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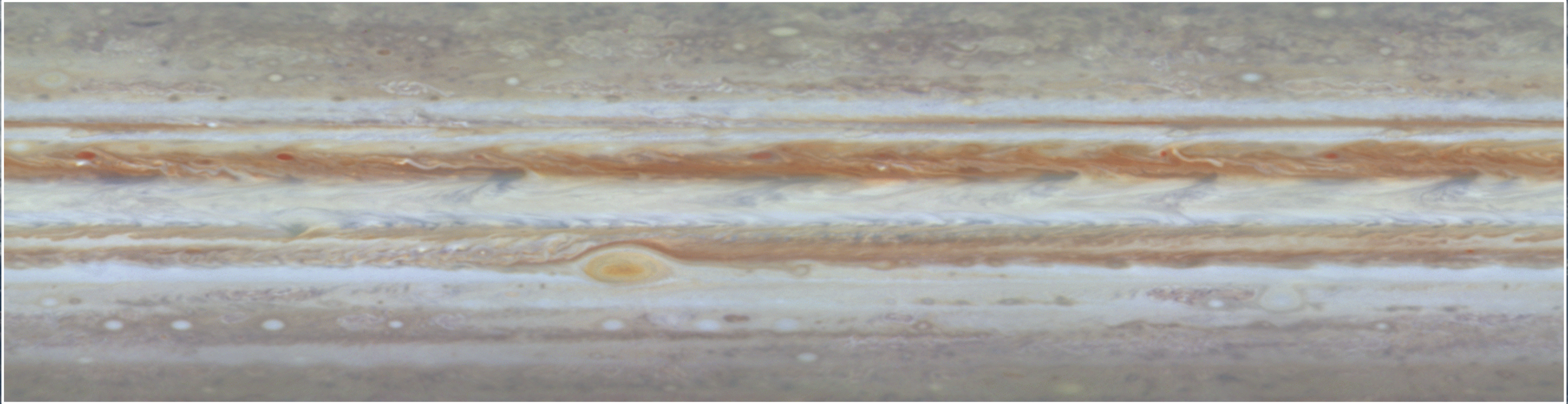
Variability of Stochastically Forced Zonal Jets

Laura Cope, Peter Haynes

Department of Applied Mathematics and Theoretical Physics, University of Cambridge



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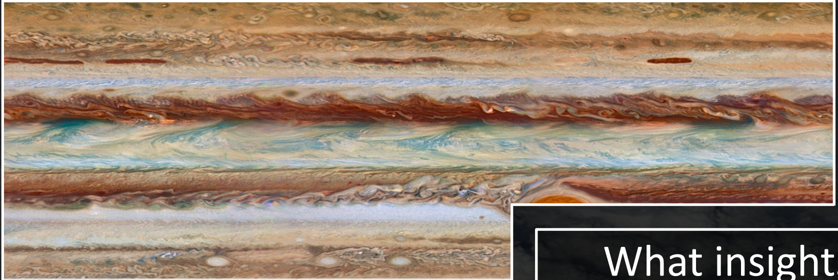
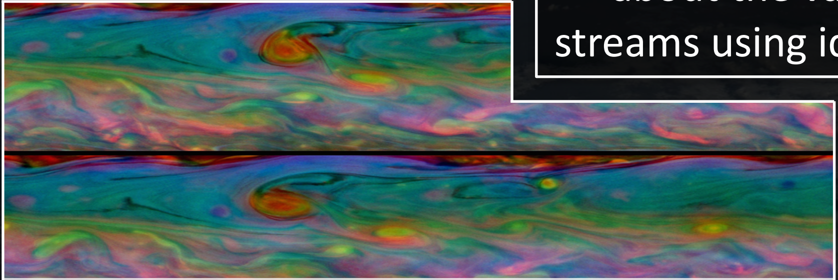
MOTIVATION

Gaseous Giant Planets



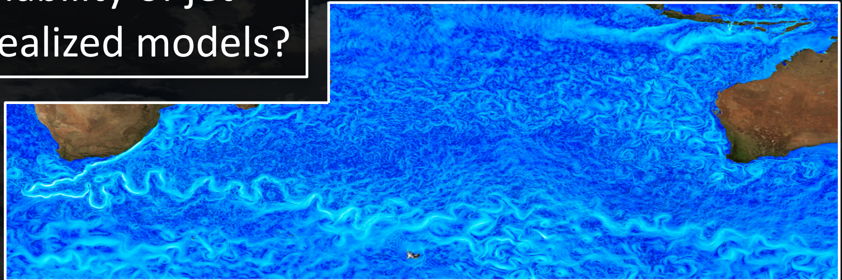
Credit: NASA, ESA



Credit: NASA/JPL-Caltech/Space Science Institute

Earth's Atmosphere & Oceans

Credit: NASA / Science Photo Library



Credit: https://www.nasa.gov

What insights can we learn about the variability of jet streams using idealized models?

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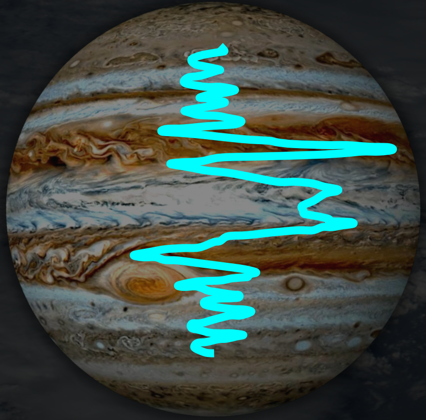
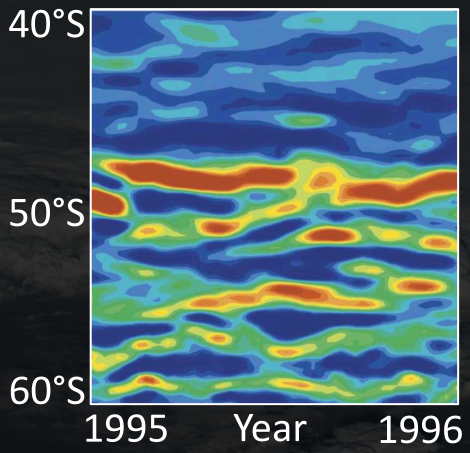
OBSERVATIONS

Jupiter



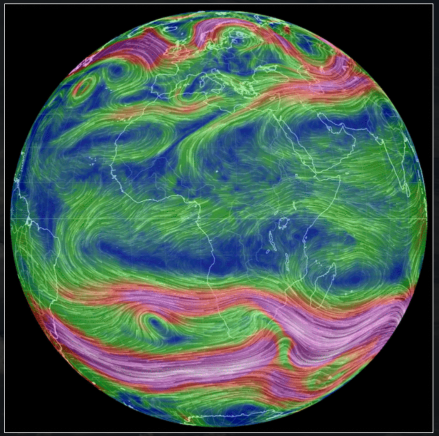
Voyager 1979-1980

Earth’s Oceans



(Sokolov, Rintoul 1996)

Earth’s Atmosphere



(earth.nullschool.net)

