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Internal Gravity Waves and Meso/Submesoscale Currents in the Ocean Anticipating High-Resolution Observations from the SWOT Swath Altimeter Mission

Edward D. Zaron

Portland State University, ezaron@pdx.edu

Cesar B. Rocha

University of California - San Diego

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1 **Meeting Summary:**

2 **Internal Gravity Waves and Meso/Sub-mesoscale Currents in the Ocean –**
3 **anticipating high-resolution observations from the Surface Water & Ocean**
4 **Topography (SWOT) swath altimeter mission***

5 Edward D. Zaron*

6 *Portland State University, Portland, Oregon*

7 Cesar B. Rocha

8 *Scripps Institution of Oceanography, University of California, San Diego, California*

9 *Corresponding author address: Department of Civil and Environmental Engineering, Portland
10 State University, PO Box 751, Portland, OR 97207.

11 E-mail: ezaron@pdx.edu

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ABSTRACT

12 Meeting Title: Interactions Between Internal Gravity Waves and Meso/Sub-
13 mesoscale Currents in the Ocean

14 What: An international group of 45 scientists met to discuss observational
15 evidence, theoretical descriptions, and consequences of interactions between
16 high-frequency internal gravity waves and low-frequency meso- and sub-
17 mesoscale currents in the ocean.

18 When: February 10–11, 2018

19 Where: Portland, Oregon

20 Satellite altimetry, an observational technique that uses radar to measure water surface elevation
21 from satellites orbiting the Earth, has provided a near-global view of ocean variability and revolu-
22 tionized oceanography in a manner similar to the role played by geostationary satellites in atmo-
23 spheric science. Data from a constellation of satellite altimeters, beginning with TOPEX/Poseidon
24 in 1992, have led to insights concerning ocean predictability and mesoscale dynamics (?), ob-
25 servations of global sea level rise and variability (?), and a renaissance in tidal studies (?). The
26 meeting held February 10-11, 2018, “Interactions Between Internal Gravity Waves and Meso/Sub-
27 mesoscale Currents in the Ocean,” convened a group of oceanographers to discuss topics likely to
28 be similarly invigorated in the near-future by the Surface Water & Ocean Topography swath al-
29 timeter mission, anticipated for launch in 2021.

30 Near-inertial waves and internal tides are the dominant modes of high-frequency internal vari-
31 ability in the ocean, and they scatter into a broad-band inertia-gravity wave spectrum. These
32 high-frequency waves interact with low-frequency motions associated with “balanced” turbulence
33 (including geostrophic mesoscale eddies and sub-mesoscale fronts and vortices with finite Rossby
34 number). Theoretical and numerical studies of the last decade have demonstrated the importance
35 of these interactions for wave dispersion and energy transfers in the 1 km-100 km scale range,
36 as well as for their effects on the spatial variability of mixing and routes to dissipation. Recent
37 studies have highlighted the potential impacts of these wave-turbulence interactions on not only
38 high-resolution in-situ observations but also high-resolution satellite observations. The workshop
39 sought to review what is known about internal wave-balanced interactions, identify questions that
40 still need to be addressed, and consider how to meet these new challenges in the context of both
41 fieldwork and numerical modeling.

42 **Highlights**

43 Several interesting themes emerged from the meeting. The main observational challenge to
44 studying interactions between internal waves and meso-/submesoscale phenomena is the wide
45 range of space and time scales that must be resolved. An ongoing study in the Western Pacific,
46 near the Luzon Strait, is using multiple gliders to observe the upper kilometer of the ocean at
47 horizontal scales from a few kilometers—the width of topographic features where internal tides
48 are generated and the size of submesoscale currents—to hundreds of kilometers, approaching the
49 scales of internal tides and geostrophic mesoscale eddies. Researchers are finding that it is possible
50 to identify baroclinic tides, which vary significantly over the time it takes for a glider to complete
51 its vertical profile, and distinguish them from the slowly-evolving meso- and submesoscale fields.
52 Observations of surface currents at 1 km-100 km scales were also reported. These are being
53 collected by high-frequency radar stations along coastlines of North America, Europe, and East
54 Asia, and analysis of these is providing information about the kinetic energy spectrum of surface
55 currents. Innovative remote sensing techniques for measuring small-scale roughness were also
56 presented which show promise for estimating divergence and rate-of-strain of surface currents.

