Sensitivity of Simulated Climate to Conservation of Momentum in Gravity Wave Drag Parameterization

T. A. Shaw, M. Sigmond & T. G. Shepherd Department of Physics, University of Toronto, Toronto, Canada
J. F. Scinocca Canadian Centre for Climate Modelling and Analysis, Victoria, Canada, email: tshaw@physics.utoronto.ca

Introduction

The Canadian Middle Atmosphere Model (CMAM; Scinocca et al. 2008) is used to examine the sensitivity of simulated climate to conservation of momentum in gravity wave drag (GWD) parameterization. Momentum conservation requires that the parameterized gravity wave momentum flux at the top of the model be zero and corresponds to the physical boundary condition of no momentum flux at the top of the atmosphere. Allowing momentum flux to escape the model domain violates momentum conservation. Here we investigate the impact of momentum conservation in two sets of model simulations. In the first set, we consider the simulation of present-day climate for two model lid height configurations, 0.001 and 10 hPa, which are identical below 10 hPa. In the second set of simulations, we consider the impact of momentum conservation and model lid height on the modeled response to idealized ozone depletion in the southern hemisphere.

Momentum Conservation Constraint & Model Experiments

Momentum conservation by parameterized gravity waves is believed to apply, to good approximation for current general circulation model resolutions, within each vertical column and hence within each latitude band. Thus, for gravity waves the Elliassen-Palm flux divergence (EPFD) $\mathcal{F} = \nabla \cdot \boldsymbol{F}/(a\rho\cos\phi)$ is strictly vertical with $F_{(z)} = -a\rho\cos\phi\overline{u'w'}$ where u' and w' are gravity wave zonal and vertical velocities. Since there is no radiation of EP flux to or from space we obtain

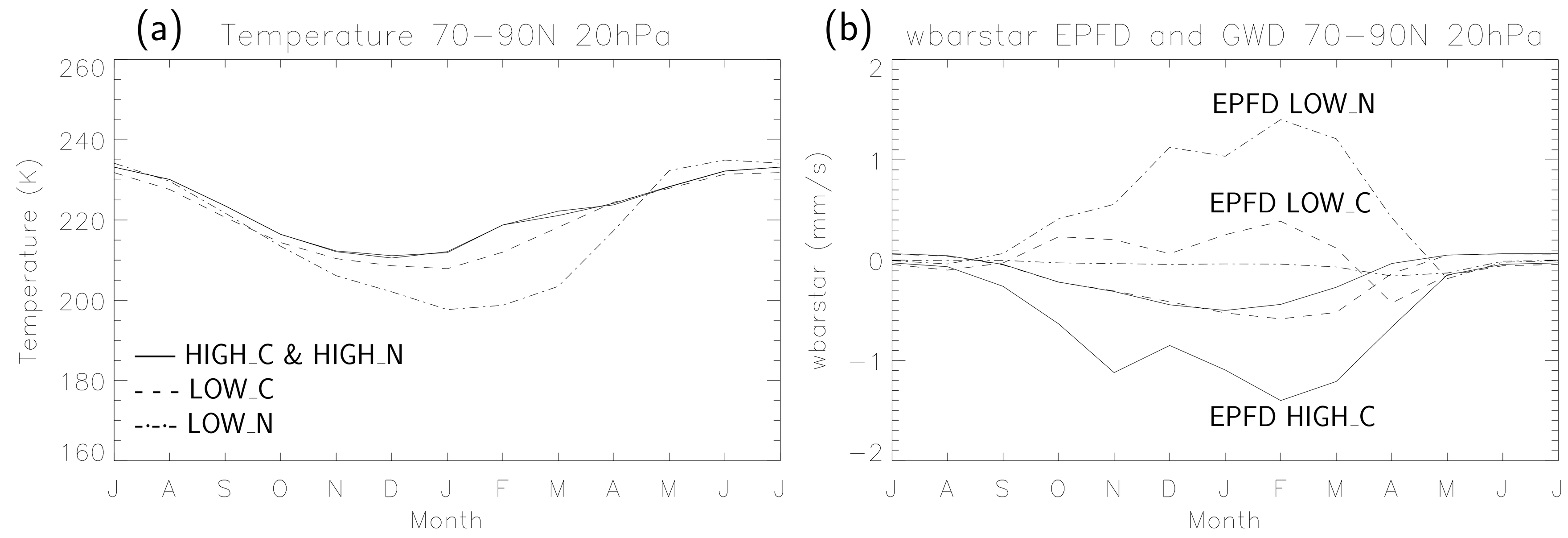
$$\int_z^\infty \rho\mathcal{F}\, dz = \rho\overline{u'w'}|_z.$$

