Gravity Wave Dynamics and Climate: An Update from the SPARC Gravity Wave Activity

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The SPARC Gravity Wave Activity in recent years has placed a focus on the role of gravity waves in driving the general circulation of the stratosphere. While planetary-scale Rossby wave-driving clearly dominates the stratospheric circulation, small biases in the zonal-mean zonal winds can have very significant effects on Rossby wave propagation. Parameterized gravity wave (GW) drag in climate models is a primary tool used to reduce zonal-mean wind biases, and hence small-scale GWs can have larger impacts by helping to shape the propagation pathways of the more dominant Rossby waves. Contribution of GWs to the stratospheric circulation in the summer hemisphere may be particularly important because Rossby waves rarely propagate in easterly winds. In the tropical stratosphere, GWs and larger-scale waves play an approximately equal role in driving the quasi-biennial oscillation (QBO; *e.g.* Kawatani *et al.*, 2010). This gives small-scale GWs an important role in regional climate through shaping teleconnection pathways. For example, Scaife *et al.* (2014) show that the QBO is an important factor in forecasting the North Atlantic Oscillation. GWs also have a role in long-range weather forecasting through their influence on planetary wave propagation and sudden stratospheric warmings (Sigmond and Scinocca, 2010; Wright *et al.*, 2010; France *et al.*, 2012; McLandress *et al.*, 2012; Tomikawa *et al.*, 2012; Sigmond *et al.*, 2013). Improving the realism of these processes in global models requires realistic GW drag forces, including their distributions with latitude and height, and their changes over the broad range of timescales for weather and climate applications. However, determining what is realistic is a challenge.

The GW activity has thus been focusing on (1) using observations and models to constrain GW momentum fluxes (the GW contribution to Eliassen-Palm flux), (2) developing methods for constraining GW forces on the circulation, and (3) identifying important sources of GW momentum flux and quantifying their geographical and seasonal variations.

In 2013 a group from the activity published their comparison of GW momentum fluxes in observations and models (Geller *et al.*, 2013). The results showed surprisingly good agreement among climate models in how much total absolute GW momentum flux is needed to obtain a reasonable simulation of the middle atmospheric circulation. Limb-scanning satellite observations have been used to derive momentum flux estimates with global coverage over three or more years, however these remain severely limited by sampling resolution: Momentum fluxes estimated from satellite observations are significantly smaller than parameterized fluxes in climate models because of limitations on the wavelengths of waves that can be observed. The satellite measurements also do not currently provide any directional information on the fluxes, and observational filtering can give the appearance that waves have dissipated when in fact they may simply not be visible due to sampling.

The above factors combine to make it impossible to directly compute the GW drag force from current satellite measurements alone. Ern *et al.* (2011) examined vertical gradients in satellite-derived GW momentum fluxes and discussed these as 'potential accelerations' of the wind. More recently Ern *et al.* (2014) refer to these gradients as GW 'drag', but members of the activity want to caution that calling this quantity 'drag' is misleading. Radiosonde profiles can also provide a measure of GW momentum flux, but as with most measurement types, the sampling limitations greatly restrict the portion of the full GW spectrum that can be observed. Measurements from long-duration super-pressure balloons (Vincent and Hertzog, 2014) offer the most accurate global-scale GW momentum flux data. Momentum fluxes derived from these balloon data include directional information and cover the full range of the GW frequency spectrum (Rabier *et al.*, 2013; Jewtoukof *et al.*, 2013), although these data are quite limited in area and time and provide data at only one altitude. So again, drag cannot be computed from these data alone. New measurements from the Antarctic MST/IS radar can provide vertical profiles of GW momentum fluxes and drag with high time-resolution but only at a single location, and need additional modeling studies to examine horizontal distributions of the drag (Sato *et al.*, 2014). Thus the GW force on the global circulation remains something not yet possible to derive directly from observations.

Global GW drag can be estimated with data assimilation techniques (Pulido and Thuburn, 2005; McLandress *et al.*, 2012). Pulido (2014) describes a new and simple method for deriving unresolved (or 'missing') drag in the extra-tropical stratosphere based on potential vorticity inversion. Pulido (2014) applied the method to an idealized model constrained by observations from reanalysis, and also showed errors that can result from estimating GW drag directly from assimilation wind increments. In particular, the wind increment method can produce erroneous latitudinal and longitudinal structure if the drag force is spatially localized.

