Gravity waves emitted from jets and fronts: lessons from idealized simulations

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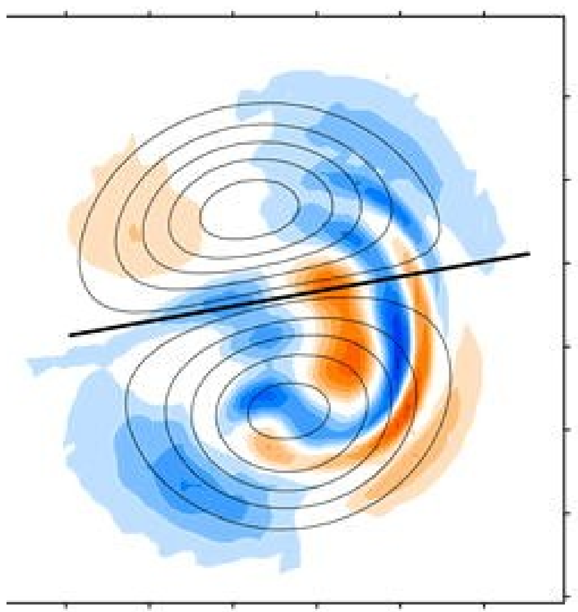
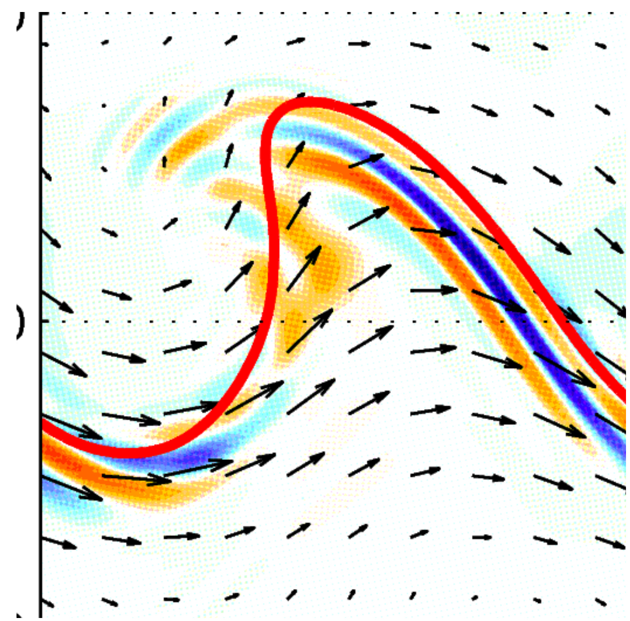




Collaboration with: Chris Snyder (NCAR), DJ Muraki (Simon Fraser Uni.), Steffen Lohrey (LMD)

Outline

1. Motivations and context
2. Wave generation in a dipole
3. Wave generation in baroclinic life cycles
4. Discussion and perspectives

1. Motivations and context

a. Theoretical

breakdown of balance = *spontaneous generation* of gravity waves (GW)

e.g. Ford, Mc Intyre and Norton 2000, Vanneste 2008

b. Practical

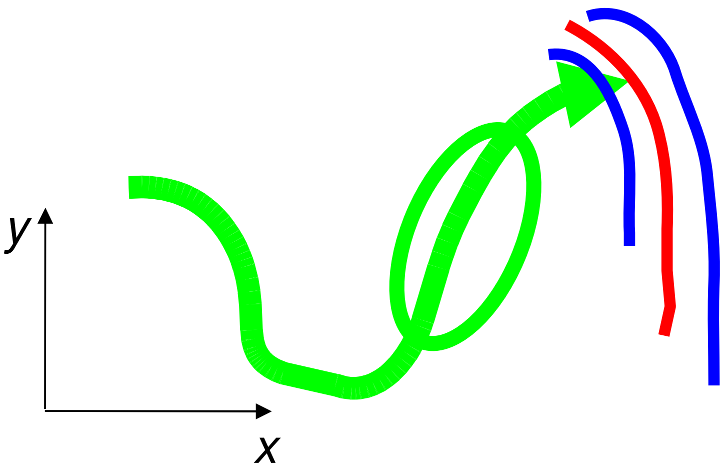
need for a better knowledge of GW sources for parameterizations

e.g. Fritts and Alexander 2003, Kim et al 2003,
Alexander et al 2010

1. Motivations and context

a. Observations

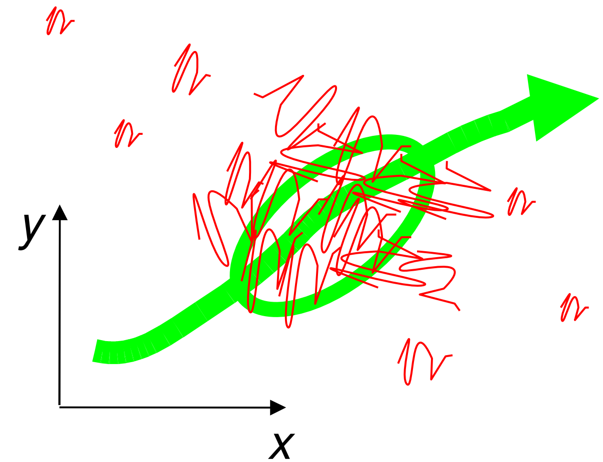
emphasis on Jet Exit Region (in particular from case studies),



identifiable, intense **IGW** in jet exit regions

e.g. Koch & Uccelini 87, Thomas et al 99, Guest et al 00, Pavelin et al 01, Plougonven & Teitelbaum 03

but also on vicinity of jets in general



enhanced small-scale variance near jets and fonts

e.g. Fritts & Nastrom 93, Eckermann & Vincent 93, Plougonven et al 03

1. Motivations and context

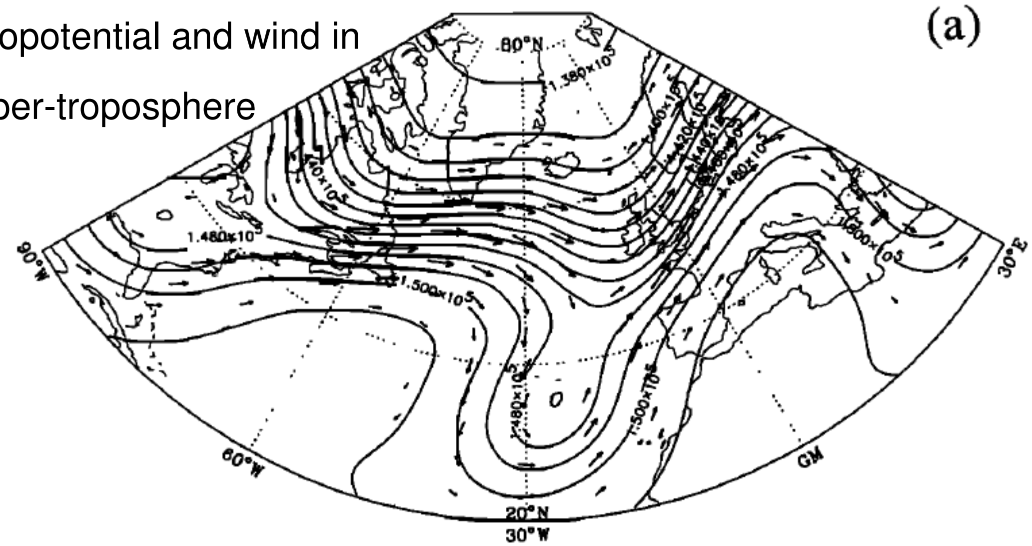
b. Simulations

also highlight Jet Exit Region, but also smaller-scale waves or waves near fronts