Increasing time variability →

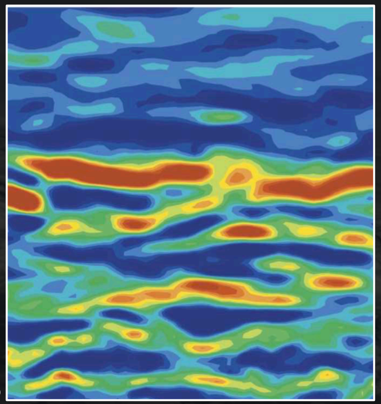
OBSERVATIONS

Jupiter

Voyager 1979-1980

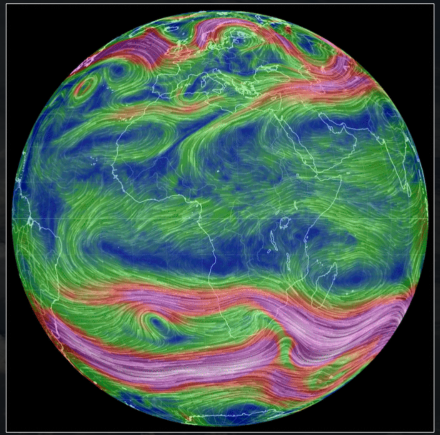
Cassini 2000

Earth's Oceans



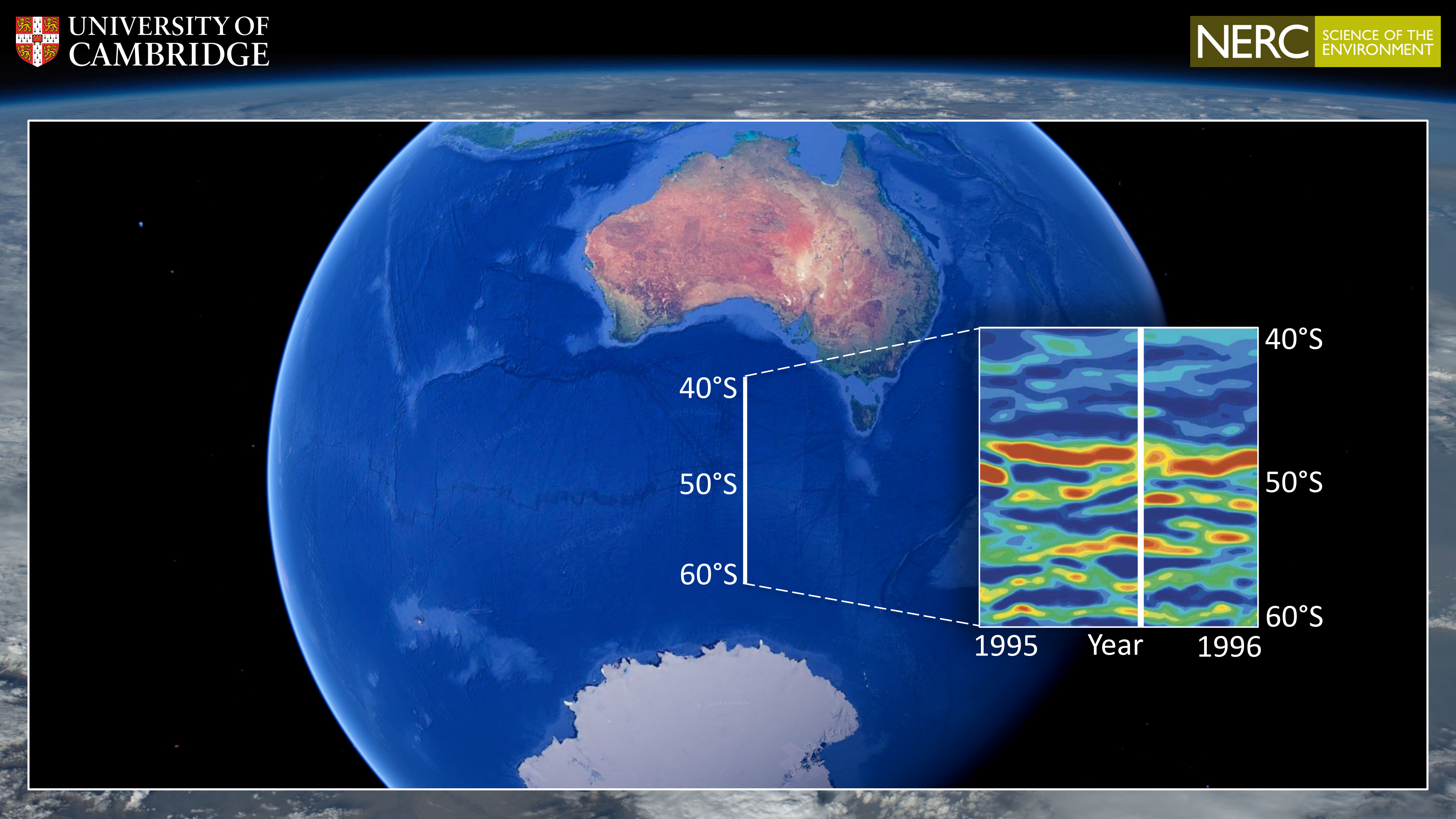
(Sokolov, Rintoul 1996)

Earth's Atmosphere



(earth.nullschool.net)

Increasing time variability →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NERC SCIENCE OF THE ENVIRONMENT
40°S
50°S
60°S
40°S
50°S
60°S
1995
Year
1996

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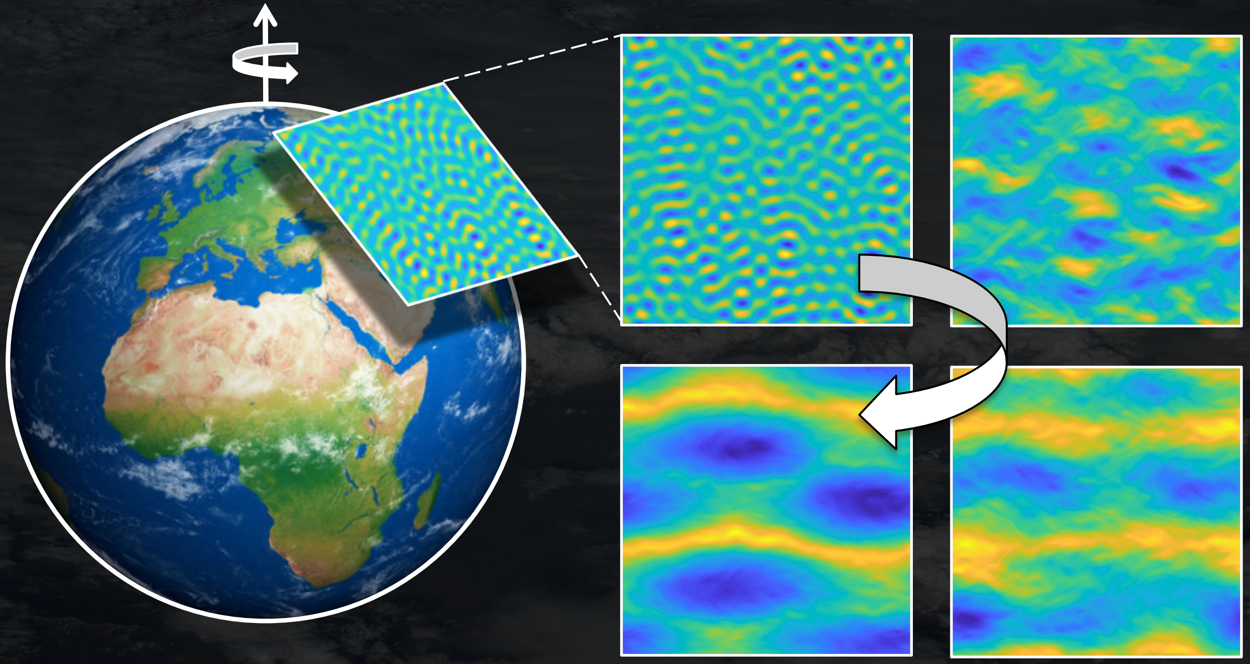
OVERVIEW OF IDEALIZED MODELS



Planetary rotation

+

Turbulence

+

Friction

↓

Jets

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IDEALIZED MODELS: MATHEMATICAL FORMULATION

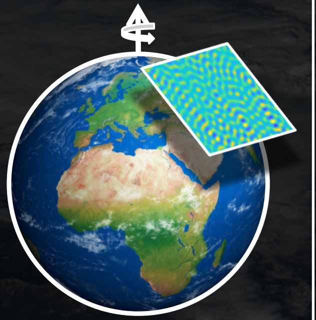
Features

2D (barotropic)

