The Abdus Salam International Centre for Theoretical Physics

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Ocean biological productivity and climate change - part III

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Ocean biological productivity and climate change

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Lecture 1: basin scale view

- Background state
- High latitude productivity

Lecture 2: subtropical gyres

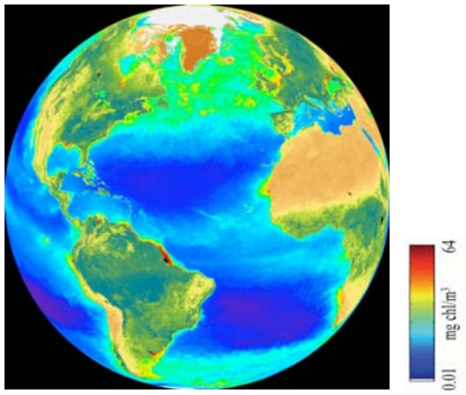
- Mid latitude productivity
- Eddy transfers

Lecture 3: boundary currents

- Barriers/blenders
- Eddy lifecycles

Lecture 4: Climate change

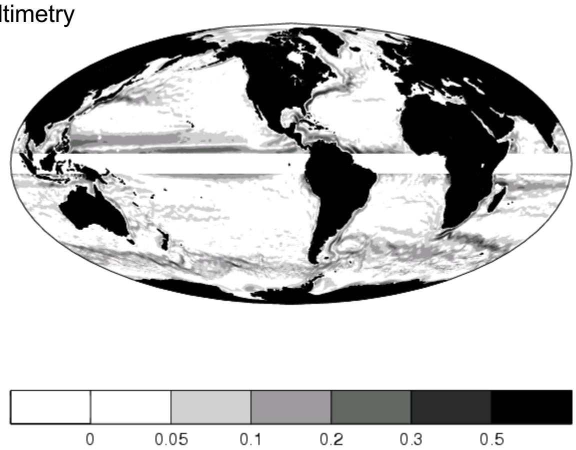
- Heat content changes in the N. Atlantic
- Ocean overturning



False colour picture of chlorophyll concentration

September 97 - August 98, SeaWIFS, NASA

Surface velocity from drifters and altimetry



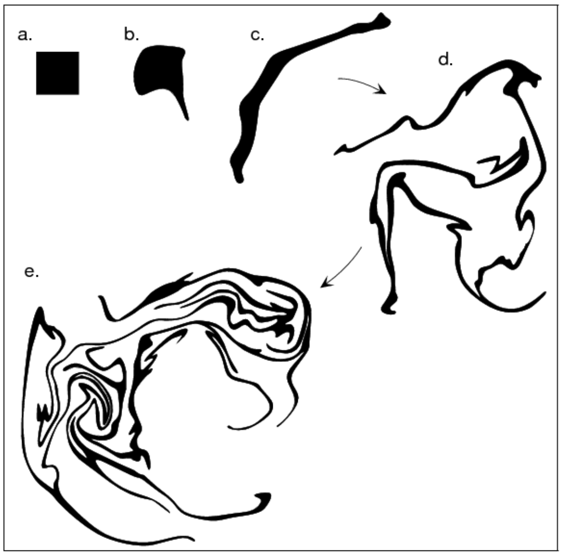
1. Stirring
2. Western boundary currents/Jets

   barrier or blender?

   nutrient streams

1. Stirring

Welander (1955)
stirring experiment

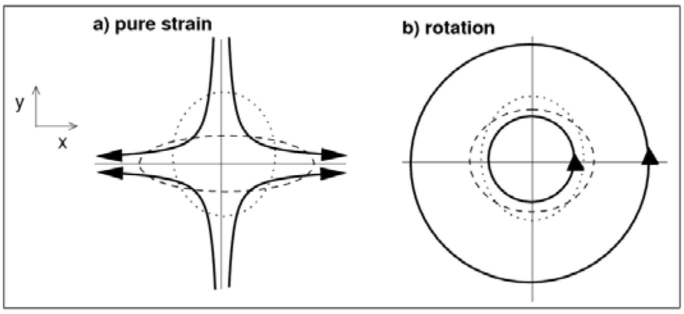


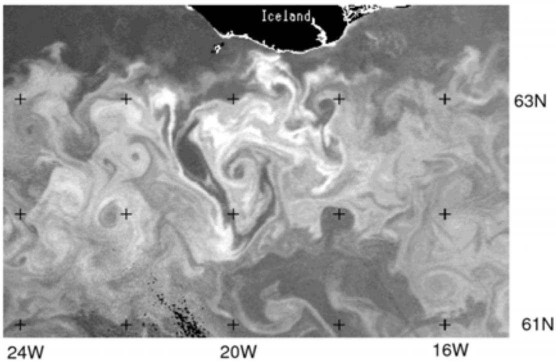
Tracer spreading set by relative size of strain rate & vorticity $\gamma^2 - \zeta^2$

