Large Scale Atmospheric Coupling Processes and Transport

William E. Ward
University of New Brunswick, Canada
Outline

• Context and Motivation
• Zonal means
• Sudden stratospheric warmings
• Tides
• Gravity waves
• Summary
Context and Motivation

• An investigation of Earth-Sun interactions can now start to be undertaken from a systems perspective.
• Further advances in this field require the detailed physical connections between atmospheric regions /ionosphere/ magnetosphere/solar wind/sun to be addressed.
• The terrestrial atmosphere/ionosphere is the most extensively and intensively observed and analysed complex physical system in the natural world.
• It is a complex non-linear system which responds non-locally to external forcing and changes in its internal characteristics.
Context and Motivation

• The reasons for the large scale zonal mean structure of the atmosphere to ~100 km is now understood but only in terms of averaged quantities i.e.
  – Eddy diffusion: a proxy for the effects of wave dissipation and turbulence.
  – Gravity wave drag: sources crudely modelled, instantaneous vertical propagation in GCM’s
  – Convective processes in troposphere parameterized.

• Challenge is to extend our understanding to 3D.

• In this talk I will summarize current thinking and note some work which is addressing this challenge.
ZONAL MEAN STRUCTURE
Radiative Equilibrium vs Realistic Thermal Structure

*Figure 3.31.* Meridional distribution of the radiative equilibrium temperature calculated by Fels et al. (1985).
Zonal Mean Winds

Zonal Solstice (June) Meridional

Thermal Wind Balance: The vertical shear of the zonal wind is directly related to the horizontal variation in temperature. Significant dynamical influences are needed to close the jets and cause the observed temperature structure. The jet reversals require a mechanism that doesn’t simply damp the motion – gravity wave dissipation is needed.

May 22-28, 2004, Banff  

GCC Summer School
At critical lines, gravity waves break because of dynamical instabilities. The waves that are not filtered continue upward and their amplitudes grow with height until they become convectively unstable at which point they undergo some dissipation. This dissipation creates a local stress which accelerates the atmosphere toward the zonal phase speed of the wave.
Temperature Anomaly Correlations between the Summer Mesosphere and Rest of Atmosphere

- Temperature anomaly correlations between the summer mesosphere and the rest of the atmosphere.
- This structure manifests ~5 days after anomalies in planetary wave activity develop in the winter hemisphere and persist for ~20 days.
- Explained as the result of circulation and gravity wave filtering changes induced by changes in planetary wave activity.
- See also Koernich and Becker (2010) and Becker (2012) for further discussion.

Karlson et al., JASTP, 2007
Sudden Stratospheric Warming

Liu and Roble, 2002
Peak of warming in the stratosphere is ~January 24, 2009. Mesospheric effects start ~January 16.
Temperature and Constituent Signatures

Figure 1. Temporal evolution of zonally averaged MIPAS temperature anomalies (with respect to the temporal average) within 70°–90°N. During the MIPAS data gap between 28 January and 5 February (grey–shaded) temperature anomalies are interpolated. Numbers at the top x–axis reflect the number of averaged observations.

Funke et al., 2010

Figure 2. Vortex-averaged MLS (top) CO (400–2500 K) and (bottom) N₂O (400–1600 K) during the 2008–2009 winter. Overlaid contours are CO values of 270 and 540 ppbv and N₂O values of 60 and 90 ppbv in 2005–2006. Yellow/magenta lines show date major SSW criteria were fulfilled in 2006/2009.

Manney et al., 2009
Gao et al., 2011

Shepherd et al., 2010

Figure 1. SATI (a) hydroxyl temperature and (b) airglow emission rates for the period from 1 to 29 January 2009 observed at Eureka (80°N, 86°W) and 87 km height.
Stratospheric Warming (CMAM)

We use a warming that occurred spontaneously in the extended CMAM to provide us with comparison fields for the warming. Note the height dependence of the warming/cooling signatures and the wind direction.
Schematic of Dynamics of Warming

- Mesopause
  - Mesospheric (GW) Induced Circulation
    - Cooling

- Stratopause
  - Stratospheric (PW) Induced Circulation
    - Heating

- Latitude → Pole
  - Warm, High Ox
  - Cool, Low Ox

- Reversed Circulation

TIDES
Atmospheric Tides

- Planetary scale oscillations whose periods are integral fractions of a solar day (diurnal: 24 h, semidiurnal: 12 h, terdiurnal: 8 h).

