SPECTRALLY RESOLVED ENERGETICS OF THE MARTIAN ATMOSPHERE.

A. M. Valeanu, P.L. Read, F. Tabataba-Vakili, L. Montabone, *Oceanic and Planetary Physics, University of Oxford, Oxford, UK (valeanu@atm.ox.ac.uk)*, **S. Lewis,** *Department of Physical Studies, Open University, Milton Keynes, UK*.

Introduction

The dynamics and pattern of energy distribution across scales of the atmosphere are a key component in understanding the general atmospheric circulation, in the validation of atmospheric models and offers a nice extension to the work on turbulence initiated by Kolmogorov (1941). The spectral analysis of turbulence is the traditional theory for obtaining information of the energy and enstrophy injection and dissipation mechanisms, and the inertial subranges, where these quantities are transported between the scales (in the literature, these regions in spectral space between the injection and dissipation scales are defined as regions of well behaved turbulence). Three dimensional turbulence is thus theorised to follow a $k^{-5/3}$ law, with k being the wavenumber (a parameter denoting the scales of flow features - i.e. eddies), with energy cascading from the larger to the smaller scales (i.e. larger eddies break into smaller ones, limited eventually by the dissipation scales). This only develops in fully isotropic settings (well behaved turbulence), which is outside the injection/dissipation scales. Throughout the years, the theory of turbulence has been formalised; with some of the additions being the structure function analysis (Lindborg, 1999) which offers a deeper mathematical understanding and the multifractal theory (Frisch and Vergassola, 1991) for a mathematical description up to the viscous cutoffs of the energy spectrum.

In the case of atmospheric turbulence, the thin aspect ratio and stratification of the spherical atmospheric shell covering our planet, determined scientists to speculate the kinetic energy spectrum (KES) as following that from the two-dimensional turbulence theory developed by Fjørtoft in 1953. Under these assumptions, the energy spectrum should have two inertial regions, the large scale $k^{-5/3}$ energy inertial range, dominated by upscale energy cascade (opposite to the 3-dimensional turbulence), followed by a k^{-3} enstrophy inertial range, dominated by a downscale enstrophy cascade. The first consistently computed energy spectrum was by Gage & Nastrom (1984) from the Global Atmospheric Sampling Program (GASP) - aircraft data. They made it clear that the preceding two-dimensional turbulence hypothesis (Fjørtoft, 1953) was far from being sufficient to account for the behaviour of the real atmosphere and discounted the band-gap hypothesis (Fiedler & Panofsky, 1970); the most surprising feature was the swapping of the two inertial ranges from 2D turbulence theory - the actual atmosphere has the k^{-3} followed by the $k^{-5/3}$. This milestone proved to be a rich source of science which branched out in its own research area. There are several mechanisms which consistently simulate the mesoscale $k^{-5/3}$ spectral dependency in the energy spectrum. Some of these interpretations which account for the various cascades that would give rise to the observed data from Gage & Nastrom (1941), are: 2D stratified turbulence - upscale energy cascade (Gage 1979, Lilly 1983), internal gravity waves - downscale energy cascade (Dewan 1979, Smith et al 1987), quasi-geostrophic dynamics - downscale cascade or surface quasigeostrophic dynamics - downscale cascade (Tulloch and Smith, 2009), 3D strongly stratified turbulence - downscale cascade (Lindborg, 2006).

The study of the energy spectrum requires global atmospheric data, and hence, until recently, our planet has been the only one which has been sufficiently well observed for such a demanding analysis. Using our MGCM, we have initiated this novel investigation into the global dynamics of the Martian atmosphere utilising high resolution simulations with our model (T170 spectral resolution). The way our MGCM works enables us to compute high precision spectra compared to other GCMs used for Mars. We are also applying the same method to the lower resolution MACDA assimilated reanalysis (T31) (Montabone et al, 2014), however, this will not include the mesoscale range, as it only has up to 31 spectral scales. The potential of such a study comes from a convolution of scientific questions.

Essentially, we would like to investigate whether there is any evidence for energy or enstrophy cascading inertial ranges in the large-scale and in the mesoscale ranges of the KES, and compare to the observations we have for Earth. We did some preliminary computations of the ES for the large scales and have already noticed many interesting features. The KES exhibits several aspects in common with the Earth, but only for certain vertical levels. We could apply what we already know from terrestrial atmospheric theories for the *apparent*-enstrophy-cascading range (where the spectrum does manifest the k^{-3} law) but we lack a well developed theory for the other layers. This poses more questions, such as: where do the similarities and differences come from? Second of all, we compute the energy and enstrophy fluxes to investigate if Mars exhibits well developed energy and/or enstrophy cascades. This would greatly boost our understanding of the mechanisms we observe in Mars' general circulation and turbulence of the atmosphere. Furthermore, we will progress to analyzing the mesoscale range and similarly infer of the cascading in the $k^{-5/3}$ range and compare to Earth. This will give insight into its association with the transfer of energy upscale or downscale. Of similar importance is the decomposition of the kinetic energy into its divergent or rotational components of the flow, and hence their dominance over the scales. As Mars is in a different regime to Earth, even after we compute the energy fluxes, we might expect interactions between scales to differ from those we see on Earth. Considering the fact that there is no well developed theory for the ES in the case of Mars, this study is a requisite for similar background-models as it has been achieved for Earth.

