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112 Walker Building,
Session 9: theory and methodology 2 (Chair: François Lott)
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Generation and impact of gravity waves from the dipole

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N. Sugimoto and R. Plougonven, **Generation and backreaction of spontaneously emitted inertia-gravity waves,** *Geophysical Research Letters*, Vol. 43, (2016), p3519-3525.

Outline

1.Motivation

- Gravity Waves (GW) and their roles
- The concept of "balanced flow" and its limitation
- Spontaneous emission of GW (Sp-GW)

2. Experimental setting

- DCPAM5-plane
- Surface modon

3. Results

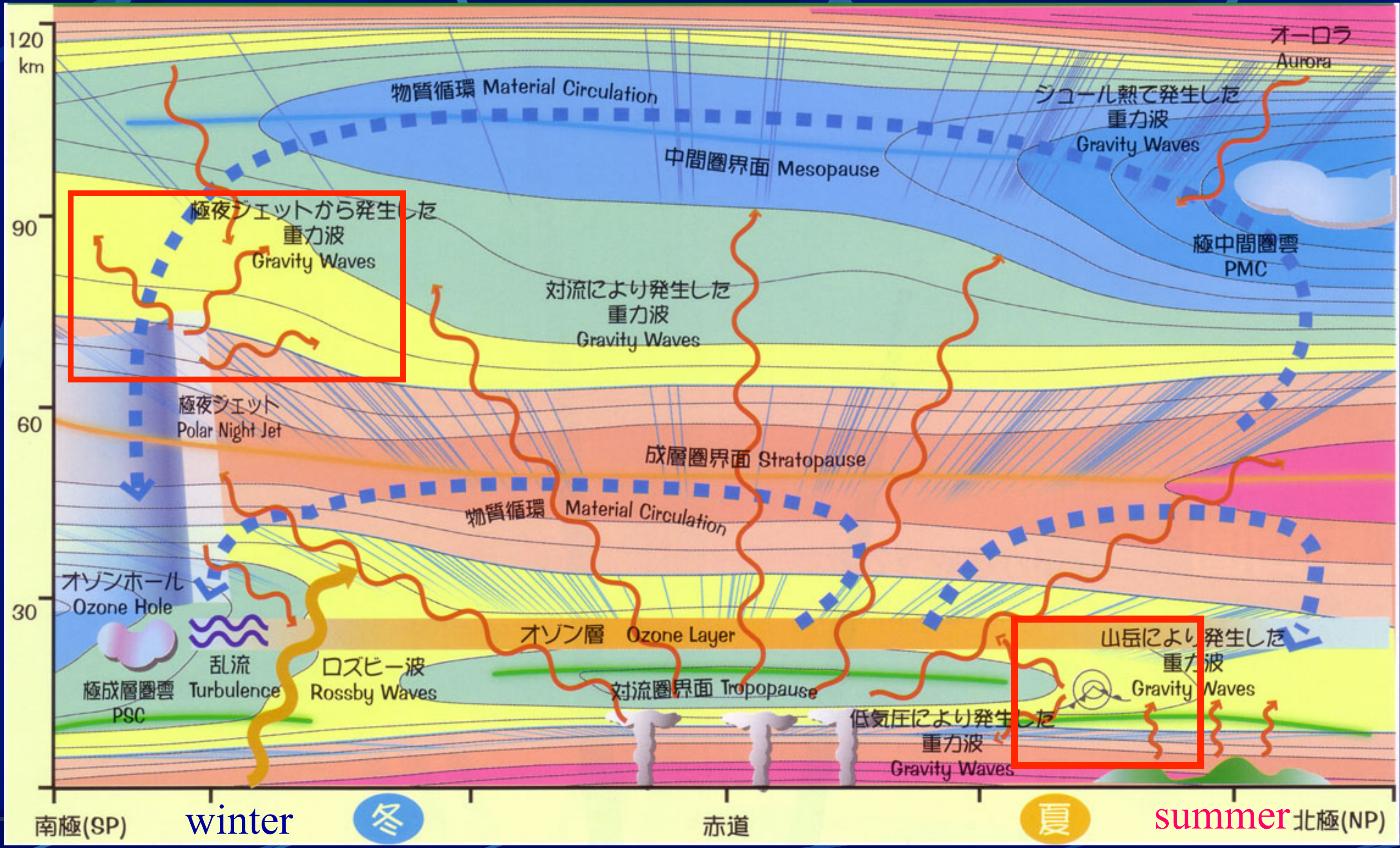
- Long-term simulation
- Quantify GW and their backreaction

4. Summary

1. Motivation

- The roles of gravity waves in the atmosphere

To better understand and quantify non-orographic sources.

