Australian National University

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Lagrangian Filtering

A novel method for separating internal waves from non-wave flows in high-resolution simulations

COSIMA Virtual Workshop 2020

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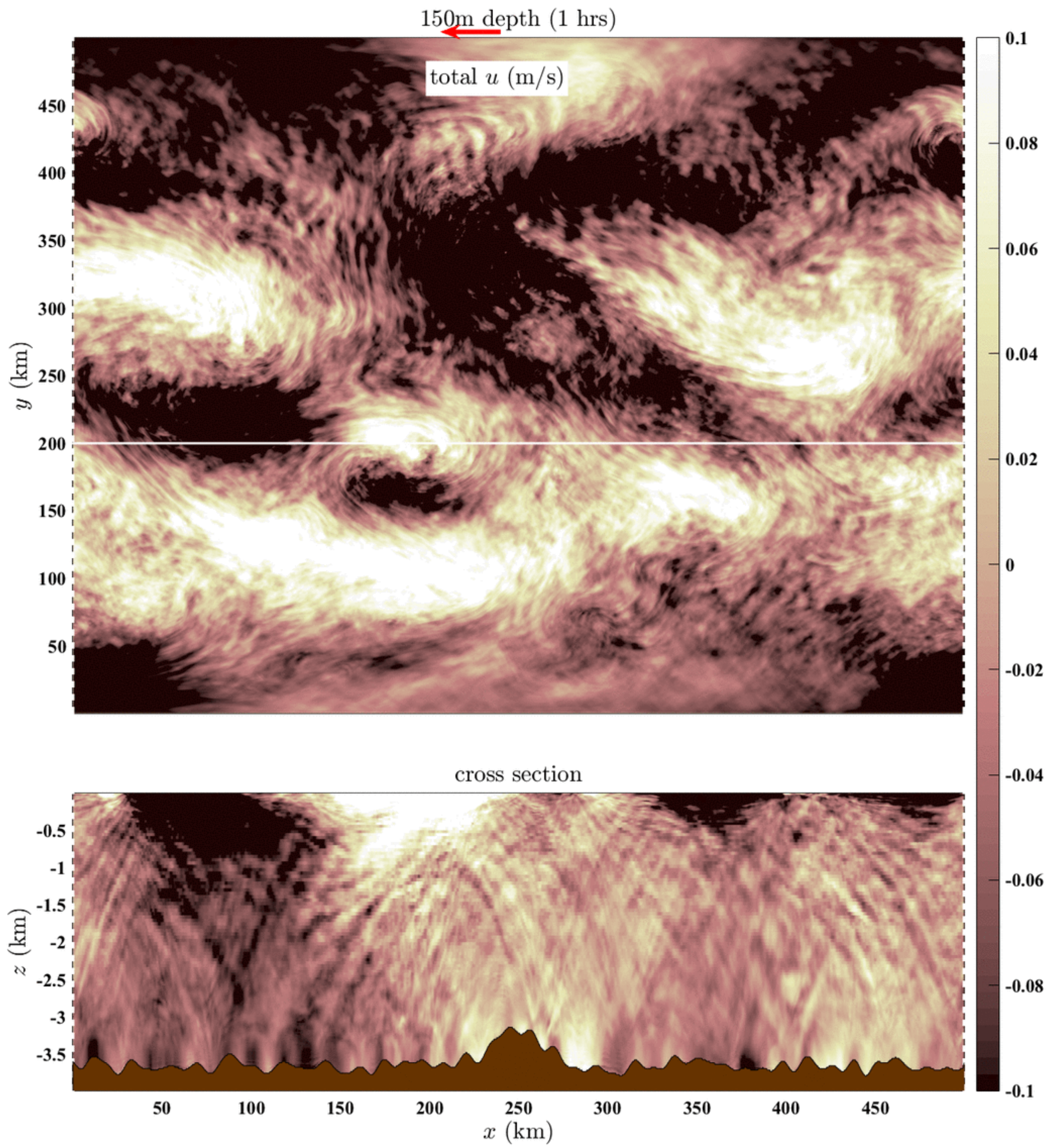


Why internal waves? A modelers perspective

- Internal waves are fast (hourly to daily) motions spanning scales from 200km to 100m
- They carry energy and momentum from the ocean boundaries into the interior
- They are responsible for both **mixing** (energy) and **forcing** (momentum) the ocean
- Many high-resolution models now resolve internal waves
- However, to quantify the wave energy and momentum in a model we need to be able to isolate internal waves from the rest of the flow…
- **Difficult! - spatial and temporal scales overlap with other phenomena**

-> How do we uniquely define an internal wave in a model?