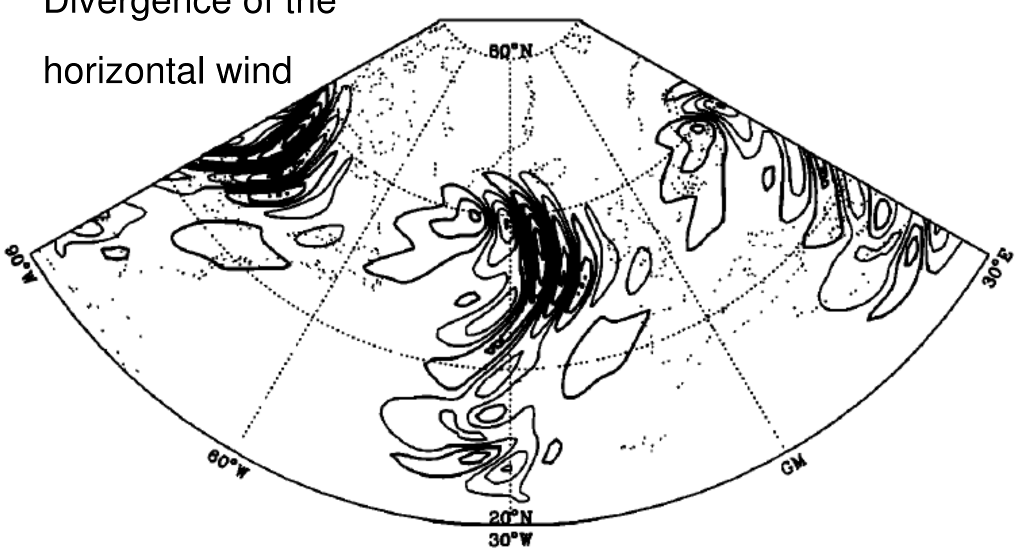
Van Tuyl and Young 1982,
Zhang 2004

Geopotential and wind in upper-troposphere

(a)



Divergence of the horizontal wind



O'Sullivan & Dunkerton 1995,

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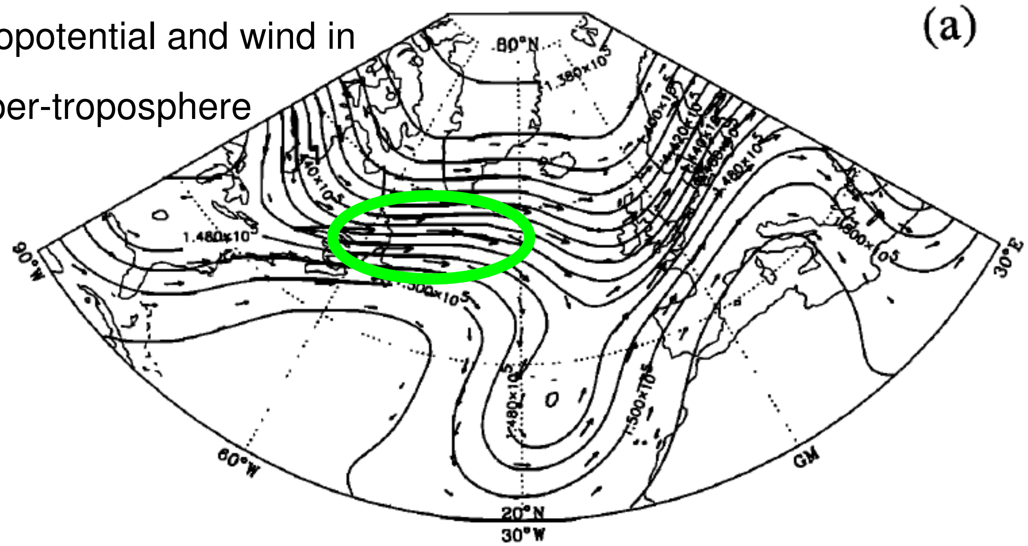

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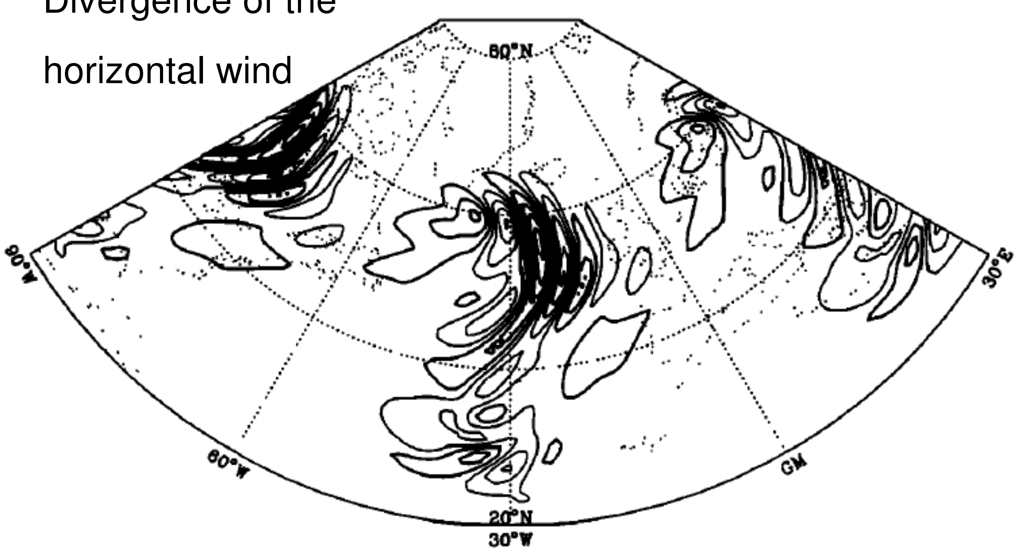

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Zhang 2004

c. Proposed mechanisms and diagnostics

geostrophic adjustment	Lagrangian Rossby numbers Koch and Dorian 1988, O'Sullivan and Dunkerton 1995, Pavelin et al 2001
balanced adjustment	residual of the NBE Zhang 2004
Lighthill radiation	forcing terms Willams et al 2005, Knox et al 2008

2. Wave generation in a dipole

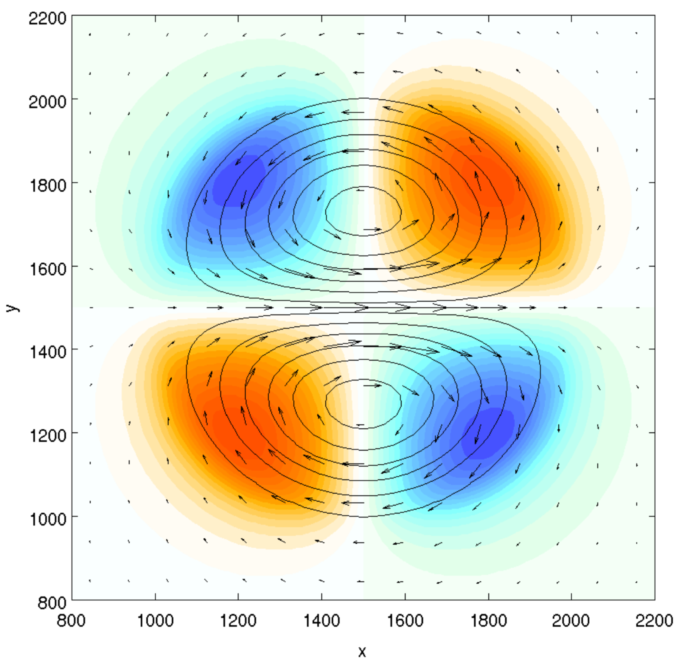
Why a dipole?

