Using satellite measurements of stellar scintillation for mapping turbulence in the stratosphere

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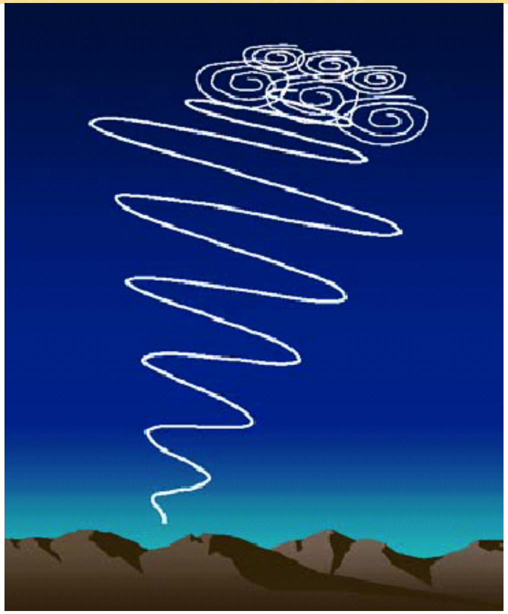
Outlines

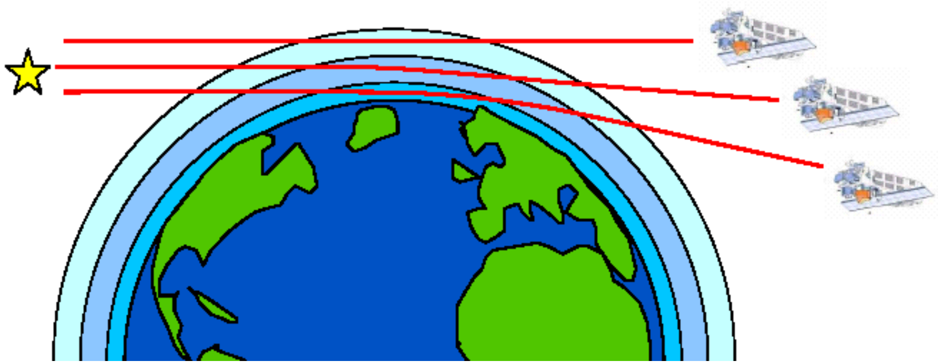
- Methodology: using space-borne stellar scintillation measurements for studies of small-scale processes in the atmosphere
- Application: results of analysis of GOMOS/Envisat scintillation measurements

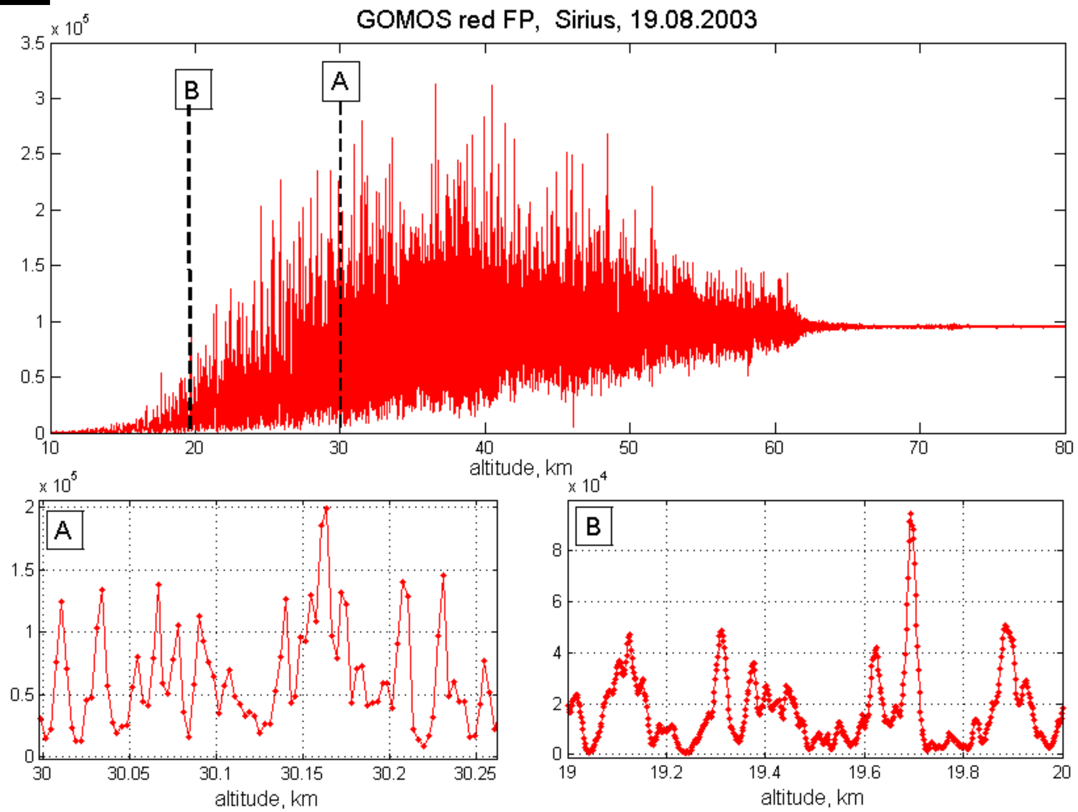
Introduction



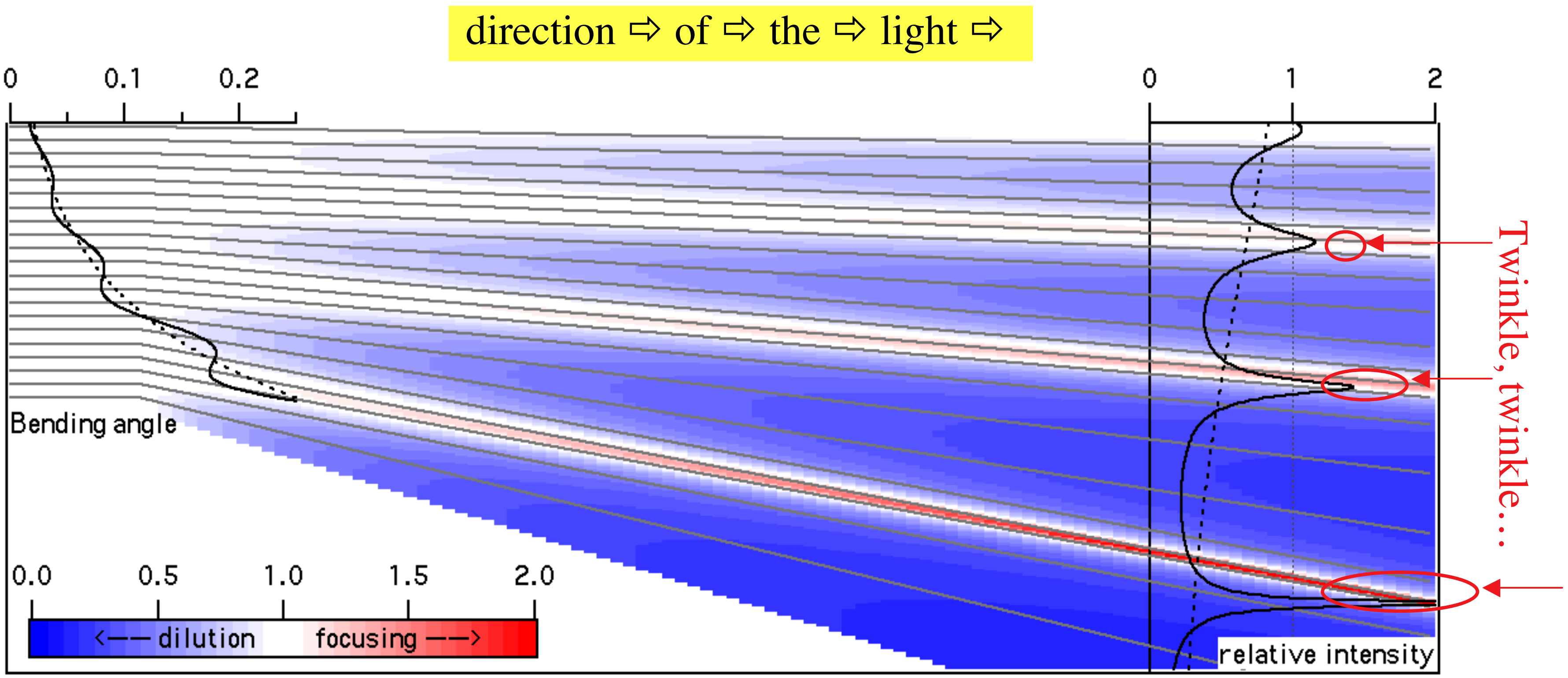
- Gravity waves, their generation, propagation and breaking
- Global effects of (relatively) small-scale gravity waves
  - influence the stratospheric circulation
  - affect ice cloud formation and polar ozone loss
  - they play an important role in driving atmospheric circulations (including quasi-biennial oscillation)
  - play an important role in controlling temperatures in the Antarctic ozone hole
- Satellite observations of stellar scintillations is the new approach for study of small-scale processes in the atmosphere

