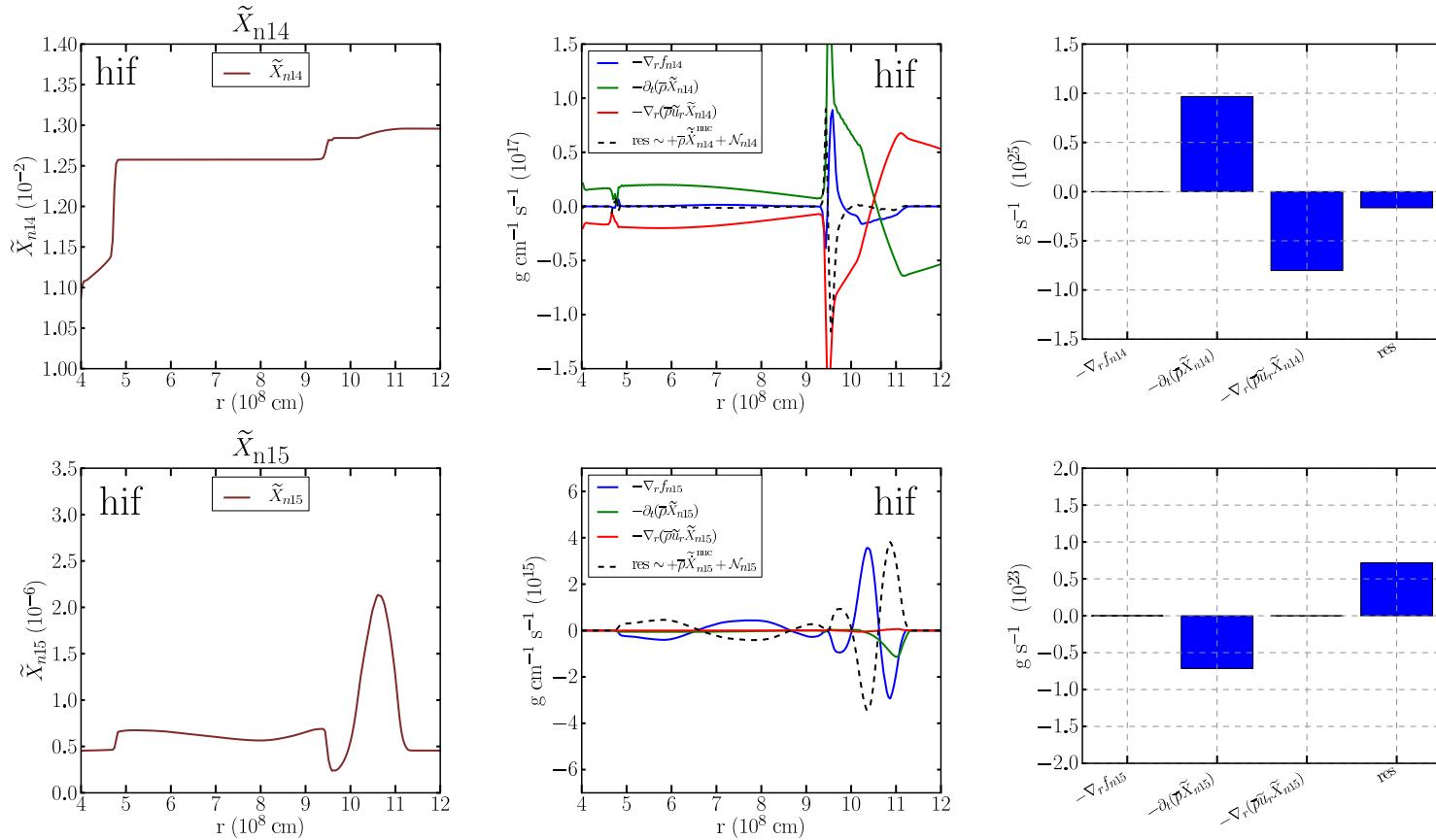


Figure 106: Mean composition equations derived from hif.3D.

15.5 Mean O¹⁵ and O¹⁶ equation

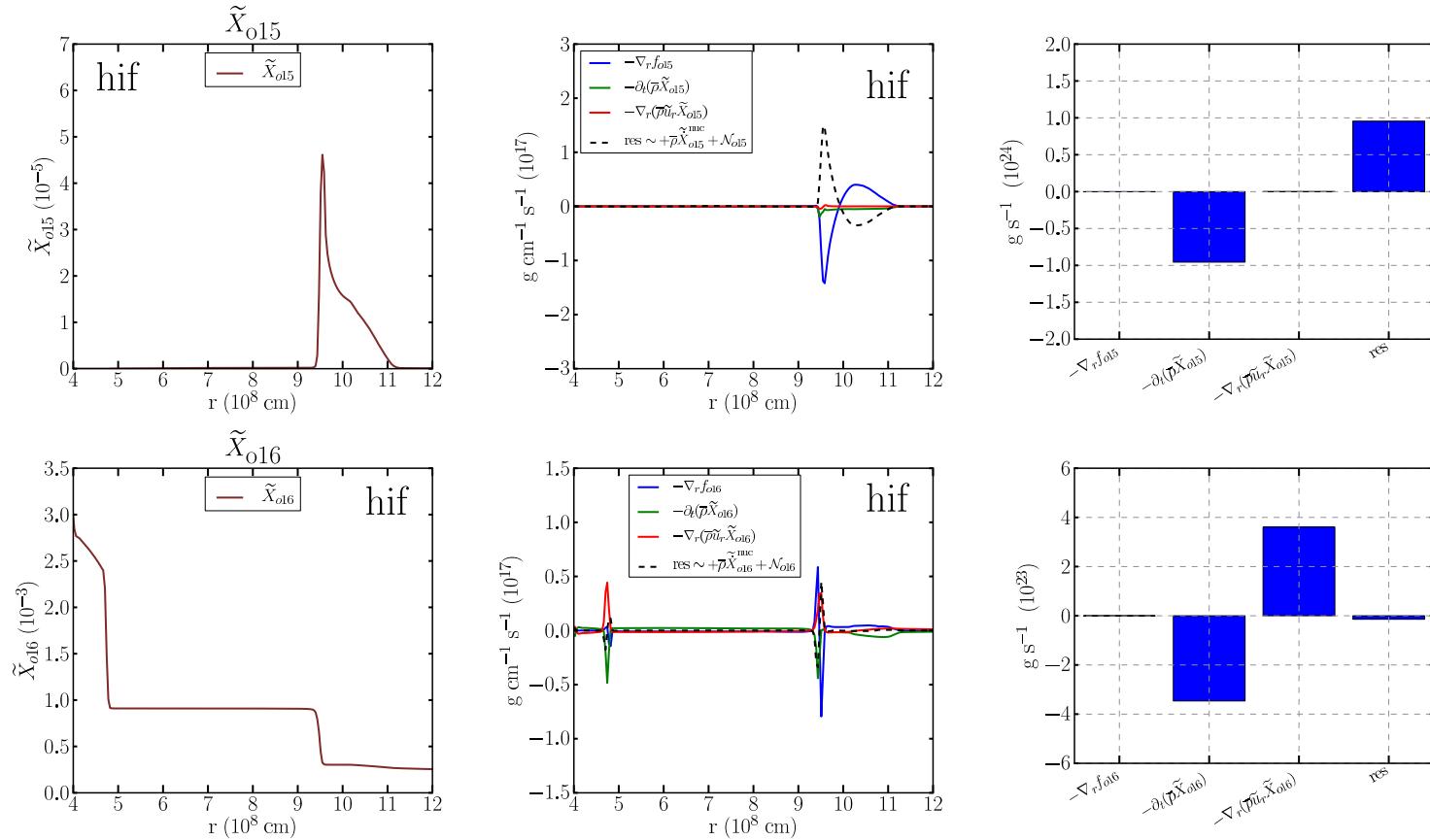


Figure 107: Mean composition equations derived from hif.3D.

15.6 Mean O¹⁷ and Ne²⁰ equation

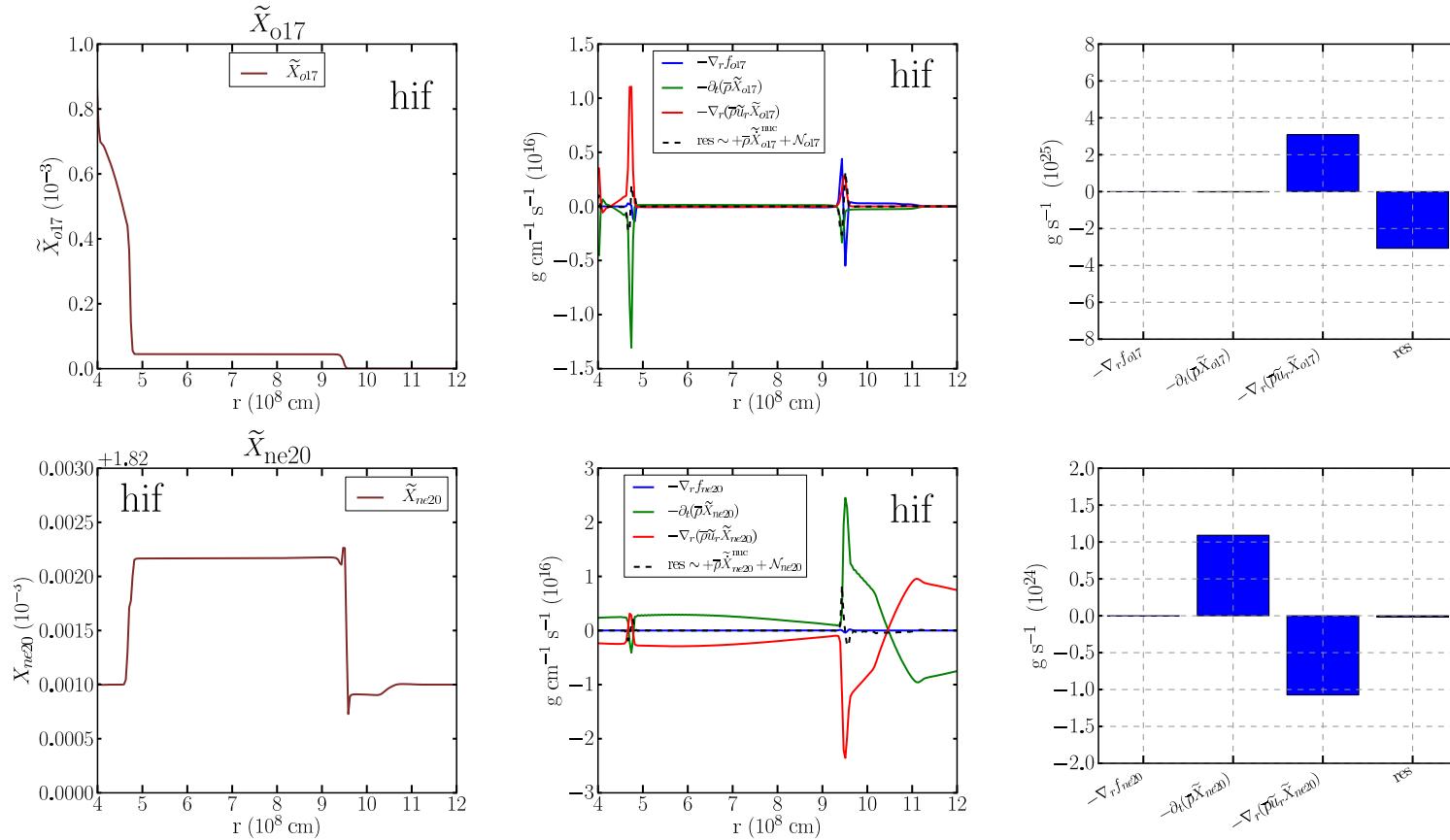


Figure 108: Mean composition equations derived from hif.3D.

15.7 Mean Mg²⁴ and Si²⁸ equation

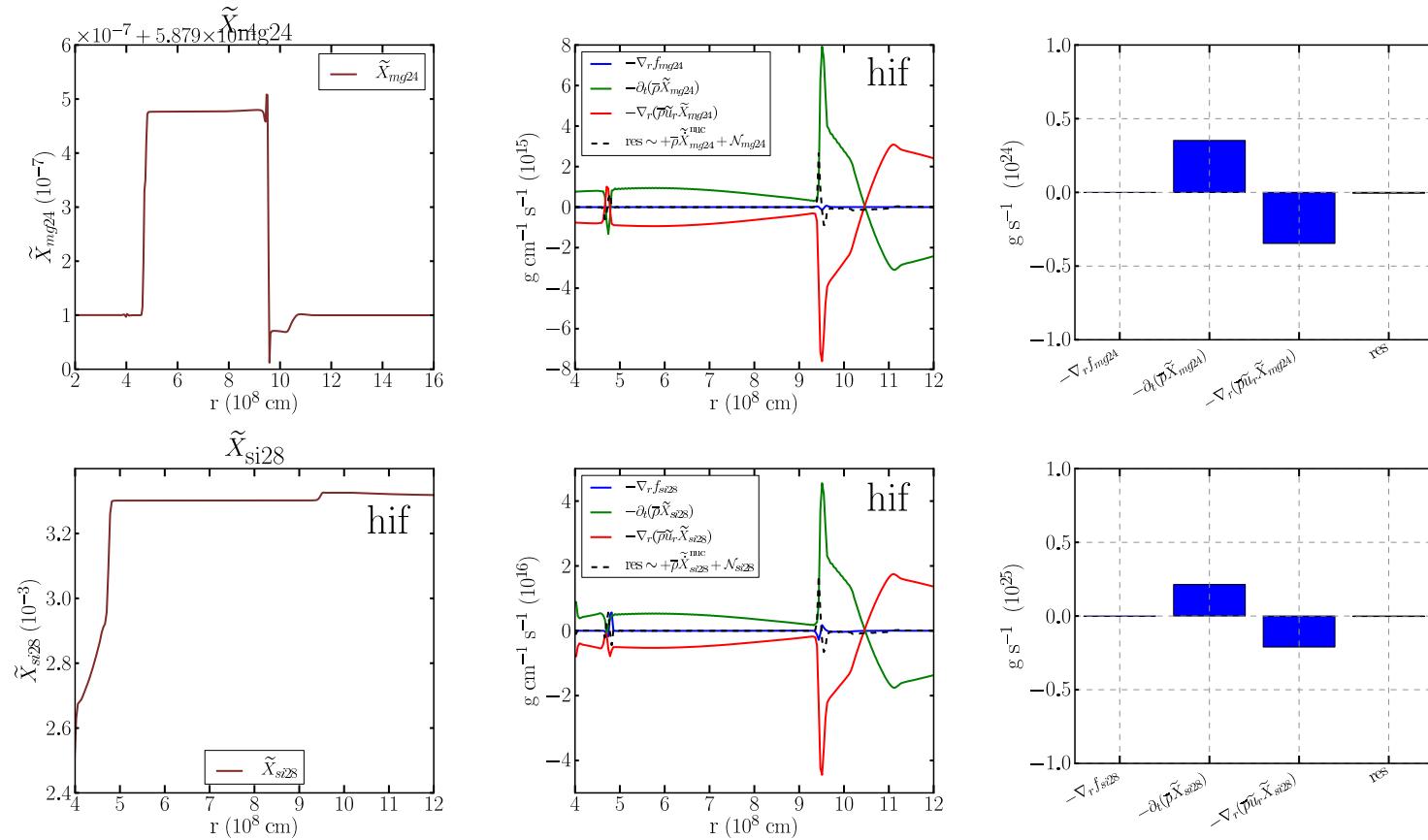


Figure 109: Mean composition equations derived from hif.3D

16 Compositon equations derived from core helium flash data

16.1 Mean He⁴ and C¹² equation

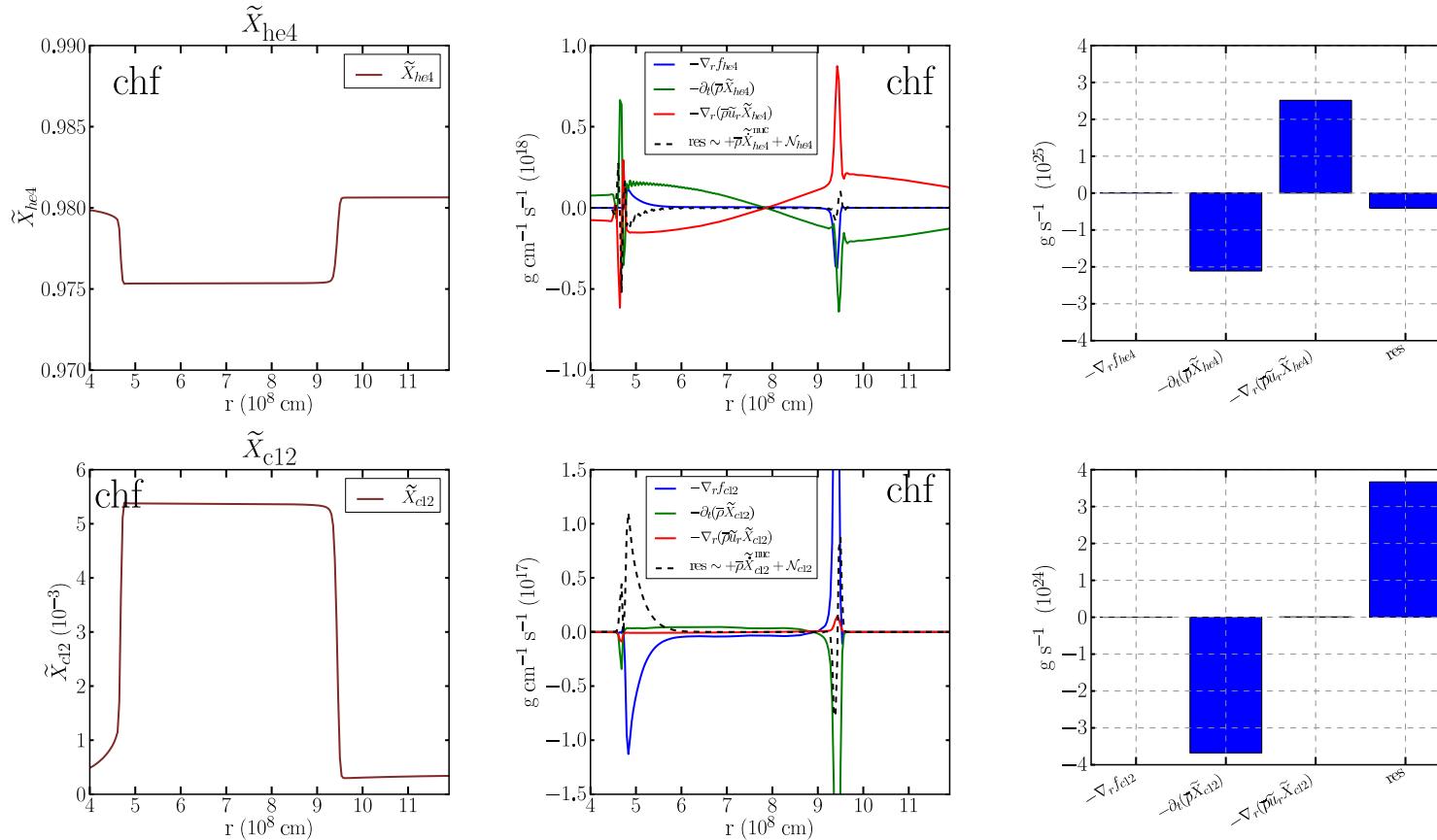


Figure 110: Mean composition equations derived from chf.3D.