Doubly periodic

Beta plane

Stochastic force



Equation of Motion: Vorticity Equation

Planetary Rotation

Stochastic forcing

Linear friction

Hyper-viscosity

$$\frac{\partial \zeta}{\partial t} + \boldsymbol{u} \cdot \nabla \zeta + \beta v = \xi - \mu \zeta + \nu_n \nabla^{2n} \zeta$$

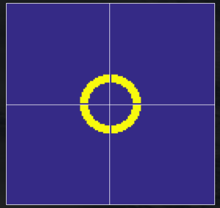
Beta, β

Energy input rate, ϵ

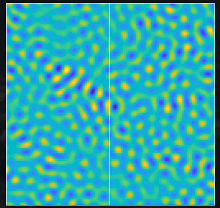
Damping rate, μ

Stochastic Force

Fourier space:



Physical space:



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IDEALIZED MODELS: MATHEMATICAL FORMULATION

Generalized Quasilinear Approximation

Reference:

Marston, Chini, Tobias (2016)

Increasing zonal wavenumber

IDEALIZED MODELS: MATHEMATICAL FORMULATION

Generalized Quasilinear Approximation

Reference:

Marston, Chini, Tobias (2016)

Low modes $\leq \Lambda$

Separation $= \Lambda$

High modes $> \Lambda$

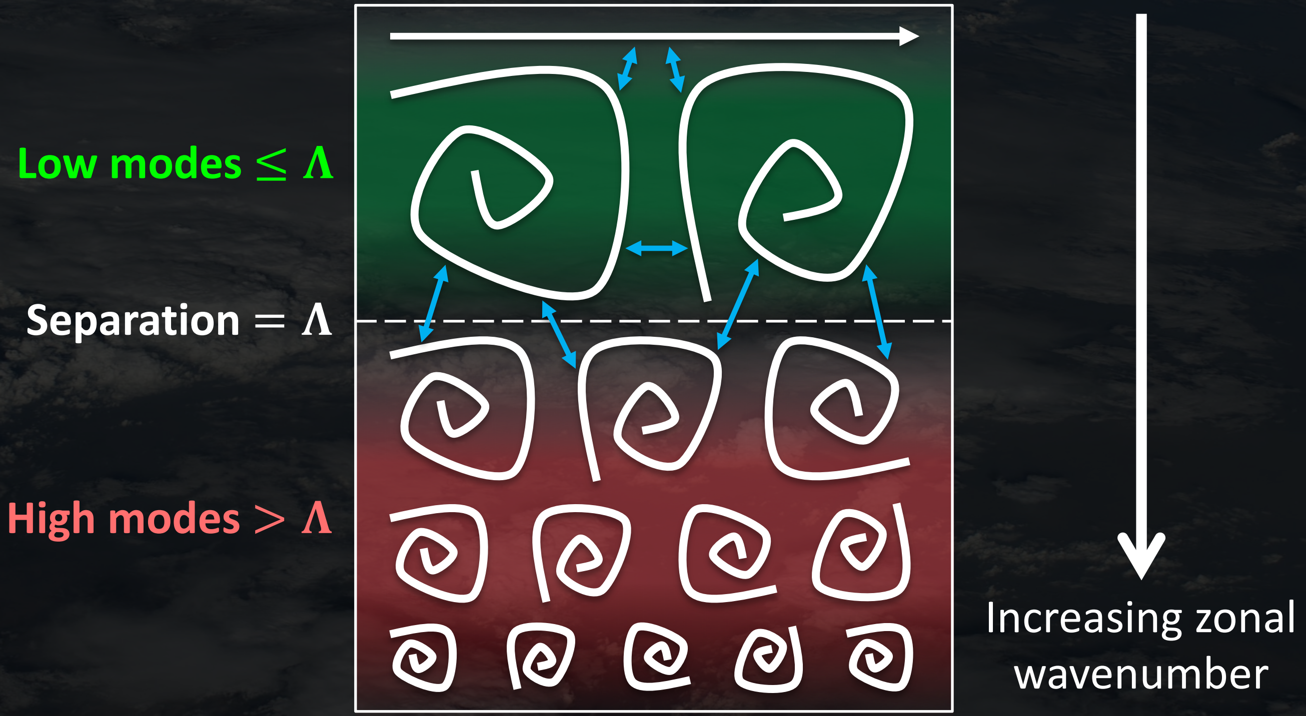
Increasing zonal wavenumber

IDEALIZED MODELS: MATHEMATICAL FORMULATION

Generalized Quasilinear Approximation

Reference:

Marston, Chini, Tobias (2016)



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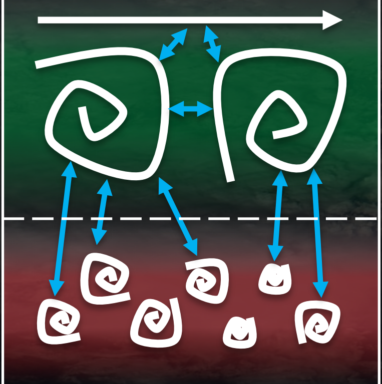
IDEALIZED MODELS: MATHEMATICAL FORMULATION

Overview

Low modes $\leq \Lambda$



High modes $> \Lambda$

Generalized Quasilinear Approximation

Low-high mode decomposition: $\psi = \sum_{|m|\leq\Lambda} e^{imx}\widehat{\psi_m} + \sum_{|m|>\Lambda} e^{imx}\widehat{\psi_m} = \bar{\psi} + \psi'$

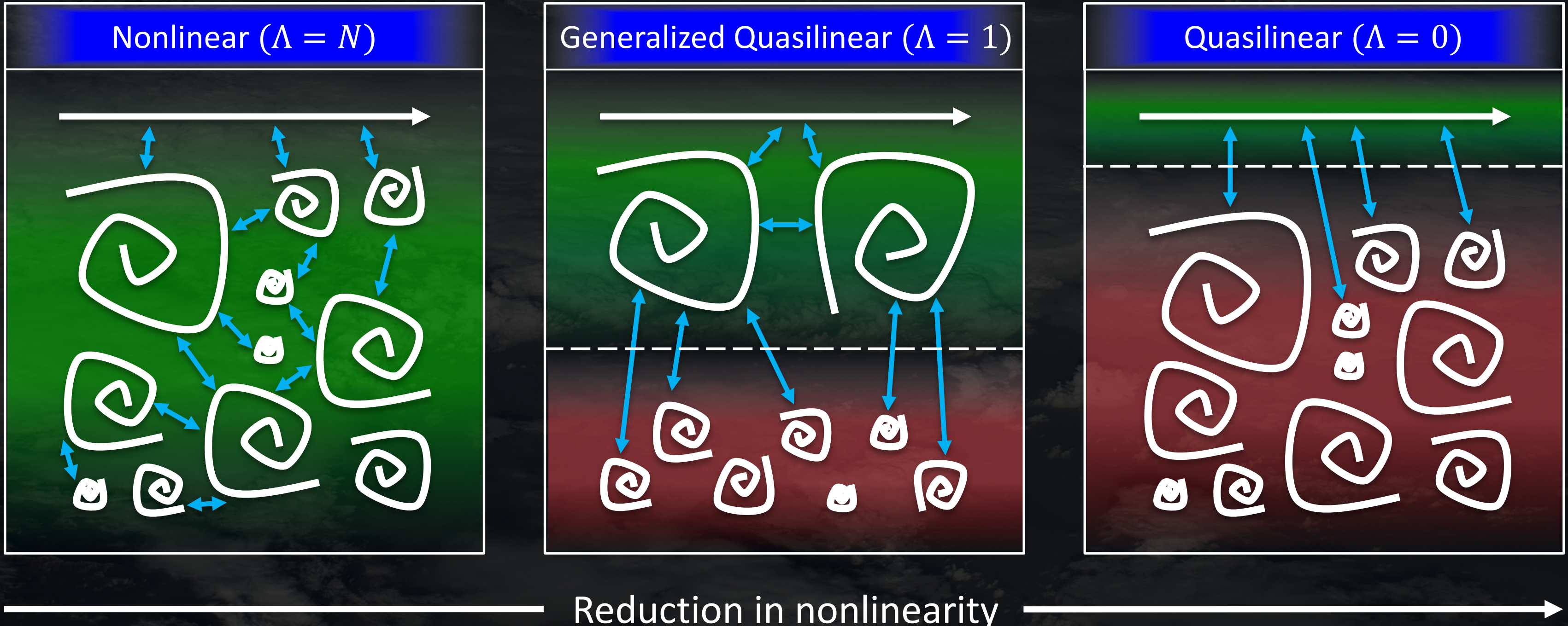
Basic vorticity equation: $\frac{\partial \zeta}{\partial t} = \mathcal{L}[\zeta] + \mathcal{N}[\zeta, \zeta]$