spread at a rate $\exp[(\gamma^2 - \zeta^2)^{1/2} t]$

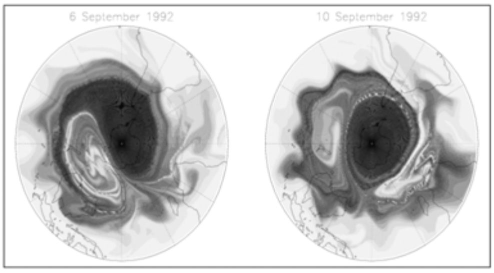
strain $\gamma^2 = \left(\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2$

vorticity $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$

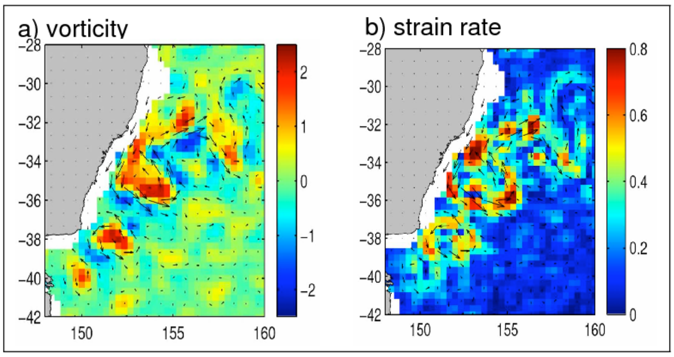




Snapshot of chlorophyll on 17 June 1991 (light, high conc.) From Martin (2003)



Snapshots of ozone distribution in stratosphere (light, high conc.) From Waugh (1993)

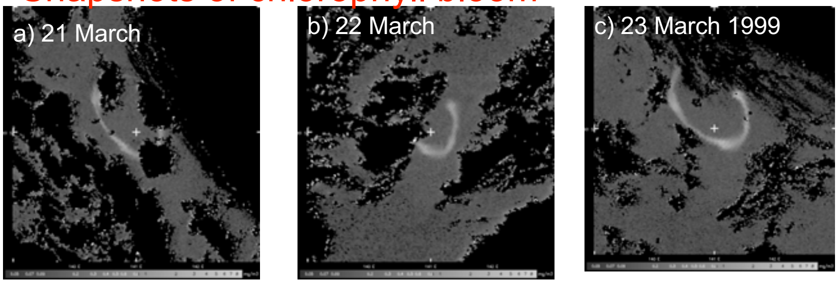


Altimetry diagnostics for East Australian Current on 19 November 1997 on 1/10 grid. By Waugh et al. (2006)

Core of eddies — high vorticity, tracer contrasts persist

Between eddies — high strain, tracer filaments drawn out

Snapshots of chlorophyll bloom



Snapshots of chlorophyll bloom (light) from Southern Ocean Iron release experiment (Abraham et al., 2000)

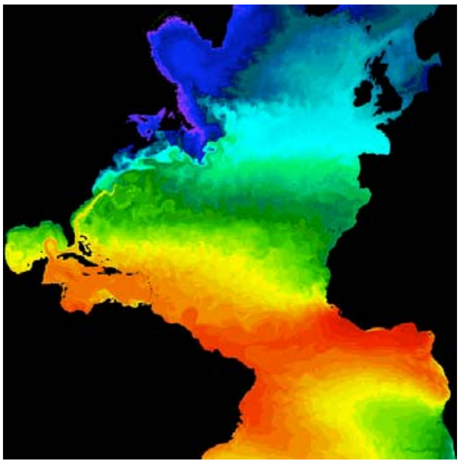
Initial iron release over limited path of 7 km in diameter

Filament 150 km long after 6 weeks.

