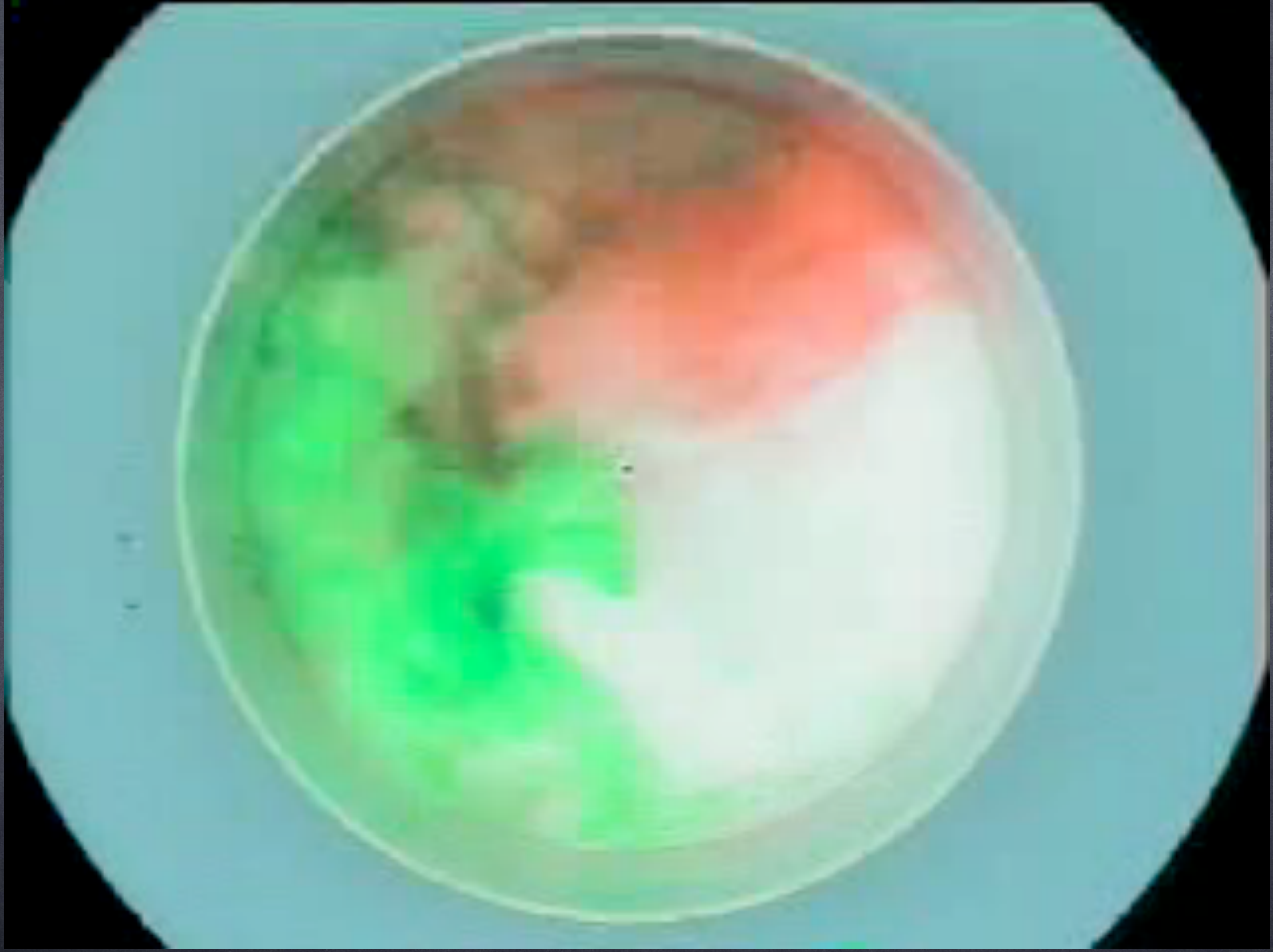
Dispersion and Dissipation– Turbulence Statistics for the Mesoscale to Finescale with Plastics on the Move

Baylor Fox-Kemper
Brown University

Feb. 23, 2022. Banff International Research Station: Predicting Pathways for Microplastic Transport in the Ocean (Online)

Sponsor: ONR N00014-17-1-2963



Nonrotating Movie Credit: J. C. Marshall Lab:
http://www-paoc.mit.edu/labweb

Rotating Movie Credit: J. C. Marshall Lab:
http://www-paoc.mit.edu/labweb

Slow Rotation, Large Ro:Marshall GFD Lab Movie & Description

Fast Rotation, Small Ro:Marshall GFD Lab Movie & Description

Traditional View of Ocean Large-Scale Motions

Geostrophic Balance

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + \mathbf{f} \times \mathbf{v} = -\frac{\nabla p}{\rho} - g\hat{\mathbf{z}} + \nu_E \nabla^2 \mathbf{v}$$

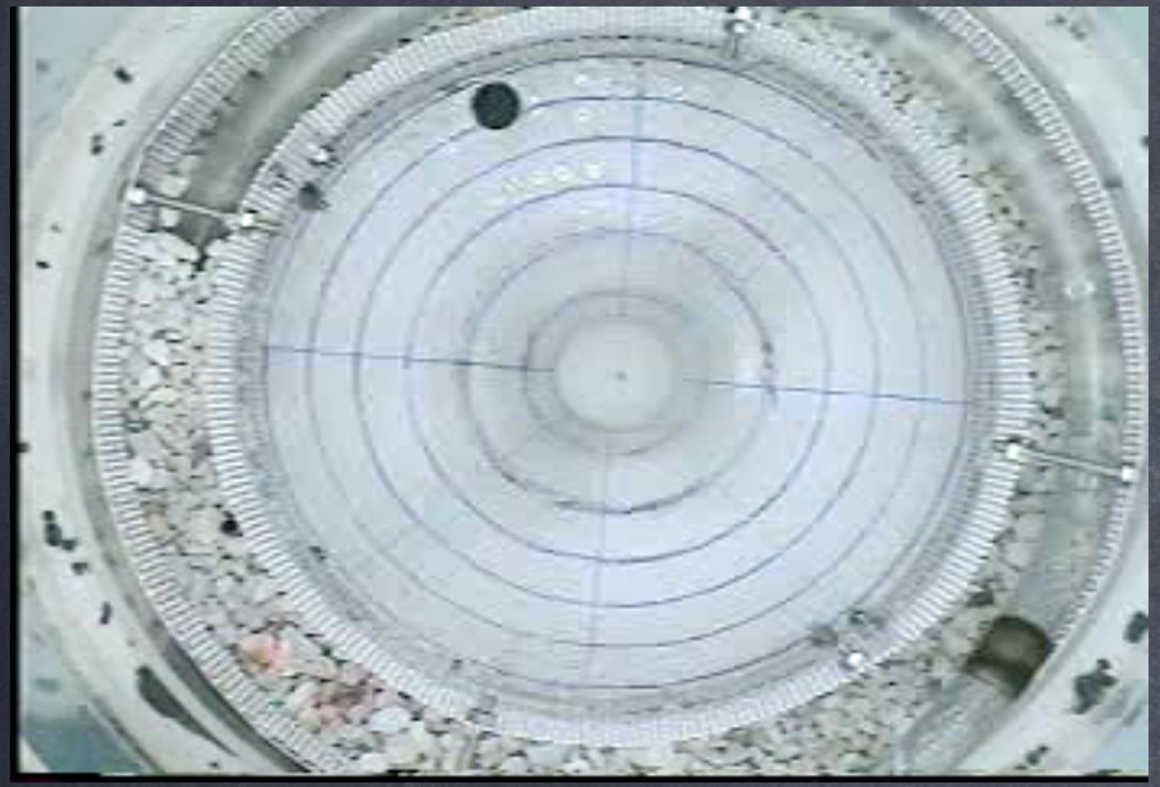
Advective Rossby Number Small

Temporal Rossby Number Small

Ekman Number Small

$$Ek = \frac{\nu_E}{fH^2} \qquad Ro_a = \frac{U}{fL} \qquad Ro_t = \frac{1}{fT}$$

Traditional View of Ocean Large-Scale Motions



Geostrophic Balance

$$\mathbf{f} \times \mathbf{v}_g = -\frac{\nabla p}{\rho_0}$$

$$\mathbf{v}_g = \hat{\mathbf{z}} \times \frac{\nabla p}{|f|\,\rho_0}$$

$$\nabla \cdot \mathbf{v}_g = 0 + \mathcal{O}(\mathrm{Ro}, \beta L/|f|, \mathrm{Ek})$$

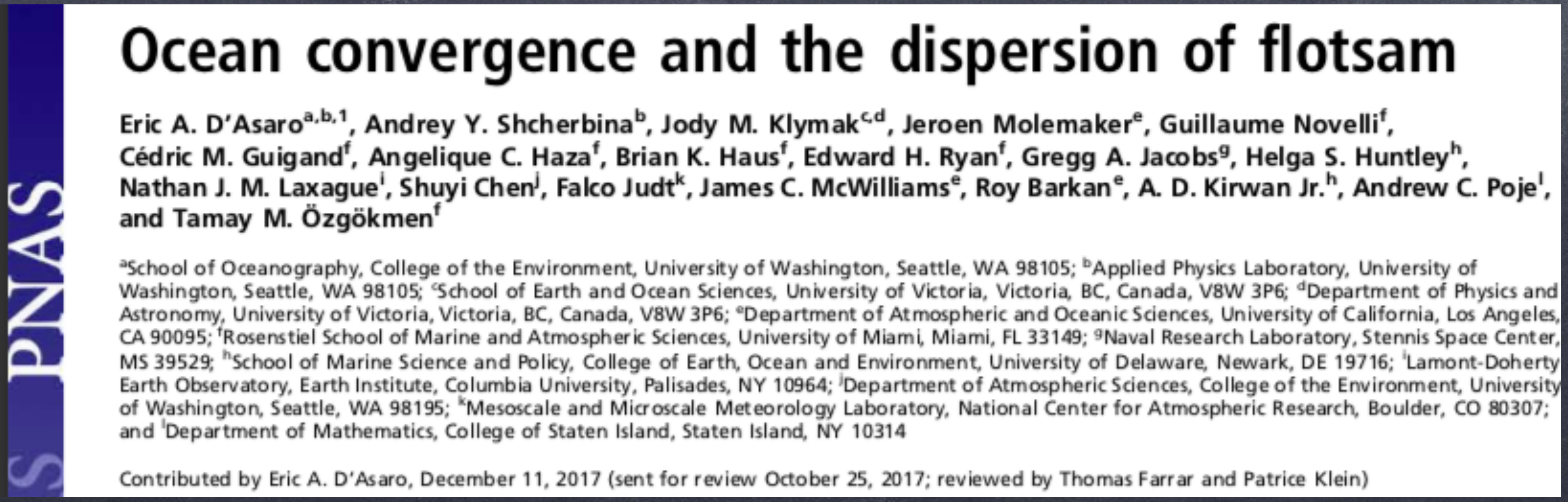
$$\nabla \times \mathbf{v}_g = \text{quasigeostrophy}$$

And so, the motions of the mesoscale do not converge to leading order as $\mathrm{Ro} \ll 1; \beta L/|f| \ll 1; \mathrm{Ek} \ll 1$

But, in the mixed layer submesoscales, a revised view:

$$\mathrm{Ro} \sim 1; \beta L/|f| \ll 1; \mathrm{Ek} \sim 1$$

Plus Stokes drift & wave effects!



PNAS

Ocean convergence and the dispersion of flotsam

Eric A. D'Asaro[a,b,1], Andrey Y. Shcherbina[b], Jody M. Klymak[c,d], Jeroen Molemaker[e], Guillaume Novelli[f], Cédric M. Guigand[f], Angelique C. Haza[f], Brian K. Haus[f], Edward H. Ryan[f], Gregg A. Jacobs[g], Helga S. Huntley[h], Nathan J. M. Laxague[i], Shuyi Chen[j], Falco Judt[k], James C. McWilliams[e], Roy Barkan[e], A. D. Kirwan Jr.[h], Andrew C. Poje[l], and Tamay M. Özgökmen[f]

[a]School of Oceanography, College of the Environment, University of Washington, Seattle, WA 98105; [b]Applied Physics Laboratory, University of Washington, Seattle, WA 98105; [c]School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada, V8W 3P6; [d]Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada, V8W 3P6; [e]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095; [f]Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL 33149; [g]Naval Research Laboratory, Stennis Space Center, MS 39529; [h]School of Marine Science and Policy, College of Earth, Ocean and Environment, University of Delaware, Newark, DE 19716; [i]Lamont-Doherty Earth Observatory, Earth Institute, Columbia University, Palisades, NY 10964; [j]Department of Atmospheric Sciences, College of the Environment, University of Washington, Seattle, WA 98195; [k]Mesoscale and Microscale Meteorology Laboratory, National Center for Atmospheric Research, Boulder, CO 80307; and [l]Department of Mathematics, College of Staten Island, Staten Island, NY 10314

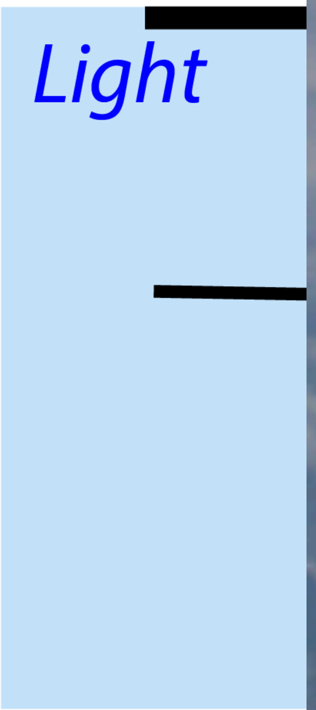
Contributed by Eric A. D'Asaro, December 11, 2017 (sent for review October 25, 2017; reviewed by Thomas Farrar and Patrice Klein)

Models

“ Mesoscale”

“ Submesosc

“Mixed laye

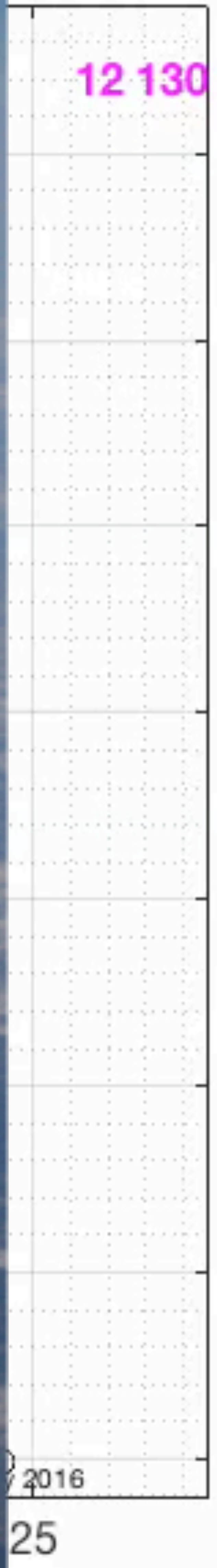


Movie & Slide
Molemaker, J.
Huntley, H.S.,

E. A. D’Asaro, D
Molemaker, A.
scale open oce
era. Frontiers i

J. Pearson, BF
Kirwan, Jr., B. I
submesoscale

Image credit: D. Schwen via C. Bitz



Entry #: V0071

Holi Tracers

Aakash Sane 1, Georgia Rhodes 2, Stewart Copeland 3,
Tal Ben-Horin 4, Baylor Fox-Kemper 5

Brown University
Rhode Island School of Design
North Carolina State University

Can we simulate the turbulent submesoscales?

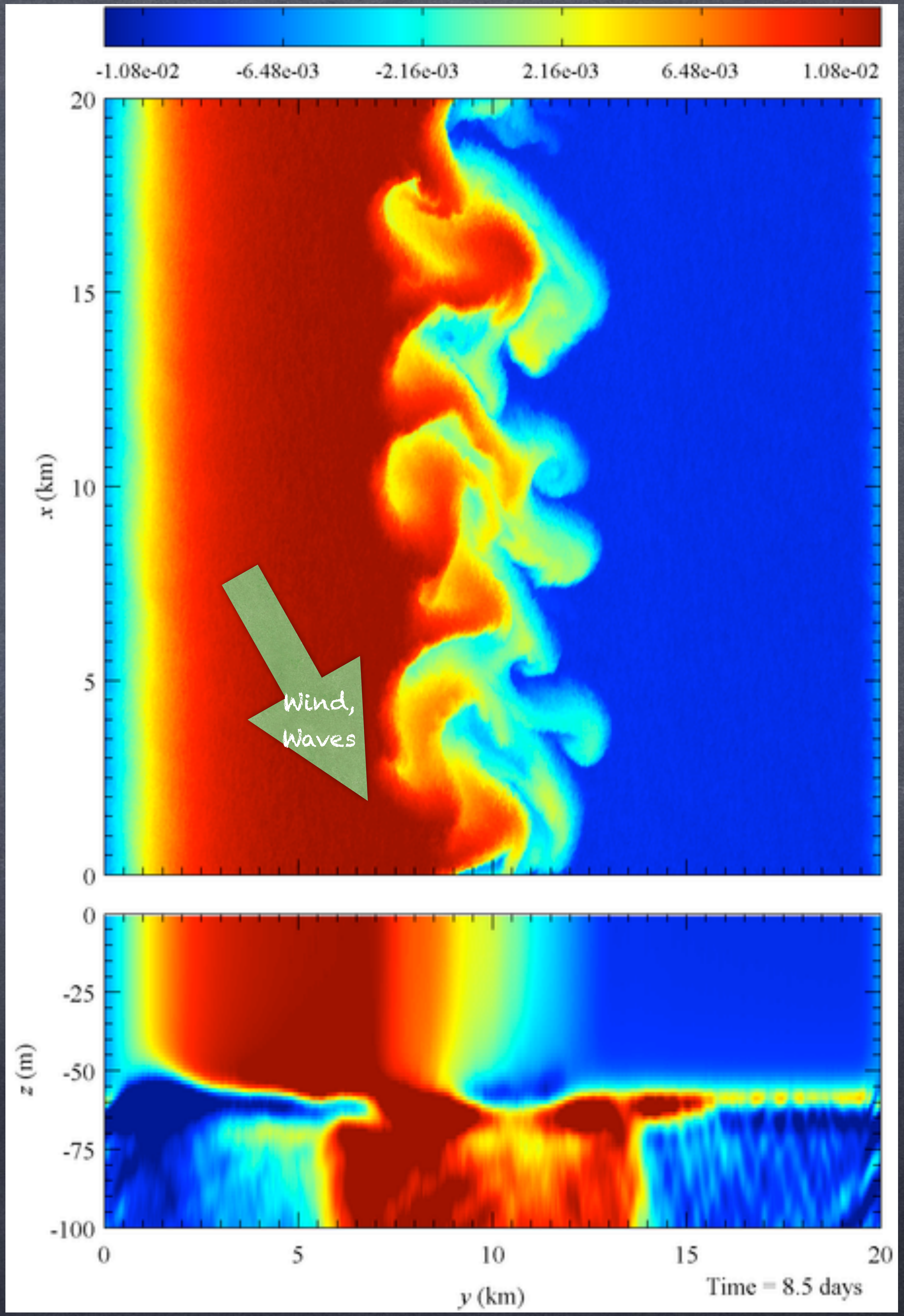
LES of Langmuir turbulence with a
submesoscale temperature front

Use NCAR LES model to solve Wave-Averaged Eqtns.