16.2 Mean O¹⁶ and Ne²⁰ equation

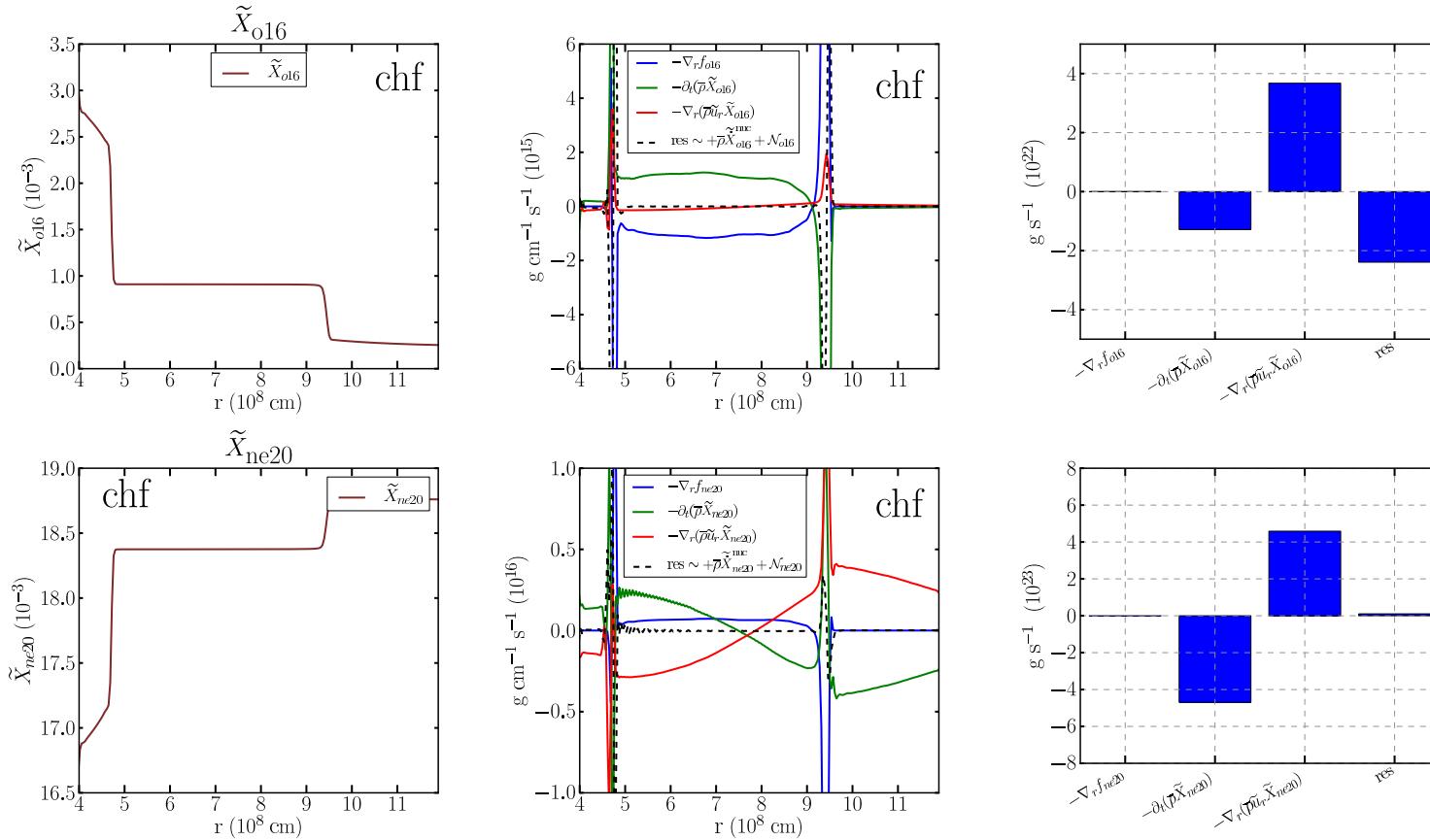


Figure 111: Mean composition equations derived from chf.3D.

17 Instantaneous hydrodynamic equations in spherical coordinates (Eulerian form)

The hydrodynamic equations of a viscous multi-component reactive gas subject to gravity and thermal transport in spherical coordinates (r, θ, ϕ) :

$$\partial_t(\rho) = - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(\rho u_\phi) \right) \quad (104)$$

$$\partial_t(\rho u_r) = - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_r^2 - \tau_{rr}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_r u_\theta - \tau_{r\theta}]) + \frac{1}{r \sin \theta} \partial_\phi([\rho u_r u_\phi - \tau_{r\phi}]) + G_r^M + \partial_r P \right) - \rho \partial_r \Phi \quad (105)$$

$$\partial_t(\rho u_\theta) = - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_\theta u_r - \tau_{\theta r}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\theta^2 - \tau_{\theta\theta}]) + \frac{1}{r \sin \theta} \partial_\phi([\rho u_\theta u_\phi - \tau_{\theta\phi}]) + G_\theta^M + \frac{1}{r} \partial_\theta P \right) - \rho \frac{1}{r} \partial_\theta \Phi \quad (106)$$

$$\partial_t(\rho u_\phi) = - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_\phi u_r - \tau_{\phi r}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\phi u_\theta - \tau_{\phi\theta}]) + \frac{1}{r \sin \theta} \partial_\phi([\rho u_\phi^2 - \tau_{\phi\phi}]) + G_\phi^M + \frac{1}{r \sin \theta} \partial_\phi P \right) - \rho \frac{1}{r \sin \theta} \partial_\phi \Phi \quad (107)$$

$$\begin{aligned} \partial_t(\rho \epsilon_T) = & - \left(\frac{1}{r^2} \partial_r(r^2[u_r(\rho \epsilon_T + P) - K \partial_r T]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta(\rho \epsilon_T + P) - K \frac{1}{r} \partial_\theta T]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi(\rho \epsilon_T + P) - K \frac{1}{r \sin \theta} \partial_\phi T) \right) + \\ & + \left(\frac{1}{r^2} \partial_r(r^2[u_j \tau_{jr}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_j \tau_{j\theta}]) + \frac{1}{r \sin \theta} \partial_\phi(u_j \tau_{j\phi}) \right) - \rho(u_r \partial_r \Phi + u_\theta \frac{1}{r} \partial_\theta \Phi + u_\phi \frac{1}{r \sin \theta} \partial_\phi \Phi) + \rho \epsilon_{nuc} \end{aligned} \quad (108)$$

$$\begin{aligned} \partial_t(\rho \epsilon_I) = & - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_r \epsilon_I]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\theta \epsilon_I]) + \frac{1}{r \sin \theta} \partial_\phi([\rho u_\phi \epsilon_I]) \right) - P \left(\frac{1}{r^2} \partial_r(r^2[u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi) \right) + \\ & + \left(\frac{1}{r^2} \partial_r(r^2[K \partial_r T]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[K \frac{1}{r} \partial_\theta T]) + \frac{1}{r \sin \theta} \partial_\phi(K \frac{1}{r \sin \theta} \partial_\phi T) \right) + (\tau_{jr} \partial_r u_j + \tau_{j\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j\phi} \frac{1}{r \sin \theta} \partial_\phi u_j) + \rho \epsilon_{nuc} \end{aligned} \quad (109)$$

$$\begin{aligned} \partial_t(\rho \epsilon_K) = & - \left(\frac{1}{r^2} \partial_r(r^2(\rho u_r \epsilon_K - u_j \tau_{jr})) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta(\rho u_\theta \epsilon_K - u_j \tau_{j\theta})) + \frac{1}{r \sin \theta} \partial_\phi(\rho u_\phi \epsilon_K - u_j \tau_{j\phi}) \right) - \\ & - \left(\frac{1}{r^2} \partial_r(r^2[P u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[P u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(P u_\phi) \right) + P \left(\frac{1}{r^2} \partial_r(r^2[u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi) \right) - \\ & - (\tau_{jr} \partial_r u_j + \tau_{j\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j\phi} \frac{1}{r \sin \theta} \partial_\phi u_j) - \rho(u_r \partial_r \Phi + u_\theta \frac{1}{r} \partial_\theta \Phi + u_\phi \frac{1}{r \sin \theta} \partial_\phi \Phi) \end{aligned} \quad (110)$$

$$\partial_t(\rho X_k) = - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_r X_k]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\theta X_k]) + \frac{1}{r \sin \theta} \partial_\phi(\rho u_\phi X_k) \right) + \rho \dot{X}_k^n \quad k = 1 \dots N_{nuc} \quad (111)$$

$$G_r^M = - \frac{(\rho u_\theta^2 - \tau_{\theta\theta})}{r} - \frac{(\rho u_\phi^2 - \tau_{\phi\phi})}{r} \quad G_\theta^M = + \frac{(\rho u_\theta u_r - \tau_{\theta r})}{r} - \frac{(\rho u_\phi^2 - \tau_{\phi\phi}) \cos \theta}{r \sin \theta} \quad G_\phi^M = + \frac{(\rho u_\phi u_r - \tau_{\phi r})}{r} + \frac{(\rho u_\phi u_\theta - \tau_{\phi\theta}) \cos \theta}{r \sin \theta} \quad (112)$$

18 Instantaneous hydrodynamic equations in spherical coordinates (Lagrangian form)

The hydrodynamic equations of a viscous multi-component reactive gas subject to gravity and thermal transport in spherical coordinates (r, θ, ϕ) are ($D_t(\cdot) = \partial_t(\cdot) + u_n \partial_n(\cdot)$ is advective derivative):

$$D_t(\rho) = -\rho \left(\frac{1}{r^2} \partial_r(r^2[u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi) \right) \quad (113)$$

$$\rho D_t(u_r) = + \left(\frac{1}{r^2} \partial_r(r^2[\tau_{rr}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\tau_{r\theta}]) + \frac{1}{r \sin \theta} \partial_\phi([\tau_{r\phi}]) - G_r^M - \partial_r P \right) + \rho g_r \quad (114)$$

$$\rho D_t(u_\theta) = + \left(\frac{1}{r^2} \partial_r(r^2[\tau_{\theta r}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\tau_{\theta\theta}]) + \frac{1}{r \sin \theta} \partial_\phi([\tau_{\theta\phi}]) - G_\theta^M - \frac{1}{r} \partial_\theta P \right) + \rho g_\theta \quad (115)$$

$$\rho D_t(u_\phi) = + \left(\frac{1}{r^2} \partial_r(r^2[\tau_{\phi r}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\tau_{\phi\theta}]) + \frac{1}{r \sin \theta} \partial_\phi([\tau_{\phi\phi}]) - G_\phi^M - \frac{1}{r \sin \theta} \partial_\phi P \right) + \rho g_\phi \quad (116)$$

$$\begin{aligned} \rho D_t(\epsilon_T) = & - \left(\frac{1}{r^2} \partial_r(r^2[u_r P - K \partial_r T]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta P - K \frac{1}{r} \partial_\theta T]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi P - K \frac{1}{r \sin \theta} \partial_\phi T) \right) - \\ & + \left(\frac{1}{r^2} \partial_r[r^2(u_j \tau_{jr})] + \frac{1}{r \sin \theta} \partial_\theta[\sin \theta(u_j \tau_{j\theta})] + \frac{1}{r \sin \theta} \partial_\phi(u_j \tau_{j\phi}) \right) + \rho(u_r g_r + u_\theta g_\theta + u_\phi g_\phi) + \rho \epsilon_{nuc} \end{aligned} \quad (117)$$

$$\begin{aligned} \rho D_t(\epsilon_I) = & - P \left(\frac{1}{r^2} \partial_r(r^2[u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi) \right) + \left(\frac{1}{r^2} \partial_r(r^2[K \partial_r T]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[K \frac{1}{r} \partial_\theta T]) + \frac{1}{r \sin \theta} \partial_\phi(K \frac{1}{r \sin \theta} \partial_\phi T) \right) + \\ & + \left(\tau_{jr} \partial_r u_j + \tau_{j\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j\phi} \frac{1}{r \sin \theta} \partial_\phi u_j \right) + \rho \epsilon_{nuc} \end{aligned} \quad (118)$$

$$\begin{aligned} \rho D_t(\epsilon_K) = & + \left(\frac{1}{r^2} \partial_r[r^2(u_j \tau_{jr})] + \frac{1}{r \sin \theta} \partial_\theta[\sin \theta(u_j \tau_{j\theta})] + \frac{1}{r \sin \theta} \partial_\phi(u_j \tau_{j\phi}) \right) - \left(\frac{1}{r^2} \partial_r(r^2[P u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[P u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(P u_\phi) \right) + \\ & + P \left(\frac{1}{r^2} \partial_r(r^2[u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi) \right) - \left(\tau_{jr} \partial_r u_j + \tau_{j\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j\phi} \frac{1}{r \sin \theta} \partial_\phi u_j \right) + \rho(u_r g_r + u_\theta g_\theta + u_\phi g_\phi) \end{aligned} \quad (119)$$

$$\rho D_t(X_k) = + \rho \dot{X}_k^n \quad k = 1 \dots N_{nuc} \quad (120)$$

$$G_r^M = - \frac{(\rho u_\theta^2 - \tau_{\theta\theta})}{r} - \frac{(\rho u_\phi^2 - \tau_{\phi\phi})}{r} \quad G_\theta^M = + \frac{(\rho u_\theta u_r - \tau_{\theta r})}{r} - \frac{(\rho u_\phi^2 - \tau_{\phi\phi}) \cos \theta}{r \sin \theta} \quad G_\phi^M = + \frac{(\rho u_\phi u_r - \tau_{\phi r})}{r} + \frac{(\rho u_\phi u_\theta - \tau_{\phi\theta}) \cos \theta}{r \sin \theta} \quad (121)$$

where ρ , u_r , u_θ , u_ϕ , P , ϵ_T , ϵ_I , ϵ_K , T , ϵ_{nuc} , X_k , and \dot{X}_k^n are the density, the radial velocity, the θ -velocity, the rotation velocity, the pressure, the total specific energy, the specific internal energy, the specific kinetic energy, the temperature, the energy generation rate per mass due to reactions, the mass fraction of species k , and the change of this mass fraction due to reactions, respectively. N_{nuc} is the number of species the gas is composed. $\tau_{ij} = 2\mu S_{ij} - 2/3\mu \nabla \cdot \mathbf{u} \delta_{ij}$ is the viscous stress, where $S_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i)$ is strain-rate, $\mu = \rho\nu$ is dynamic viscosity and ν is the kinematic viscosity. K is thermal conductivity. g_i is gravitational acceleration in r, θ, ϕ and Φ is gravitational potential. G are geometric terms.

19 Reynolds decomposition

Reynolds decomposition:

$$A(r, \theta, \phi) = \overline{A}(r) + A'(r, \theta, \phi) \quad (122)$$

Definition of the averaging space-time operator:

$$\overline{A(r)} = \frac{1}{\Delta T \Delta \Omega} \int_{\Delta T} \int_{\Delta \Omega} A(r, \theta, \phi) dt d\Omega \quad (123)$$

Some properties of the operator:

$$\overline{A'} = 0 \quad (124)$$

$$\overline{\overline{A}} = \overline{A} \quad (125)$$

$$(A')' = A' \quad (126)$$

$$\overline{\overline{AB}} = \overline{A} \overline{B} \quad (127)$$

$$\overline{AB} = \overline{A} \overline{B} + \overline{A'B'} \quad (128)$$

$$\overline{A'B'} = \overline{A'} \overline{B} \quad (129)$$

20 Favre decomposition

Favre decomposition:

$$F = \tilde{F}(r) + F''(r, \theta, \phi) \quad (130)$$

Definition of the averaging operator:

$$\tilde{F} = \frac{\overline{\rho F}}{\overline{\rho}} \quad (131)$$

Some properties of the operator:

$$\overline{\rho F''} = \widetilde{F''} = 0 \quad (132)$$

$$\widetilde{F} = \overline{F} + \frac{\overline{\rho F'}}{\overline{\rho}} \quad (133)$$

$$F'' = F' - \frac{\overline{\rho F'}}{\overline{\rho}} \rightarrow \overline{F''} = -\frac{\overline{\rho F'}}{\overline{\rho}} \quad (134)$$

$$\overline{\rho F'' G''} = \overline{\rho} \widetilde{F'' G''} \quad (135)$$

21 Derivation of first order moments

21.1 Mean continuity equation

We begin by instantaneous 3D continuity equation and apply "ensemble" (space-time) averaging (Sect.1):

$$\partial_t \rho = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi (\rho u_\phi) \right) \quad (136)$$

$$\partial_t \bar{\rho} = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi (\rho u_\phi) \right) \xrightarrow{0} \text{"ensemble" (space-time) averaging} \quad (137)$$

$$\partial_t \bar{\rho} = - \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \tilde{u}_r]) \quad (138)$$

$$\partial_t \bar{\rho} = - \tilde{u}_r \partial_r \bar{\rho} - \bar{\rho} \frac{1}{r^2} \partial_r (r^2 \tilde{u}_r) \quad (139)$$

$$\partial_t \bar{\rho} + \tilde{u}_r \partial_r \bar{\rho} = - \bar{\rho} \frac{1}{r^2} \partial_r (r^2 \tilde{u}_r) \quad (140)$$

$$\tilde{D}_t \bar{\rho} = - \bar{\rho} \tilde{d} \quad (141)$$

21.2 Mean radial momentum equation

We begin by instantaneous 3D radial momentum equation and apply "ensemble" (space-time) averaging (Sect.1):

$$\partial_t \rho u_r = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r^2 - \tau_{rr}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_r u_\theta - \tau_{r\theta}]) + \frac{1}{r \sin \theta} \partial_\phi ([\rho u_r u_\phi - \tau_{r\phi}]) + G_r^M + \partial_r P \right) + \rho g_r \quad (142)$$

$$\partial_t \bar{\rho} u_r = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r^2 - \tau_{rr}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_r u_\theta - \tau_{r\theta}]) + \frac{1}{r \sin \theta} \partial_\phi ([\rho u_r u_\phi - \tau_{r\phi}]) + \bar{G}_r^M + \partial_r \bar{P} \right) + \bar{\rho} g_r \quad (143)$$

$$\partial_t \bar{\rho} u_r = - \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} u_r u_r]) - \frac{1}{r^2} \partial_r (r^2 \bar{\tau}_{rr}) - \bar{G}_r^M - \partial_r \bar{P} + \bar{\rho} g_r \quad \text{we neglect mean viscosity } \bar{\tau} \quad (144)$$

$$\partial_t \bar{\rho} \widetilde{u_r} = -\frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \widetilde{u_r u_r}]) - \bar{G}_r^M - \partial_r \bar{P} + \bar{\rho} \widetilde{g}_r \quad (145)$$

$$\partial_t \bar{\rho} \widetilde{u_r} = -\frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \widetilde{u_r u_r} + \bar{\rho} \widetilde{u_r'' u_r''}]) - \bar{G}_r^M - \partial_r \bar{P} + \bar{\rho} \widetilde{g}_r \quad (146)$$

$$\partial_t \bar{\rho} \widetilde{u_r} + \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \widetilde{u_r u_r}]) = -\frac{1}{r^2} \partial_r (\bar{\rho} \widetilde{u_r'' u_r''}) - \bar{G}_r^M - \partial_r \bar{P} + \bar{\rho} \widetilde{g}_r \quad (147)$$

$$\bar{\rho} \widetilde{D}_t \widetilde{u_r} = -\nabla_r \widetilde{R}_{rr} - \bar{G}_r^M - \partial_r \bar{P} + \bar{\rho} \widetilde{g}_r \quad (148)$$

