

Joint inversion of time-variable elevation and gravity to reveal seasonal and inter-annual changes of the volume density of Martian snow

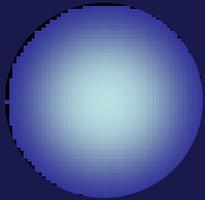
$$\text{Density} = \frac{\text{(gravity) Weight}}{\text{Volume (topography)}}$$



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Gravity (2way Doppler) / Topography (MOLA)

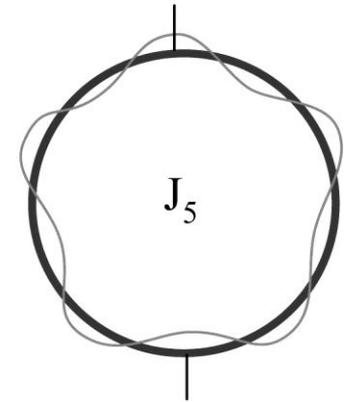
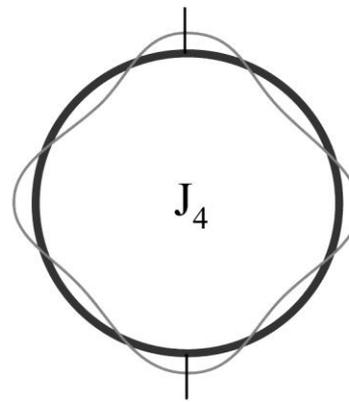
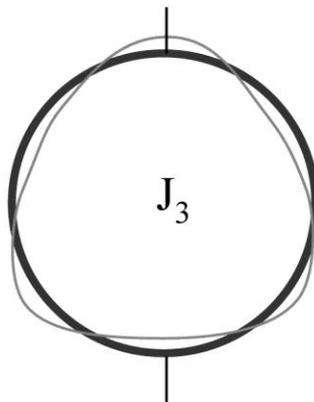
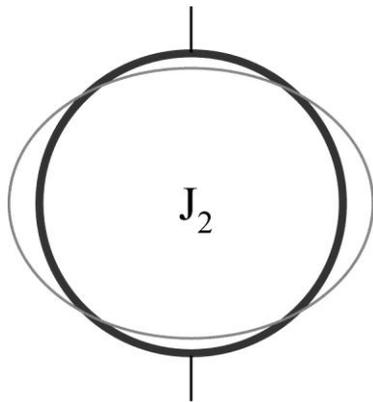
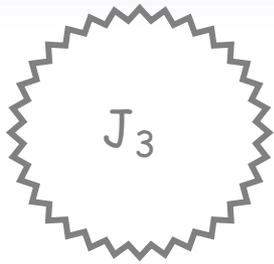


MOLA
10Hz/1.064 μ m
Accuracy < 1 m
Footprint 168 m ϕ
Spacing 300 m

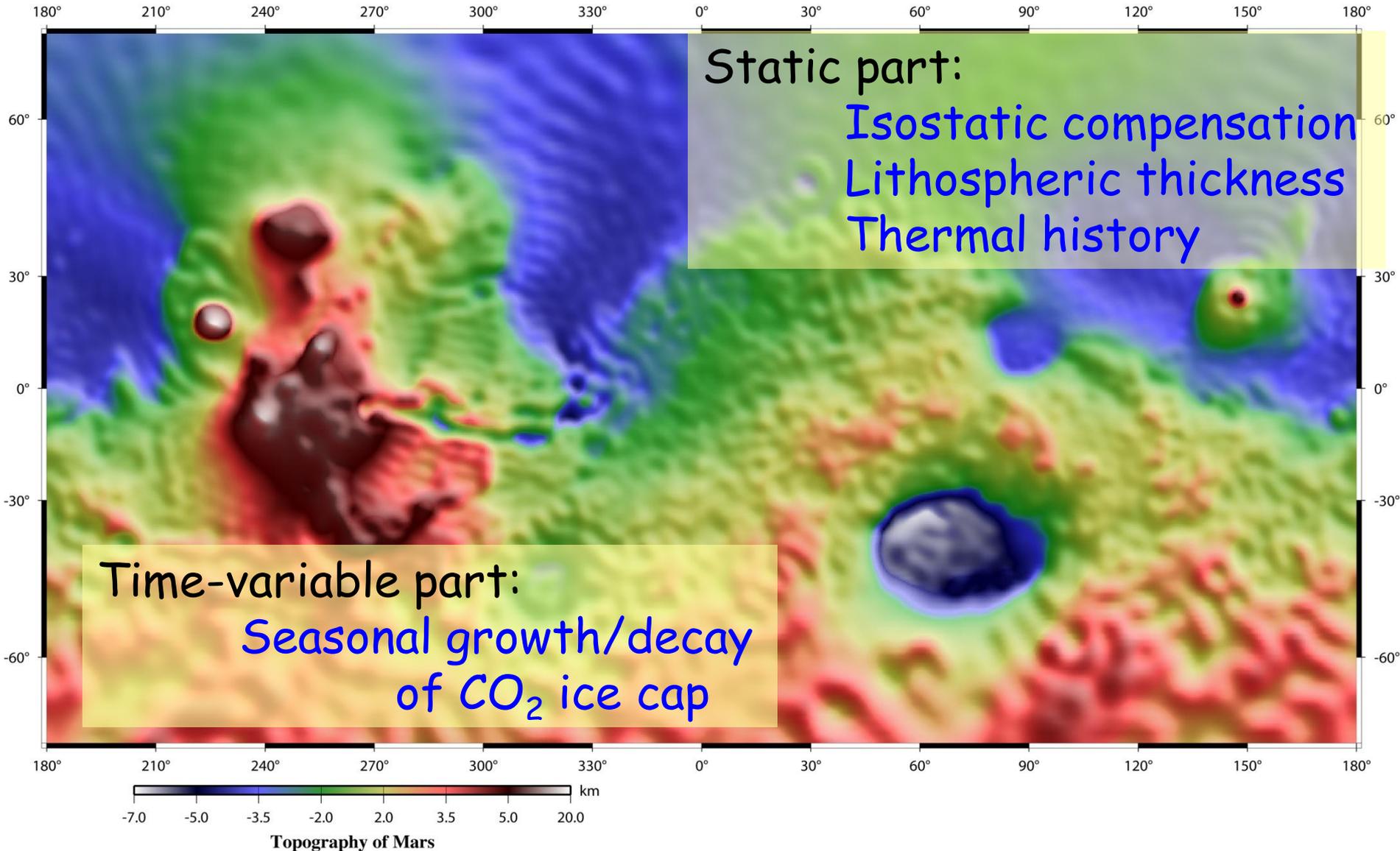
2-way Doppler
7.9/8.4 GHz
10 second interval
Accuracy < 0.1 mm/s