Defining an internal wave

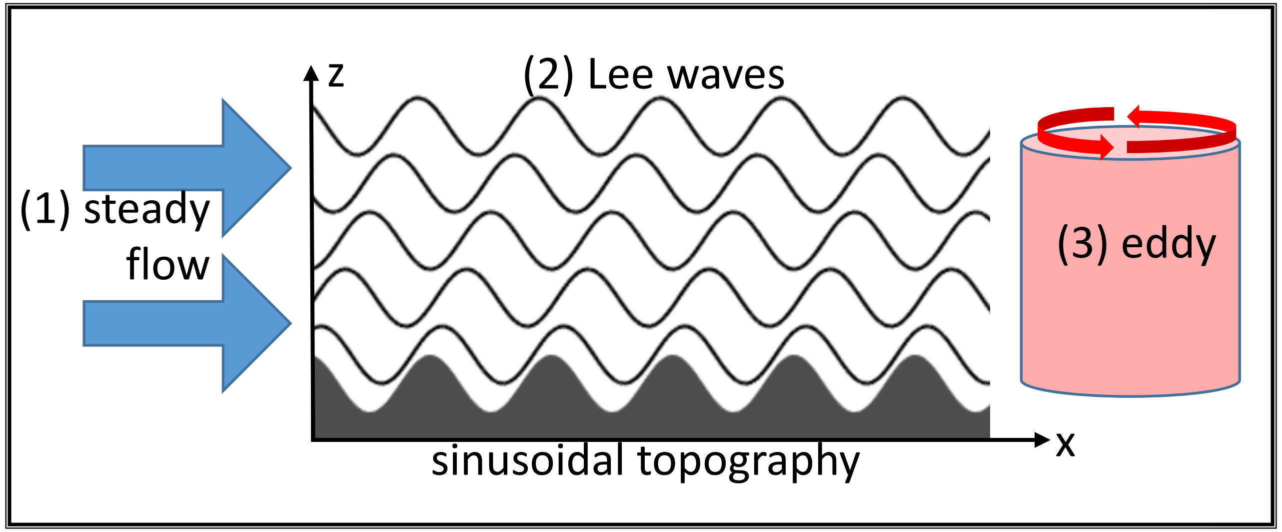
$$\omega^2 = \frac{f^2m^2 + N^2(k^2+l^2)}{k^2 + l^2 + m^2} = f^2 + \frac{N^2(k^2+l^2)}{m^2} > f^2$$

- ω is the frequency, $\vec{k} = (k, l, m)$ is the wavevector
- Internal waves have a minimum frequency = Coriolis parameter f
- But they are also affected by any "mean" flows in which they propagate in two major ways
  - Effective vorticity: $f^2 \rightarrow f_{eff}^2 = \left(f + \frac{\partial v}{\partial x}\right)\left(f - \frac{\partial u}{\partial y}\right)$
  - Doppler shifting: $\omega \rightarrow \omega + (k\,u + l\,v)$
- A wave propagating with a mean flow will have a frequency less than f (and possibly zero; e.g. lee waves, other trapped waves).
- So there is no time-scale separation! This is a problem…

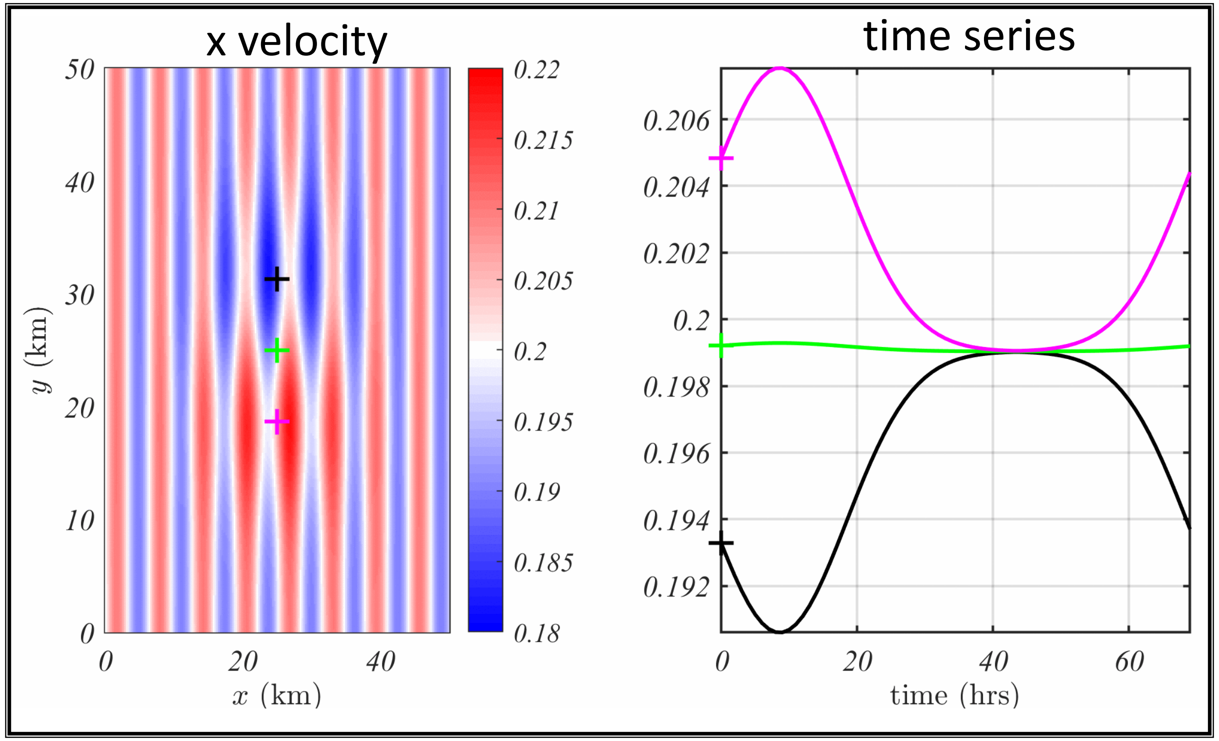
So, what's the problem?