21.3 Mean polar momentum equation

We begin by instantaneous 3D polar momentum equation and apply "ensemble" (space-time) averaging (Sect.1):

$$\partial_t \rho u_\theta = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_\theta u_r - \tau_{\theta r}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta^2 - \tau_{\theta \theta}]) + \frac{1}{r \sin \theta} \partial_\phi (\rho u_\theta u_\phi - \tau_{\theta \phi}) \right) + G_\theta^M + \frac{1}{r} \partial_\theta P - \rho \frac{1}{r} \partial_\theta \Phi \quad (149)$$

$$\partial_t \bar{\rho} \widetilde{u_\theta} = - \left(\overline{\frac{1}{r^2} \partial_r (r^2 [\rho u_\theta u_r - \tau_{\theta r}])} + \overline{\frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta^2 - \tau_{\theta \theta}])} + \overline{\frac{1}{r \sin \theta} \partial_\phi (\rho u_\theta u_\phi - \tau_{\theta \phi})} \right)^0 + \bar{G}_\theta^M + \frac{1}{r} \partial_\theta \bar{P} + \bar{\rho} \widetilde{g}_\theta \quad (150)$$

$$\partial_t \bar{\rho} \widetilde{u_\theta} = -\frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \widetilde{u_\theta u_r}]) + \frac{1}{r^2} \partial_r (r^2 \bar{\tau}_{\theta r})^0 - \bar{G}_\theta^M - \frac{1}{r} \partial_\theta \bar{P} + \bar{\rho} \widetilde{g}_\theta^0 \text{ we neglect mean viscosity } \bar{\tau} \text{ and gravity in } \theta \quad (151)$$

$$\partial_t \bar{\rho} \widetilde{u_\theta} = -\frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \widetilde{u_\theta u_r}]) - \bar{G}_\theta^M - \frac{1}{r} \partial_\theta \bar{P} \quad (152)$$

$$\partial_t \bar{\rho} \widetilde{u_\theta} = -\frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \widetilde{u_\theta u_r} + \bar{\rho} \widetilde{u_\theta'' u_r''}]) - \bar{G}_\theta^M - \frac{1}{r} \partial_\theta \bar{P} \quad (153)$$

$$\partial_t \bar{\rho} \widetilde{u_\theta} + \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} \widetilde{u_\theta u_r}]) = -\frac{1}{r^2} \partial_r (r^2 \bar{\rho} \widetilde{u_\theta'' u_r''}) - \bar{G}_\theta^M - \frac{1}{r} \partial_\theta \bar{P} \quad (154)$$

$$\bar{\rho} \widetilde{D}_t \widetilde{u_\theta} = -\nabla_r \widetilde{R}_{\theta r} - \bar{G}_\theta^M - (1/r) \partial_\theta \bar{P} \quad (155)$$

21.4 Mean azimuthal momentum equation

We begin by instantaneous 3D azimuthal momentum equation and apply "ensemble" (space-time) averaging (Sect.1):

$$\partial_t(\rho u_\phi) = - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_\phi u_r - \tau_{\phi r}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\theta u_\phi - \tau_{\theta \phi}]) + \frac{1}{r \sin \theta} \partial_\phi([\rho u_\phi^2 - \tau_{\phi \phi}]) + G_\phi^M + \frac{1}{r \sin \theta} \partial_\phi P \right) - \rho \frac{1}{r \sin \theta} \partial_\phi \Phi \quad (156)$$

$$\begin{aligned} \partial_t \overline{\rho u_\phi} &= - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_\phi u_r - \tau_{\phi r}]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\theta u_\phi - \tau_{\theta \phi}]) + \frac{1}{r \sin \theta} \partial_\phi([\rho u_\phi^2 - \tau_{\phi \phi}]) + \overline{G_\phi^M} + \frac{1}{r \sin \theta} \partial_\phi \overline{P} \right) + \\ &\quad + \overline{\rho g_\phi} \end{aligned} \quad (157)$$

$$\partial_t \overline{\rho u_\phi} = - \frac{1}{r^2} \partial_r(r^2[\overline{\rho u_\phi u_r}]) - \frac{1}{r^2} \partial_r(r^2 \overline{\tau_{\phi r}}) + \overline{G_\phi^M} - \overline{\rho g_\phi} \xrightarrow{0} \text{we neglect mean viscosity } \tau \text{ and gravity in } \phi \quad (158)$$

$$\partial_t \overline{\rho \tilde{u}_\phi} = - \frac{1}{r^2} \partial_r(r^2[\overline{\rho u_\phi \tilde{u}_r}]) + \overline{G_\phi^M} \quad (159)$$

$$\partial_t \overline{\rho \tilde{u}_\phi} = - \frac{1}{r^2} \partial_r(r^2[\overline{\rho \tilde{u}_\phi \tilde{u}_r} - \overline{\rho u_\phi'' u_r''}]) - \overline{G_\phi^M} \quad (160)$$

$$\partial_t \overline{\rho \tilde{u}_\phi} + \frac{1}{r^2} \partial_r(r^2[\overline{\rho \tilde{u}_\phi \tilde{u}_r}]) = - \frac{1}{r^2} \partial_r(r^2 \overline{\rho u_\phi'' u_r''}) - \overline{G_\phi^M} \quad (161)$$

$$\overline{\rho \tilde{D}_t \tilde{u}_\phi} = - \nabla_r \tilde{R}_{\phi r} - \overline{G_\phi^M} \quad (162)$$

21.5 Mean internal energy equation

We begin by instantaneous 3D internal energy equation and apply "ensemble" (space-time) averaging (Sect.1):

$$\begin{aligned} \partial_t(\rho \epsilon_I) &= - \left(\frac{1}{r^2} \partial_r(r^2[\rho u_r \epsilon_I]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[\rho u_\theta \epsilon_I]) + \frac{1}{r \sin \theta} \partial_\phi(\rho u_\phi \epsilon_I) \right) - P \left(\frac{1}{r^2} \partial_r(r^2[u_r]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi(u_\phi) \right) + \\ &\quad + \left(\frac{1}{r^2} \partial_r(r^2[K \partial_r T]) + \frac{1}{r \sin \theta} \partial_\theta(\sin \theta[K \frac{1}{r} \partial_\theta T]) + \frac{1}{r \sin \theta} \partial_\phi(K \frac{1}{r \sin \theta} \partial_\phi T) \right) + \left(\tau_{j_r} \partial_r u_j + \tau_{j_\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j_\phi} \frac{1}{r \sin \theta} \partial_\phi u_j \right) + \rho \epsilon_{\text{nuc}} \end{aligned} \quad (163)$$

$$\begin{aligned} \partial_t \bar{\rho} \epsilon_I = & - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r \epsilon_I]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta \epsilon_I]) + \frac{1}{r \sin \theta} \partial_\phi (\rho u_\phi \epsilon_I) \right)^0 - P \left(\frac{1}{r^2} \partial_r (r^2 [u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [u_\phi] \right) + \\ & + \left(\frac{1}{r^2} \partial_r (r^2 [K \partial_r T]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [K \frac{1}{r} \partial_\theta T]) + \frac{1}{r \sin \theta} \partial_\phi [K \frac{1}{r \sin \theta} \partial_\phi T] \right)^0 + \left(\tau_{jr} \partial_r u_j + \tau_{j\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j\phi} \frac{1}{r \sin \theta} \partial_\phi u_j \right) + \bar{\rho} \epsilon_{\text{nuc}} \end{aligned} \quad (164)$$

$$\partial_t \bar{\rho} \epsilon_I = - \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} u_r \epsilon_I]) - \bar{P} \bar{d} + \frac{1}{r^2} \partial_r (r^2 [\chi \partial_r T]) + \tau_{ji} \partial_i u_j + \bar{\rho} \epsilon_{\text{nuc}} \quad (165)$$

$$\partial_t \bar{\rho} \tilde{\epsilon}_I = - \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} u_r \tilde{\epsilon}_I]) - \bar{P} \bar{d} + \frac{1}{r^2} \partial_r (r^2 [\chi \partial_r T]) + \tau_{ji} \partial_i u_j + \bar{\rho} \epsilon_{\text{nuc}} \quad (166)$$

$$\partial_t \bar{\rho} \tilde{\epsilon}_I = - \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} u_r \tilde{\epsilon}_I]) - \frac{1}{r^2} \partial_r (r^2 [\bar{\rho} u''_r \tilde{\epsilon}'_I]) - \bar{P} \bar{d} + \frac{1}{r^2} \partial_r (r^2 [\chi \partial_r T]) + \bar{\tau}_{ji} \partial_i \bar{u}_j + \bar{\tau}'_{ji} \partial_i u'_j + \bar{\rho} \tilde{\epsilon}_{\text{nuc}} \quad \text{we neglect } \bar{\tau} \quad (167)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_I = - \nabla_r f_I - \bar{P} \bar{d} + \nabla_r f_T + \bar{\tau}'_{ji} \partial_i u'_j + \bar{\rho} \tilde{\epsilon}_{\text{nuc}} \quad (168)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_I = - \nabla_r (f_I + f_T) - \bar{P} \bar{d} - \bar{P}' \bar{d}' + \varepsilon_k + \bar{\rho} \tilde{\epsilon}_{\text{nuc}} \quad (169)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_I = - \nabla_r (f_I + f_T) - \bar{P} \bar{d} - W_P + \varepsilon_k + \bar{\rho} \tilde{\epsilon}_{\text{nuc}} \quad (170)$$

21.6 Mean kinetic energy equation

We begin by instantaneous 3D kinetic energy equation and apply "ensemble" (space-time) averaging (Sect.1):

$$\begin{aligned} \partial_t (\rho \epsilon_K) = & - \left(\frac{1}{r^2} \partial_r (r^2 (\rho u_r \epsilon_K - u_j \tau_{jr})) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta (\rho u_\theta \epsilon_K - u_j \tau_{j\theta})) + \frac{1}{r \sin \theta} \partial_\phi (\rho u_\phi \epsilon_K - u_j \tau_{j\phi}) \right) - \\ & - \left(\frac{1}{r^2} \partial_r (r^2 [P u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [P u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi (P u_\phi) \right) + P \left(\frac{1}{r^2} \partial_r (r^2 [u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [u_\phi] \right) - \\ & - \left(\tau_{jr} \partial_r u_j + \tau_{j\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j\phi} \frac{1}{r \sin \theta} \partial_\phi u_j \right) - \rho (u_r \partial_r \Phi + u_\theta \frac{1}{r} \partial_\theta \Phi + u_\phi \frac{1}{r \sin \theta} \partial_\phi \Phi) \end{aligned} \quad (171)$$

$$\begin{aligned} \partial_t \overline{\rho \epsilon_K} = & - \left(\frac{1}{r^2} \partial_r [r^2 (\rho u_r \epsilon_K - u_j \tau_{jr})] + \frac{1}{r \sin \theta} \partial_\theta [\sin \theta (\rho u_\theta \epsilon_K - u_j \tau_{j\theta})] + \frac{1}{r \sin \theta} \partial_\phi [\rho u_\phi \epsilon_K - u_j \tau_{j\phi}] \right)^0 - \\ & - \left(\frac{1}{r^2} \partial_r (r^2 [P u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [P u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [P u_\phi] \right)^0 + P \left(\frac{1}{r^2} \partial_r (r^2 [u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [u_\phi] \right) - \\ & - \left(\tau_{jr} \partial_r u_j + \tau_{j\theta} \frac{1}{r} \partial_\theta u_j + \tau_{j\phi} \frac{1}{r \sin \theta} \partial_\phi u_j \right) + \rho (u_r g_r + \cancel{u_\theta g_\theta} + \cancel{u_\phi g_\phi})^0 \end{aligned} \quad (172)$$

$$\partial_t \overline{\rho \epsilon_K} = - \frac{1}{r^2} \partial_r [r^2 (\overline{\rho u_r \epsilon_K})] - \frac{1}{r^2} \partial_r [r^2 (\overline{u_j \tau_{jr}})] - \frac{1}{r^2} \partial_r (r^2 [\overline{P u_r}]) + \overline{P d} - \overline{\tau_{ji} \partial_i u_j} + \overline{\rho u_r g_r} \quad (173)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = - \frac{1}{r^2} \partial_r [r^2 (\overline{\rho u'_r \epsilon''_K})] - \frac{1}{r^2} \partial_r [r^2 (\overline{u'_j \tau'_{jr}})] - \frac{1}{r^2} \partial_r [r^2 (\overline{u'_j \tau'_{jr}})] - \frac{1}{r^2} \partial_r (r^2 [\overline{P u_r}]) - \frac{1}{r^2} \partial_r (r^2 [\overline{P' u'_r}]) + \overline{P} \bar{d} + \overline{P' d'} - \varepsilon_k - \bar{\rho} \overline{u'_r} \tilde{g}_r + \bar{\rho} \overline{u_r} \tilde{g}_r \quad (174)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = - \frac{1}{r^2} \partial_r [r^2 (\overline{\rho u'_r \epsilon''_K})] - \frac{1}{r^2} \partial_r [r^2 (\overline{u'_j \tau'_{jr}})] - \frac{1}{r^2} \partial_r (r^2 [\overline{P u_r}]) - \frac{1}{r^2} \partial_r (r^2 [\overline{P' u'_r}]) + \overline{P} \bar{d} + W_P - \varepsilon_k + W_b + \bar{\rho} \overline{u_r} \tilde{g}_r \quad (175)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = - \nabla_r \overline{\rho u'_r \epsilon''_K} - \nabla_r f_\tau - (\overline{P} \nabla_r \bar{u}_r + \bar{u}_r \partial_r \overline{P}) - \nabla_r f_P + \overline{P} \bar{d} + W_P - \varepsilon_k + W_b + \bar{\rho} \overline{u_r} \tilde{g}_r \quad (176)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = - \nabla_r \overline{\rho u'_r \epsilon''_K} - \nabla_r f_\tau - \overline{P} \bar{d} - \bar{\rho} \overline{u_r} \tilde{g}_r - \nabla_r f_P + \overline{P} \bar{d} + W_P - \varepsilon_k + W_b + \bar{\rho} \overline{u_r} \tilde{g}_r \quad (177)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = - \nabla_r \overline{\rho u''_r \epsilon''_K} - \nabla_r (f_\tau + f_P) + W_P - \varepsilon_k + W_b \quad (178)$$

Second way:

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = + \bar{\rho} \tilde{D}_t \tilde{u}_i \tilde{u}_i + \bar{\rho} \tilde{D}_t \tilde{u}'_i \tilde{u}''_i \quad (179)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = + \bar{\rho} \tilde{D}_t \tilde{u}_i \tilde{u}_i + \bar{\rho} \tilde{D}_t \tilde{k} \quad (180)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_K = - \nabla_r (f_k + f_P + f_\tau) - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + W_P - \varepsilon_k + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) \quad (181)$$

where equation for the \tilde{k} is derived later.

21.7 Mean total energy equation

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_t = + \bar{\rho} \tilde{D}_t \tilde{\epsilon}_I + \bar{\rho} \tilde{D}_t \tilde{\epsilon}_K \quad (182)$$

$$\bar{\rho} \tilde{D}_t \tilde{\epsilon}_t = - \nabla_r (f_I + f_T + f_k + f_P + f_\tau) - \overline{P} \bar{d} - \tilde{R}_{ir} \partial_r \tilde{u}_i + W_b + S + \bar{\rho} \tilde{D}_t (\tilde{u}_i \tilde{u}_i / 2) \quad (183)$$

21.8 Mean pressure equation

We begin by deriving 3D instantaneous pressure equation and then apply "ensemble" (space-time) averaging (Sect.1):

$$dP = \frac{\partial P}{\partial \rho} \Big|_{\epsilon_I} d\rho + \frac{\partial P}{\partial \epsilon_I} \Big|_{\rho} d\epsilon_I = \frac{P}{\rho} (1 - \Gamma_3 + \Gamma_1) d\rho + \rho (\Gamma_3 - 1) d\epsilon_I \quad (184)$$

$$D_t P = + \frac{P}{\rho} (1 - \Gamma_3 + \Gamma_1) D_t \rho + (\Gamma_3 - 1) \rho D_t \epsilon_I \quad (185)$$

$$D_t P = - (1 - \Gamma_3 + \Gamma_1) P d + (\Gamma_3 - 1) (-P d + \mathcal{S} + \nabla \cdot F_T + \tau_{ij} \partial_i u_j) \quad (186)$$

$$\partial_t P = - u_n \partial_n P - (1 - \Gamma_3 + \Gamma_1) P d + (\Gamma_3 - 1) (-P d + \mathcal{S} + \nabla \cdot F_T + \tau_{ij} \partial_i u_j) \quad (187)$$

$$\partial_t P = - \left(\frac{1}{r^2} \partial_r (r^2 [P u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [P u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [P u_\phi] \right) + (1 - \Gamma_1) P d + (\Gamma_3 - 1) (\mathcal{S} + \nabla \cdot F_T + \tau_{ij} \partial_i u_j) \quad (188)$$

$$\partial_t \bar{P} = - \left(\frac{1}{r^2} \partial_r (r^2 [P u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [P u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [P u_\phi] \right)^0 + (1 - \Gamma_1) \bar{P} d + (\Gamma_3 - 1) (\mathcal{S} + \nabla \cdot F_T + \tau_{ij} \partial_i u_j) \quad (189)$$

$$\partial_t \bar{P} = - \frac{1}{r^2} \partial_r (r^2 [\bar{P} u_r]) - \frac{1}{r^2} \partial_r (r^2 [\bar{P}' u'_r]) + (1 - \Gamma_1) \bar{P} \bar{d} + (1 - \Gamma_1) \bar{P}' \bar{d}' + (\Gamma_3 - 1) (\mathcal{S} + \frac{1}{r^2} \partial_r (r^2 \chi \partial_r T) + \tau'_{ij} \partial_i u'_j + \tau'_{ij} \partial_i u'_j) \quad (190)$$

$$\partial_t \bar{P} = - \nabla_r \bar{P} \bar{u}_r - \nabla_r f_P + (1 - \Gamma_1) \bar{P} \bar{d} + (1 - \Gamma_1) W_P + (\Gamma_3 - 1) (\mathcal{S} + \nabla_r f_T + \varepsilon_k) \quad (191)$$

$$\partial_t \bar{P} = - \bar{u}_r \partial_r \bar{P} - \bar{P} \bar{d} - \nabla_r f_P + (1 - \Gamma_1) \bar{P} \bar{d} + (1 - \Gamma_1) W_P + (\Gamma_3 - 1) (\bar{\mathcal{S}} + \nabla_r f_T + \varepsilon_k) \quad (192)$$

$$\partial_t \bar{P} + \bar{u}_r \partial_r \bar{P} = - \nabla_r f_P - \Gamma_1 \bar{P} \bar{d} + (1 - \Gamma_1) W_P + (\Gamma_3 - 1) (\mathcal{S} + \nabla_r f_T + \varepsilon_k) \quad (193)$$

$$\textcolor{red}{\partial_t \bar{P} = - \nabla_r f_P - \Gamma_1 \bar{P} \bar{d} + (1 - \Gamma_1) W_P + (\Gamma_3 - 1) (\mathcal{S} + \nabla_r f_T + \varepsilon_k)} \quad (194)$$