Simple flow : **stationary** in the co-moving frame
Complex enough : **model of jet-streaks** (includes a 'jet exit')

Snyder et al 2007, Viudez 2007, 2008, Zhang, Wang and Snyder 2008

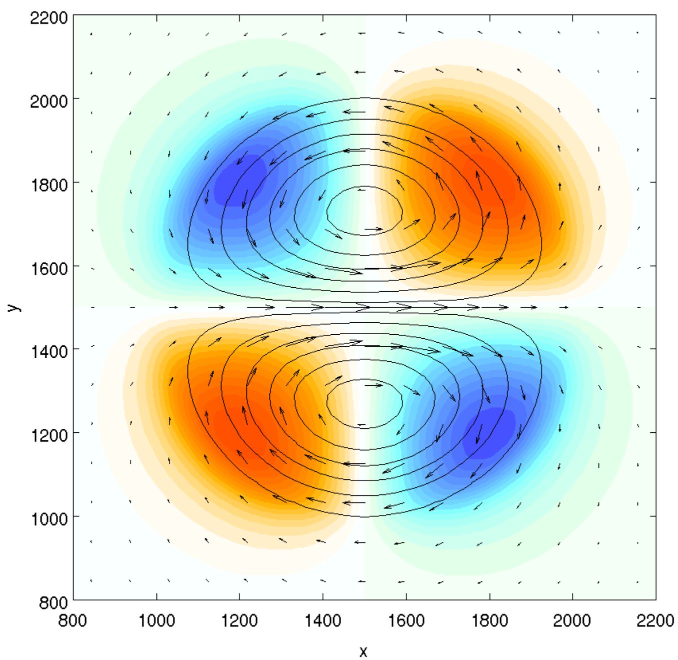
Numerical Setup

Initial condition = exact Surface Quasi-Geostrophic (SQG) dipole Muraki and Snyder 2007
Model = Boussinesq, Primitive Equations,
x, y periodic domain (3000 x 3000 km), 15 km deep, sponge layer



Initial Condition

QG evolution



Snyder, Muraki, Plougonven and Zhang 2007

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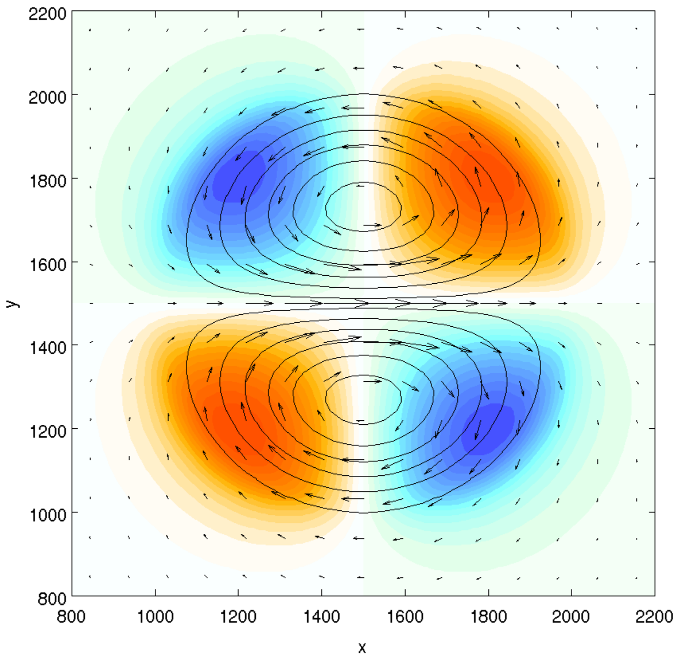
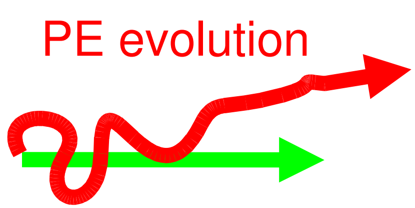
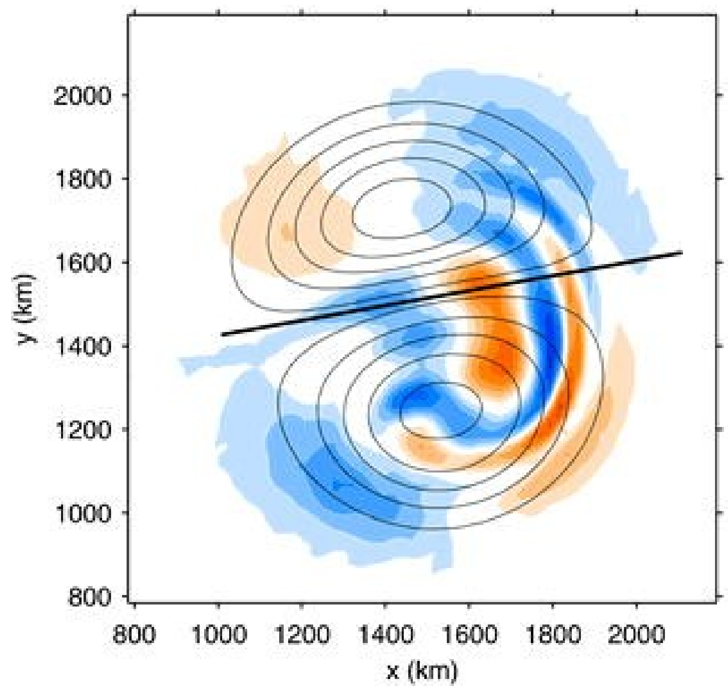


