

Statistical Physics for Stronger Ocean Modeling

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LONG-TERM GOALS

Our aim is to improve parameterizations of subgrid-scale motions, including eddies, diapycnal mixing and shelf/slope exchange. In applying such parameterizations, we seek to build stronger capability for realistic ocean models and forecasts.

OBJECTIVES

Having largely met our goals of testing statistical mechanics-based eddy parameterization and strengthening its theoretical foundations, we have shifted attention toward improving model representations of diapycnal mixing, which is highly heterogeneous and process-dependent. We have sought to develop explicit expressions for the parameter dependence of double-diffusive mixing, and to assess the importance of differential transport of T and S by intermittent weak turbulence. We also seek to determine parameter dependences of shelf-slope exchange processes, which are neglected in most circulation models.

APPROACH

In further developing and testing statistical mechanics-based parameterization of eddies, we have continued to (i) numerically test underlying concepts [Merryfield and Holloway], and (ii) apply practical descriptions of entropy-gradient forcing in ocean circulation models, comparing against other parameterizations and observational data [Holloway, collaborators M. England (UNSW), L. Nazarenko (Goddard Inst.), X. Zhang and T. Sou (IOS)]. Modeling efforts have focussed on the Arctic and North Atlantic Oceans, where known anthropogenic tracer pathways enable quantitative comparisons.

In developing parameterizations of diapycnal mixing, we have employed numerical process models which yield explicit values for fluxes and advance physical understanding [Merryfield, Holloway, undergrad M. Grinder, collaborator A. Gargett (IOS)].

To develop better knowledge of the parametric dependence of shelf/slope exchange processes, we employ layered numerical models of shelf-slope circulation [Holloway, grad student D. Eurin, co-sponsored by S. Allen, UBC].

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WORK COMPLETED

Development was undertaken of improved Arctic models for use in appraising eddy parameterizations (e.g., Nazarenko, Holloway and Tausnev 1998). In one such model, restoring surface boundary conditions were replaced by more realistic heat and fresh water flux schemes incorporating long wave, short wave, sensible and latent heat fluxes, precipitation, river runoff and evaporation, and heat and fresh water exchange with snow and sea ice. To model tracer pathways reliably requires some representation of boundary inflow and outflow. In this model, boundary baroclinic velocities are set to geostrophic flow implied by Levitus climatology. Outflows carry interior tracer values, and inflows are assigned a blend of interior values and climatological data. A second model eliminates the need for uncertain open boundary treatments by means of a rotated and stretched grid which concentrates resolution in the Arctic while allowing exchange with a more coarsely resolved global ocean. The model incorporates an elastic-plastic-viscous ice submodel (Hunke and Dukowicz 1998), and surface fluxes based on observed air temperature, specific humidity, and precipitation.

A code previously developed for solving the Boussinesq equations in two dimensions was modified to represent large-aspect ratio diffusive intrusions. Parameterizations for double-diffusive, convective, and background turbulent fluxes were incorporated.

Development continued of a layered model for shelf/slope exchange studies.

RESULTS

Further computations were undertaken of two-layer quasigeostrophic flow over ridges and seamounts. In one set of runs, forcing was applied in both layers instead of in the top layer alone. As before, upper-layer mean flow reversed sense when “bottom friction” (lower-layer Rayleigh damping) became sufficiently large. These surprising reversals, which are consistent with entropy-gradient forcing, are therefore not a consequence of forcing the upper layer alone. When smooth rather than bumpy topography was considered, reversals occurred for much lower values of Rayleigh damping than before (Fig. 1). This is consistent with a weakening of entropy-gradient forcing in the absence of topographic roughness.

A study undertaken with M. England compared modeled chlorofluorocarbon (CFC) distributions in the North Atlantic with those observed (England and Holloway 1998). Among models with realistic surface forcing, a model using statistical-mechanical eddy parameterization produced the most realistic CFC distributions due to its superior representation of the deep western boundary undercurrent.

A second modeling study examined Arctic transport pathways for Atlantic inflow (Nazarenko, Holloway and Tausnev 1998). A model using statistical-mechanical eddy parameterization exhibited pathways in qualitative agreement with (somewhat sparse) observations, whereas a model using conventional eddy-viscosity parameterization was in very poor agreement.