21.9 Mean enthalpy equation

We start from the total energy equation, where we can substitute $\rho \epsilon_t = \rho h + \rho \epsilon_k - P$ (for clarity reasons we use here more compact vector notation):

$$\partial_t \epsilon_t + \vec{\nabla} \cdot ((\rho \epsilon_t + P) \vec{u}) = \rho \vec{u} \cdot \vec{g} + \vec{\nabla} \cdot F_T + \mathcal{S} \quad (195)$$

$$\partial_t (\rho h + \rho \epsilon_k - P) + \vec{\nabla} \cdot (\rho h \vec{u} + \rho \epsilon_k \vec{u}) = \rho \vec{u} \cdot \vec{g} + \vec{\nabla} \cdot F_T + \mathcal{S} \quad (196)$$

$$\partial_t \rho h + \textcolor{brown}{\partial_t \rho \epsilon_k} - \textcolor{blue}{\partial_t P} = - \vec{\nabla} \cdot (\rho h \vec{u} + \rho \epsilon_k \vec{u}) + \rho \vec{u} \cdot \vec{g} + \vec{\nabla} \cdot F_T + \mathcal{S} \quad (197)$$

$$\partial_t \rho h + \left[- \vec{\nabla} \cdot (\rho \epsilon_k \vec{u}) - \vec{\nabla} \cdot (P \vec{u}) + P (\vec{\nabla} \cdot \vec{u}) + \rho \vec{u} \cdot \vec{g} + \nabla_i u_j \tau_{ji} \right] - \left[- \vec{\nabla} \cdot (P \vec{u}) + (1 - \Gamma_1) P \vec{\nabla} \cdot \vec{u} + (\Gamma_3 - 1) (\mathcal{S} + \vec{\nabla} \cdot F_T + \tau_{ij} \partial_j u_i) \right] = \quad (198)$$

$$= - \vec{\nabla} \cdot (\rho h \vec{u} + \rho \epsilon_k \vec{u}) + \rho \vec{u} \cdot \vec{g} + \vec{\nabla} \cdot F_T + \mathcal{S} \quad (199)$$

$$\partial_t \rho h + \left[- \vec{\nabla} \cdot (\rho \epsilon_k \vec{u}) - \vec{\nabla} \cdot (P \vec{u}) + P (\vec{\nabla} \cdot \vec{u}) + \rho \vec{u} \cdot \vec{g} + \nabla_i u_j \tau_{ji} \right] + \textcolor{blue}{\vec{\nabla} \cdot (P \vec{u}) - P \vec{\nabla} \cdot \vec{u} + \Gamma_1 P \vec{\nabla} \cdot \vec{u} - \Gamma_3 (\mathcal{S} + \vec{\nabla} \cdot F_T) + (\mathcal{S} + \vec{\nabla} \cdot F_T) -} = \quad (200)$$

$$- (\Gamma_3 - 1) \tau_{ij} \partial_j u_i = - \vec{\nabla} \cdot (\rho h \vec{u} + \rho \epsilon_k \vec{u}) + \rho \vec{u} \cdot \vec{g} + \vec{\nabla} \cdot F_T + \mathcal{S} \quad (201)$$

So, from the above we have:

$$\partial_t \rho h + \nabla_i u_j \tau_{ji} + \Gamma_1 P \vec{\nabla} \cdot \vec{u} - \Gamma_3 \mathcal{S} - \Gamma_3 \vec{\nabla} \cdot F_T - (\Gamma_3 - 1) \tau_{ij} \partial_j u_i = -\vec{\nabla} \cdot (\rho h \vec{u}) \quad (202)$$

$$\rho D_t h = -\Gamma_1 P \vec{\nabla} \cdot \vec{u} + \Gamma_3 \mathcal{S} + \Gamma_3 \vec{\nabla} \cdot F_T - \nabla_i u_j \tau_{ji} + (\Gamma_3 - 1) \tau_{ij} \partial_j u_i \quad (203)$$

$$\bar{\rho} \tilde{D}_t \tilde{h} = -\nabla_r f_h - \Gamma_1 \bar{P} \bar{d} - \Gamma_1 W_P + \Gamma_3 \mathcal{S} + \Gamma_3 \nabla_r f_T - \nabla_r \bar{u}_j \tau_{jr} + (\Gamma_3 - 1) \bar{\tau}_{ij} \partial_j u_i \quad (204)$$

$$\bar{\rho} \tilde{D}_t \tilde{h} = -\nabla_r (f_h + f_\tau) - \Gamma_1 \bar{P} \bar{d} - \Gamma_1 W_P + \Gamma_3 \mathcal{S} + \Gamma_3 \nabla_r f_T + (\Gamma_3 - 1) \varepsilon_k \quad (205)$$

21.10 Mean temperature equation

We begin by deriving 3D instantaneous temperature equation and then apply "ensemble" (space-time) averaging (Sect.1):

$$dT = \frac{\partial T}{\partial \rho} \Big|_{\epsilon_I} d\rho + \frac{\partial T}{\partial \epsilon_I} \Big|_\rho d\epsilon_I = \left(\frac{T}{\rho} (\Gamma_3 - 1) - \frac{P}{\rho^2} \frac{1}{c_v} \right) d\rho + \frac{1}{c_v} d\epsilon_I \quad (206)$$

$$D_t T = + \frac{T}{\rho} (\Gamma_3 - 1) D_t \rho - \frac{P}{\rho^2} \frac{1}{c_v} D_t \rho + \frac{1}{c_v} D_t \epsilon_I \quad (207)$$

$$D_t T = - \frac{T}{\rho} (\Gamma_3 - 1) (\rho d) + \frac{P}{\rho^2} \frac{1}{c_v} (\rho d) + \frac{1}{c_v} \left(-\frac{Pd}{\rho} + \frac{\nabla \cdot F_T}{\rho} + \frac{\tau_{ij} \partial_j u_i}{\rho} + \frac{\mathcal{S}}{\rho} \right) \quad (208)$$

$$D_t T = -(\Gamma_3 - 1) T d + \frac{\nabla \cdot F_T}{c_v \rho} + \frac{\tau_{ij} \partial_j u_i}{c_v \rho} + \frac{\mathcal{S}}{c_v \rho} \quad (209)$$

$$\partial_t T = -u_n \partial_n T - (\Gamma_3 - 1) T d + \frac{\nabla \cdot F_T}{c_v \rho} + \frac{\tau_{ij} \partial_j u_i}{c_v \rho} + \frac{\mathcal{S}}{c_v \rho} \quad (210)$$

$$\partial_t T = - \left(\frac{1}{r^2} \partial_r (r^2 [T u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [T u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [T u_\phi] \right) + T d - (\Gamma_3 - 1) T d + \frac{\nabla \cdot F_T}{c_v \rho} + \frac{\tau_{ij} \partial_j u_i}{c_v \rho} + \frac{\mathcal{S}}{c_v \rho} \quad (211)$$

$$\partial_t \bar{T} = - \left(\frac{1}{r^2} \partial_r (r^2 [\bar{T} u_r]) + \overbrace{\frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\bar{T} u_\theta]) + \frac{1}{r \sin \theta} \partial_\phi [\bar{T} u_\phi]}^{0} \right) + \bar{T} d - (\Gamma_3 - 1) \bar{T} d + \frac{\nabla \cdot F_T}{c_v \rho} + \frac{\tau_{ij} \partial_j u_i}{c_v \rho} + \frac{\mathcal{S}}{c_v \rho} \quad (212)$$

$$\partial_t \bar{T} = -\nabla_r \bar{T} \bar{u}_r - \nabla_r f_T + \bar{T} d - \Gamma_3 \bar{T} d + \bar{T} d + \overline{(\nabla \cdot F_T)/(c_v \rho)} + \overline{(\tau_{ij} \partial_j u_i)/(c_v \rho)} + \overline{\mathcal{S}/(c_v \rho)} \quad (213)$$

$$\bar{u}_r \partial_r \bar{T} = -\bar{T} \bar{d} - \nabla_r f_T + \bar{T} d - \Gamma_3 \bar{T} d + \bar{T} d + \overline{(\nabla \cdot F_T)/(c_v \rho)} + \overline{(\tau_{ij} \partial_j u_i)/(c_v \rho)} + \overline{\mathcal{S}/(c_v \rho)} \quad (214)$$

$$\bar{D}_t \bar{T} = -\bar{T} \bar{d} - \nabla_r f_T + \bar{T} d - \Gamma_3 \bar{T} d + \bar{T} d + \overline{(\nabla \cdot F_T)/(c_v \rho)} + \overline{(\tau_{ij} \partial_j u_i)/(c_v \rho)} + \overline{\mathcal{S}/(c_v \rho)} \quad (215)$$

$$\bar{D}_t \bar{T} = -\bar{T} \bar{d} - \nabla_r f_T + \bar{T} d - \Gamma_3 \bar{T} d + \bar{T} \bar{d} + \overline{T' d'} + \overline{(\nabla \cdot F_T)/(c_v \rho)} + \overline{(\tau_{ij} \partial_j u_i)/(c_v \rho)} + \overline{\mathcal{S}/(c_v \rho)} \quad (216)$$

$$\bar{D}_t \bar{T} = -\nabla_r f_T + \bar{T} d - \Gamma_3 \bar{T} d + \bar{T}' d' + \overline{(\nabla \cdot F_T)/(c_v \rho)} + \overline{(\tau_{ij} \partial_j u_i)/(c_v \rho)} + \overline{\mathcal{S}/(c_v \rho)} \quad (217)$$

$$\bar{D}_t \bar{T} = -\nabla_r f_T + \bar{T} \bar{d} + \bar{T}' d' - \Gamma_3 (\bar{T} \bar{d} + \bar{T}' d') + \bar{T}' d' + \overline{(\nabla \cdot F_T)/(c_v \rho)} + \overline{(\tau_{ij} \partial_j u_i)/(c_v \rho)} + \overline{\mathcal{S}/(c_v \rho)} \quad (218)$$

$$\bar{D}_t \bar{T} = -\nabla_r f_T + (1 - \Gamma_3) \bar{T} \bar{d} + (2 - \Gamma_3) \bar{T}' d' + \overline{(\nabla \cdot F_T)/(c_v \rho)} + \overline{(\tau_{ij} \partial_j u_i)/(c_v \rho)} + \overline{\mathcal{S}/(c_v \rho)} \quad (219)$$

21.11 Mean angular momentum equation (z-component)

Z component of the specific angular momentum is defined as $j_z = r \sin \theta u_\phi$. We begin by multiplying the instantaneous 3D azimuthal momentum equation by $r \sin \theta$, neglect viscosity and ϕ component of gravity and obtain (Sect.1):

$$r \sin \theta \partial_t (\rho u_\phi) = -r \sin \theta \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_\phi u_r - \tau_{\phi r}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta u_\phi - \tau_{\theta \phi}]) + \frac{1}{r \sin \theta} \partial_\phi ([\rho u_\phi^2 - \tau_{\phi \phi}]) + G_\phi^M + \frac{1}{r \sin \theta} \partial_\phi P \right) - \cancel{-r \sin \theta \rho \frac{1}{r \sin \theta} \partial_\phi \Phi}^0 \quad (220)$$

$$r \sin \theta \partial_t (\rho u_\phi) = -r \sin \theta \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_\phi u_r]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta u_\phi]) + \frac{1}{r \sin \theta} \partial_\phi ([\rho u_\phi^2]) + G_\phi^M + \frac{1}{r \sin \theta} \partial_\phi P \right) \quad (221)$$

$$\partial_t \rho j_z = -\frac{1}{r^2} \partial_r (r^2 \rho j_z u_r) - \frac{1}{r \sin \theta} \partial_\theta (\sin \theta \rho j_z u_\theta) - \frac{1}{r \sin \theta} \partial_\phi (\rho j_z u_\phi) - \partial_\phi P \quad (222)$$

$$\partial_t \overline{\rho j_z} = -\frac{1}{r^2} \partial_r (r^2 \overline{\rho j_z u_r}) - \cancel{\frac{1}{r \sin \theta} \partial_\theta (\sin \theta \overline{\rho j_z u_\theta})}^0 - \cancel{\frac{1}{r \sin \theta} \partial_\phi (\overline{\rho j_z u_\phi})}^0 - \cancel{\partial_\phi \overline{P}}^0 \quad (223)$$

$$\partial_t \overline{\rho j_z} = -\frac{1}{r^2} \partial_r (r^2 \overline{\rho j_z u_r}) \quad (224)$$

$$\partial_t \overline{\rho j_z} = -\frac{1}{r^2} \partial_r (r^2 \overline{\rho j_z} \widetilde{u_r}) - \frac{1}{r^2} \partial_r (r^2 \overline{\rho j_z''} \widetilde{u_r''}) \quad (225)$$

$$\partial_t \overline{\rho j_z} + \frac{1}{r^2} \partial_r (r^2 \overline{\rho j_z} \widetilde{u_r}) = -\frac{1}{r^2} \partial_r (r^2 \overline{\rho j_z''} \widetilde{u_r''}) \quad (226)$$

$$\overline{\rho D_t j_z} = -\nabla_r f_{j_z} \quad (227)$$

21.12 Mean α equation

We begin by 3D instantaneous composition equation and then apply "ensemble" (space-time) averaging (Sect.1):

$$\partial_t (\rho X_\alpha) = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r X_\alpha]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta X_\alpha]) + \frac{1}{r \sin \theta} \partial_\phi [\rho u_\phi X_\alpha] \right) + \rho \dot{X}_\alpha^{\text{nuc}} \quad \alpha = 1 \dots N_{\text{nuc}} \quad (228)$$

$$\partial_t \overline{\rho X_\alpha} = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r X_\alpha]) + \cancel{\frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\rho u_\theta X_\alpha])}^0 + \cancel{\frac{1}{r \sin \theta} \partial_\phi [\rho u_\phi X_\alpha]}^0 \right) + \overline{\rho \dot{X}_\alpha^{\text{nuc}}} \quad (229)$$

$$\partial_t \overline{\rho \widetilde{X}_\alpha} = -\frac{1}{r^2} \partial_r (r^2 [\overline{\rho u_r} \widetilde{X}_\alpha + \overline{\rho u_r''} \widetilde{X}_\alpha'']) + \overline{\rho \widetilde{X}_\alpha}^{\text{nuc}} \quad (230)$$

$$\partial_t \overline{\rho \widetilde{X}_\alpha} + \frac{1}{r^2} \partial_r (r^2 [\overline{\rho u_r} \widetilde{X}_\alpha]) = -\frac{1}{r^2} \partial_r (\overline{\rho u_r''} \widetilde{X}_\alpha'') + \overline{\rho \widetilde{X}_\alpha}^{\text{nuc}} \quad (231)$$

$$\overline{\rho D_t \widetilde{X}_\alpha} = -\nabla_r f_\alpha + \overline{\rho \widetilde{X}_\alpha}^{\text{nuc}} \quad (232)$$

21.13 Mean number of nucleons per isotope (A) equation

We begin by deriving 3D instantaneous A equation and then apply "ensemble" (space-time) averaging (Sect.1):

$$A = + \left(\sum_{\alpha} \frac{X_{\alpha}}{A_{\alpha}} \right)^{-1} \quad (233)$$

$$D_t A = + D_t \left(\sum_{\alpha} \frac{X_{\alpha}}{A_{\alpha}} \right)^{-1} = + D_t \frac{1}{\sum_{\alpha} (X_{\alpha}/A_{\alpha})} = - \frac{D_t \sum_{\alpha} (X_{\alpha}/A_{\alpha})}{[\sum_{\alpha} (X_{\alpha}/A_{\alpha})]^2} = - A^2 D_t \sum_{\alpha} \frac{X_{\alpha}}{A_{\alpha}} \quad (234)$$

$$D_t A = - A^2 D_t \sum_{\alpha} \frac{X_{\alpha}}{A_{\alpha}} = - A^2 \sum_{\alpha} \frac{A_{\alpha} D_t X_{\alpha} - X_{\alpha} D_t A_{\alpha}}{A_{\alpha}^2} = - A^2 \sum_{\alpha} \frac{A_{\alpha} D_t X_{\alpha}}{A_{\alpha}^2} \quad (235)$$

$$D_t A = - A^2 \sum_{\alpha} \frac{A_{\alpha} D_t X_{\alpha}}{A_{\alpha}^2} = - A^2 \sum_{\alpha} \frac{A_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}^2} = - A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (236)$$

$$\rho D_t A = - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (237)$$

$$\partial_t \rho A = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r A]) + \frac{1}{r \sin \theta} \partial_{\theta} (\sin \theta [\rho u_{\theta} A]) + \frac{1}{r \sin \theta} \partial_{\phi} [\rho u_{\phi} A] \right) - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (238)$$

$$\partial_t \overline{\rho A} = - \left(\overline{\frac{1}{r^2} \partial_r (r^2 [\rho u_r A])} + \overline{\frac{1}{r \sin \theta} \partial_{\theta} (\sin \theta [\rho u_{\theta} A])} + \overline{\frac{1}{r \sin \theta} \partial_{\phi} [\rho u_{\phi} A]} \right) - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (239)$$

$$\partial_t \overline{\rho A} = - \overline{\frac{1}{r^2} \partial_r (r^2 [\rho u_r A])} - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (240)$$

$$\partial_t \widetilde{\rho A} = - \overline{\frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r A}])} - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (241)$$

$$\partial_t \widetilde{\rho A} = - \overline{\frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r A}])} - \overline{\frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r' A'}])} - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (242)$$

$$\partial_t \widetilde{\rho A} + \overline{\frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r A}])} = - \overline{\frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r' A'}])} - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (243)$$

$$\rho \widetilde{D}_t \widetilde{A} = - \nabla_r f_A - \rho A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (244)$$