Scintillation of stars



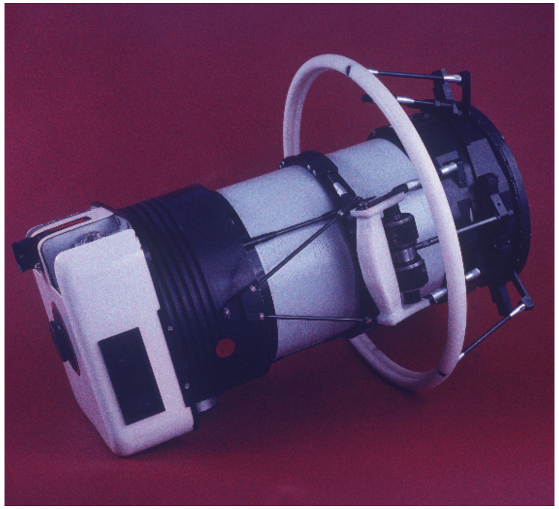


Scintillation of stars: a simplified qualitative explanation



Past and present space-borne stellar scintillation measurements

- Past:
  - EFO-2 photometer, Russian MIR station (1996-1999)
    - Sampling frequency up to 16 kHz
    - Central wavelength 485 nm
    - Man-controlled photometer (~100 occultations, within ±60° latitudinal band)
- Present: scintillation measurements by GOMOS fast photometers (since March 2002)
  - First bi-chromatic scintillation measurements
    - Blue 470-520 nm
    - Red 650-700 nm
  - Sampling frequency 1 kHz
  - Global coverage
  - Objectives
    - Scintillation correction of spectrometer data
    - High resolution temperature profile
    - **Small scale structures of air density, stratospheric dynamics**



EFO-2 fast photometer

GOMOS fast photometer

General strategy for retrieval of information about air density irregularities

- 3D distribution from 1D scintillation measurements?
  - The problem is severely ill-posed

- Approach proposed in [Gurvich and Kan, 2003]

> - 1 step. The spectrum of the air density irregularities is parameterized
> - 2 step. 3D-spectrum of air density irregularities →1d-scintillation spectrum at observation point (The theoretical relations are found)
> - 3 step. The parameters of the spectral model are retrieved via fitting experimental scintillation spectra

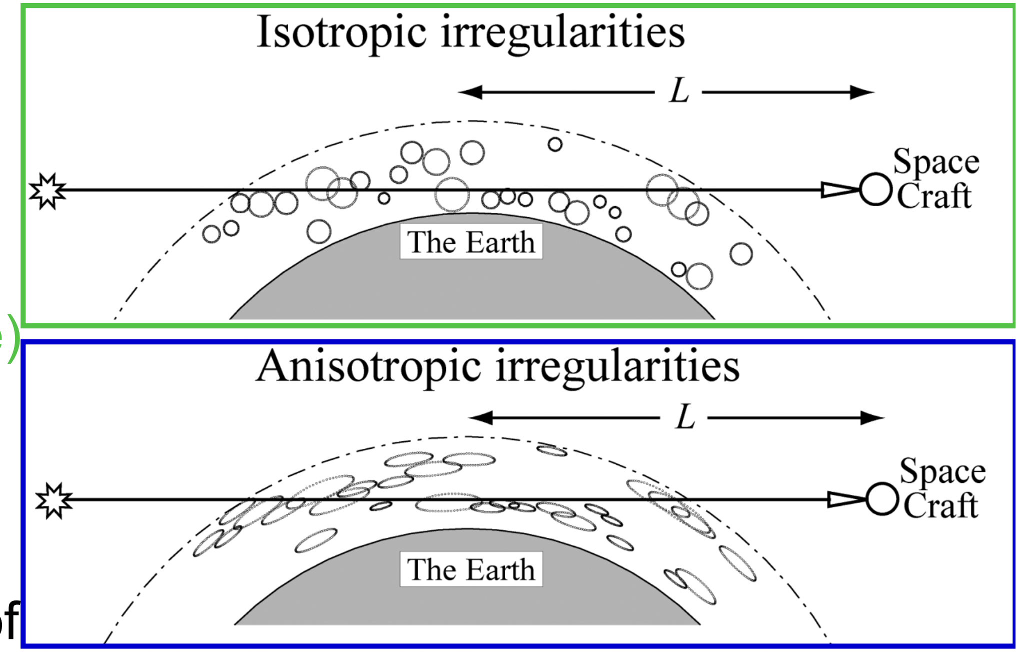
Structure of air density irregularities

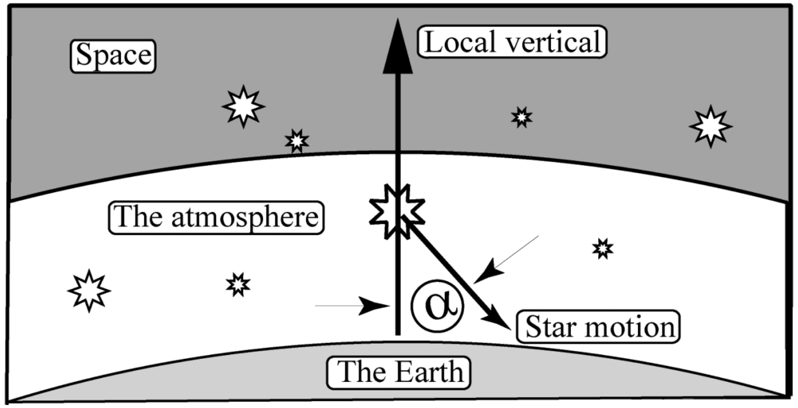
- Anisotropic irregularities
  - Elongated in horizontal direction
  - Generated by internal gravity waves
- Isotropic irregularities (turbulence)
  - Result from breaking of internal gravity waves
  - Dynamic instabilities
- Two-component spectral model of relative fluctuations of air density

$$\Phi_\nu = \Phi_W + \Phi_K$$

anisotropic

isotropic





Spectrum of anisotropic irregularities

- corresponds to anisotropic irregularities generated by a random ensemble of internal gravity waves

$$\Phi_W = C_W \eta^2 \left(\kappa_z^2 + \varsigma^2 \kappa_\perp^2 + \kappa_0^2\right)^{-5/2} \varphi\left(\frac{k}{\kappa_W}\right)$$

$$k^2 = \eta^2 \kappa_\perp^2 + \kappa_z^2$$

$$\kappa_\perp^2 = \kappa_x^2 + \kappa_y^2$$

  - C_W is the structure characteristic
  - η is the anisotropy coefficient
  - $2\pi/\kappa_0$ is the outer scale
  - $2\pi/\kappa_W$ is the inner scale