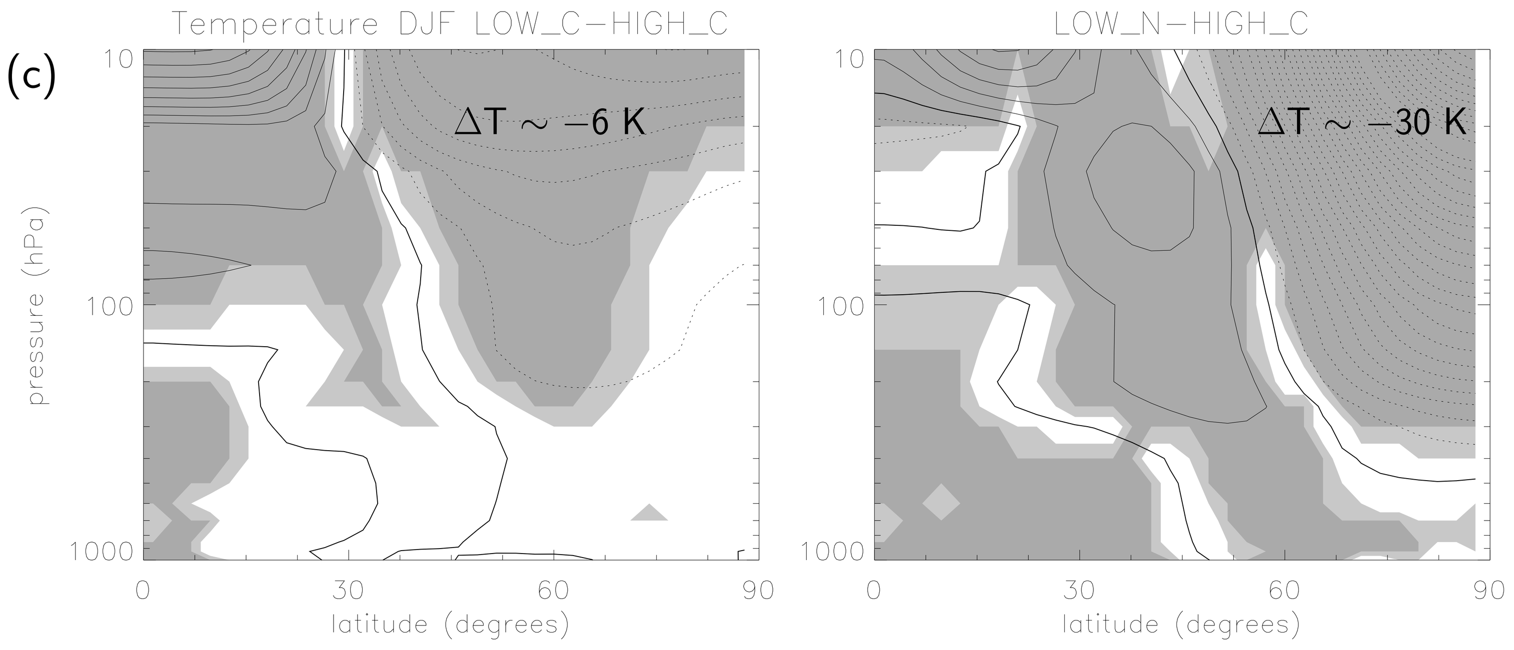
This relation says that any zonal momentum flux through z must be entirely absorbed in the atmosphere above to ensure conservation of momentum (Shepherd & Shaw 2004). A violation of momentum conservation occurs when gravity wave momentum flux is lost to space, for example.