- **Migrating tides** propagate westward with the apparent motion of the sun (zonal wavenumber = frequency [maxima per day]). They are generated mainly by solar heating absorbed in the troposphere and stratosphere.

- **Nonmigrating tides** do not travel with the sun (can propagate eastward, westward or standing). They are mainly generated by the heating differences associated with topography, latent heat release and nonlinear interactions among various waves.

![Diagram showing Diurnal D,S,T, Westward w,e,s, Zonal WN 0-5 connections]

- Dws
- Diurnal D,S,T
- Westward w,e,s
- Zonal WN 0-5
Classical Tidal Theory

Analysis of Laplace’s tidal equation (for a windless and isothermal atmosphere) shows that eigenfunctions exist with specific latitudinal structures for each wavenumber.

Although idealized these functions provide a useful framework for analysing tidal signatures even in a realistic atmosphere.

Fig. 6. Diurnal Hough functions for zonal wavenumbers $s = 0$ (D0), $s = 1$ (DW1), $s = 2$ (DW2), and $s = -3$ (DE3). The index $m$ is related to the number of nodes in latitude, and is positive for propagating modes and negative for trapped modes.

Forbes and Wu, JAS, 2006
Tidal Components – Equatorial Region

Little energy at high wavenumbers

March

CMAM

June

Vertical Profiles of Tidal Components

Hagan et al.,
2009

Figure 4. TIME-GCM equatorial zonal wind amplitude (m/s) profiles for the dominant global waves that characterize the September solar minimum results: the migrating diurnal (DW1) and semidiurnal (DW2) tides, the eastward propagating zonal wave number 3 diurnal tide (DE3), the eastward propagating zonal wave number 2 semidiurnal tide (SE2), and stationary planetary wave 4 (sPW4).
The observations with the IMAGE-FUV imager

Immel et al., 2006

These images are representative of the local ionospheric properties at 20:00 LT, averaged over March 20 – April 20, 2002
Short Term Variability of Components

CMAM Migrating Diurnal U (m/s) at 95km in March

CMAM Diurnal U (m/s) East+West WN1 at 95km in March

CMAM Diurnal U (m/s) WN1+2+3 at 95km in March

CMAM Diurnal U (m/s) WN1+2 at 95km in March

OH Airglow vs Temperature (SABER)

Xu et al., 2010
GRAVITY WAVE EFFECTS

Baumgarten and Fritts, 2014

Figure 2. Expanded view of the projected image similar to Figure 1 but at 23:00 UT showing the GW and instability features revealed by NLC imaging in greater detail. The spatial scale is shown at the bottom. See text for details.
Spatial Distribution of Gravity Wave Flux using SABER

Ern et al., 2012
Modeling Gravity Waves in a GCM

Miyoshi et al., 2014

High spatial resolution modeling efforts with whole atmosphere models are starting to include resolved gravity waves. The model on the left has a 1 degree by 1 degree resolution (able to resolve gravity waves down to a wavelength of ~400 km.)

Figure 5. (left) Longitude (0–40°E)-time section of the zonal wind fluctuation due to GWs at 20°S on 18 June at a height of 300 km. Positive (negative) values indicate eastward (westward) wind component, respectively. Units are m s^{-1}. (middle) As in the Figure 5 (left) except for the wind fluctuation due to westward moving components. (right) As in Figure 5 (left) except for the wind fluctuation due to eastward moving components.
Realistic Gravity Wave Propagation in a Tidal Field

This figure demonstrates the effect inclusion of time-dependence (propagation) and horizontal refraction leads to a significant decrease in gravity wave drag. Full includes consideration of horizontal refraction and finite propagation velocity. noRef excludes refraction but still includes the finite propagation velocity. TS (time slice) is the parameterization included in most models (i.e. no horizontal refraction and instantaneous propagation. Background winds from Hammonia are used for these simulations.
Summary

• Although zonal mean latitudinal structures can be explained using large scale dynamical considerations this involves averaging over the detailed 3D physical processes.

• In this paper, some examples of observations and modeling which are addressing the 3D nature of atmospheric dynamics and transport are outlined.

• Congruency between understood and resolved 3D processes and the zonal mean behaviour is necessary for a deeper understanding of coupling in our atmosphere.

• Thank you for your attention!