Mars Global Surveyor

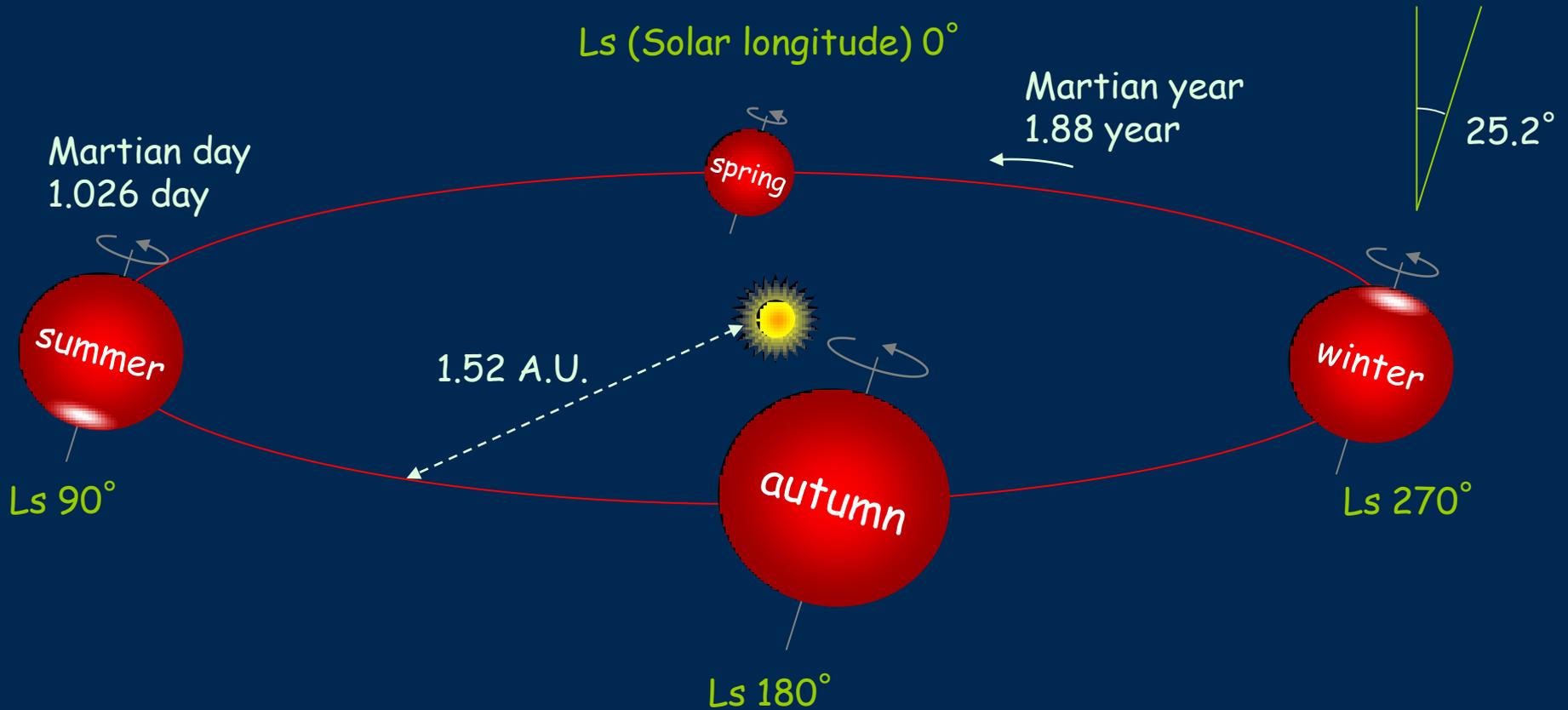
Gravity / topography model with spherical harmonics



Free-air gravity anomaly 10^4 m/s^2 (degrees/90 deg 80_{20}) no C_{20}

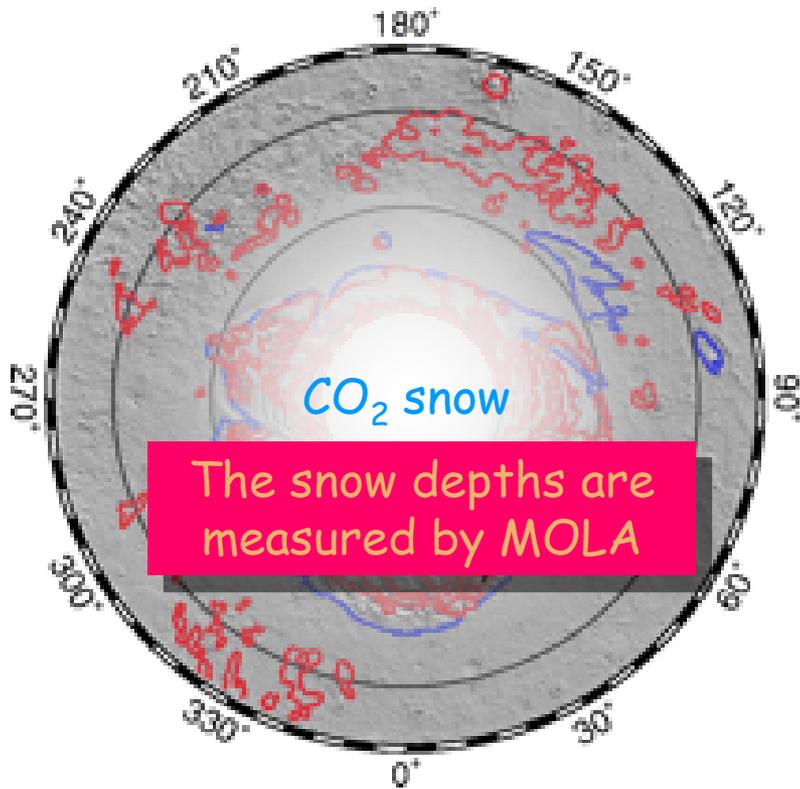


Movement of Mars



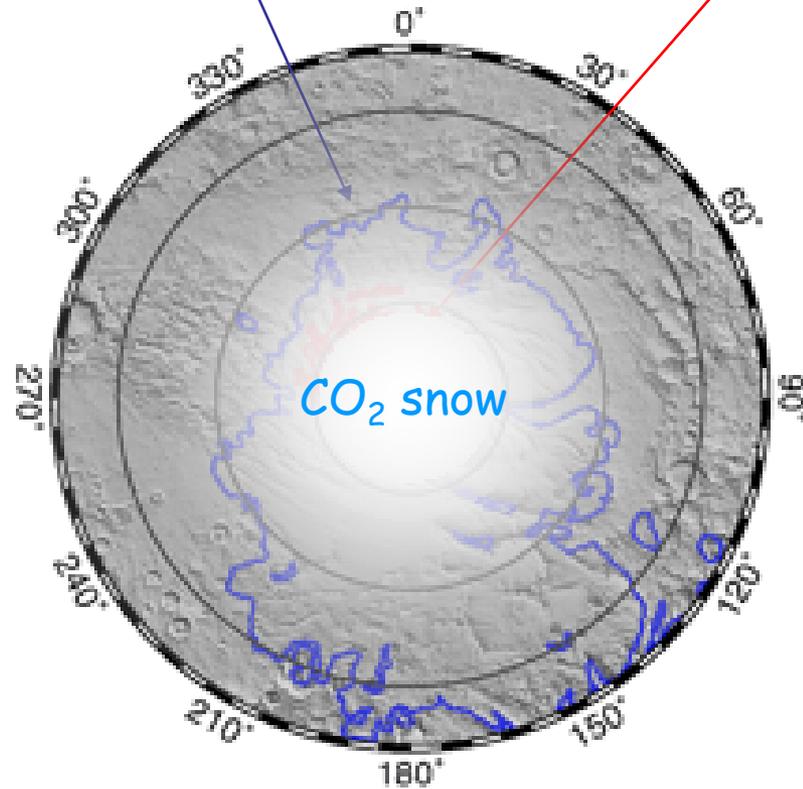
Polar elevated terrain
(water ice + dust)

Residual ice cap
(water ice)