Energy across scales

Turbulence can be studied through the structure function analysis or from the properties of the kinetic energy spectrum of the atmosphere. The former is accomplished by computing the statistical moments of the velocity difference between 2 generic points separated by a given distance. These quantities are proven to have connections to the statistical mean of the kinetic energy and energy fluxes, and thus are equivalent to the the energy spectrum analysis. The latter involves the use of two dimensional Fourier transforms or the spherical harmonic decomposition, combined with the analysis of the spectral fluxes. Our work follows from Tabataba-Vakili et al (2015), which uses the Boer (1989) method for computing the energy cycle of the Martian atmosphere. The Lorenz energy budget (Lorenz, 1955) was thus derived from the MACDA dataset. The chosen method for this study is the state-of-the-art algorithm extracted from the 2013 paper by Lindborg & Augier. The algorithm they developed adds to the aforementioned, topography, exact 3D advection terms and the separation of the vertical flux from the energy transfer between spherical harmonics. This is a straightforward extension of the Tabataba-Vakili et al (2015) analysis.

Lindborg & Augier used their formulation as a benchmarking tool to point out various inconsistencies in simulating mesoscale turbulence of Earth's atmosphere by two conventional GCMs: the Atmospheric GCM for the Earth Simulator (AFES) and the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS). Remarkably, their work showed that the AFES which used a triangular truncated spectral resolution of T639 with 24 vertical levels performed better at simulating the $k^{-5/3}$ inertial range, compared with the superior resolution of T1279 with 91 levels that the ECMWF-IFS uses. The crux of the energy cycle stands in the principle of conservation of energy, which greatly constrains the dynamics of the atmosphere. In accordance with the Lorenz (1955) theory, the Lindborg & Augier algorithm computes the spectral

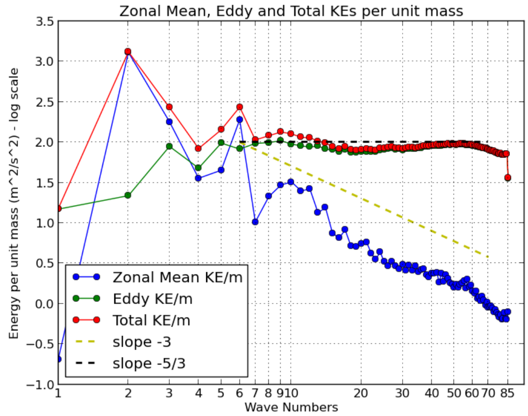

Figure 1: The T85L25 compensated ES of the full atmosphere (ignoring the top 3 "sponge" layers) weighted over sigma levels and at sol 572-602 in Curiosity-time. The spectrum starts directly with the "$-5/3$" law predicted by Kolmogorov.

terms from the energy conservation equations

$$\partial_t E_K^{lm}(p) = C^{lm}(p) + T_K^{lm}(p) + L^{lm}(p) + \partial_p F_{K\uparrow}^{lm}(p) - D_K^{lm}(p), \quad (1)$$

$$\partial_t E_A^{lm}(p) = G^{lm}(p) - C^{lm}(p) + T_A^{lm}(p) + \partial_p F_{A\uparrow}^{lm}(p) - D_A^{lm}(p), \quad (2)$$

where E_K and E_A are the mean kinetic and available potential energies (KE and APE) per unit mass and hence $\partial_t E_{K,A}$ are their time-evolution equivalents; G is the differential heating at large scales and latent heat release, C represents the APE to KE conversion, $F_{A\uparrow}$ and $F_{K\uparrow}$ are vertical fluxes, D_K and D_A are diffusion terms, T_K and T_A are transfer terms due to nonlinear interactions and finally L is the transfer term from Coriolis effects. The superscripts lm are the spherical harmonic numbers and the dependency (p) denotes the invocation of a pressure level coordinate system. the topography is introduced by the use of the Heaviside function $\beta(\mathbf{x}_h, p) = H[p_s(\mathbf{x}_h) - p]$ into the fields: $\tilde{f}(\mathbf{x}_h, p) = \beta(\mathbf{x}_h, p) f(\mathbf{x}_h, p)$. This complete view is initially applied to the T31L17 MACDA dataset with the plan for computing the full T170L25 MGCM free-run and reanalysis spectra underway.

The Mars Model

The model used in this study is a recent version of the joint LMD and UK assimilation MGCM (Forget et al, 1999). It is based on an adiabatic, multi-level, primitive-equation atmospheric model which uses a spherical geometry with representation of the fields at each level as a jagged-triangular truncated series of spherical harmonics. The code is compiled for an initial T31 and T85 resolution free runs, and will be applied for our T170 runs for a complete analysis of the spectrally resolved energetics down to mesoscale range.

Energy Spectra

Figure 1 displays the compensated energy spectrum (sol 572-602 Curiosity time - northern hemisphere Summer), validating the existence of the energy inertial range. A preliminary decomposition into rotational and divergent parts of the KE spectrum shows that the eddy KE is dominating the inertial range while, as expected, the zonal mean KE is relevant at global scales. A surprising feature is the absence of a k^{-3} enstrophy inertial range that we see on Earth. A more systematic approach, taking into account the full T170 spectrum (which cover an extensive mesoscale range) and the fluxes is currently under way, hence, more details on the type of inertial range and its importance in the full turbulence image of the Martian atmosphere will be presented in due course.

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