REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
08-11-2001	Final Progress Report	Nov 97 - Oct 01

4. TITLE AND SUBTITLE

Coherent Spatial Patterns and Material Transport in Oceanic Flows

5a. CONTRACT NUMBER n/a

5b. GRANT NUMBER N00014-98-1-0165

5c. PROGRAM ELEMENT NUMBER n/a

6. AUTHOR(S)

McWilliams, James C

5d. PROJECT NUMBER n/a

5e. TASK NUMBER n/a

5f. WORK UNIT NUMBER n/a

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Inst. of Geophysics and Planetary Physics
University of California, Los Angeles
405 Hilgard Ave., Box 951567
Los Angeles, CA 90095-1567

8. PERFORMING ORGANIZATION REPORT NUMBER n/a

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
ONR 311
800 North Quincy Street
Arlington, VA 22217

10. SPONSOR/MONITOR'S ACRONYM(S) ONR

11. SPONSORING/MONITORING AGENCY REPORT NUMBER n/a

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for public release

20011116 214

13. SUPPLEMENTARY NOTES

none

14. ABSTRACT

The main subject of the grant is spontaneous emergence, dynamics, and properties of the coherent spatial patterns in oceanic flows. The oceanic regimes include convection with rotation, wind-driven circulation of the midlatitude ocean, thermohaline circulation, coastal currents near the U.S. West Coast, planetary boundary layers, and surface gravity waves. Consideration is also given to interactions between the coherent patterns, material transport, and spontaneous low-frequency variability. Some of the results are used for developing improved computational algorithms and parameterizations for oceanic models.

15. SUBJECT TERMS

Coherent spatial patterns, material transport, oceanic flows

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU		Dr. James C. McWilliams, PI
					19b. TELEPONE NUMBER *(Include area code)* 310-206-2829

Coherent Spatial Patterns and Material Transport in Oceanic Flows

James C. McWilliams
Department of Atmospheric Sciences and
Institute of Geophysics and Planetary Physics
University of California, Los Angeles
Los Angeles, CA 90095-1565
Phone:(310)206-2829 Fax:(310)206-5219 Email:jcm@atmos.ucla.edu

Award N00014-98-1-0165, November 1997 – October 2001
http://www.onr.navy.mil/oas/onrpgahm.htm

LONG-TERM GOALS

The long-term goal of this project was to develop the theory and computational simulation capabilities related to fundamental problems in several canonical regimes of oceanic currents. The three regimes are wind-driven gyres and the associated mesoscale eddies in bounded, mid-latitude basins; coastal currents near irregular coastlines and topography and the small-scale eddies they engender; and marine planetary boundary layers, in both the lower atmosphere and upper ocean, with plumes, vortices, surface gravity waves, and Langmuir circulations. The organizing focus of the research is on the coherent spatial patterns that spontaneously emerge in the turbulent flows typical of these different regimes and that subsequently dominate both the flow evolution and the associated transport of material by the currents.

OBJECTIVES

The objectives of this project were **(1)** to develop the fundamental mathematical theory, where advances seem feasible that are relevant to the regimes above, and **(2)** to develop algorithms and obtain accurate computational solutions of paradigmatic examples of these regimes; to educe the dominant coherent structures; to analyze their space-time behavior and their governing dynamical processes; and to integrate parcel trajectories in the velocity fields they provide to determine their mechanisms of material transport.

APPROACH

The scientific methodology was theory and computation. This body of research was done as part of a mature research program, wherein the computational models and solutions from other projects were extended to meet the objectives above and personnel from these other projects participated here on a part-time basis. Furthermore, the work was done partly in collaboration with other oceanographers—and communicated through interdisciplinary seminars and workshops—to increase the cross-fertilization between mathematics, computational science, and oceanography. The products of the project are primarily the scientific publications listed below, about half of which are on topics not in the direct line of work on the other grants.