- The associated 1D vertical spectrum for $\kappa_0 << \kappa_z << \kappa_W$ corresponds to the model of the saturated gravity waves

$$V(\kappa_z) \approx C_W \frac{2\pi}{3} \kappa_z^{-3}$$

$$V_{\delta T/T} = A \frac{\omega_{BV}^4}{g^2} \kappa_z^{-3}$$

Spectrum of isotropic irregularities

- Spectrum of locally isotropic turbulence (Kolmogorov model)

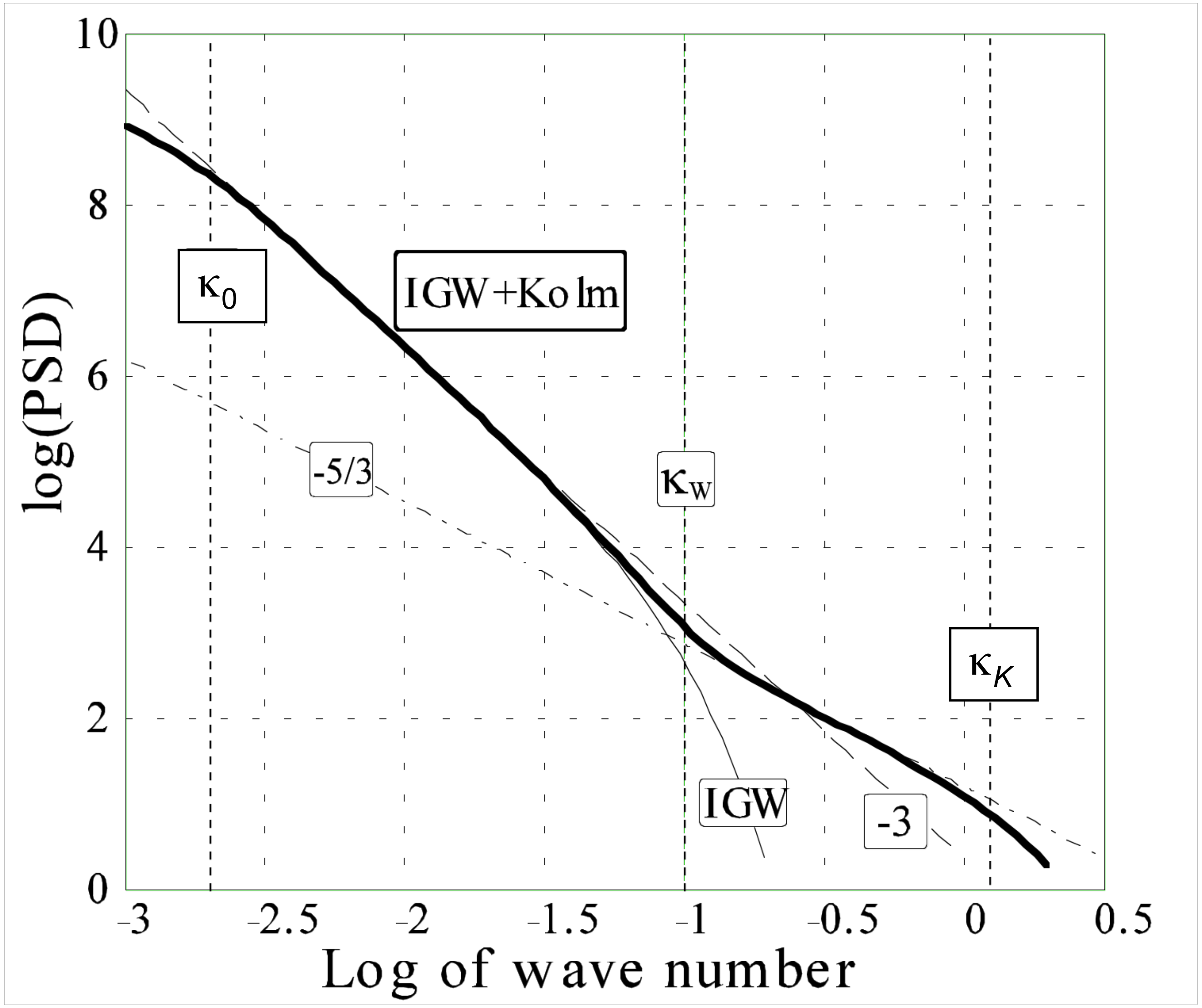
$$\Phi_K(k) = 0.033 C_K k^{-11/3} \exp(-(k/\kappa_K)^2)$$

$$k^2 = k_x^2 + k_y^2 + k_z^2$$

  - C_K is the structure characteristic
  - κ_K is the wavenumber corresponding to inner scale of isotropic irregularities (Kolmogorov scale)

- The corresponding 1D spectrum follows well-known -5/3 power law
- Individual turbulent patches are not resolved, C_K represents the effective value in the region of interaction of light wave and the turbulent atmosphere

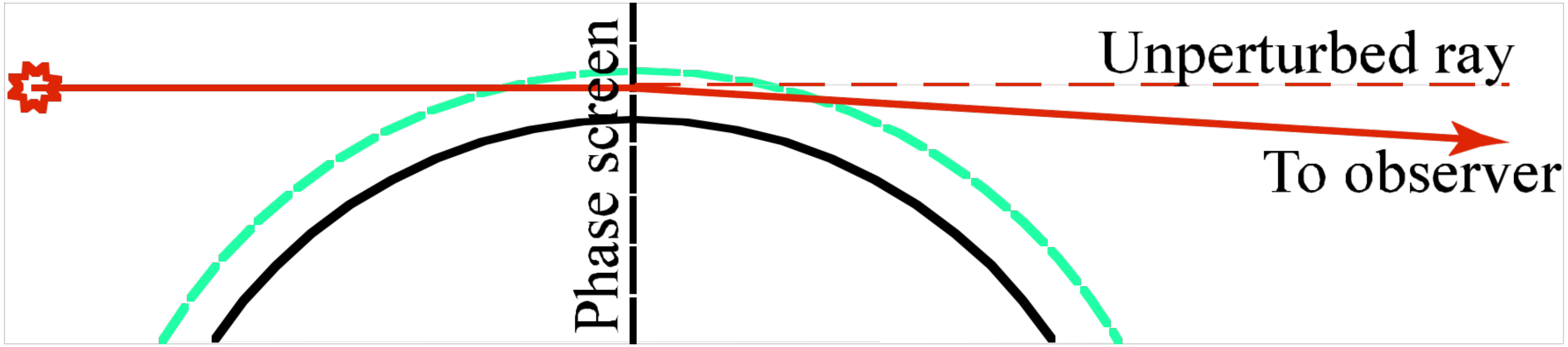
Model of 1D vertical spectra of air density irregularities



Modelled scintillation spectra

- Stratospheric distortion of light rays
  - Distortion of optical path (eikonal)
- Frozen field assumption
- Phase screen approximation

