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13. ABSTRACT

This is a grant for a theoretical and computational research program on the nonlinear dynamics of ocean currents. Its particular targets are the coherent patterns of flow which emerge in turbulence, and the mechanisms they provide for the transport and mixing of material properties in the fluid. This type of behavior is believed to occur quite generally, and this belief is tested by focusing on four oceanic regimes: (1) mid-latitude, wind-driven gyres and mesoscale eddies in bounded ocean basins, (2) coastal currents near irregular topography and coastlines and the eddies they generate, (3) plumes, vortices, and Langmuir cells in marine planetary boundary layers, in both the lower atmosphere and upper ocean, and (4) the dynamical influences of surface gravity waves on upper ocean currents and eddies through the vortex force proportional to their Stokes drift and other time-averaged effects, both in deep water and in the littoral zone. As a general framework for these particular topics, research also is being done on the general theory of vortices, geophysical turbulence, and Lagrangian dynamics, as well as on improvements in computational methods.

The methodology in each regime is to obtain accurate computational solutions of canonical examples of the phenomena using a collection of (mostly) previously developed numerical models, to educe the dominant coherent structures and analyze their space-time behavior and governing dynamical processes, and to integrate families of parcel trajectories in the velocity fields they provide to determine their mechanisms for Lagrangian transports.

This research is done as part of a mature research program, wherein the numerical models and solutions coming from other projects are extended to meet the objectives above, and personnel from these projects participate to a limited degree. Furthermore, this research is done partly in collaboration with other oceanographers and applied and computational mathematicians, in part to cross fertilize between these disciplines.

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ATTENTION: Wen C. Masters
Program Officer

SUBJECT: Annual Performance Report for N00014-98-1-0165
P. I.: James C. McWilliams

Dear Dr. Masters:

In accordance with the requirements of the subject grant, please find enclosed original and (2) copies of the Annual Performance Reports.

If you have any questions about the enclosed documents, please feel free to call Professor James C. McWilliams at (310) 206-2829.

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Sincerely yours,

Keith R. Olwin, Executive Administrator
Institute of Geophysics and
Planetary Physics

Enclosure:

cc: J. C. McWilliams
Naval Research Laboratory
Naval Research Regional Office
Defense Technical Information Center

Office of Naval Research
Principal Investigator's Progress Report
COHERENT SPATIAL PATTERNS AND MATERIAL TRANSPORT IN OCEANIC FLOWS
ONR Contract Number ONR N00014-98-1-0165

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For the period 1 November 1997 to 31 October 1998

This contract is for theoretical and computational research on several canonical regimes of oceanic currents. Its organizing theme is the coherent spatial patterns which spontaneously emerge in the types of turbulence typical of these different regimes and which subsequently dominate both the flow dynamics and the associated transport of material properties. The progress report covers all relevant research by the Principal Investigator, which is broader than the particular activities paid for through this contract. Bracketed references are to the appended Bibliography of "active" papers during the reporting period.

GENERAL THEORY OF VORTICES, TURBULENCE, AND LAGRANGIAN DYNAMICS

A pervasive behavior in ocean circulation is geostrophic or gradient-wind momentum balance between Coriolis, centrifugal, and pressure-gradient horizontal forces; this behavior is relevant to several of the canonical regimes discussed below. Advances have been made in understanding the trajectories of material-transporting Meddies [MM], interactions among material-transporting coherent vortices in homogeneous turbulence [MWY, SMS, WPM, YSMG], and the mathematical structure and spatial patterns of Lagrangian accelerations [HMK]. Another research subject is the dynamical boundary between the "slow" balanced motions and faster inertia-gravity waves; in this category advances have been made in understanding the adjustment to balance in a non-rotating, stably stratified fluid [LeM] and in an identification of PDE change-of-type boundary for the nonlinear Balance Equations which appears to often, and perhaps generally, coincide with the onset of "fast" instabilities, one of which had not previously been identified [MY, MYCG, SM]. Future research will address the generality of this new fast instability.

WIND-DRIVEN GYRES AND MESOSCALE EDDIES

Wind-driven gyres have narrow boundary currents and are unstable to mesoscale eddies. We are calculating families of idealized numerical solutions for this regime. Advances have been made in demonstrating the existence of large-scale, low-frequency intrinsic variability associated with reshaping the eddy-intensified off-shore Gulf Stream and its recirculation zones [BMa]; the onset of instability within the Western Boundary Current prior to its separation point [BMb]; the simultaneous convergence of large-scale mean currents and eddy fluxes and divergence of the coherent-eddy distribution functions as the numerical resolution and Reynolds number increase [SMTW]; and the efficient generation of spiciness (i.e., density compensating fluctuations in temperature and salinity) by fluctuating currents in the presence of large-scale mean T and S gradients [SDDM]. A substantial new enterprise is diagnosing a variety of Lagrangian statistics in this regime, including material trajectories and transport mechanisms. We have evaluated a Lobe-Dynamics characterization for cross-jet fluxes in weakly transient solutions near the root of the bifurcation sequence (in parallel with Wiggins *et al.*), and we are developing a spatially inhomogeneous stochastic trajectory (i.e., Langevin-Markov) model for simulating complex, chaotic gyre transports in the fully developed turbulent regime beyond the root of the sequence. Another future research topic is the influence of topographic slopes on the dynamics and transport of Western Boundary Currents.