Since GW drag is now recognized as an important component of atmospheric models used for regional climate prediction and long-range weather forecasting, new emphasis lies on including realistic sources of GWs as well as testing and improving GW parameterization methods for global models. Parameterizations that permit climate and weather feedbacks on sources are being included in more models (Richter *et al.*, 2010; Kim *et al.*, 2013; Schirber *et al.*, 2014a; Richter *et al.*, 2014a,b), and experiments with these models show some intriguing connections between the stratosphere and the surface. For example, Richter *et al.*, (2010) show how changes in surface friction create a chain reaction on orographic GWs, planetary waves, and sudden stratospheric warming frequency. In the tropics, sensitivity to the details of the method of GW parameterization has been shown to strongly influence predicted changes in the QBO period (Schirber *et al.*, 2014b). It is clear that changes in the strength of the QBO have occurred in recent years (Kawatani and Hamilton, 2013), an observation that puts new emphasis on the importance of longer-term QBO prediction. At extra-tropical latitudes, GW sources include not only flow over topography, but also precipitating storms, fronts, and jets (Hoffmann *et al.*, 2013; Alexander and Grimsdell, 2013; Hendricks *et al.*, 2014). Plougonven and Zhang (2014) provide a review of research on jet and frontal sources. Theoretical studies of GW radiating from these sources continue (*e.g.* Yasuda *et al.*, 2014a,b). Sources of GWs are clearly very intermittent (Hertzog *et al.*, 2008; 2012; Wright *et al.*, 2013) and new stochastic parameterization methods better capture this intermittency (Eckermann *et al.*, 2011; Lott *et al.*, 2012) as well as more realistic effects on the stratospheric circulation.

Other new work related to parameterization methods examines horizontal and time-dependent GW propagation, which are neglected in most climate model parameterizations (Choi and Chun, 2013; Kalisch *et al.*, 2014). The ray-based parameterization method of Song and Chun (2008) includes these effects, but the computational costs currently prohibit application of such methods in long-term climate runs. Several global modelling groups are instead running short-term climate and weather simulations at extremely high resolution, where these effects can be explicitly resolved (Sato *et al.*, 2012; Preusse *et al.*, 2014). Although analyses of waves in such high-resolution simulations suggest much of the GW spectrum remains unresolved (**Figure 1**), continuing studies with high-resolution models are beginning to reveal details about GW sources and propagation that assist in the interpretation of observations.

One way that GWs and chemistry are linked is through the stratospheric transport circulation (or residual circulation). The role of GWs in this circulation is a research area ripe with new developments. Climate models almost uniformly predict an increasing trend in the strength of the transport circulation in the next century, and the role for GWs in this trend is still debated. Different models have different recipes for planetary wave, synoptic wave, and GW contributions to driving the stratospheric transport circulation as revealed in model inter-comparisons and summarized in a recent review by Butchart (2014). Cohen *et al.* (2014) provide a potential explanation for the spread among different model recipes. Their idealized model studies showed that localized intense GW forces were largely compensated by reductions in forcing due to resolved Rossby waves, with almost no net influence on the transport circulation. They also found evidence for this compensation acting in full physics climate models (Cohen *et al.*, 2013). New theoretical developments have also provided a three-dimensional formulation for the residual circulation (Kinoshita and Sato,