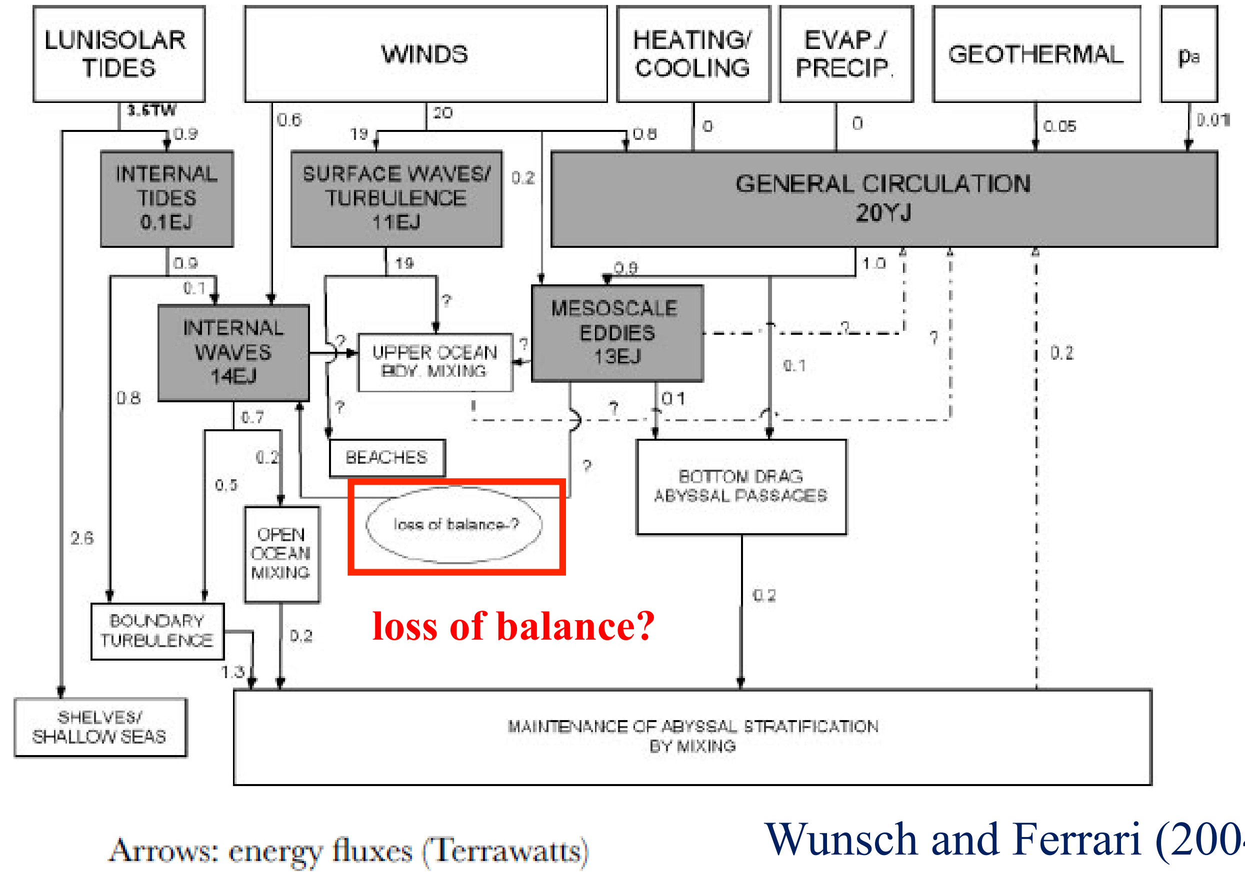


PANSY project (2005)

- Global energy budget in the ocean

To quantify energy derived from mesoscale eddies due to GW radiation.

✓ A possible flux (~1.5TW) estimated by laboratory experiment *(Williams et al., 08)* is usually referred *(Ferrari & Wunsch (10) etc.)*



Wunsch and Ferrari (2004)

Large scale motions in geophysical flow (rotating stratified flow) are nearly balanced … but limitation.

- “Balanced Flow”

✓ GW filtered out by construction.
✓ Flow evolution obtained from potential vorticity (advection and inversion).

Lorenz(80), Leith(80), Ford(94), Warn(97), Ford et al.(00) etc.; Slow (quasi-)manifold
Gent & McWilliams(83), Spall & McWilliams(92), Sugimoto et al.(07a); Balance regimes

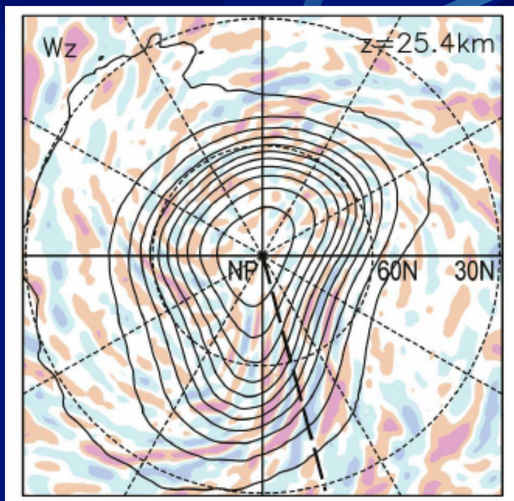
- “Spontaneous emission” of gravity waves (Sp-GW)

✓ Inevitable radiation.
✓ Demonstration in shallow water (Lighthill radiation).

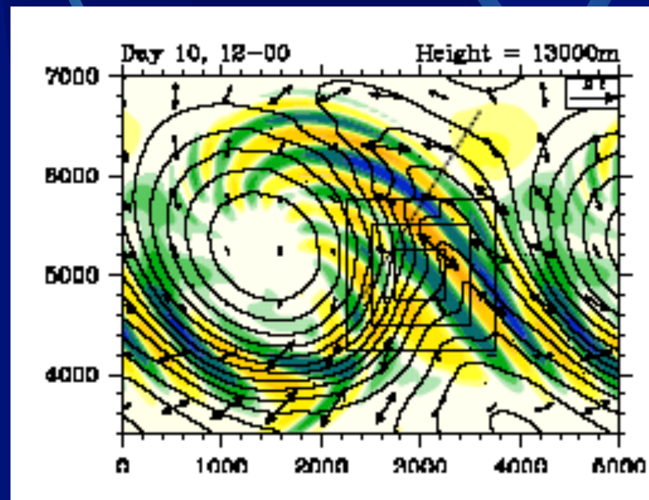
Ford (94), Sugimoto et al. (05, 07b, JAS08, 12); Analogy with sound wave radiation
Sugimoto et al. (JFM15a), Sugimoto (PoF15b); Cyclone-anticyclone asymmetry in GW

Spontaneous emission of GW (Sp-GW) in continuous fluid

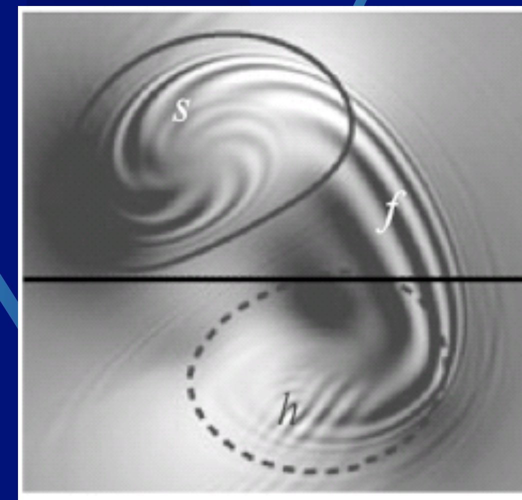
- ✓ The dipole has emerged as a paradigm to understand Sp-GW from both obs. and idealized simulations. *See reviews by Vanneste (13), Plougonven & Zhang (14)*



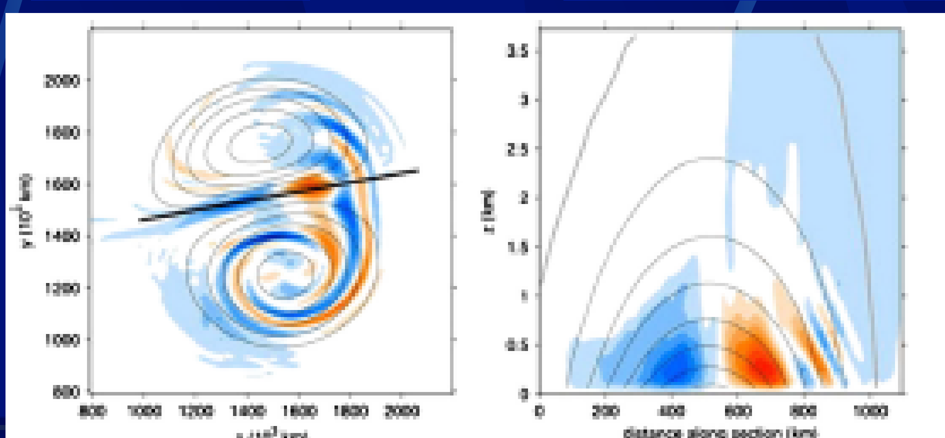
Sato(99, 08)