57 A number of theoretical studies were reviewed that—in contrast to observational studies—
58 isolate the physical mechanisms of interactions. One study, based on an asymptotic model that
59 coupled near-inertial waves coupled with quasi-geostrophic flow, predicts a transfer of energy
60 from the geostrophic flow to the waves related to the reduction of wave length scales by advec-
61 tion and refraction. Another study showed how wave dissipation can catalyze a net conversion of
62 otherwise reversible energy exchange from a geostrophic flow to near-inertial waves. Also, high
63 resolution, idealized Boussinesq numerical simulations were reported in which energy transfers
64 were decomposed in terms of deformation shear production and buoyancy fluxes; this enabled an

65 assessment of the role of wind-driven internal waves in damping mesoscale eddies. Interpretation
66 of even these simplified studies is complicated by the three-dimensional nature of the interactions,
67 and the apparent mixture of direct energy exchanges versus scale-dependent energy cascades.

68 The meeting featured results from an increasing number of studies with realistic numerical mod-
69 els that include both high-frequency forcing from tides, winds, or both, and low-frequency forcing
70 from winds and buoyancy fluxes. Reported simulations have horizontal resolutions down to hun-
71 dreds of meters and upper-ocean vertical resolution of a few meters, thus resolving geostrophic
72 eddies, ageostrophic fronts, and internal waves. Presentations described how the models are be-
73 ing used to investigate the origin of the internal-wave continuum, and to design the SWOT cal-
74 ibration/validation field campaign. Interesting comparisons of HYCOM, MITgcm, and ROMS
75 simulations show disagreements in internal-wave energy across models, unrelated to grid reso-
76 lution, which are currently under investigation by the modeling community. Comparisons with
77 observations highlight the overall realism of global internal-tide-resolving models, but they are
78 also finding order-of-magnitude local discrepancies that deserve further investigation. Increas-
79 ing resolution of the models presents challenges for analysis of flow interactions, and there is
80 renewed interest in the relationships between kinematic versus dynamical flow decompositions –
81 divergent/rotational versus wave/balanced versus high-/low-frequency – and their usefulness for
82 interpreting both models and observations.

83 **Outcomes**

84 The workshop provided the opportunities to exchange information between communities which
85 do not frequently interact. Historically, studies of ocean mesoscale and submesoscale turbulence
86 have not been closely tied to studies of inertia-gravity internal waves. Studies of large-scale ocean
87 turbulence have been dominated by an emphasis on potential vorticity dynamics, while studies of

88 inertia-gravity waves emphasize linear wave dispersion, ray tracing, and wave action conservation.
89 The fields have generally emphasized different observational techniques aligned with the time and
90 spatial scales of interest.

91 Planning for the SWOT mission is motivating more interactions between these communities,
92 because of the unique potential of the mission to observe inertia-gravity waves, mesoscale, and
93 submesoscale processes expressed in the topography of the ocean surface. Learning from these
94 observations will be a challenge because the 21-day repeat sampling of the mission will alias
95 high-frequency inertia-gravity waves and rapidly-evolving submesoscale structures. Nonetheless,
96 specialists from diverse areas recognize the potential significance of making sustained, near-global
97 measurements of sea-surface height across the 1 km to 100 km range of scales.

98 Outcomes of the meeting include new collaborations between modelers and observationalists,
99 such as plans to investigate the degree to which predictable baroclinic tidal variability can be
100 mapped and removed from observations. There are also plans to revise the SWOT white pa-
101 pers to explicitly highlight linkages between mesoscale, submesoscale, and inertia-gravity wave
102 phenomena and dynamics. This should provide a forum for communicating with the broader
103 oceanographic community in order to plan for and maximize the SWOT mission's science results.

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113 FIG. 1. This snapshot of surface current speed in the Western North Pacific from a $(1/48)^\circ$ -resolution MITgcm
 114 simulation illustrates familiar features such as the Kuroshio Current and its mesoscale meanders and rings. Also
 115 visible are wave patterns caused by internal tides emanating from Luzon Strait and the Aleutians Islands, and
 116 ubiquitous sub-mesoscale currents. High-resolution simulations such as this are being used to study interactions
 117 between internal gravity waves and meso/sub-mesoscale currents, as discussed at the workshop (image provided
 118 by Dimitris Menemenlis).