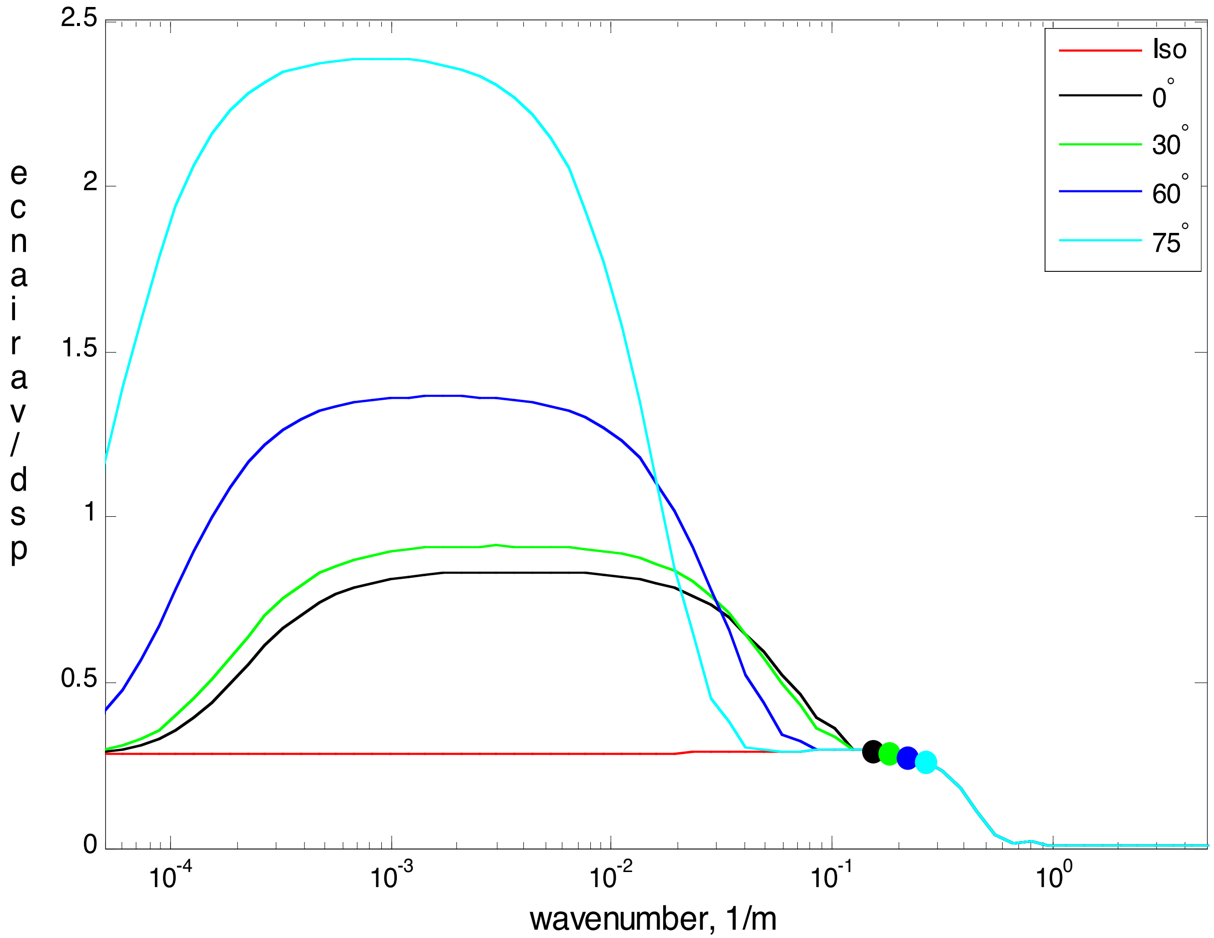
$$\Psi = \int_{\mathrm{ray}} dl N(\mathbf{r})$$



- Scintillation spectrum (weak scintillation)

3d spectrum of air density irregularities $\Phi_\nu(k_x, k_y, k_z)$ → 2d spectrum of eikonal fluctuations $F_\Psi(k_y, k_z)$ → 2d spectrum of scintillation → 1d spectrum of scintillation

Scintillation spectra



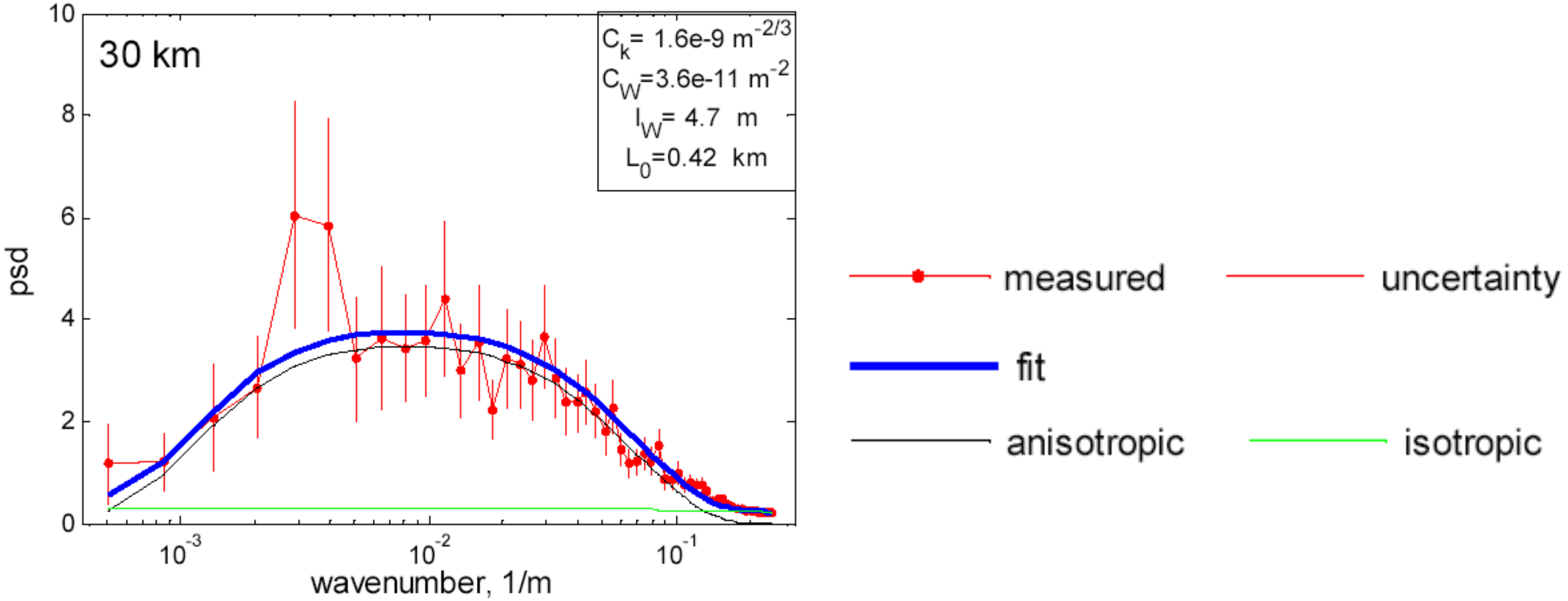
$$V^{\mathrm{mod}}(k) = C_K V_{iso}(k) + C_W\, V_{aniso}(k,\, \kappa_W, \kappa_0)$$