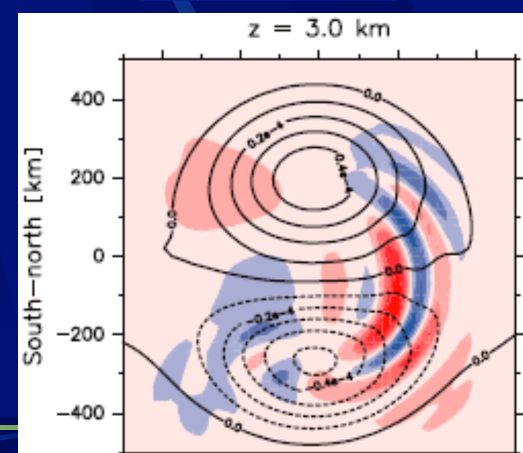
Plougonven *et al*.(05)



Viudes(07)



Snyder *et al*.(07)



Yasuda, Sato, and Sugimoto(15)

Generation mechanism (small-scale GW, backreaction, wave capture)

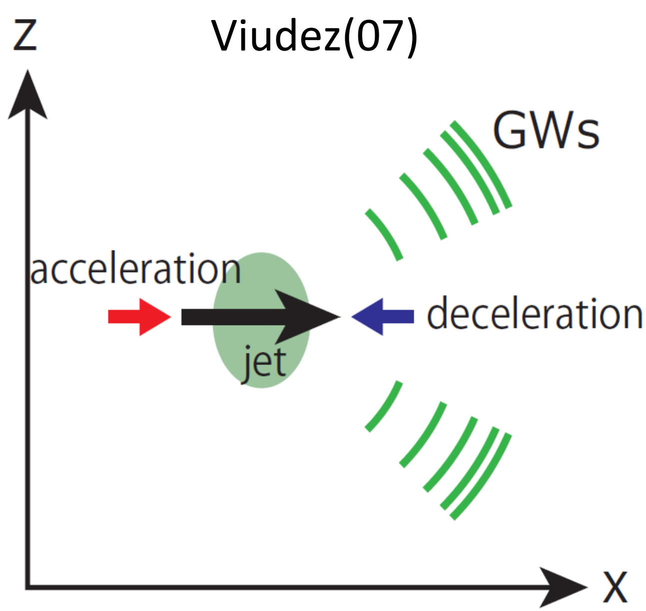
Y. Yasuda, K. Sato, and N. Sugimoto: A Theoretical Study on the Spontaneous Radiation of Inertia-gravity Waves Using the Renormalization Group(RG) Method.（JAS2015a, b).

- Construction of the new theory using RG method (Part I).
- Verification of the theory by JMA-NHM simulation (Part II).

GW are radiated from slaved components through quasi-resonance

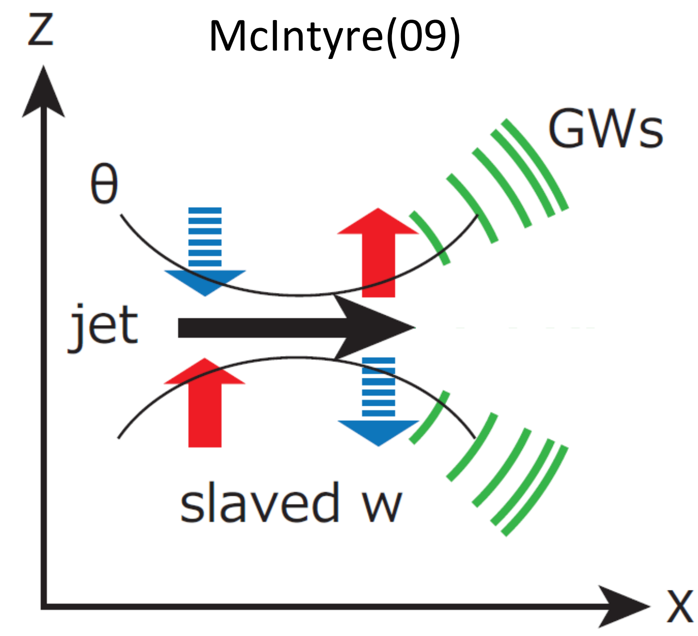
Velocity-variation mechanism

Viudez(07)



Mountain-wave-like mechanism

McIntyre(09)



This Study

Revisits the spontaneous emission of GW in a dipole

- Long-term simulation to identify the backreaction of GW.
- Estimate energy leaks from dipole due to GW.
- Dependence on Rossby number (Ro).
- Dependence on resolution.

Provide a revised figure of the energy flux for ocean's energy budget based on more physical background.

Experimental setting

DCPAM5-plane (Dennou-Club Planetary Atmospheric Model)

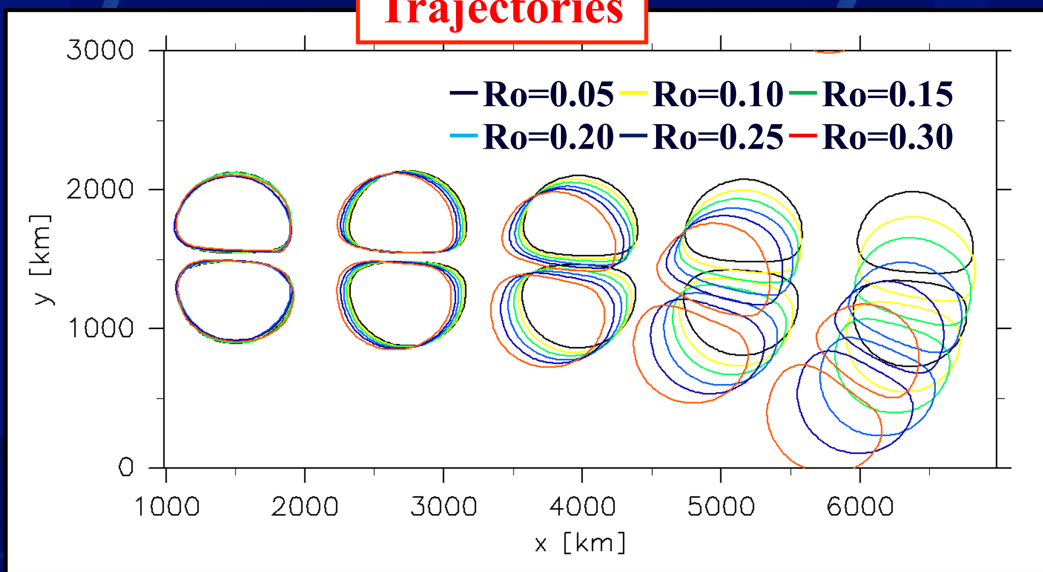
- ✓ 3D Primitive equations on *f*-plane without moist process
- ✓ Domain: 3000 km×3000 km×20 km (doubly periodic boundary condition)
- ✓ Resolution: 128×128×80 to 256×256×80 (Δx,Δy～23.4-11.7 km, Δz～250 m)
- ✓ Sponge layer exist above 15 km

Initial condition & parameter

- ✓ Surface modon *(Muraki and Snyder, 2007)*
- ✓ Size: 500 km×500 km×5 km
- ✓ $f=10^{-4}$ (1/s), N=0.01 (1/s), $\theta_0/g=30.6$ (K s^2/m)