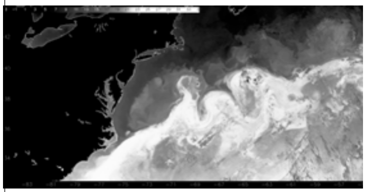
Effective strain rate $\gamma_e = \frac{1}{t}\log_e\left(\frac{\Delta x(t)}{\Delta x(0)}\right)$ ~ ln(150 km/30km)/33d = 0.05 day^{-1}

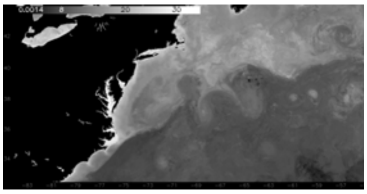
For reactive tracers (e.g. chlorophyll), patterns reflect that of a physical tracer *as long as* effective strain rate > growth rate

2. Western boundary currents

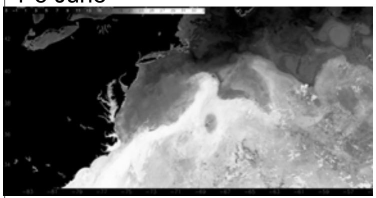


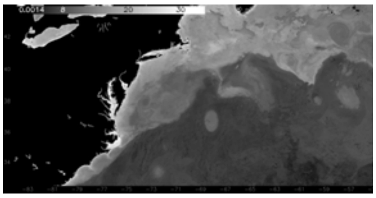
16-20 May 2006 NASA MODIS Sea-surface temperature and Chlorophyll



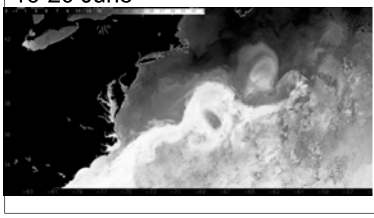


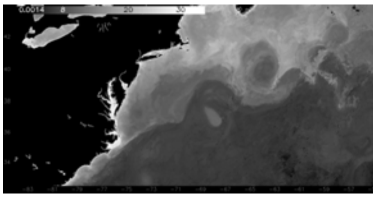
1-5 June





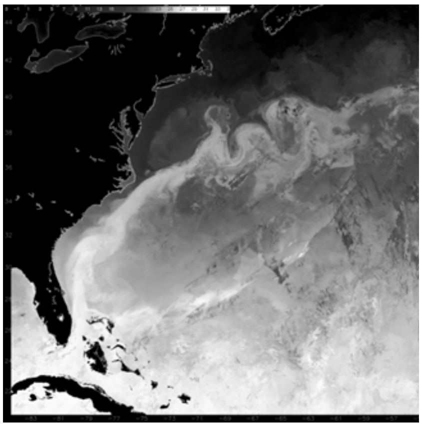
16-20 June

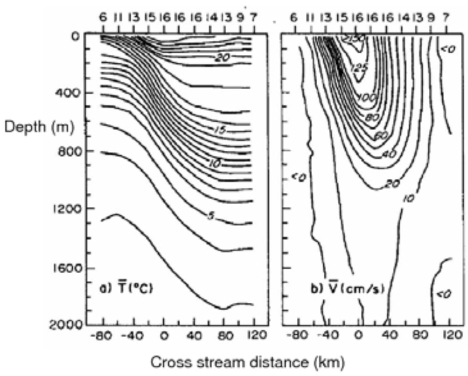




2.1 Lagrangian structure

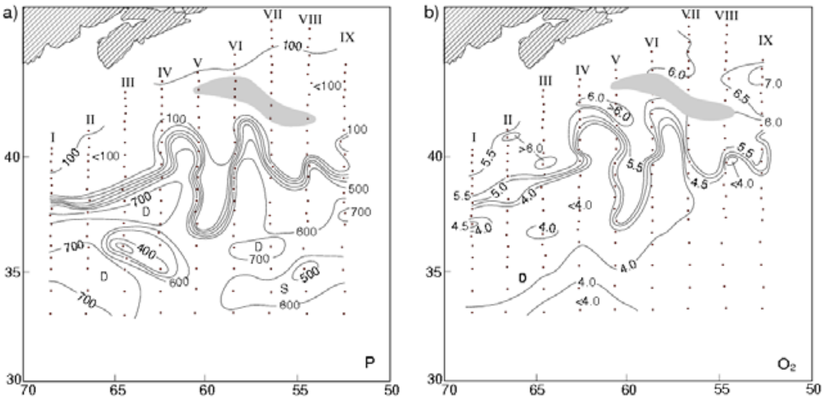
MODIS Sea surface temperature, 16-20 May 2006 (dark is cold)





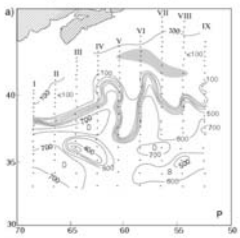
Halkin & Rossby (1985) Cross-section of the Gulf Stream, based upon 16 sections using a co-ordinate system following the centre of the stream.