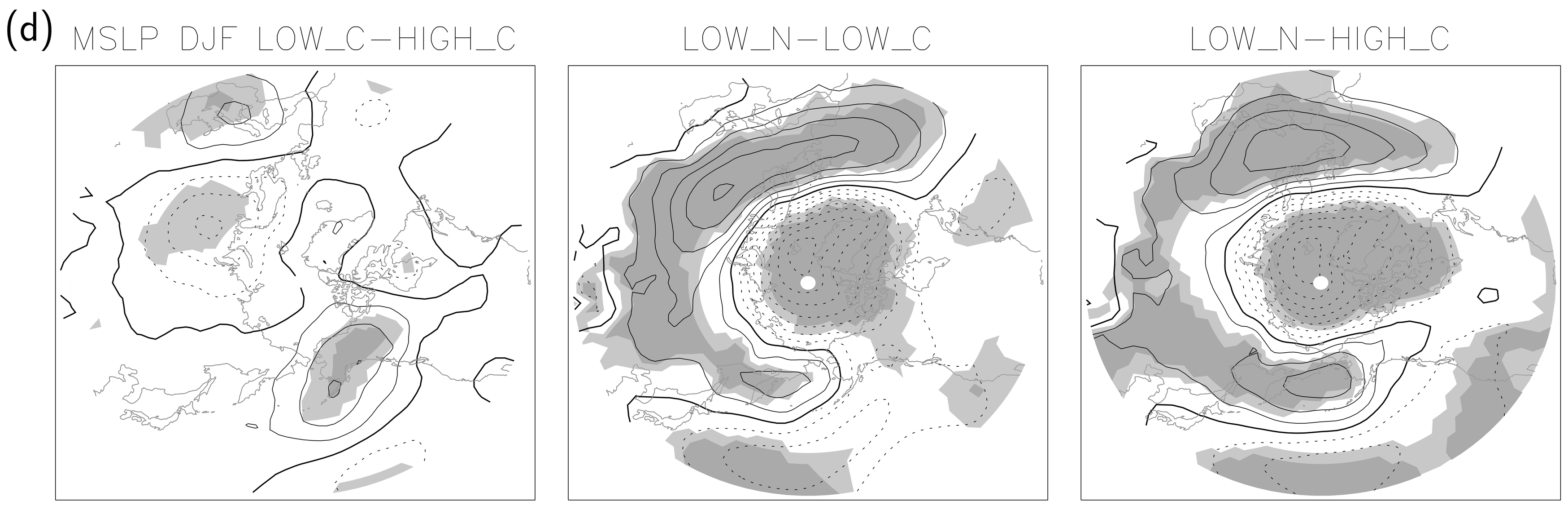
The impact of momentum conservation in GWD parameterization (both orographic and nonorographic) was explored in two sets of four CMAM experiments, each run for forty years. The first four experiments, labelled HIGH_C (high configuration, conservative), HIGH_N (high, non-conservative), LOW_C (lowered, conservative), and LOW_N (lowered, non-conservative) explore the sensitivity of the zonal-mean control climate to the position of the model lid with and without conservation of parameterized momentum flux. The second set of four experiments, labelled O3_HIGH_C (high, conservative, ozone hole), O3_HIGH_N (high, non-conservative, ozone hole), O3_LOW_C (lowered, conservative, ozone hole), and O3_LOW_N (lowered, non-conservative, ozone hole) explore the sensitivity of the response to imposed ozone depletion in the southern hemisphere. In all cases, conservation of momentum is enforced by depositing the parameterized gravity wave momentum flux at the model lid in the uppermost model level, within each model grid box.