2 Versions: 1 With Waves & Winds
1 With only Winds

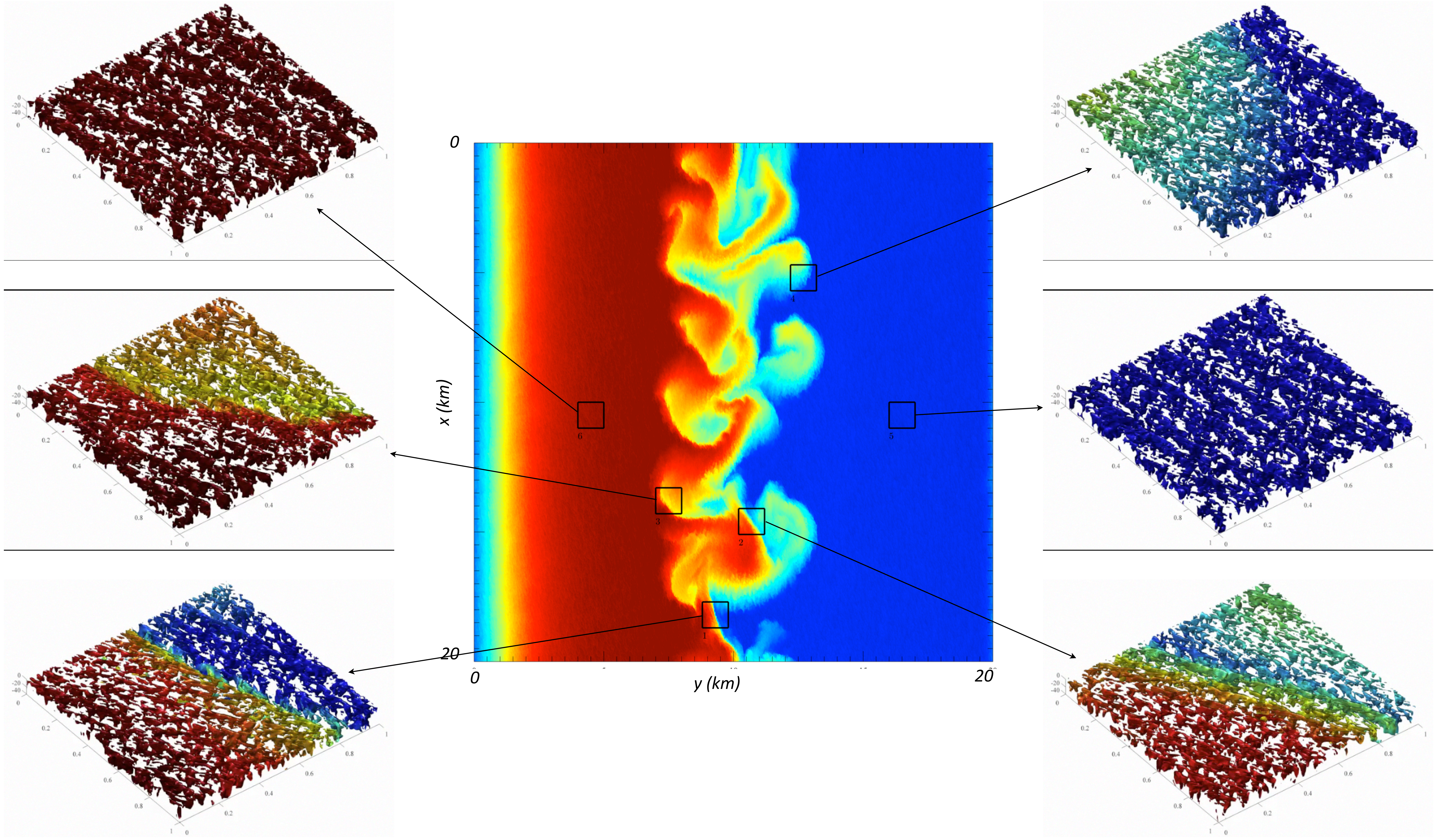
Computational parameters:
Domain size: 20km x 20km x -160m
Grid points: 4096 x 4096 x 128
Resolution: 5m x 5m x -1.25m

Movie: P. Hamlington



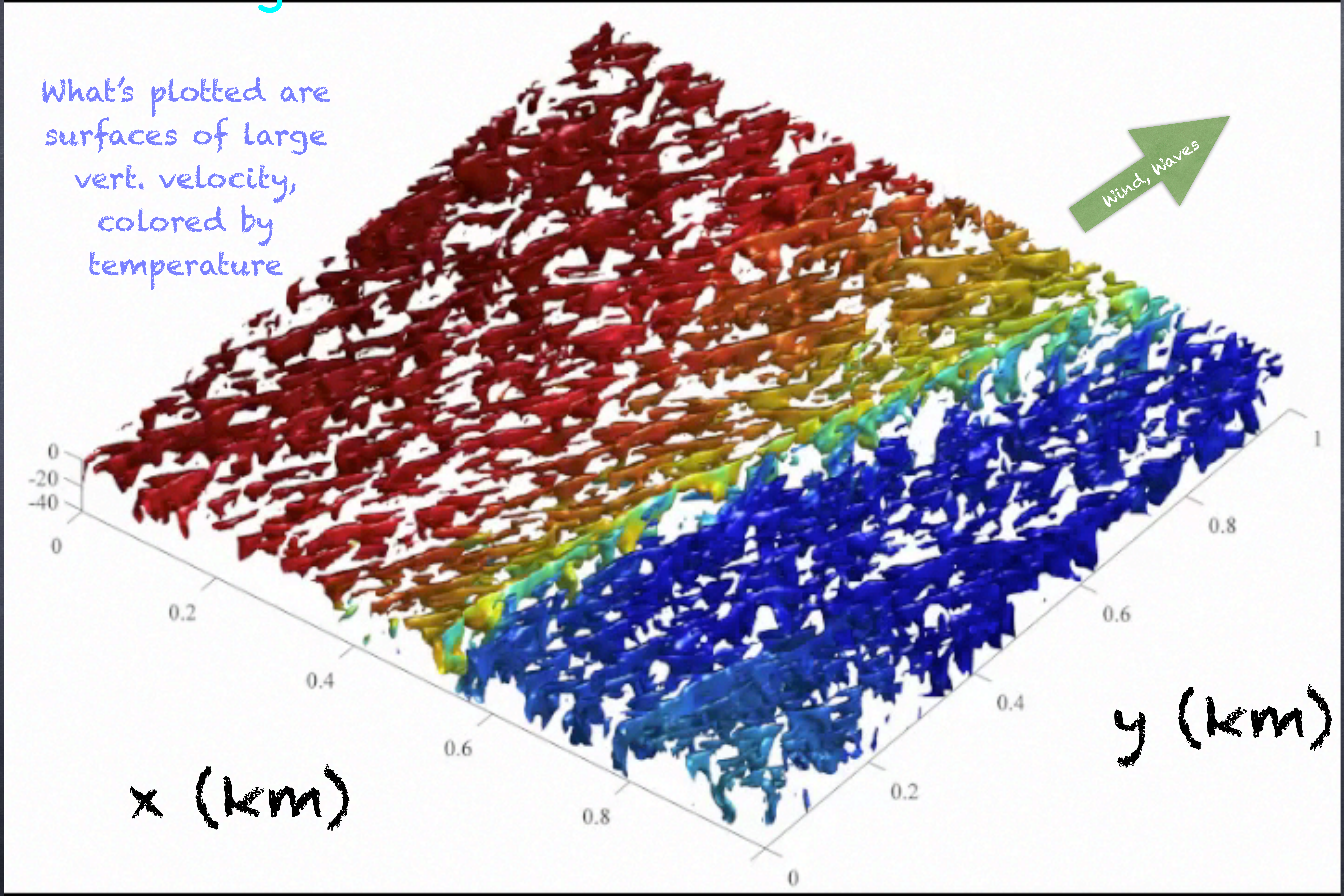
P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

Diverse types of interaction: Stronger Langmuir (small) Turbulence



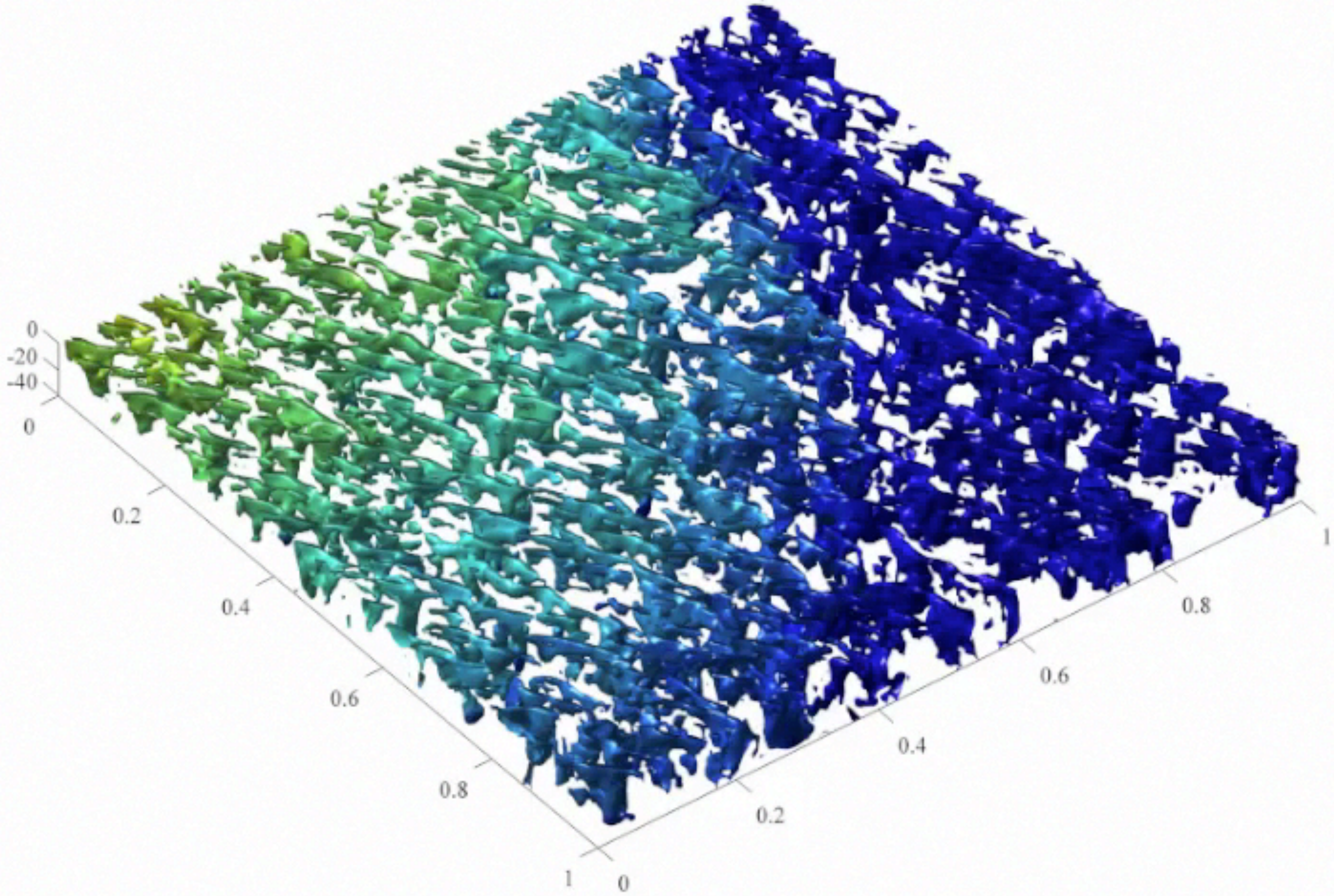
P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. Journal of Physical Oceanography, 44(9):2249-2272, September 2014.

Large Eddy Simulations, Observations, Constrain Langmuir Turbulence Parameterizations



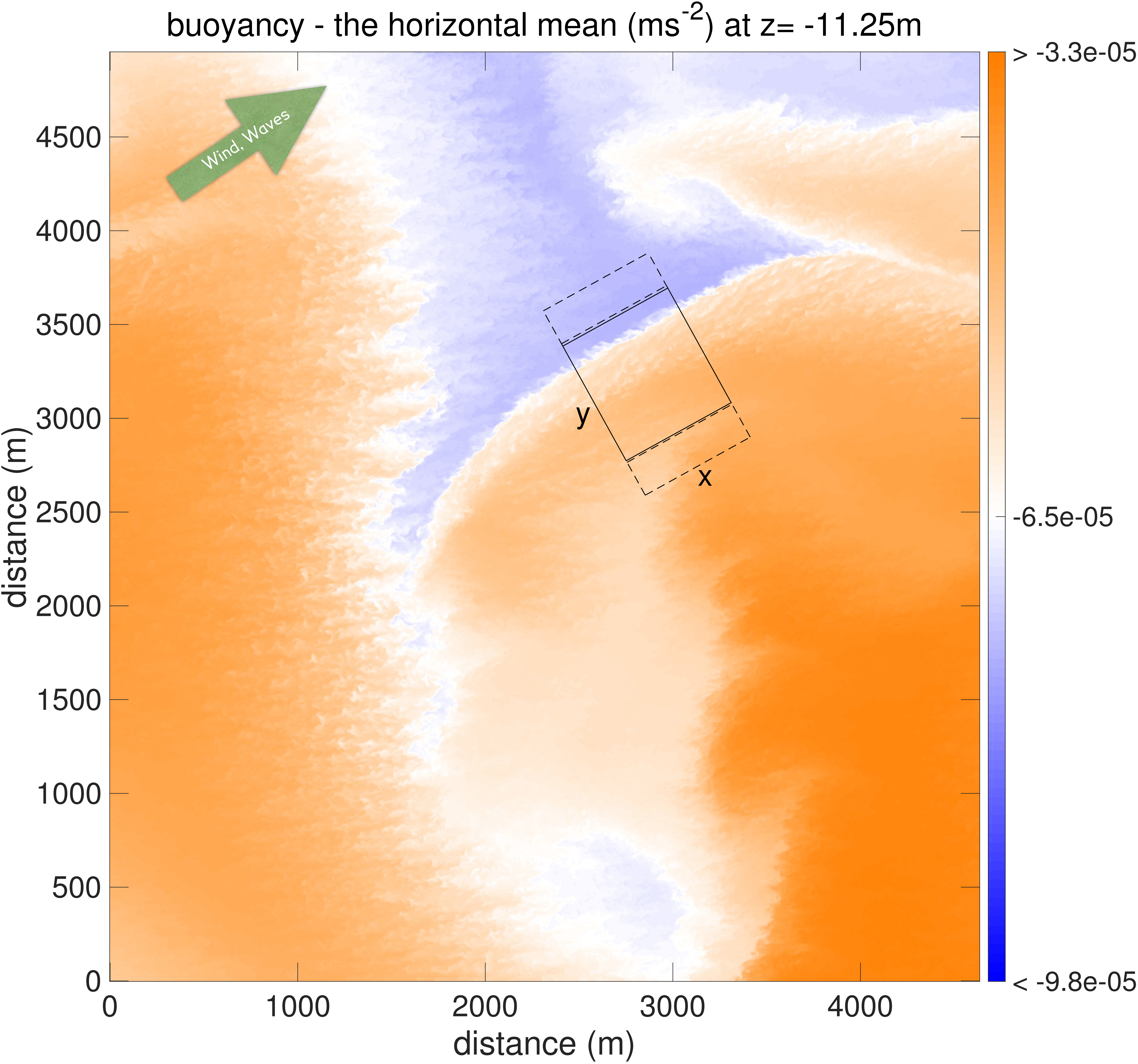
What's plotted are surfaces of large vert. velocity, colored by temperature

P. E. Hamlington, L. P. Van Roekel, BFK, K. Julien, and G. P. Chini. Langmuir-submesoscale interactions: Descriptive analysis of multiscale frontal spin-down simulations. JPO, 44(9):2249-2272, 2014.



0
-20
-40
0
0.2
0.4
0.6
0.8
1
0
0.2
0.4
0.6
0.8
1

T



N. Suzuki, B. Fox-Kemper, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, May 2016.

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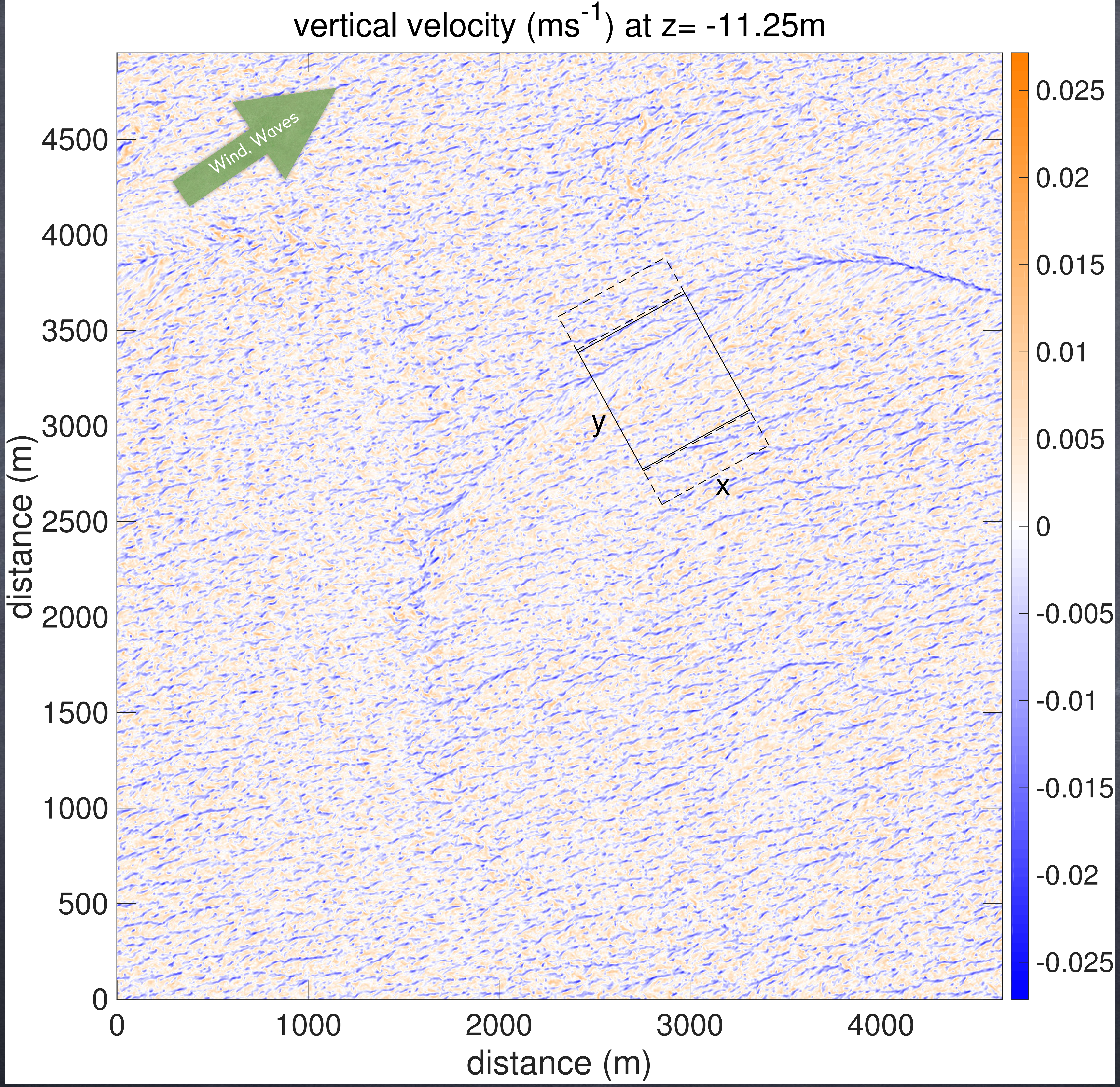
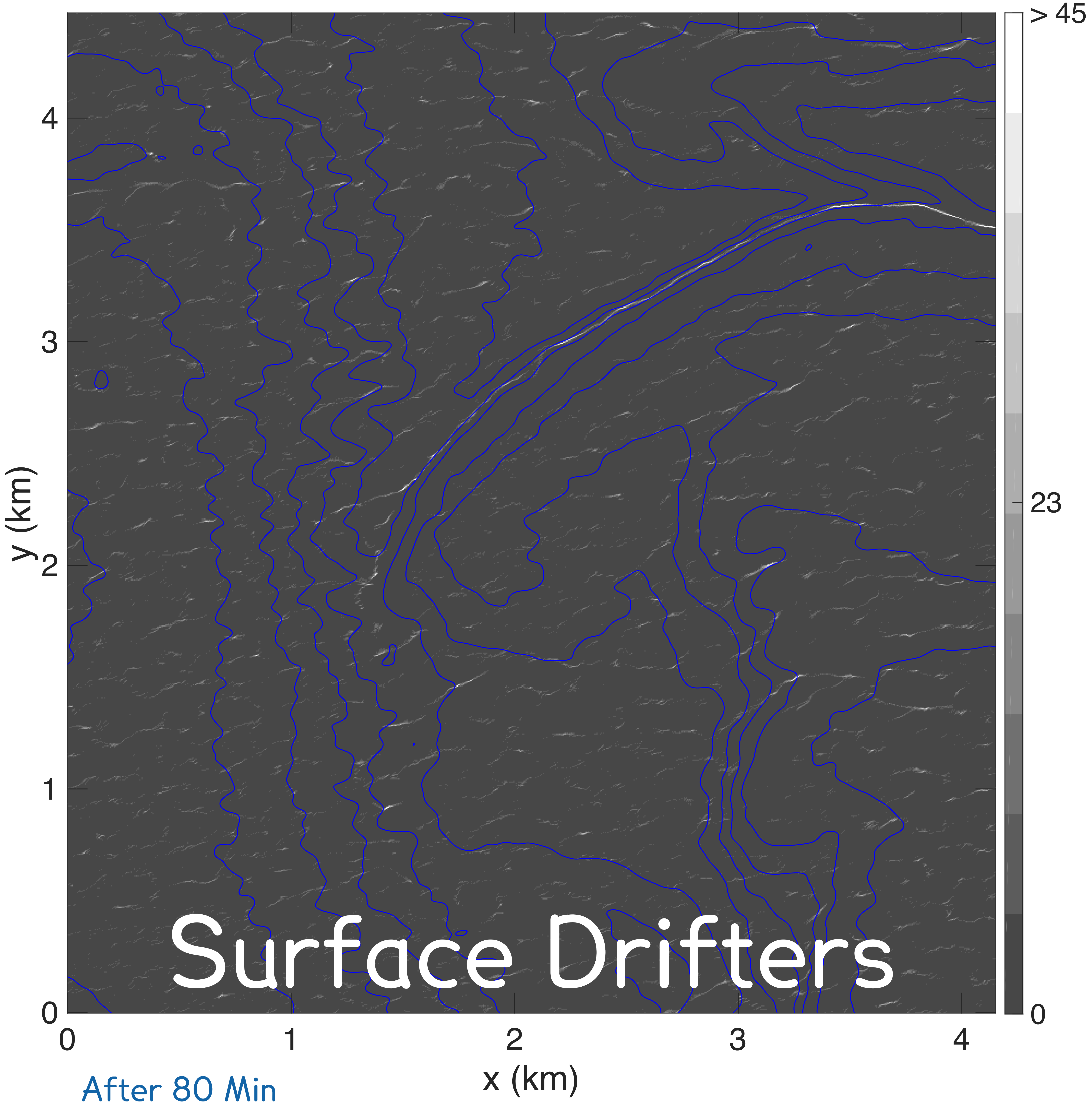