Support at UCLA was provided by this grant for Annalisa Bracco and Paul Graves (graduate students); Pavel Berloff, Jeroen Molemaker, and Alexander Shchepetkin (postdoctoral researchers); and Irad Yavneh and Jim McWilliams (visiting and resident faculty). The research helped us sustain substantial collaborations with Sonya Legg (WHOI), Peter Sullivan (NCAR), Juan Restrepo (University of Arizona), and Jeffrey Weiss (University of Colorado).

WORK COMPLETED

The work completed under this project is reported in the publications listed below (cited here as numbers in brackets).

New mathematical theories were developed for the following problems: **(1)** the limits of integrability for rotating, stratified currents that satisfy the constraint of gradient-wind momentum balance, as do most large-scale and mesoscale currents [2, 9, 25]; **(2)** high-order, parametrically randomized Markov trajectory models for transport by geostrophic currents [24, 26]; **(3)** asymptotic (*i.e.,* wave-averaged), coupled evolution equations for currents and surface-gravity waves in the upper ocean [35, 41]; and (**4**) coherent vortex adjustment and recovery in response to small-scale perturbations that evolve as vortex Rossby waves [27].

Computational solutions were obtained and analyzed for the following oceanic regimes: wind gyres at large Reynolds number [10, 11, 17]; transport of material in wind gyres [22, 24, 26]; Stokes-Ekman currents and sea-level bias in altimetry analysis due to surface gravity waves [41, 44]; geostrophic turbulence [2, 7, 12, 15] and isolated mesoscale eddy dynamics [1, 5, 14, 23]; linear instabilities of gradient-wind balanced currents to unbalanced, small-scale motions [3, 6, 18, 21, 25]; material transport by mesoscale eddies [7, 8, 13, 14, 16, 20]; convective plumes and their interaction with mesoscale eddies [4, 13, 16, 19, 40]; statistical equilibrium dynamics of eastern-boundary (upwelling) currents in subtropical gyres [29, 30, 32, 33]; buoyancy- and stress-driven marine planetary boundary layers [19, 37, 38, 39, 40]; Langmuir turbulence in the oceanic boundary layer [36, 43, 44]; and surface gravity wave influences in the atmospheric boundary layer [42, 44, 45].

New computational algorithms were developed for the following numerical models and their components: an iterative, multi-grid method for the time integration of the gradient-wind balance equations within the limits of their integrability [2]; an accurate, shape-preserving, weakly dissipative advection algorithm for incompressible flows [28]; and methods for stable, open-domain boundary conditions for long-time integrations of regional models, for accurate pressure-gradient force in terrain-following coordinates, and for stable time integration with a free upper surface using a large time-step size [30, 31, 34]. The latter are important elements in the Regional Oceanic Modeling System (ROMS), in which we are playing a lead developmental role.