- Let's consider lee waves as an example

Schematic side-on view



Top/plan view



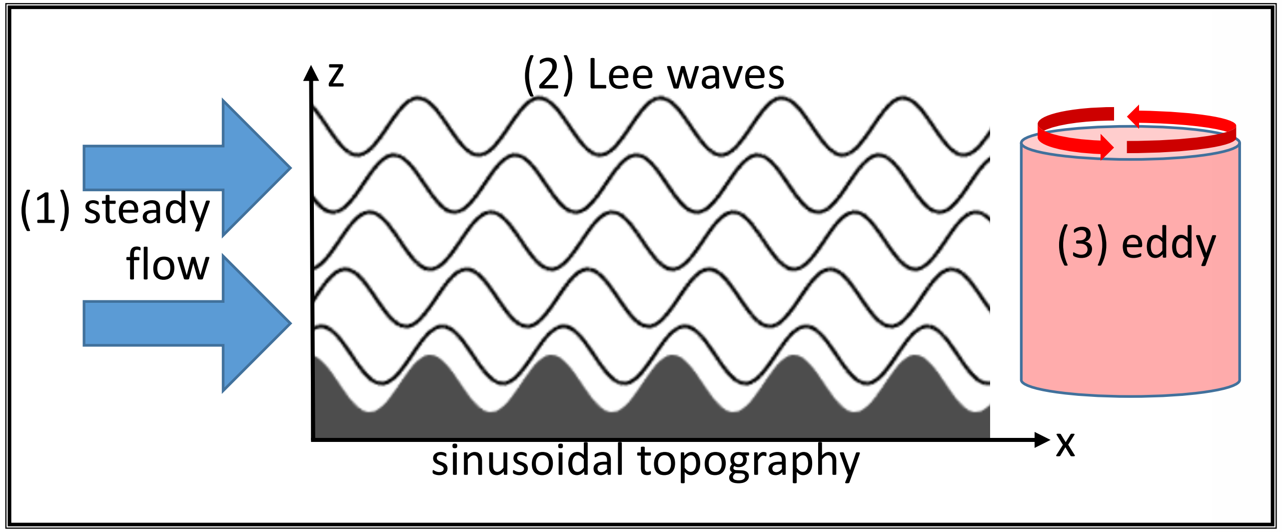
When sampling at fixed points

- Trapped/lee wave signals are not observed in time series
- Eddy is seen as a fast motion due to advection past the fixed points
- Internal waves **cannot** in general be identified as "fast motions" when sampling at fixed points