Impact on Control Climate

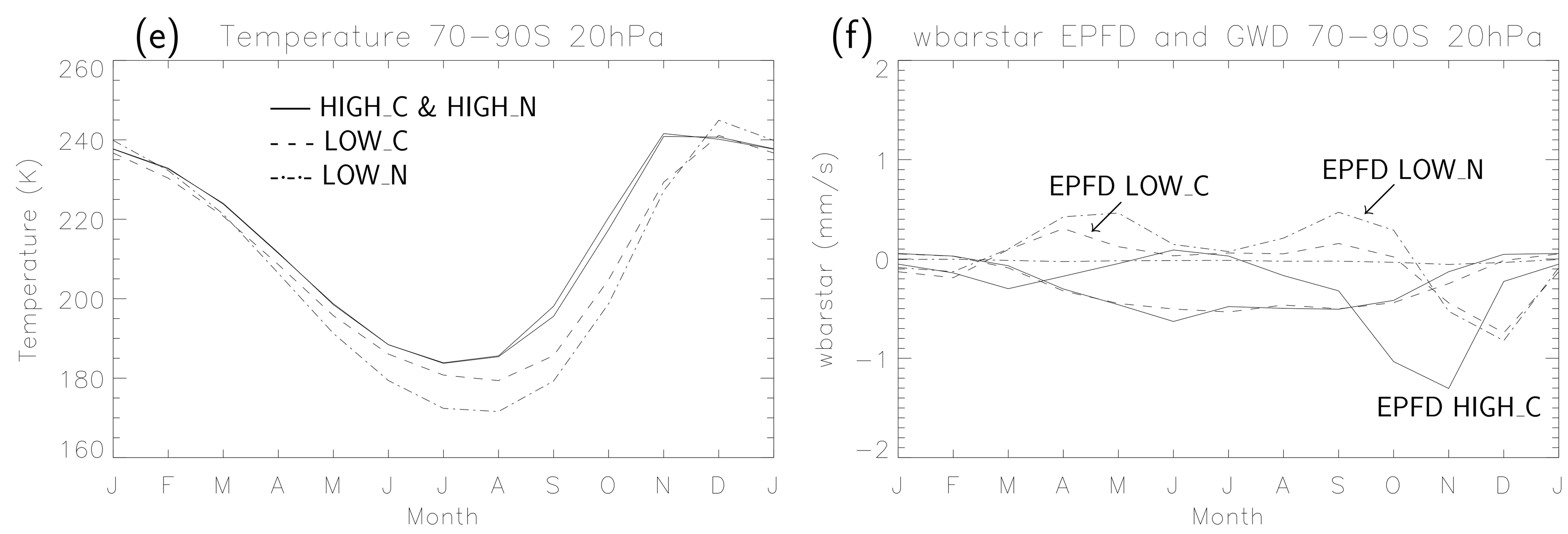
- Impact on Northern Hemisphere climate: Seasonal cycle of monthly mean (a) Temperature and (b) vertical residual velocity averaged north of 70°N at 20 hPa. Differences of (c) zonal mean temperature (contour interval 1 K) and (d) mean sea level pressure (30-90°N, contour interval 1 hPa) in December, January and February.