21.14 Mean charge per isotope (Z) equation

We begin by deriving 3D instantaneous Z equation and then apply "ensemble" (space-time) averaging (Sect.1):

$$Z = + A \sum_{\alpha} \frac{Z_{\alpha} A_{\alpha}}{A_{\alpha}} \quad (245)$$

$$D_t Z = + D_t \left(A \sum_i \frac{Z_{\alpha} A_{\alpha}}{A_{\alpha}} \right) = \sum_{\alpha} \frac{Z_{\alpha} X_{\alpha}}{A_{\alpha}} D_t A + A \sum_{\alpha} D_t \frac{Z_{\alpha} X_{\alpha}}{A_{\alpha}} \quad (246)$$

$$D_t Z = - \sum_{\alpha} \frac{Z_{\alpha} X_{\alpha}}{A_{\alpha}} A^2 \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + A \sum_{\alpha} \frac{A_{\alpha} D_t Z_{\alpha} X_{\alpha} - Z_{\alpha} X_{\alpha} D_t A_{\alpha}}{A_{\alpha}^2} \quad (247)$$

$$D_t Z = - Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + A \sum_{\alpha} \frac{A_{\alpha} D_t Z_{\alpha} X_{\alpha}}{A_{\alpha}^2} \quad (248)$$

$$D_t Z = - Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + A \sum_{\alpha} \frac{Z_{\alpha} D_t X_{\alpha} + X_{\alpha} D_t Z_{\alpha}}{A_{\alpha}^2} \quad (249)$$

$$D_t Z = - Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (250)$$

$$\rho D_t Z = - \rho Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + \rho A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (251)$$

$$\partial_t \bar{\rho} \bar{Z} = - \left(\frac{1}{r^2} \partial_r (r^2 [\rho u_r Z]) + \frac{1}{r \sin \theta} \partial_{\theta} (\sin \theta [\rho u_{\theta} Z]) + \frac{1}{r \sin \theta} \partial_{\phi} [\rho u_{\phi} Z] \right) \overset{0}{\longrightarrow} - \rho Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + \rho A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (252)$$

$$\partial_t \bar{\rho} \bar{Z} = - \frac{1}{r^2} \partial_r (r^2 [\rho u_r \bar{Z}]) - \rho Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + \rho A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (253)$$

$$\partial_t \bar{\rho} \widetilde{Z} = - \frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r Z}]) - \rho Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + \rho A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (254)$$

$$\partial_t \bar{\rho} \widetilde{Z} = - \frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r Z}]) - \frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u''_r Z''}]) - \rho Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + \rho A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (255)$$

$$\partial_t \bar{\rho} \widetilde{Z} + \frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u_r Z}]) = - \frac{1}{r^2} \partial_r (r^2 [\widetilde{\rho u''_r Z''}]) - \rho Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + \rho A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (256)$$

$$\bar{\rho} \widetilde{D}_t \widetilde{Z} = - \nabla_r f_Z - \rho Z A \sum_{\alpha} \frac{\dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} + \rho A \sum_{\alpha} \frac{Z_{\alpha} \dot{X}_{\alpha}^{\text{nuc}}}{A_{\alpha}} \quad (257)$$

21.15 Mean entropy equation

We can derive the mean entropy equation in the following way (Sect.1):

$$\rho D_t s = + (\nabla \cdot F_T + \mathcal{S} + \varepsilon_k) / T \quad (258)$$

$$\partial_t \rho s + \nabla_r (\rho s u_r) = + (\nabla \cdot F_T + \mathcal{S} + \varepsilon_k) / T \quad (259)$$

$$\partial_t \bar{\rho} \bar{s} + \nabla_r \bar{\rho} \bar{u}_r \bar{s} = + \overline{(\nabla \cdot F_T + \mathcal{S} + \varepsilon_k) / T} \quad (260)$$

$$\partial_t \bar{\rho} \bar{s} + \nabla_r (\bar{\rho} \bar{u}_r \bar{s}) = - \nabla_r (\bar{\rho} \bar{s}'' \bar{u}_r'') + \overline{\nabla \cdot F_T / T} + \overline{\mathcal{S} / T} + \overline{\varepsilon_k / T} \quad (261)$$

$$\bar{\rho} \tilde{D}_t \tilde{s} = - \nabla_r f_s + \overline{\nabla \cdot F_T / T} + \overline{\mathcal{S} / T} + \overline{\varepsilon_k / T} \quad (262)$$

22 General formula for second and third order moments and variances

22.1 Second-order moments

In order to calculate evolution equations for correlations of two arbitrary fluctuations, we can derive the following general formula.

$$\begin{aligned} \bar{\rho} \widetilde{D}_t c'' d''' - \overline{\rho D_t c'' d'''} &= \bar{\rho} (\partial_t \widetilde{c'' d'''} + \widetilde{u}_n \partial_n \widetilde{c'' d'''}) - \overline{\rho (\partial_t c'' d''' + u_n \partial_n c'' d''')} = \bar{\rho} \partial_t \widetilde{c'' d'''} + \bar{\rho} \widetilde{u}_n \partial_n \widetilde{c'' d'''} - \overline{\rho \partial_t c'' d'''} - \overline{\rho u_n \partial_n c'' d'''} = \\ &= \bar{\rho} \partial_t \widetilde{c'' d'''} + \bar{\rho} \widetilde{u}_n \partial_n \widetilde{c'' d'''} - (\overline{\partial_t \rho c'' d'''} - \overline{c'' d''' \partial_t \rho}) - \overline{\rho u_n \partial_n c'' d'''} = \end{aligned} \quad (263)$$

$$= \bar{\rho} \partial_t \widetilde{c'' d'''} + \bar{\rho} \widetilde{u}_n \partial_n \widetilde{c'' d'''} - \partial_t \bar{\rho} \widetilde{c'' d'''} - \overline{c'' d''' \partial_n \rho u_n} - \overline{\rho u_n \partial_n c'' d'''} = \quad (264)$$

$$= \bar{\rho} \partial_t \widetilde{c'' d'''} + \bar{\rho} \widetilde{u}_n \partial_n \widetilde{c'' d'''} - (\bar{\rho} \partial_t \widetilde{c'' d'''} + \widetilde{c'' d''' \partial_t \rho}) - \overline{c'' d''' \partial_n \rho u_n} - \overline{\rho u_n \partial_n c'' d'''} = \quad (265)$$

$$= \bar{\rho} \partial_t \widetilde{c'' d'''} + \bar{\rho} \widetilde{u}_n \partial_n \widetilde{c'' d'''} - (\bar{\rho} \partial_t \widetilde{c'' d'''} - \widetilde{c'' d''' \partial_n \bar{\rho} \widetilde{u}_n}) - \overline{c'' d''' \partial_n \rho u_n} - \overline{\rho u_n \partial_n c'' d'''} = \quad (266)$$

$$= \bar{\rho} \partial_t \widetilde{c'' d'''} - \bar{\rho} \partial_t \widetilde{c'' d'''} + \bar{\rho} \widetilde{u}_n \partial_n \widetilde{c'' d'''} + \widetilde{c'' d''' \partial_n \bar{\rho} \widetilde{u}_n} - \overline{\partial_n \rho u_n c'' d'''} = \quad (267)$$

$$= \partial_n \bar{\rho} \widetilde{u}_n \widetilde{c'' d'''} - (\overline{\partial_n \rho \widetilde{u}_n c'' d'''} + \overline{\partial_n \rho u_n'' c'' d'''}) = -\overline{\partial_n \rho u_n'' c'' d'''} \quad (268)$$

$$\bar{\rho} \widetilde{D}_t \widetilde{c'' d'''} = \overline{\rho D_t c'' d'''} - \overline{\partial_n \rho u_n'' c'' d'''} = \overline{c'' \rho D_t d'''} + \overline{d''' \rho D_t c''} - \overline{\partial_n \rho u_n'' c'' d'''} \quad (269)$$

$$\rho D_t c'' = \rho D_t c - \rho D_t \tilde{c} = \rho D_t c - \rho \widetilde{D}_t \tilde{c} - \rho u_n'' \partial_n \tilde{c} = \rho D_t c - \frac{\rho}{\bar{\rho}} [\bar{\rho} \widetilde{D}_t \tilde{c}] - \rho u_n'' \partial_n \tilde{c} \quad (270)$$

$$\rho D_t d'' = \rho D_t d - \rho D_t \tilde{d} = \rho D_t d - \rho \widetilde{D}_t \tilde{d} - \rho u_n'' \partial_n \tilde{d} = \rho D_t d - \frac{\rho}{\bar{\rho}} [\bar{\rho} \widetilde{D}_t \tilde{d}] - \rho u_n'' \partial_n \tilde{d} \quad (271)$$

$$\bar{\rho} \widetilde{D}_t \widetilde{c'' d'''} = \overline{c'' \left(\rho D_t d - \frac{\rho}{\bar{\rho}} [\bar{\rho} \widetilde{D}_t \tilde{d}] - \rho u_n'' \partial_n \tilde{d} \right)} + \overline{d''' \left(\rho D_t c - \frac{\rho}{\bar{\rho}} [\bar{\rho} \widetilde{D}_t \tilde{c}] - \rho u_n'' \partial_n \tilde{c} \right)} - \overline{\partial_n \rho c'' d''' u_n''} \quad (272)$$

$$\bar{\rho} \widetilde{D}_t \widetilde{c'' d'''} = +\overline{c'' \rho D_t d} - \overline{\rho c'' u_n'' \partial_n \tilde{d}} + \overline{d''' \rho D_t c} - \overline{\rho d''' u_n'' \partial_n \tilde{c}} - \overline{\partial_n \rho c'' d''' u_n''} \quad (273)$$

22.2 Third-order moments

In order to calculate evolution equations for correlations of three arbitrary fluctuations, we can derive the following general formula.

$$\bar{\rho} \tilde{D}_t c'' \widetilde{d''} e'' - \overline{\rho D_t c'' d'' e''} = \bar{\rho} (\partial_t c'' \widetilde{d''} e'' + \tilde{u}_n \partial_n c'' \widetilde{d''} e'') - \overline{\rho (\partial_t c'' d'' e'' + u_n \partial_n c'' d'' e'')} = \quad (274)$$

$$= \bar{\rho} \partial_t c'' \widetilde{d''} e'' + \bar{\rho} \tilde{u}_n \partial_n c'' \widetilde{d''} e'' - \overline{\rho \partial_t c'' d'' e''} - \overline{\rho u_n \partial_n c'' d'' e''} = \quad (275)$$

$$= \bar{\rho} \partial_t c'' \widetilde{d''} e'' + \bar{\rho} \tilde{u}_n \partial_n c'' \widetilde{d''} e'' - (\partial_t \rho c'' \widetilde{d''} e'' - \overline{c'' d'' e'' \partial_t \rho}) - \overline{\rho u_n \partial_n c'' d'' e''} = \quad (276)$$

$$= \bar{\rho} \partial_t c'' \widetilde{d''} e'' + \bar{\rho} \tilde{u}_n \partial_n c'' \widetilde{d''} e'' - \partial_t \bar{\rho} c'' \widetilde{d''} e'' - (\overline{c'' d'' e'' \partial_n \rho u_n} + \overline{\rho u_n \partial_n c'' d'' e''}) = \quad (277)$$

$$= \bar{\rho} \partial_t c'' \widetilde{d''} e'' + \bar{\rho} \tilde{u}_n \partial_n c'' \widetilde{d''} e'' - (\bar{\rho} \partial_t c'' \widetilde{d''} e'' + \overline{c'' d'' e'' \partial_t \bar{\rho}}) - \overline{\partial_n c'' d'' e'' \rho u_n} = \quad (278)$$

$$= \bar{\rho} \tilde{u}_n \partial_n c'' \widetilde{d''} e'' + \overline{c'' d'' e'' \partial_n \bar{\rho} \tilde{u}_n} - \overline{\partial_n c'' d'' e'' \rho \tilde{u}_n} - \overline{\partial_n c'' d'' e'' \rho u_n''} = \quad (279)$$

$$= -\overline{\partial_n c'' d'' e'' \rho u_n''} \quad (280)$$

$$= -\overline{\partial_n c'' d'' e'' \rho u_n''} \quad (281)$$

$$\overline{\rho D_t c'' d'' e''} = \overline{\rho c'' d'' D_t e''} + \overline{\rho c'' e'' D_t d''} + \overline{\rho d'' e'' D_t c''} \quad (282)$$

$$\overline{c'' d'' \rho D_t e''} = \overline{c'' d'' \rho D_t e} - \overline{c'' d'' \rho D_t \tilde{e}} = \overline{c'' d'' \rho D_t e} - \overline{c'' d'' \rho (\partial_t \tilde{e} + u_n \partial_n \tilde{e})} = \quad (283)$$

$$= \overline{c'' d'' \rho D_t e} - \overline{c'' d'' \rho \partial_t \tilde{e}} - \overline{c'' d'' \rho u_n \partial_n \tilde{e}} = \overline{c'' d'' \rho D_t e} - \overline{\rho c'' \widetilde{d''} \partial_t \tilde{e}} - (c'' d'' \rho \tilde{u}_n \partial_n \tilde{e} + \overline{c'' d'' \rho u_n'' \partial_n \tilde{e}}) = \quad (284)$$

$$= \overline{c'' d'' \rho D_t e} - (\overline{\rho c'' \widetilde{d''} \partial_t \tilde{e}} + \overline{\rho c'' \widetilde{d''} \tilde{u}_n \partial_n \tilde{e}}) - \overline{\rho c'' \widetilde{d''} u_n'' \partial_n \tilde{e}} = \quad (285)$$

$$= \overline{c'' d'' \rho D_t e} - \overline{\rho c'' \widetilde{d''} \tilde{D}_t \tilde{e}} - \overline{\rho c'' \widetilde{d''} u_n'' \partial_n \tilde{e}} \quad (286)$$

$$\bar{\rho} \tilde{D}_t c'' \widetilde{d''} e'' = \overline{c'' d'' \rho D_t e} - \overline{\rho c'' \widetilde{d''} \tilde{D}_t \tilde{e}} - \overline{\rho c'' \widetilde{d''} u_n'' \partial_n \tilde{e}} + \quad (287)$$

$$+ \overline{c'' e'' \rho D_t \tilde{d}} - \overline{\rho c'' \widetilde{e''} \tilde{D}_t \tilde{d}} - \overline{\rho c'' \widetilde{e''} u_n'' \partial_n \tilde{d}} + \quad (288)$$

$$+ \overline{d'' e'' \rho D_t c} - \overline{\rho d'' e'' \tilde{D}_t \tilde{c}} - \overline{\rho d'' e'' u_n'' \partial_n \tilde{c}} - \quad (289)$$

$$- \overline{\partial_n c'' d'' e'' \rho u_n''} \quad (290)$$

22.3 Reynolds and Favrian variance

The Reynolds variance can be derived in following way:

$$\tilde{D}_t \overline{c'd'} - \overline{D_t c'd'} = +\partial_t \overline{c'd'} + \tilde{u}_n \partial_n \overline{c'd'} - (\partial_t \overline{c'd'} + \overline{u_n} \partial_n \overline{c'd'}) = \quad (291)$$

$$= +\partial_t \overline{c'd'} + \tilde{u}_n \partial_n \overline{c'd'} - \partial_t \overline{c'd'} - \tilde{u}_n \partial_n \overline{c'd'} - \overline{u''_n} \partial_n \overline{c'd'} = \quad (292)$$

$$= -\overline{u''_n} \partial_n \overline{c'd'} \quad (293)$$

Next step:

$$\tilde{D}_t \overline{c'd'} = \overline{D_t c'd'} - \overline{u''_n} \partial_n \overline{c'd'} = \overline{c'D_t d'} + \overline{d'D_t c'} - \overline{u''_n} \partial_n \overline{c'd'} \quad (294)$$

Next step:

$$D_t c' = D_t c - D_t \bar{c} = D_t c - \tilde{D}_t \bar{c} - u''_n \partial_n \bar{c} \quad (295)$$

$$D_t d' = D_t d - D_t \bar{c} = D_t d - \tilde{D}_t \bar{d} - u''_n \partial_n \bar{d} \quad (296)$$

Now let's put these equations in the Equation 294:

$$\tilde{D}_t \overline{c'd'} = +\overline{c'D_t d'} + \overline{d'D_t c'} - \overline{u''_n} \partial_n \overline{c'd'} = \quad (297)$$

$$= +\overline{c'(D_t d - \tilde{D}_t \bar{d} - u''_n \partial_n \bar{d})} + \overline{d'(D_t c - \tilde{D}_t \bar{c} - u''_n \partial_n \bar{c})} - \overline{u''_n} \partial_n \overline{c'd'} = \quad (298)$$

$$= +\overline{c'D_t d} - \overline{c'u''_n} \partial_n \bar{d} + \overline{d'D_t c} - \overline{d'u''_n} \partial_n \bar{c} - \overline{u''_n} \partial_n \overline{c'd'} = \quad (299)$$

$$= +\overline{c'D_t d} - \overline{c'u''_n} \partial_n \bar{d} + \overline{d'D_t c} - \overline{d'u''_n} \partial_n \bar{c} - \overline{\partial_n u''_n} \overline{c'd'} + \overline{c'd' \partial_n u''_n} \quad (300)$$

From this general formula by substituting $d = c$ we get:

$$\tilde{D}_t \overline{c'c'} = +2\overline{c'D_t c} - 2\overline{c'u''_n} \partial_n \bar{c} - \overline{u''_n} \partial_n \overline{c'c'} = \quad (301)$$

$$= +2\overline{c'D_t c} - 2\overline{c'u''_n} \partial_n \bar{c} - \overline{\partial_n u''_n} \overline{c'c'} + \overline{c'c' \partial_n u''_n} \quad (302)$$

The Favrian variance can be easily derived from general equation for second-order moments Equation 273 ie.

$$\overline{\rho \tilde{D}_t c'' d''} = +\overline{c'' \rho D_t d} - \overline{\rho c'' u''_n} \partial_n \tilde{d} + \overline{d'' \rho D_t c} - \overline{\rho d'' u''_n} \partial_n \tilde{c} - \overline{\partial_n \rho c'' d'' u''_n} \quad (303)$$

Now, substitute $d = c$ and you'll get the equation for Favrian variance:

$$\overline{\rho \tilde{D}_t c'' c''} = +2\overline{c'' \rho D_t c} - 2\overline{\rho c'' u''_n} \partial_n \tilde{c} - \overline{\partial_n \rho c'' c'' u''_n} \quad (304)$$

23 Derivation of second-order moments equations

23.1 Reynolds stress equation

We can derive the Reynolds stress equation using the general formula for second order moments, where we substitute c'' with u_i'' and d'' with u_j'' .

$$\bar{\rho} \widetilde{D}_t \widetilde{c''d''} = \overline{c'' \rho D_t d} - \bar{\rho} \widetilde{c'' u_n'' \partial_n d} + \overline{d'' \rho D_t c} - \bar{\rho} \widetilde{d'' u_n'' \partial_n c} - \overline{\partial_n \rho c'' d'' u_n''} \quad (305)$$

$$\underbrace{\bar{\rho} \widetilde{D}_t \widetilde{u_i'' u_j''}}_{\bar{\rho} \widetilde{D}_t (\widetilde{R}_{ij}/\bar{\rho})} = \overline{u_i'' \rho D_t u_j} - \underbrace{\bar{\rho} \widetilde{u_i'' u_n'' \partial_n \tilde{u}_j}}_{\widetilde{R}_{in} \partial_n \tilde{u}_j} + \overline{u_j'' \rho D_t u_i} - \underbrace{\bar{\rho} \widetilde{u_j'' u_n'' \partial_n \tilde{u}_i}}_{\widetilde{R}_{jn} \partial_n \tilde{u}_i} - \underbrace{\overline{\nabla \cdot \rho u_i'' u_j'' u_n''}}_{\nabla \cdot \rho u_i'' u_j'' u_n''} \quad (306)$$

So, the general formula for Reynolds stress \widetilde{R}_{ij} is:

$$\bar{\rho} \widetilde{D}_t (\widetilde{R}_{ij}/\bar{\rho}) = - \left(\widetilde{R}_{in} \partial_n \tilde{u}_j + \widetilde{R}_{jn} \partial_n \tilde{u}_i \right) - \left(\nabla_r \bar{\rho} u_i'' \widetilde{u_j'' u_r''} + \overline{G_{rr}^R} \right) + \overline{u_i'' \rho D_t u_j} + \overline{u_j'' \rho D_t u_i} \quad (307)$$