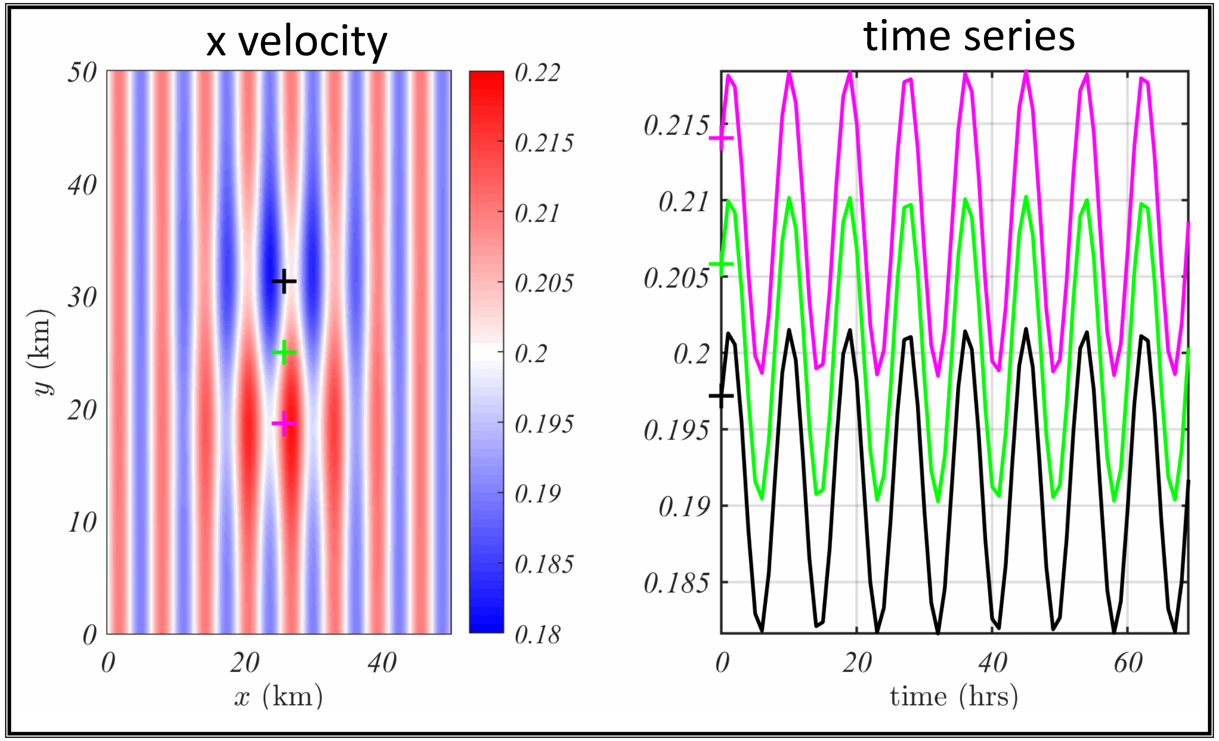
So, what's the problem?

- Let's consider lee waves as an example

Schematic side-on view



Top/plan view



When sampling at flow-following points

- Variation in space become a variation in time
- Trapped/lee wave signals are clearly observed
- Eddy is not observed since points move with the eddy.
- Internal waves **can** be identified as "fast motions" when sampling in a flow-following frame