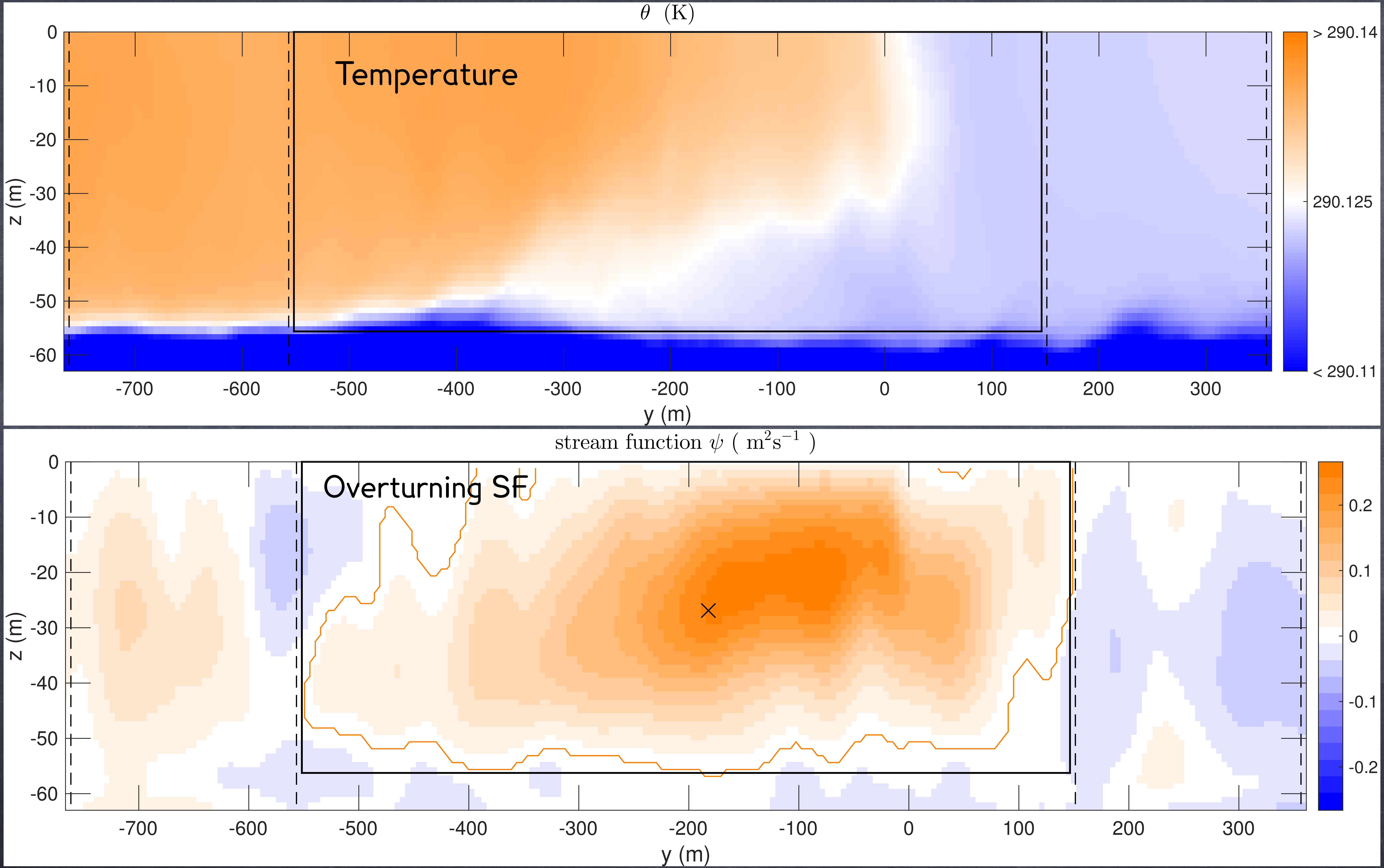
N. Suzuki, B. Fox-Kemper, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, May 2016.

Initially every surface node has 1 drifter,
so there are 851796 drifters in the picture



Surface Drifters

After 80 Min



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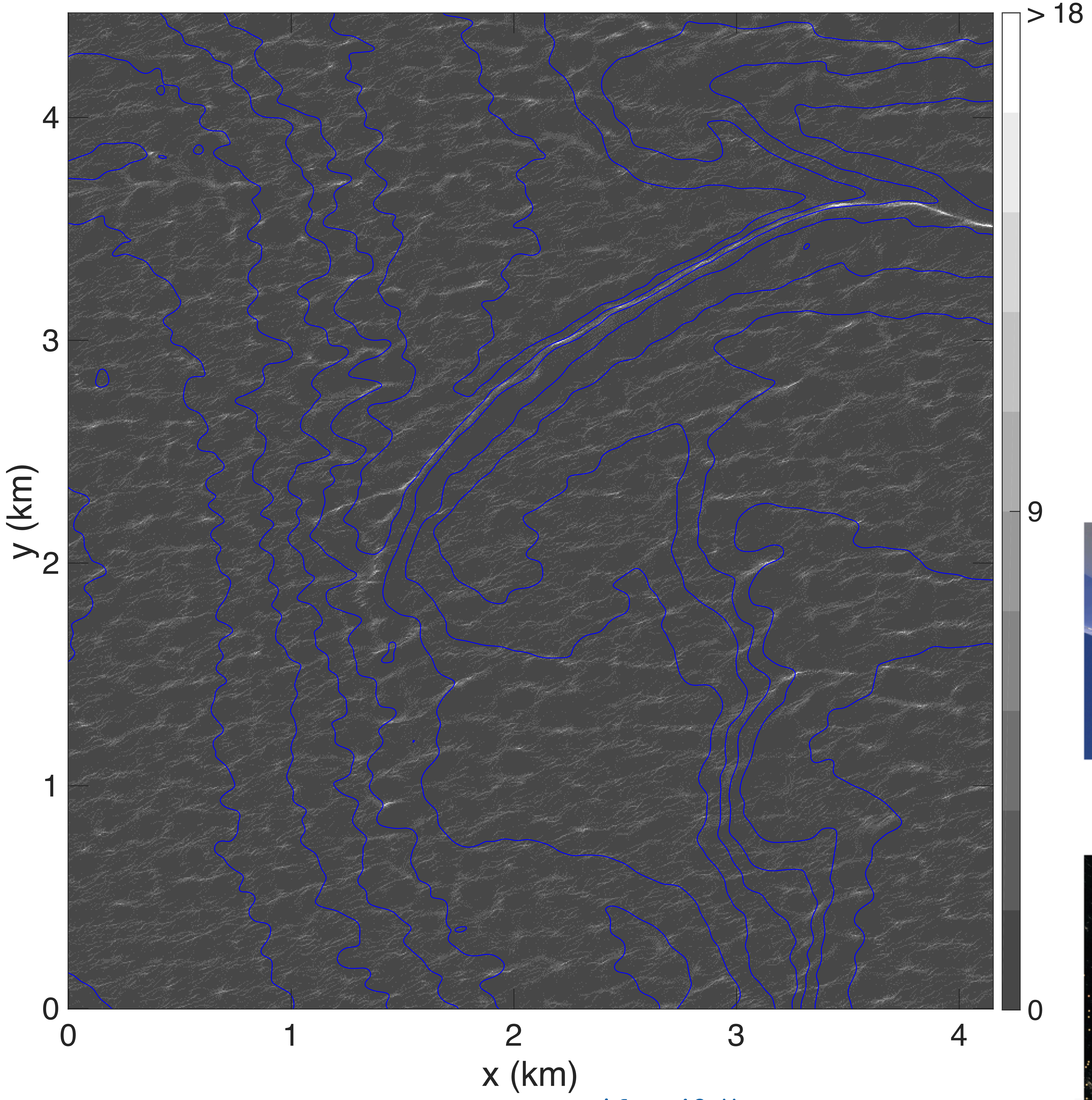
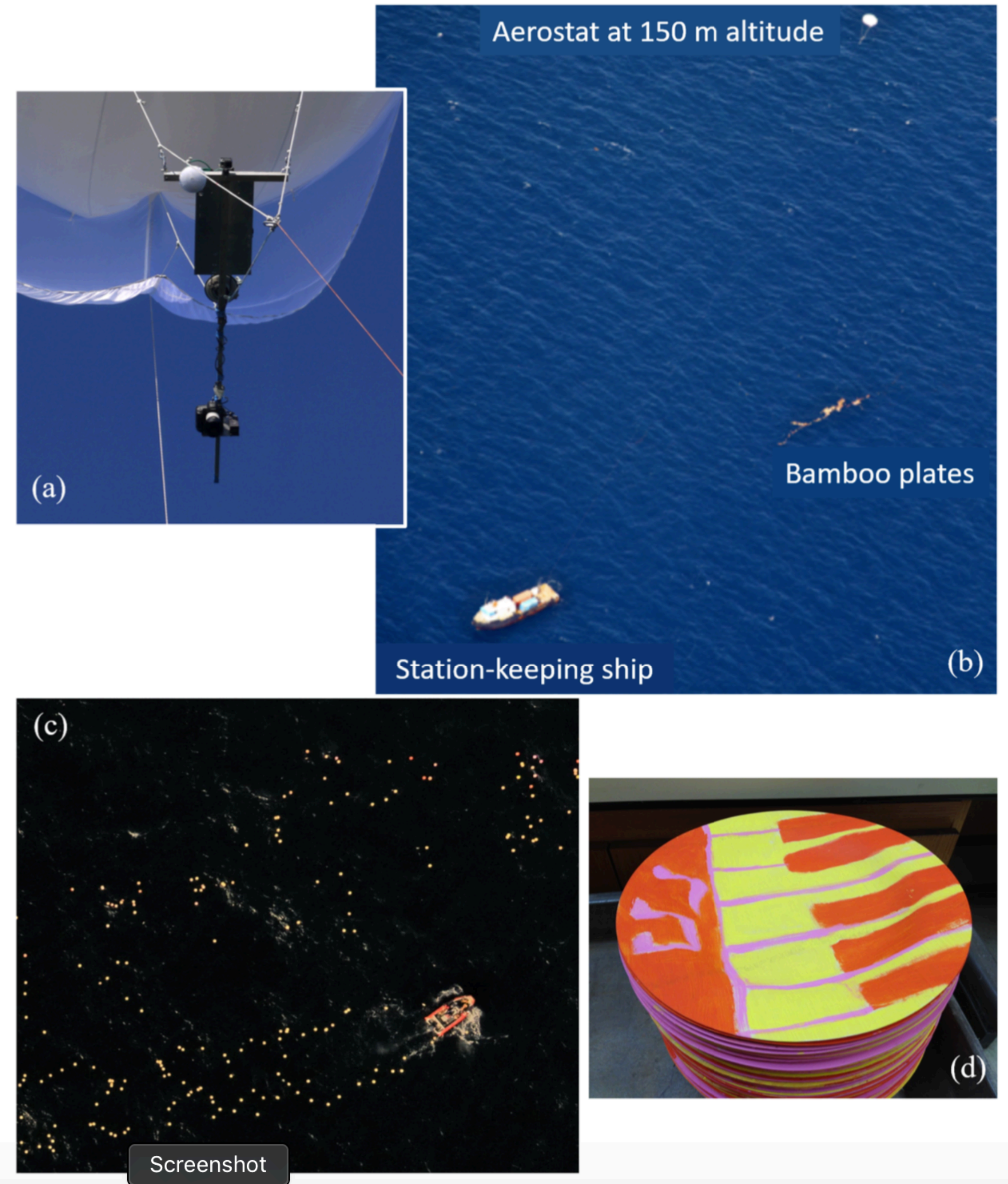


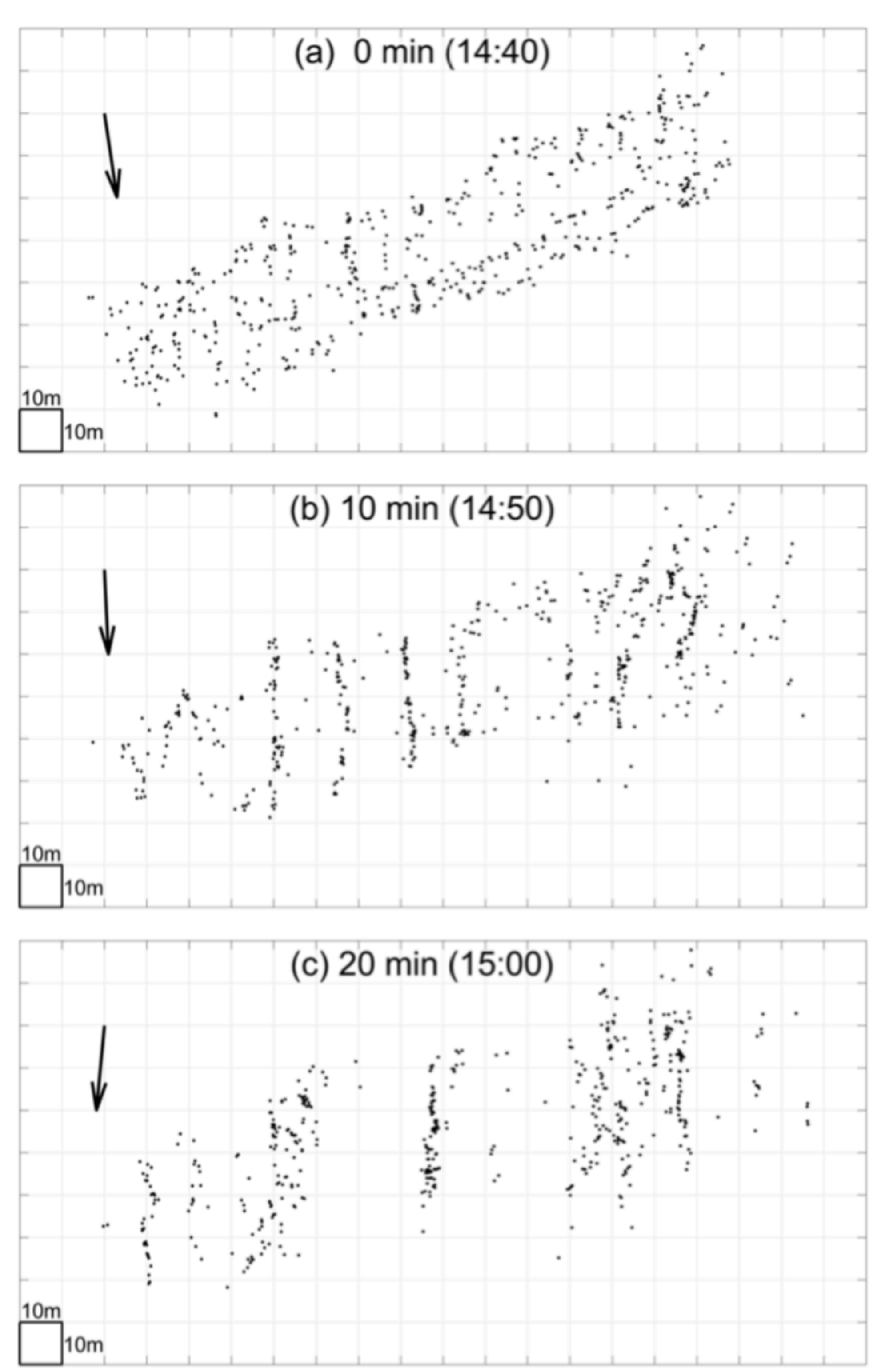
After 40 Min

N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. JGR-Oceans, 121:1-18, 2016.

N. Suzuki, BFK, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. JGR-Oceans, 121:1-28, 2016.

Chang, H., Huntley, H.S., Kirwan Jr, A.D., Carlson, D.F., Mensa, J.A., Mehta, S., Novelli, G., Özgökmen, T.M., Fox-Kemper, B., Pearson, B. and Pearson, J., 2019. Small-scale dispersion in the presence of Langmuir circulation. Journal of Physical Oceanography, (2019).