Initial Condition



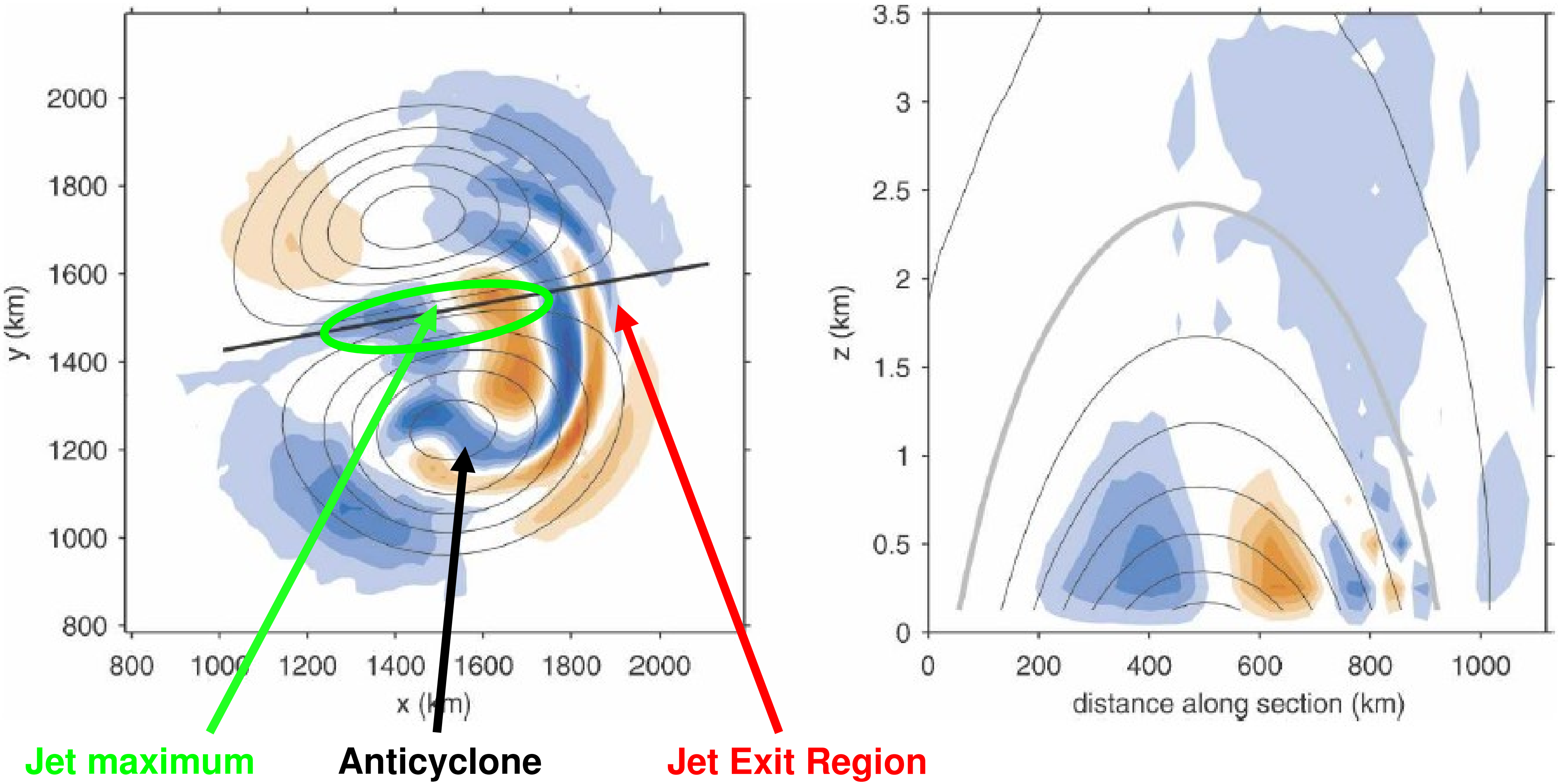


Snyder, Muraki, Plougonven and Zhang 2007

2. Wave generation in a dipole

Structure of emitted waves :

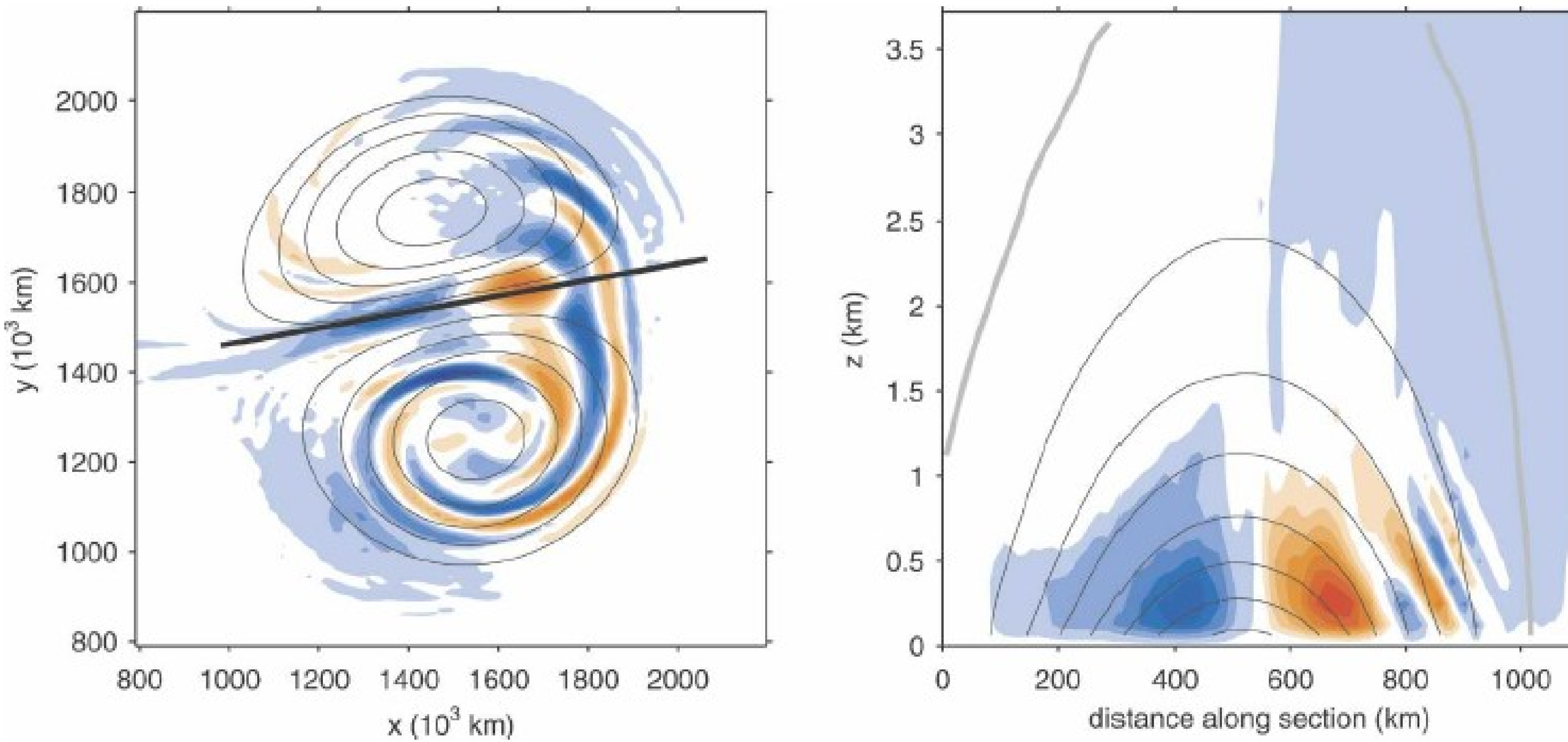
From reference simulation (*dx* = 23.4 km, *dz* = 250 m)



2. Wave generation in a dipole

Structure of emitted waves :

From doubled resolution simulation (dx = 11.7 km, dz = 125 m)



2. Wave generation in a dipole

Emission mechanism:

Waves are **small perturbations** to a **nearly balanced flow:**

1. **Separate flow :**

$$u = \overline{u} + u'$$

2. **Linearize** about **balanced dipole**

3. **Evolve perturbations**:

A without forcing (homogeneous solutions)

B with forcing (forced solutions)

2. Wave generation in a dipole

Emission mechanism:

$$\partial_t \overline{u} + \partial_t u' + \overline{\mathbf{u}} \cdot \nabla \overline{u} + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} + \mathbf{u}' \cdot \nabla u' - f\,\overline{v} - f\,v' + \partial_x\,\overline{\phi} + \partial_x\,\phi' = 0\ ,$$

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\,v' + \partial_x\,\phi' = \mathcal{F}_u + \mathcal{O}(u'^2)\ ,$$

$$\text{where} \quad \mathcal{F}_u = -\left(\partial_t \overline{u} + \overline{\mathbf{u}} \cdot \nabla \overline{u} - f\,\overline{v} + \partial_x\,\overline{\phi}\right)\ .$$

2. Wave generation in a dipole

Emission mechanism:

$$\partial_t \overline{u} + \partial_t u' + \overline{\mathbf{u}} \cdot \nabla \overline{u} + \overline{\mathbf{u}} \cdot \nabla u'$$
$$+ \mathbf{u}' \cdot \nabla \overline{u} + \mathbf{u}' \cdot \nabla u' - f\,\overline{v} - f\,v' + \partial_x \overline{\phi} + \partial_x \phi' = 0\ ,$$