Low modes: $\frac{\partial \bar{\zeta}}{\partial t} = \mathcal{L}[\bar{\zeta}] + \bar{\mathcal{N}}[\bar{\zeta}, \bar{\zeta}] + \bar{\mathcal{N}}[\zeta', \zeta']$

High modes: $\frac{\partial \zeta'}{\partial t} = \mathcal{L}[\zeta'] + \mathcal{N}'[\bar{\zeta}, \zeta'] + \xcancel{[\mathrm{HHNL}]}$

Vorticity equation: $\frac{\partial \zeta}{\partial t} + \boldsymbol{u} \cdot \nabla\zeta + \beta v - [\mathrm{HHNL}] = \xi - \mu\zeta + \nu_n \nabla^{2n}\zeta$

SUMMARY OF IDEALIZED MODELS



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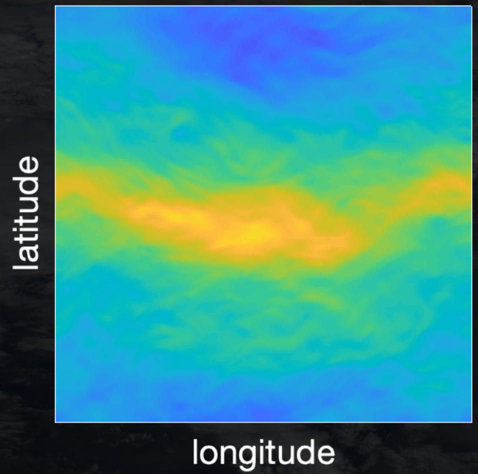
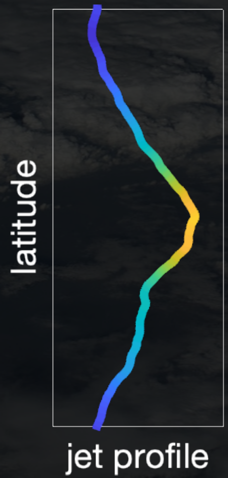
NUMERICAL SIMULATIONS – NONLINEAR (NL) MODEL

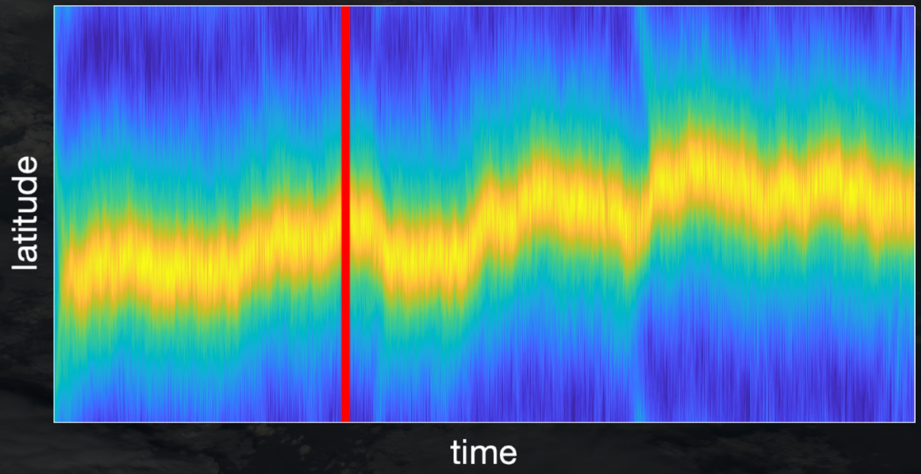
Zonal velocity field



Zonal mean zonal velocity

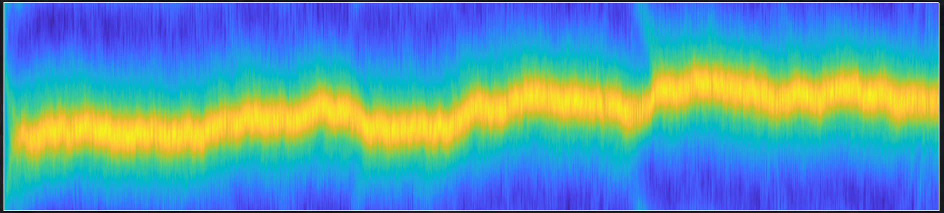


Zonal mean zonal velocity evolution in time

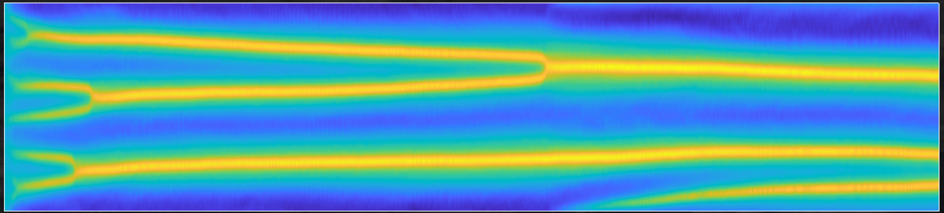


NONLINEAR (NL) MODEL – TYPES OF VARIABILITY

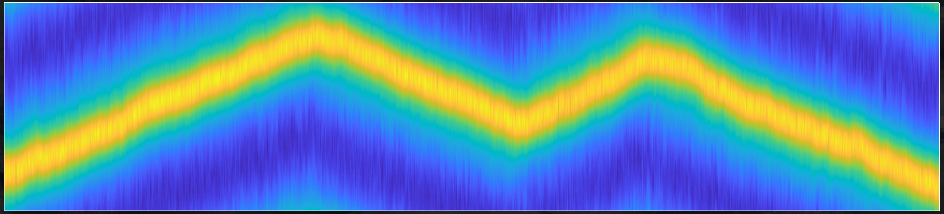
Randomly wandering



Merging & nucleating



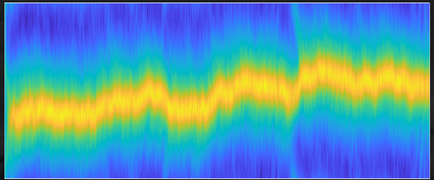
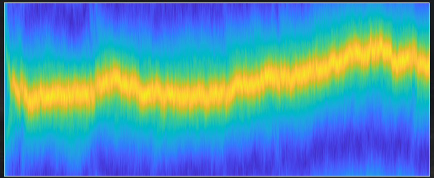
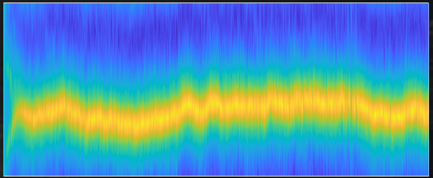
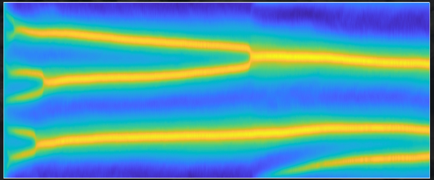
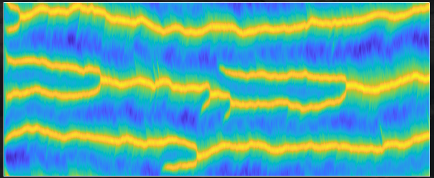
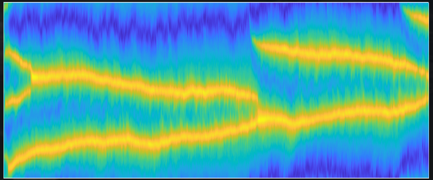
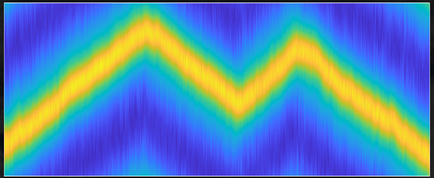
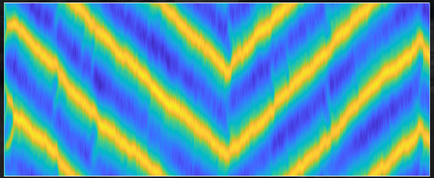
Migrating