Expressions for vertical heat and salt fluxes from salt fingering were developed using simple theoretical arguments. The value of a parameter in these expressions was calibrated using fluxes from explicit simulations of fingering at density ratios $R_\rho = \alpha \partial_z T / \beta \partial_z S$ ranging from

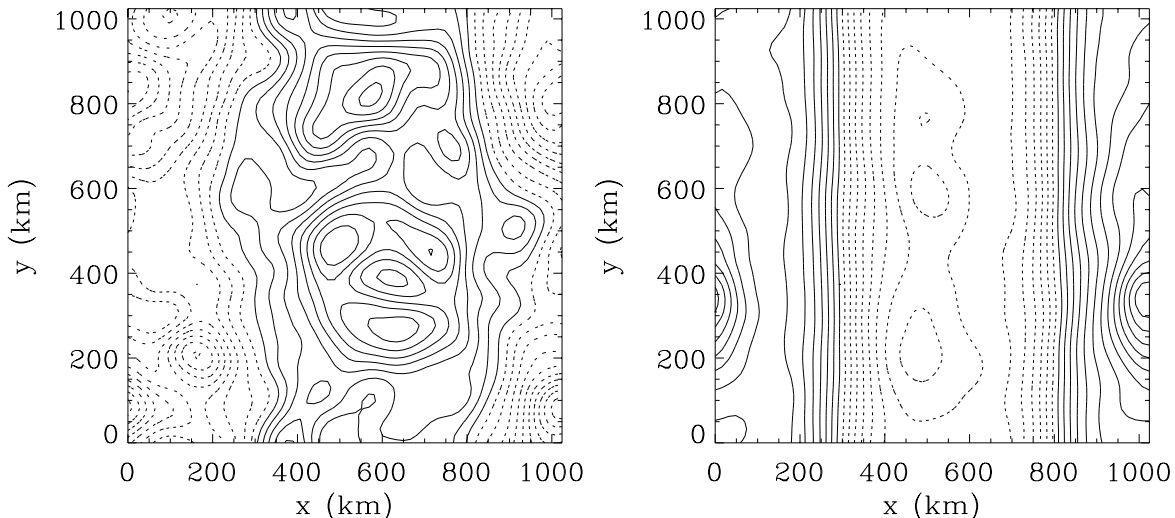


Figure 1: Streamlines for upper-layer mean flow over a bumpy ridge (left) and smooth ridge (right) subject to identical forcing and dissipation. Solid lines denote positive and dashed lines negative values; a two-layer quasigeostrophic model is considered. The reversed sense of flow for the smooth ridge is consistent with the idea that fluctuations drive mean flow toward higher entropy (Merryfield and Holloway 1998).

1.25 to 20. The resulting effective diffusivities K_S and K_T for salt and heat are

$$K_S \approx 0.09(1 - \tau R_\rho)/(R_\rho - 1) \text{ cm}^2\text{s}^{-1},$$

$$K_T \approx K_S(R_\rho)R_f/R_\rho,$$

where $\tau \approx 0.01$ is the ratio of molecular salt to heat diffusivity, and flux ratio R_f is a weakly varying function of R_ρ which remains within 10% of 0.56 for $1.25 \leq R_\rho \leq 20$.

Computations also were undertaken of vertical mixing across stabilizing T and S gradients by bursts of microscale turbulence in two dimensions (Merryfield, et al. 1998a). Effective diffusivities for T exceeded those for S in all instances. A regime was identified in which the fluxes significantly differ, and exceed the thermal conductive flux by at least an order of magnitude. This suggests that the hypothesis that diapycnal mixing coefficients for T and S may differ (Gargett and Holloway 1992) should be taken seriously.

Numerical simulations of diffusive intrusions unexpectedly showed that intrusions can evolve into thermohaline staircases containing alternating fingering and convective layers, as well as “conventional” intrusions containing pronounced T and S inversions (Fig. 2). This prompted a theoretical investigation of the parameter dependence of these two outcomes. Conclusions are that (i) staircases occur for R_ρ below a threshold value (ii) threshold R_ρ increases as the level of background turbulence decreases (iii) threshold R_ρ increases as effective Prandtl number decreases. This suggests that staircases occur where R_ρ and/or turbulence levels are especially low, much as observed (Schmitt 1994). An important implication for models which parameterize diapycnal mixing due to salt fingering is that net transports can be countergradient due to the advective contribution from intrusive motions.