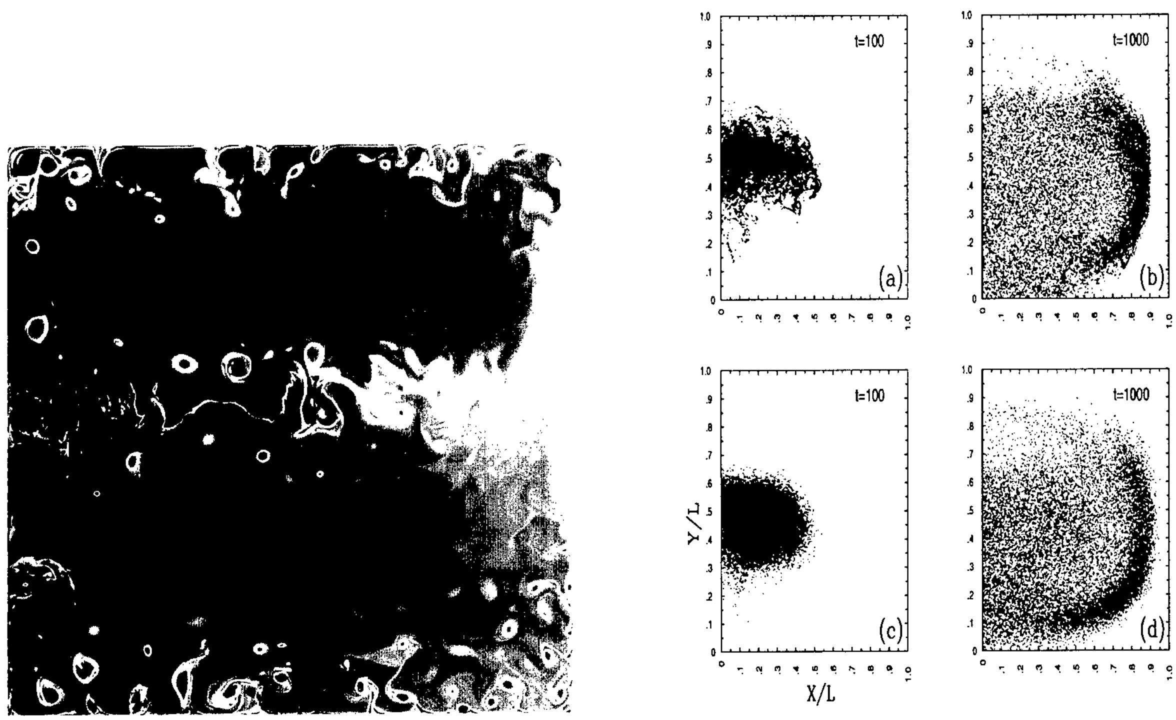

Figure 1: Wind-driven oceanic gyres. **Left**: Instantaneous horizontal distribution of potential vorticity in the upper ocean, showing the two large-scale gyres, the western boundary current and its separated meandering interior extension, and many coherent mesoscale vortices [17]. L is the basin dimension. **Right**: Horizontal distributions of an ensemble of particles released at random times in the southern-gyre western-boundary current: left column, after 100 days; right column, after 1000 days; top row, fluid-dynamical simulation; bottom row, 3rd-order Markov stochastic trajectory model [24].

RESULTS

Here we present a few results as highlights from the work done.

Wind Gyres and Mesoscale Eddies

We idealize the problem of wind-driven, mid-latitude circulation as the statistical equilibrium state of a rotating, stably stratified fluid in a bounded domain in response to a steady, spatially varying surface stress. This solution exhibits a sequence of bifurcations towards a kind of fully developed turbulence as the Reynolds number Re is increased. By obtaining computational solutions for unprecedentedly large Re and intergration times, we have been able to demonstrate two important phenomena. One is that increasing circulation variance with Re develops at large-scales and low-frequencies (*i.e.*, thousands of km and years), in addition to the primary instabilities of the gyre circulation at the mesoscale [10]. Insofar as this variability influences the surface temperature and thus the atmosphere—yet to be assessed—this is thus a source of interannual natural variability in climate. The second phenomenon is the increasing emergence with Re of coherent vortices as the dominant structural form of the mesoscale eddies, embedded within the basin-filling gyre circulations in Fig. 1-Left [17].

We have analyzed how these distinctive fluctuating current patterns transport material on the scale of the gyres, *i.e.*, on a scale relevant to equilibrating and changing the general circulation. Also, we have developed a hierarchy of spatially inhomogeneous and anisotropic, stochastic trajectory models, using the formalism of Markov processes of order n, to mimic these large-scale transport rates with mathematically much smaller and simpler calculations than with fluid dynamics. This is done by fitting the stochastic model parameters to statistics calculated from the fluid dynamical simulations. We have found that using orders $n = 2$ and $n = 3$ greatly improves the transport mimicry, compared to the more traditional orders of $n = 0$ (*i.e.*, random walk or eddy diffusion) and $n = 1$ (Langevin), because they admit anomalous dispersion behavior at times intermediate between the mesoscale and gyre scale [24, 26]. An illustration of the transport pattern and stochastic simulation skill is in Fig. 1-Right, at two times relevant to how quickly material spreads to fill the southern gyre ($t = 100$ days after particle release) and how slowly it subsequently spreads into the northern gyre ($t = 1000$ days).