Result 1

New type of variability found: jets migrate north and south

ALL MODELS – TYPES OF VARIABILITY

	NL Model ($\Lambda = N$)	GQL Model ($\Lambda = 1$)	QL Model ($\Lambda = 0$)
Randomly wandering			
Merging & nucleating			
Migrating			No clear migration

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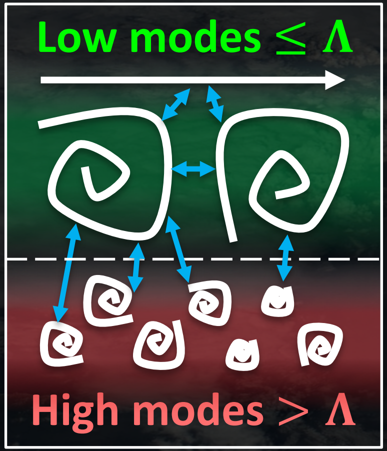
A CLOSER LOOK AT ZONAL JET MIGRATION

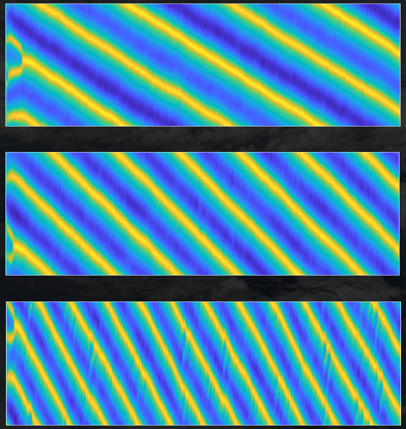
Question 1

Why do jets migrate only when $\Lambda \geq 1$?



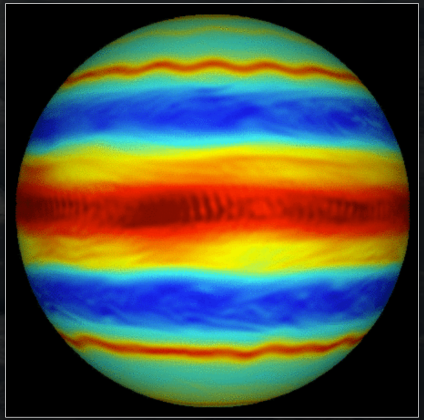
Question 2

Can we predict the speed of migration?



Question 3

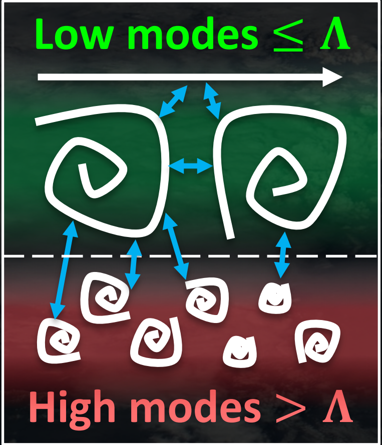
Do jets migrate in more complex systems?



A CLOSER LOOK AT ZONAL JET MIGRATION

Question 1

Why do jets migrate only when $\Lambda \geq 1$?



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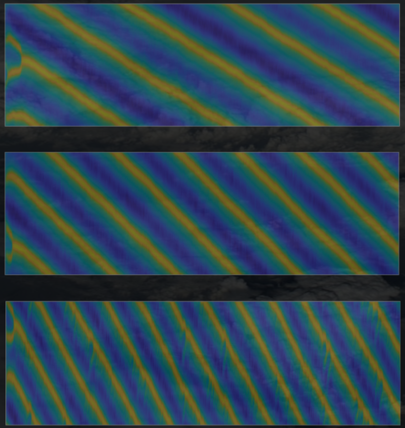

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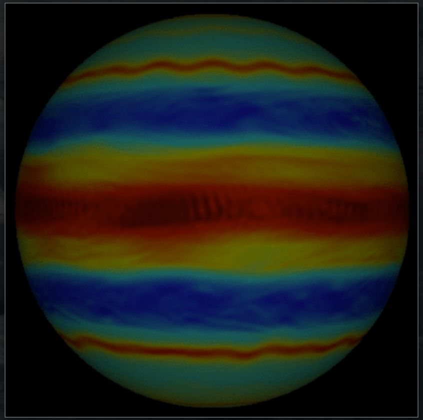
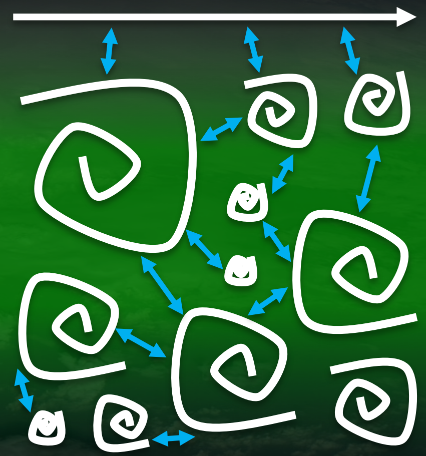


AN INTRODUCTION TO ZONONS

Zonons (Nonlinear waves)

Coherent structures excited by Rossby waves with *same* k_x and *same phase speed*

NL Model $(\Lambda = N)$



Reference: Sukoriansky, Dikovskaya, Galperin (2008), PRL

AN INTRODUCTION TO ZONONS

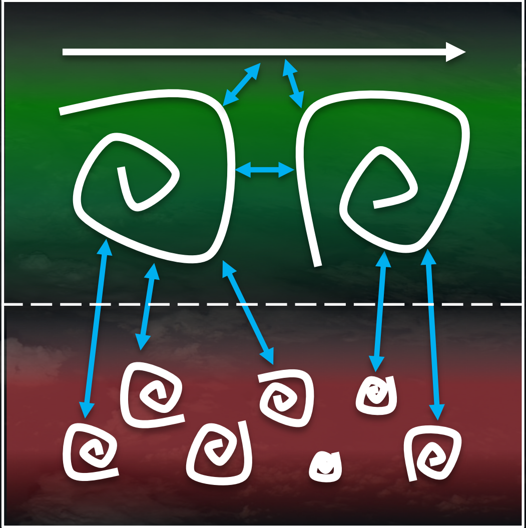
Zonons (Nonlinear waves)

Coherent structures excited by Rossby waves with *same* k_x and *same phase speed*

Linear Rossby wave

Nonlinear zonons

GQL Model ($\Lambda = 1$)