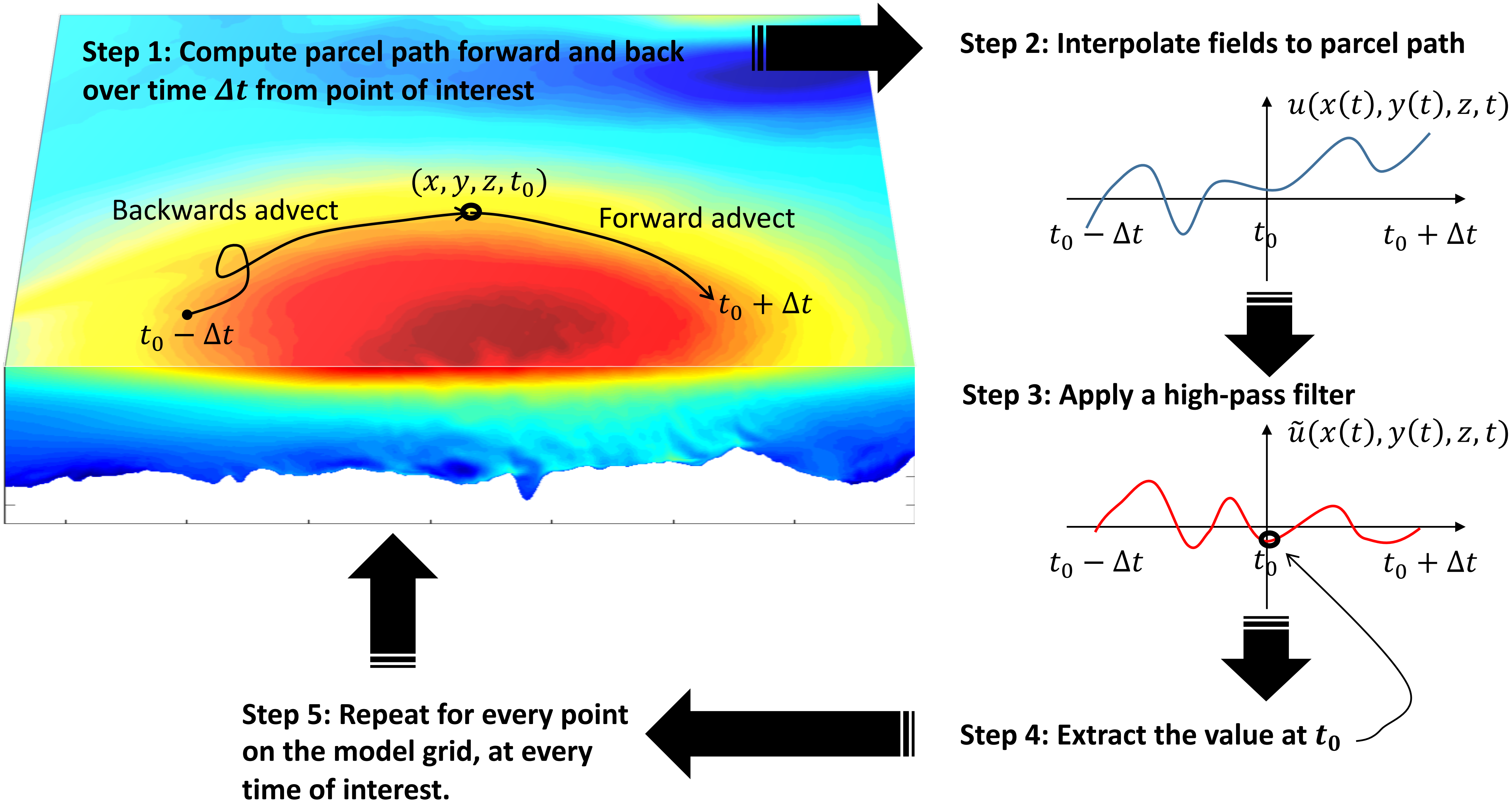
Defining an internal wave

$$\omega^2 = f_{eff}^2 + \frac{N^2(k^2+l^2)}{m^2} > f_{eff}^2$$

in a flow-following frame

- The Doppler shift vanishes in a flow-following (Lagrangian) frame, since we are moving with the flow
- Internal waves therefore have a minimum frequency in such a frame
- There is (spatio-)temporal scale separation
- **We have the basis of a filter!**