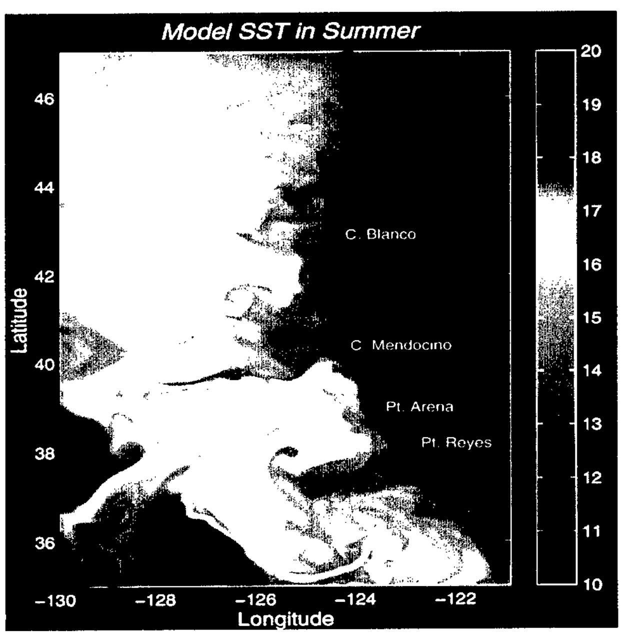

Figure 2: Instantaneous sea-surface temperature [^{o} C] along the U.S. West Coast showing coastal upwelling and coherent squirts, jets, and hammerhead vortices transporting the cold water into the interior [33].

Coastal Currents

We have been developing the Regional Oceanic Circulation Model (ROMS) and using it to investigate the current structure and transport in the upwelling region off the U.S. West Coast. Our essential conception of this regime is that it is a statistical equilibrium, regional response to the mean-seasonally varying winds, in particular the equatorward/alongshore wind that is strongest in spring and summer [33]. Simulated sea-surface temperature patterns (Fig. 2) are morphologically similar to satellite images of temperature and color (*i.e.*, biological abundance). These patterns are controlled by the mesoscale and sub-mesoscale ($\sim$ 10 km) eddies that arise from instabilities of the mean along-shore currents, with strong alongshore modulation by the coastline irregularities (*e.g.*, offshore squirts more often near capes). There is progressive movement of mean-seasonal currents and eddy energy offshore and downwards into the oceanic interior in an annually recurrent cycle, as well as in response to interannual events such as El Niño. Since this oceanic region is one of atypically high sediment stirring, biological productivity, and biogeochemical cycling, the transports by these distinctive eddy currents are important to further diagnose and understand, and we now have a simulation capability that can be exploited for this.

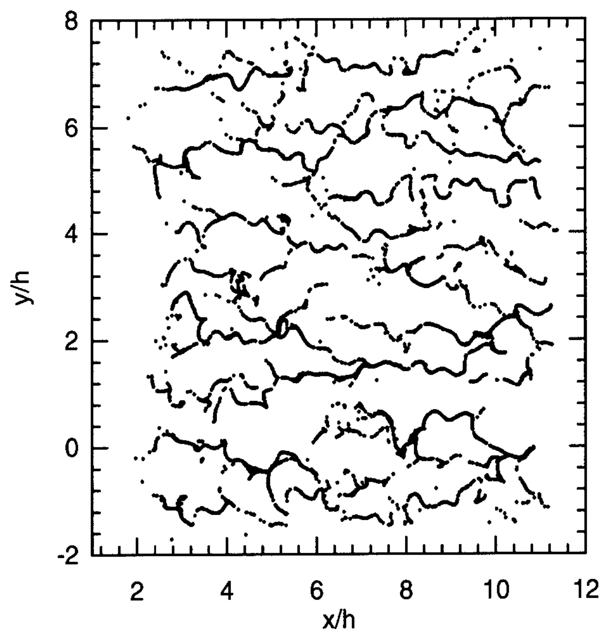

Figure 3: Instantaneous horizontal distribution of buoyant particles at the sea surface at a time 15 minutes after being released randomly. The evident pattern of convergence lines is due to Langmuir circulations in an oceanic planetary boundary layer with wind stress and surface gravity waves' Stokes drift [36]. h is the boundary layer depth.