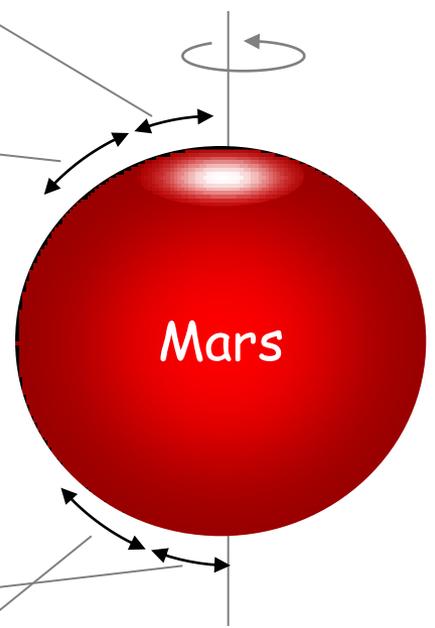
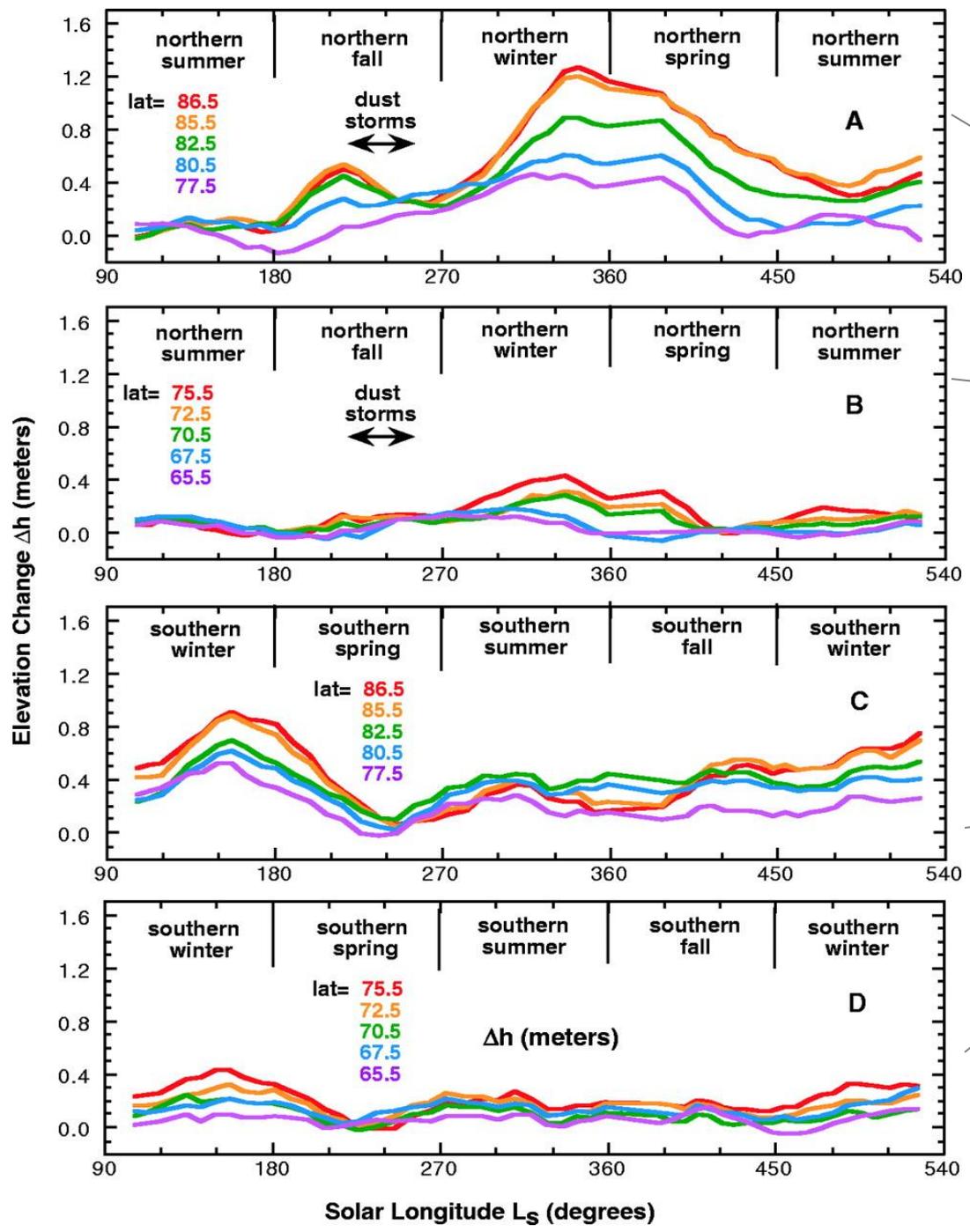
The snow depths are measured by MOLA

North Pole



South Pole

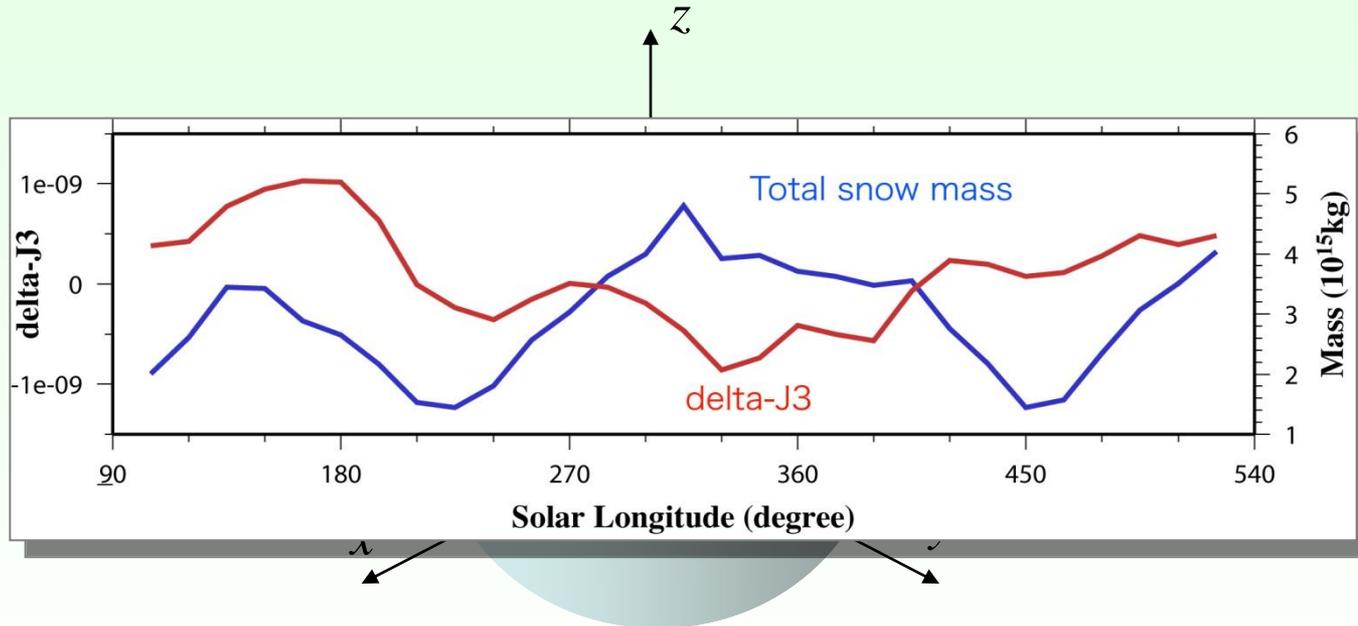
Seasonal change in the polar topography



Altimetric J_3 vs Gravimetric J_3

Altimetric J_3

Calculation of Stokes' Coefficients from snow depth data

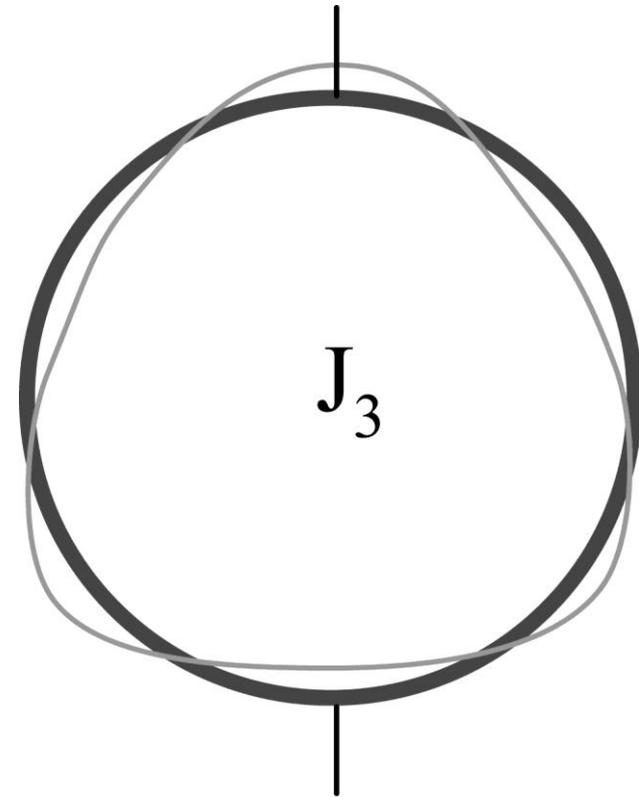
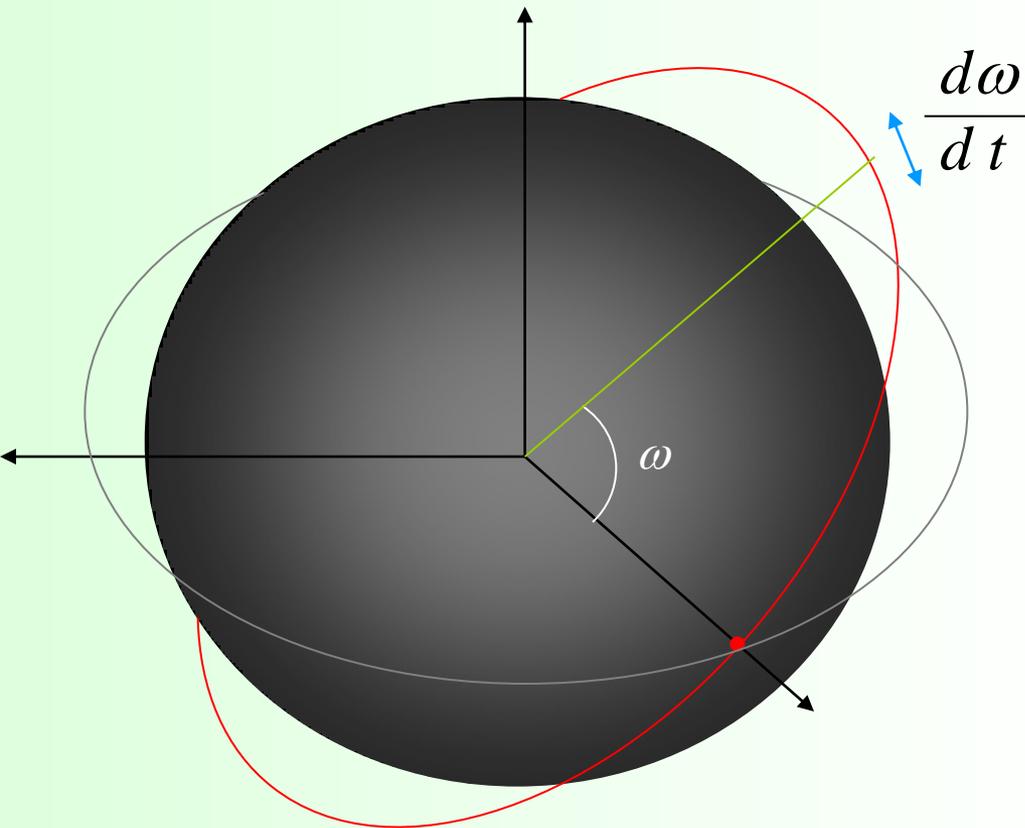