2.2 Property contrasts

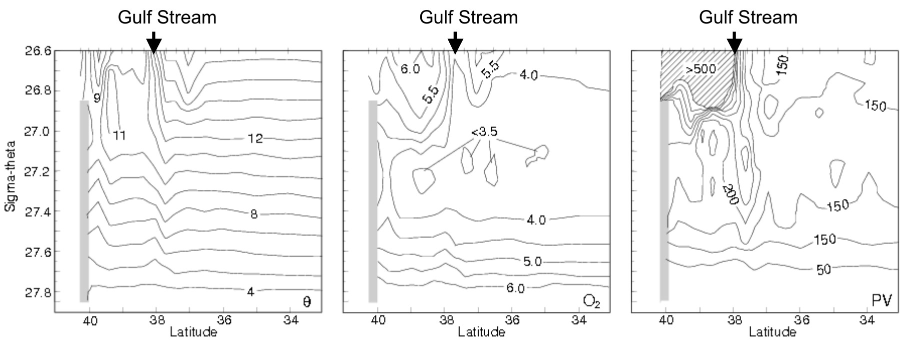


Maps of the downstream extent of the Gulf Stream: depth of σ=26.8 and dissolved O_2 (ml l^{-1}). Bower et al. (1985)

Property contrasts — barrier or blender?



Property contrasts across the Gulf Stream (along 68.5W, section 1) from Bower et al. (1985):

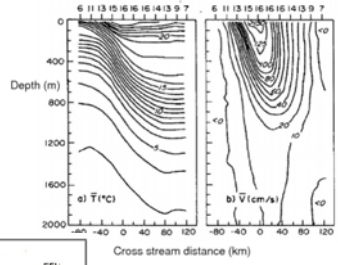


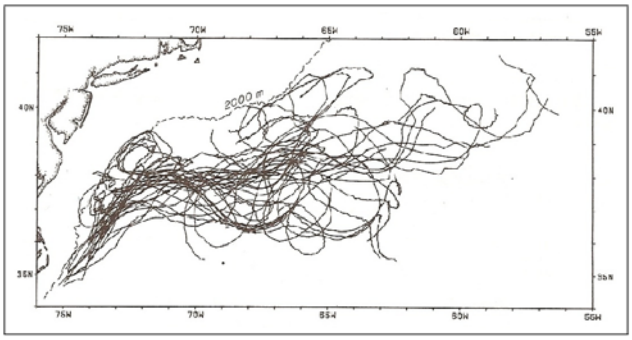
potential temperature

dissolved oxygen

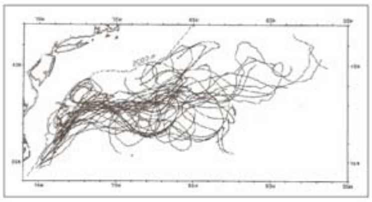
large-scale potential vorticity

2.3 Lagrangian view of particle exchange





Composite of 37 float trajectories: isopycnal floats seeded between 400m and 700m off Cape Hatteras and tracked for up to 2 years. From Bower and Rossby (1989)

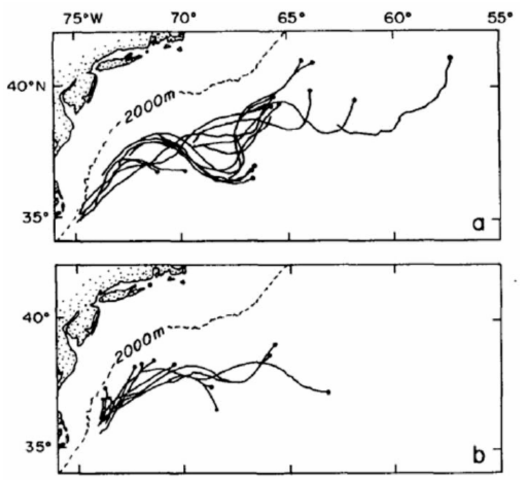


Trajectories up to first point of escape from the Gulf Stream:

a) 11 to 16°C

b) 7 to 11°C

(Bower & Rossby, 1989)