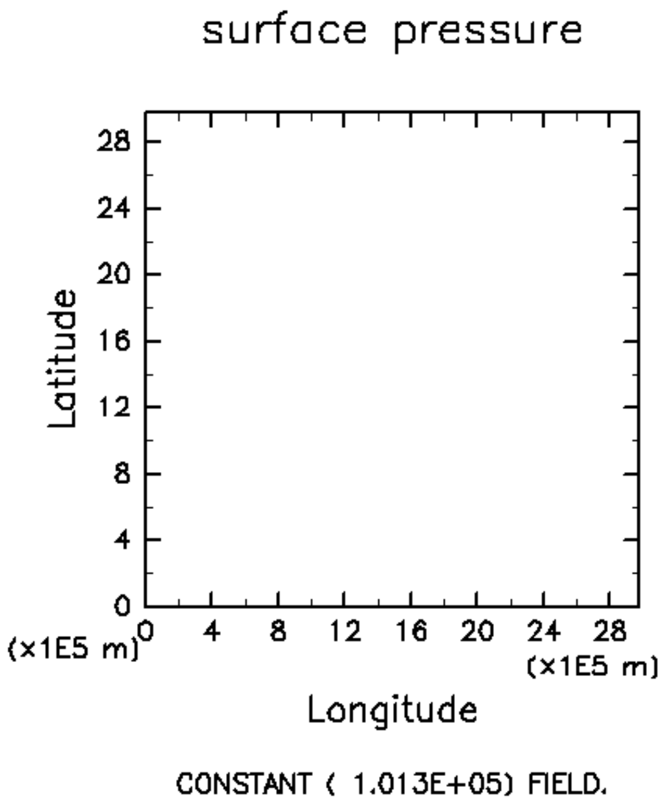
Ro	U_{max} (m/s)	T (days)	Δt (min)	Hd (day)
0.05	2.5	504	15	0.60
0.10	5.0	252	15	0.30
0.15	7.5	168	10	0.20
0.20	10.0	126	10	0.15
0.25	12.5	100.8	5	0.12
0.30	15.0	84	5	0.1

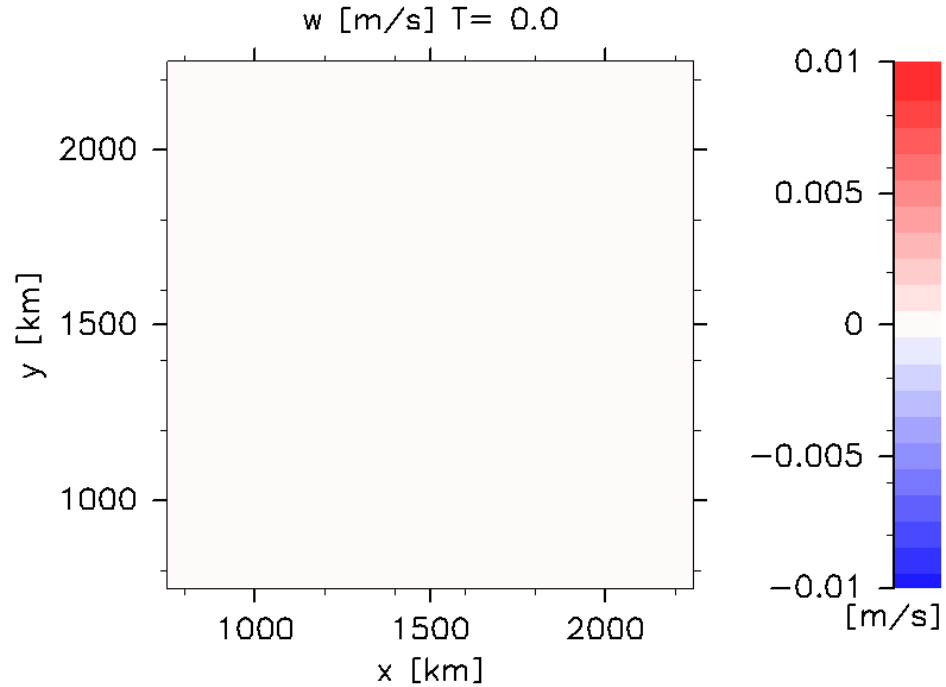
Trajectories



Time evolutions of surface pressure and vertical velocity

Ro=0.3 (128×128×80)