$$\Delta J_n \equiv -\Delta C_{n0} = \frac{3}{2a\rho_{ave}(2n+1)} \int \Delta\sigma(\theta, \phi) \tilde{P}_{n0}(\sin\theta) \cos\theta d\theta$$

Average snow density : 0.91 g/cm³

Gravimetric J_3

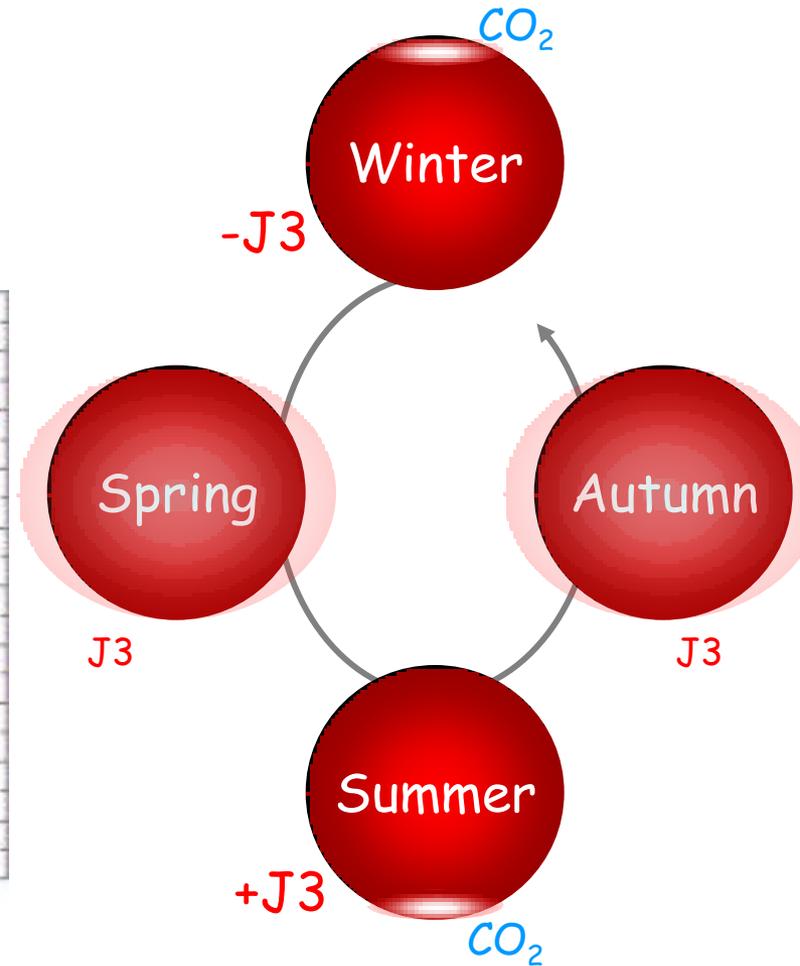
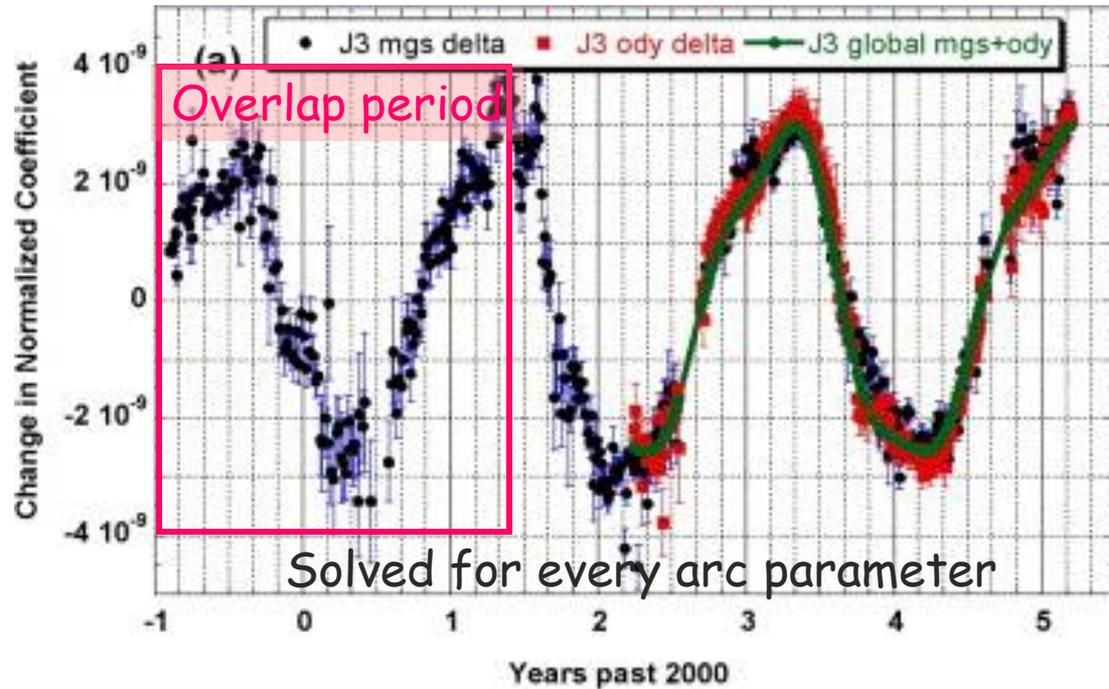
Odd zonal harmonics changes the argument of pericenter