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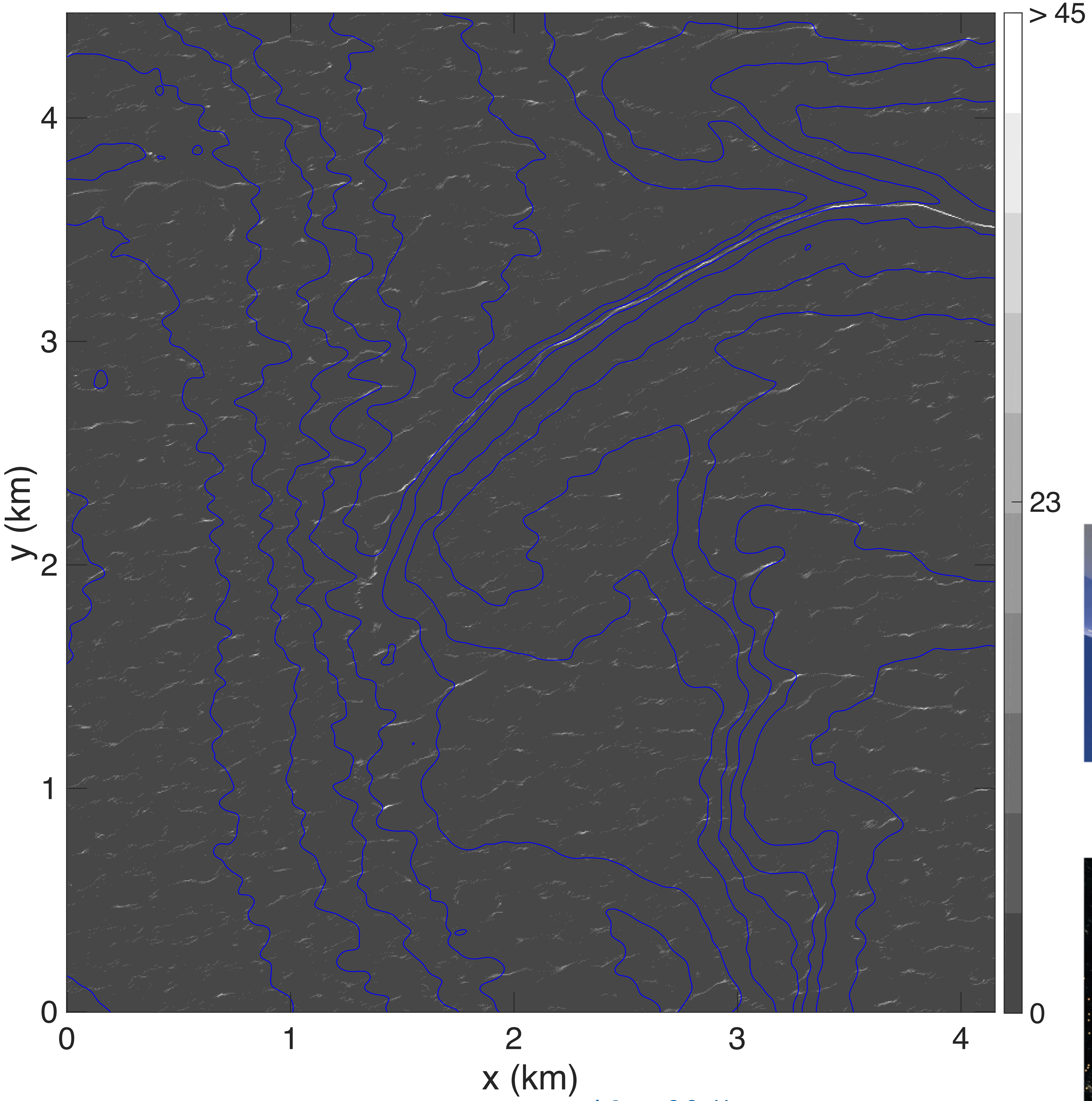

After 80 Min

N. Suzuki and BFK. Understanding Stokes forces in the wave-averaged equations. JGR-Oceans, 121:1-18, 2016.

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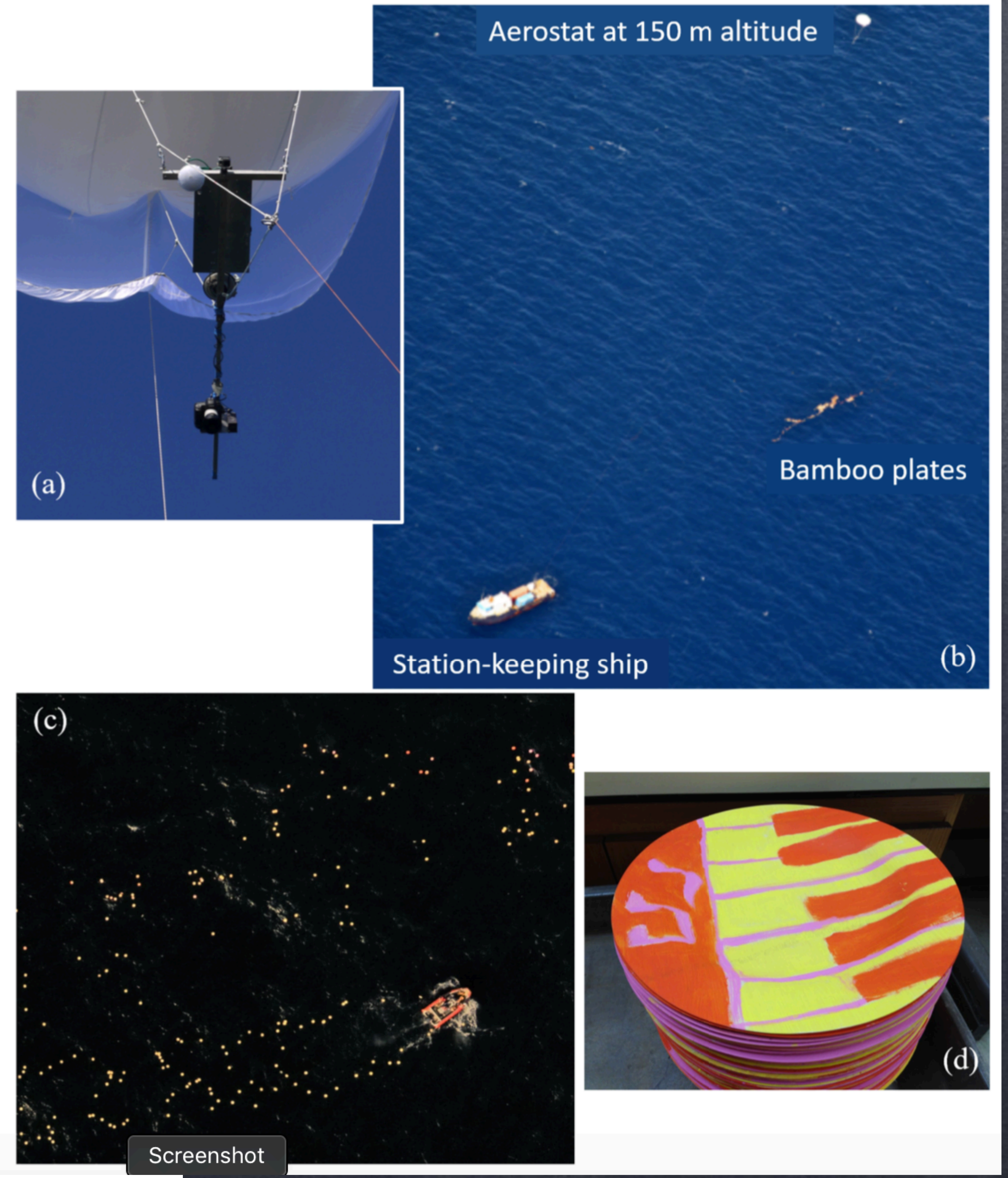
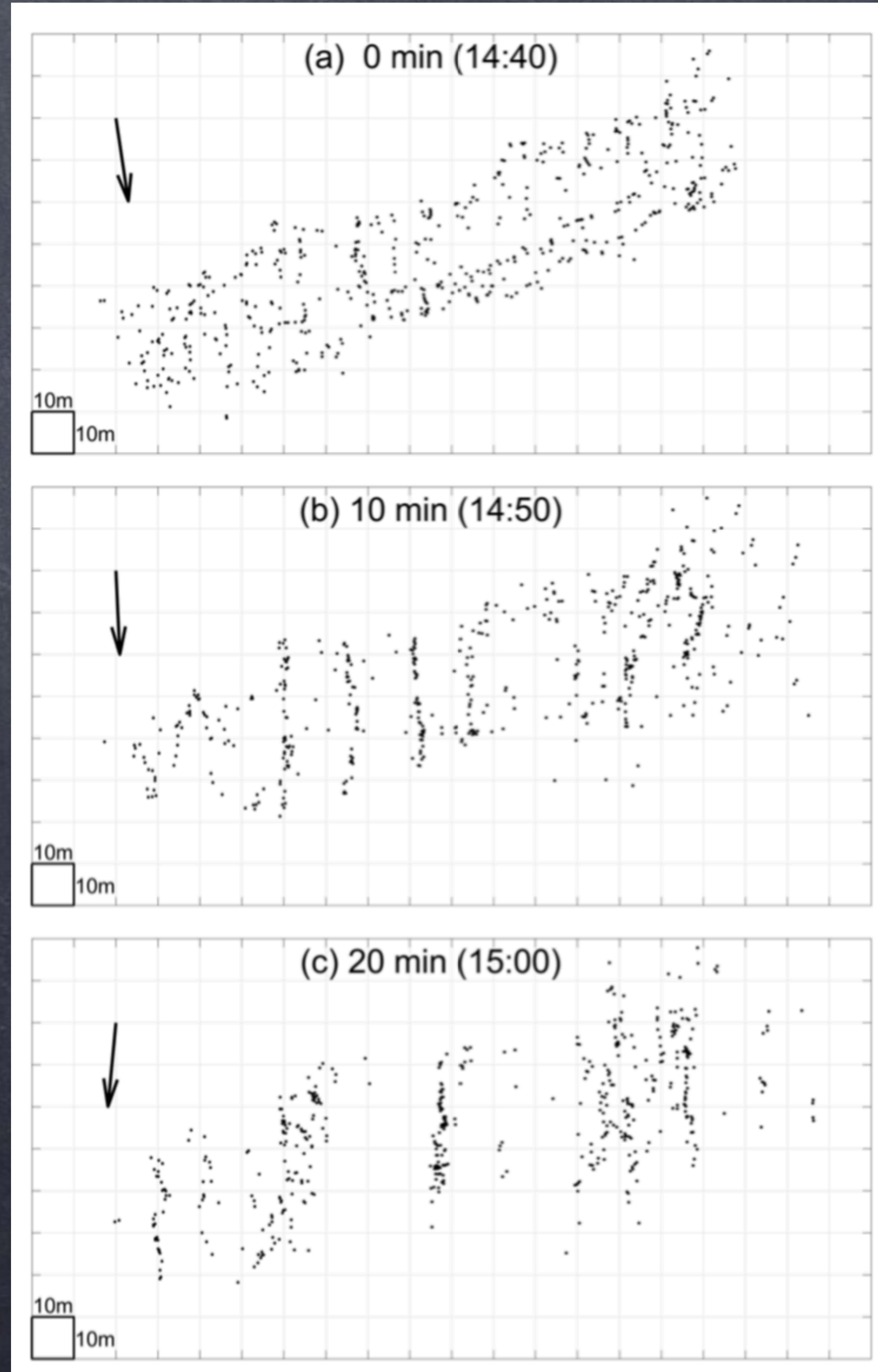




Why Fronts?

- Fronts are consistently present and ubiquitous
    - They can be the result of mesoscale straining
    - They can be the result of vertical mixing
    - They are sharpened by frontogenesis
    - Frontogenesis is arrested by turbulence & instabilities
    - Fronts & their instabilities lead to dynamical restratification

A. Bodner, BFK, L. Van Roekel, J. McWilliams, and P. Sullivan. A perturbation approach to understanding the effects of turbulence on frontogenesis. Journal of Fluid Mechanics, 883:A25, 2020.

N. Suzuki, BFK, P. E. Hamlington, and L. P. Van Roekel. Surface waves affect frontogenesis. Journal of Geophysical Research-Oceans, 121:1-28, 2016.

What sets frontal scale?

Buoyancy
& along-front
Velocity

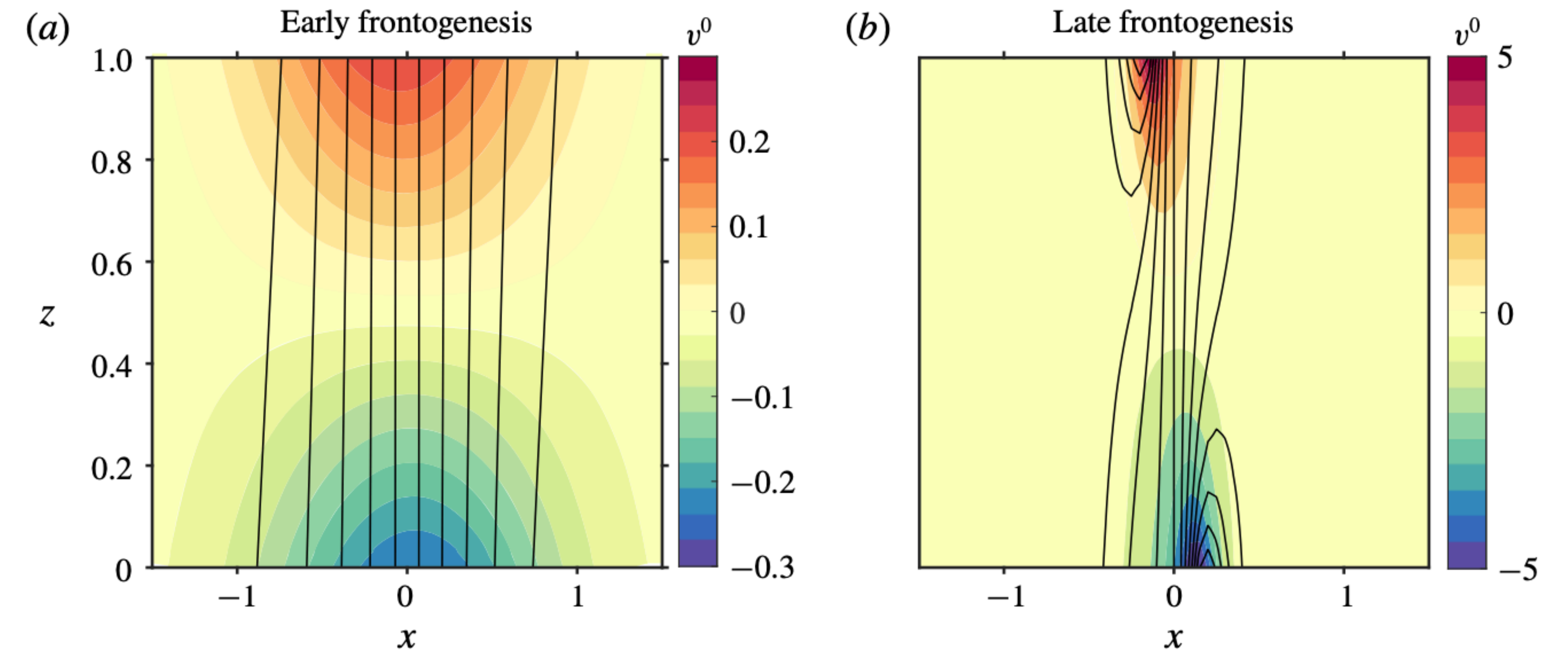


FIGURE 2. Cross-frontal profiles of the zeroth-order along-front velocity v^0 (shading) at

Frontogenetic
Streamfct.
& buoyancy

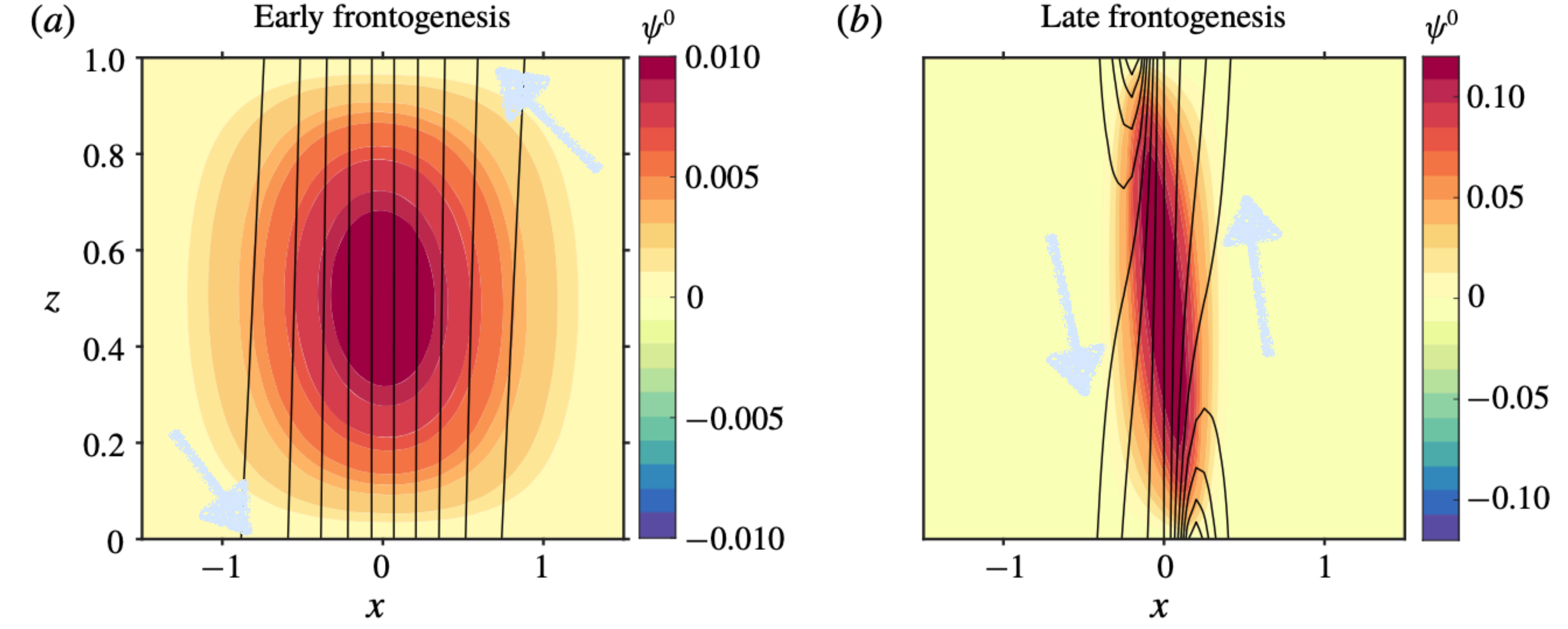
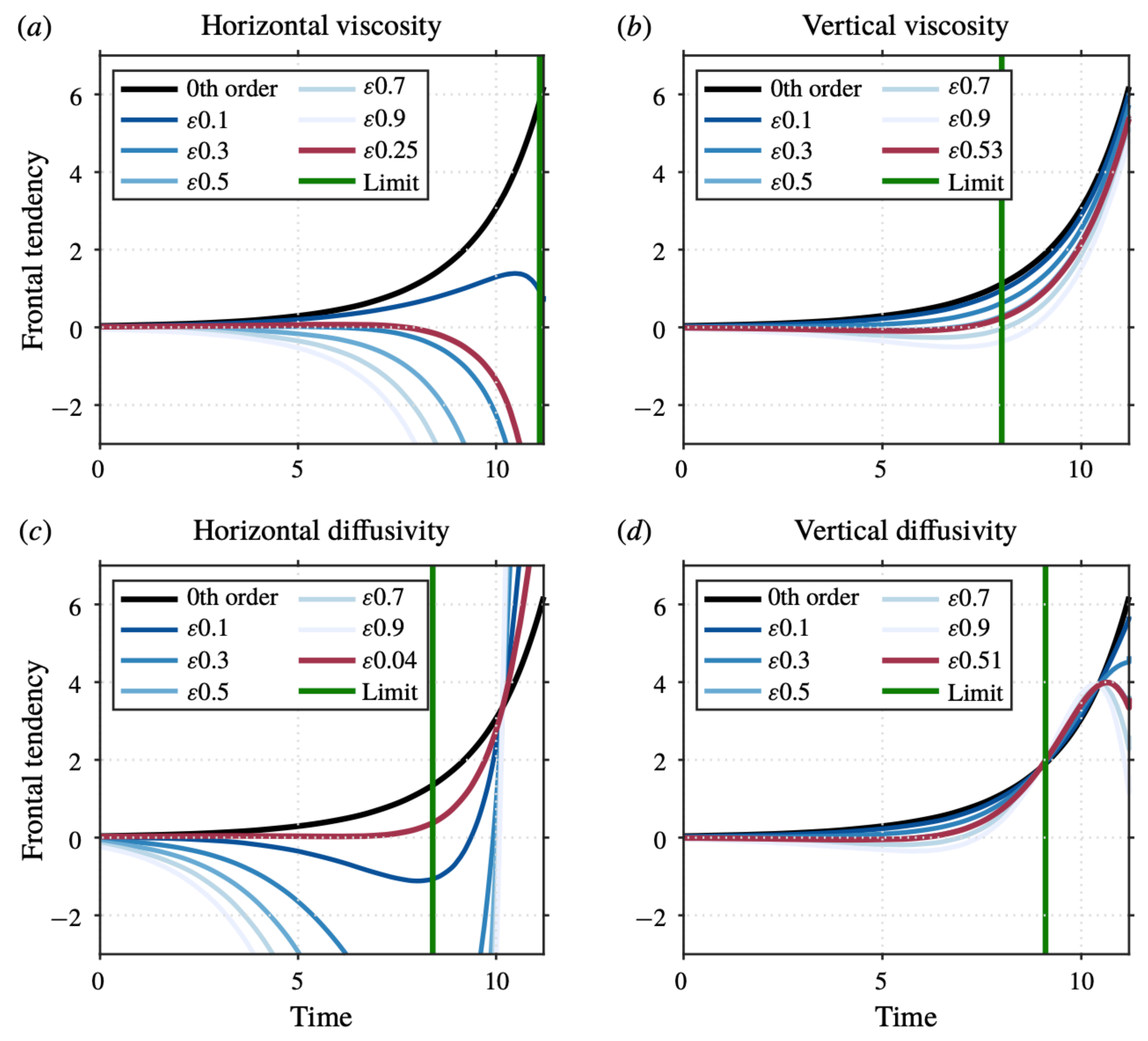


FIGURE 4. Contours show buoyancy as in figure 2, shading shows the zeroth-order streamfunction ψ^0.