COASTAL CURRENTS

Our primary effort here has been to develop a new model capable of realistic coastal simulations, which we will apply both to the U.S. West Coast and more idealized problems. The new model has important algorithmic improvements in advection, topographic representation, time-stepping of stiff gravity waves, and open boundary conditions [SAHMM]. The initial simulations have been for the mean seasonal cycle of the West Coast circulation at a sequence of grid-resolutions that extend to vigorous coastal eddy cycles involving topographically triggered "squirts and jets" in the cross-shore material transports [MaMS]. We are currently assessing this solution in comparison with CalCOFI and satellite SST, SAR, color images and altimetry. Future research is to further extend the development to include biogeochemical cycles and transports and embedded sub-domains for very fine resolution in particular locations. We also will develop idealized solutions for topography-jet-eddy interactions and material transport to investigate the influence of fine-scale boundary complexity.

MARINE PLANETARY BOUNDARY LAYERS

As part of the ONR Deep Convection Labrador Sea experiment, we have investigated the way that the coherent structures of deep convection contribute to the buoyancy flux in this regime. This research includes a study of buoyant plumes in homogeneous convection [JLMW], but it is primarily focused on how prior mesoscale eddies ("preconditioning") establish a persistent spatial heterogeneity after convection arises. This heterogeneity alters the net vertical profile of temperature change through secondary circulations around the eddies [LMG], it induces substantial spiciness in interior T-S fluctuations [LMa], it creates a post-convection relaxation process that homogenizes and restratifies the region outside of surviving eddies but maintains persistent material anomalies inside them [LMb], and it causes Lagrangian measurements (e.g., from floats) to be biased in their sampling characteristics by focusing material trajectories in particular locations [LMc]. As part of the ONR Marine Boundary Layer experiments, we have examined how coherent structures carry momentum, buoyancy, and material fluxes through buoyancy- and stress-driven oceanic and atmospheric boundary layers [LMSM, WML, MMS]. We have demonstrated the nature of "Langmuir turbulence" that arises in Large-Eddy Simulations (LES) based on a theory of averaging over weakly nonlinear surface gravity waves and shown good qualitative agreement in near-surface debris patterns seen by mariners and measured by sonars [MSM]. We have developed a LES code that allows a moving surface, through which we impose gravity wave motions within the boundary layers [SMM]. Future research will be on resolved (rather than *a priori* averaged) surface wave effects by Stokes drift, wave-correlated material and momentum vertical fluxes, and wave-breaking giving enhanced near-surface stirring and dissipation.

EFFECTS OF SURFACE GRAVITY WAVES ON OCEAN CURRENTS

In addition to the wave-related boundary-layer research described above, we have derived a general theory of how weakly nonlinear surface gravity waves provide dynamical influences on the lower-frequency currents, largely through the action of the Lagrangian Stokes drift but also through altered surface boundary conditions [MR]. This theory is applied to the mean basin-scale circulation, with the prediction that the classical Ekman and Sverdrup transport laws apply to the mean Lagrangian flow (i.e., have a wave-driven component as well); we hope that a new ONR experiment can be devised to test this prediction. Another important prediction is that satellite altimetry and other measurements of sea level need to be corrected for a wave-averaged bias before being interpreted as the geostrophic dynamic pressure. These predictions are evaluated using a global wind climatology and an empirical equilibrium wind-wave relationship. Future research will address wave-current interactions in shallow coastal areas, again in a wave-phase-averaged theory.

NUMERICAL METHODS

New algorithmic developments are needed in our computational models for the above phenomena. Recent advances are a new quasi-monotone advection operator discretization [SchM], a multigrid solver for the Balance Equations [YSMG], a moving surface in our LES code [MMS, SMM], and the Regional Ocean Modeling System for coastal circulation [SAHMM].

PERSONNEL AND FUNDS

The principal expenditure under this contract has been for Dr. Pavel Berloff's salary. In addition, a month's summer salary was paid to Prof. Jeffrey Weiss (University of Colorado) for his collaboration. In the coming year, support will be drawn for Dr. Berloff and perhaps Drs. Alexander Shchepetkin and Jeroen Molemaker (a recent Ph.D. graduate from the University of Utrecht). Another possibility could be partial salary support for Prof. Irad Yavneh if he opts for a sabbatical at UCLA next year (if so, a budget increment might be requested).

August 1998

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