Mean equation for \widetilde{R}_{rr}

$$\bar{\rho} \widetilde{D}_t (\widetilde{R}_{rr}/\bar{\rho}) = - \left(\widetilde{R}_{rn} \partial_n \tilde{u}_r + \widetilde{R}_{rn} \partial_n \tilde{u}_r \right) - \left(\nabla_r 2 f_k^r + \overline{G_{rr}^R} \right) + 2 \overline{u_r'' \rho D_t u_r} \quad (308)$$

where

$$\overline{u_r'' \rho D_t u_r} = \overline{u_r'' \left(\frac{1}{r^2} \partial_r (r^2 [\tau_{rr}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\tau_{r\theta}]) + \frac{1}{r \sin \theta} \partial_\phi ([\tau_{r\phi}]) - G_r^M - \partial_r P + \rho g_r \right)} \quad (309)$$

$$\overline{u_r'' \rho D_t u_r} = \overline{u_r'' (\nabla_r \tau_{rr} + \nabla_\theta \tau_{r\theta} + \nabla_\phi \tau_{r\phi} - G_r^M - \partial_r P + \rho g_r)} \quad (310)$$

Some terms can be further manipulated in following way:

$$+ \overline{u''_r \nabla_r \tau_{rr}} = \overline{u''_r} \overline{\nabla_r \tau_{rr}} + \overline{u''_r \nabla_r \tau'_{rr}} = \overline{u''_r} \overline{\nabla_r \tau_{rr}} + \overset{0}{\nabla_r (\overline{u''_r \tau'_{rr}})} - \overline{\tau'_{rr}} \overline{\partial_r u''_r} \quad (311)$$

$$+ \overline{u''_r \nabla_\theta \tau_{r\theta}} = \overline{u''_r} \overline{\nabla_\theta \tau_{r\theta}} + \overset{0}{\overline{u''_r \nabla_\theta \tau'_{r\theta}}} = \overline{\nabla_\theta (u''_r \tau'_{r\theta})} - \overline{\tau'_{r\theta}} \frac{1}{r} \overline{\partial_\theta u''_r} \quad (312)$$

$$+ \overline{u''_r \nabla_\phi \tau_{r\phi}} = \overline{u''_r} \overline{\nabla_\phi \tau_{r\phi}} + \overset{0}{\overline{u''_r \nabla_\phi \tau'_{r\phi}}} = \overline{\nabla_\phi (u''_r \tau'_{r\phi})} - \overline{\tau'_{r\phi}} \frac{1}{r \sin \theta} \overline{\partial_\phi u''_r} \quad (313)$$

$$- \overline{u''_r G_r^M} = - \overline{u''_r G_r^M} \quad (314)$$

$$- \overline{u''_r \partial_r \bar{P}} = - \overline{u''_r \partial_r \bar{P}} - \overline{u''_r \partial_r \bar{P}'} = - \overline{u''_r \partial_r \bar{P}} - \overline{\nabla_r (u''_r P')} + \overline{P' \nabla_r u''_r} \quad (315)$$

$$+ \overline{u''_r \rho g_r} \sim \overline{u''_r \rho g_r} = 0 \quad (316)$$

Final equation is:

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{rr}/\bar{\rho} \right) = - 2 \tilde{R}_{rr} \partial_r \tilde{u}_r - \nabla_r \tilde{F}_{rrr}^R - \overline{G_{rr}^R} + 2 \nabla_r (\overline{u''_r \tau'_{rr}}) - 2 \overline{u''_r G_r^M} - 2 \overline{u''_r \partial_r \bar{P}} - 2 \nabla_r (\overline{u''_r P'}) + 2 \overline{P' \nabla_r u''_r} - \quad (317)$$

$$- 2 \left(\overline{\tau'_{rr} \partial_r u''_r} + \overline{\tau'_{r\theta}} \frac{1}{r} \overline{\partial_\theta u''_r} + \overline{\tau'_{r\phi}} \frac{1}{r \sin \theta} \overline{\partial_\phi u''_r} \right)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{rr}/\bar{\rho} \right) = - \nabla_r (2f_k^r + 2f_P + 2f_\tau^r) + 2W_b - 2 \tilde{R}_{rr} \partial_r \tilde{u}_r + 2 \overline{P' \nabla_r u''_r} - 2 \overline{u''_r G_r^M} - \overline{G_{rr}^R} - 2 \varepsilon_k^r \quad (318)$$

Mean equation for $\tilde{R}_{\theta\theta}$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\theta\theta}/\bar{\rho} \right) = - \left(\tilde{R}_{\theta n} \partial_n \tilde{u}_\theta + \tilde{R}_{\theta n} \partial_n \tilde{u}_\theta \right) - \left(\nabla_r 2f_k^\theta - \overline{G_{\theta\theta}^R} \right) + 2 \overline{u'_\theta \rho D_t u_\theta} \quad (319)$$

$$(320)$$

where

$$\overline{u'_\theta \rho D_t u_\theta} = \overline{u'_\theta} \left(\frac{1}{r^2} \partial_r (r^2 [\tau_{\theta r}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\tau_{\theta\theta}]) + \frac{1}{r \sin \theta} \partial_\phi [\tau_{\theta\phi}] \right) - G_\theta^M - \frac{1}{r} \partial_\theta P + \rho g_\theta \quad (321)$$

$$\overline{u'_\theta \rho D_t u_\theta} = \overline{u'_\theta} \left(\nabla_r \tau_{\theta r} + \nabla_\theta \tau_{\theta\theta} + \nabla_\phi \tau_{\theta\phi} - G_\theta^M - \frac{1}{r} \partial_\theta P + \rho g_\theta \right) \quad (322)$$

Some terms can be further manipulated in following way:

$$+\overline{u''_r \nabla_r \tau_{\theta r}} = \overline{\cancel{u''_r} \nabla_r \cancel{\tau_{\theta r}}} + \overline{0} - \overline{\tau'_{\theta r} \partial_r u''_\theta} \quad (323)$$

$$+\overline{u''_\theta \nabla_\theta \tau_{\theta\theta}} = -\overline{\tau'_{\theta\theta} \frac{1}{r} \partial_\theta u''_\theta} \quad (324)$$

$$+\overline{u''_\theta \nabla_\phi \tau_{\theta\phi}} = -\overline{\tau'_{\theta\phi} \frac{1}{r \sin \theta} \partial_\phi u''_\theta} \quad (325)$$

$$-\overline{u''_\theta G_\theta^M} = -\overline{u''_\theta G_\theta^M} \quad (326)$$

$$-\overline{u''_\theta \frac{1}{r} \partial_\theta P} = -\overline{u''_\theta \frac{1}{r} \partial_\theta \bar{P}} - \overline{u''_\theta \frac{1}{r} \partial_\theta P'} = -\overline{\cancel{u''_\theta} \frac{1}{r} \partial_\theta \bar{P}} - \overline{\frac{1}{r \sin \theta} \partial_\theta (\sin \theta u''_\theta P')} + \overline{P' \frac{1}{r \sin \theta} \partial_\theta (\sin \theta u''_\theta)} \quad (327)$$

$$+\overline{u''_\theta \rho g_\theta} = 0 \quad (328)$$

Final equation is:

$$\begin{aligned} \bar{\rho} \tilde{D}_t \left(\tilde{R}_{\theta\theta} / \bar{\rho} \right) = & -2 \tilde{R}_{\theta r} \partial_r \tilde{u}_\theta - \nabla_r 2 f_k^\theta - \overline{G_{\theta\theta}^R} + 2 \nabla_r (\overline{u''_\theta \tau'_{\theta r}}) - 2 \overline{u''_\theta G_\theta^M} + 2 \overline{P' \nabla_\theta u''_\theta} - \\ & - 2 \left(\overline{\tau'_{\theta r} \partial_r u''_\theta} - \overline{\tau'_{\theta\theta} \frac{1}{r} \partial_\theta u''_\theta} - \overline{\tau'_{\theta\phi} \frac{1}{r \sin \theta} \partial_\phi u''_\theta} \right) \end{aligned} \quad (329)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\theta\theta} / \bar{\rho} \right) = -\nabla_r (2 f_k^\theta + 2 f_\tau^\theta) - 2 \tilde{R}_{\theta r} \partial_r \tilde{u}_\theta + 2 \overline{P' \nabla_\theta u''_\theta} - 2 \overline{u''_\theta G_\theta^M} - \overline{G_{\theta\theta}^R} - 2 \varepsilon_k^\theta \quad (330)$$

Mean equation for $\tilde{R}_{\phi\phi}$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\phi\phi} / \bar{\rho} \right) = - \left(\tilde{R}_{\phi n} \partial_n \tilde{u}_\phi + \tilde{R}_{\phi n} \partial_n \tilde{u}_\phi \right) - \left(\nabla_r 2 f_k^\phi + \overline{G_{\phi\phi}^R} \right) + 2 \overline{u''_\phi \rho D_t u_\phi} \quad (331)$$

where

$$\overline{u''_\phi \rho D_t u_\phi} = \overline{u''_\phi \left(\frac{1}{r^2} \partial_r (r^2 [\tau_{\phi r}]) + \frac{1}{r \sin \phi} \partial_\phi (\sin \phi [\tau_{\phi\theta}]) + \frac{1}{r \sin \phi} \partial_\phi [\tau_{\phi\phi}] - G_\phi^M - \frac{1}{r \sin \theta} \partial_\phi P + \rho g_\phi \right)} \quad (332)$$

$$\overline{u''_\phi \rho D_t u_\phi} = \overline{u''_\phi \left(\nabla_r \tau_{\phi r} + \nabla_\theta \tau_{\phi\theta} + \nabla_\phi \tau_{\phi\phi} - G_\phi^M - \frac{1}{r \sin \theta} \partial_\phi P + \rho g_\phi \right)} \quad (333)$$

Some terms can be further manipulated in following way:

$$+\overline{u''_r \nabla_r \tau_{\phi r}} = \overline{\cancel{u''_r} \nabla_r \tau_{\phi r}}^0 + \nabla_r (\overline{u''_r \tau'_{\phi r}}) - \overline{\tau'_{\phi r} \partial_r u''_\phi} \quad (334)$$

$$+\overline{u''_r \nabla_\theta \tau_{\phi \theta}} = -\overline{\tau'_{\phi \theta} \frac{1}{r} \partial_\theta u''_\phi} \quad (335)$$

$$+\overline{u''_r \nabla_\phi \tau_{\phi \phi}} = -\overline{\tau'_{\phi \phi} \frac{1}{r \sin \theta} \partial_\phi u''_\phi} \quad (336)$$

$$-\overline{u''_r G_\phi^M} = -\overline{u''_r G_\phi^M} \quad (337)$$

$$-\overline{u''_r \frac{1}{r \sin \theta} \partial_\phi P} = -\overline{u''_r \frac{1}{r \sin \theta} \partial_\phi \bar{P}} - \overline{u''_r \frac{1}{r \sin \theta} \partial_\phi P'} = -\overline{\cancel{u''_r} \frac{1}{r \sin \theta} \partial_\phi \bar{P}}^0 - \overline{\cancel{\frac{1}{r \sin \theta} \partial_\phi (u''_r P')}}^0 + \overline{P' \frac{1}{r \sin \theta} \partial_\phi (u''_r)} \quad (338)$$

$$+\overline{u''_r \rho g_\phi} = 0 \quad (339)$$

Final equation is:

$$\begin{aligned} \bar{\rho} \tilde{D}_t \left(\tilde{R}_{\phi \phi} / \bar{\rho} \right) = & -2 \tilde{R}_{\phi r} \partial_r \tilde{u}_\phi - \nabla_r 2 f_k^\phi - \overline{G_{\phi \phi}^R} + 2 \nabla_r (\overline{u''_r \tau'_{\phi r}}) - 2 \overline{u''_r G_\phi^M} + 2 \overline{P' \nabla_\phi u''_\phi} - \\ & - 2 \left(\overline{\tau'_{\phi r} \partial_r u''_\phi} - \overline{\tau'_{\phi \theta} \frac{1}{r} \partial_\theta u''_\phi} - \overline{\tau'_{\phi \phi} \frac{1}{r \sin \theta} \partial_\phi u''_\phi} \right) \end{aligned} \quad (340)$$

$$\bar{\rho} \tilde{D}_t \left(\tilde{R}_{\phi \phi} / \bar{\rho} \right) = -\nabla_r (2 f_k^\phi + 2 f_\tau^\phi) - 2 \tilde{R}_{\phi r} \partial_r \tilde{u}_\phi + 2 \overline{P' \nabla_\phi u''_\phi} - 2 \overline{u''_r G_\phi^M} - \overline{G_{\phi \phi}^R} - 2 \varepsilon_k^\phi \quad (341)$$

23.2 Turbulent kinetic energy equations

$$\tilde{k} = +\frac{1}{2}\tilde{R}_{ii}/\bar{\rho} \quad (342)$$

$$\bar{\rho}\tilde{D}_t\tilde{k} = -\nabla_r(f_k + f_P) - \tilde{R}_{ir}\partial_r\tilde{u}_i + W_b + W_P + \mathcal{N}_k \quad (343)$$

$$\tilde{k}^r = +\frac{1}{2}\tilde{R}_{rr}/\bar{\rho} \quad (344)$$

$$\bar{\rho}\tilde{D}_t\tilde{k}^r = -\nabla_r(f_k^r + f_P) - \tilde{R}_{rr}\partial_r\tilde{u}_r + W_b + \overline{P'\nabla_r u''_r} + \mathcal{G}_k^r + \mathcal{N}_{kr} \quad (345)$$

$$\tilde{k}^h = +\tilde{k}_\theta + \tilde{k}_\phi = +\frac{1}{2}(\tilde{R}_{\theta\theta} + \tilde{R}_{\phi\phi})/\bar{\rho} \quad (346)$$

$$\bar{\rho}\tilde{D}_t\tilde{k}^h = -\nabla_r f_k^h - (\tilde{R}_{\theta r}\partial_r\tilde{u}_\theta + \tilde{R}_{\phi r}\partial_r\tilde{u}_\phi) + (\overline{P'\nabla_\theta u''_\theta} + \overline{P'\nabla_\phi u''_\phi}) + \mathcal{G}_k^h + \mathcal{N}_{kh} \quad (347)$$

23.3 Turbulent mass flux equation

The turbulent mass flux equation can be derived in the following way:

$$\rho D_t \tilde{c} - \rho \tilde{D}_t \tilde{c} = \rho \partial_t \tilde{c} + \rho u_n \partial_n \tilde{c} - [\rho \partial_t \tilde{c} + \rho \tilde{u}_n \partial_n \tilde{c}_n] = \rho(u_n - \tilde{u}_n) \partial_n \tilde{c} = \rho u_n'' \partial_n \tilde{c} \quad (348)$$

$$\rho D_t c'' = \rho D_t c - \rho D_t \tilde{c} = \rho D_t c - \rho \tilde{D}_t \tilde{c} - \rho u_n'' \partial_n \tilde{c} = \rho D_t c - \frac{\rho}{\bar{\rho}}[\bar{\rho} \tilde{D}_t \tilde{c}] - \rho u_n'' \partial_n \tilde{c} \quad (349)$$

$$\rho D_t u_r'' = + \left(\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 [\tau_{rr}]) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\sin \theta [\tau_{r\theta}]) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} ([\tau_{r\phi}]) - G_r^M - \frac{\partial P}{\partial r} \right) + \rho g_r + \quad (350)$$

$$+ \frac{\rho}{\bar{\rho}} \left(\frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr} - \tau_{rr}) + \overline{G_r^M} + \frac{\partial}{\partial r} \overline{P} - \overline{\rho g_r} \right) - \rho u_n'' \partial_n \tilde{u}_r \quad (351)$$

$$\tilde{D}_t \overline{u_i''} = \overline{D_t u_i'' - u_n'' \partial_n u_i''} = \overline{\partial_t u_i''} + \overline{u_n \partial_n u_i''} - \overline{u_n'' \partial_n u_i''} = \overline{\partial_t u_i''} + \overline{u_n \partial_n u_i''} + \overline{\tilde{u}_n \partial_n u_i''} - \overline{u_n \partial_n u_i''} = \overline{\partial_t u_i''} + \overline{\tilde{u}_n \partial_n u_i''} = \tilde{D}_t \overline{u_i''} \quad (352)$$

$$\bar{\rho} \tilde{D}_t \overline{u_i''} = \frac{\bar{\rho}}{\rho} [\rho D_t u_i''] - \overline{\rho u_n'' \partial_n u_i''} \quad (353)$$

$$\begin{aligned} \bar{\rho} \widetilde{D}_t \bar{u}_r'' &= \frac{\bar{\rho}}{\rho} [\rho D_t u_r''] - \bar{\rho} u_n'' \partial_n \bar{u}_r'' = \\ &= \frac{\bar{\rho}}{\rho} \left[\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau_{rr}) - G_r^M - \frac{\partial}{\partial r} P + \rho g_r + \frac{\rho}{\bar{\rho}} \left(\frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr} - \bar{\tau}_{rr}) + \bar{G}_r^M + \frac{\partial}{\partial r} \bar{P} - \bar{\rho} \tilde{g}_r \right) - \rho u_n'' \partial_n \bar{u}_r \right] - \bar{\rho} u_n'' \partial_n \bar{u}_r'' = \end{aligned} \quad (354)$$

$$= \frac{\bar{\rho}}{\rho} \left[\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau_{rr}) \right] - \left[\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau_{rr}) \right] - \frac{\bar{\rho}}{\rho} G_r^M + \bar{G}_r^M - \frac{\bar{\rho}}{\rho} \left[\frac{\partial}{\partial r} P \right] + \left[\frac{\partial}{\partial r} P \right] + \frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n \bar{u}_r - \bar{\rho} u_n'' \partial_n u_r'' \quad (355)$$

$$= \left[\frac{\bar{\rho}}{\rho} - 1 \right] \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau_{rr}) - \left[\frac{\bar{\rho}}{\rho} - 1 \right] G_r^M - \left[\frac{\bar{\rho}}{\rho} - 1 \right] \frac{\partial}{\partial r} P + \frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n u_r'' = \quad (356)$$

$$= + \frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n u_r'' - \frac{\rho'}{\rho} \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau_{rr}) + \frac{\rho'}{\rho} G_r^M + \frac{\rho'}{\rho} \frac{\partial}{\partial r} P = \quad (357)$$

$$= + \frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n u_r'' - \rho' v \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 (\bar{\tau}_{rr} + \tau'_{rr})) + \rho' v \frac{\partial}{\partial r} (\bar{P} + P') + \rho' v \bar{G}_r^M = \quad (358)$$

$$= + \frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n u_r'' - \rho' v \left(\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \bar{\tau}_{rr}) - \frac{\partial}{\partial r} \bar{P} \right) - \rho' v \left(\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau'_{rr}) - \frac{\partial}{\partial r} P' \right) + \rho' v \bar{G}_r^M = \quad (359)$$

$$= + \frac{1}{r^2} \frac{\partial}{\partial r} r^2 (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n u_r'' + b \left(\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \bar{\tau}_{rr}) - \frac{\partial}{\partial r} \bar{P} \right) - \rho' v \left(\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \tau'_{rr}) - \frac{\partial}{\partial r} P' \right) + \rho' v \bar{G}_r^M = \quad (360)$$

$$= + \nabla_r (\tilde{R}_{rr}) - \bar{\rho} \bar{u}'' \cdot \nabla u_r - b \nabla_r \bar{\tau}_{rr} - b \partial_r \bar{P} + \rho' v \partial_r P' - \rho' v \nabla_r \tau'_{rr} + \rho' v \bar{G}_r^M \quad (361)$$

$$\bar{\rho} \widetilde{D}_t \bar{u}_r'' = + \nabla_r (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n u_r - b \nabla_r \bar{\tau}_{rr} - b \partial_r \bar{P} + \rho' v \partial_r P' - \rho' v \nabla_r \tau'_{rr} + \rho' v \bar{G}_r^M = \quad (362)$$

$$= + \nabla_r (\tilde{R}_{rr}) - \bar{\rho} u_n'' \partial_n \bar{u}_r - \bar{\rho} \partial_n u_n'' \bar{u}' + \bar{\rho} u'_r \partial_n u_n'' - b \partial_r \bar{P} + \rho' v \partial_r P' - \rho' v \nabla_r \tau'_{rr} + \rho' v \bar{G}_r^M = \quad (363)$$

$$= (+ \nabla_r (\tilde{R}_{rr}) - \bar{\rho} \nabla_r u_n'' u'_r) - \bar{\rho} u_n'' \nabla_r \bar{u}_r + \bar{\rho} u'_r d'' - b \partial_r \bar{P} + \rho' v \partial_r P' - \rho' v \nabla_r \tau'_{rr} + \rho' v \bar{G}_r^M = \quad (364)$$

$$= -(\rho' u'_r u'_r / \bar{\rho}) \partial_r \bar{\rho} + (\tilde{R}_{rr} / \bar{\rho}) / \partial_r \bar{\rho} - \bar{\rho} \nabla_r (u_n'' u'_r) + \nabla_r \rho' u'_r u'_r - \bar{\rho} u'_r \nabla_r \bar{u}_r + \bar{\rho} u'_r d'' - b \partial_r \bar{P} + \rho' v \partial_r P' - \rho' v \nabla_r \tau'_{rr} + \rho' v \bar{G}_r^M \quad (365)$$