Reference: Sukoriansky, Dikovskaya, Galperin (2008), PRL

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AN INTRODUCTION TO ZONONS

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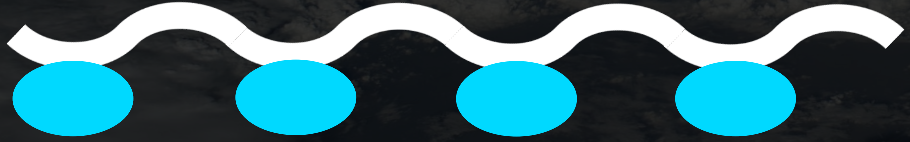
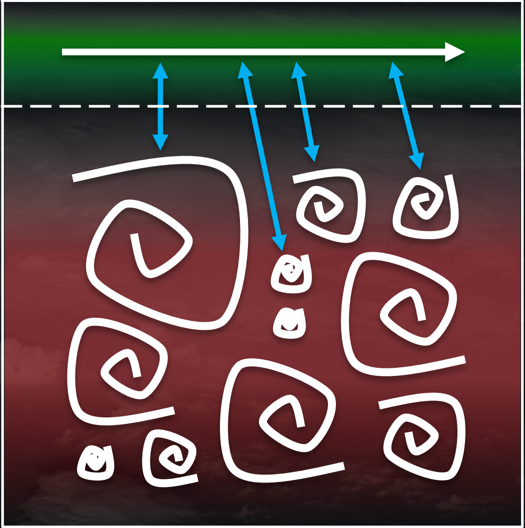
Coherent structures excited by Rossby waves with *same* k_x and *same phase speed*

Linear Rossby wave



Nonlinear zonons

QL Model $(\Lambda = 0)$



Reference: Sukoriansky, Dikovskaya, Galperin (2008), PRL

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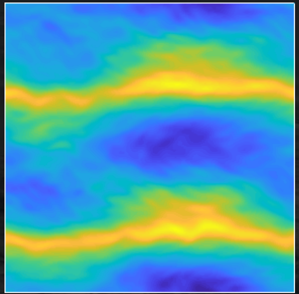
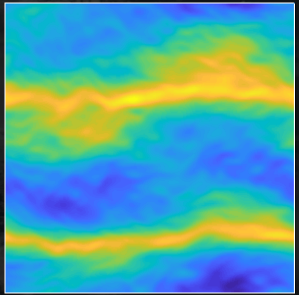
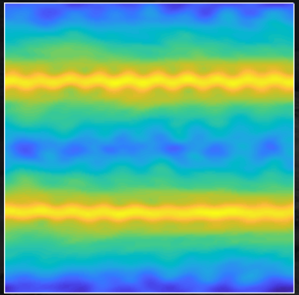
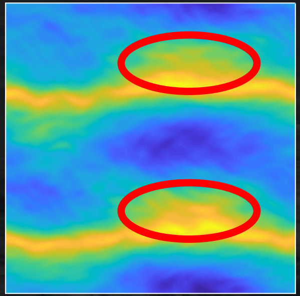
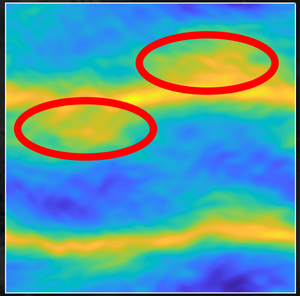
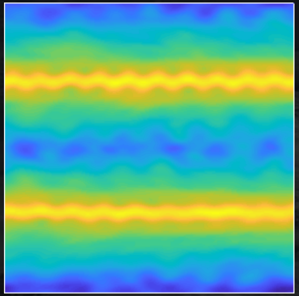
Q1: WHY DO JETS MIGRATE ONLY WHEN $\Lambda \geq 1$?

	NL Model	QL Model
Migrating North		No clear migration
Not Migrating		

Result 2

Migration requires $\Lambda \geq 1$ when jets and zonons coexist

Q1: WHY DO JETS MIGRATE ONLY WHEN $\Lambda \geq 1$?

	NL Model	QL Model
Migrating North		No clear migration
Not Migrating		

Result 2

Migration requires $\Lambda \geq 1$ when jets and zonons coexist

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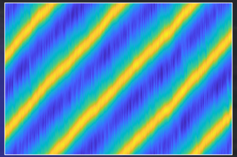
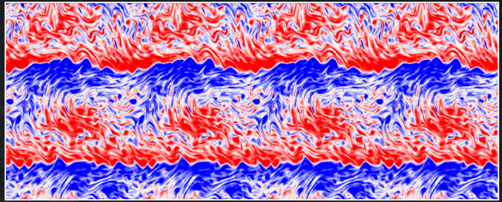
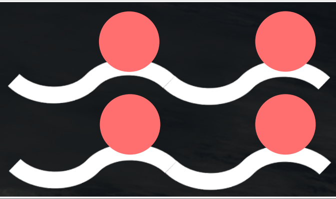
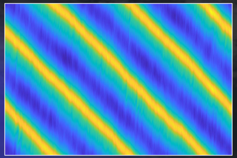
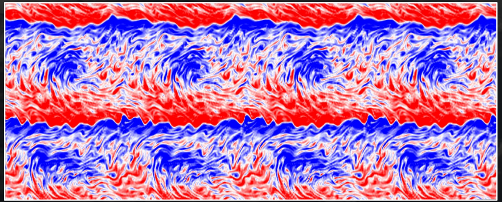
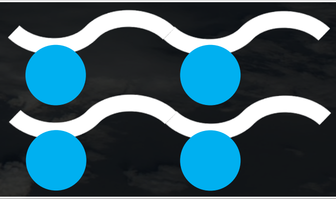
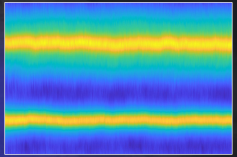
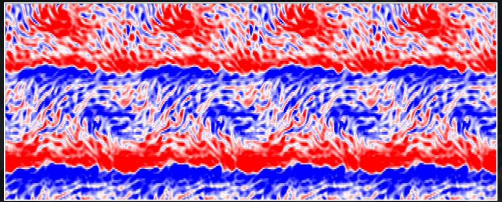
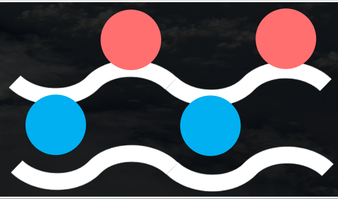
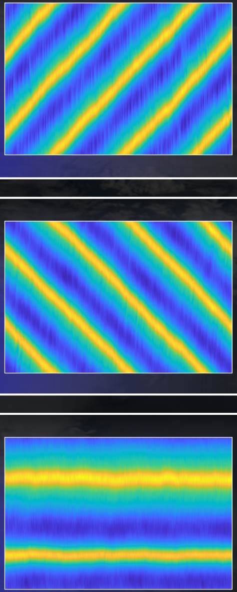
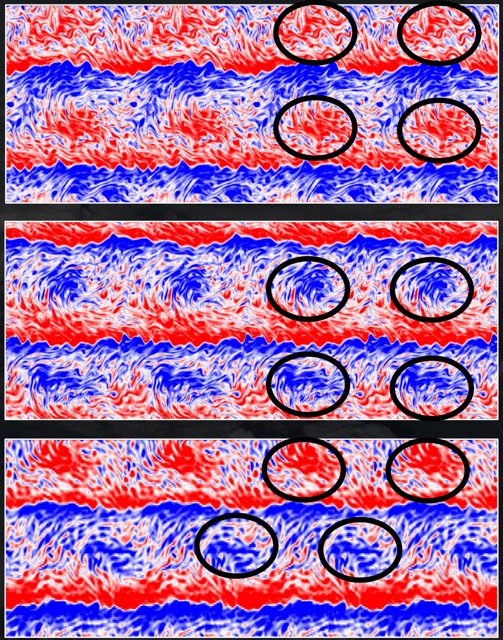
Q1: WHY DO JETS MIGRATE ONLY WHEN $\Lambda \geq 1$?