Floats are swept further along the stream within light surfaces

Dispersion statistics for 95 floats released:

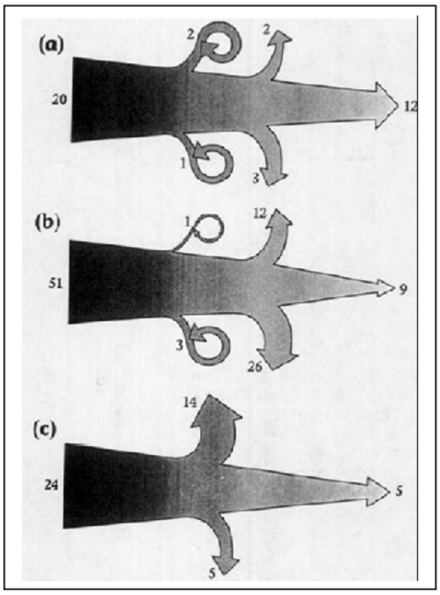
a) 14.5-17°C;

b) 12-14.5°C;

c) 7-12°C.

Bower and Lozier (1994)

Again, more floats remain within the stream along the lighter surfaces.



No. of floats deployed

No. of floats in stream after 30 days

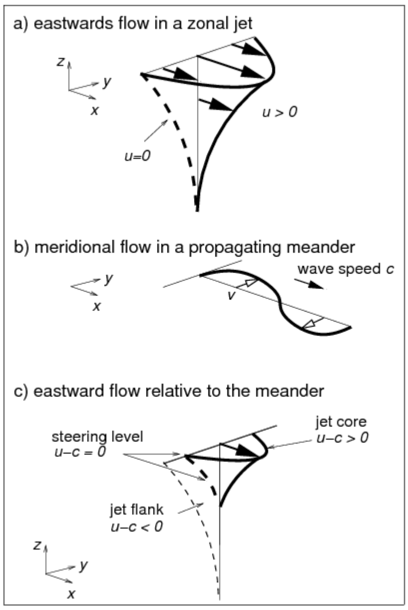
2.4 Kinematic view

Consider

- simple jet & propagating meander
- particles only cross jet via the meanders
- steering level (u-c=0) on flanks of jet at surface & at core of jet at depth
- enhanced transfer at steering level

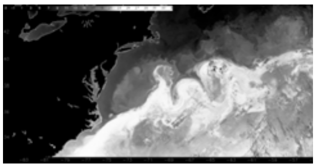
Hence, strong property contrasts at surface

Weak contrasts at depth



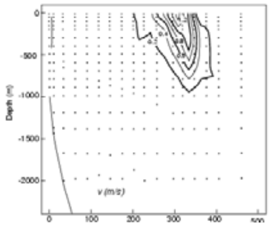
Based on discussion by Pratt et al. (1995)

2.5 Downstream tracer flux

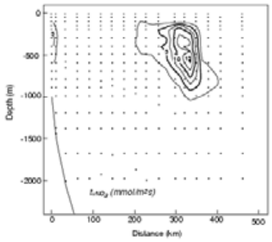


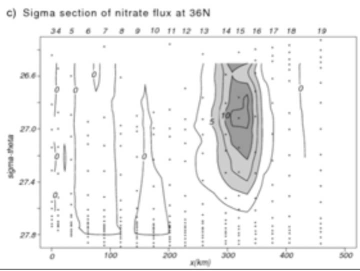
Pelegri & Csanady (1991)

v



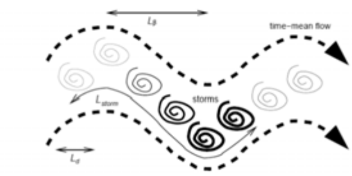
v N at 36N





Property flux along lighter surfaces and not denser surfaces

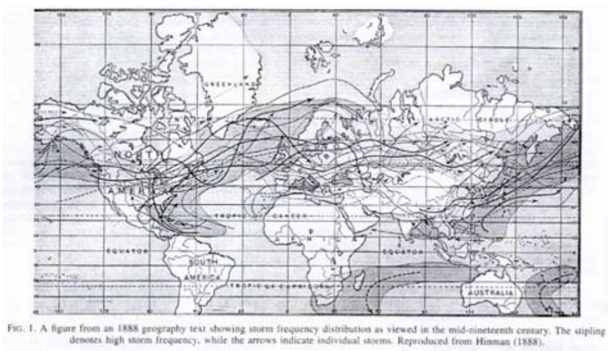
2.6 Return to eddy lifecycles



Ocean eddies form in unstable jets, amplify, then decay.