Marine Planetary Boundary Layers

Oceanic surface gravity waves have a mean Lagrangian motion, the Stokes drift. The dynamics of wind-driven oceanic currents in the presence of Stokes drift are modified by the addition of so-called vortex forces and wave-induced material advection, as well by wave-averaged effects in the surface boundary conditions for the dynamic pressure, sea level, and vertical velocity, for which we have derived a formal asymptotic theory based on the separation of time scales between waves and currents [35, 41]. These effects are significant on the basin scale, where they imply modifications of the traditional oceanographic prescriptions for the Ekman and Sverdrup transports and for the use of satellite altimeters to infer surface dynamic pressure. They are also significant on the much smaller scale of planetary boundary-layer turbulence in the upper ocean. For typical wind and wave conditions, the vortex forces give rise to Langmuir circulations (*i.e.,* strong roll cells aligned with the wind direction), which substantially increase the vertical mixing efficiency across the boundary layer, compared to shear boundary layers without wave influences [36, 43]. Langmuir circulations are familiar to mariners for their gathering of surfactants into convergence lines, and our computational simulations based on the wave-averaged theory manifest such lines with varying degrees of pattern irregularity depending upon the degree of wave influence (Fig. 3).

IMPACT/APPLICATIONS

The primary impacts are through the scientific discoveries and insights reported in publications, but the accompanying developments for the Large-Eddy Simulation code (at NCAR) and the Regional Oceanic Systems Model (at UCLA) benefit other users and their applications.

TRANSITIONS

At present there is no evident, continuous path for doing the type of research that this grant has provided a foundation for. The serendipitous conjunction of oceanography and geophysical fluid dynamics with computational and applied mathematics is, in my now extensive experience, a very fruitful arena for making advances in fundamental theory and concepts, but it is not an approach that is regularly supported by public agencies. Opportunities for continuation will be sought, partly by occasional inquiries to ONR programs.

RELATED PROJECTS

This research was done partially overlapping in time and contents with two other ONR programs that had the following grants:

Intermittency and Coherent Structures near the Air-Sea Interface in the Planetary Boundary Layers, N00014-92-F-0117, 1992-1998, PI C.-H. Moeng, Co-PI J. McWilliams & Surface Gravity Waves and Coupled Marine Boundary Layers, N00014-00-C-0180 and -10249, 1999 to 2006, PI C.-H. Moeng, Co-PI J. McWilliams.

Deep Convection in the Ocean, N00014-95-0316 and 1-0889, 1995-1998, PI J. McWilliams.

PUBLICATIONS

1. Wind Gyres and Mesoscale Eddies

[1] Morel, Y., & J.C. McWilliams, 1997: Evolution of isolated interior vortices in the ocean. *J. Phys. Ocean.* **27**, 727-748.

[2] Yavneh, I., A.F. Shchepetkin, J.C. McWilliams, & L.P. Graves, 1997: Multigrid solution of rotating, stably stratified flows: The balance equations and their turbulent dynamics. *J. Comp. Phys.* **136**, 245-262.

[3] Smyth, W.D. & J.C. McWilliams, 1998: Instability of an axisymmetric vortex in a stably stratified rotating environment. *Theor. and Comp. Fluid Dyn.* **11**, 305-322.

[4] Legg, S., J.C. McWilliams, & J. Gao, 1998: Localization of deep ocean convection by a geostrophic eddy. *J. Phys. Ocean.* **48**, 944-970.

[5] Sutyrin, G.G., J.C. McWilliams, & R. Saravanan, 1998: Co-rotating stationary states and vertical alignment of geostrophic vortices with thin cores. *J. Fluid Mech.* **357**, 321-349.

[6] McWilliams, J.C., & I. Yavneh, 1998: Fluctuation growth and instability associated with a singularity of the Balance Equations. *Physics of Fluids* **10**, 2587-2596.

[7] Hua, B.L., J.C. McWilliams, & P. Klein, 1998: Lagrangian acceleration and dispersion in geostrophic turbulence. *J. Fluid Mech.* **366**, 87-108.