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\,v' + \partial_x \phi' = \mathcal{F}_u + \mathcal{O}(u'^2)\ ,$$

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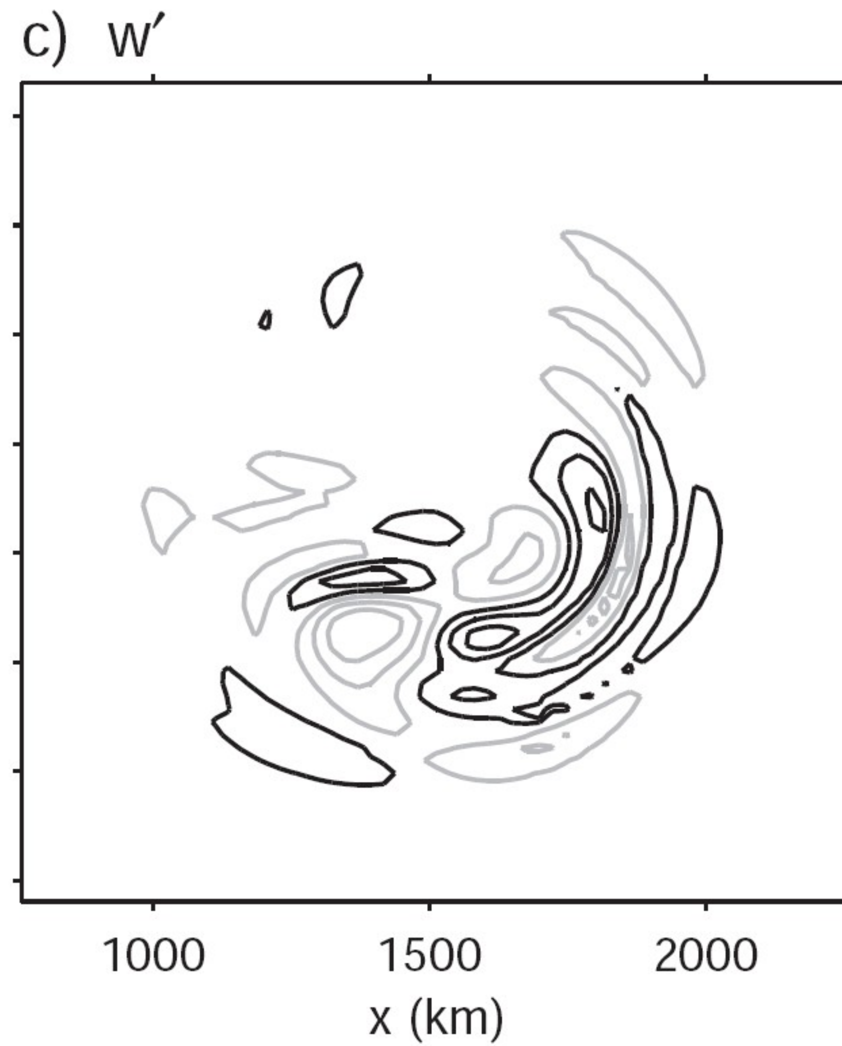
2. Wave generation in a dipole

A Homogeneous solutions (= ageostrophic instability)?

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\, v' + \partial_x \phi' = 0$$



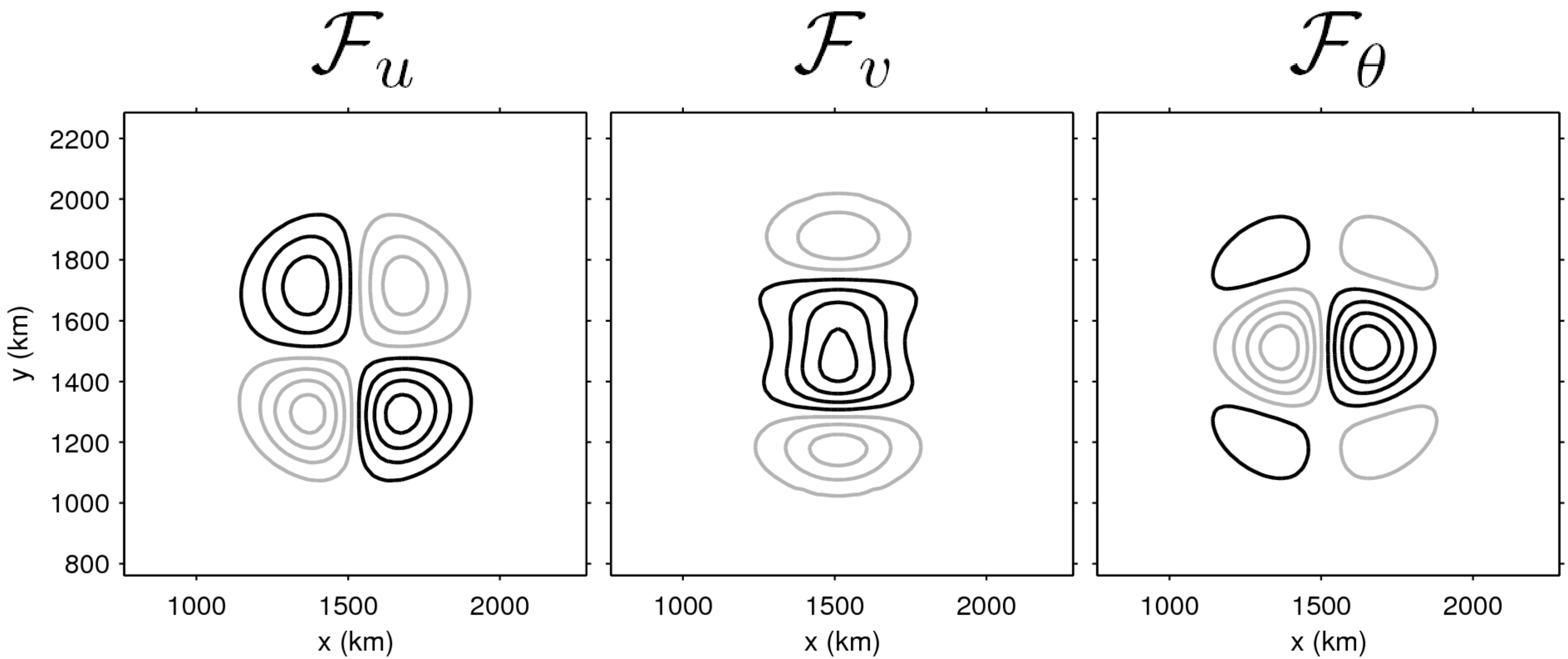
No growth,
but
the structure of the waves is present

- not an instability,
- background flow crucial

2. Wave generation in a dipole

B Forced solutions ?