Inversion

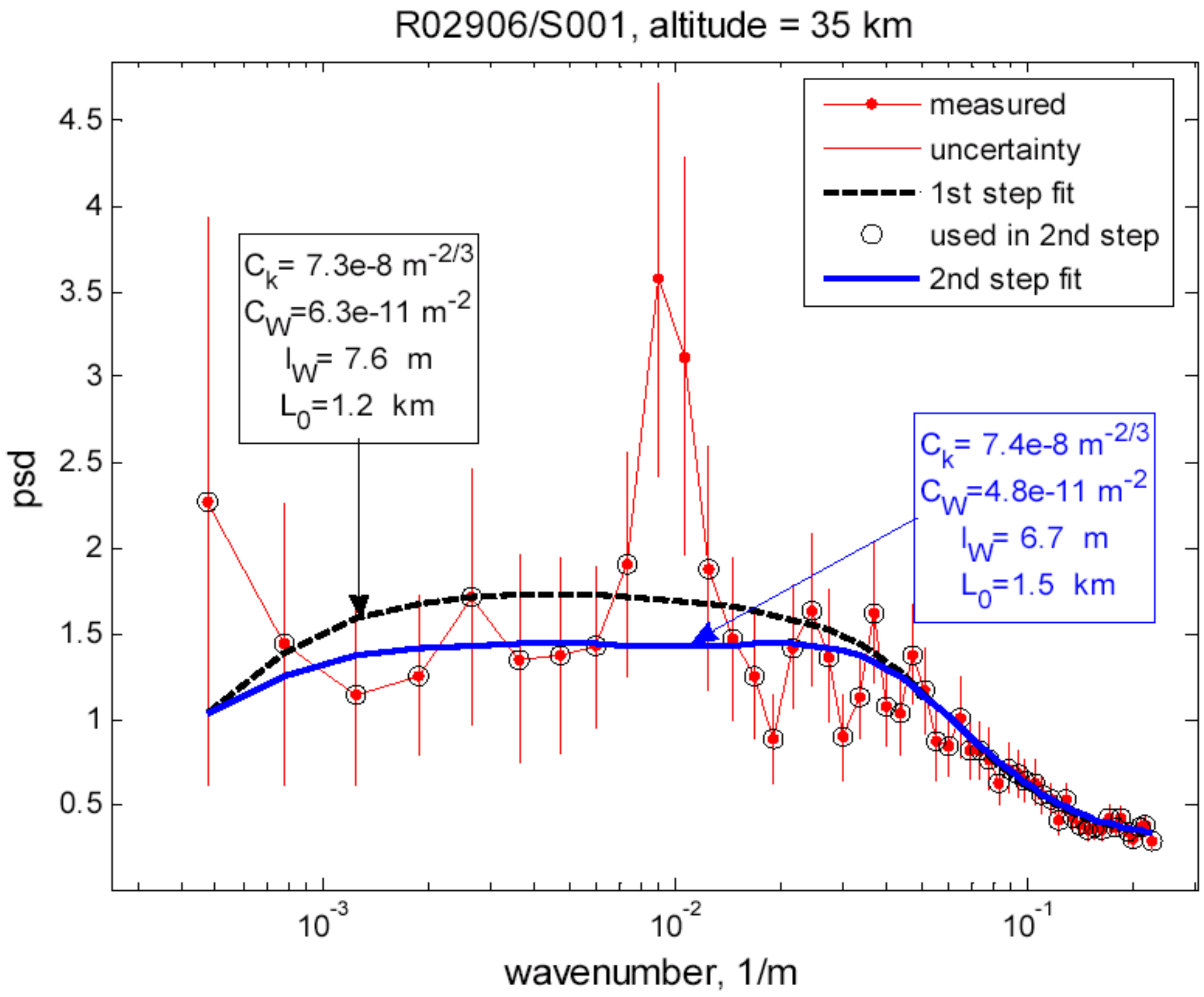
- $V_{meas} = C_K V_{iso} + C_W V_{aniso}(\kappa_W, \kappa_0) + \delta$
- Maximum likelihood method, which is equivalent to minimization of

$$\chi^2 = \left(C_K V_{iso} + C_W \mathbf{V}_{aniso}(\kappa_W, \kappa_0) - \mathbf{V}^{meas}\right)^T \mathbf{S}^{-1} \left(C_K V_{iso} + C_W \mathbf{V}_{aniso}(\kappa_W, \kappa_0) - \mathbf{V}^{meas}\right)$$

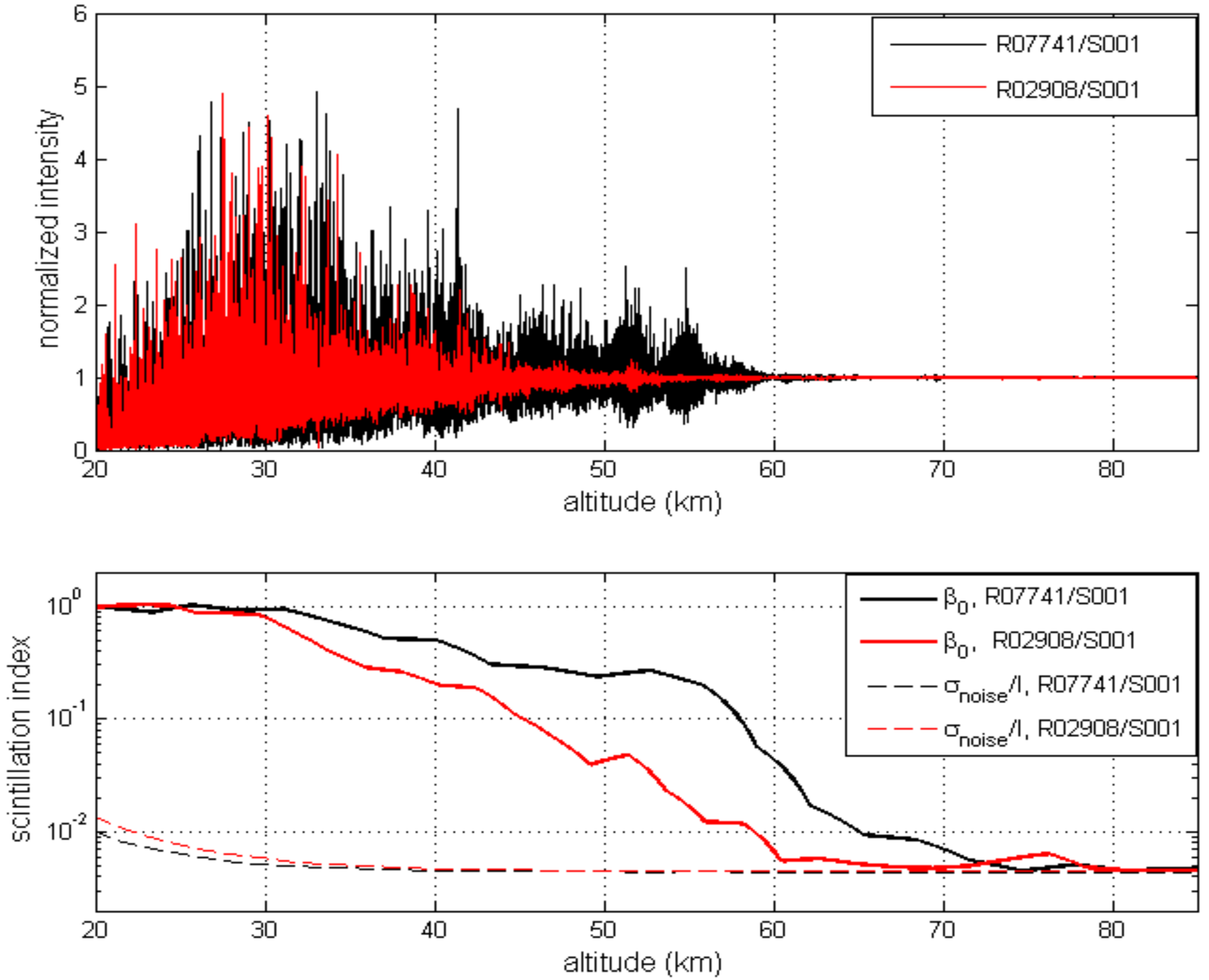
- Combination of linear and non-liner optimization
  - Non-linear fit (Levenberg-Marquardt) for κ_W and κ_0
  - Linear fit (weighted least-squares method) for C_K and C_W