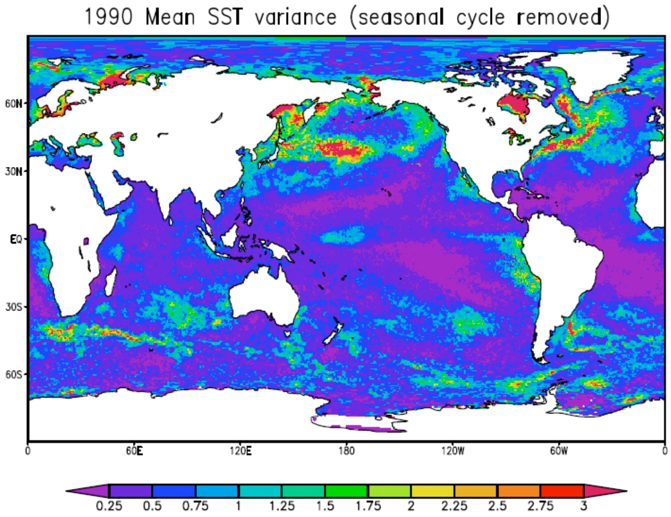
— eddy fluxes change during this life cycle

Analogous to atmospheric storm tracks

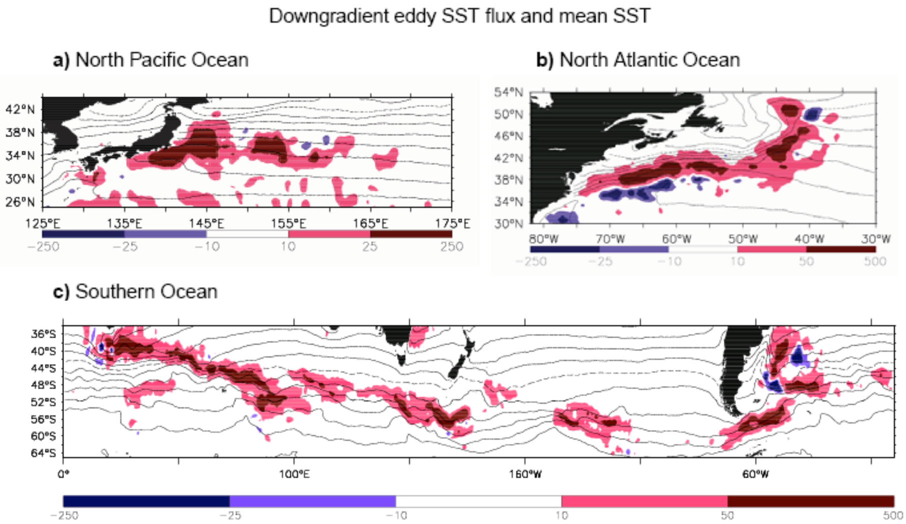


Hinman (1888)

Cyclonic, low-pressure systems / regions of cyclogenesis upstream of most frequent storm occurrence.



(Removed 5-daily mean seasonal cycle for 1990-2002)



Williams, Wilson & Hughes (2007).

2.7 Eddy transfer of conserved tracers

derive Tracer variance equation

$$\frac{\partial C}{\partial t} + \mathbf{u} \bullet \nabla C = F$$

…writing $\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}'$

minus

$$\frac{\partial \overline{C}}{\partial t} + \overline{\mathbf{u} \bullet \nabla C} = \overline{F}$$

$$\frac{\partial C'}{\partial t} + \mathbf{u} \bullet \nabla C' + \mathbf{u}' \bullet \nabla \overline{C} - \overline{\mathbf{u}' \bullet \nabla C'} = F'$$