[8] Weiss, J.B., A. Provenzale, & J.C. McWilliams, 1998: Lagrangian dynamics in high-dimensional point-vortex systems. *Phys. Fluids* **10**, 1929-1941.

[9] McWilliams, J.C., I. Yavneh, M.J.P. Cullen, & P.R. Gent, 1998: The breakdown of large-scale flows in rotating, stratified fluids. *Phy. Fluids* **10**, 3178-3184.

[10] Berloff, P.S., & J.C. McWilliams, 1999a: Large-scale, low-frequency variability in wind-driven ocean gyres. *J. Phys. Ocean* **29**, 1925-1949.

[11] Berloff, P.S., & J.C. McWilliams, 1999b: Quasigeostrophic dynamics of the western boundary current. *J. Phys. Ocean* **29**, 2607-2634.

[12] McWilliams, J.C., J.B. Weiss, & I. Yavneh, 1999: The vortices of homogeneous geostrophic turbulence. *J. Fluid Mech.* **401**, 1-26.

[13] Legg, S., & J.C. McWilliams, 1999: Temperature and salinity variability in heterogeneous oceanic convection. *J. Phys. Ocean.* **30**, 1188-1206.

[14] Von Hardenberg, J., J.C. McWilliams, A. Provenzale, A. Shchepetkin, J.B. Weiss, 2000: Vortex merging in quasigeostrophic flows. *J. Fluid Mech.* **412**, 331-353.

[15] Bracco, A., J.C. McWilliams, G. Murante, A. Provenzale, & J.B. Weiss, 2000: Revisiting two-dimensional turbulence at modern resolution. *Physics of Fluids* **12**, 2931-2941.

[16] Legg, S., & J.C. McWilliams, 2001: Convective modifications of a geostrophic eddy field. *J. Phys. Ocean.* **31**, 874-891.

[17] Siegel, A., J.B. Weiss, J. Toomre, J.C. McWilliams, P. Berloff, & I. Yavneh, 2001: Eddies and vortices in ocean basin dynamics. *Geophys. Res. Lett.* **28**, 3183-3186.

[18] Molemaker, M.J., J.C. McWilliams, & I. Yavneh, 2000: Instability and equilibration of centrifugally-stable stratified Taylor-Couette flow. *Phys. Rev. Lett.* **86**, 5270-5273.

[19] Legg, S., K. Julien, J. McWilliams, & J. Werne, 2001: Vertical transport by convective plumes: modification by rotation. *Physics and Chemistry of the Earth* **26**, 259-262.

[20] Legg, S., & J.C. McWilliams, 2001: Sampling characteristics from isobaric floats in a convective eddy field. *J. Phys. Ocean*, **31**, 874-891.

[21] Yavneh, I., J.C. McWilliams, & M.J. Molemaker, 2001: Non-axisymmetric instability of centrifugally stable, stratified Taylor-Couette flow. *J. Fluid. Mech.* **448**, 1-21.

[22] Berloff, P., J.C. McWilliams, & A. Bracco, 2001: Material transport in the mid-latitude oceanic circulation. *J. Phys. Ocean.*, in press.

[23] Morel, Y., & J.C. McWilliams, 2001: Effects of isopycnal and diapycnal mixing on the stability of oceanic currents. *J. Phys. Ocean.*, in press.

[24] Berloff, P., & J.C. McWilliams, 2001a: Material transport in oceanic gyres. Part II: Hierarchy of stochastic models. *J. Phys. Ocean.*, in press.

[25] McWilliams, J.C., M.J. Molemaker, & I. Yavneh, 2001: From stirring to mixing of momentum: Cascades from balanced flows to dissipation in the oceanic interior. *'Aha Huliko'a Proceedings: 2001*, U. Hawaii, in press.

[26] Berloff, P., & J.C. McWilliams, 2001b: Material transport in oceanic gyres. Part III: Randomized stochastic models. In preparation.

[27] McWilliams, J.C., L.P. Graves, & M.T. Montgomery, 2001: A formal theory for vortex Rossby waves and vortex evolution. In preparation.