Filtering quasi-periodic structures



Altitude range



Indication on gravity wave breaking in polar night jet

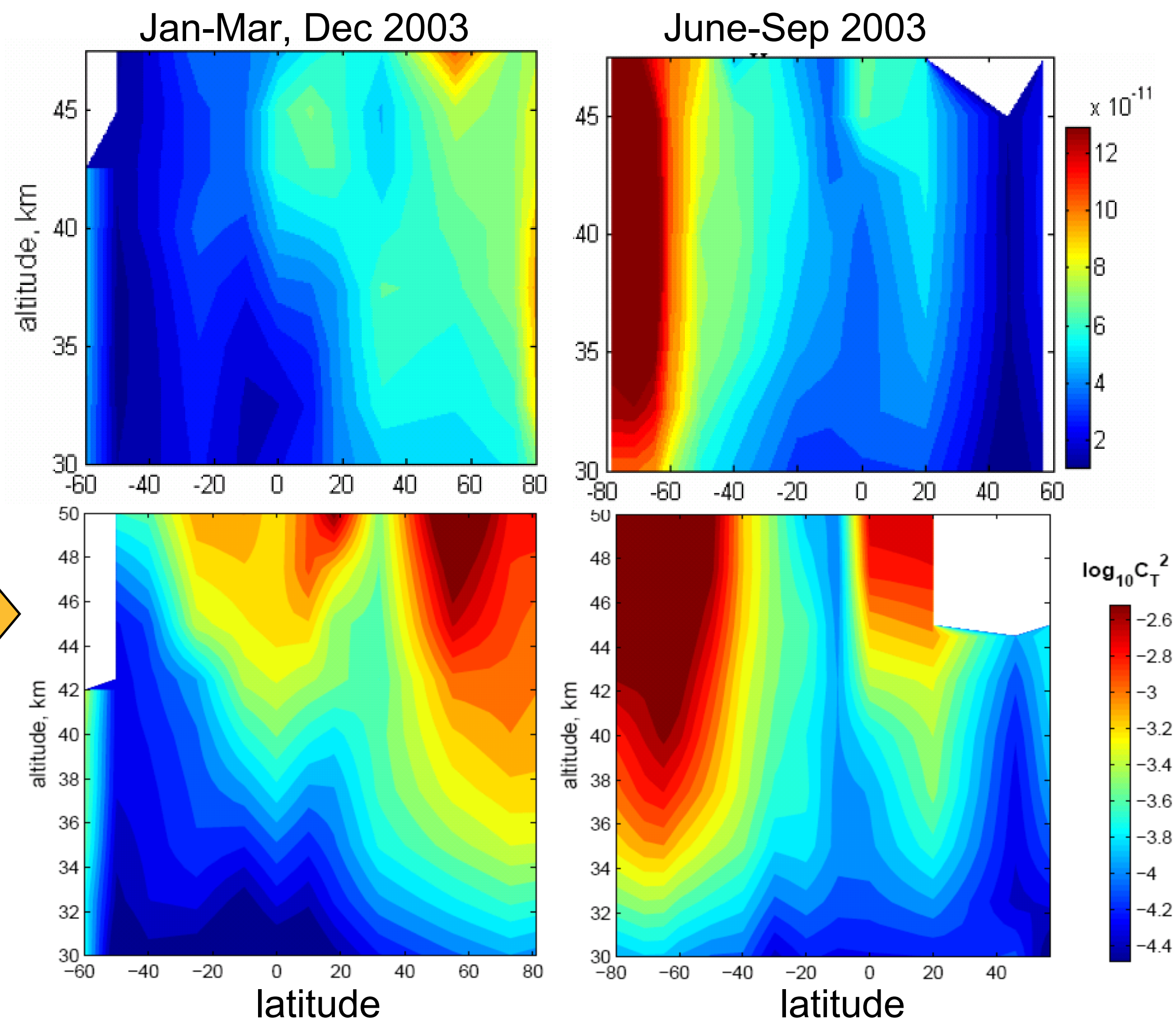
- Qualitative: Sofieva et al. (2007), Global analysis of scintillation variance: Indication of gravity wave breaking in the polar winter upper stratosphere, *Geophys. Res. Lett.*, 34, L03812, doi:10.1029/2006GL028132

Gravity wave structure characteristic $C_W(m^{-2})$

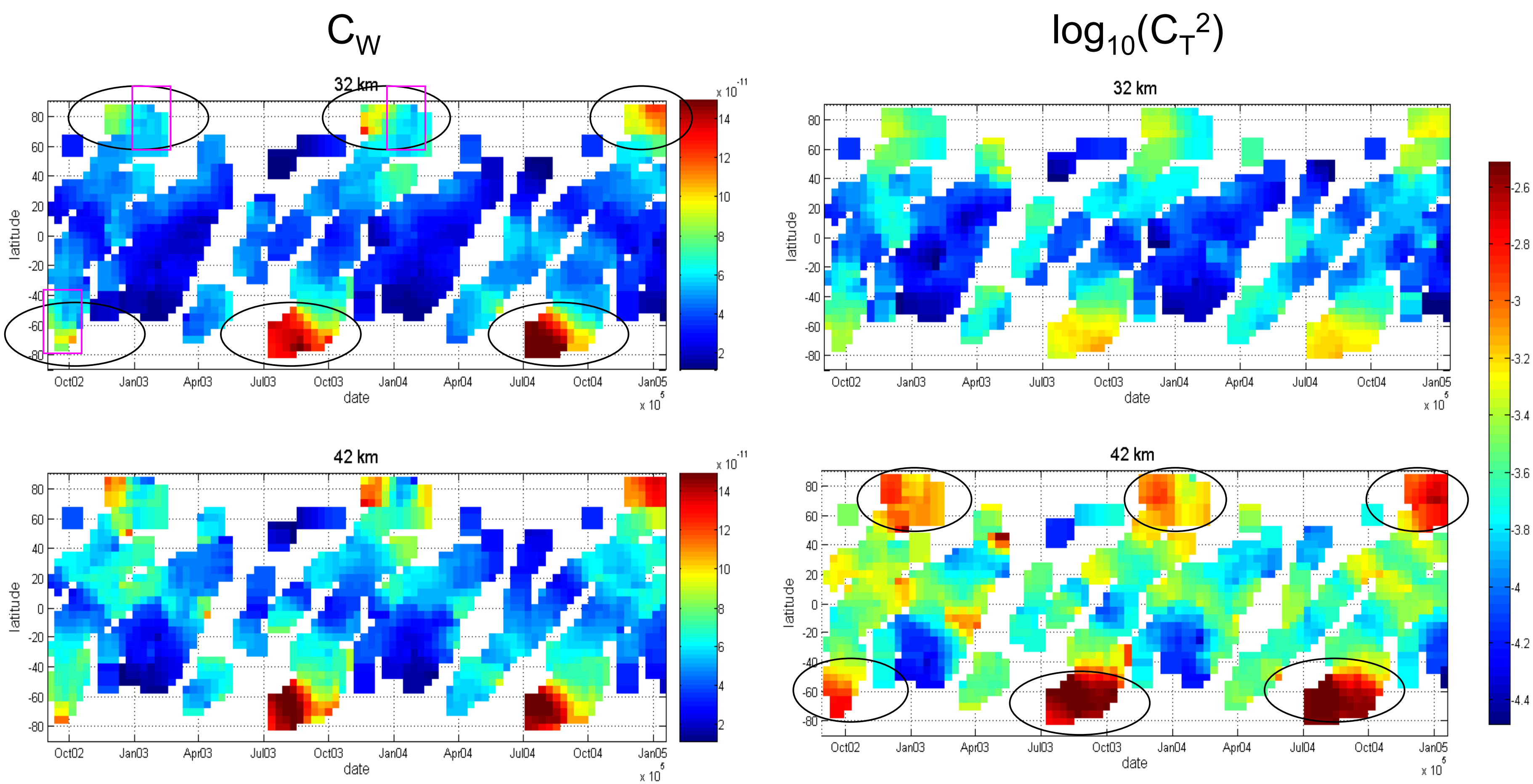
Turbulence structure characteristic $C_T^2(K^2m^{-2/3})$