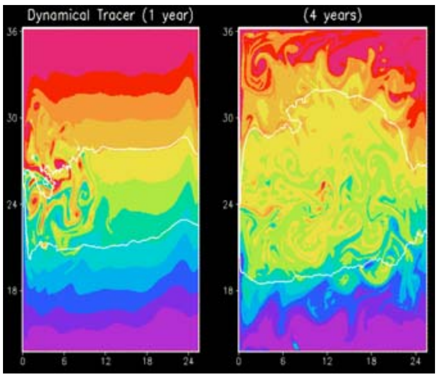
Multiply by C' and take time-mean

$$\overline{\frac{\partial}{\partial t}\left(\frac{C'^2}{2}\right)} + \overline{\overline{\mathbf{u}} \bullet \nabla\left(\frac{C'^2}{2}\right)} + \overline{\mathbf{u}' \bullet \nabla\left(\frac{C'^2}{2}\right)} + \overline{\mathbf{u}'C'} \bullet \nabla \overline{Q} = \overline{F'C'}$$

$$\overline{\frac{D}{Dt}\left(\overline{\frac{C'^2}{2}}\right)} + \overline{\mathbf{u}'C'} \bullet \nabla \overline{Q} = \overline{F'C'}$$

Eddy flux directed down gradient

either when Lagrangian growth of variance or dissipation of variance



Double wind-driven gyre

- 1/16 deg.

see tracer plotted on isopycnal

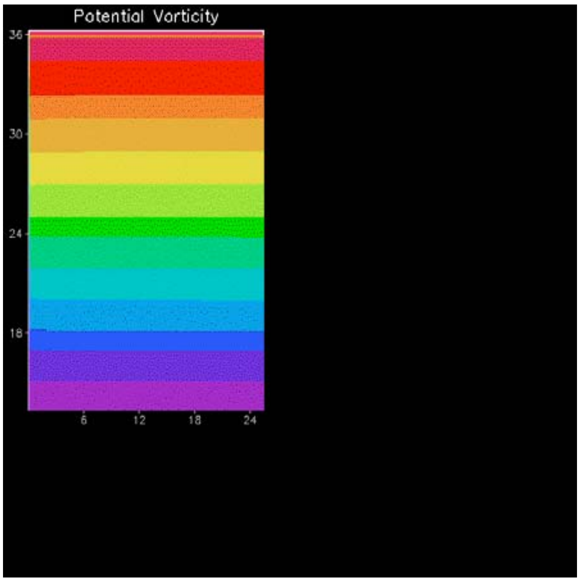
See fine eddy scales

Reversing pattern of up & down gradient fluxes

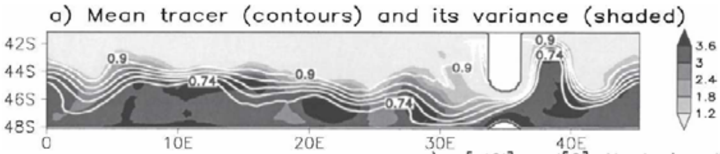
Systematic down-gradient transfer over ocean gyres

Wilson and Williams (2004) JPO

Model animation



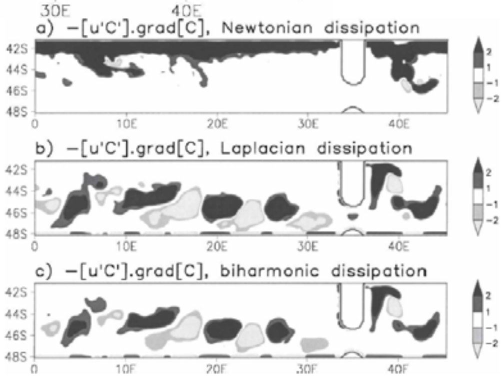
Idealised eddy-resolving tracer experiment for a channel



3 experiments with different choice of dissipation in tracer equation

$$\frac{\partial N}{\partial t} + \overline{u}.\nabla\overline{N} + \overline{u'.\nabla N'} = S$$

$$\overline{\frac{D}{Dt}N'^2} + \overline{u'N'}.\nabla\overline{N} = -Sink$$

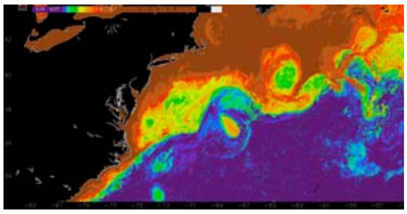


Eddy flux is down gradient for dark shading

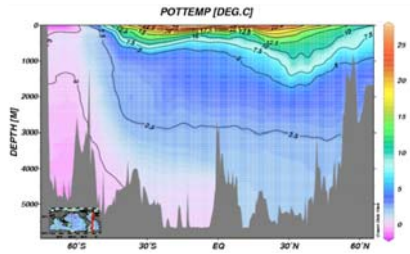
Expect down-gradient eddy flux where eddies formed & where nitrate strongly consumed