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\, v' + \partial_x \phi' = \mathcal{F}_u$$



N.B. forcing is <u>large-scale</u>

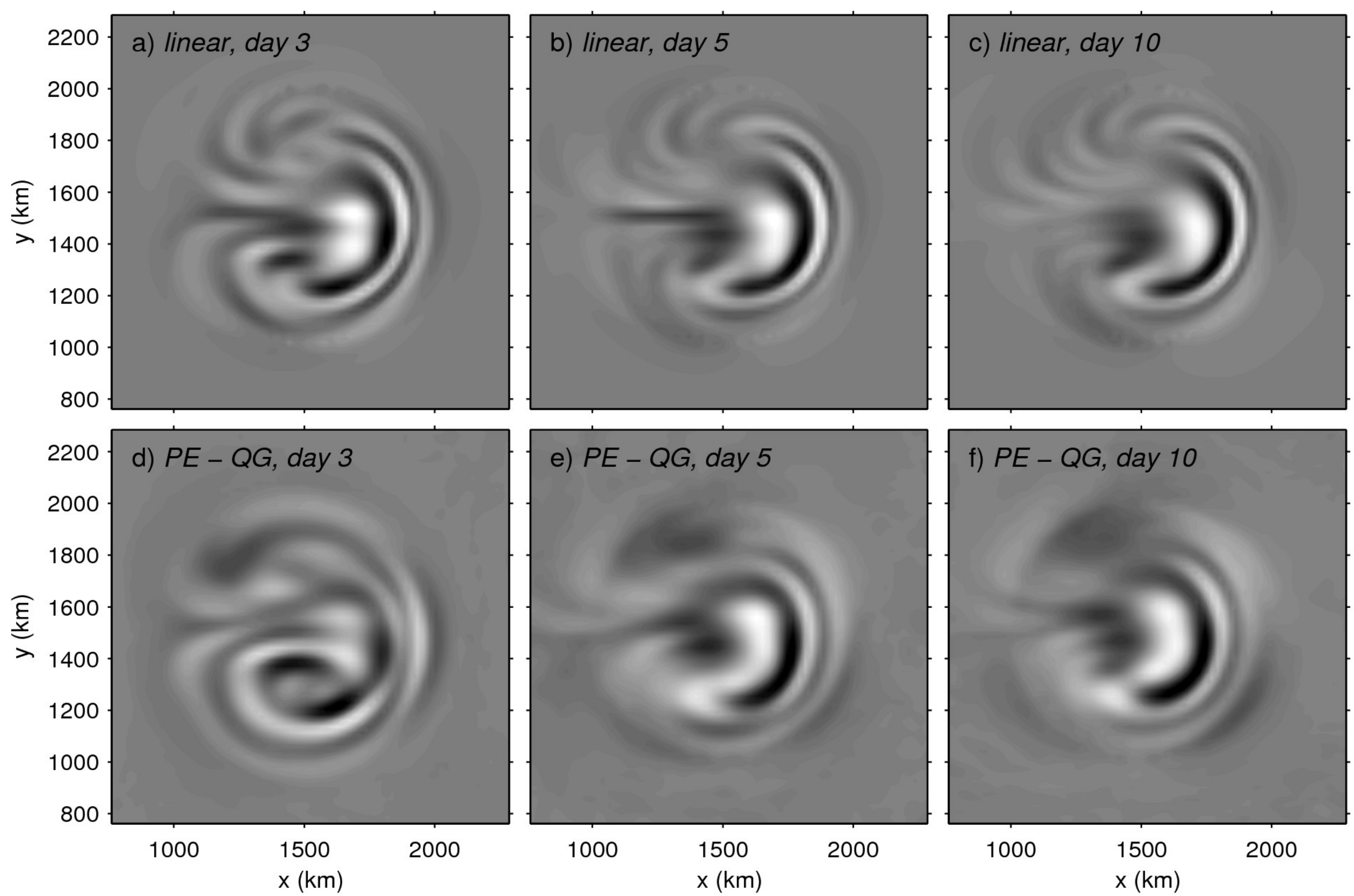
2. Wave generation in a dipole

Forced solutions ?

$$\partial_t u' + \overline{\mathbf{u}} \cdot \nabla u' + \mathbf{u}' \cdot \nabla \overline{u} - f\, v' + \partial_x \phi' = \mathcal{F}_u$$

Forced linear prediction :

Full simulation :



3. Wave generation in baroclinic life cycles

9 baroclinic life cycles

varying jet strength and

background shear

Weather **R**esearch and

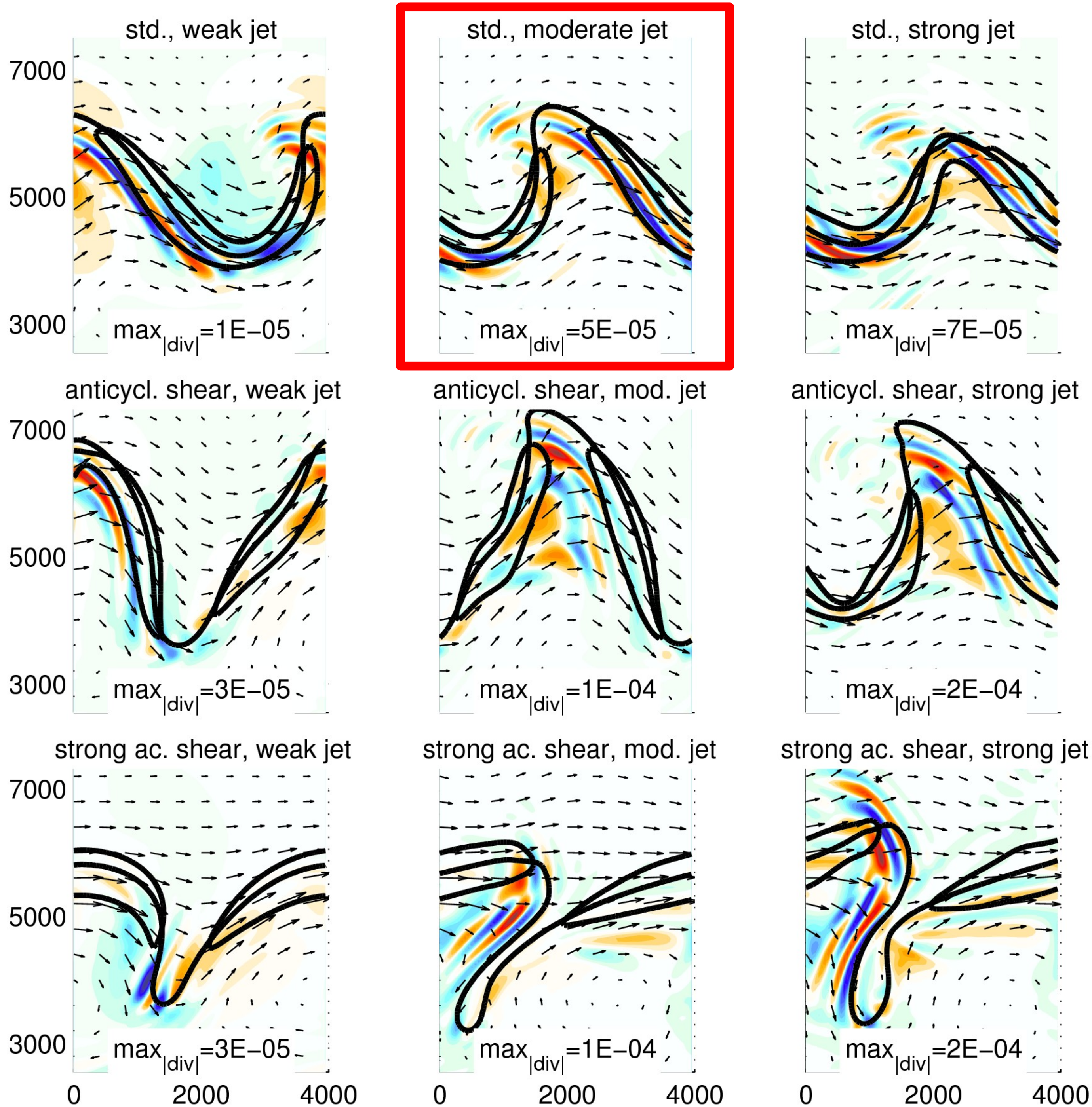
Forecast

f-plane, periodic Domain:

10,000 x 4000 x 30 km

Resolution:

dx = 50 km, dz = 250 m

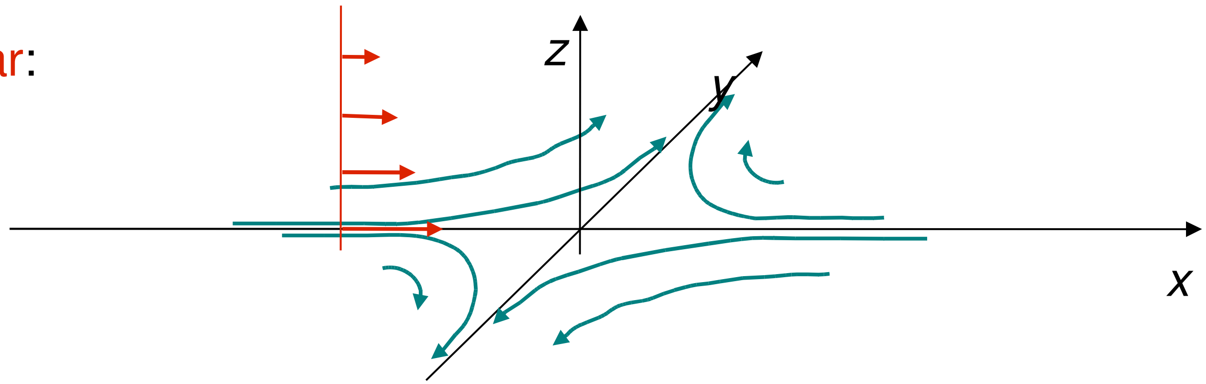


Reference simulation described in Plougonven & Snyder 2005, 07

3. Wave generation in baroclinic life cycles

Orientation and intrinsic frequency well approximated from knowledge of

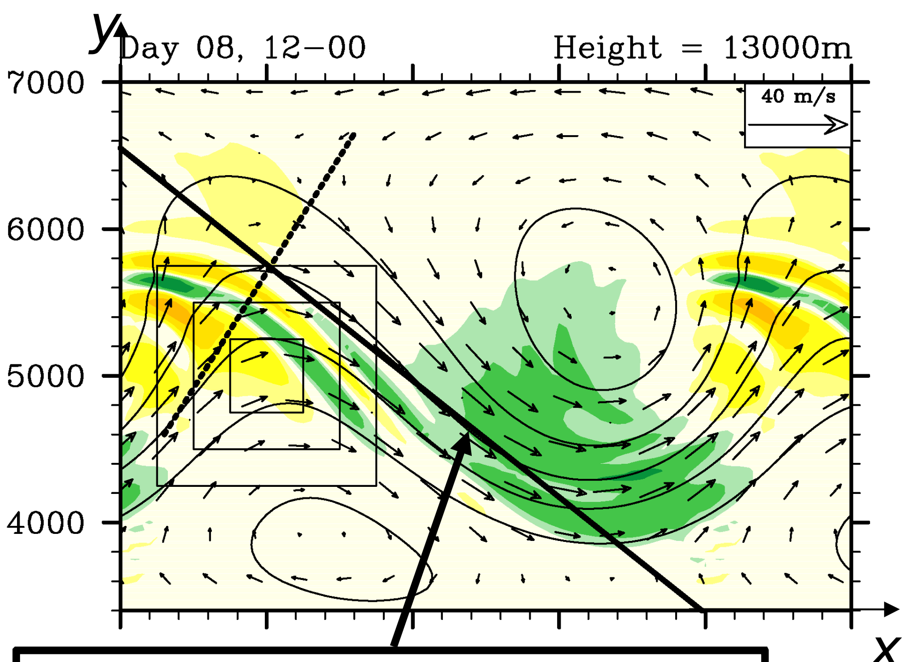
background strain and vertical shear:



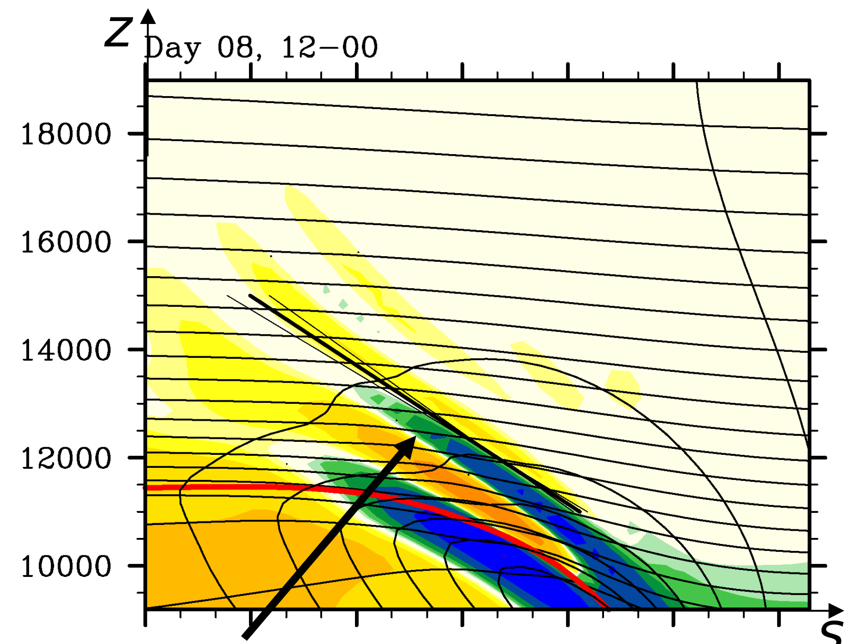
'*Wave capture*'

(Bühler and McIntyre 2005,

Badulin and Shrira 1993)



Orientation predicted from the large-scale deformation



Predicted slope

Plougonven and Snyder 2005

4 Discussion and perspectives

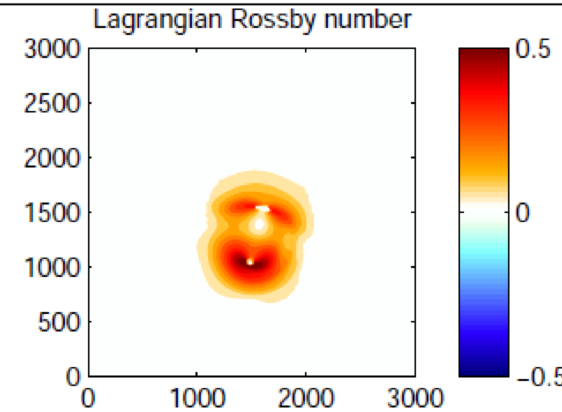
Diagnostics suggested for wave emission:

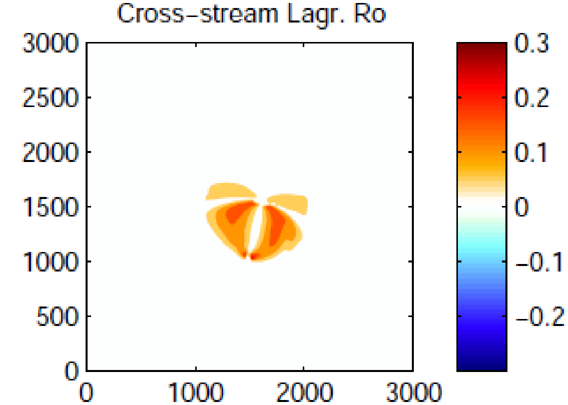
e.g. Lagrangian Rossby numbers:

$$Ro_L = \frac{|dV/dt|}{f|V|} = \frac{|V_{ag}|}{|V|} \;, \; Ro_L^{\perp} \simeq \frac{|V_{ag}^{\perp}|}{|V|}$$