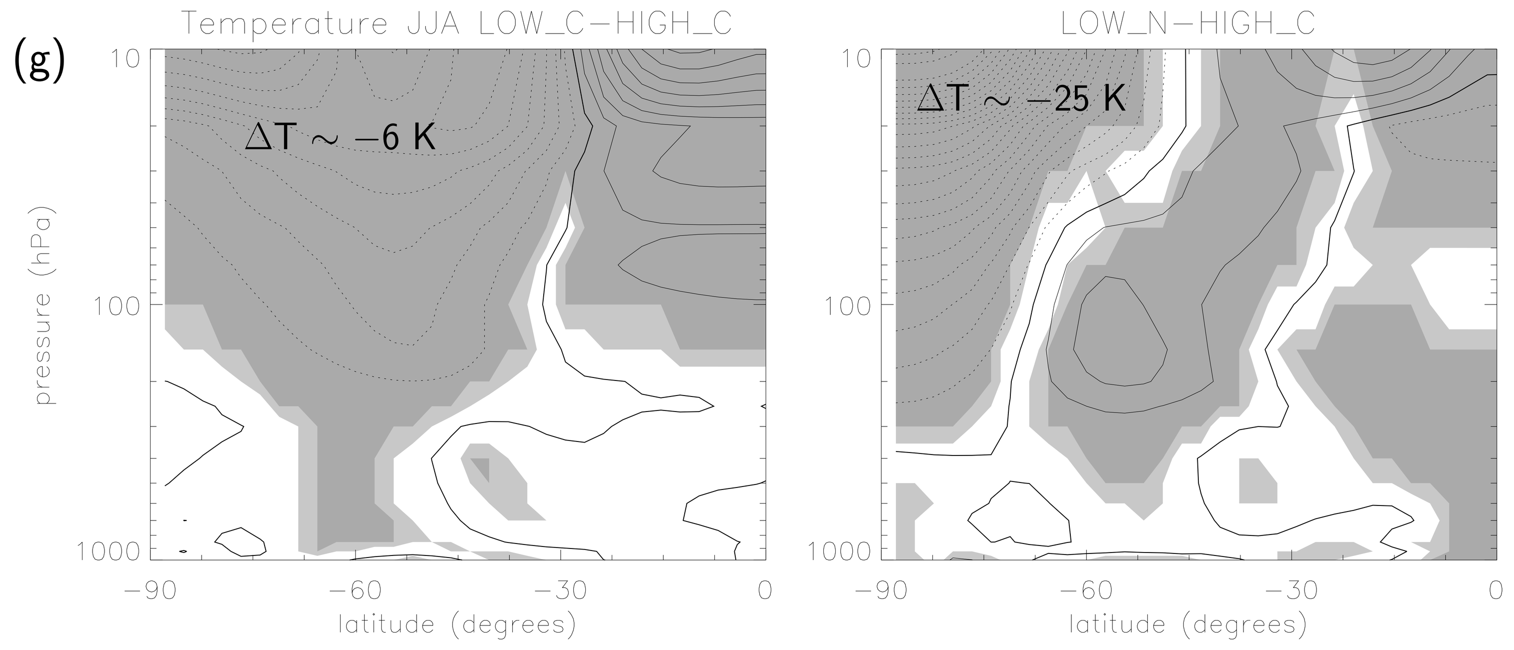


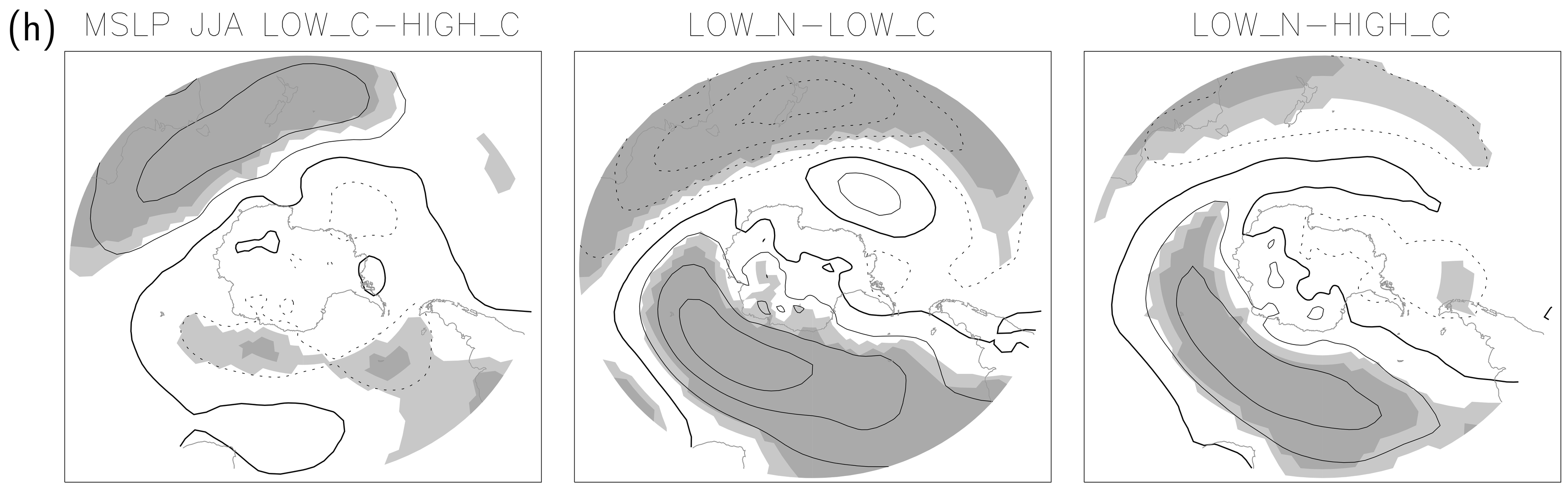




- Impact on Southern Hemisphere climate: Seasonal cycle of monthly mean (e) Temperature and (f) vertical residual velocity averaged south of 70°S at 20 hPa. Differences of (g) zonal mean temperature (contour interval 1 K) and (h) mean sea level pressure (30-90°S, contour interval 1 hPa) in June, July and August.