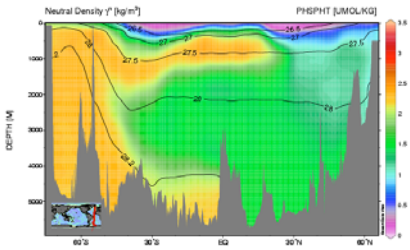
Wilson & Williams (2006)

2.8 Eddy isopycnal fluxes for nutrients



MODIS surface chlorophyll 16-20 June 2006





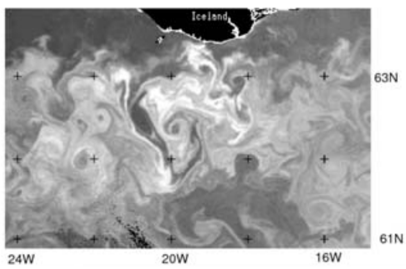
Eddy flux directed down gradient along isopycnals $\overline{u'N'}.\nabla\overline{N} < 0$

either when

• growth of variance

•strong conversion of inorganic to organic nutrients

Conclusions

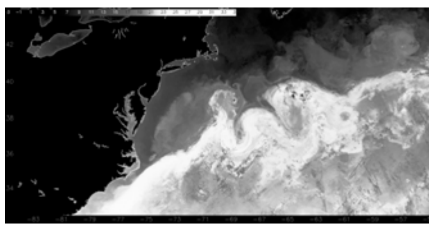


Stirring

- Enhanced between eddies, reduced within vortices

Boundary currents

- Barrier / blender— link between tracer plume & kinematics of meanders & jet



Eddy fluxes

- Vertical rectification (important for biology)
- Isopycnic fluxes — down-gradient when Lagrangian increase of variance or dissipation of variance

Challenge remains to address systematic effects of the fine scales on the larger-scale ocean

Further reading (in addition to those in last lecture):

Bower, A.S., H.T. Rossby and J.L. Lillibridge, 1985. The Gulf Stream -Barrier or Blender? J. Phys. Oceanogr., 15, 24-32.

Martin, A.P., 2003. Phytoplankton patchiness: the role of lateral stirring and mixing.Progr. in Oceanogr., 57, 125-174.

Detailed References (in addition to those in last lecture):

Abraham, E.R., C.S. Law, P.W. Boyd, S.J. Lavender, M.T. Maldonado and A.R. Bowie, 2000. Importance of stirring in the development of an iron-fertilized phytoplankton bloom. Nature, 407, 727-730.

Bower, A.S. and T. Rossby, 1989. Evidence of cross-frontal exchange processes in the Gulf Stream based on isopycnal RAFOS float data. J. Phys. Oceanogr., 19, 1177--1190.

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Pratt, L.J., M.S. Lozier and N. Beliakova, 1995. Parcel trajectories in quasigeostrophic jets: neutral modes. J. Phys. Oceanogr., 25, 1451-1466.

Waugh, D.W., 1993. Subtropical stratospheric mixing linked to disturbances on the polar vortices. Nature, 365, 535-537.

Waugh, D. W., E.R. Abraham and M. M. Bowen, 2006. Spatial variations of stirring in the surface ocean: A case study of the Tasman Sea. J. Phys. Oceanogr., 36, 526--542.

Welander, P, 1955. Studies on the general development of motion in a two-dimensional, ideal fluid. Tellus, 7, 141--156.

Williams, R.G., C. Wilson and C.W. Hughes, 2007: Ocean and atmosphere storm tracks: the role of eddy vorticity forcing. *Journal of Physical Oceanography*, in press.

Wilson, C. and R.G. Williams, 2004: Why are eddy fluxes of potential vorticity difficult to parameterise? Journal of Physical Oceanography, 34, 1, 142-155.

Wilson, C. and R.G. Williams, 2006: When are eddy tracer fluxes directed down gradient? Journal of Physical Oceanography, 36, 2, 189-201.