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Mixing and Transport in the Mediterranean Salt Tongue

Abstract

The influences of time dependent motions on the mixing and transport of salt and heat in the Mediterranean salt tongue are considered. Two points of view are presented, the first considers salt as a passive tracer which is simply advected with the local flow while the second assumes salinity is dynamically active in determining the local velocity field and, hence, its own advection. The time dependent motion in this case is driven by baroclinic instability of the large scale flow. The results indicate that both mixing due to turbulent motions and eddy fluxes resulting from baroclinic instability are likely to be important in determining the large scale distribution of salinity in the Mediterranean salt tongue.

Introduction

The present study is motivated by recent Eulerian and Lagrangian observations near 1000 m in the Mediterranean salt tongue in the eastern North Atlantic. These data indicate that the low frequency motion within the salt tongue is zonally enhanced, has small meridional scales, and exceeds the mean velocities by more than an order of magnitude (Spall *et al.*, 1993). The nature of the observed variability is consistent with two distinct source mechanisms. Wave motions found to the south of the salt tongue are believed to be the signature of baroclinic Rossby waves generated at the meandering Cape Verde Front to the south (Spall, 1992). The low frequency zonal motions found within the salt tongue are consistent with the baroclinic instability of the large scale flow (Spall, 1993).

Turbulent mixing

The Lagrangian trajectories have been used to estimate the horizontal diffusivities in the vicinity of the salt tongue and the relative influences of turbulent mixing and mean advection on the dispersion of water parcels. The theory of mixing due to homogeneous, stationary turbulence (Taylor, 1921) is used to estimate mixing coefficients. The results indicate that mixing is nonhomogeneous with the zonally enhanced motions within the core of the salt tongue ($8–25x10^6$ $cm^2 s^{-1}$) more effective at mixing than the wave motions which dominate the variability to the south of the salt tongue ($3–5x10^6$ $cm^2 s^{-1}$). The mixing is also non-isotropic within the core of the salt tongue due to the zonal nature of the variability while the mixing to the south of the salt tongue is essentially isotropic. A comparison with mixing coefficients calculated directly from the dispersion of the floats gives the same result within 95% confidence limits, indicating that the floats are in a random walk regime and that dispersion is well represented by stationary homogeneous turbulence.

The relative influence of the time dependent motion on the dispersion of passive parcels may be estimated by the ratio of the root mean square displacement due to random mixing and the displacement due to the mean advection. This ratio is plotted in Figure 1 as a function of time for the zonal component (X) and meridional component (Y) of the wave-like floats (south of the salt tongue core) and zonal floats (within the salt tongue core). Because the contribution from the mean advection increases linearly with time and the mixing dispersion increases as the square root of time, the mean component will eventually dominate the dispersion. At the level of mixing estimated from the floats, however, the time dependent motion is still dominant over the mean after 5 years. Thus, over the time scale of the observations, the mixing of water parcels in the Mediterranean salt tongue is dominated by turbulent mixing. Additional data would probably result in weaker mean velocities and an even larger contribution due to the time dependent motion.

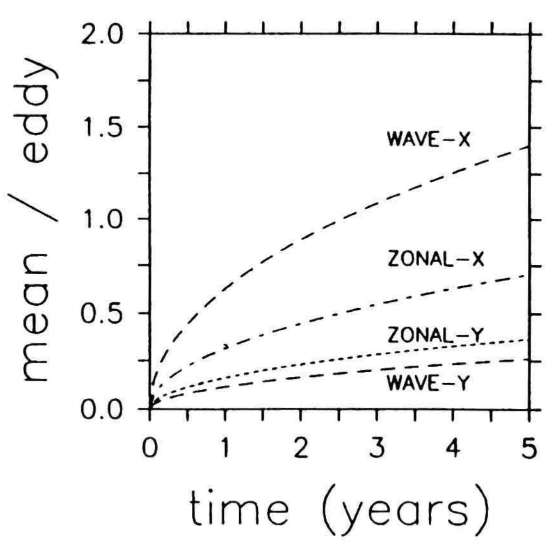

Fig. 1. Ratio of mean to eddy contributions for particle dispersion as a function of time. The turbulent motion dominates particle dispersion for both the zonal floats within the core of the salt tongue and the wave floats to the south.

