

# Planetary waves: a numerical study of Rossby waves

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## Abstract

In this article, we study Rossby waves using different both implicit and explicit schemes for solving the wave equation numerically. We consider both the advantages and disadvantages of both methods, as well as their efficiency and accuracy. From this analysis, we find that

## 1 Introduction

We encounter wave phenomena everywhere in the natural sciences. From quantum mechanics to oceanography, we find that be it the motion of a particle or the ocean, we require knowledge of wave-like behaviour to solve the problem. In quantum mechanics, a particle's wave function is described by a complex-valued diffusion equation, the Schrödinger equation, while in oceanography, we can describe ocean waves using the wave equation,

$$\frac{\partial^2 u}{\partial x^2} = \frac{\partial^2 u}{\partial t^2}, \quad (1)$$

where  $x$  and  $t$  denote the spatial and temporal coordinates, respectively. The wave equation will be the topic of this paper, in particular, we will model Rossby waves, first identified by Rossby (1939). These are inertial, planetary waves in the Earth's atmosphere and ocean which motions contribute to extreme weather (Mann et al., 2017), might drive the El-Niño southern oscillation (ENSO) (Bosc and Delcroix, 2008), and is also produced by ENSO, see Battisti (1989). While we hope the reader appreciate the wide range of phenomena related to these waves, our article is a numerical study of the waves isolated from other processes. We therefore begin by describing fun-

damental theory of waves and partial differential equations in the Theory section, present our algorithm and the technicalities relating to its implementation. In the Results section, we present our data as figures, before discussing their implications in the Discussion section. Concluding our paper, we present our final thoughts on the topic of simulating Rossby waves.

## 2 Theory

### 2.1 Partial differential equations

Partial differential equations can often be separated into a set of coupled ordinary differential equations which are easier to solve.

### 2.2 Properties of waves

Waves are solutions of the wave equation (see eq. 1), and have certain properties including

### 2.3 Rossby wave equation

Rossby waves are low frequency waves induced by the meridional variation of the Coriolis parameter  $f$ . This parameter depends on the rotation of the Earth  $\Omega$  and the latitude  $\varphi$ , and

is given by

$$f = \Omega \sin \varphi. \quad (2)$$

An approximation where  $f$  is set to vary linear in space is called the  $\beta$ -plane approximation, and can be written as

$$f = f_0 + \beta y, \quad (3)$$

where  $\beta = \frac{df}{dy} \Big|_{\varphi_0} = \frac{2\Omega}{a} \cos \varphi_0$ ,  $a$  being the radius of the Earth. Combining the  $\beta$ -plane approximation with the shallow water vorticity equation, you get the quasi-geostrophic vorticity equation. This can be linearised, and by assuming a constant mean flow without bottom topography, you get the barotropic Rossby wave equation:

$$(\partial_t + U \partial_x) \nabla_H \psi + \beta \partial_x \psi = 0. \quad (4)$$

Here,  $\psi$  is the stream function describing the velocity perturbation,  $\partial_x$  denotes  $\frac{\partial}{\partial x}$ ,  $\nabla_H$  is the horizontal divergence  $\partial x + \partial y$  and  $U$  is the mean velocity. In this report, we will assume no mean velocity, i.e.  $U = 0$ , in which case equation (4) simplifies to

$$\partial_t \nabla_H \psi + \beta \partial_x \psi = 0. \quad (5)$$

Two forms of boundaries will be examined in this report, that is periodic and constant boundaries. The first case can be used to describe an atmosphere that wraps around the earth, where the stream function is equal at the end-points. The latter case, where the stream function has a constant value at the boundaries, can be used to describe an ocean basin.

A possible solution to (5) in one dimension with periodic boundaries, where  $x \in [0, L]$ , is given by

$$\psi = A \cos(kx - \omega t), \quad (6)$$

where  $k = \frac{2n\pi}{L}$  and  $\omega = -\frac{\beta L}{2n\pi}$ . The phase speed  $c$  can be calculated through the dispersion relation, given by

$$c = \frac{\omega L}{2n\pi} = -\beta \left( \frac{L}{2n\pi} \right)^2. \quad (7)$$

Since  $\beta$  is positive for all latitudes, the phase speed will be negative, implying that Rossby waves travels from east to west in a bounded domain.

The same problem, but with constant boundaries equal to zero, has the possible solution

$$\psi = A \sin \left( \frac{\pi n}{L} x \right) \cos(kx - \omega t), \quad (8)$$

with  $k = \frac{L}{\pi n}$  and  $\omega = -\frac{\beta}{2k}$ . Here, the phase speed is given by

$$c = \frac{\omega L}{2n\pi} = -\frac{\beta}{4} \quad (9)$$

Again, the phase speed is negative. Equation (8) describes a cosine wave where the amplitude is dependent on the position, following a sine curve with zeros at the boundaries.