A. Bodner, BFK, L. Van Roekel, J. McWilliams, and P. Sullivan. A perturbation approach to understanding the effects of turbulence on frontogenesis. Journal of Fluid Mechanics, 883:A25, 2020.

Turbulence—
here as eddy
viscosity &
diffusivity—
perturbs the
rate of
frontogenesis

Can “arrest”
the front at
a particular
scale



A. Bodner, BFK, L. Van Roekel, J. McWilliams, and P. Sullivan. A perturbation approach to understanding the effects of turbulence on frontogenesis. Journal of Fluid Mechanics, 883:A25, 2020.

see also: P. Sullivan and J. McWilliams. Frontogenesis and frontal arrest of a dense filament in the oceanic surface boundary layer. Journal of Fluid Mechanics, J. Fluid Mech. (2018), 837, 341-380.

Based on a (very few) observations, the standard has been to set

$$L_f = \max\left(\frac{NH}{|f|}, \frac{M^2H}{f^2}, L_{f,\min}\right)$$

But, this doesn't make a lot of sense—the deformation radius doesn't halt frontogenesis… turbulence & instabilities do.

Insist on TTW:

All 3 terms contribute

$$\nabla_H b = -f\hat{\mathbf{z}} \times \frac{\partial \mathbf{u}}{\partial z} + \frac{\partial^2 \overline{\mathbf{u}'w'}}{\partial z^2}$$

$$\mathrm{Ro} \sim 1; \beta L/|f| \ll 1; \mathrm{Ek} \sim 1$$

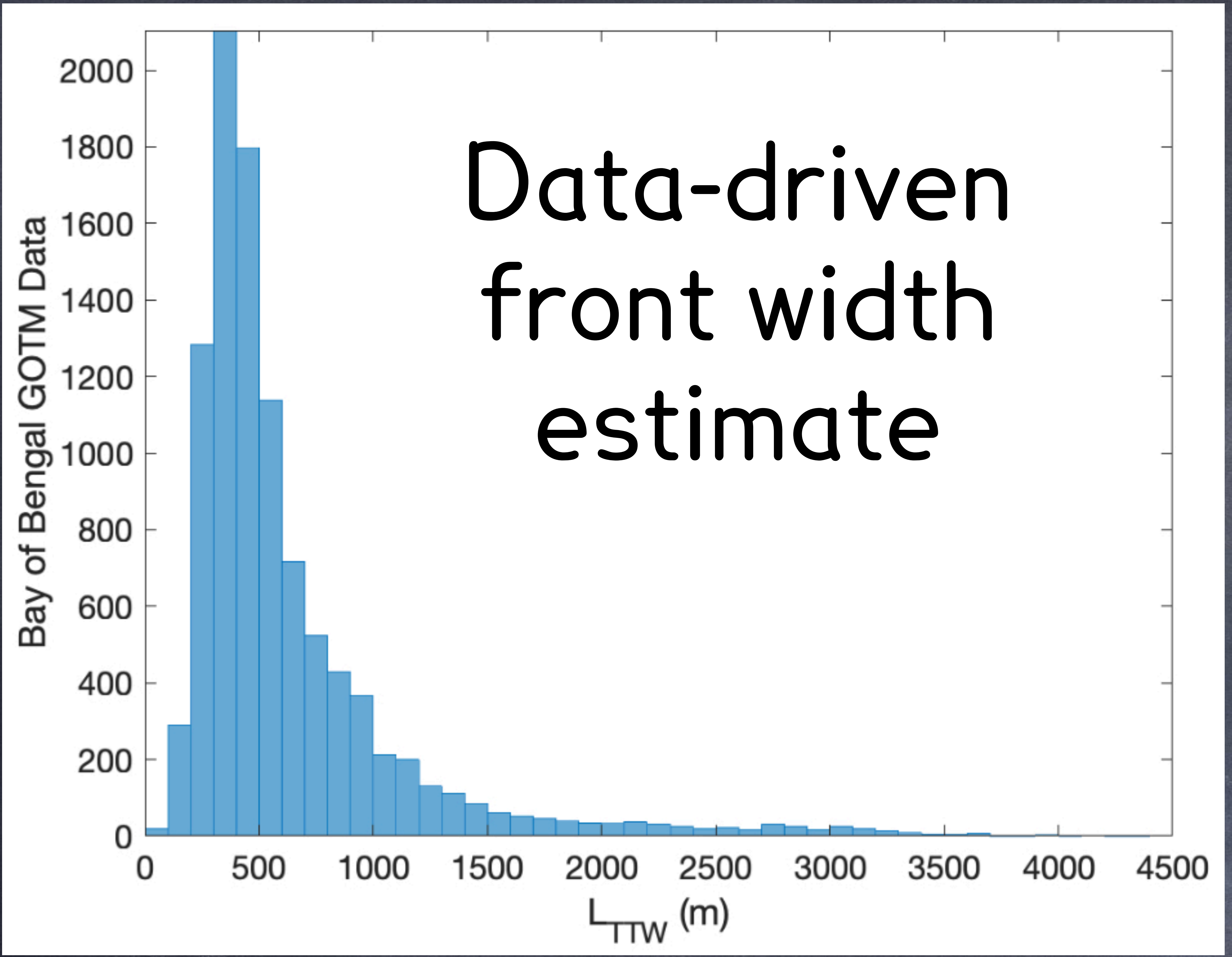
Then, a new scaling for frontal width (Bodner, 2021)

$$\boxed{L_f = Ri \cdot c_3 \cdot c_2^2 \cdot \frac{(m_* {u_*}^3 + n_* {w_*}^3)^{2/3}}{f^2} \cdot \frac{1}{h}}$$

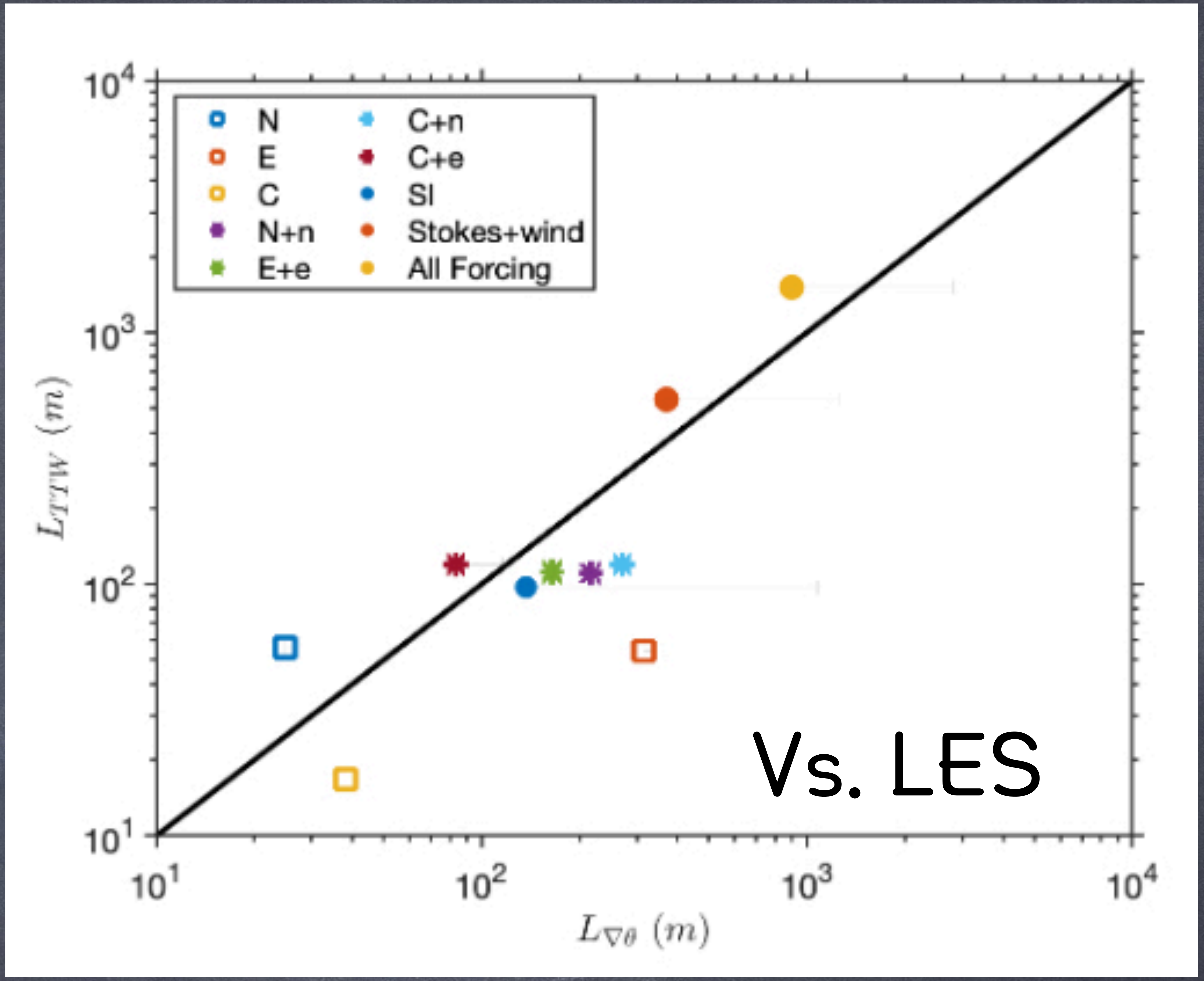
B. Fox-Kemper, G. Danabasoglu, R. Ferrari, S. M. Griffies, R. W. Hallberg, M. M. Holland, M. E. Maltrud, S. Peacock, and B. L. Samuels. Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. Ocean Modelling, 39:61-78, 2011.

D. Calvert, A. Nurser, M. J. Bell, and BFK. The impact of a parameterisation of submesoscale mixed layer eddies on mixed layer depths in the NEMO ocean model. Ocean Modelling, 154:101678, 2020.

A. Bodner. The Dynamic Interplay between Submesoscales and Boundary Layer Turbulence. PhD thesis, Brown University, October 2021.