$$C_T^2 = \langle T \rangle^2 C_K$$

Sofieva et al., GRL, 2009

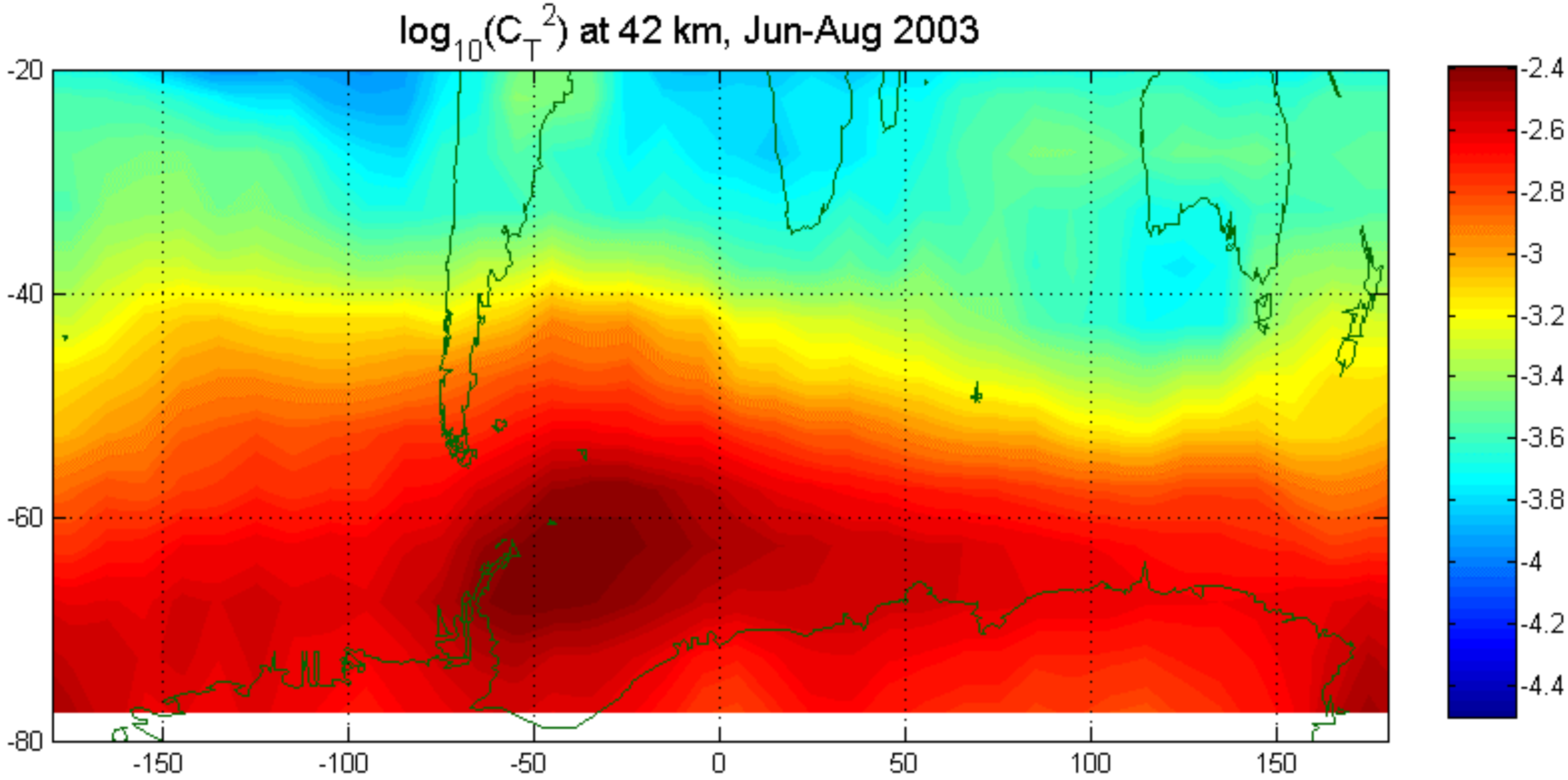


Latitude-time sections at selected altitudes

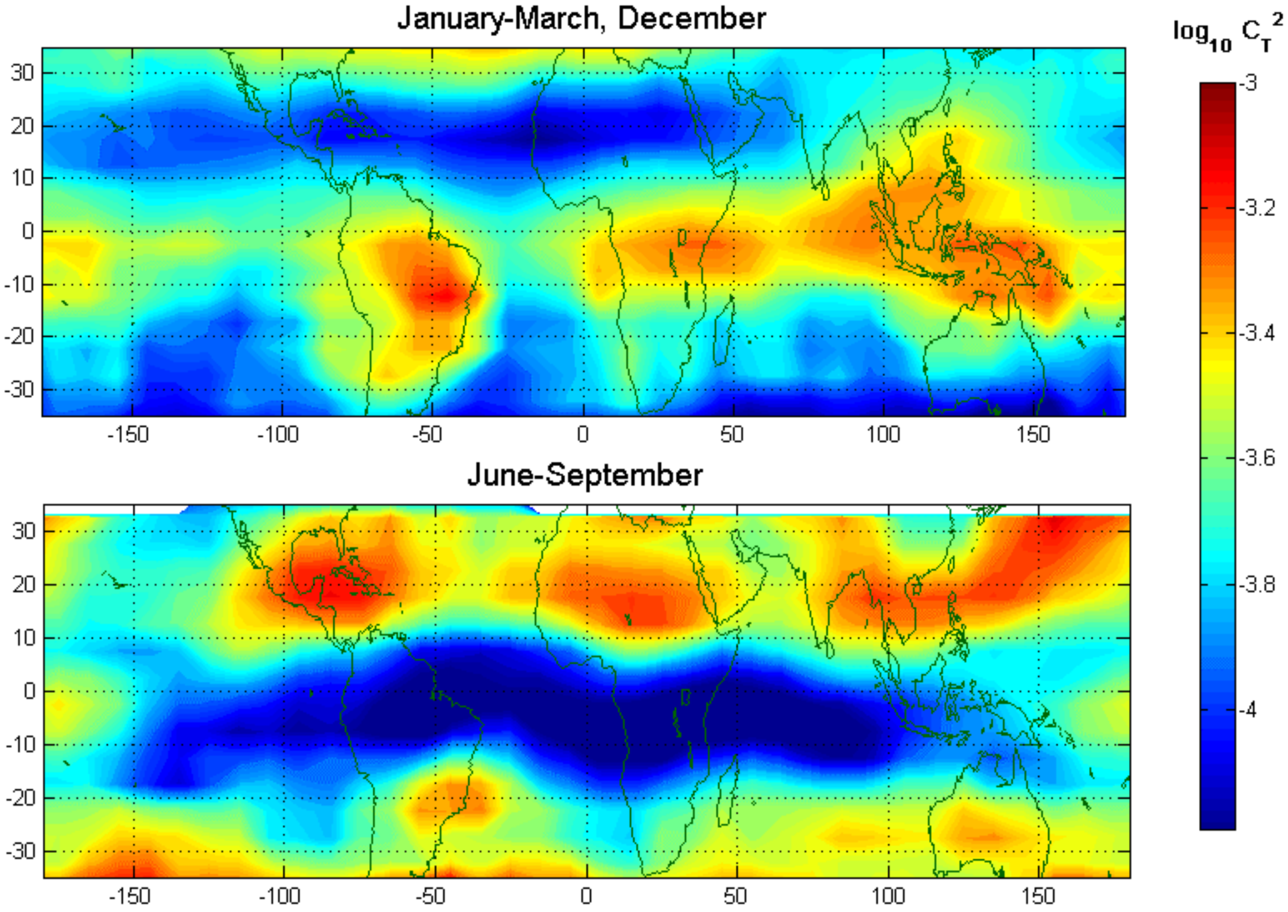


- Large enhancements of both GW and turbulent components at high latitudes in winter: seems to be GW breaking related to polar night jet
- Smaller Cw values immediately after sudden stratospheric warmings

C_T^2 in SH polar winter stratosphere (at 42 km)