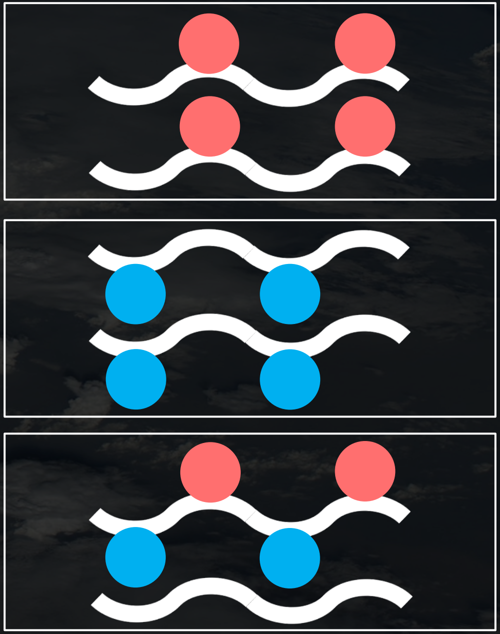
	$\zeta(x, y, t)$	Schematic
Migrating north 		
Migrating south 		
Not migrating 		

Q1: WHY DO JETS MIGRATE ONLY WHEN $\Lambda \geq 1$?

	$\zeta(x, y, t)$	Schematic
Migrating north		
Migrating south		
Not migrating		







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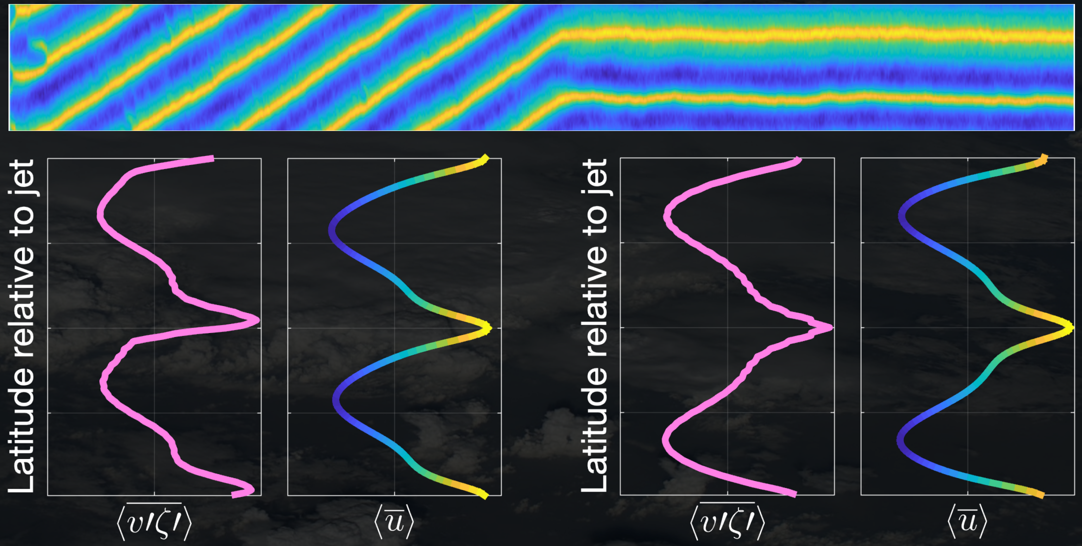
Q1: WHY DO JETS MIGRATE ONLY WHEN $\Lambda \geq 1$?

Zonal mean forcing

$$\frac{\partial \bar{u}}{\partial t} = \overline{v'\zeta'} - \mu\bar{u}$$

Reynolds stress force

Zonal mean flow

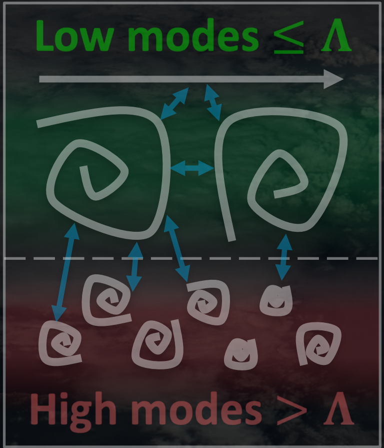


Result 3 Migration requires an asymmetric eddy forcing and mean flow

A CLOSER LOOK AT ZONAL JET MIGRATION

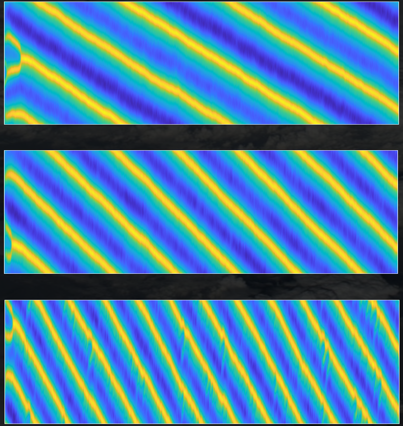
Question 1

Why do jets migrate only when $\Lambda \geq 1$?



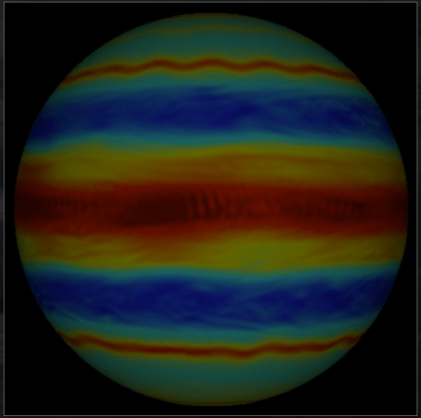
Question 2

Can we predict the speed of migration?



Question 3

Do jets migrate in more complex systems?



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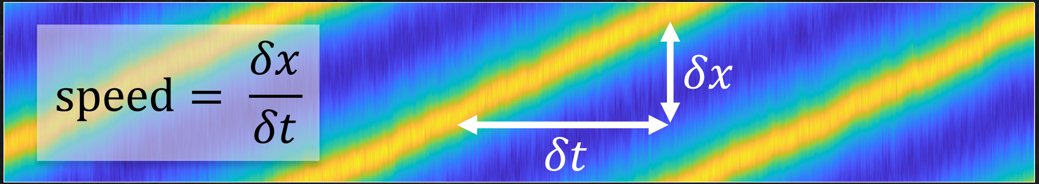
Q2: CAN WE PREDICT THE SPEED OF MIGRATION?

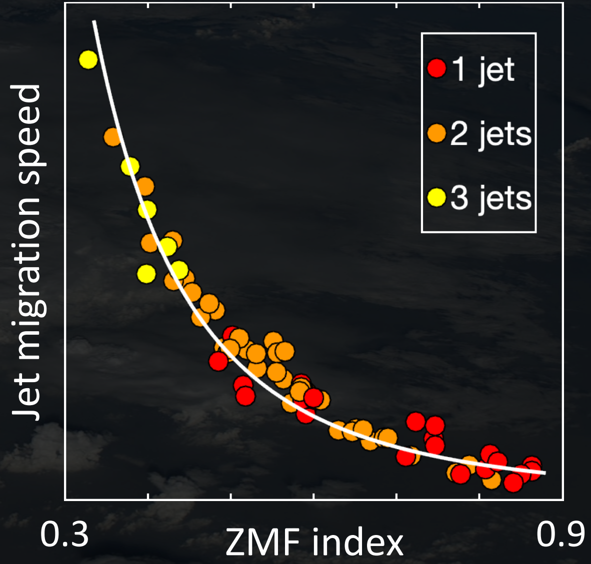


Zonal mean flow index (ZMF)

ZMF = Fraction of energy in mean flow

0 ⟵⟶ 1

No jets | Eddies & jets | No eddies



Result 4 Migration speed is given approximately by: $\text{speed} \propto (\text{ZMF})^{-3}$

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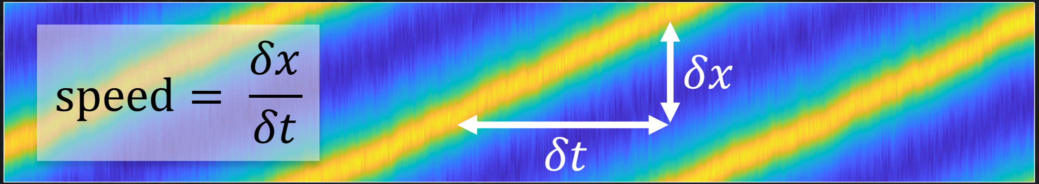
Q2: CAN WE PREDICT THE SPEED OF MIGRATION?