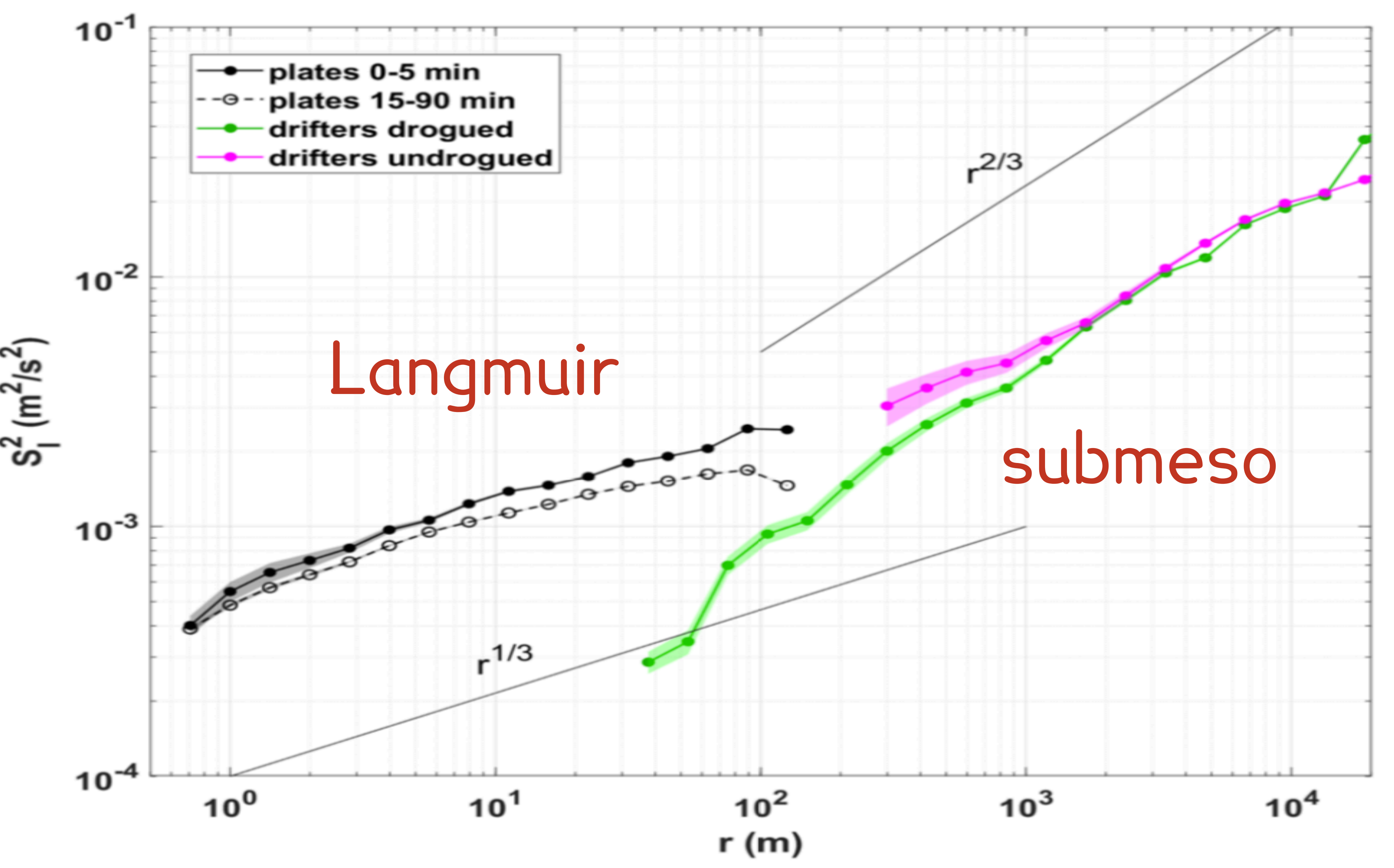


Data-driven front width estimate

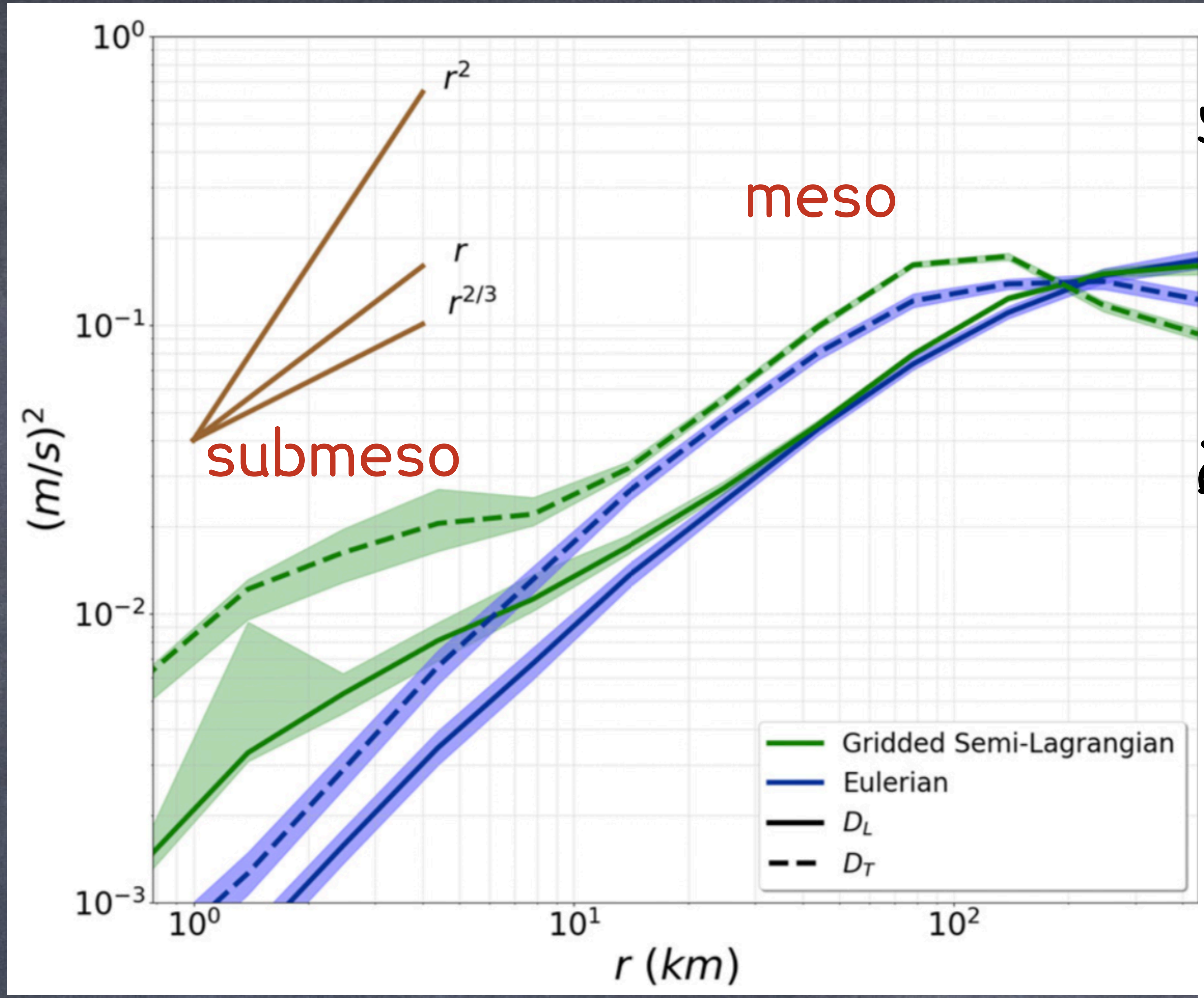


Vs. LES

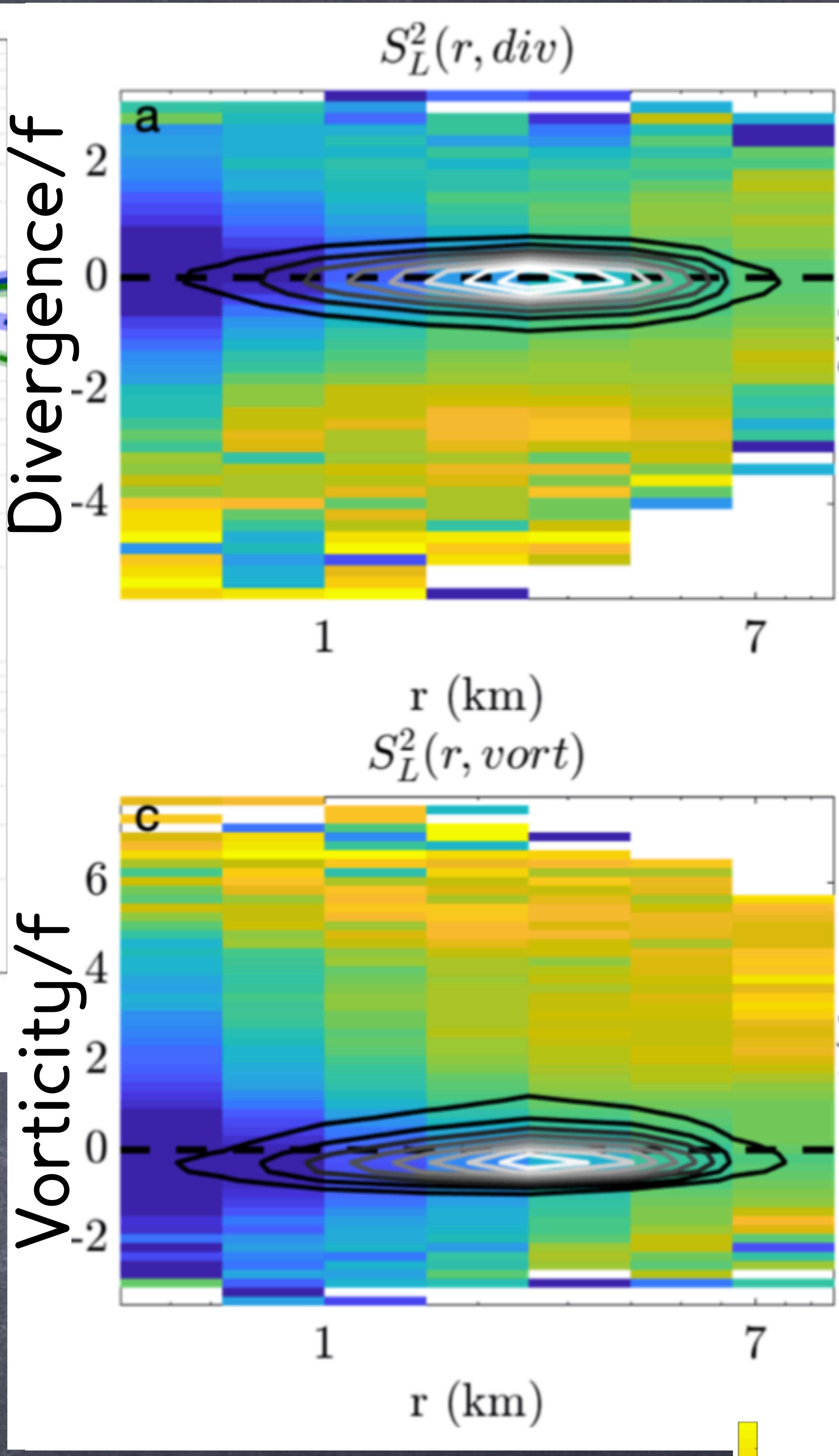
A. Bodner. The Dynamic Interplay between Submesoscales and Boundary Layer Turbulence. PhD thesis, Brown University, October 2021.



Observed Plates & Drifters



Simulated Drifters
and Eulerian Grid



$$S_L^2 = \langle \{ [\vec{\mathbf{u}}(\vec{\mathbf{x}} + \vec{\mathbf{r}}) - \vec{\mathbf{u}}(\vec{\mathbf{x}})] \cdot \hat{\mathbf{r}} \}^2 \rangle$$

Observed Eulerian currents
& Lagrangian SFs

J. Pearson, BFK, R. Barkan, J. Choi, A. Bracco, and J. C. McWilliams. Impacts of convergence on Lagrangian statistics in the Gulf of Mexico. JPO, 49(3):675-690, 2019.

H. Chang, H. S. Huntley, J. A. D. Kirwan, D. F. Carlson, J. A. Mensa, S. Mehta, G. Novelli, T. Ozgokmen, BFK, B. Pearson, J. Pearson, R. Harcourt, and A. J. Poje. Small-scale dispersion in the presence of Langmuir circulation. JPO, 49(12):3069-3085, December 2019.

J. Pearson, BFK, B. Pearson, H. Chang, B. K. Haus, J. Horstmann, H. S. Huntley, A. D. Kirwan, Jr., B. Lund, and A. Poje. Biases in structure functions from observations of submesoscale flows. JGR-Oceans, 125:e2019JC015769, May 2020.

"Cascade" Scalings

3D: Richardson/Kolmogorov/Smagorinsky/Corrsin

$$E \propto \epsilon^{2/3}\ell^{5/3}, \quad S_2 \propto \epsilon^{2/3} r^{2/3}, \quad \epsilon \propto \nu \alpha^2, \quad \nu = \mathrm{Pr}\, \kappa \propto \Delta x^2 |\alpha| \propto \epsilon^{1/3}\ell^{4/3}$$

2D: Barnier/Kraichnan/Leith

$$E \propto \eta^{2/3}\ell^3, \quad S_2 \propto \eta^{2/3} r^2, \quad \eta \propto \nu (\nabla\omega)^2, \quad \nu =\propto \Delta x^3 |\nabla\omega| \propto \eta^{1/3}\ell^2, \quad \kappa \propto ?$$

QG: Barnier/Charney/QGLeith

$$E \propto \eta^{2/3}\ell^3, \quad S_2 \propto \eta^{2/3} r^2, \quad \eta \propto \nu (\nabla q)^2, \quad \nu = \kappa_{Redi} = k_{GM} \propto \Delta x^3 |\nabla q| \propto \eta^{1/3}\ell^2$$

Submesoscale: McWilliams/?/?F-K?

$$E \propto \ell^2, \quad S_2 \propto r^1, \quad d/dt(PE + KE) = ??, \quad \nu = ?, \quad \kappa = ?$$

What about Geostrophic Coherent Structures?

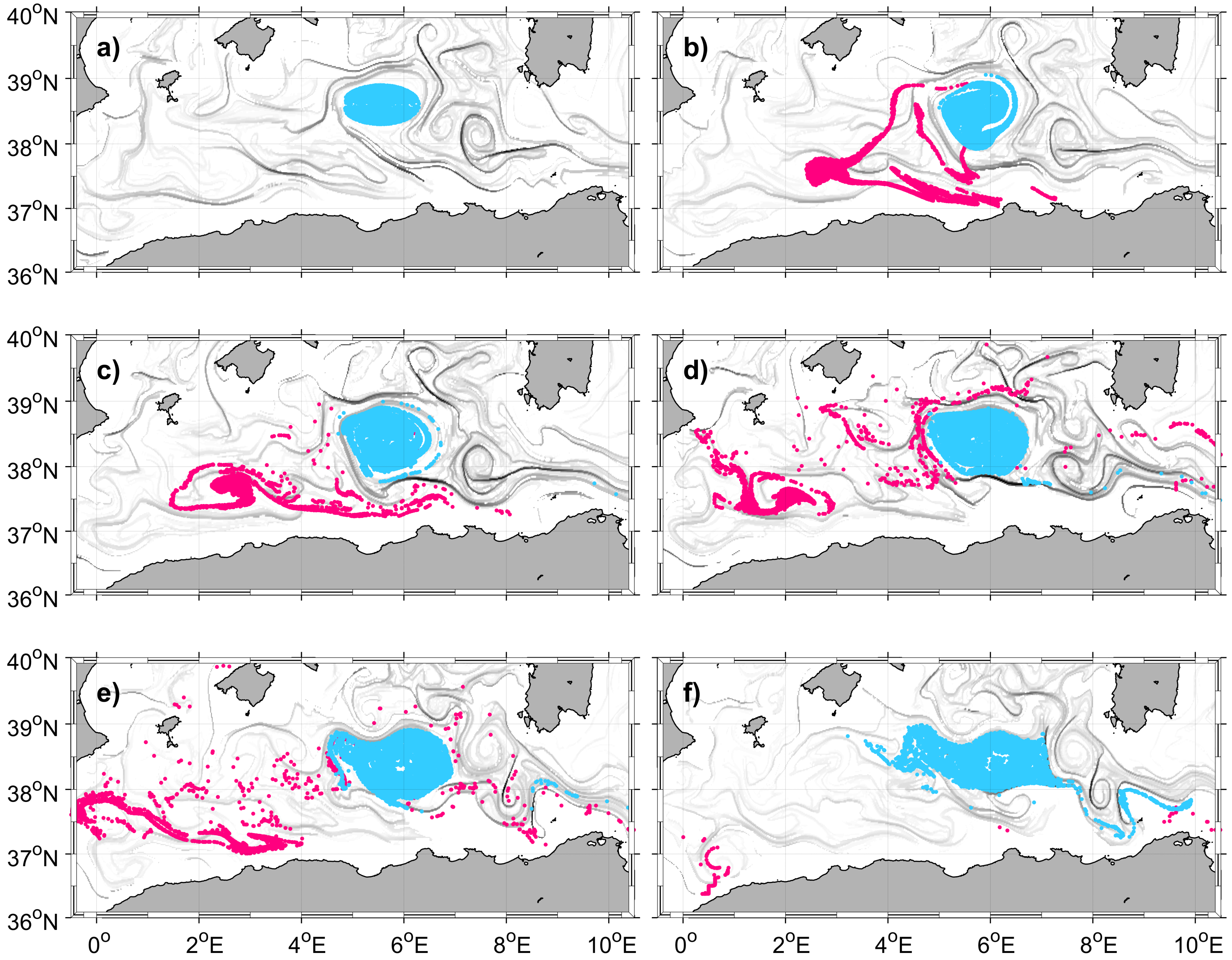


Fig. 5. Evolution during one month (a) January 26, b) January 31, c) February 5, d) February 10, e) February 15 and f) February 20, 2005) of two sets of 10000 passive tracers launched with the same initial conditions in the interior of a mesoscale eddy. One set is advected by the geostrophic field (in cian) and the other set is advected by the total velocity field (in pink). The attracting geostrophic LCS are displayed in the background in gray (darker grey for more intense LCS).

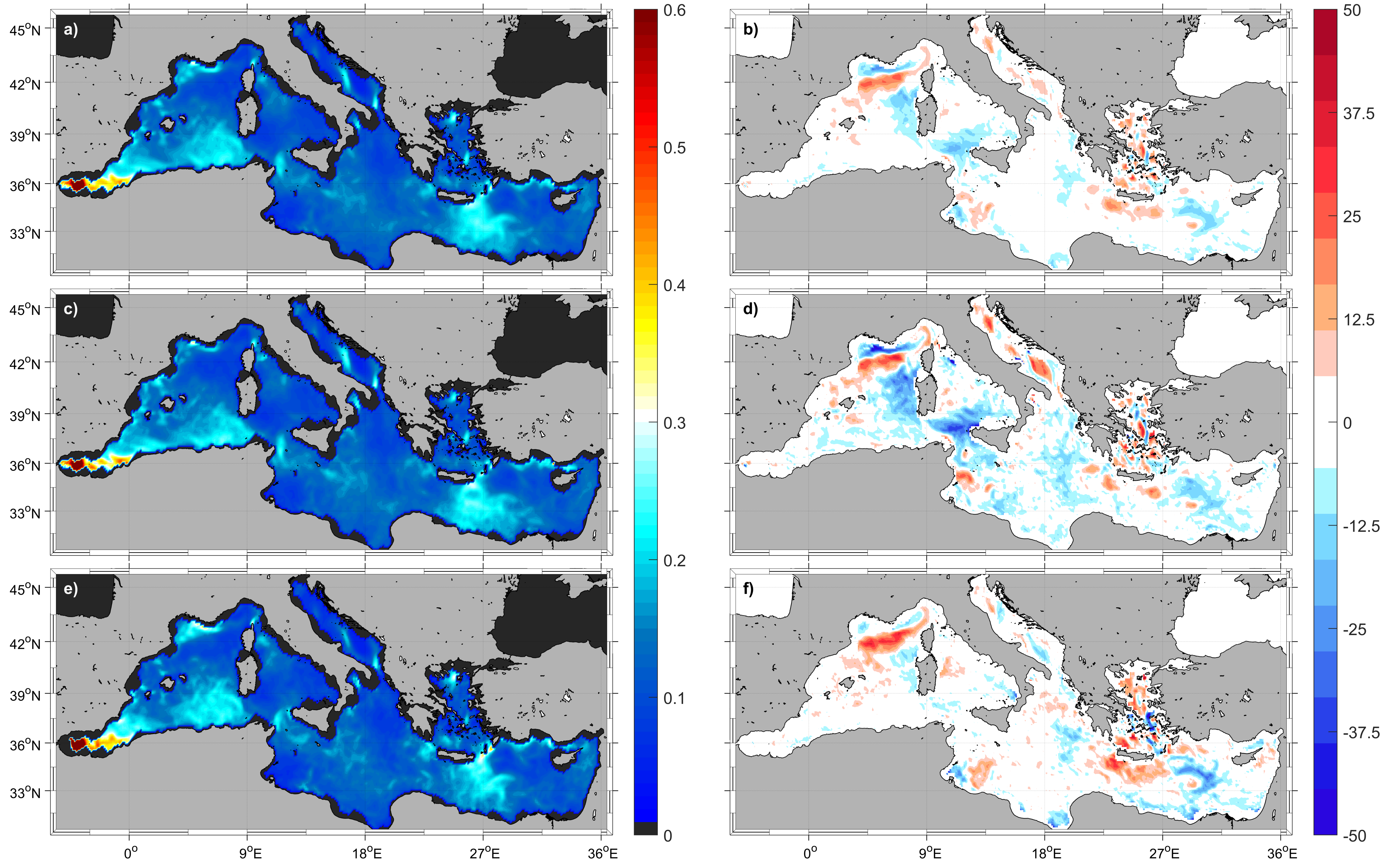
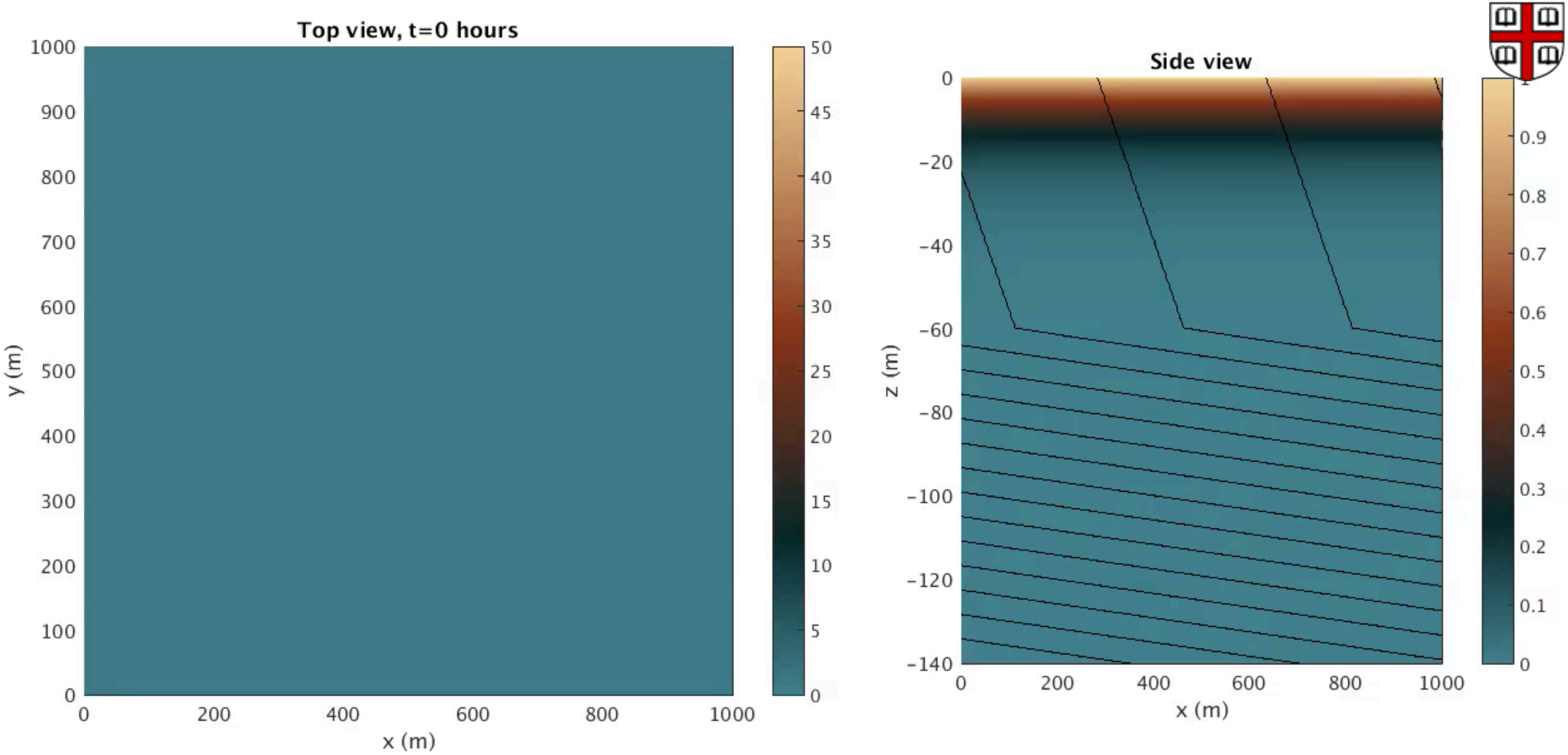


Fig. 6. Spatial distribution of the time average of backward FSLE$_T$, in $days^{-1}$, over: a) the 24 years of data (from 1994 to 2018); c) only averaging over winter months (DJFM); and e) only averaging over summer months (JJAS). Contribution of the ageostrophic currents proportional to the total horizontal stirring in % (FSLE$_T$ - FSLE$_g$)/FSLE$_T$), for b) the total period; d) for winter; and f) for summer. The initial separation is $\delta = 1/8°$ and the final separation, $r\delta = 1°$.

I.e., ageostrophic (Stokes, Ekman) change
FSLE by about 25% of geostrophic...
not the same structures!