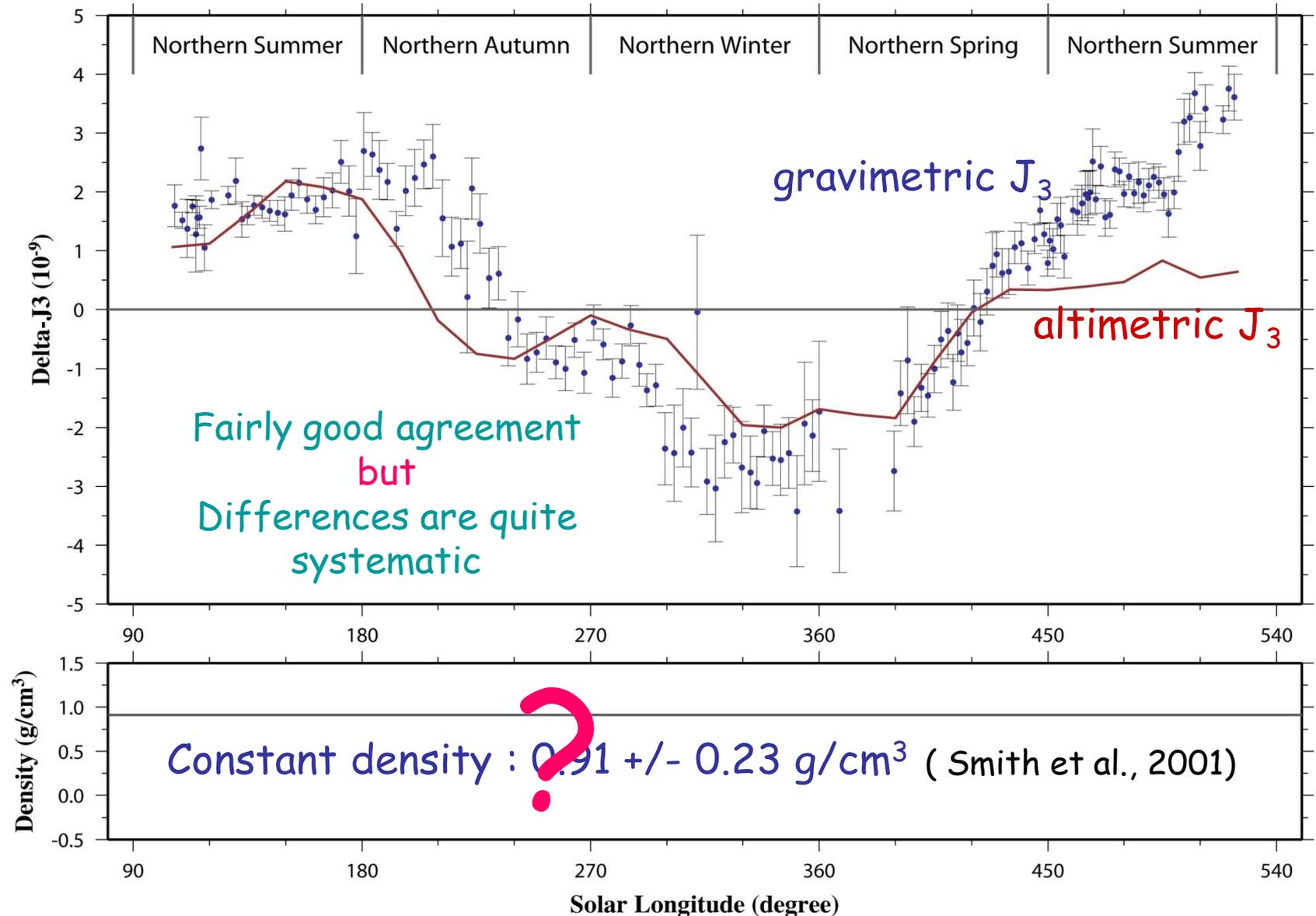
$$\delta J_3 \equiv \delta J_3 + 1.26 \delta J_5 + 1.31 \delta J_7 + 1.25 \delta J_9 + \dots$$

(Konopliv et al., 2006)