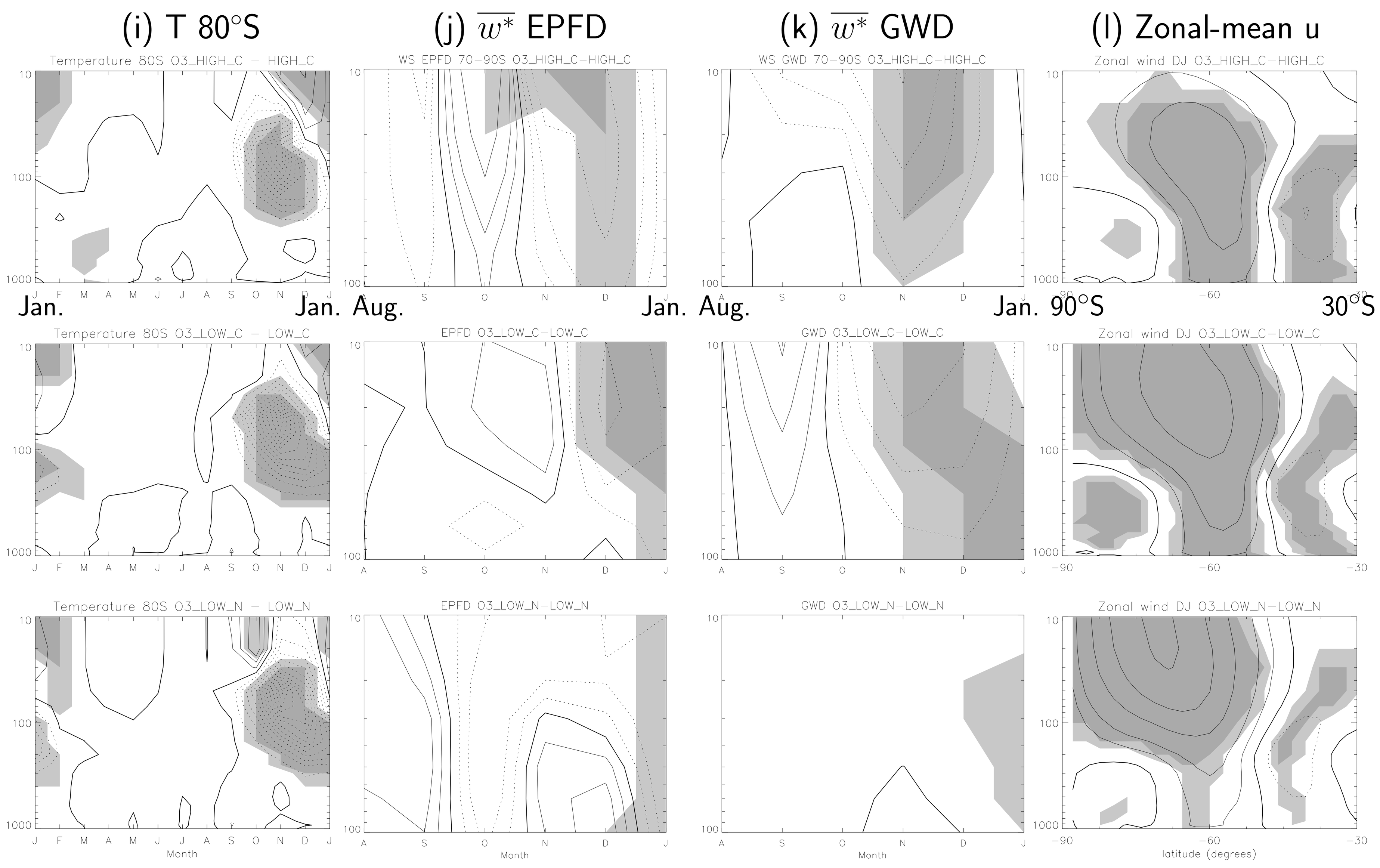




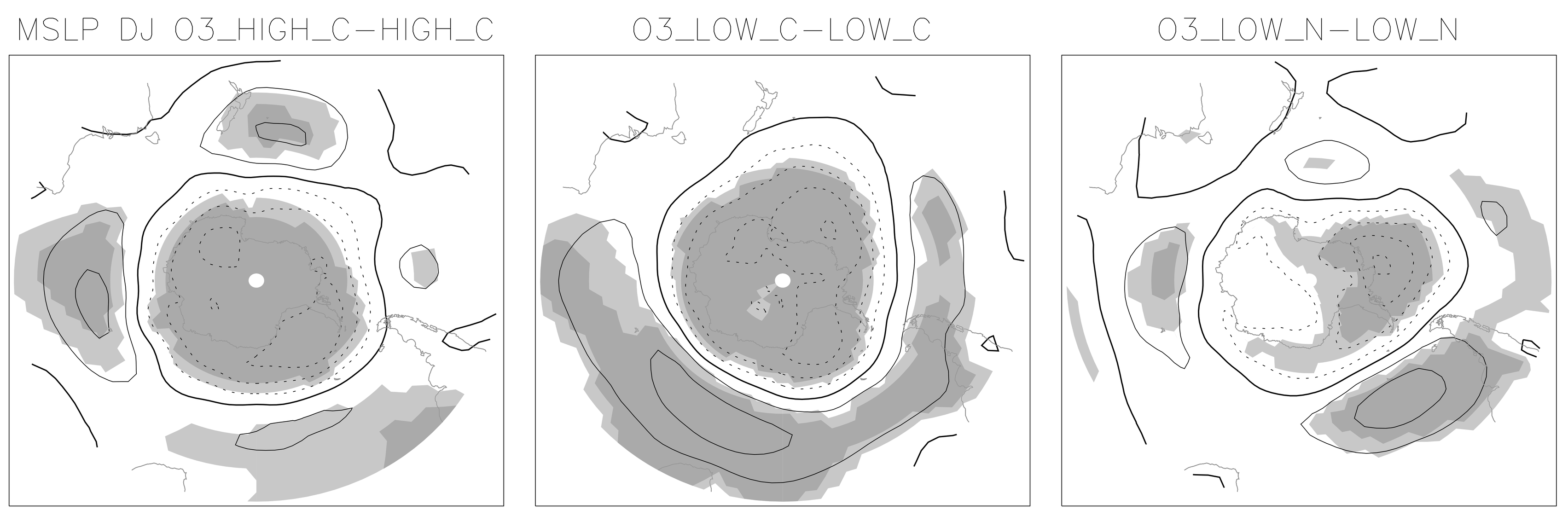
Impact on the Response to Idealized Ozone Depletion

The seasonal cycle of prescribed ozone in CMAM was altered to include a representation of springtime polar ozone depletion in the southern hemisphere. The perturbation had a cosine squared weighting in the vertical between 300 and 30 hPa, in latitude between 65°S and 70°S with complete depletion south of 70°S and in time between August and December, maximizing in October. An analogous ozone depletion perturbation experiment was performed by Shaw & Shepherd (2007) using a zonally symmetric model and focusing solely on the nonorographic GWD response.

- (i) Response of the Temperature at 80°S (contour 1K), residual vertical velocity averaged 70-90°S attributable to (j) EPFD and (k) GWD (orographic and nonorographic) (contours ± 0.1, ± 0.2, ± 0.5, ± 1.0 mms^{-1}) and (l) zonal-mean zonal wind in December and January (30-90°S, contour 2 m/s) to the imposed ozone depletion.



- Response of the mean sea level pressure from 30-90°S in December and January (contour interval 1 hPa) to the imposed ozone depletion.



Summary & Discussion

Every implementation of a flux-based GWD parameterization requires that a decision be made regarding what to do with the gravity wave momentum flux at the model lid. The usual practice is to let the flux escape rather than be conserved. Here we have used the CMAM to quantify the impact of momentum conservation on modeled climate and on its response to idealized ozone depletion. We find very little impact of momentum conservation on the control