SYNOPTIC/MESOSCALE PROCESSES

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Keywords : Advection, Diffusivity, Distribution, Dynamics, Eddy, Energy, Mesoscale, Nutrients, Plankton, Propagation, Scales, Spectrum, Statistics, Transport

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Summary

Oceanic "weather" on scales 10-500 km, 10-200 days exceeds the kinetic energy in the basin-scale mean flow by a global-average factor of five. Most of their energy derives via baroclinic instability, especially in strong (boundary) currents, from potential energy in the large-scale density field maintained by wind forcing. The length scale is controlled by the internal Rossby radius of deformation and energy exchanges to larger scales limited by the linearising effect of Rossby wave dispersion. A tendency to propagate westward (on the rotating spheroidal earth) helps to distribute eddy energy widely, but advection by mean flows is often faster. Thus eddy energy distribution is

qualitatively similar to that of kinetic energy in the large-scale mean flow, being high near western boundary currents, several eastern boundary currents, the Southern Ocean and near-equatorial regions. Eddies effectively disperse water properties, notably potential vorticity, have some mean effects (momentum and constituent advection) and affect nutrient supply and plankton. Thereby they are important to longer-term ocean "climate" and property distributions.

1. Introduction

The ocean contains energy on all scales from molecular to global, seconds to centuries and longer. This sub-topic covers the oceanic equivalent of atmospheric weather; the corresponding oceanic scales are 10-500 km (shorter than atmospheric), 10-200 days (longer than atmospheric weather). These ranges are particularly energetic, exceeding the kinetic energy in the basin-scale mean flow by a factor 10 or more in most of the ocean. Such "mesoscale" energy is manifested as mid-ocean eddies and as boundary current variations that develop from meanders to eddies and rings. Identified forms include chains of shear eddies, individual spiral eddies, eddies behind islands, eddies due to irregular coasts, eddies where flows meet or diverge, mushroom-shaped flows and attached eddies. Gulf Stream rings (well-developed results of boundary current instability) and "Meddies" (deriving from discrete volumes of water detaching from the saline Mediterranean outflow) are frequently cited examples. Where "free" in the ocean interior, these features may propagate with dynamics related to Rossby waves: see *Waves*. They are important to longer-term ocean "climate" and property distributions.

2. Dynamics

2.1. Origin, Forcing

Ocean circulation on 1000 km scales has abundant potential energy, implicit in sloping density contours, for the observed mesoscale intensity. However, the available potential energy cannot be extracted on the largest scale. Instead, it is converted to eddy kinetic and potential energy at the shorter synoptic/mesoscale, principally via baroclinic or sometimes barotropic instability. In general, instability requires adjacent regions with opposite signs of the gradient of potential vorticity $(f+\zeta)/h$; here f is 2(vertical component of earth's rotation), ζ is relative vorticity of the flow (neglected in a first-order estimate) and h is a layer depth. The adjacency is lateral for barotropic instability (typically of a jet) and may be in the vertical for baroclinic instability. In particular, potential vorticity is expected to increase northwards but thickening density layers poleward from the equator can imply decreasing potential vorticity in some depth range, as found in the North Atlantic in 10°-32°N. Early simple models of baroclinic instability were developed for the atmosphere assuming lateral density gradients and corresponding vertical shear for unidirectional flow U(z) (only). Calculations for various mean density fields and corresponding U(z) representative of the ocean suggest a maximum growth rate of order $(80\text{ days})^{-1}$ for a wavelength of order 200 km (these values are sensitive to the choice of profile; various profiles have been used).