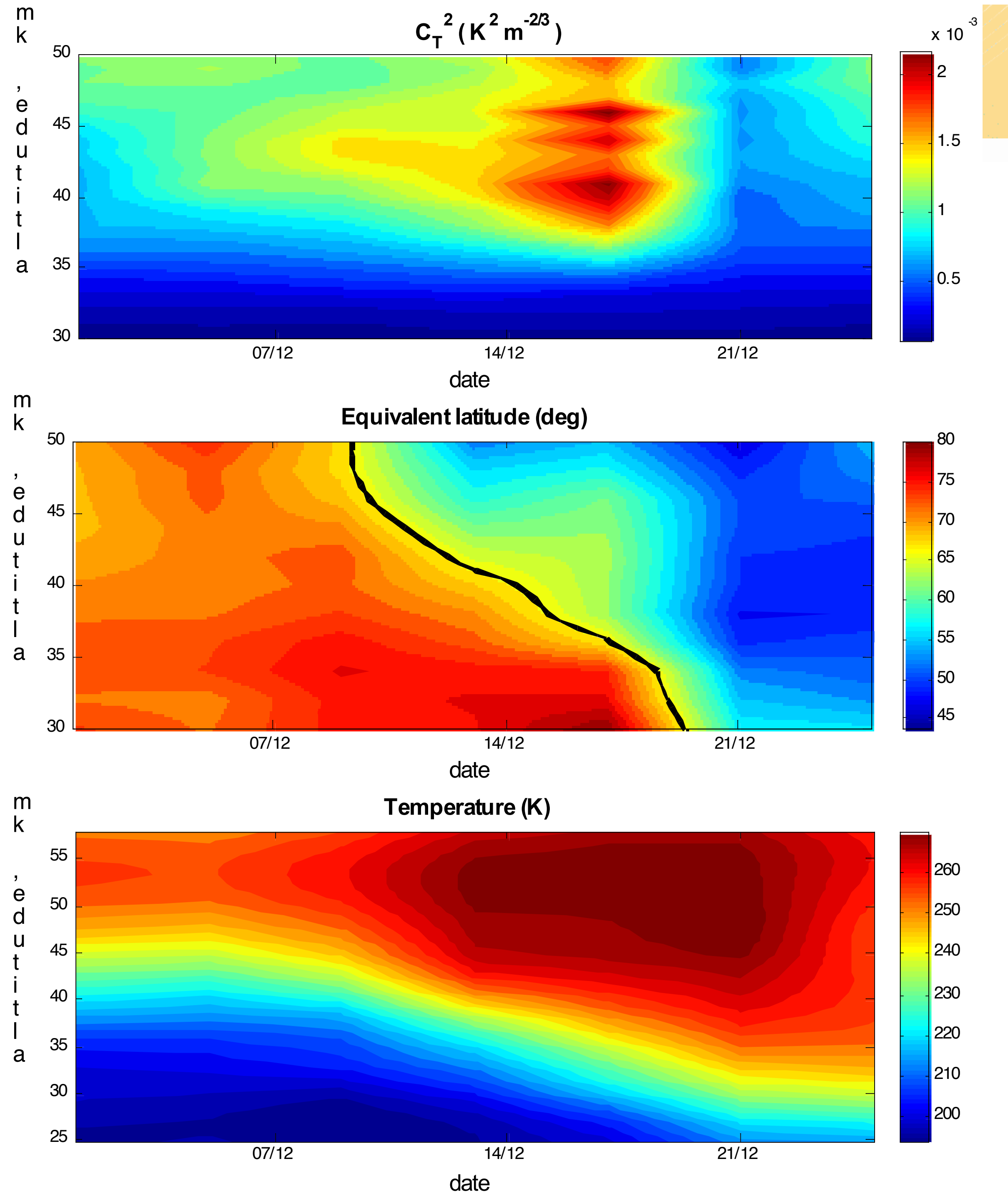
C_T^2 in tropics (at 42 km)



- Turbulence intensity is smaller in tropics than in polar regions; it has a pronounced zonal structure
- Average values of C_T^2 follow the sub-solar latitude
- Almost all of the local enhancements are over continents
- Many of enhancements correspond well to the typical regions of deep convection
- No systematic increase of C_T^2 over large mountain regions is observed

Gurvich et al., 2007, GRL

Evolution of C_T^2 at 80 N during the sudden stratospheric warming in December 2003



Sofieva et al., (2007): Reconstruction of internal gravity wave and turbulence parameters in the stratosphere using GOMOS scintillation measurements, *Journal of Geophys. Res.*, 112, D12113, doi:10.1029/2006JD007483

Sofieva et al., 2009, GRL

GW spectra parameters in 2003

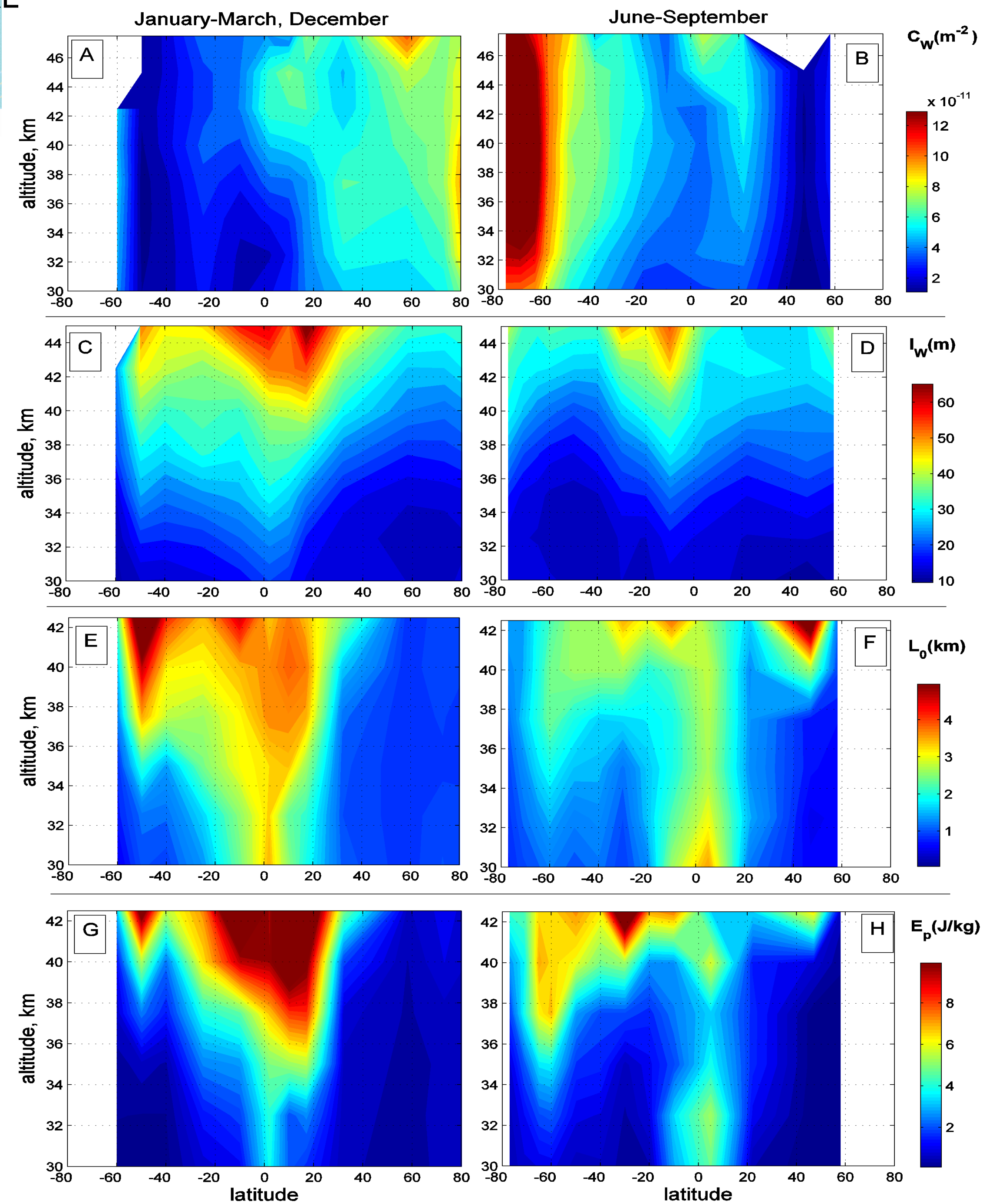
C_W

Inner scale

outer scale

GW potential energy per unit mass

$$E_p = \frac{2\pi}{3}\left(\frac{g}{\omega_{BV}}\right)^2 C_W \kappa_0^{-2}$$



Summary, discussion, future work

- The presented results are the start in studying small-scale air density irregularities
- Strength of scintillation method:
  - It covers the wavenumber range of transition of GW spectrum to turbulence -> possibility of visualizing GW breaking
  - Scintillation are affected by small-vertical-scale GW -> importance for GW parameterizations in GCM models
  - Other measurements at such small vertical resolution are scarce in this altitude range
- The processing of the 2002-Jan 2005 dataset has been recently completed, the data analyses are on-going