Numerical simulations also were undertaken of double-diffusive intrusions growing at a thermohaline front. Intrusions developed much as in the laterally uniform computations of Walsh

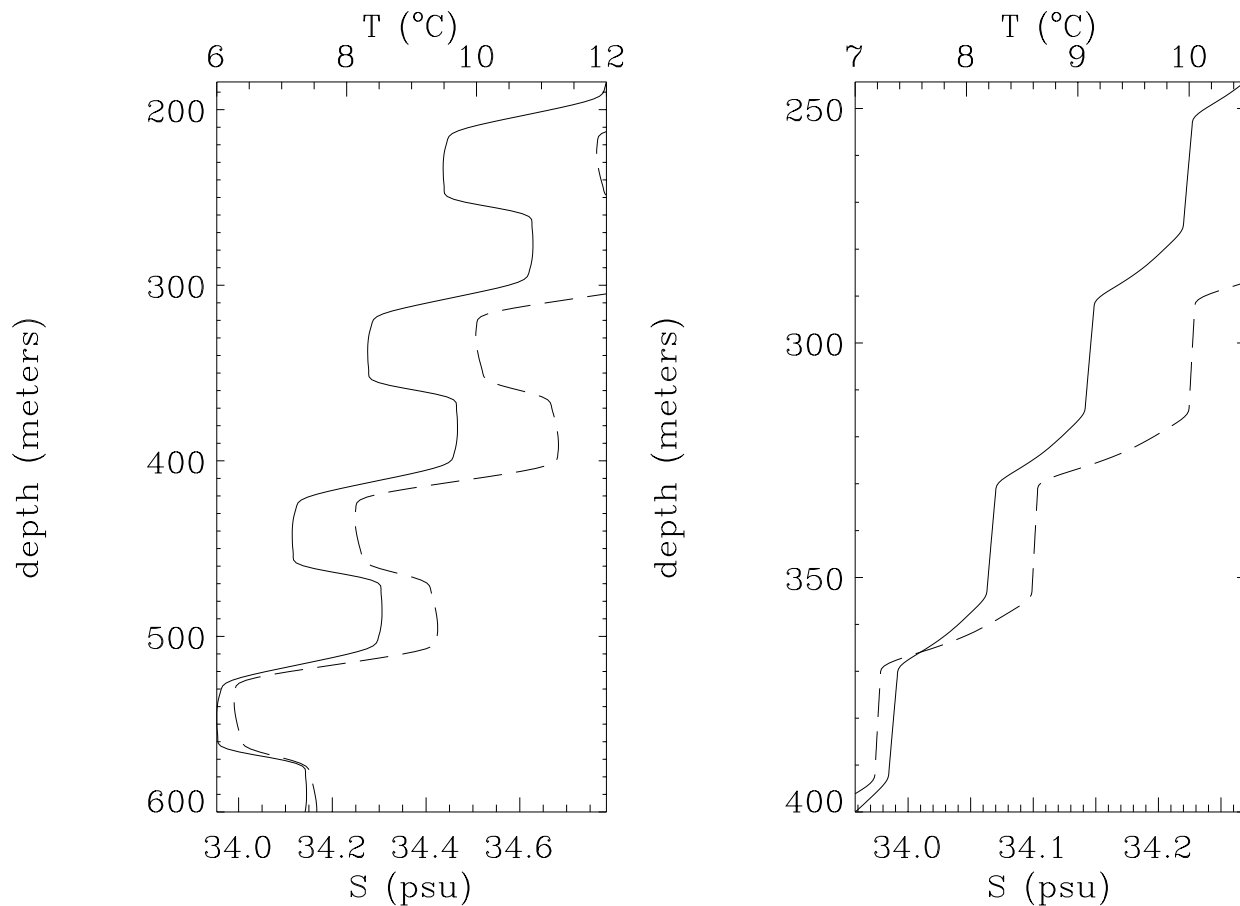


Figure 2: Vertical profiles of temperature T and salinity S for intrusions having $R_\rho = 1.6$ and diffusivity due to background turbulence of $K_{\text{turb}} = 0.1 \text{ cm}^2\text{s}^{-1}$ (left) and $K_{\text{turb}} = 0.01 \text{ cm}^2\text{s}^{-1}$ (right). In the latter instance, intrusions evolve toward a staircase-like configuration in which fingering interfaces alternate with convective layers.

and Ruddick (1998), except that intrusion development lagged away from mid-front (Fig. 3). In analyzing the results, we are seeking to determine parameter dependences of isopycnal and diapycnal intrusion fluxes.