Gravimetric J_3



Comparison between gravimetric and altimetric J_3



Compaction makes snow denser

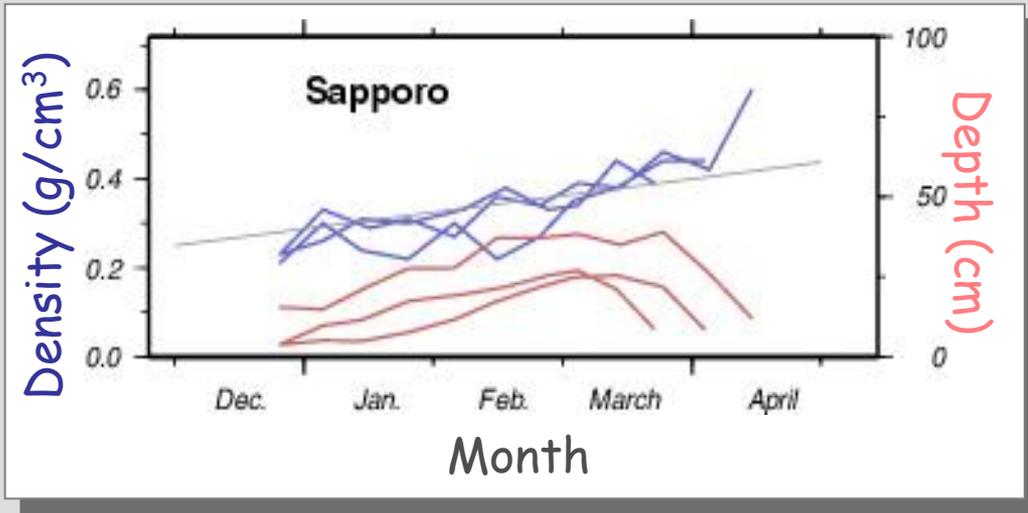
Dry Ice



$$\text{Density} = \frac{\text{Weight}}{\text{Volume}}$$

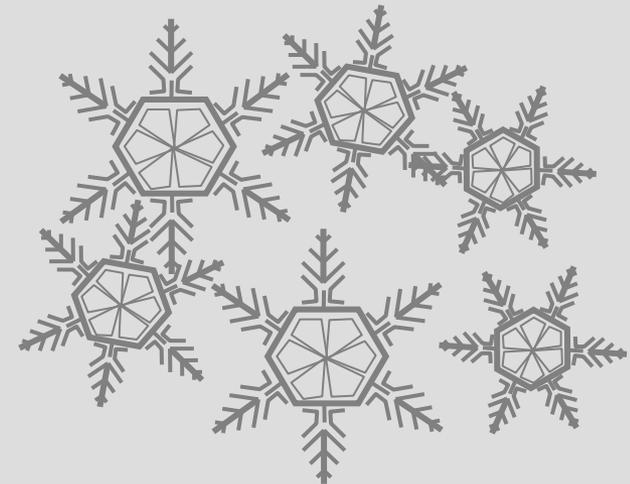


Snow pack becomes denser

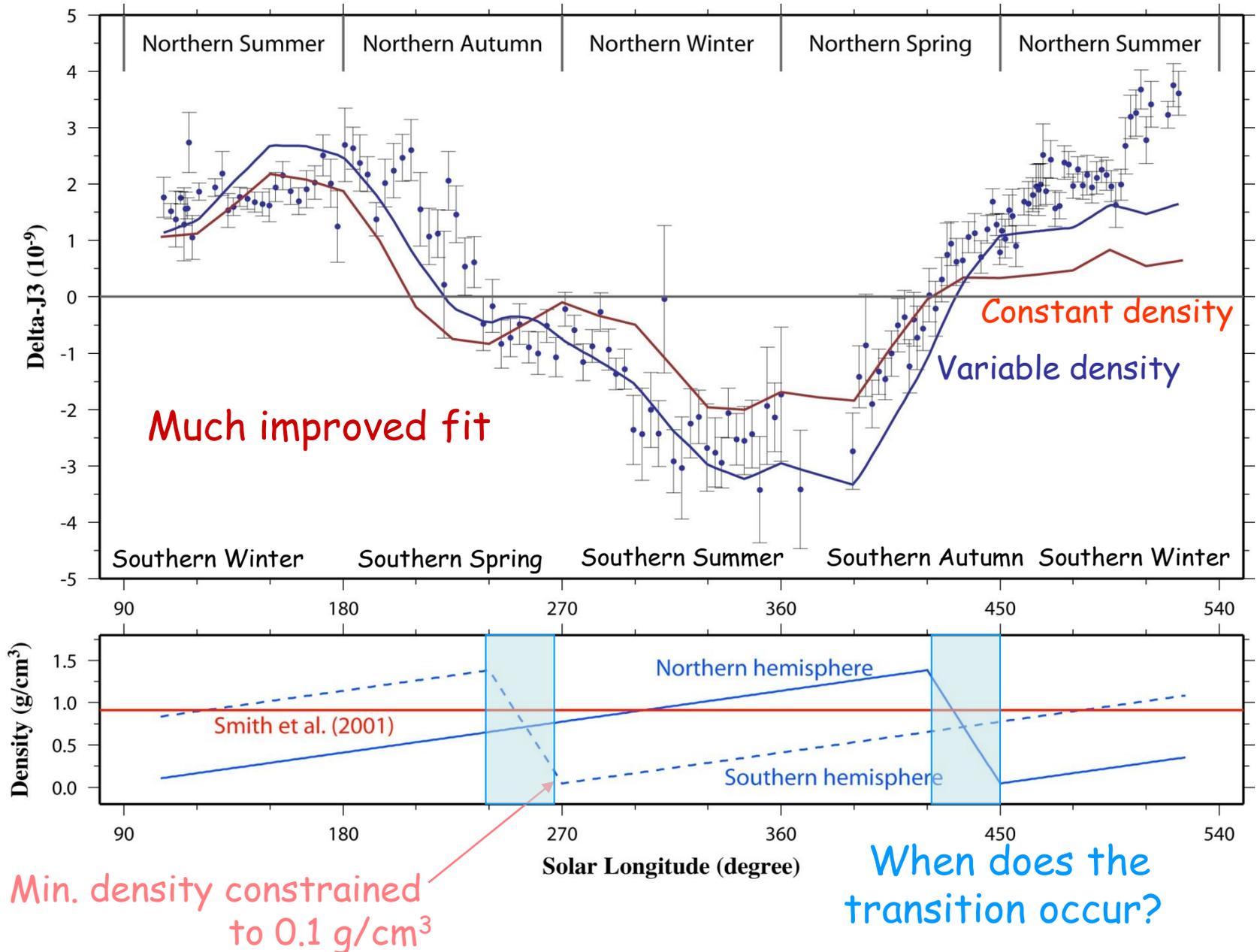


Hachikubo, A. et al., Report of pit-wall observations of snow cover in Sapporo 1996-97, *Low Temperature Sci., Ser. A., Data Report*, 56, 1-8, 1997

Gravitational compaction
Sintering (recrystallization)



Estimation of time-variable snow density



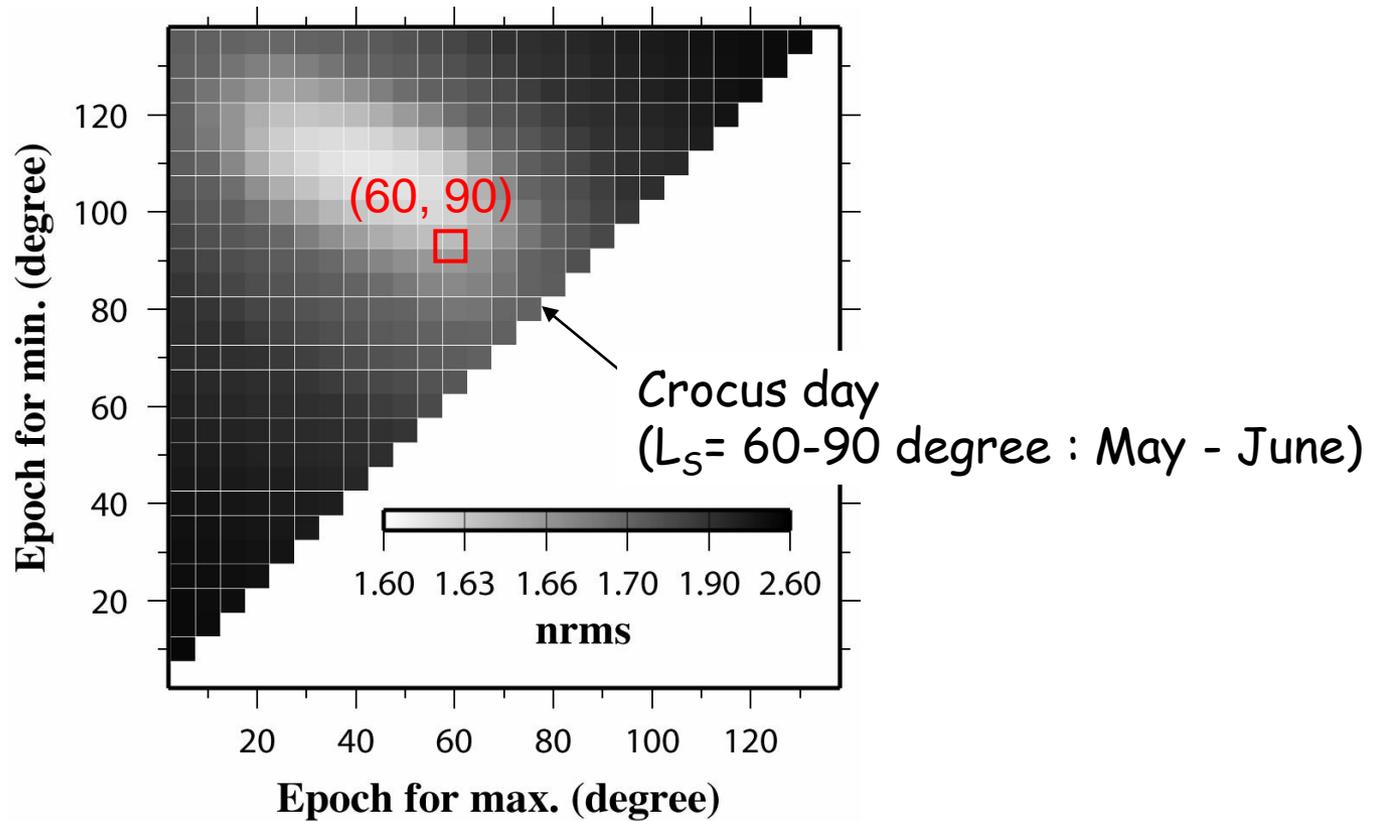
Wild Crocus in front of Mt. Eiger (from Wikipedia)