(Koch and Dorian, 1988, O'Sullivan & Dunkerton, 1995, Zhang et al 2000, Plougonven et al 2003)

Not useful on their own: **do not take into account advection**





Diagnostic for propagation effects (*wave capture):*

Okubo-Weiss parameter:

$$\boxed{W = \sigma^2 - \zeta^2}$$

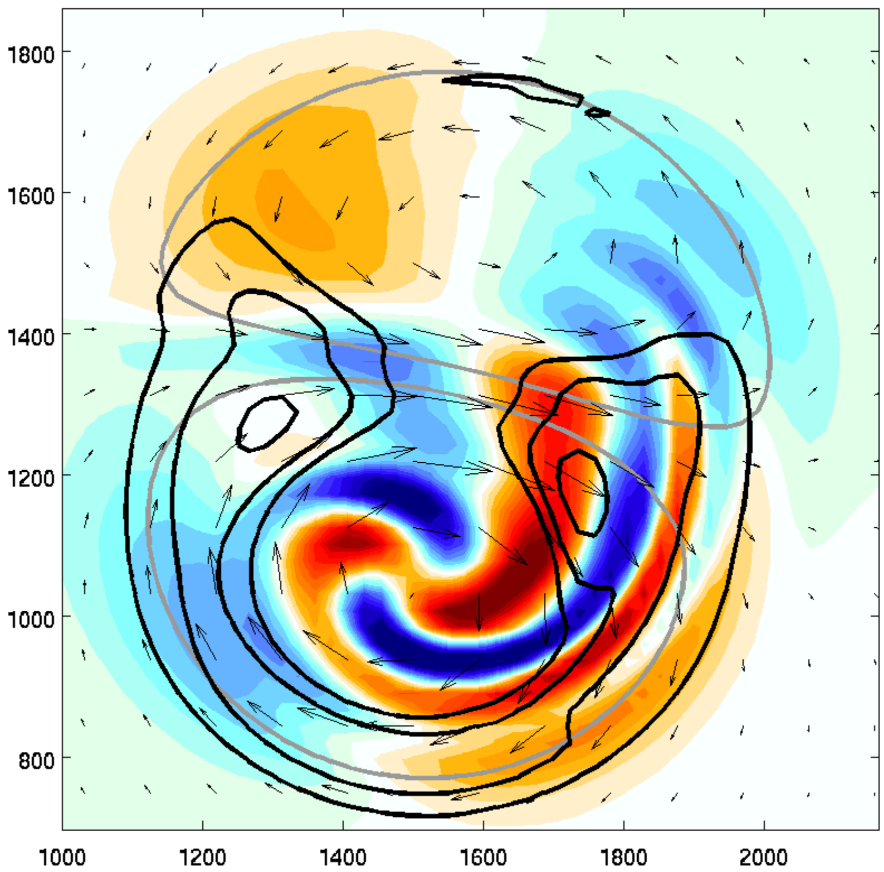
strain

relative vorticity

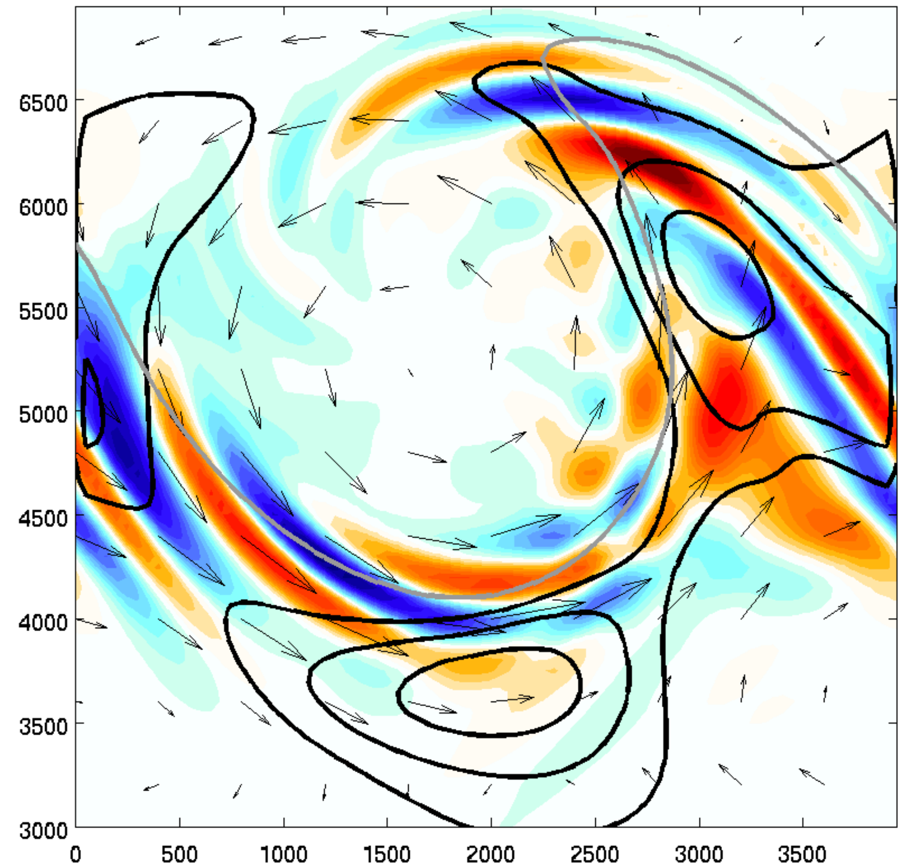
4 Discussion and perspectives

Relevance of the Okubo-Weiss parameter :

Dipole simulations



Baroclinic life cycles



Limitations: does not distinguish Jet Exit and Jet Entrance Regions

no information on amplitudes *a priori*

4 Discussion and perspectives

Jet Exit Region Emitted (JEREmi) waves systematic in idealized simulations

They result from **small unbalanced forcing + strong advection**

→ **forcing alone is not sufficient** to predict waves

→ not geostrophic adjustment, not Lighthill radiation

Propagation effects *(wave capture)* shape the wavepacket

(relevant diagnostics: strain, vertical shear, Okubo-Weiss parameter, relative vorticity)

Implication: dynamics of GW in complex flow (strain, shear...) may be more important than a diagnostic of the forcing of imbalance from dry dynamics

Remaining **open issues** :

1- other GW in idealized baroclinic life cycles, and later in the cycles?

2- diagnostic for the **amplitude** of these waves, combining forcing and advection?

3- relevance in **real flows**? Importance of **moist processes**?

Some references:

Context on the limitations of balance and spontaneous generation:

Ford, McIntyre and Norton, 2000, J. Atmos. Sci.

Vanneste, 2008, J. Atmos. Sci.

Lott, Plougonven and Vanneste, 2010, J. Atmos. Sci.

Context on gravity waves:

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Gravity waves in a shear, in a strain:

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Bühler and McIntyre, 2005, J. Fluid Mech.

Baroclinic life cycles:

Plougonven and Snyder, 2005, Geophys. Res. Lett.

Plougonven and Snyder, 2007, J. Atmosph. Sci.

Dipole:

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Wang, Zhang and Snyder, 2008, J. Atmos. Sci.

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Generation mechanisms:

Plougonven and Zhang, 2007, J. Atmos. Sci.

Plougonven, Snyder and Zhang, 2009, J. Atmos. Sci.

Thank you for your attention !