23.4 Density-specific volume covariance equation

The density-specific volume ($v = 1/\rho$) covariance ($b = -\overline{\rho'v'}$) equation can be derived from the continuity equation in the following way.

$$\partial_t \rho + \partial_n (\rho u_n) = 0 \quad (366)$$

$$\partial_t \bar{\rho} + \bar{u}_n \partial_n \bar{\rho} = -\bar{\rho} \partial_n \bar{u}_n \quad (367)$$

$$\partial_t \bar{\rho} + \bar{u}_n \partial_n \bar{\rho} - \overline{u''_n} \partial_n \bar{\rho} = -\bar{\rho} \partial_n \bar{u}_n + \bar{\rho} \partial_n \overline{u''_n} \quad (368)$$

$$\bar{D}_t \bar{\rho} = +\overline{u''_n} \partial_n \bar{\rho} - \bar{\rho} \partial_n \bar{u}_n + \bar{\rho} \partial_n \overline{u''_n} \quad (369)$$

$$\bar{D}_t \bar{\rho} = +(\overline{u''_n} \partial_n \bar{\rho} + \bar{\rho} \partial_n \overline{u''_n}) - \bar{\rho} \partial_n \bar{u}_n \quad (370)$$

$$\bar{D}_t \bar{\rho} = -\bar{\rho} \partial_n \bar{u}_n + \partial_n (\overline{u''_n} \bar{\rho}) \quad (371)$$

$$\partial_t \rho + \partial_n (\rho u_n) = 0 \quad (372)$$

$$\partial_t (1/v) + \partial_n (u_n/v) = 0 \quad (373)$$

$$-\partial_t v + v \partial_n u_n - u_n \partial_n v = 0 \quad (374)$$

$$\partial_t v - v \partial_n u_n - u_n \partial_n v + u_n \partial_n v + u_n \partial_n v = 0 \quad (375)$$

$$\partial_t v - \partial_n (v u_n) + 2u_n \partial_n v = 0 \quad (376)$$

$$\partial_t \bar{v} - \partial_n (\overline{v u_n}) + 2\overline{u_n} \partial_n \bar{v} = 0 \quad (377)$$

$$\bar{D}_t \bar{v} = +\overline{v} \partial_n \bar{u}_n - \partial_n \overline{u'_n v'} + 2\overline{v'} \partial_n u'_n \quad (378)$$

$$b = -\overline{\rho'v'} = \overline{\rho v} - 1 \quad (379)$$

$$\bar{D}_t b = \bar{\rho} \bar{D}_t \bar{v} + \bar{v} \bar{D}_t \bar{\rho} \quad (380)$$

Using previously derived equations for $\bar{D}_t \bar{v}$ and $\bar{D}_t \bar{\rho}$ we get:

$$\bar{D}_t b = -\bar{\rho} \partial_n \overline{\rho' u'_n} + 2\bar{\rho} \overline{v'} \partial_n \overline{u'_n} + \bar{v} \partial_n \overline{\rho u''_n} \quad (381)$$

23.5 Mean internal energy flux equation

We can derive the internal energy flux equation using the general formula for second order moments, where we substitute c with ϵ_I and d with u_i .

$$\bar{\rho} \tilde{D}_t \widetilde{c'' d''} = \overline{c'' \rho D_t d} - \bar{\rho} \widetilde{c'' u''_n} \partial_n \widetilde{d} + \overline{d'' \rho D_t c} - \bar{\rho} \widetilde{d'' u''_n} \partial_n \widetilde{c} - \overline{\partial_n \rho c'' d'' u''_n} \quad (382)$$

$$\bar{\rho} \tilde{D}_t (f_I / \bar{\rho}) = \mathcal{N}_{fI} - \nabla_r f_I^r - f_I \partial_r \widetilde{u}_r - \widetilde{R}_{rr} \partial_r \widetilde{\epsilon}_I - \overline{\epsilon_I''} \partial_r \overline{P} - \overline{\epsilon_I''} \partial_r \overline{P'} - \overline{u''_r} \overline{(Pd)} + \overline{u''_r} \overline{(\mathcal{S} + \nabla \cdot f_T)} + \mathcal{G}_I + \mathcal{N}_{fI} \quad (383)$$

23.6 Mean enthalpy flux equation

We can derive the enthalpy flux equation using the general formula for second order moments, where we substitute c with h and d with u_i .

$$\bar{\rho} \tilde{D}_t \tilde{c''} \tilde{d''} = \overline{c'' \rho D_t d} - \bar{\rho} \tilde{c''} \tilde{u_n''} \partial_n \tilde{d} + \overline{d'' \rho D_t c} - \bar{\rho} \tilde{d''} \tilde{u_n''} \partial_n \tilde{c} - \overline{\partial_n \rho c'' d'' u_n''} \quad (384)$$

$$\bar{\rho} \tilde{D}_t (f_h / \bar{\rho}) = -\nabla_r f_h^r - f_h \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{h} - \overline{h'' \partial_r P} - \overline{h'' \partial_r P'} - \Gamma_1 \overline{u_r'' (Pd)} + \Gamma_3 \overline{u_r'' (\mathcal{S} + \nabla \cdot F_T)} + \mathcal{G}_h + \mathcal{N}_h \quad (385)$$

23.7 Mean entropy flux equation

We can derive the entropy flux equation using the general formula for second order moments, where we substitute c with s and d with u_i .

$$\bar{\rho} \tilde{D}_t \tilde{c''} \tilde{d''} = \overline{c'' \rho D_t d} - \bar{\rho} \tilde{c''} \tilde{u_n''} \partial_n \tilde{d} + \overline{d'' \rho D_t c} - \bar{\rho} \tilde{d''} \tilde{u_n''} \partial_n \tilde{c} - \overline{\partial_n \rho c'' d'' u_n''} \quad (386)$$

$$\bar{\rho} \tilde{D}_t (f_s / \bar{\rho}) = -\nabla_r f_s^r - f_s \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{s} - \overline{s'' \partial_r P} - \overline{s'' \partial_r P'} + \overline{u_r'' (\mathcal{S} + \nabla \cdot f_T) / T} + \mathcal{G}_s + \mathcal{N}_{f_s} \quad (387)$$

23.8 Mean composition flux equation in r direction.

We can derive the composition flux equation using the general formula for second order moments, where we substitute c with X_α and d with u_i .

$$\bar{\rho} \tilde{D}_t \tilde{c''} \tilde{d''} = \overline{c'' \rho D_t d} - \bar{\rho} \tilde{c''} \tilde{u_n''} \partial_n \tilde{d} + \overline{d'' \rho D_t c} - \bar{\rho} \tilde{d''} \tilde{u_n''} \partial_n \tilde{c} - \overline{\partial_n \rho c'' d'' u_n''} \quad (388)$$

$$\bar{\rho} \tilde{D}_t (f_\alpha / \bar{\rho}) = -\nabla_r f_\alpha^r - f_\alpha \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_\alpha - \overline{X_\alpha'' \partial_r P} - \overline{X_\alpha'' \partial_r P'} + \overline{u_r'' \rho \dot{X}_\alpha^{\text{nuc}}} + \mathcal{G}_\alpha + \mathcal{N}_{f_\alpha} \quad (389)$$

Please note that the last term $\overline{\partial_n \rho X_i'' u_i'' u_n''} \equiv \overline{\nabla \cdot (\rho X_i'' \mathbf{u}'') \mathbf{u}''}$ is div of 2nd order tensor and $\overline{\nabla \cdot (\rho X_i'' \mathbf{u}'') \mathbf{u}''}(\mathbf{e}_r) = \nabla_r \overline{\rho X_i u_i'' u_r''} - \overline{\rho X_i'' u_\theta'' u_\theta'' / r} - \overline{\rho X_i'' u_\phi'' u_\phi'' / r}$

Further calculation requires the following hydrodynamic equations:

$$\rho D_t (u_r) = + \left(\frac{1}{r^2} \partial_r (r^2 [\tau_{rr}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\tau_{r\theta}]) + \frac{1}{r \sin \theta} \partial_\phi ([\tau_{r\phi}]) - G_r^M - \partial_r P \right) + \rho g_r \quad (391)$$

$$\rho D_t (X_i) = + \rho \dot{X}_i^n \quad i = 1 \dots N_{\text{nuc}} \quad (392)$$

For radial component of the flux, where $u_i = u_r$ and changing order of terms for clarity reasons we get:

$$\bar{\rho} \tilde{D}_t \tilde{X_i''} \tilde{u_r''} = \left(-\overline{\partial_n \rho X_i'' u_r'' u_n''} \right) - \bar{\rho} \tilde{X_i''} \tilde{u_n''} \partial_n \tilde{u_r} - \bar{\rho} \tilde{u_r''} \tilde{u_n''} \partial_n \tilde{X_i} + \overline{X_i'' \rho D_t u_r} + \overline{u_r'' \rho D_t X_i} \quad (393)$$

$$\bar{\rho} \tilde{D}_t (f_i / \bar{\rho}) = \left(-\nabla_r f_i^r - \overline{\rho X_i'' u_\theta'' u_\theta'' / r} - \overline{\rho X_i'' u_\phi'' u_\phi'' / r} \right) - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i + \overline{X_i'' (\nabla \cdot \tau_r - G_r^M - \partial_r P + \rho g_r)} + \overline{u_r'' \rho \dot{X}_i^{\text{nuc}}} \quad (394)$$

Let's reorganize the terms again and split $P = \bar{P} + P'$ to get the equation to shape it has in the paper:

$$\bar{\rho}\tilde{D}_t(f_i/\bar{\rho}) = -\nabla_r f_i^r - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i - \overline{X''_i} \partial_r \bar{P} - \overline{X''_i} \partial_r \bar{P}' + \overline{X''_i} \rho g_r + u''_r \rho \dot{X}_i^{\text{nuc}} \xrightarrow{0} \quad (395)$$

$$-\overline{\rho X''_i u''_\theta u''_\theta / r} - \overline{\rho X''_i u''_\phi u''_\phi / r} - \overline{X''_i G_r^M} - \overline{X'' \nabla \cdot \tau_r} \quad (396)$$

$$\bar{\rho}\tilde{D}_t(f_i/\bar{\rho}) = -\nabla_r f_i^r - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i - \overline{X''_i} \partial_r \bar{P} - \overline{X''_i} \partial_r \bar{P}' + \overline{u''_r} \rho \dot{X}_i^{\text{nuc}} \quad (397)$$

$$-\overline{\rho X''_i u''_\theta u''_\theta / r} - \overline{\rho X''_i u''_\phi u''_\phi / r} - \overline{X''_i G_r^M} - \overline{\nabla \cdot X''_i \tau_r} + \overline{\tau_r \nabla X''_i} \quad (398)$$

$$\text{The viscoity } \tau \text{ is 2nd order tensor and } -\overline{\nabla \cdot X''_i \tau_r} = -\nabla_r \overline{X''_i \tau_{rr}} + \overline{X'' \tau_{\theta\theta} \tau_{\theta\theta} / r} + \overline{X'' \tau_{\phi\phi} \tau_{\phi\phi} / r} \quad (399)$$

$$\bar{\rho}\tilde{D}_t(f_i/\bar{\rho}) = -\nabla_r f_i^r - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i - \overline{X''_i} \partial_r \bar{P} - \overline{X''_i} \partial_r \bar{P}' + \overline{u''_r} \rho \dot{X}_i^{\text{nuc}} \quad (400)$$

$$-\overline{\rho X''_i u''_\theta u''_\theta / r} - \overline{\rho X''_i u''_\phi u''_\phi / r} - \overline{X''_i G_r^M} - \nabla_r (\overline{X''_i \tau_{rr}}) + \overline{X'' \tau_{\theta\theta} \tau_{\theta\theta} / r} + \overline{X'' \tau_{\phi\phi} \tau_{\phi\phi} / r} \quad (401)$$

$$-\overline{\tau_{rr} \partial_r X''_i} - \overline{\tau_{r\theta} (1/r) \partial_\theta X''_i} - \overline{\tau_{r\phi} (1/r \sin \theta) \partial_\phi X''_i} \quad (402)$$

$$\bar{\rho}\tilde{D}_t(f_i/\bar{\rho}) = -\nabla_r f_i^r - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i - \overline{X''_i} \partial_r \bar{P} - \overline{X''_i} \partial_r \bar{P}' + \overline{u''_r} \rho \dot{X}_i^{\text{nuc}} \quad (403)$$

$$-\overline{\rho X''_i u''_\theta u''_\theta / r} - \overline{\rho X''_i u''_\phi u''_\phi / r} - \overline{X''_i G_r^M} - \nabla_r (\overline{X''_i \tau_{rr}}) - \varepsilon_i \quad (404)$$

$$\bar{\rho}\tilde{D}_t(f_i/\bar{\rho}) = -\nabla_r f_i^r - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i - \overline{X''_i} \partial_r \bar{P} - \overline{X''_i} \partial_r \bar{P}' + \overline{u''_r} \rho \dot{X}_i^{\text{nuc}} \quad (405)$$

$$-\overline{\rho X''_i u''_\theta u''_\theta / r} - \overline{\rho X''_i u''_\phi u''_\phi / r} - \overline{X''_i G_r^M} + \mathcal{N}_{fi} \quad (406)$$

$$\bar{\rho}\tilde{D}_t(f_i/\bar{\rho}) = -\nabla_r f_i^r - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i - \overline{X''_i} \partial_r \bar{P} - \overline{X''_i} \partial_r \bar{P}' + \overline{u''_r} \rho \dot{X}_i^{\text{nuc}} \quad (407)$$

$$+ \overline{G_r^i} - \overline{X''_i G_r^M} + \mathcal{N}_{fi} \quad (408)$$

$$\bar{\rho}\tilde{D}_t(f_i/\bar{\rho}) = -\nabla_r f_i^r - f_i \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{X}_i - \overline{X''_i} \partial_r \bar{P} - \overline{X''_i} \partial_r \bar{P}' + \overline{u''_r} \rho \dot{X}_i^{\text{nuc}} \quad (409)$$

$$+ \mathcal{G}_i + \mathcal{N}_{fi} \quad (410)$$

The exact formulation of the geometry and viscosity terms is:

$$\mathcal{G}_i = \overline{G_r^i} - \overline{X''_i G_r^M} \quad (411)$$

$$\mathcal{N}_{fi} = -\nabla_r (\overline{X''_i \tau_{rr}}) - \overline{\tau_{r\theta} (1/r) \partial_\theta X''_i} - \overline{\tau_{r\phi} (1/r \sin \theta) \partial_\phi X''_i} + \overline{X'' \tau_{\theta\theta} \tau_{\theta\theta} / r} + \overline{X'' \tau_{\phi\phi} \tau_{\phi\phi} / r} \quad (412)$$

23.9 Mean composition equation in θ direction.

t.b.d

23.10 Mean A and Z flux equations

We can derive the composition flux equation using the general formula for second order moments, where we substitute c with A or Z and d with u_i .

$$\bar{\rho} \tilde{D}_t c'' \widetilde{d''} = \overline{c'' \rho D_t d} - \overline{\rho c'' u_n'' \partial_n \tilde{d}} + \overline{d'' \rho D_t c} - \overline{\rho d'' u_n'' \partial_n \tilde{c}} - \overline{\partial_n \rho c'' d'' u_n''} \quad (413)$$

$$\bar{\rho} \tilde{D}_t (f_A / \bar{\rho}) = \mathcal{N}_{fA} - \nabla_r f_A^r - f_A \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{A} - \overline{A'' \partial_r \bar{P}} - \overline{A'' \partial_r \bar{P'}} - \overline{u_r'' \rho A^2 \Sigma_\alpha \dot{X}_\alpha^{\text{nuc}} / A_\alpha} + \mathcal{G}_A \quad (414)$$

$$\begin{aligned} \bar{\rho} \tilde{D}_t (f_Z / \bar{\rho}) = & \mathcal{N}_{fZ} - \nabla_r f_Z^r - f_Z \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{Z} - \overline{Z'' \partial_r \bar{P}} - \overline{Z'' \partial_r \bar{P'}} - \overline{u_r'' \rho Z A \Sigma_\alpha (\dot{X}_\alpha^{\text{nuc}} / A_\alpha)} - \\ & - \overline{u_r'' \rho A \Sigma_\alpha (Z_\alpha \dot{X}_\alpha^{\text{nuc}} / A_\alpha)} + \mathcal{G}_Z \end{aligned} \quad (415)$$

23.11 Mean angular momentum flux equation

We can derive the angular momentum flux equation using the general formula for second order moments, where we substitute c with j_z and d with u_i .

$$\bar{\rho} \tilde{D}_t c'' \widetilde{d''} = \overline{c'' \rho D_t d} - \overline{\rho c'' u_n'' \partial_n \tilde{d}} + \overline{d'' \rho D_t c} - \overline{\rho d'' u_n'' \partial_n \tilde{c}} - \overline{\partial_n \rho c'' d'' u_n''} \quad (416)$$

$$\bar{\rho} \tilde{D}_t (f_{jz} / \rho) = - \nabla_r f_{jz}^r - f_{jz} \partial_r \tilde{u}_r - \tilde{R}_{rr} \partial_r \tilde{j}_z - \overline{j_z'' \partial_r \bar{P}} - \overline{j_z'' \partial_r \bar{P'}} + \mathcal{G}_{jz} + \mathcal{N}_{jz} \quad (417)$$