climate with the model lid at 0.001 hPa, which is expected due to the small amount of gravity wave momentum flux reaching 0.001 hPa. When the lid is lowered to 10 hPa and momentum is conserved, there is only a modest impact on the climate in the northern hemisphere; however the southern hemisphere climate is more adversely affected by the deflection of resolved waves near the model lid. When momentum is not conserved in the 10 hPa model the climate is further degraded in both hemispheres, particularly in winter at high latitudes, and the impact of momentum conservation extends all the way to the surface.

In the second set of simulations, we consider the impact of momentum conservation and model lid height on the modeled response to ozone depletion in the southern hemisphere, and find that the response can display significant sensitivity to both factors. In particular, both the lower stratospheric polar temperature and surface responses are significantly altered when the lid is lowered, with the effect being most severe when momentum is not conserved.

References

Scinocca, J. F., N. M. McFarlane, M. Lazare, and D. Plummer, 2008: The CCCma third generation AGCM and its extension into the middle atmosphere. *Atmos. Chem. and Phys. Discus.*, **8**, 7883-7930.
Shaw, T. A., and T. G. Shepherd, 2007: Angular momentum conservation and gravity wave drag parameterization: Implications for climate models. *J. Atmos. Sci.*, **64**, 190-203.
Shepherd, T.G., and T.A. Shaw, 2004: The angular momentum constraint on climate sensitivity and downward influence in the middle atmosphere. *J. Atmos. Sci.*, **61**, 2899–2908.