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  The repository principally contains the compiled products rather than the source for size reasons.
- Associated Python code (as Jupyter notebooks mostly) will be held on the same repository. The source data however might be big, so I am going to be naughty and possibly just refer you to where you might get the data if that is the case (e.g. JRA-55 data). I know I should make properly reproducible binders etc., but I didn't...
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OCES 2003 : Descriptive Physical Oceanography

(a.k.a. physical oceanography by drawing pictures)

Lecture 9: Mechanical forcing 3 (wind)

Outline

- wind forcing

  → wind forcing patterns (more in OCES 4001)
- Ekman transport/spirals

  → rotation influences

  → implied up/downwelling
- vorticity

  → cf. "spin", angular momentum

  → relation to wind stress curl, Ekman suction and Ekman pumping

Key terms: trade winds, prevailing westerlies, monsoons, Ekman flow, Ekman con/divergence (down/upwelling)

Recap: equations of motion

Denoting $\boldsymbol{u} = (u, v)$ and $\boldsymbol{u}_3 = (u, v, w)$, to numerous approximations (!!!) (see OCES 3203) ocean dynamics is governed by

$$\rho_0 \left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + 2\boldsymbol{\Omega} \times \boldsymbol{u} \right) = -\nabla p + \boldsymbol{F_u} + \boldsymbol{D_u} \tag{1}$$

$$\frac{\partial p}{\partial z} = -\rho g \tag{2}$$

$$\nabla \cdot \boldsymbol{u}_3 = 0 \tag{3}$$

$$\left(\frac{\partial T}{\partial t} + \boldsymbol{u}_3 \cdot \nabla T \right) = F_T + D_T \tag{4}$$

$$\left(\frac{\partial S}{\partial t} + \boldsymbol{u}_3 \cdot \nabla S \right) = F_S + D_S \tag{5}$$

$$\rho = \rho(T, S, p) \tag{6}$$

Respectively, (1) momentum equation, (2) hydrostatic balance, (3) incompressibility, (4) temperature equation, (5) salinity equation, and (6) equation of state (EOS)

Recap: Geostrophic flows

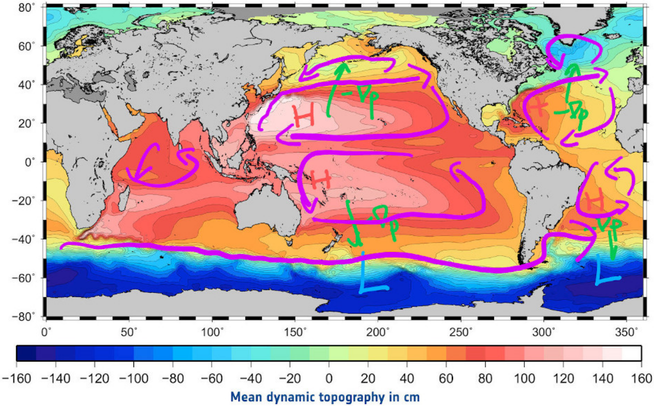


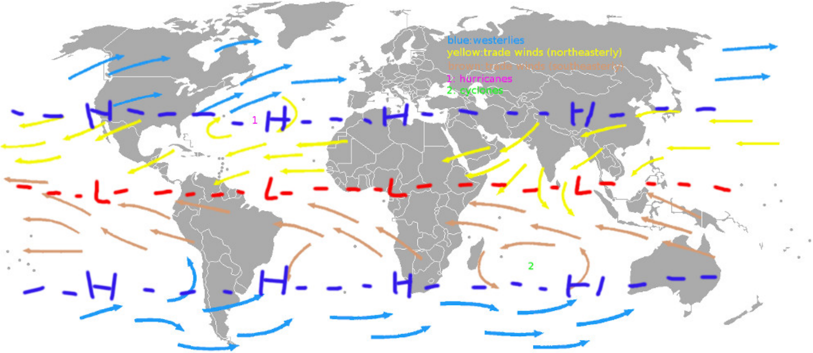
Figure: Time-mean global SSH (also called mean dynamic topography, with time-mean currents drawn on (notice the orientation around high/low SSH regions). Modified from Rio *et al* (2011), J. Geophys. Res: Oceans.