IMPACT/APPLICATIONS

Accurate and process-dependent subgrid scale transport parameterizations will enable modeling practice to advance and have better predictive capability.

TRANSITIONS

The statistical mechanical (neptune) treatment of eddy momentum transport has been incorporated as an option in version 2.2 of the GFDL Ocean circulation model (MOM).

RELATED PROJECTS

Holloway leads an Arctic ice/ocean/atmosphere modeling effort as part of an Ocean Climate

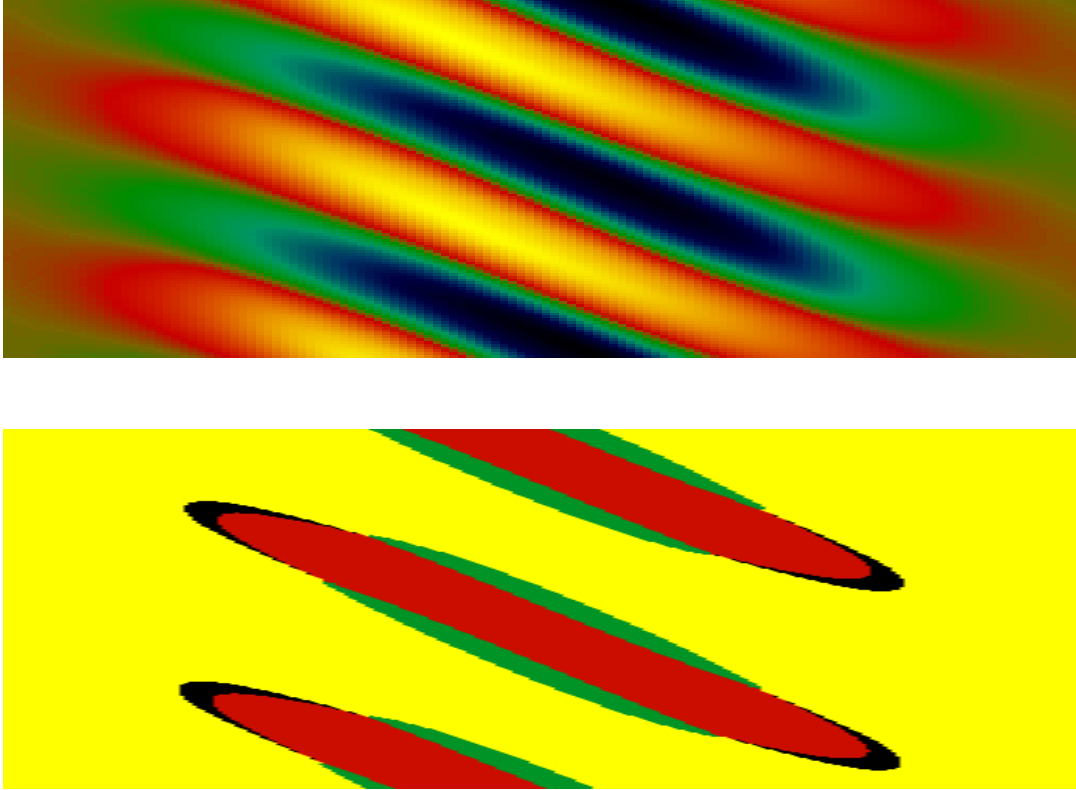


Figure 3: Development of double-diffusive intrusions at a thermohaline front. Top: Deviation of salinity S from initial state. Warm colors represent positive values, and cool colors negative values. Bottom: Local stability properties. Yellow: salt fingering; red: diffusive convection; black: stable; green: convection. Initial vertical profiles of T and S were linear with density ratio $R_\rho = 1.6$; horizontally T and S varied according to density-compensating hyperbolic tangent functions. Mixing parameterizations are similar to those in Walsh and Ruddick (1998), with background turbulent diffusivity $0.3 \text{ cm}^2\text{s}^{-1}$.

initiative by the Department of Fisheries and Oceans. Funding to Holloway is 60k/year (Canadian \$) for two years with notional commitment to third and fourth years. This work reinforces our ONR-funded research by advancing the state of ocean models used to implement and test subgrid-scale parameterizations.

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