A baroclinic instability mechanism

Traditional models of the large scale salt balance in the Mediterranean salt tongue have been based on the steady advection-diffusion equations. Numerical models allow for time dependent motion and an active salinity field but typically have either non-eddy resolving or marginally eddy-resolving resolution. While these prognostic models incorporate more realistic physics, basin scale computations prohibit extensive explorations of parameter space and local dynamics are often dependent on the basin scale circulation, making cause and effect difficult to sort out. We present here a simple theory which might account for observed characteristics of the low frequency variability within oceanic subtropical gyres, and demonstrates how an active salinity field might give rise to fluxes of heat and salt which are important in the overall budgets in the region of the salt tongue.

Linear theory

Linear quasigeostrophic stability theory is a useful starting point to illustrate the basic mechanism at work. The equations appropriate for non-zonal flows are derived from the conservation of quasigeostrophic potential vorticity by making use of a simple coordinate transformation (Pedlosky, 1979). The mean velocity profile used in the stability analysis is based on the hydrographic data of Saunders (1982) appropriate for the large scale flow in the North Atlantic east of the Mid-Atlantic ridge and within the core of the salt tongue, approximately 35 N to 45 N. The essential features of the mean state are southward flow in the upper 500 m, a reversal with northward flow between 500 m and 2000 m, and weak southward flow between 2000 m and the bottom. The background stratification is taken to be exponential.

The maximum growth rate as a function of the mean flow direction and the wave vector direction are shown in Figure 2. This preferentially zonal orientation of the perturbations results from the competition between maximal energy release for a wave vector oriented parallel to the mean flow and the beta effect, which stabilizes the flow for perturbations across the mean potential vorticity gradient (Pedlosky, 1979). This demonstrates that, for weak vertical shears typical of subtropical gyre interiors, the stabilizing influence of beta is sufficiently strong that the only perturbations which can efficiently extract energy from the mean flow are nearly zonal. This zonal enhancement of the low frequency variability is qualitatively consistent with observations found in many regions of the subtropical gyres.

The waves have periods of between 3 and 10 years so that the perturbations are essentially stationary during the growth period (0.5 to 1 year). The most unstable modes have wavelengths of approximately 75 to 100 km. The depths of the maximum and minimum eddy density fluxes may be directly related to the basic parameters which define the mean state. For a vertical velocity profile typical of the Canary Basin at latitudes of the salt tongue, the maximum positive

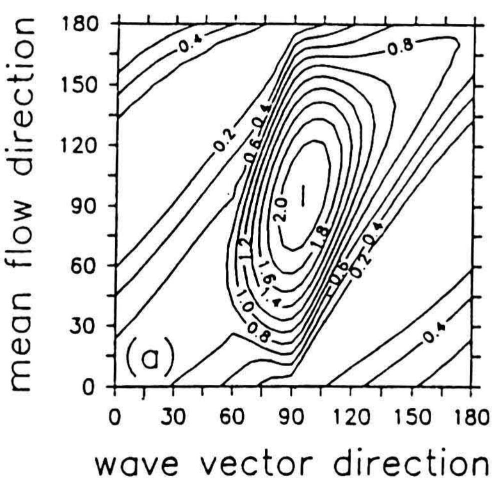

Fig. 2. Growth rate of the fastest growing wave (years^{-1}) as a function of mean flow direction and wave vector direction (0^0 is to the east). For mean flow angles between 20^0 and 160^0 the fastest growing waves propagate in a nearly north-south direction, resulting in zonal perturbations.

eddy density flux is centered near the core of the Mediterranean salt tongue and has a similar vertical scale of 1000 m. This similarity suggests that these eddy fluxes might contribute to the offshore flux of salt in this region.

Nonlinear regime

Although linear theory is very useful for understanding the underlying physics of the perturbations, a nonlinear model is required to investigate the large amplitude regime and to obtain a quantitative estimate of the salt flux carried by these waves. A random superposition of small perturbations between 50 km and 300 km wavelength were added to a uniform velocity profile at the center of a periodic channel (300 km in length) in a nonlinear primitive equation model (SPEM, Haidvogel *et al.*, 1991) and integrated for 700 days. After 250 days the initially uniform meridional flow has developed large amplitude zonal jets which then become unstable and break down into mesoscale eddies with amplitude 1–5 cm s^{-1}, close to the observed eddy kinetic energy in this region.

The zonal density flux on day 400 at the center of the channel is shown in Figure 3. The basic structure predicted by the simple linear theory carries over into the large amplitude interactive wave regime. There are a variety of scales which develop out of the initial conditions, however, the dominant meridional wavenumber is on the order of 100 km, in general agreement with linear theory. In this large amplitude regime, there is a significant transfer of energy from the low frequency, zonal regime of the growing waves to the more isotropic higher frequency mesoscale band as the jets become unstable. It is important to note that the mesoscale eddies which result from the instability of the early zonal jets do not prohibit the continued westward flux of density due to baroclinic instability of the large scale flow.