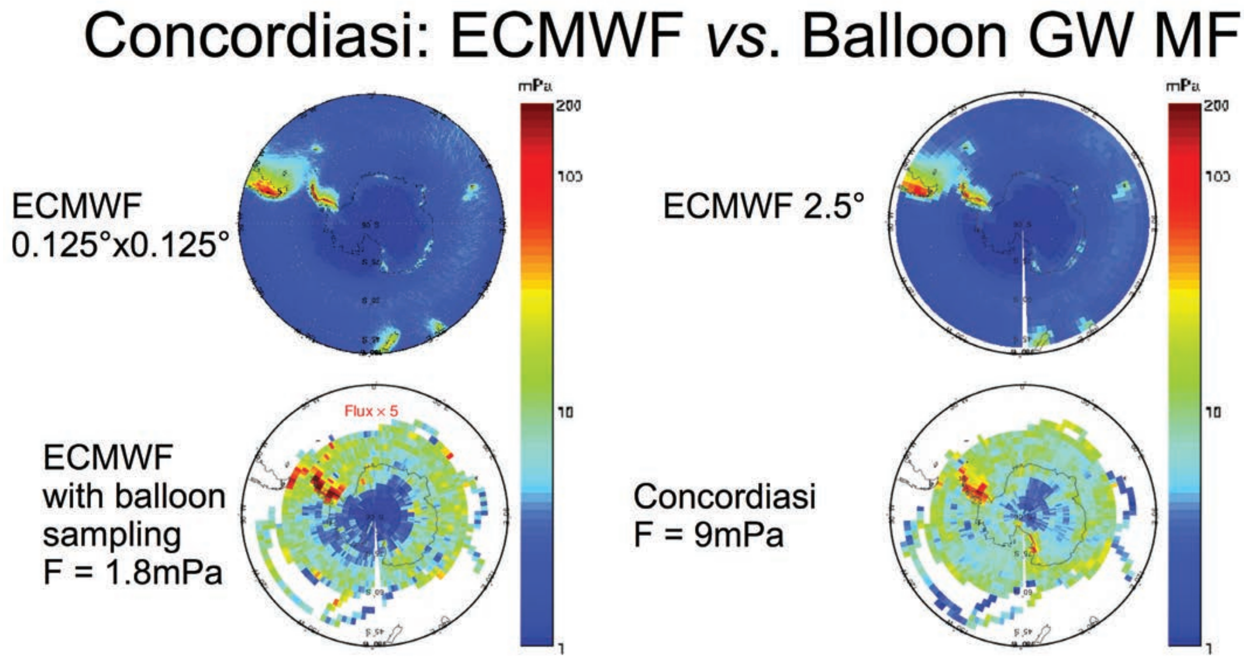

Figure 1: Comparison of momentum fluxes at 20km altitude from ECMWF analysis and Concordiasi superpressure balloon measurements from September 2009-January 2010. (a) ECMWF at native resolution, (b) 2.5° Concordiasi-like resolution, (c) and with the space/time balloon sampling taken into account, multiplied by 5x. (d) GW momentum fluxes inferred from the Concordiasi balloon campaign. The spatial distribution of GW fluxes agree well (except over Antarctica), but the ECMWF fluxes are underestimated by a factor of five, essentially due to the limited resolution of the ECMWF model. [Jewtoukoff *et al.*, 2015]

2013a,b). Small-scale GW forcing is generally zonally asymmetric, and the new three-dimensional form of the residual circulation can describe the zonally asymmetric response (Sato *et al.*, 2013).

We have summarized only a sample of new developments related to GWs in the recent literature here, highlighting a few recent results from researchers active in the SPARC Gravity Wave Activity, and choosing a focus on stratosphere-troposphere connections and their role in climate. Many other GW studies can be found in the literature that we have not covered here, and many new developments are underway. Just as planetary waves were a major focus of research in the mid-20th century as researchers began to model the global atmospheric circulation, today's global models have begun to directly simulate portions of the GW spectrum. The resulting studies of non-linear dynamical interactions between waves of all scales place GW dynamics at the centre of a 'new scale of interest' for modelling the global circulation.

Acknowledgements

The International Space Science Institute (ISSI) provided support to the group for 2013 and 2014 meetings in Bern, Switzerland, where many of the results described here were discussed. The authors would like to thank the participants in those ISSI meetings and those who contributed input for this article: Julio Bacmeister, Andrew Bushell, Naftali Cohen, Stephanie Evan, Marvin Geller, Albert Hertzog, Yoshio Kawatani, David Long, François Lott, Elisa Manzini, Charles McLandress, Peter Preusse, Manuel Pulido, Corwin Wright, and Nedjeljka Žagar.

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