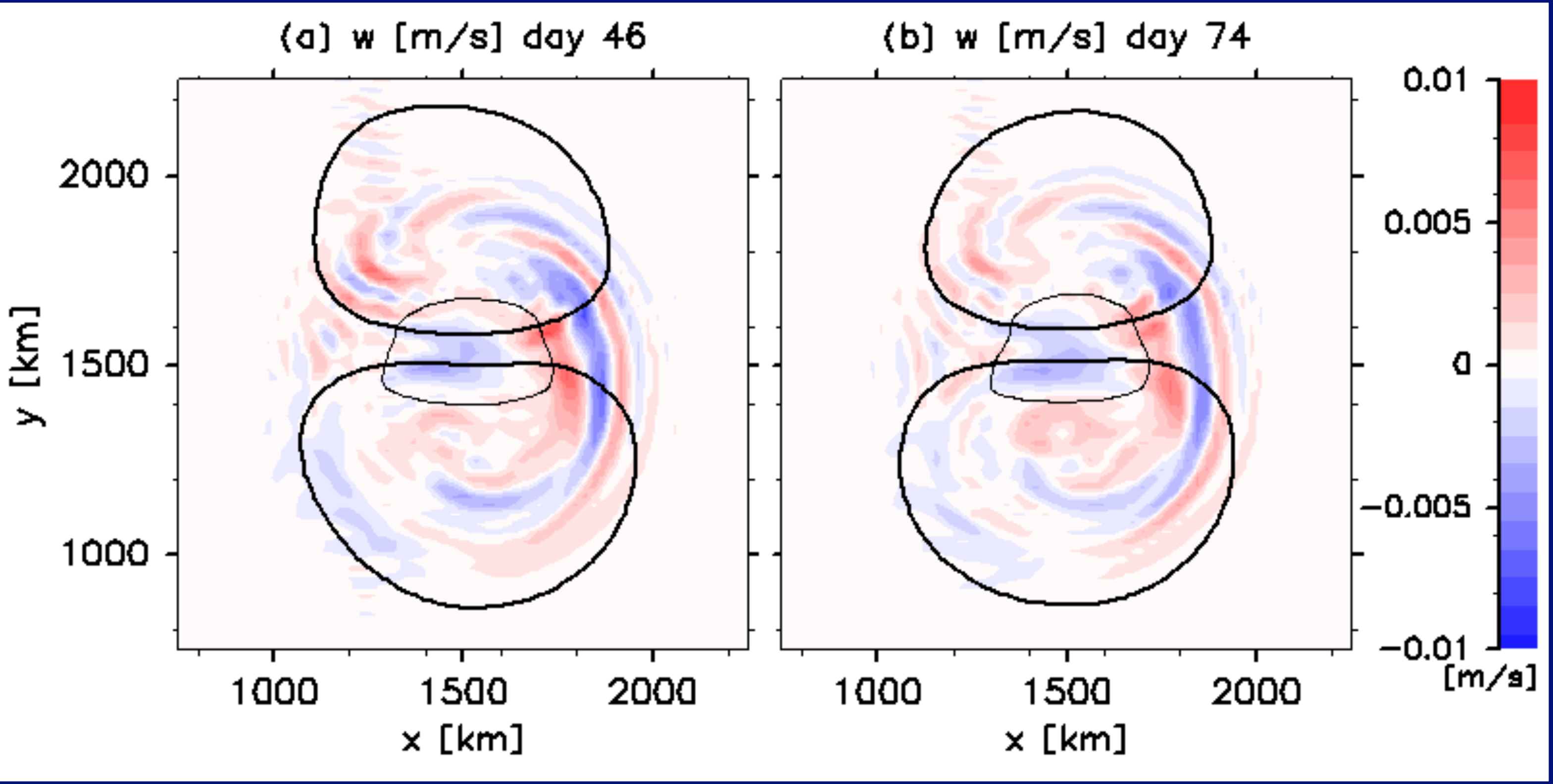
time=0 day

-01-16

Ps.nc@Ps

Vertical velocities after long-term integration

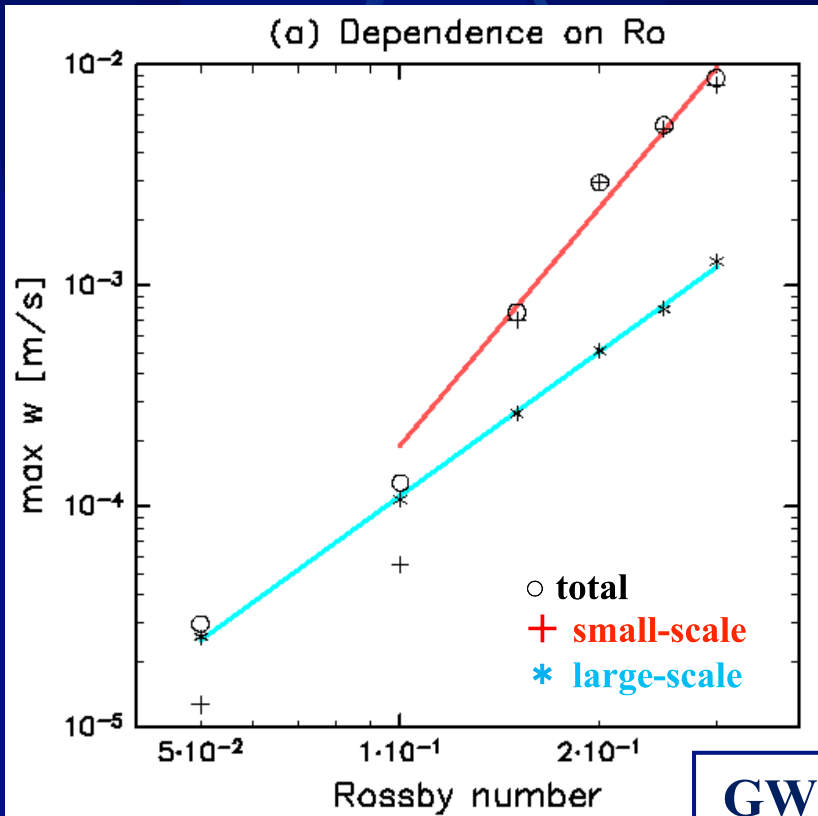
Ro=0.3 (128×128×80)



"Quasi-stationary state".
Deviation from stationarity: emission and dissipation of GW

Emission occurs at well-resolved scales, and dissipation at the smallest scales

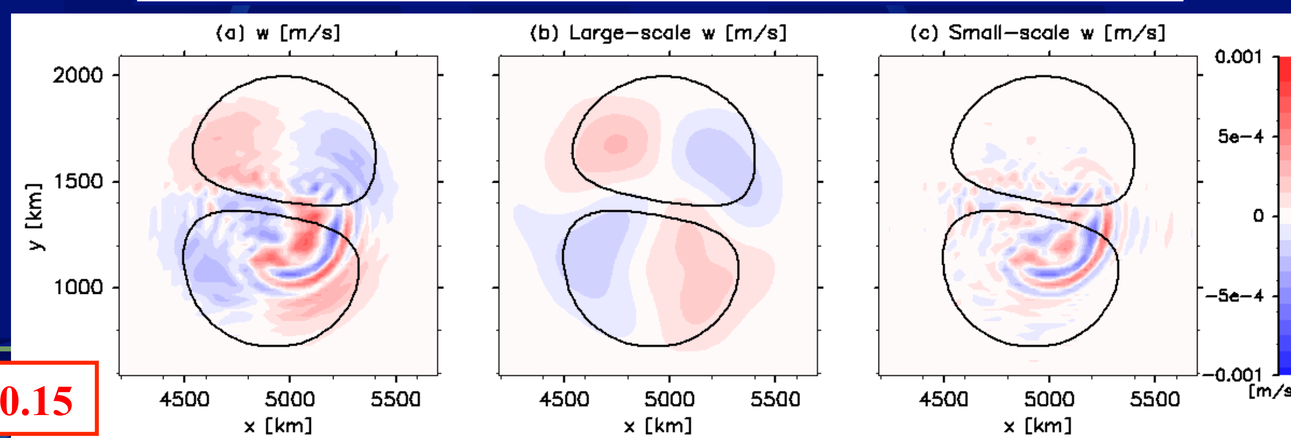
Dependence of the amplitude of GW on Rossby number



For the maximum w, 3.5th power of Ro

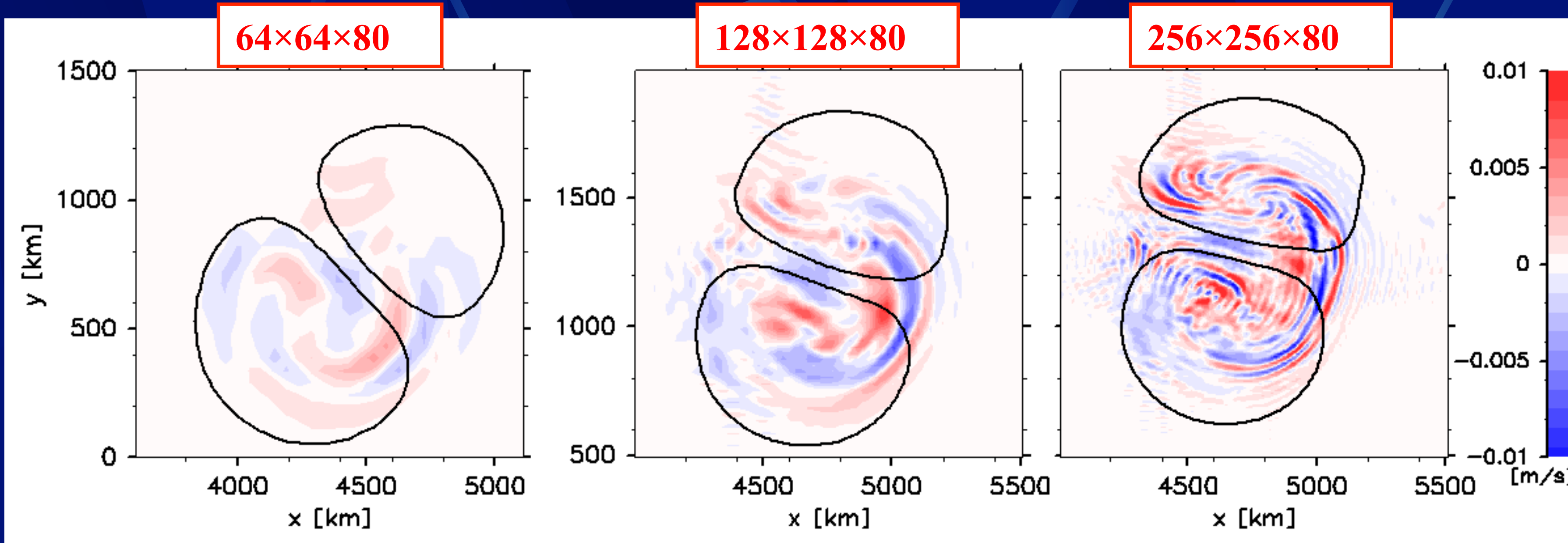
GW component is extracted by spatial filter