Crocus day = the day when old snow disappears

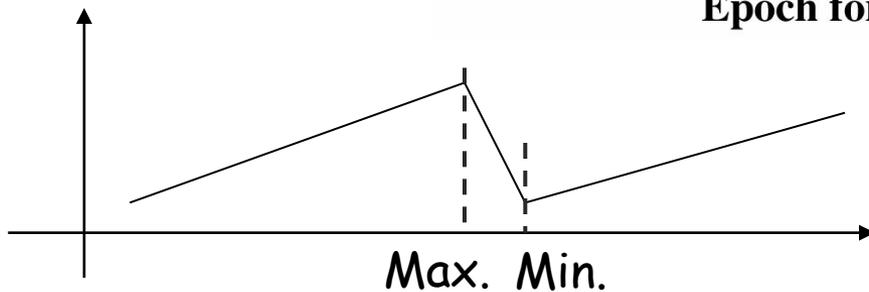


Grid-search for the crocus day

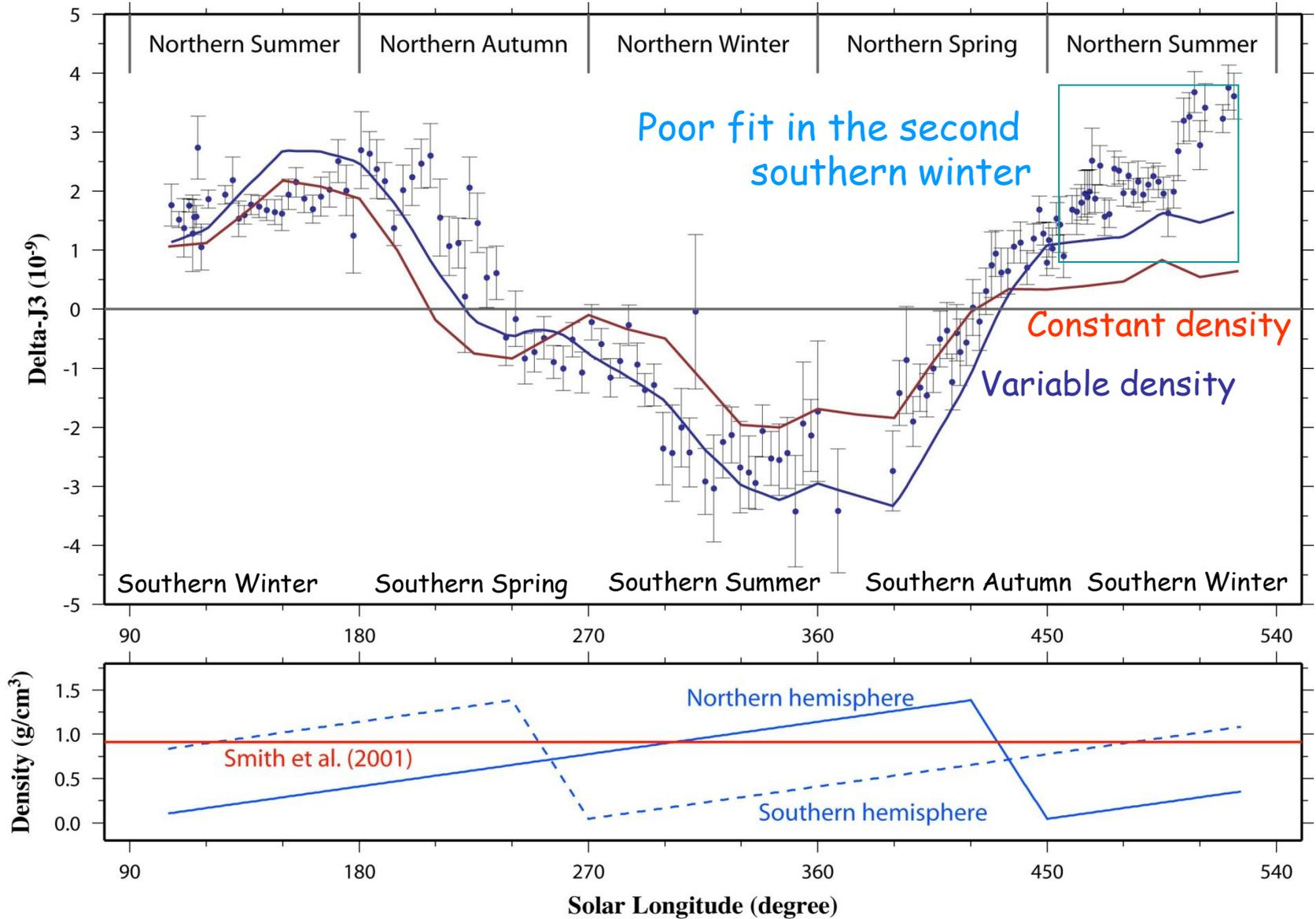
Epoch setting for time-variable snow density



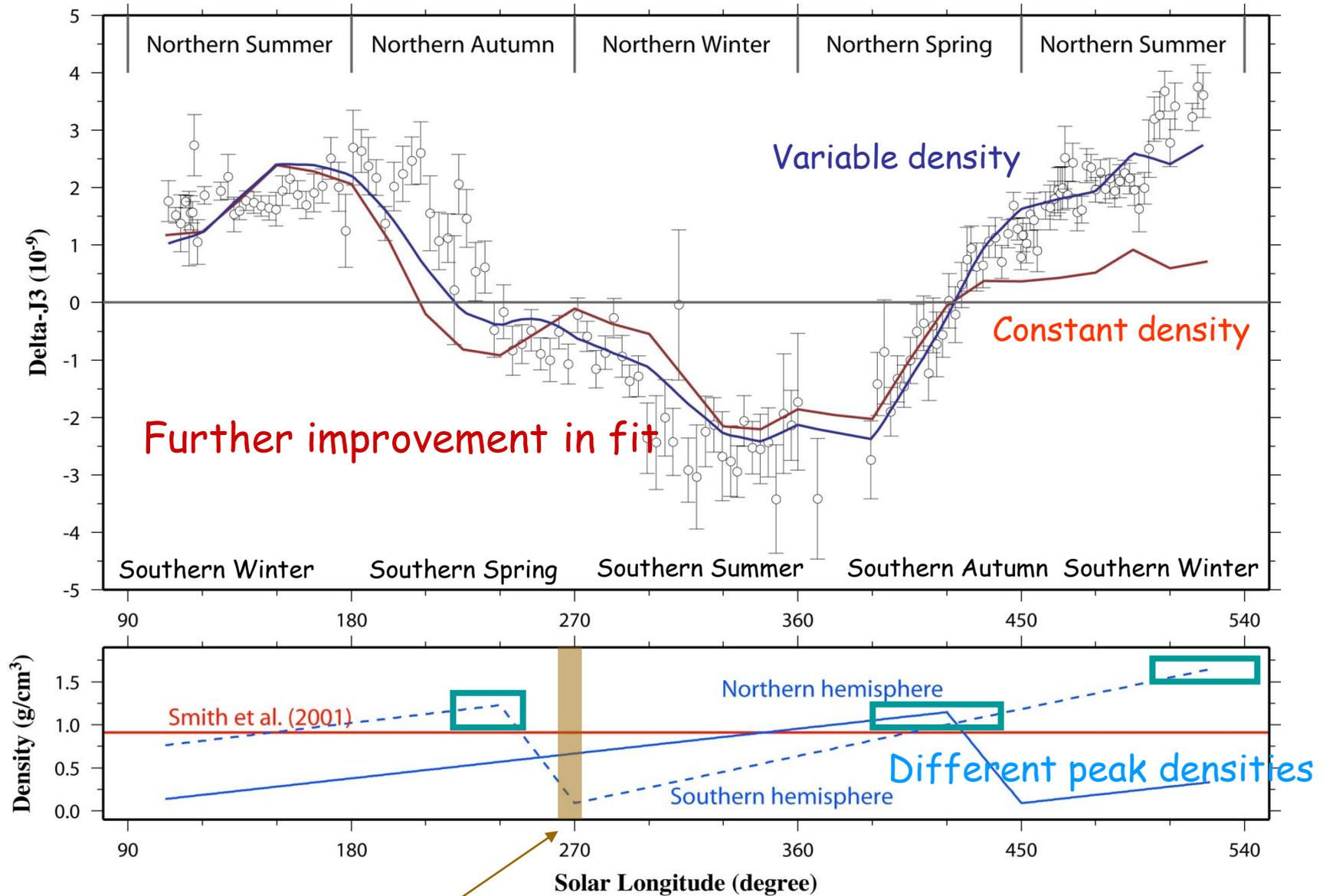
Snow density



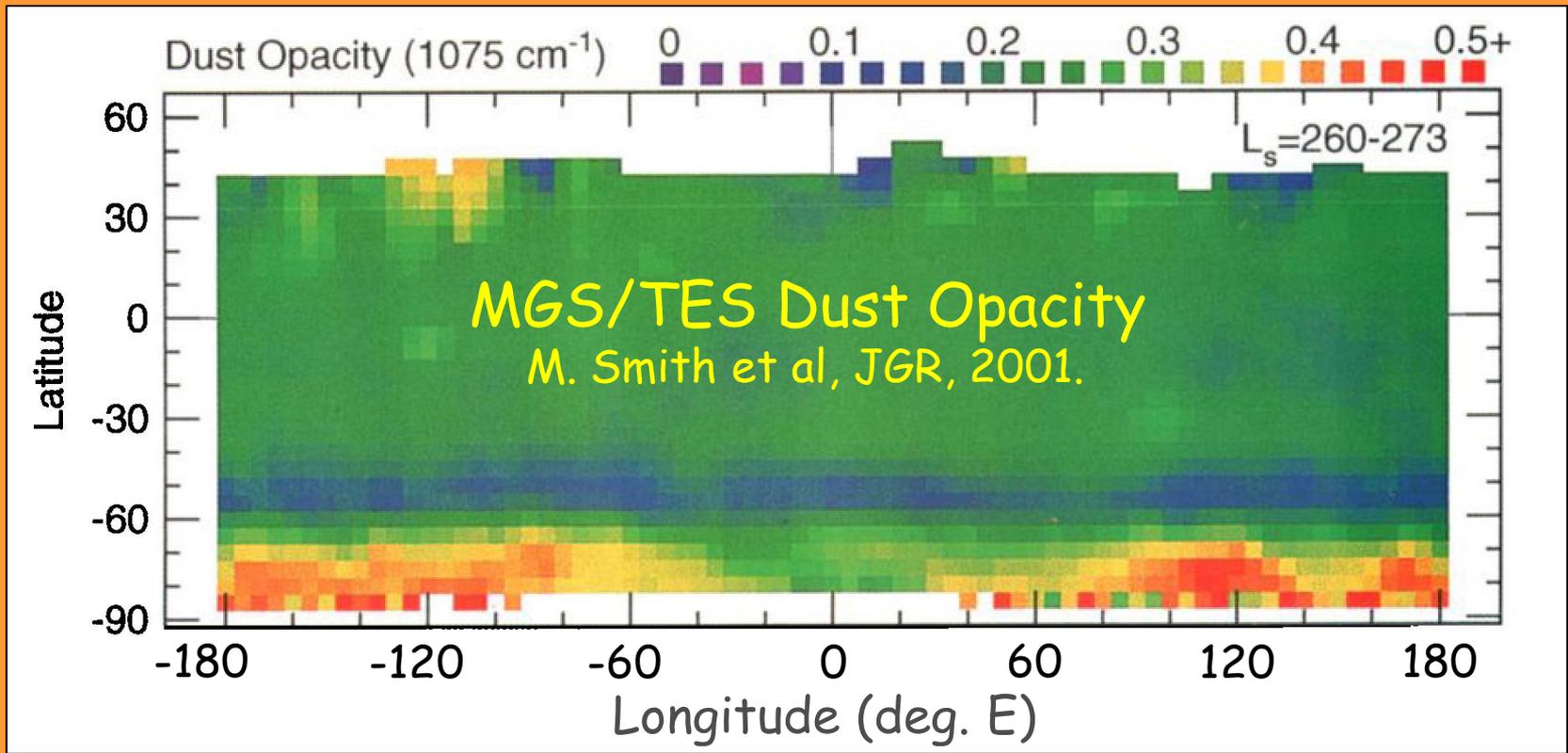
Estimation of time-variable snow density