23.12 Pressure flux equation in r direction

We can derive the pressure flux equation using the general formula for second order moments, where we substitute c with P and d with u_r .

$$\begin{aligned} \tilde{D}_t \widetilde{c' d'} &= \overline{c' D_t d} - \overline{c' u_n'' \partial_n \bar{d}} + \overline{d' D_t c} + \overline{d' u_n'' \partial_n \bar{c}} - \overline{\partial_n u_n'' c' d'} + \overline{c' d'' \partial_n u_n''} \\ \tilde{D}_t \overline{P' u_r'} &= \overline{P' D_t u_r} - \overline{P' u_n'' \partial_n \bar{u}_r} + \overline{u_r' D_t \bar{P}} + \overline{u_r' u_n'' \partial_n \bar{P}} - \overline{\partial_n u_n'' P' u_r'} + \overline{P' u_r'' \partial_n u_n''} \\ \tilde{D}_t \overline{P' u_r'} &= \overline{P' D_t u_r} - \overline{P' u_r'' \partial_r \bar{u}_r} + \overline{u_r' D_t \bar{P}} + \overline{u_r' u_r'' \partial_r \bar{P}} - \nabla_r \overline{P' u_r'' u_r'} + \overline{P' u_r'' d''} \end{aligned} \quad (418)$$

The evolution equation for $D_t u_r$ (see Sect.18) is

$$\rho D_t (u_r) = + \left(\frac{1}{r^2} \partial_r (r^2 [\tau_{rr}]) + \frac{1}{r \sin \theta} \partial_\theta (\sin \theta [\tau_{r\theta}]) + \frac{1}{r \sin \theta} \partial_\phi ([\tau_{r\phi}]) - G_r^M - \partial_r P \right) + \rho g_r \quad (419)$$

By neglecting viscosity and dividing by ρ , it becomes:

$$D_t (u_r) = - G_r^M / \rho - \partial_r P / \rho + g_r \quad (420)$$

The evolution equation for $D_t P$ (see Sect.21.8) is

$$D_t P = - (1 - \Gamma_3 + \Gamma_1) P d + (\Gamma_3 - 1) (-P d + S + \nabla \cdot F_T + \tau_{ij} \partial_i u_j) \quad (421)$$

By neglecting viscosity, it becomes:

$$D_t P = - (1 - \Gamma_3 + \Gamma_1) P d + (\Gamma_3 - 1) (-P d + S + \nabla \cdot F_T) \quad (422)$$

We continue here by putting everything together and neglecting heat flux due to conduction and radiation F_T :

$$\tilde{D}_t \overline{P' u'_r} = \overline{P' (-G_r^M / \rho - \partial_r P / \rho + g_r)} - \overline{P' u''_r} \partial_r \bar{u}_r + \overline{u'_r} (- (1 - \Gamma_3 + \Gamma_1) P d + (\Gamma_3 - 1) (-P d + S + \nabla \cdot F_T)) + \overline{u'_r u''_r} \partial_r \bar{P} - \nabla_r \overline{P' u''_r u'_r} + \overline{P' u''_r d''} \quad (423)$$

$$\tilde{D}_t \overline{P' u'_r} = - \overline{P' G_r^M / \rho} - \overline{P' \partial_r P / \rho} + \overline{P' g_r} - \overline{P' u''_r} \partial_r \bar{u}_r - (1 - \Gamma_3 - \Gamma_1) \overline{u'_r P d} - (\Gamma_3 - 1) \overline{u'_r P \bar{d}} + (\Gamma_3 - 1) \overline{u'_r \rho \varepsilon_{nuc}} + \overline{u'_r u''_r} \partial_r \bar{P} - \nabla_r \overline{P' u''_r u'_r} + \overline{P' u''_r d''} \quad (424)$$

$$\tilde{D}_t \overline{P' u'_r} = - \nabla_r f_p^r - f_p \partial_r \bar{u}_r + \overline{u'_r u''_r} \partial_r \bar{P} - (1 - \Gamma_3 - \Gamma_1) \overline{u'_r P d} - (\Gamma_3 - 1) \overline{u'_r P \bar{d}} + (\Gamma_3 - 1) \overline{u'_r \rho \varepsilon_{nuc}} + \overline{P' u''_r d''} - \overline{P' G_r^M / \rho} - \overline{P' \partial_r P / \rho} \quad (425)$$

With a little more algebraic modifications, we get the final form:

$$\tilde{D}_t \overline{P' u'_r} = - \nabla_r f_p^r - f_p \partial_r \bar{u}_r + \overline{u'_r u''_r} \partial_r \bar{P} + \Gamma_1 \overline{u'_r P d} + (\Gamma_3 - 1) \overline{u'_r \rho \varepsilon_{nuc}} + \overline{P' u''_r d''} - \overline{P' G_r^M / \rho} - \overline{P' \partial_r P / \rho} \quad (426)$$

23.13 Pressure flux equation in θ direction

t.b.d.

24 Derivation of variance equations

The derivation of final variance equations can be achieved by utilization of general formula for variances (see Sect.22.3) and similar algebraic manipulation as shown in previous sections.

We show derivation of enthalpy variance equation only as an example

24.1 Enthalpy variance equation

We begin with general formula for Favrian variance equation:

$$\overline{\rho} \tilde{D}_t \widetilde{c'' c''} = +2\overline{c'' \rho D_t c} - 2\overline{\rho c'' u''_n} \partial_n \widetilde{c} - \overline{\partial_n \rho c'' c'' u''_n} \quad (427)$$

We substitute specific enthalpy $h = \epsilon_I + P/\rho$ for the c and get:

$$\bar{\rho} \tilde{D}_t \tilde{h}'' \tilde{h}'' = + \overline{2h''\rho D_t h} - 2\bar{\rho} \tilde{h}'' \tilde{u}_n'' \partial_r \tilde{h} - \nabla_r \overline{\rho h'' h'' u_r''} \quad (428)$$

Now, we have to derive evolution equation for specific enthalpy:

$$\rho D_t h = \rho \partial_t h + u_r \partial_r h = \partial_t \rho h + \nabla_r \rho u_r h = \partial_t (\rho \epsilon_I + P) + \nabla_r \rho u_r (\epsilon_I + P/\rho) \quad (429)$$

$$\rho D_t h = \partial_t \rho \epsilon_I + \nabla_r \rho u_r \epsilon_I + \partial_t P + \nabla_r u_r P \quad (430)$$

$$\rho D_t h = \rho D_t \epsilon_I + \partial_t P + u_r \partial_r P + P \nabla_r u_r \quad (431)$$

$$\rho D_t h = \rho D_t \epsilon_I + D_t P + P \nabla_r u_r \quad (432)$$

For the internal energy evolution (see Sect.21.5) and neglecting viscosity and thermal transport due to conduction and radiation, we have :

$$\rho D_t \epsilon_I = -Pd + \rho \varepsilon_{nuc} \quad (433)$$

The evolution equation for $D_t P$ (see Sect.21.8) is

$$D_t P = -(1 - \Gamma_3 + \Gamma_1) Pd + (\Gamma_3 - 1)(-Pd + S + \nabla \cdot F_T + \tau_{ij} \partial_i u_j) \quad (434)$$

Now, let us combine everything together:

$$\rho D_t h = -Pd + \rho \varepsilon_{nuc} - (1 - \Gamma_3 + \Gamma_1) Pd - (\Gamma_3 - 1) Pd + (\Gamma_3 - 1) \rho \varepsilon_{nuc} + Pd \quad (435)$$

$$\rho D_t h = -(1 - \Gamma_3 + \Gamma_1) Pd - (\Gamma_3 - 1) Pd + \Gamma_3 \rho \varepsilon_{nuc} \quad (436)$$

$$\rho D_t h = (\Gamma_3 - 1) Pd - \Gamma_1 Pd - (\Gamma_3 - 1) Pd + \Gamma_3 \rho \varepsilon_{nuc} \quad (437)$$

$$\rho D_t h = (\Gamma_3 - 1) Pd - \Gamma_1 Pd - (\Gamma_3 - 1) Pd + \Gamma_3 \rho \varepsilon_{nuc} \quad (438)$$

$$\rho D_t h = -\Gamma_1 Pd + \Gamma_3 \rho \varepsilon_{nuc} \quad (439)$$

Substituting $\rho D_t h$ to our general equation for Favrian enthalpy variance, we get

$$\bar{\rho} \tilde{D}_t \tilde{h}'' \tilde{h}'' = + \overline{2h''(-\Gamma_1 Pd + \Gamma_3 \rho \varepsilon_{nuc})} - 2\bar{\rho} \tilde{h}'' \tilde{u}_n'' \partial_r \tilde{h} - \nabla_r \overline{\rho h'' h'' u_r''} \quad (440)$$

$$\bar{\rho} \tilde{D}_t \tilde{h}'' \tilde{h}'' = -2\Gamma_1 \bar{h}'' Pd + 2\Gamma_3 \bar{h}'' \rho \varepsilon_{nuc} - 2f_h \partial_r \tilde{h} - \nabla_r f_h^r \quad (441)$$

After rearranging of these terms, we get final form of the equation to be:

$$\bar{\rho} \tilde{D}_t \tilde{h}'' \tilde{h}'' = -\nabla_r f_h^r - 2f_h \partial_r \tilde{h} - 2\Gamma_1 \bar{h}'' Pd + 2\Gamma_3 \bar{h}'' \rho \varepsilon_{nuc} \quad (442)$$

25 Divergence of tensors in spherical geometry up to third order

BACKGROUND READING:

CONTINUUM MECHANICS (Lecture Notes)

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$$\nabla(\cdot) = \sum_n \frac{\mathbf{e}_n}{h_n} \frac{\partial(\cdot)}{\partial x_n} \quad : \text{nabla operator} \quad \mathbf{V} = \sum_i V_i \mathbf{e}_i \quad : \text{tensor of first order (vector)} \quad (443)$$

$$\mathbf{S} = \sum_{ij} S_{ij} (\mathbf{e}_i \otimes \mathbf{e}_j) \quad : \text{tensor of second order} \quad (444)$$

$$\mathbf{T} = \sum_{ijk} T_{ijk} (\mathbf{e}_i \otimes \mathbf{e}_j \otimes \mathbf{e}_k) \quad : \text{tensor of third order} \quad (445)$$

$$\nabla \cdot \mathbf{V} = \sum_i \frac{1}{h_i} \left[\frac{\partial V_i}{\partial x_i} + \sum_m \Gamma_{mi}^i V_m \right] \quad : \text{div of first order tensor (vector)} \quad (446)$$

$$\nabla \cdot \mathbf{S} = \sum_{ij} \frac{1}{h_i} \left[\frac{\partial S_{ij}}{\partial x_i} + \sum_m \Gamma_{mi}^i S_{mj} + \sum_m \Gamma_{mi}^j S_{im} \right] \mathbf{e}_j \quad : \text{div of second order tensor} \quad (447)$$

$$\nabla \cdot \mathbf{T} = \sum_{ijk} \frac{1}{h_i} \left[\frac{\partial T_{ijk}}{\partial x_i} + \sum_m \Gamma_{mi}^i T_{mjk} + \sum_m \Gamma_{mi}^j T_{imk} + \sum_m \Gamma_{mi}^k T_{ijm} \right] (\mathbf{e}_j \otimes \mathbf{e}_k) \quad : \text{div of third order tensor} \quad (448)$$

$$x_1 = r \quad x_2 = \theta \quad x_3 = \phi \quad (\text{coordinates}) \quad (449)$$

$$\mathbf{e}_1 = \mathbf{e}_r \quad \mathbf{e}_2 = \mathbf{e}_\theta \quad \mathbf{e}_3 = \mathbf{e}_\phi \quad (\text{unit base vectors}) \quad (450)$$

$$h_1 = h_r = 1 \quad h_2 = h_\theta = r \quad h_3 = h_\phi = r \sin \theta \quad (\text{scale factors}) \quad (451)$$

$$\begin{pmatrix} \Gamma_{r\theta}^\theta = 1 & \Gamma_{r\phi}^\phi = \sin \theta & \Gamma_{\theta\phi}^\phi = \cos \theta \\ \Gamma_{\theta\theta}^\theta = -1 & \Gamma_{\phi\phi}^\theta = -\sin \theta & \Gamma_{\phi\phi}^\phi = -\cos \theta \end{pmatrix} \quad \text{Christoffel symbols} \quad (452)$$

Divergence of first order tensor $\nabla \cdot \mathbf{V}$

$$\frac{1}{r^2} \frac{\partial(r^2 V_r)}{\partial r} + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(V_\theta \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial V_\phi}{\partial \phi} \quad (453)$$

Divergence of second order tensor $\nabla \cdot \mathbf{S}$

$$S_r(\mathbf{e}_r) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 S_{rr}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta S_{\theta r}) + \frac{1}{r \sin \theta} \frac{\partial S_{\phi r}}{\partial \phi} - \frac{S_{\theta \theta}}{r} - \frac{S_{\phi \phi}}{r} \quad (454)$$

$$S_\theta(\mathbf{e}_\theta) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 S_{r\theta}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta S_{\theta \theta}) + \frac{1}{r \sin \theta} \frac{\partial S_{\phi \theta}}{\partial \phi} + \frac{S_{\theta r}}{r} - \frac{S_{\phi \phi} \cos \theta}{r \sin \theta} \quad (455)$$

$$S_\phi(\mathbf{e}_\phi) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 S_{r\phi}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta S_{\theta \phi}) + \frac{1}{r \sin \theta} \frac{\partial S_{\phi \phi}}{\partial \phi} + \frac{S_{\phi r}}{r} + \frac{S_{\phi \theta} \cos \theta}{r \sin \theta} \quad (456)$$

Divergence of third order tensor $\nabla \cdot \mathbf{T}$

$$T_{rr} (\mathbf{e}_r \otimes \mathbf{e}_r) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{rrr}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta rr}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi rr}}{\partial \phi} - \frac{T_{\theta \theta r}}{r} - \frac{T_{\theta r \theta}}{r} - \frac{T_{\phi \phi r}}{r} - \frac{T_{\phi r \phi}}{r} \quad (457)$$

$$T_{r\theta} (\mathbf{e}_r \otimes \mathbf{e}_\theta) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{rr\theta}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta r\theta}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi r\theta}}{\partial \phi} - \frac{T_{\theta \theta \theta}}{r} + \frac{T_{\theta \theta r}}{r} - \frac{T_{\phi \phi \theta}}{r} - \frac{T_{\phi r \phi} \cos \theta}{r \sin \theta} \quad (458)$$

$$T_{r\phi} (\mathbf{e}_r \otimes \mathbf{e}_\phi) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{rr\phi}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta r\phi}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi r\phi}}{\partial \phi} + \frac{T_{\theta \theta \phi}}{r} - \frac{T_{\phi \phi \phi}}{r} + \frac{T_{\phi r \phi} \cos \theta}{r \sin \theta} \quad (459)$$

$$T_{\theta r} (\mathbf{e}_\theta \otimes \mathbf{e}_r) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{r\theta r}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta \theta r}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi \theta r}}{\partial \phi} + \frac{T_{\theta \theta r}}{r} - \frac{T_{\theta \theta \theta}}{r} - \frac{T_{\phi \phi r} \cos \theta}{r \sin \theta} - \frac{T_{\phi \theta \phi}}{r} \quad (460)$$

$$T_{\theta \theta} (\mathbf{e}_\theta \otimes \mathbf{e}_\theta) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{r\theta \theta}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta \theta \theta}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi \theta \theta}}{\partial \phi} + \frac{T_{\theta \theta \theta}}{r} + \frac{T_{\theta \theta r}}{r} - \frac{T_{\phi \phi \theta} \cos \theta}{r \sin \theta} - \frac{T_{\phi \theta \phi} \cos \theta}{r \sin \theta} \quad (461)$$

$$T_{\theta \phi} (\mathbf{e}_\theta \otimes \mathbf{e}_\phi) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{r\theta \phi}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta \theta \phi}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi \theta \phi}}{\partial \phi} + \frac{T_{\theta \theta \phi}}{r} + \frac{T_{\phi \theta r}}{r} + \frac{T_{\phi \theta \phi} \cos \theta}{r \sin \theta} \quad (462)$$

$$T_{\phi r} (\mathbf{e}_\phi \otimes \mathbf{e}_r) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{r\phi r}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta \phi r}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi \phi r}}{\partial \phi} - \frac{T_{\theta \phi \theta}}{r} + \frac{T_{\phi \phi r}}{r} + \frac{T_{\phi \theta \phi} \cos \theta}{r \sin \theta} - \frac{T_{\phi \phi \phi}}{r} \quad (463)$$

$$T_{\phi \theta} (\mathbf{e}_\phi \otimes \mathbf{e}_\theta) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{r\phi \theta}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta \phi \theta}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi \phi \theta}}{\partial \phi} + \frac{T_{\theta \phi \theta}}{r} + \frac{T_{\phi \phi \theta}}{r} + \frac{T_{\phi \theta \phi} \cos \theta}{r \sin \theta} - \frac{T_{\phi \theta \phi}}{r \sin \theta} \quad (464)$$

$$T_{\phi \phi} (\mathbf{e}_\phi \otimes \mathbf{e}_\phi) : \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 T_{r\phi \phi}) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta}(\sin \theta T_{\theta \phi \phi}) + \frac{1}{r \sin \theta} \frac{\partial T_{\phi \phi \phi}}{\partial \phi} + \frac{T_{\phi \phi \phi}}{r} + \frac{T_{\phi \theta \phi} \cos \theta}{r \sin \theta} + \frac{T_{\phi \phi r}}{r} + \frac{T_{\phi \phi \phi} \cos \theta}{r \sin \theta} \quad (465)$$

Bibliography

- D. Arnett, C. Meakin, and P. A. Young. Convection Theory and Sub-Photospheric Stratification. *Apj*, 710:1619–1626, February 2010. doi: 10.1088/0004-637X/710/2/1619.
- Didier Besnard, FH Harlow, RM Rauenzahn, and C Zemach. Turbulence transport equations for variable-density turbulence and their relationship to two-field models. Technical report, Los Alamos National Lab., NM (United States), 1992.
- P. Chassaing, R.A. Antonia, F. Anselmet, L. Joly, and R. Sarkar. *Variable Density Fluid Turbulence*. Kluwer Academic Publishers, 2010.
- C. A. Meakin and D. Arnett. Turbulent Convection in Stellar Interiors. I. Hydrodynamic Simulation. *Apj*, 667:448–475, September 2007. doi: 10.1086/520318.
- M. Mocák, E. Müller, A. Weiss, and K. Kifonidis. The core helium flash revisited. II. Two and three-dimensional hydrodynamic simulations. *AaA*, 501:659–677, July 2009. doi: 10.1051/0004-6361/200811414.
- M. Mocák, L. Siess, and E. Müller. Multidimensional hydrodynamic simulations of the hydrogen injection flash. *AaA*, 533:A53, September 2011. doi: 10.1051/0004-6361/201116940.
- M. Viallet, C. Meakin, D. Arnett, and M. Mocák. Turbulent Convection in Stellar Interiors. III. Mean-field Analysis and Stratification Effects. *Apj*, 769:1, May 2013. doi: 10.1088/0004-637X/769/1/1.