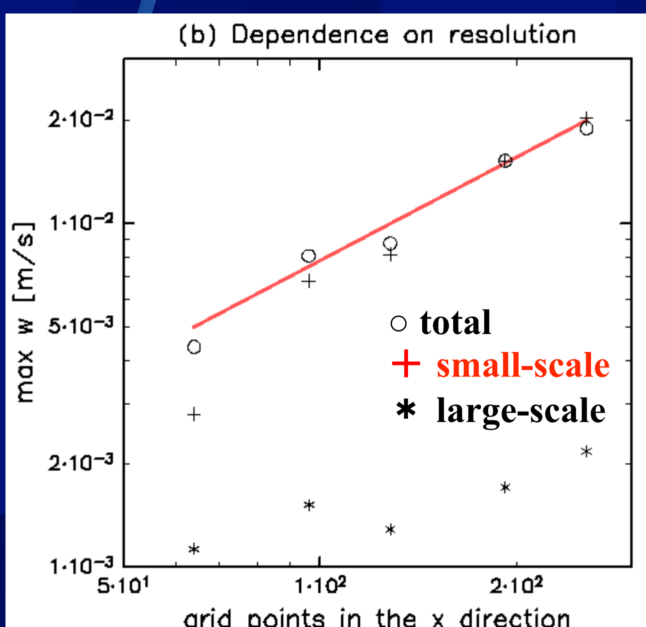
128×128×80 grids



Ro=0.15

Dependence on the resolution (Ro=0.3)





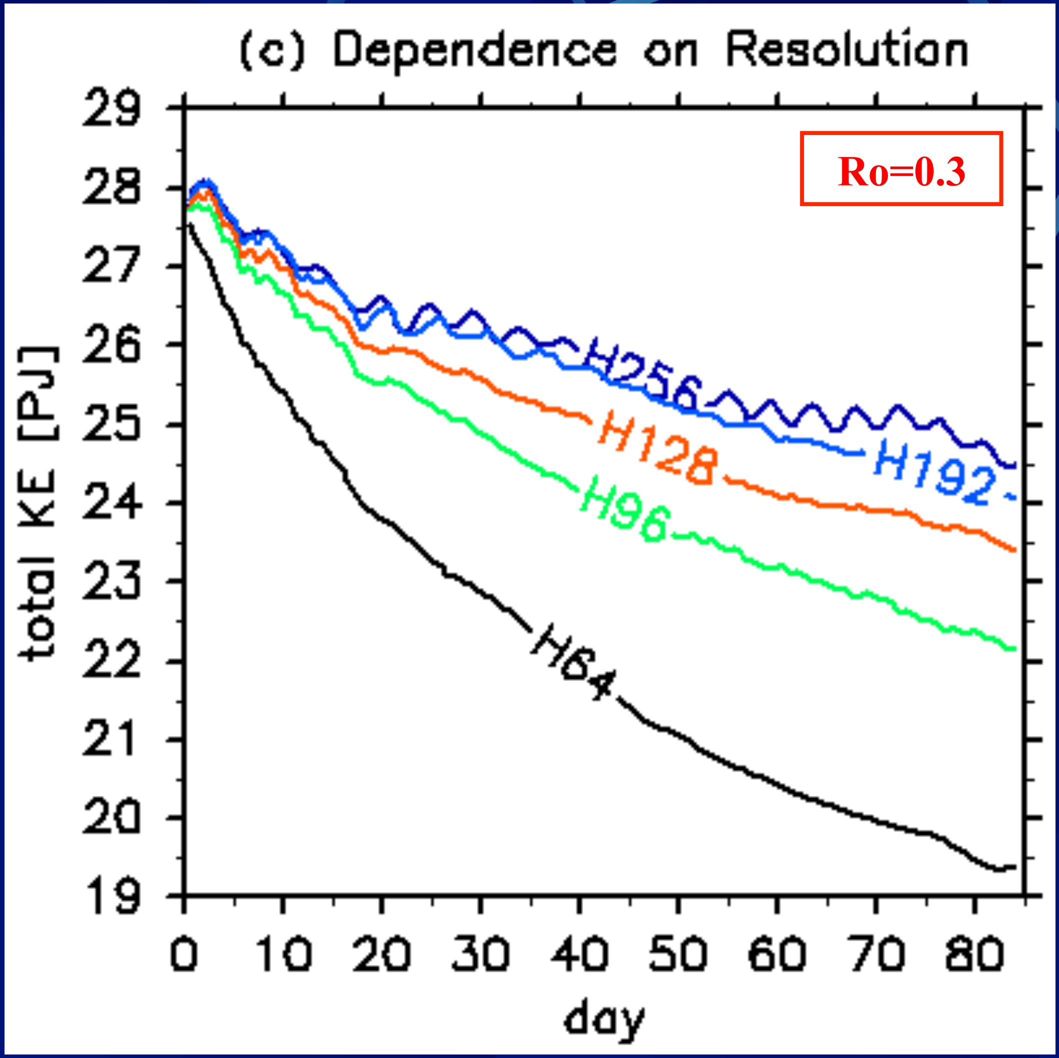
Horizontal resolution determines the wavenumber of GW

GW proportional to horizontal resolution

✓ Qualitative expectations from describing the evolution of a known source with increased resolution