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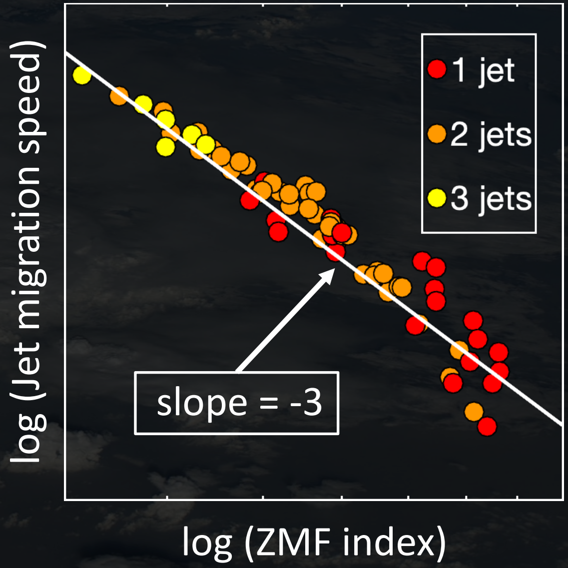

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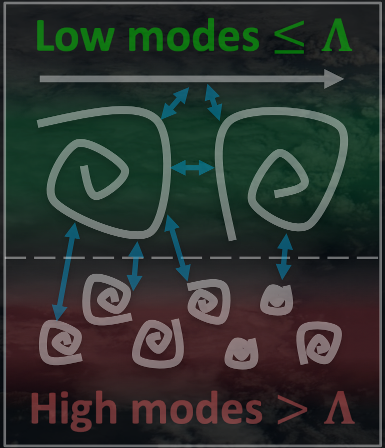
A CLOSER LOOK AT ZONAL JET MIGRATION

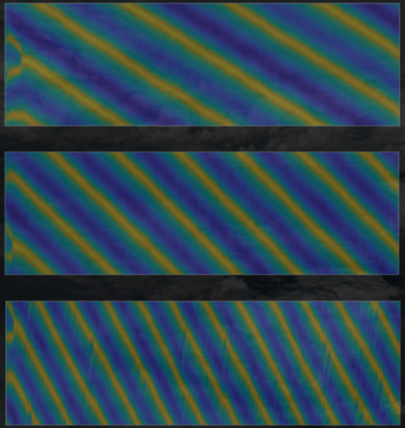
Question 1

Why do jets migrate only when $\Lambda \geq 1$?



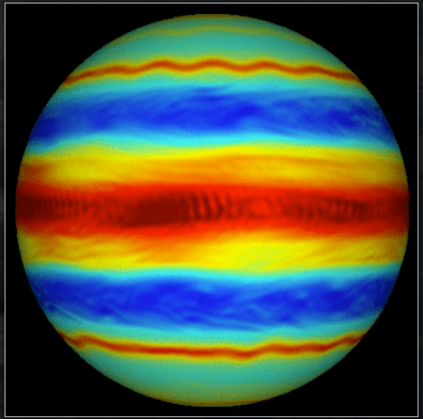
Question 2

Can we predict the speed of migration?



Question 3

Do jets migrate in more complex systems?



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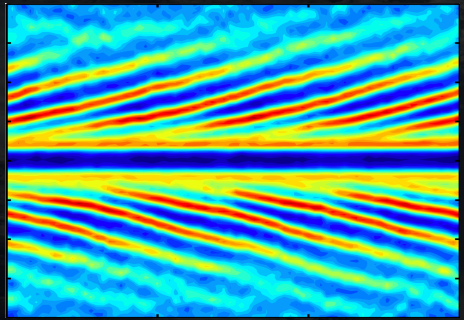
Q3: DO JETS MIGRATE IN MORE COMPLEX SYSTEMS?

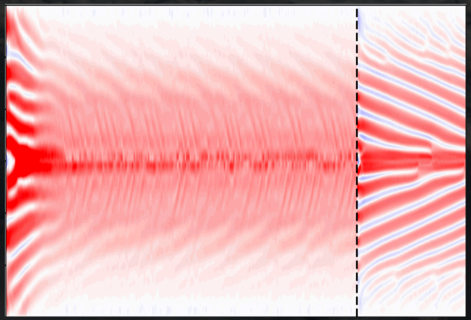
General circulation model: Poleward drift

Kemke & Kaspi (2015), JAMES



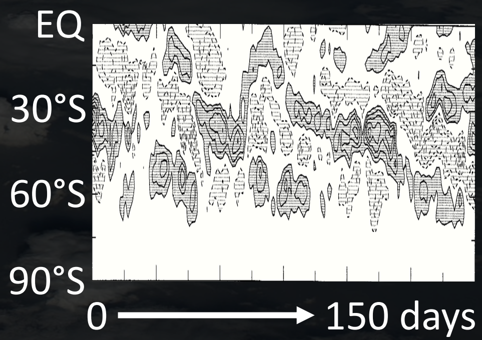
General circulation model: Equatorward drift

Young, Read & Wang (2019), Icarus



Atmosphere observations: Poleward drift

Feldstein (1998), JAS



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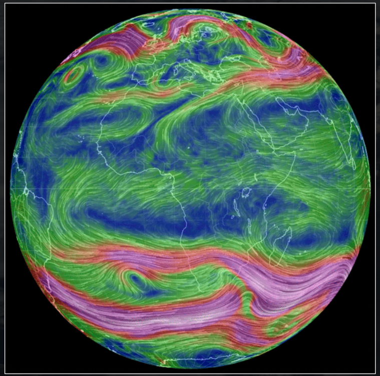
CONCLUSIONS

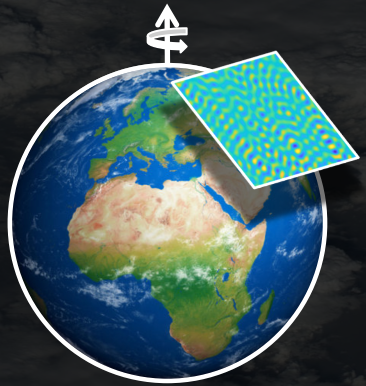
OBJECTIVE

Study of jet stream variability



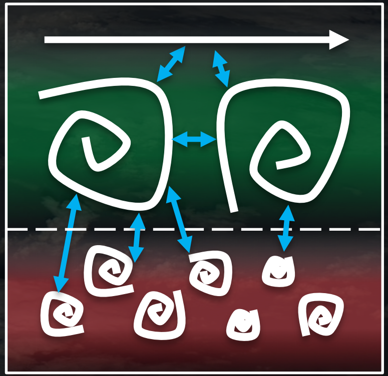
MODELS

Rotation + turbulence + friction = zonal jet



METHOD

Generalized quasilinear approximation



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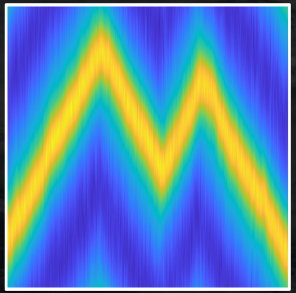
CONCLUSIONS

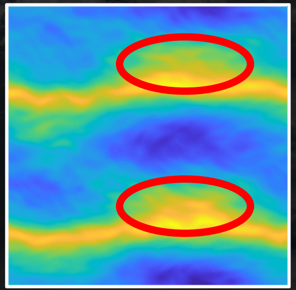
1

New type of jet variability found: migrating jets



2

Migration requires $\Lambda \geq 1$ when jets and zonons coexist



3

Migration requires an asymmetric eddy forcing

4

Migration speed is approximately: $\text{speed} \propto (\text{ZMF})^{-3}$