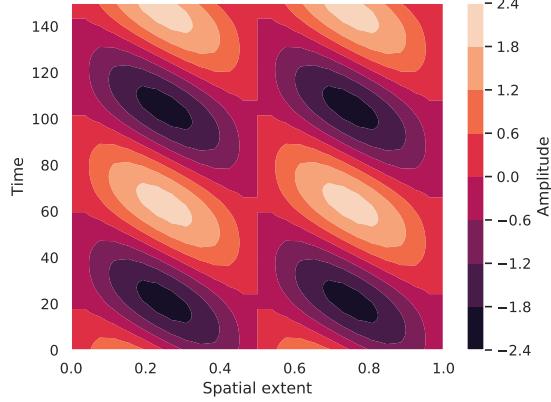
## 2.4 Implementation

We implement our algorithms in C++ using the armadillo and LAPACK libraries to handle matrix operations. To analyse data and produce figures, we use python 3.6 with a standard set of modules: matplotlib, numpy and seaborn.

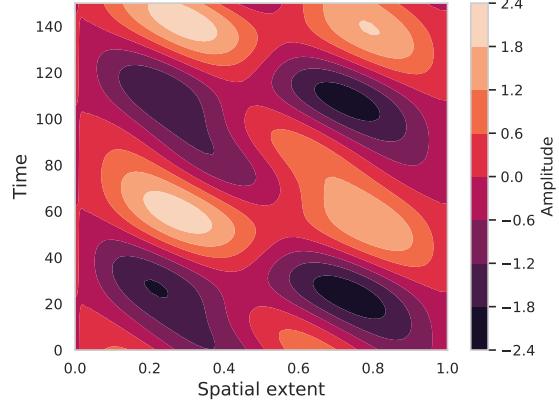
We implement our algorithm using methods as outlined by Sjur and Kallmyr (2018). For closed boundaries we have the Dirichlet boundary conditions and can use gaussian elimination to solve the set of equations. In the case of periodic boundaries our matrix become non-tridiagonal, and we have to use LU decomposition to solve the differential equation.

## 3 Results

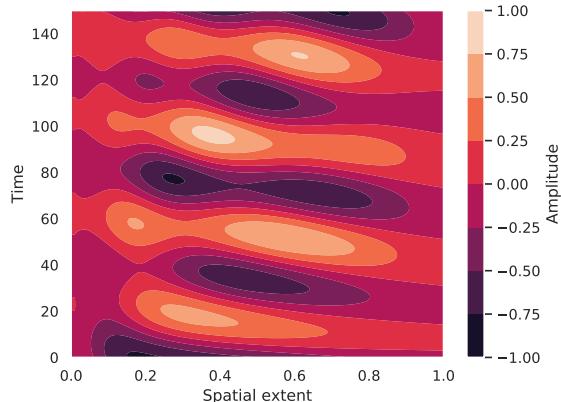
Looking at Figure 1, we see the time evolution of a sine wave in the bounded domain. The wave propagated towards the east, and we saw a clear distinction between phases.



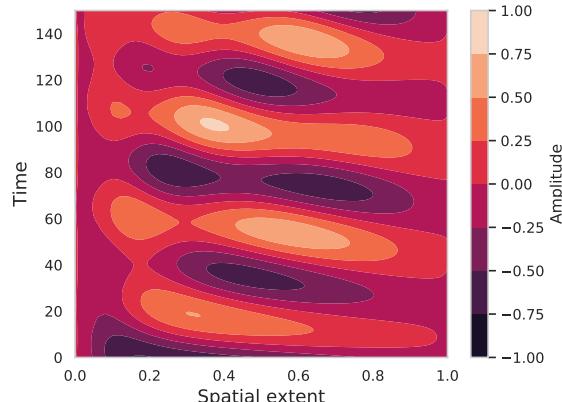
*Figure 1: Hov Müller diagram of a bounded Rossby wave with a initial sine wave using a explicit scheme.*



*Figure 3: Hov Müller diagram of a Rossby wave with periodic boundary conditions, initially a sine wave using a explicit scheme.*



*Figure 2: Hov Müller diagram of a bounded Rossby wave initially a gaussian using a explicit scheme.*



*Figure 4: Hov Müller diagram of a Rossby wave with periodic boundary conditions, initially a gaussian using a explicit scheme.*

<b>n</b>	<b>t<sub>g</sub>/t<sub>s</sub></b>	<b>t<sub>LU</sub>/t<sub>s</sub></b>
10	2.08	3.70
$10^2$	1.89	$1.00 \cdot 10^2$
$10^3$	1.48	$1.05 \cdot 10^4$
$10^4$	1.43	$1.18 \cdot 10^6$
$10^5$	1.39	-
$10^6$	1.41	-
$10^7$	1.39	-

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*Table 1: Ratio between CPU time for the general algorithm ( $t_g$ ), the special algorithm ( $t_g$ ) and the LU decomposition algorithm ( $t_{LU}$ ) for different matrix sizes ( $n$ ). The LU decomposition crashed for  $n$  greater than  $10^4$ .*

## 4 Discussion

## 5 Conclusion

## References

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**A**

$$A = \begin{bmatrix} b_1 & c_1 & 0 & \dots & \dots & 0 \\ a_1 & b_2 & c_2 & 0 & \dots & 0 \\ 0 & a_2 & b_3 & c_3 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & \ddots & a_{n-2} & b_{n-1} & c_{n-1} \\ 0 & \dots & \dots & 0 & a_{n-1} & b_n \end{bmatrix},$$