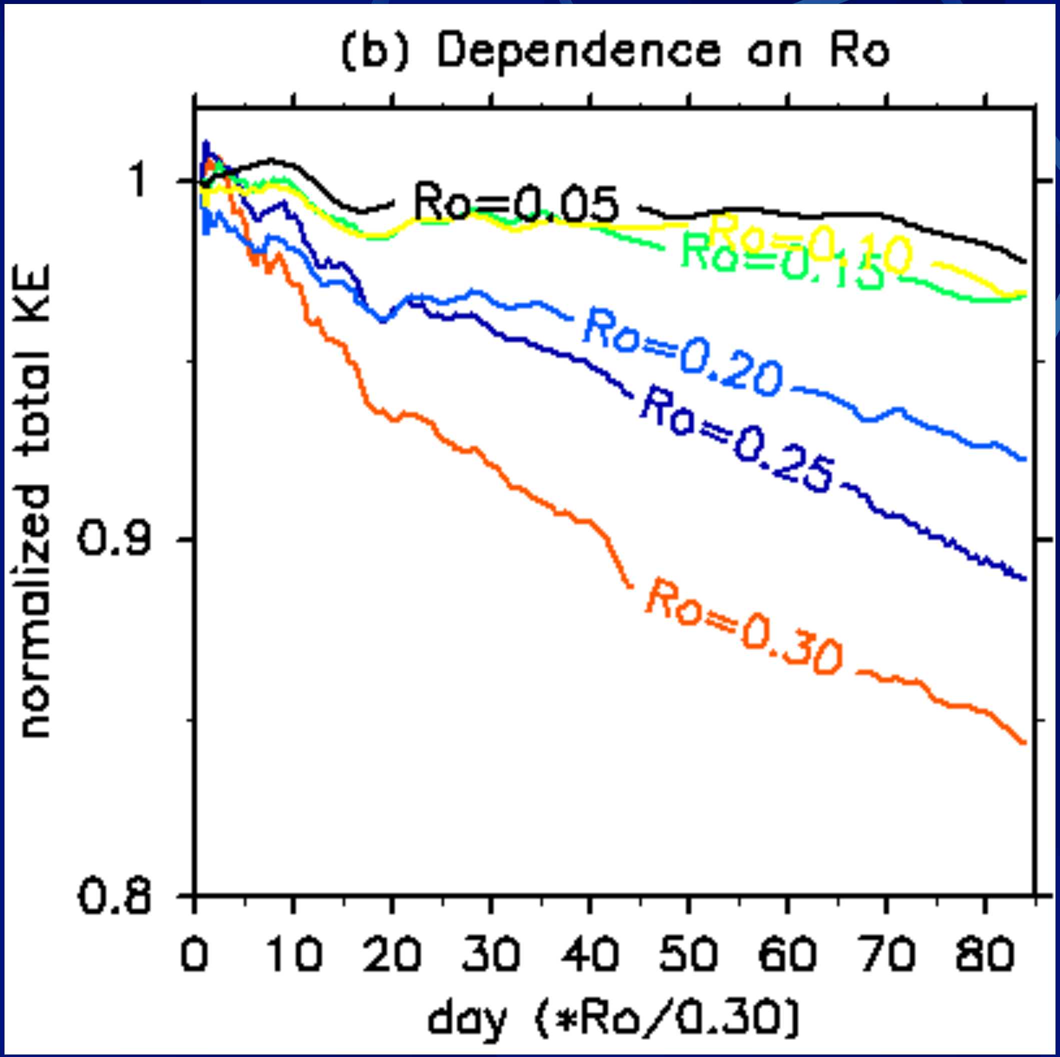
$$E_{IGW} = \frac{\rho}{2}(\hat{u}^2 + \hat{w}^2) + N^2\hat{\theta}^2 = \frac{\rho}{2}\hat{w}^2\left(\frac{m^2}{k^2} + 1\right) + N^2\hat{\theta}^2 \sim \frac{\rho}{2}\hat{w}^2\left(\frac{m^2}{k^2}\right),$$

- Emission is well resolved (despite persistent sensitivity of the small-scale waves to the resolution).



Energy derived from the dipole almost saturates for H192 and H256

- Leakage of energy from the dipole can be estimated.



128×128×80 grids

~15% of TKE derived by the dipole during 84 days for Ro=0.3 (~0.2%/day)

Physically based upper bound for the leakage of energy from balanced motions in the ocean

4. Summary and discussion

- Spontaneous emission of GW in a dipole is revisited.
  - Maximum wave vertical velocity is proportional to the resolution.
  - The energy extracted by the waves is weakly sensitive to the resolution.
  - The dipole loses at most 0.2% energy per day to inertia-gravity waves.
- Global energy budget in the ocean will be revised.
  - A maximum flux of energy from balanced motions is estimated by ~0.3 TW, which is weaker than the 1-1.5 TW often considered.
  - This estimate is still upper bound because balanced eddies tend to be monopole with weaker Ro and would have kinetic energy only several tens of percent of the total energy ~13 EJ.