2. Coastal Currents

[28] Shchepetkin, A., & J.C. McWilliams, 1998: Quasi-monotone advection schemes based on explicit locally adaptive dissipation. *Monthly Weather Review* **126**, 1541-1580.

[29] Miller, A.J., J.C. McWilliams, N. Schneider, J.S. Allen, J.A. Barth, R.C. Beardsley, T.K. Chereskin, C.A. Edwards, R.L. Haney, K.A. Kelly, J.C. Kindle, L.N. Ly, J.R. Moisan, M.A. Noble, P.P. Niiler, L.Y. Oey, F.B. Schwing, R.K. Shearman, & M.S. Swenson, 1999: Observing and modeling the California Current System. *EOS* **80**, 533-539.

[30] Marchesiello, P., J.C. McWilliams, & A. Shchepetkin, 2001a: Open boundary conditions for long-term integration of regional ocean models. *Ocean Modelling* **3**, 1-20.

[31] Shchepetkin, A.F., & J.C. McWilliams, 2001: A method for computing horizontal pressure-gradient force in an oceanic model with a non-aligned vertical coordinate. *Int. J. Numer. Methods in Fluids*, submitted.

[32] Song, Y.T., Y. Chao, P. Marchesiello, & J.C. McWilliams, 2001: A computational study of the role of topography in coastal upwelling and cross-shore exchange. *J. Phys. Ocean*, submitted.

[33] Marchesiello, P., J.C. McWilliams, & A. Shchepetkin, 2001b: Equilibrium structure and dynamics of the California Current System, *J. Phys. Ocean*, submitted.

[34] Shchepetkin, A.F., & J.C. McWilliams, 2001b: The Regional Oceanic Modeling System: A split-explicit, free-surface, topography-following-coordinate oceanic model. In preparation.

[35] McWilliams, J.C., & J. Restrepo, 2001: Interaction of waves and currents in shallow coastal waters. In preparation.

3. Marine Planetary Boundary Layers

[36] McWilliams, J.C., P.P. Sullivan, & C.-H. Moeng, 1997: Langmuir turbulence in the ocean. *J. Fluid Mech.* **334**, 1-30.

[37] Lin, C.-L., C.-H. Moeng, P.P. Sullivan, & J.C. McWilliams, 1997: The effect of surface roughness on flow structures in a neutrally stratified planetary boundary layer flow. *Physics of Fluids* **9**, 3225-3249.

[38] Wang, D., J.C. McWilliams, & W.G. Large, 1998: Large Eddy Simulation of the diurnal cycle of deep equatorial turbulence. *J. Phys. Ocean.* **28**, 129-148.

[39] McWilliams, J.C., C.-H. Moeng, & P.P. Sullivan, 1999: Turbulent fluxes and coherent structures in marine boundary layers: Investigations by Large-Eddy Simulation. In: *Air-Sea Exchange: Physics, Chemistry, Dynamics, and Statistics*, G. Geernaert, ed., 507-538.

[40] Julien, K., S. Legg, J.C. McWilliams, & J. Werne, 1999: Plumes in rotating convection. Part 1. Ensemble statistics and dynamical balances. *J. Fluid Mech.* **391**, 151-187.

[41] McWilliams, J.C. & J.M. Restrepo, 1999: The wave-driven ocean circulation. *J. Phys. Ocean* **29**, 2523-2540.

[42] Sullivan, P.P., J.C. McWilliams, & C.-H. Moeng, 2000: Simulations of turbulent flow over idealized water waves. *J. Fluid Mech.* **404**, 47-85.

[43] McWilliams, J.C., & P.P. Sullivan, 2001: Vertical mixing by Langmuir circulations. *Spill Science and Technology* **6**, 225-237.

[44] McWilliams, J.C., & P.P. Sullivan, 2001: Surface-wave effects on winds and currents in marine boundary layers. In: *Environmental Fluid Dynamics*, J. Lumley, ed., Sringer-Verlag, in press.

[45] Sullivan, P.P., & J.C. McWilliams, 2001: Turbulent flow over water waves in the presence of stratification, *Physics of Fluids*, submitted.