Introducing the Lagrangian filter

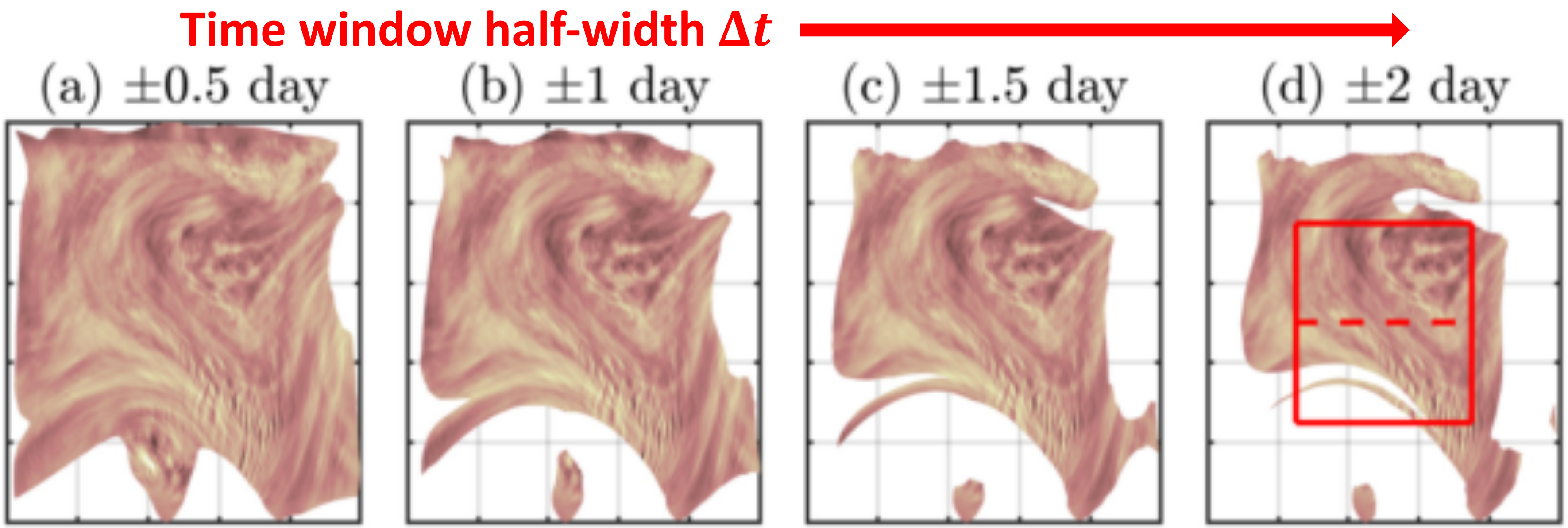


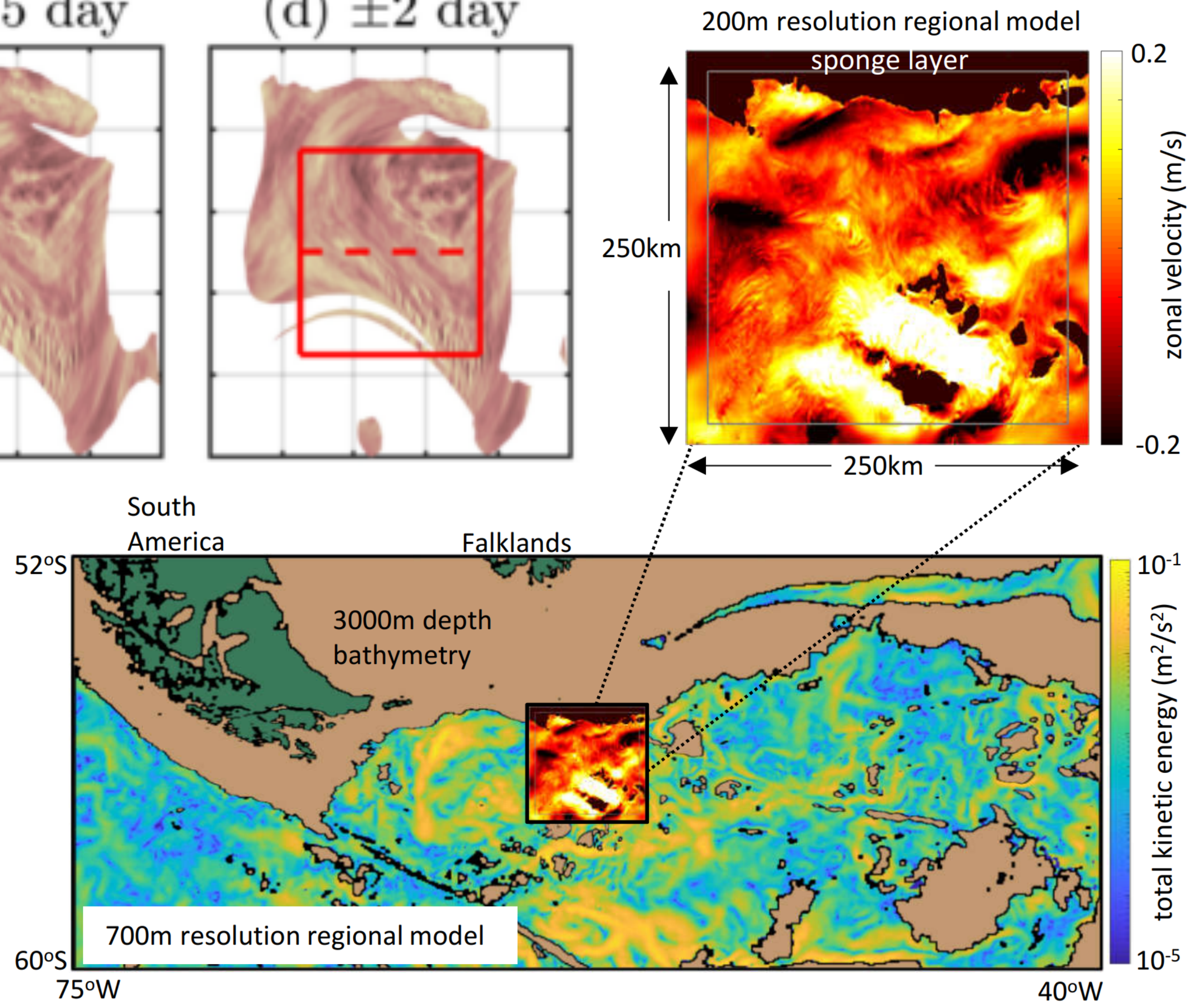
Introducing the Lagrangian filter

Parameter selections

1. **Filter cut-off frequency:** just below f, or f_{eff}
2. **Time resolution of model output:** must be able to resolve the wave frequencies of interest. Typical periods are ~12 hours -> hourly output
3. **Time window half-width Δt**: numerical choice. Smaller = less advection, so quicker. Δt = 1 to 2 days satisfactory in most cases