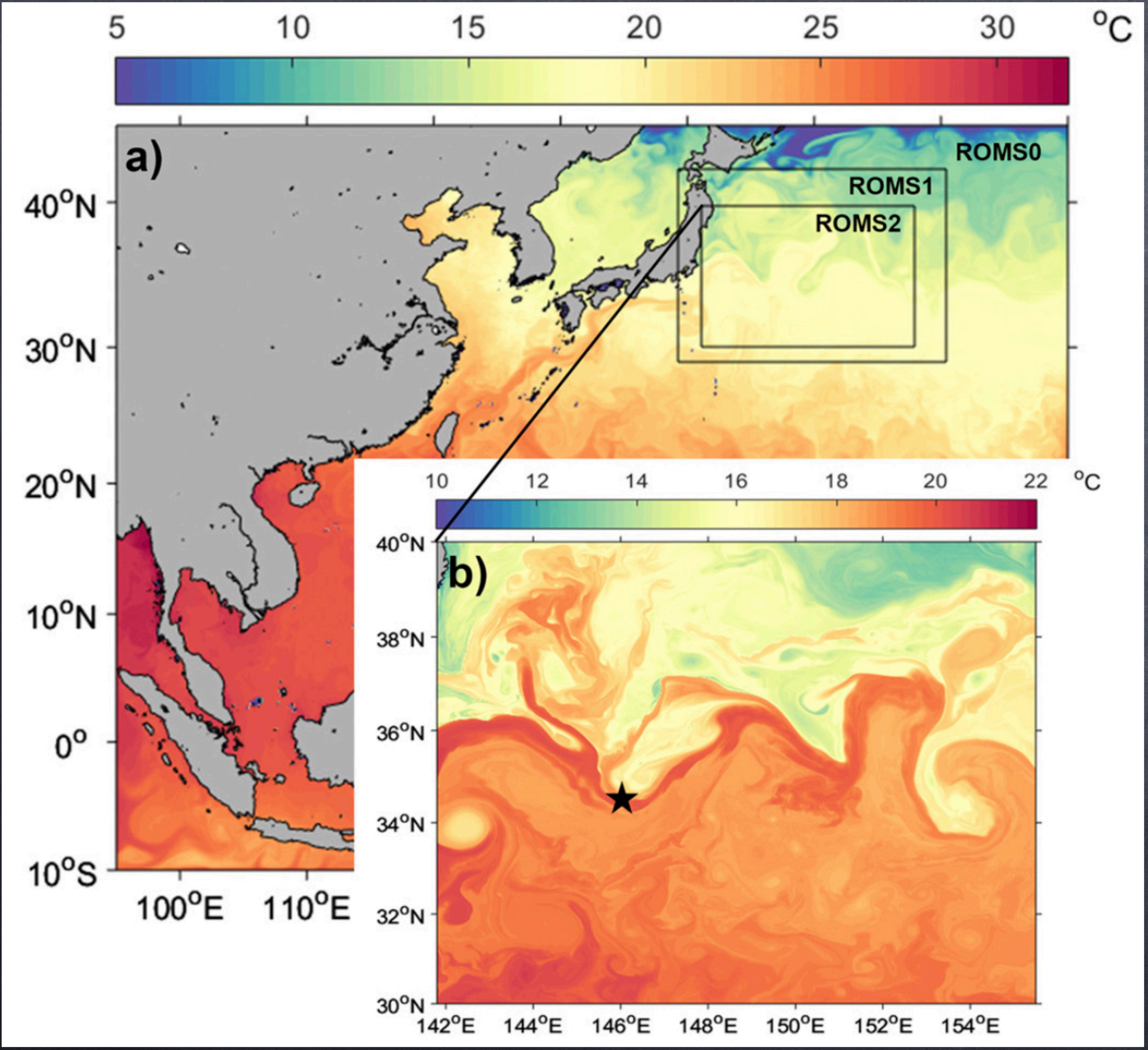
V. Morales-Marquez, I. Hernandez-Carrasco, BFK, and A. Orfila. Ageostrophic contribution by the wind and waves induced flow to the lateral stirring in the Mediterranean Sea. Journal of Physical Oceanography, November 2021. Submitted.

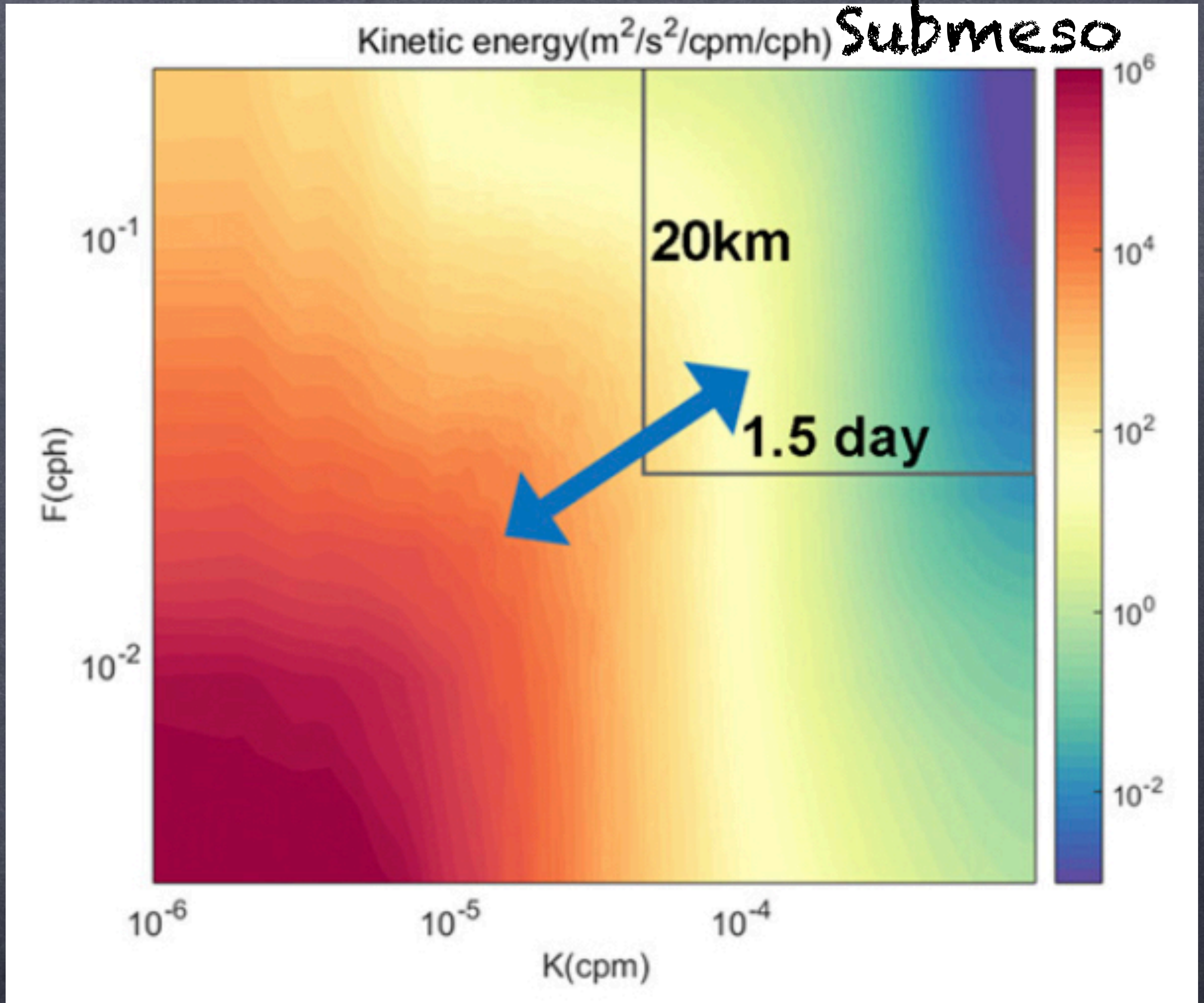
What if tracers are only moderately buoyant? Do they submerge at fronts?



Movie Courtesy of John Taylor: See Taylor, J.R., 2018. Accumulation and subduction of buoyant material at submesoscale fronts. Journal of Physical Oceanography, 48(6), pp.1233-1241.

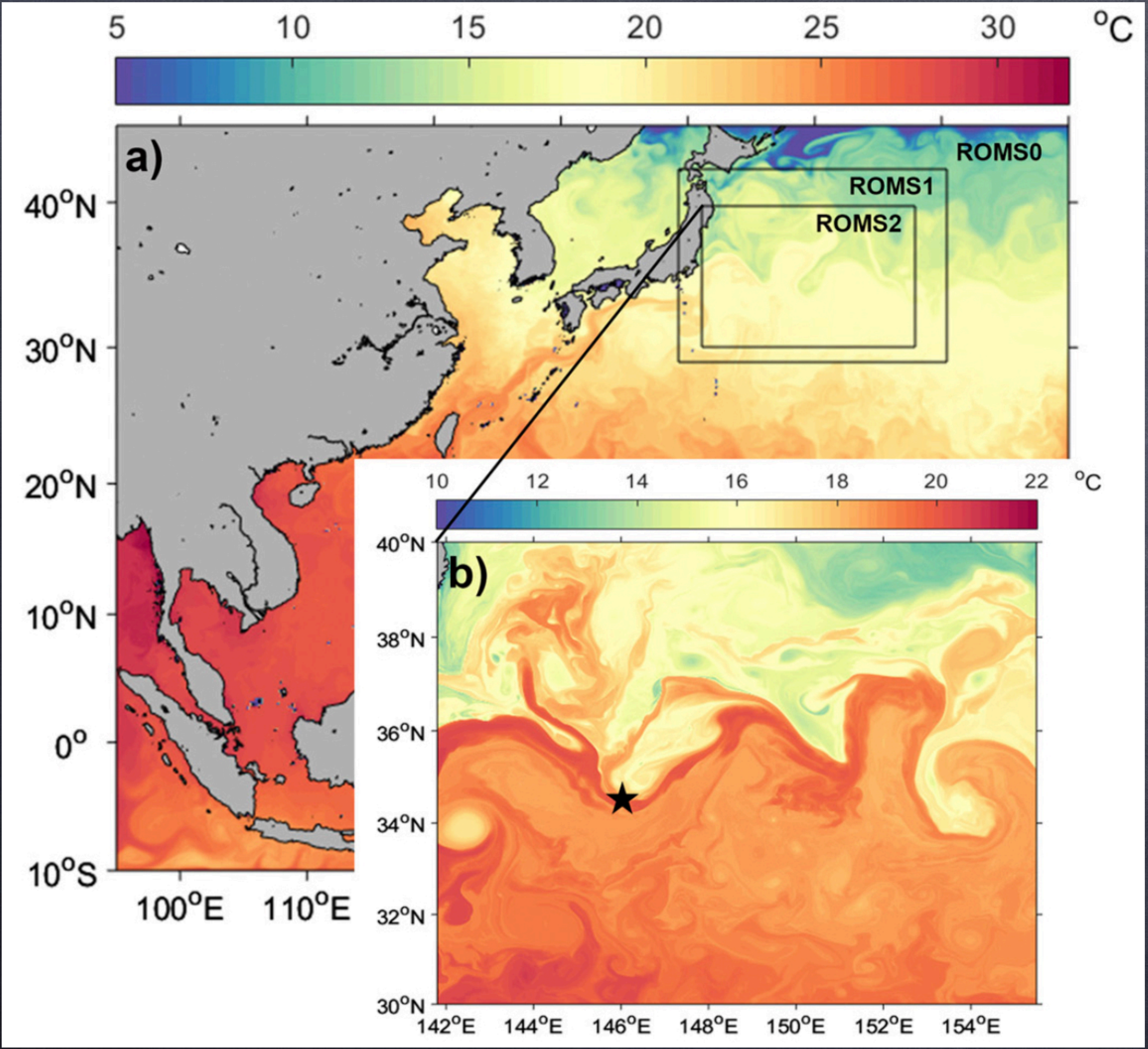
Pacific Modeling for a Frequency-Wavenumber perspective...

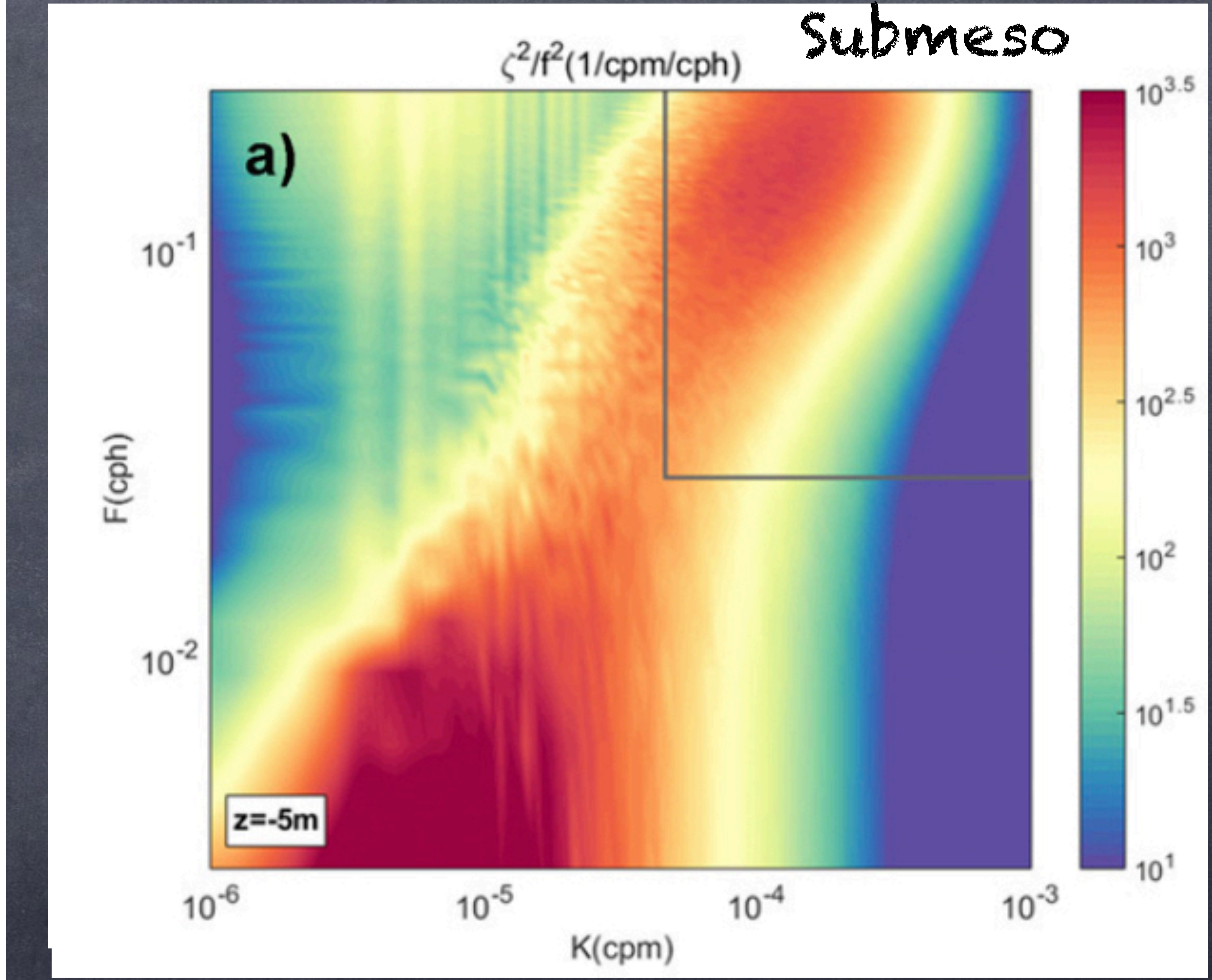




H. Cao, BFK, and Z. Jing. Submesoscale eddies in the upper ocean of the Kuroshio Extension from high-resolution simulation: Energy budget. Journal of Physical Oceanography, 51(7):2181-2201, July 2021.

Pacific Modeling for a Frequency-Wavenumber perspective...





H. Cao, BFK, and Z. Jing. Submesoscale eddies in the upper ocean of the Kuroshio Extension from high-resolution simulation: Energy budget. Journal of Physical Oceanography, 51(7):2181-2201, July 2021.

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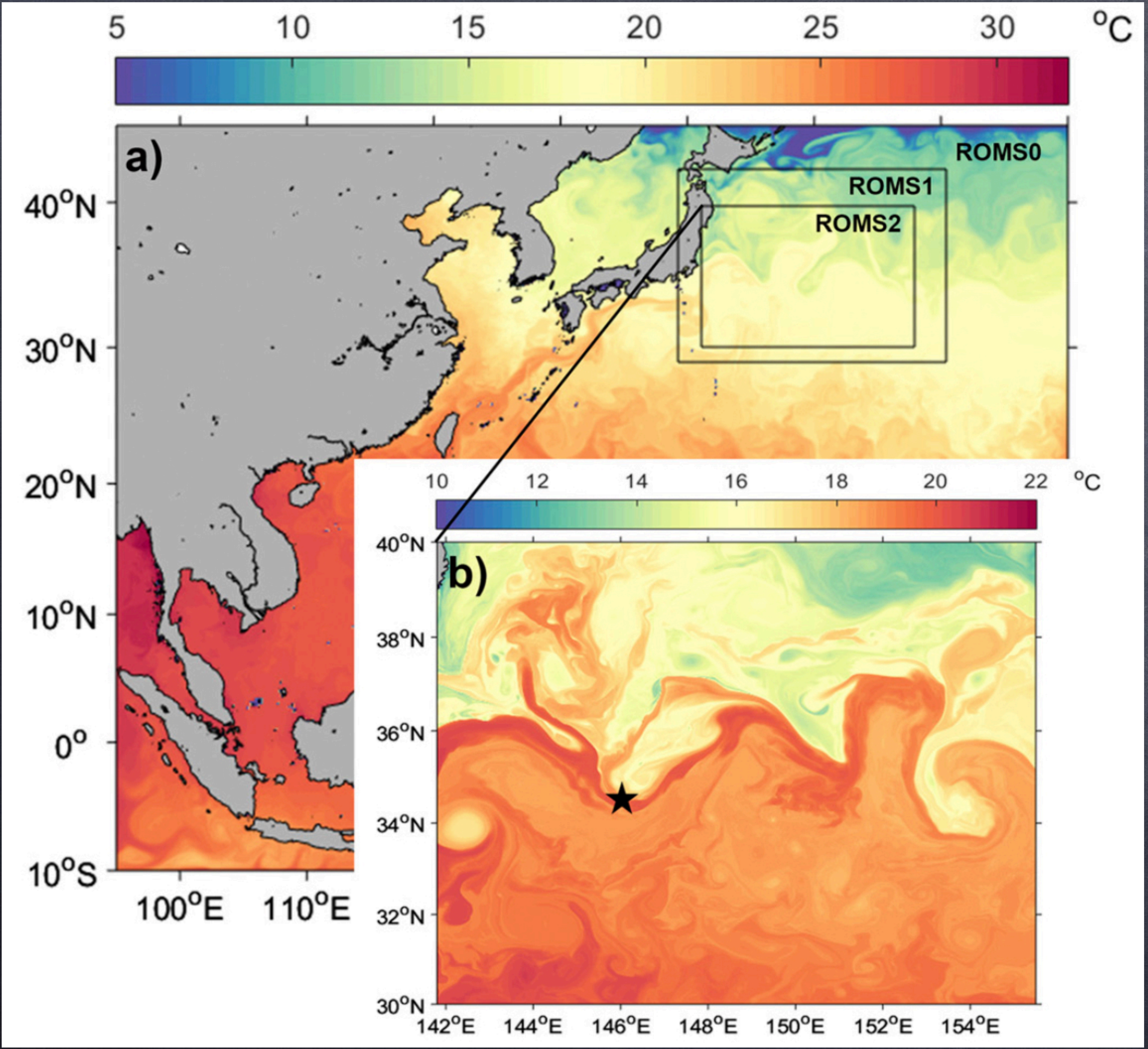