Estimation of time-variable snow density



Large dust storm around the South Pole



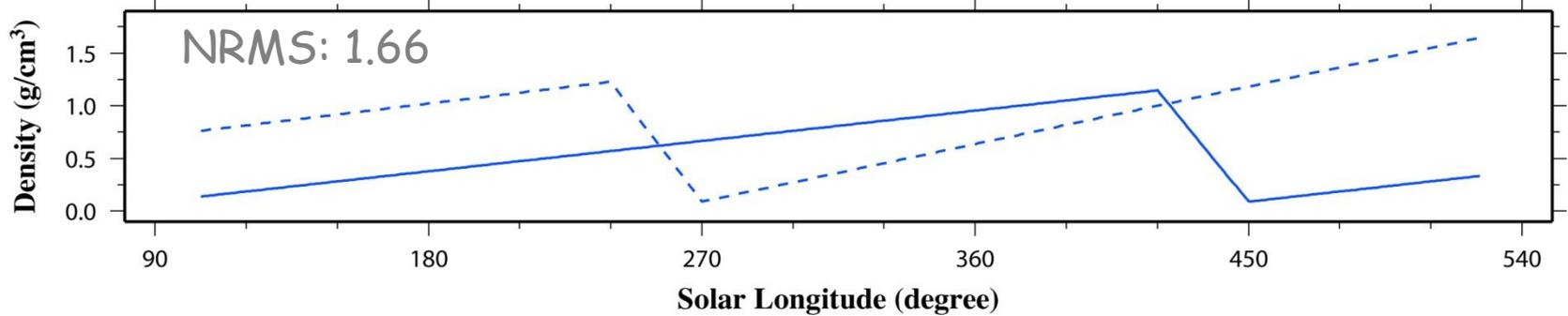
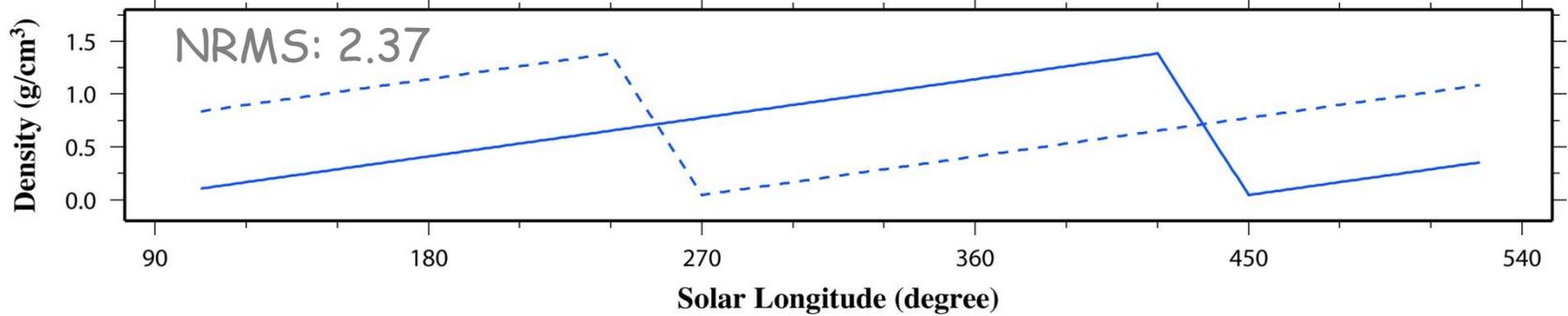
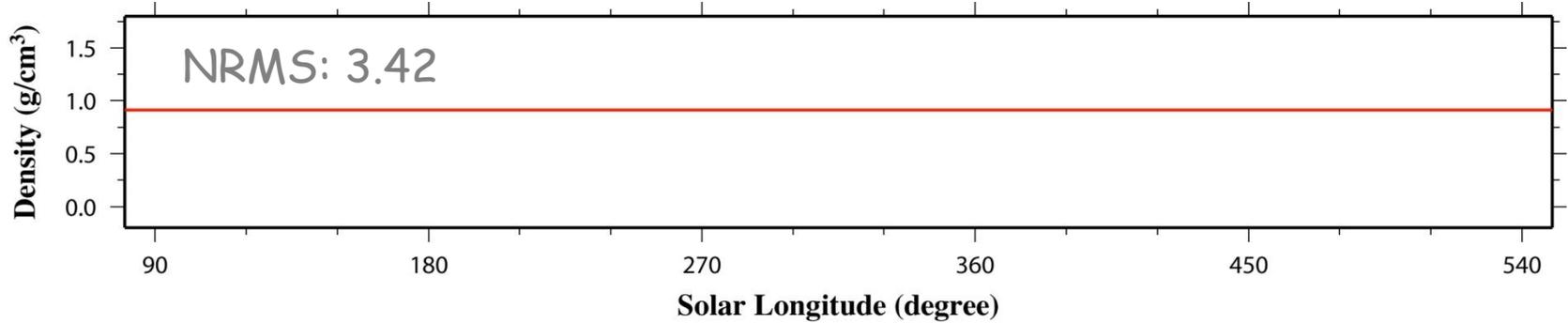
er

$\sim 1 \text{ g/cm}^3$

$> 1.5 \text{ g/cm}^3$



Change in Model and Decrease of NRMS



Possible sources of error (for absolute value of density)

Neglect of coefficients higher than J_9

J_9 is ~10 % of J_3

Up to 20 % (overestimate ρ)

Seasonal variation of atmospheric pressure

Can be assessed with global circulation models

A few % or less

Mars Deformation due to snow load : influence in gravity

Load Love number k_3^L ?

(k_3^L : -0.05~-0.08, Métivier et al., 2008)

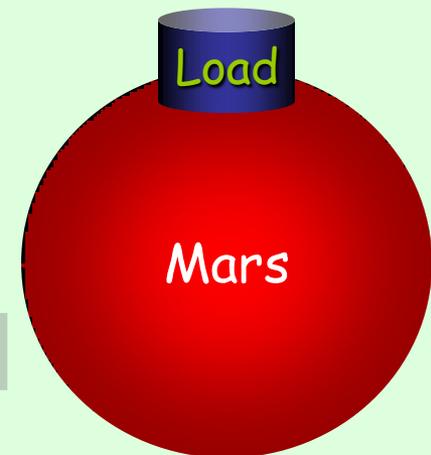
Up to 10 % (underestimate ρ)

Mars Deformation due to snow load : influence in measured snow depth

Load Love number h_3^L ?

(h_3^L : -0.21~-0.30, Métivier et al., 2008)

Less than 1 %



An aerial photograph of the Martian South Pole, showing a complex, layered structure of ice and snow. The terrain is characterized by numerous ridges, valleys, and circular features, indicating a long history of glacial and periglacial processes. The overall appearance is that of a vast, intricate ice cap.

Thank you for your attention

Martian South Pole