References

- ✓ Sugimoto, N., K. Ishioka, and S. Yoden, **Balance regimes for the stability of a jet in an *f*-plane shallow water system**, *Fluid Dynamics Research*, Vol. 39, (2007), p353-377.
- ✓ Sugimoto, N., K. Ishioka, and S. Yoden, **Gravity wave radiation from unsteady rotational flow in an *f*-plane shallow water system**, *Fluid Dynamics Research*, Vol. 39, (2007), p731-754.
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- ✓ Sugimoto, N. and K. Ishii, **Spontaneous Gravity Wave Radiation in Shallow Water System on a Rotating Sphere**, *Journal of the Meteorological Society Japan*, Vol.90, (2012), p101-125.
- ✓ Yasuda, Y., K. Sato, and N. Sugimoto, **A theoretical study on the spontaneous radiation of inertia-gravity waves using the renormalization group method. Part I: Derivation of the renormalization group equations**, *Journal of the Atmospheric Sciences*, Vol. 72, No. 3, (2015), p957-983.
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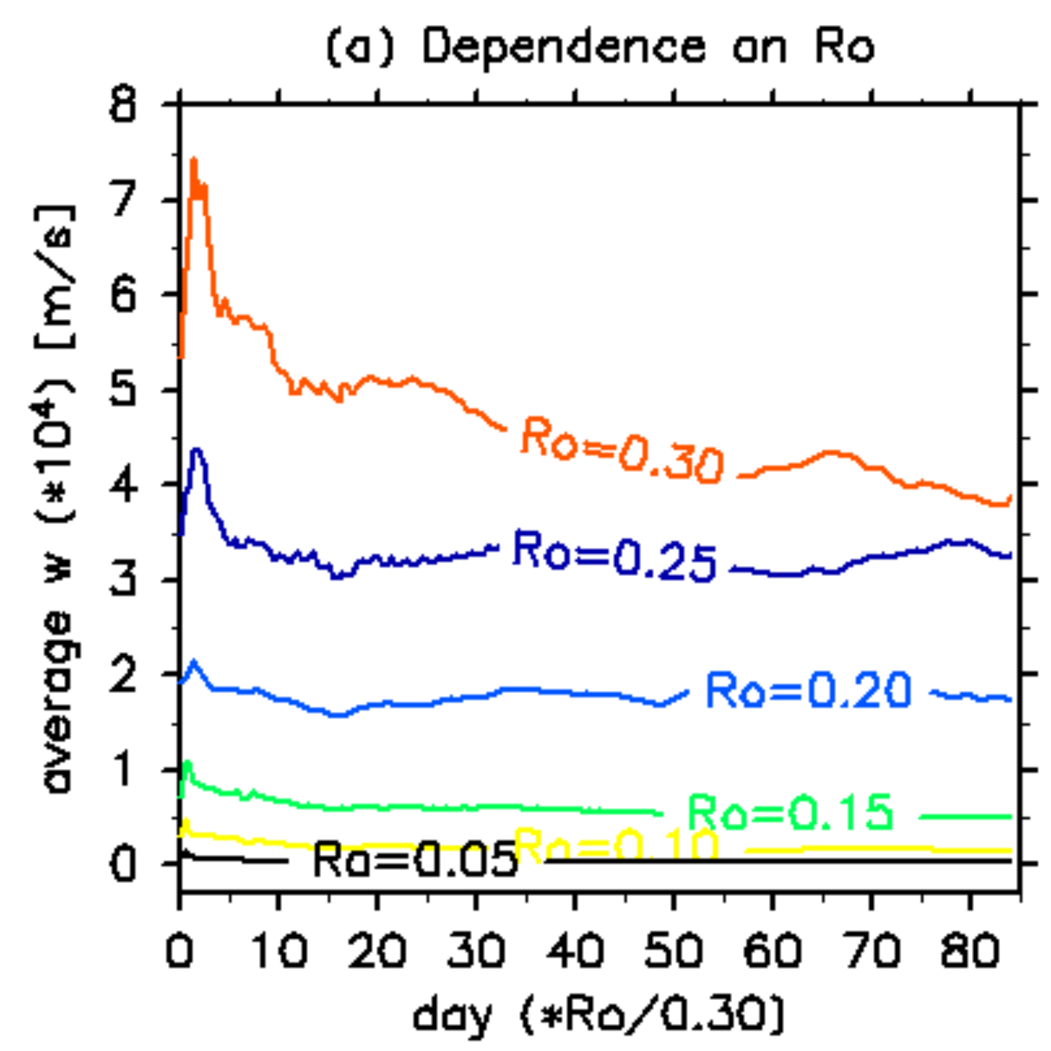
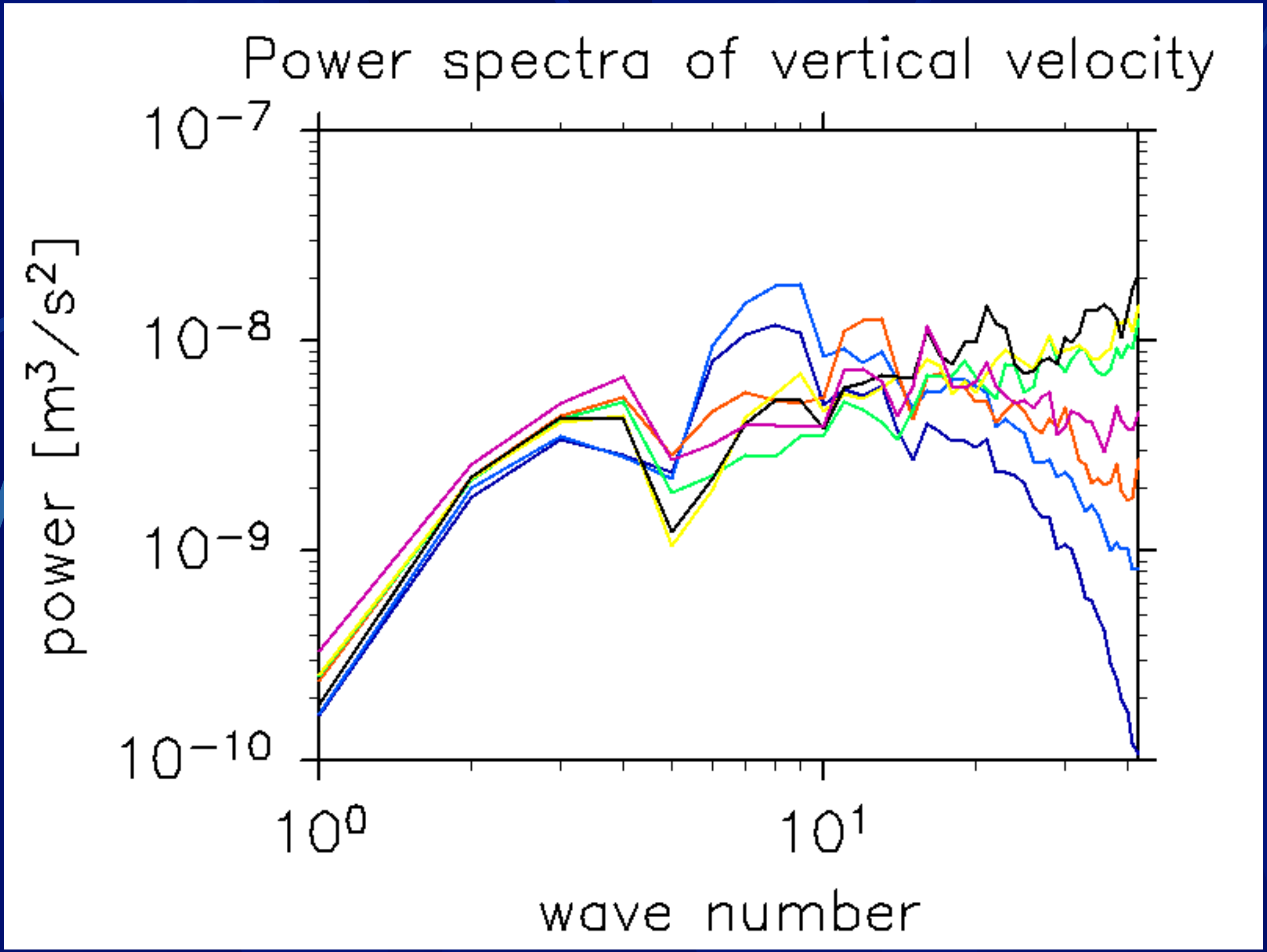
- ✓ Sugimoto, N., K. Ishioka, H. Kobayashi, and Y. Shimomura, **Cyclone-anticyclone asymmetry in gravity wave radiation from a co-rotating vortex pair in rotating shallow water**, *Journal of Fluid Mechanics*, Vol. 772, (2015), p80-106.
- ✓ Sugimoto, N., **Inertia-gravity wave radiation from the merging of two co-rotating vortices in the f-plane shallow water system**, *Physics of Fluids*, Vol. 27, (2015), 121701
- ✓ Sugimoto, N. and R. Plougonven, **Generation and impact of spontaneously emitted inertia-gravity waves**, *Geophysical Research* Letters, Vol. 43, (2016), p3519-3525.
- ✓ Sugimoto, N., **Inertia-gravity wave radiation from the elliptical vortex in the f-plane shallow water system**, *Physics of Fluids*, in preparation.

- Dependence on Rossby number



128×128×80 grids

Continuous GW radiation for Ro>0.15



At day 28 for Ro=0.3 runs with different e-folding time of the hyper diffusion 0.025 (blue), 0.05 (light blue), 0.1 (red), 0.2 (purple), 0.5 (green), 1 (yellow), and 2 days (black).