The shorter scale of the instabilities corresponds to steeper isopycnal slopes and correspondingly greater kinetic energy; the ratio of available potential energy to kinetic energy in a circulatory system is estimated as (system scale/internal Rossby radius L_R)^2 ~ 1000 for the ocean basin scale and L_R of order 30 km (see below). In general terms, instability waves develop into finite-amplitude meanders which continue to grow, sometimes to the extent that a portion of fluid is enclosed, forming an eddy, restoring an approximation to the original flow but with overall flattening of isopycnals. Gulf Stream meanders and ring development have been studied with a numerical (quasi-geostrophic) model. It was found that (ocean-side, cyclonic) cold-core ring development involves baroclinic conversion of available potential energy to kinetic energy in meander side jets (and reverse conversion at the bottom of a meander). Development of a (shelf-side, anticyclonic) warm-core ring involves differential horizontal advection; the leading edge of a northward meander is nearly stationary whereas the trailing edge becomes greatly distorted leading to cut-off and an eddy (ring). Some eastern boundary currents also show instabilities: meanders, filaments and eddies.

Strong lateral shear and barotropic instability may be another source. Flow past a sharp corner (change of coast direction > 40º approx.) can form an eddy; separation can be encouraged by counter-flow beneath. The process is inhibited by rotation. Eddies may also form as part of boundary current separation, e.g. by the Loop Current in the Gulf of Mexico and the East Australian Current.

In shelf seas, baroclinic instability at fronts bounding coastal currents, or tidal mixing fronts, can also lead to eddy formation. After a change in coastal current inflow, for example, meanders can grow on the bounding front to give a vortex pair that transports water away from the coast and induces near-bed flow comparable with surface flow. Anticyclonic above cyclonic vorticity from the front tends to remain in the developed eddies. At a tidal mixing front, small displacements can lead to eddy pairs with matching behaviour of surface and bottom fronts. Cyclonic vorticity on the stratified side and anticyclonic vorticity on the mixed side (from the along-front flow) tend to be retained but with the mixed-side anticyclonicity suppressed by greater friction. Such eddies often dominate cross-frontal transport.

Winds are the main forcing for large (1000 km) scale ocean currents and circulation. Hence winds force mesoscale eddies indirectly via instabilities of this large-scale flow. A balance is reached in which the large-scale flow and eddy intensity suffice for energy transfer to eddies to offset the continuing wind input. Any wind forcing of reduced scale can directly drive oceanic synoptic/mesoscale features. Normally, undistorted winds do not have the appropriate scales, and direct energy input to the baroclinic mesoscale is much slower than is estimated for input from instability of the large-scale circulation. However (a) the latter is localised; in quiet areas direct wind-forcing may give comparable energy input, (b) longer-period weather or seasonal winds around islands, mountains or coastal features can make a better match of scales.

The Gulf of Tehuantepec appears to be an example where eddies are induced by wind-forcing channelled through a gap in the central American mountain chain. Local circulatory wind stress induced by mountains and islands may be another source of energy. Tropical cyclones and larger near-equatorial oceanic scales may also be better matched. On the other hand, high latitudes favour forcing of barotropic-scale motion only.

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Biographical Sketch

John M. Huthnance was born in 1948 in Reading, England, and graduated in mathematics from Cambridge University in 1969, with a PhD in mathematics applied to tidal currents over topography (1973). After a postdoctoral year at the Institute of Geophysics and Planetary Physics (Scripps, San Diego) and three years as a Post-Doctoral Research Assistant and Lecturer in the Department of Oceanography, University of Liverpool, he moved in 1977 to Bidston Observatory (then part of the Institute of Oceanographic Sciences, now the Proudman Oceanographic Laboratory) where he is now Deputy Director.

During this time, other roles have been Honorary Secretary, (UK) Challenger Society for Marine Science, Scientific co-ordinator of the UK Natural Environment Research Council (NERC's) North Sea Project, Co-ordinator of the EU-MAST project "Processes in Regions of Freshwater Influence" and components of the large-scale "Ocean Margin Exchange" project, and service on several NERC committees. He has held an Honorary Professorship of the School of Ocean Sciences, University of Wales and is currently a Visiting Professor of the Department of Earth and Ocean Sciences, University of Liverpool.

Research interests are in marine dynamics, especially of the seas over the continental shelf and slope; waves over topography and their implications for residual circulation, sediment movement and ocean-shelf coupling and exchange; promotion of coupled models (physics-sediment-biology).