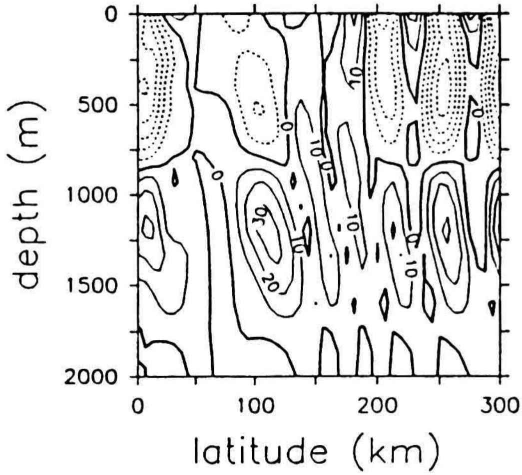

Fig. 3. Zonal perturbation density flux on day 400 from the primitive equation model, upper 2000 m only (10^7 g cm^{-2} s^{-1}). Note the positive flux (westward salt flux) over a depth range roughly corresponding to the dept of the Mediterranean salt tongue.

This is demonstrated in Figure 4, which shows the meridionally averaged zonal density flux as a function of time. The first 250 days are in the small amplitude linear regime, the fluxes are of the correct sign to release potential energy of the mean flow into kinetic energy of the growing waves. After 250 days the perturbations become large, an order of magnitude larger than the mean flow, and break down into meso scale eddies. After the first set of waves have become unstable (400 days), the mean state is still unstable and continues to flux density to the west in general agreement with linear theory. Two more wave

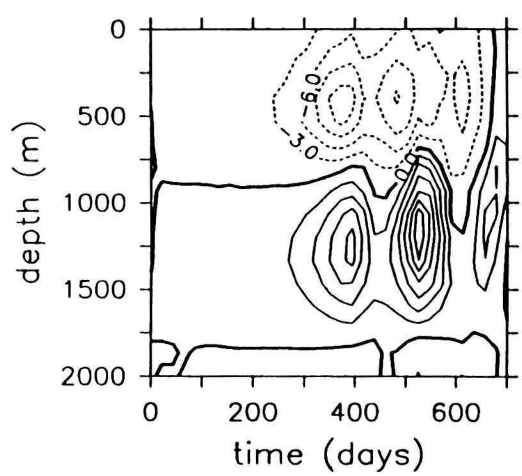

Fig. 4. Zonal perturbation density flux averaged over the meridional extent of the channel as a function of time. Three cycles of wave growth and instability are seen in the large amplitude, interactive regime.

cycles of growth and instability take place between days 400 and 700. The final cycle is much weaker than those previous because of the potential energy represented by the vertical shear in the mean state has essentially all been converted to the kinetic energy of the eddy field. Physics which are unresolved in the present simple model serve to maintain the observed mean large scale flow and provide an energy source for the continued eddy density flux.

Salt transport

The previous discussion has been in terms of the eddy density flux, however, as salinity makes an important contribution to the density of seawater within the salt tongue, these unstable waves also transport salt. An important parameter in relating density flux to salt flux is the horizontal density ratio R_H, which measures the relative influences of temperature and salinity to the zonal horizontal density gradient. A value of $R_H > 1$ indicates that the temperature gradient contributes more strongly to the density gradient than salinity. The climatological value of R_H within the core of the salt tongue increases from approximately 1.05 at 15^0 W to 1.25 at 27^0 W. The nonlinear primitive equation model was integrated using both temperature and salinity with a linear equation of state and $R_H = 1.2$. Integrating over the meridional extent of the salt tongue, approximately 10^0 of latitude, the average salt flux carried by these waves would be approximately $2x10^6\ m^3\ m^{-1}$ ppt. The total anomalous flux of salt through the Strait of Gibraltar is estimated to be approximately $1.6 \times 10^6\ m^3\ s^{-1}$ ppt (Bryden and Kinder, 1991).

It is likely that in the real ocean, which contains many processes not considered here, the present mechanism will be less effective at transporting salt than is found in this simple calculation. The main points in this analysis are that the theory is consistent with the observed variability, that the structure of the salt transported by the waves is very similar to the observed structure of the salt tongue, and that the waves are capable of transporting an amount of salt which may be important in the overall salt budget of the Mediterranean salt tongue. It would, of course, be interesting to investigate this mechanism in the context of a more complete ocean model, which includes frontal regions, mesoscale eddies, Meddies, external forcing, small scale mixing, and an explicit Mediterranean outflow.

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