Example: Scotia Sea regional model

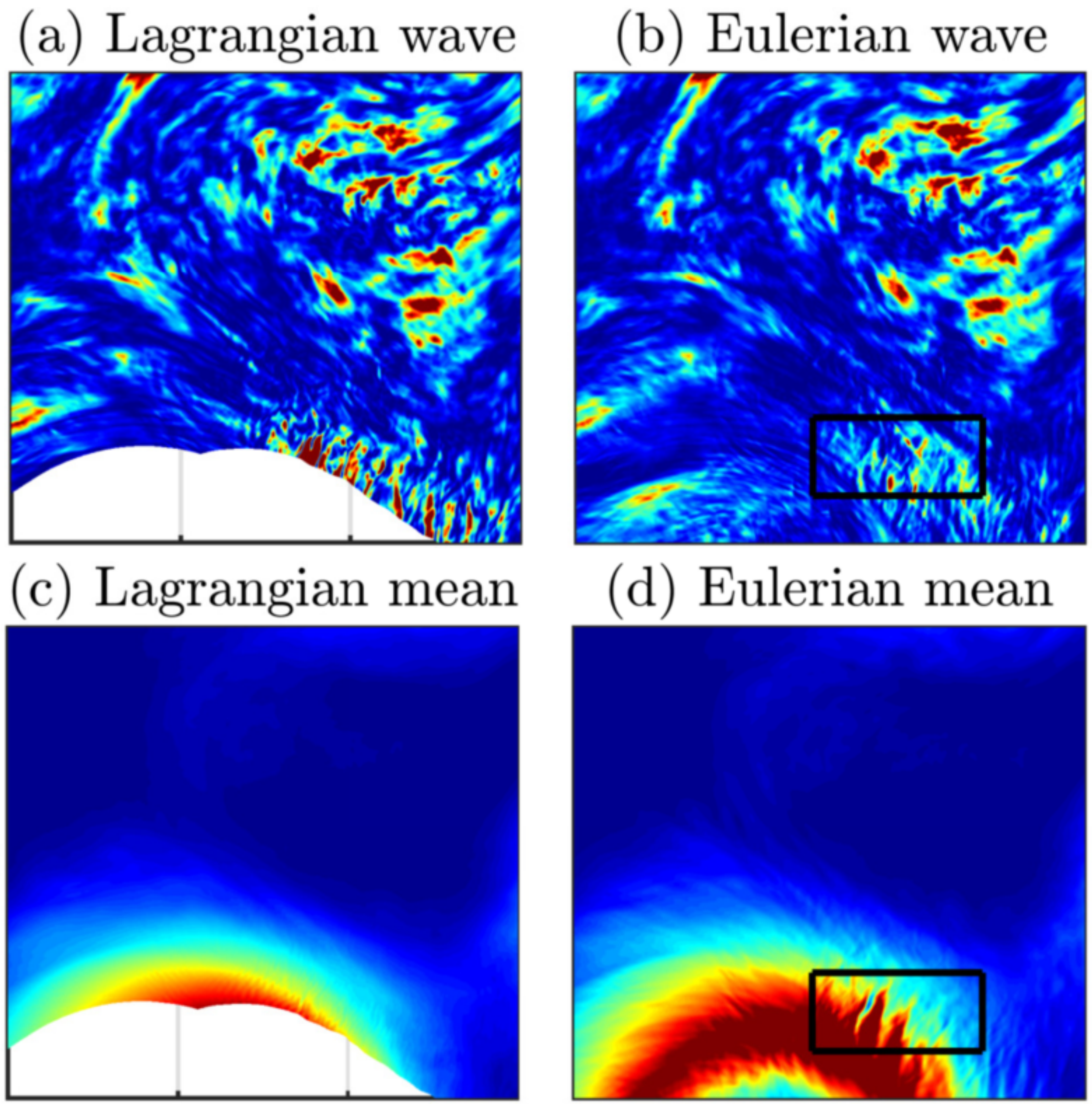




- 700m regional model run by Nick Velzeboer during his Honours 2019
- 200m model nested within 700m

