Gravity wave parameter estimation using data assimilation

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Motivation

Brief Outline

1. Estimation of the gravity wave drag.
2. Gravity wave parameter estimation.

**Motivation:** R. Garcia’s talk. Tuning subjetively the parameters produces good fit to a feature but misfit of other several features.

**Aim:**

To develop an inverse technique that searches an optimal set of parameters in the *whole* control space (space formed by the free parameters).

The evolution of the model with the optimal set of parameters, by definition, gives the *best fit* to the observations.

One must be able to include readily a very large set of observations.
GCMs do not resolve all the motion scales, because of this, they are not able to capture the systematic momentum forcing that is produced by small-scale gravity waves.

Is there an objective way to find the source of the momentum deficit, i.e., the exact time and position where the momentum error (missing gravity wave drag) is produced?

4D Variational data assimilation (4DVar).

If we force the momentum equations with this estimated 4D vector field (RHS forcing term), the model will evolve exactly as the true state.

**Advantages:**

- Large-scale observations are only needed.
- It only detects the effect of *unresolved* waves.
Using data assimilation to diagnose ’missing drag’

4DVar can be used to estimate unknown parameters of a model.

There is no background information (perfect ignorance), so the cost function is defined as

$$J = \frac{1}{2} \sum_{i=1}^{n} (H[y_i] - x_i)^T R^{-1} (H[y_i] - x_i)$$

where $x_i$ is the model state, $y_i$ are the observations. The state is given by the model evolution from $t_0$ to $t_i$

$$x_i = M(x_0, X, t_i)$$

E.g. $$\partial_t (\sigma Q) + \nabla \cdot (\sigma Q u - \hat{k} \times \dot{\theta} \partial_{\theta} u) = X_\zeta$$

The model state is a function of the initial condition and also of the ’missing drag’. Then $J = J(x_0, X)$.

Therefore, if we know $x_0$ the control space of the cost function is only the field $X$. The minimum of the cost function gives the optimal ’missing drag’ (Pulido and Thuburn, QJ 2005).
Real estimations: Met Office analysis

Observations: Met Office middle atmosphere analyses.

Model: University of Reading, mechanistic global model. Adjoint model.

Cost function: potential vorticity and pseudo-density (function of temperature only) are used as observed variables which are taken from Met Office analyses.

Control space: Curl of drag only.

Estimated zonal mean monthly averaged zonal drag. From Pulido and Thuburn JC 2008
Integrating drag and neglecting the top momentum flux:

\[ F_b = \int_{\theta_t}^{\theta_b} \sigma X_x \, d\theta. \]

For February (upper panels) and October (Lower panels)
Can GW schemes with optimal parameters reproduce the estimated missing drag?

Scinocca JAS (2003) scheme assumes an isotropic launch EP momentum flux spectrum given by

$$E(c, z_l) = \frac{4E_*}{\pi c_*^2} c \left[ 1 + \left( \frac{c}{c_*} \right)^4 \right]^{-1}$$

$c_* \equiv \frac{N_l \lambda_*}{2\pi}$ is the characteristic phase speed and $E_*$ the total momentum flux.

The dissipation of the waves is activated when a component of the spectrum exceeds a saturation threshold given by

$$E_s(c, z) = \frac{S_* E_*}{c_*^2} \frac{\rho(z) N_l}{\rho_l N(z)} \frac{[c - u(z)]^2}{c}$$

The momentum flux that is eliminated and the drag are given by

$$E_T(z) = E_* - \int_0^{c_c} [E(c, z_l) - E_s(c, z)] \, dc \quad X = \rho^{-1} \partial_z E_T.$$
Optimal parameters: Variational data assimilation

The cost function is defined as: $J = (\mathbf{x} - \mathbf{y})^T R^{-1} (\mathbf{x} - \mathbf{y})$ where $\mathbf{y}$ is the observed GWD profile and $\mathbf{x} = X(E_*, \lambda_*, S_*)$ is the forcing resulting from the GW scheme.

Variational data assimilation technique similar to GW drag estimation, the minimization is performed by a conjugate gradient method.

4DVar does not work! Switches, ill-conditioning, nonlinear processes.
Genetic algorithm

Implementation of the algorithm Pikaia (Charbonneau, 2002). It applies essential ideas of natural selection.

A population of $K=100$ sets of parameters is evolved during $N=200$ generations.

The optimal parameters are retrieved even in the presence of local minima.

Global parameter estimation does not give a good representation of the ‘observed’ drag.
Zonal wind and temperature is taken from Met Office analysis.

The GWD field estimated with the ASDE-4DVar technique (Pulido and Thuburn, JC 2008) for July 2002 is used as observational forcing profile $\mathbf{y}$.

Optimal parameters $E_*$ (left) $\lambda_*$ (middle) and $S_*$ (right) for July 2002
Case $y = X$: Estimated GWD and EP div

Observed ASDE forcing (left panels).
Estimated forcing using GW scheme with optimum parameters (right panel).
Case $y = \rho X$ : Estimated GWD and EP div

Observed ASDE forcing (left panels). Estimated forcing using GW scheme with optimum parameters (right panel).
For $J \propto \rho X$, the inverse technique fits the lower part of the profile with the Eastward waves of the spectrum, then the amplitude and characteristics of the Westward waves of the spectrum are already determined by the assumption of isotropy.

There is a net EP flux at launch height found in the ’observed’ GWD however the parameterization assumes an isotropic spectrum.

The parameterization is unable to fit the whole height range of the drag profile. Possible relaxations are launch height and a nonisotropic launch flux.
Varying the launch height

Can the net momentum flux found at 70 hPa be produced by filtering at lower heights?

Cost function for cases with different launch height. The problem is not solved by varying the launch height!
Relaxing the parameterization

We take a nonisotropic launch spectrum where the free parameters are: $E^*_E, E^*_W, E^*_N, E^*_S, \lambda_*,$ and $S_*$. 

Thanks to M. Keller.
Comparison of GW parameterizations


Error in the parameterizations with optimal parameters for July.

Error in the parameterizations for every month.

Thanks to G. Scheffler (Poster T-1).
Conclusions

- The parameterizations cannot reproduce the upper and lower part of the 'observed missing forcing' at the same time. The assumption of isotropy may not be a good approximation.

- Parameterizations have been designed with only a few free parameters. A consequence of this strategy is the weak sensitivity of the parameters and the resultant difficulty in fitting standard high latitude drag profiles.

- A redesign and some relaxation of assumptions in the parameterizations may be required in order to make an optimal use of observational information.

Pulido, Polavarapu, Shepherd, and Thuburn 2011: to be submitted to QJ.

Pulido and Rodas, 2011 Higher order ray tracing: Gaussian beam. JAS, 68, 46-60.