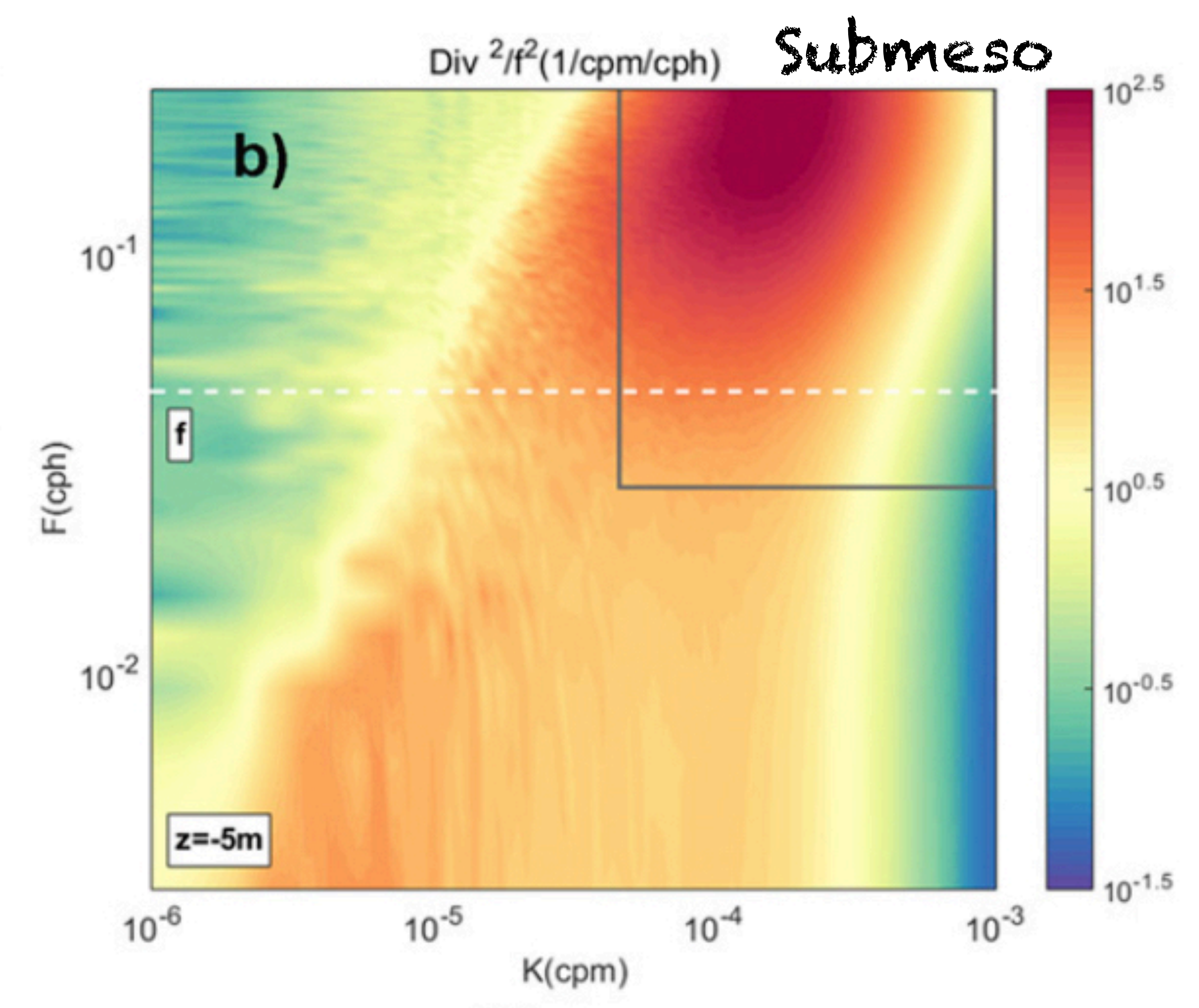

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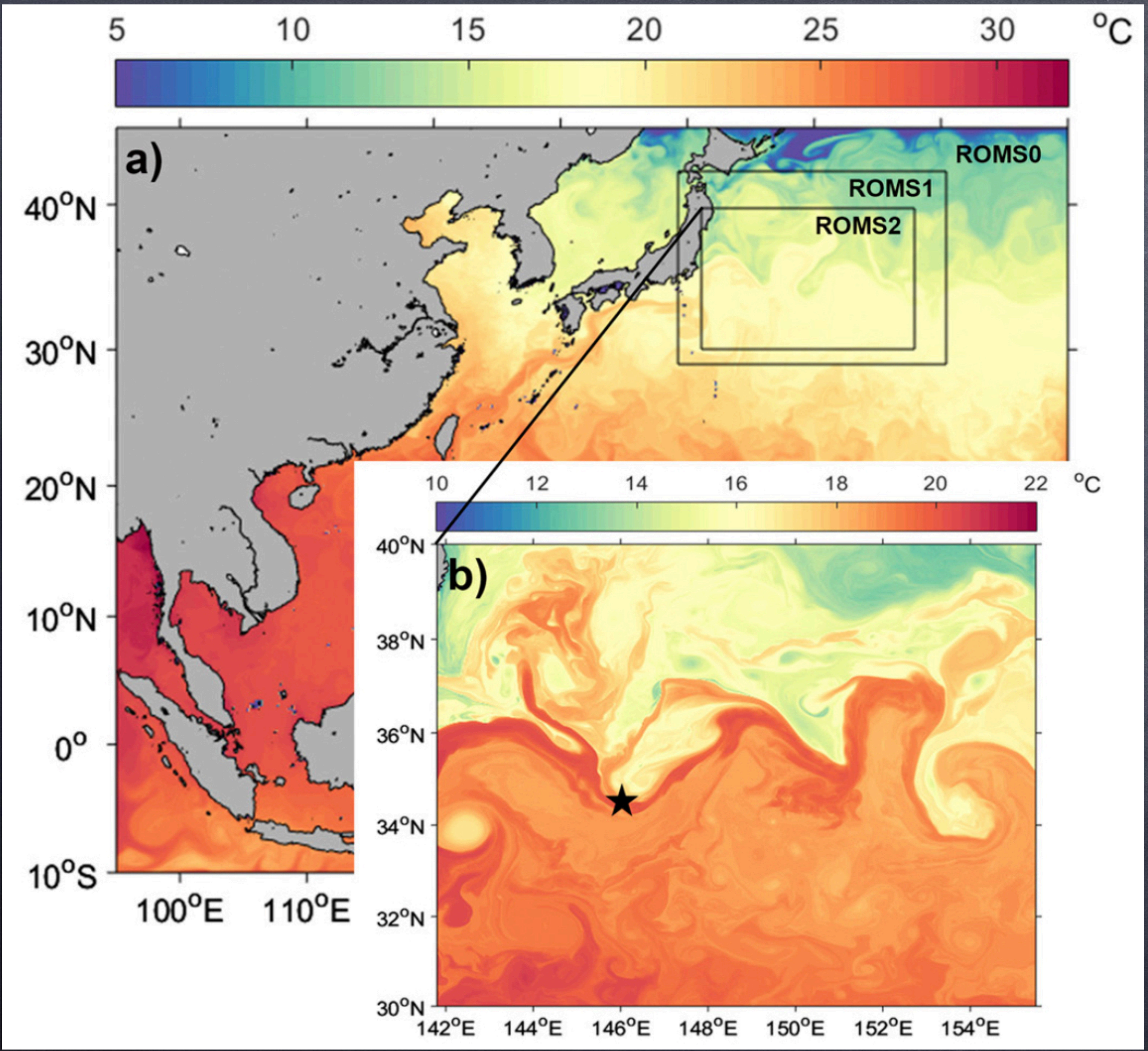

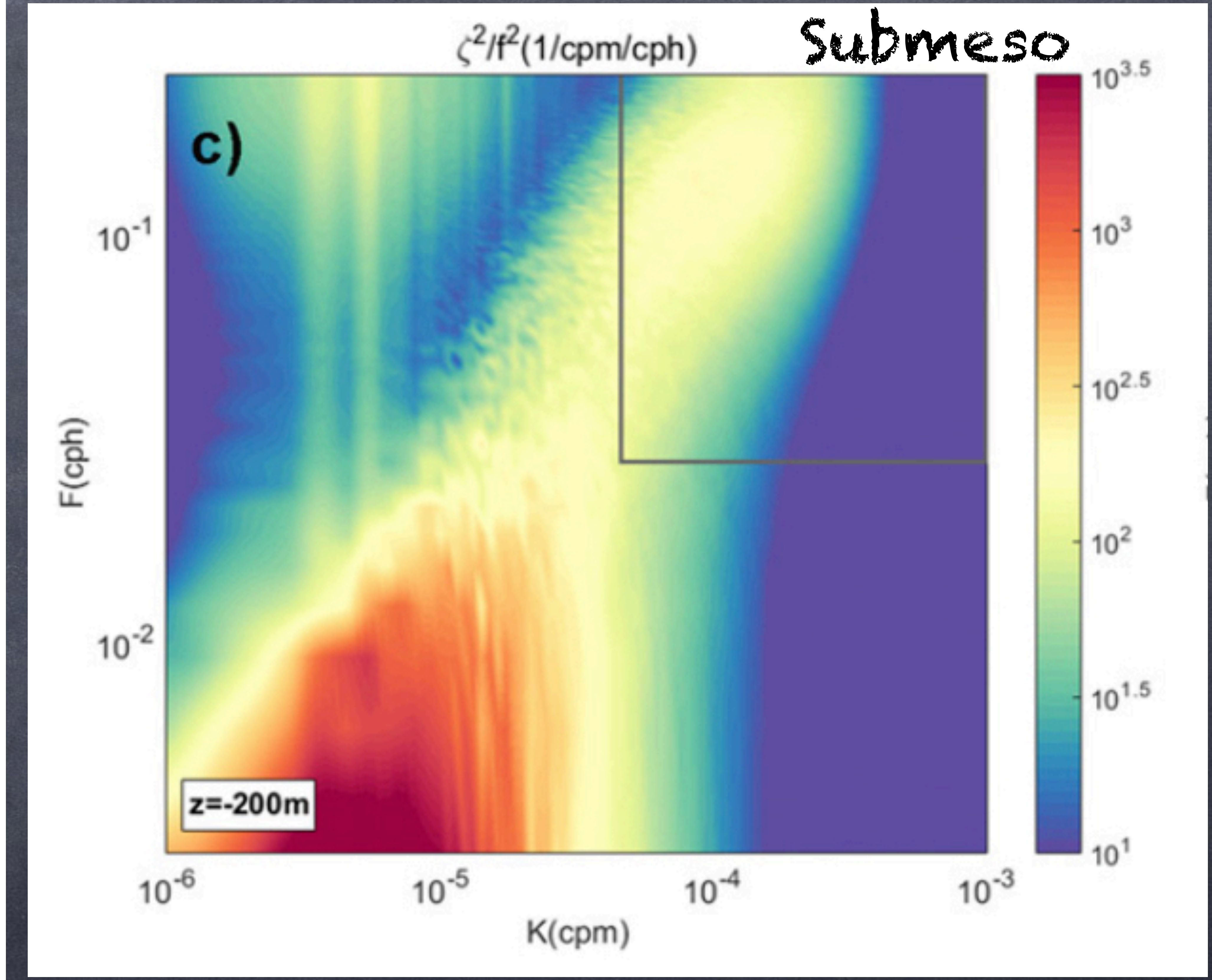

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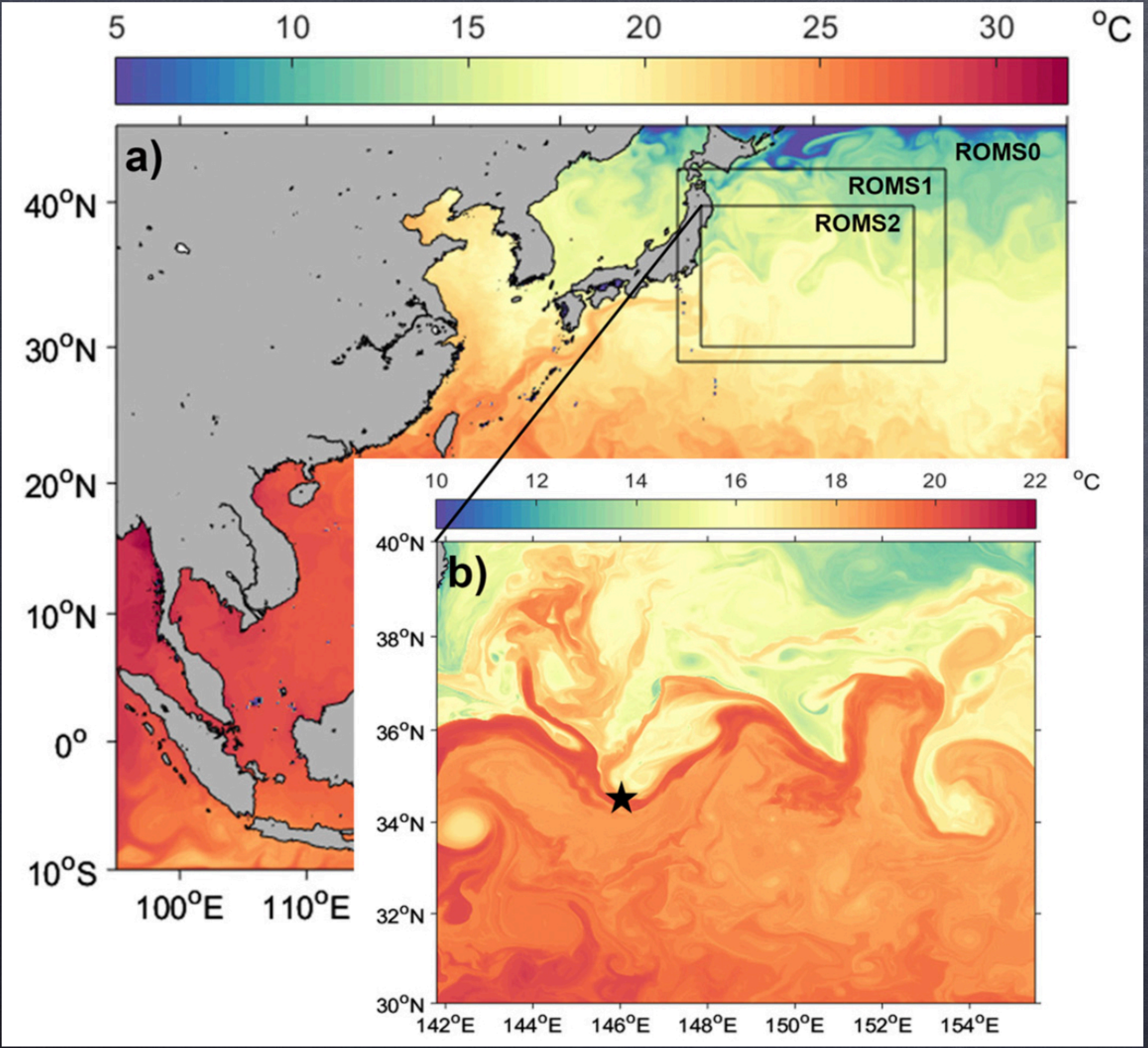

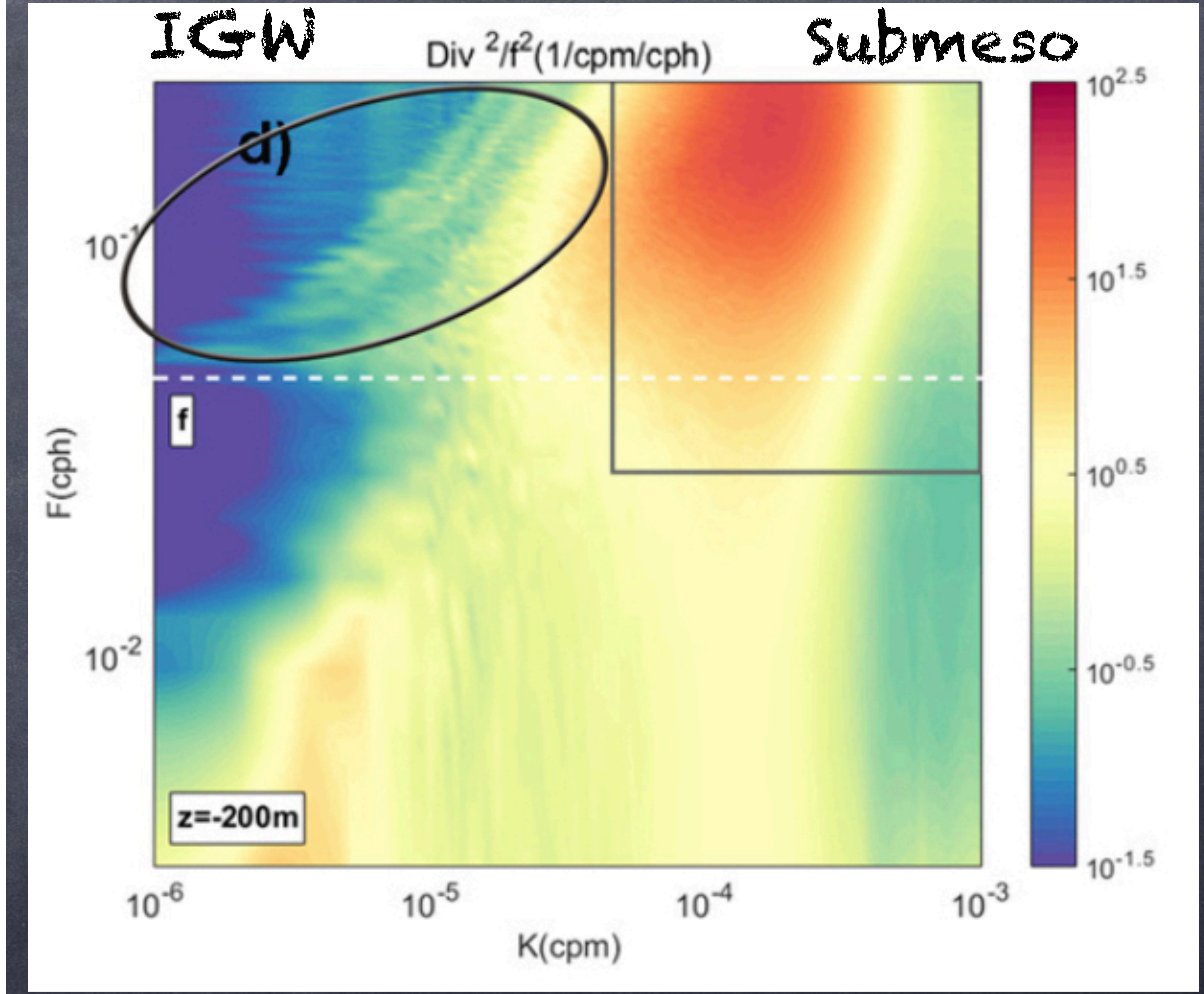

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Conclusions

- The traditional understanding of mesoscale transport:
  - Divergenceless, quasi-2D or quasigeostrophic flow, coherent structures
- At the submesoscale
  - Rossby~1, Ekman~1, Burger~1
  - Convergences at fronts are local collection points
  - Dispersion overall, slower than over mesoscales
  - Different statistics for Lagrangian & Eulerian measurements due to convergences
  - Different coherent structures due to Stokes & Ekman effects
- What sets the frontal scale?
  - Turbulence, which can be scaled by surface forcing
- For these reasons, submesoscales dominate the statistics of convergence/divergence
- At even smaller scales, Langmuir cells feature strong convergences/windrows

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