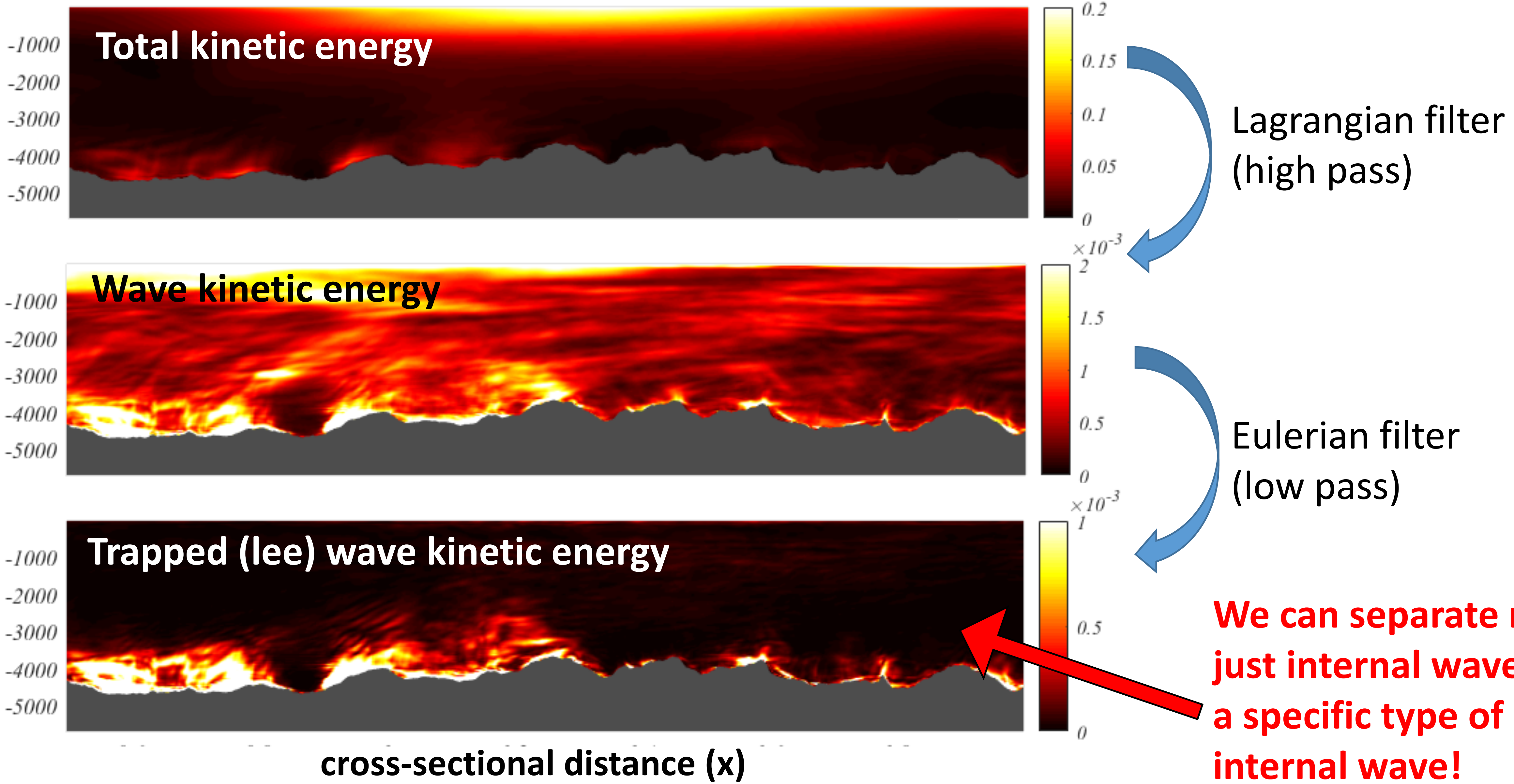
Example: Scotia Sea regional model

- Comparison of Lagrangian filter with traditional fixed point (Eulerian) filter
- Eulerian misidentifies trapped waves as mean flow
- Underestimates wave energy by 20-50%



Example: Scotia Sea regional model

- We can apply filters sequentially to isolate specific phenomena…



We can separate not just internal waves, but a specific type of internal wave!

The Python package – now available

https://github.com/angus-g/lagrangian-filtering

- Available through *conda* package manager
- Advection kernel uses OceanParcels (http://oceanparcels.org/)
- Input: netcdf files for (u,v) at minimum, plus other variables of interest (e.g. T, S, rho, p)
- Output: netcdf files containing filtered wave fields on the same grid
- Can be trivially parallelised since every time and z-level is independent.
- Takes of order 5 min per time per level on a single core, or about 3 hrs for 1 month of hourly output parallelised over 500 cores on *gadi*

Summary

- Novel method to uniquely separate internal waves in model flow fields
- Allows computation of wave energetics (see Jemima's talk)
- Now available as an easy-to-use Python package: https://github.com/angus-g/lagrangian-filtering. Feedback welcome!
- Methods paper in preparation for JAMES
- Example applications (thus far):
    - Nagai et al (2016) – Kuroshio model
    - Shakespeare and Hogg (2017,18,19) – spontaneous generation, and tidal forcing
    - Bachman et al (in rev.) – internal tides in a Coral Triangle regional model
- Features still under development; e.g.
    - Improving interpolation near topography
    - Vorticity-dependent filter cut-off frequencies
    - Support for arbitrary model grids
    - Diagnosis functions: e.g. extracting spectra along parcel paths