- contours of SSH related to isobars via hydrostatic balance

  → flow is **along** rather than **across** isobars (Coriolis effect, see last Lec.)

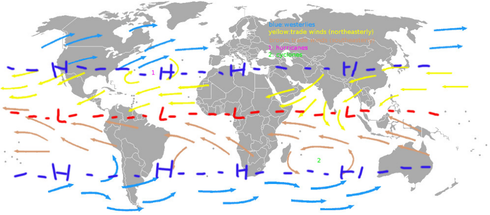
Atmospheric wind patterns

A source of momentum into ocean from atmospheric winds, so what do the wind patterns look like globally?



- deflection from direction of $-\nabla p$, geostrophic winds

Atmospheric wind patterns



- EQ is a low pressure region

  → convection, ITCZ
- subtropical highs around 30° N/S

  → edge of Hadley cell (see OCES 4001)
- W to E winds in Tropics and Polar regions are Easterlies

  → coming from the **East**

  → $u < 0$ and Westward here
- E to W winds in mid-latitudes are Westerlies

  → $u > 0$ and Eastward here

Atmospheric wind patterns: monsoons

Seasonal reversing winds (origin from موسم, “seasons”)

- oscillations in the pressure patterns (seasonal forcing)
  $\rightarrow$ land-sea contrasts (temperature more stable over ocean largely (!) due to higher heat capacity)

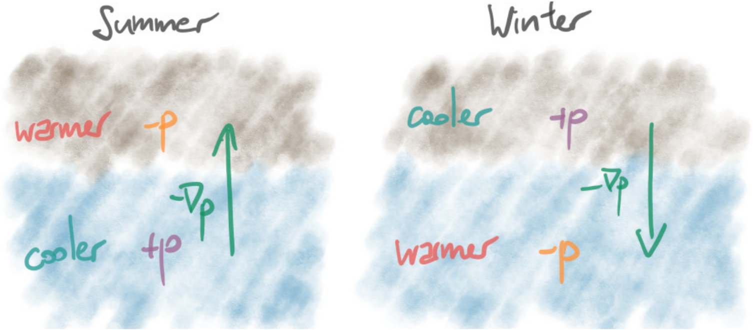


Figure: Schematic of monsoons, arising from changes in pressure gradients largely governed by heat. Actual wind direction slightly deflected because of Coriolis (see schematic in Ekman spirals later).

Wind forcing

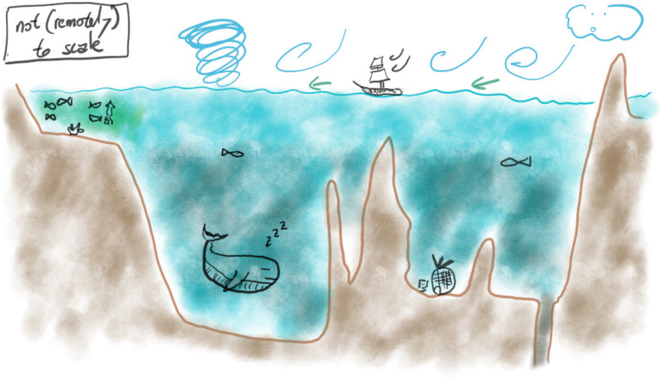


Figure: Schematic of ocean forcing.

- how does wind force the ocean?

Wind forcing: Ekman layer

Figure: Schematic of Ekman layer (boundary denoted by orange).

- wind a source of momentum for the ocean
- but influence has vertical limit

- direct influence only over the Ekman (boundary) layer
- difference in wind/current speed $\Rightarrow$ transfer of momentum ocean (usually into ocean and hence **source**; why?)

  $\rightarrow$ molecular diffusive rate $\Rightarrow$ very slow! (see next Lec.)

  $\rightarrow$ instabilities $\Rightarrow$ <u>much</u> faster (because on dynamical time-scales; see Lec. 17)

Q. there is a source but where is the sink? transfer below the Ekman layer? (see Lec. 13)

Wind forcing

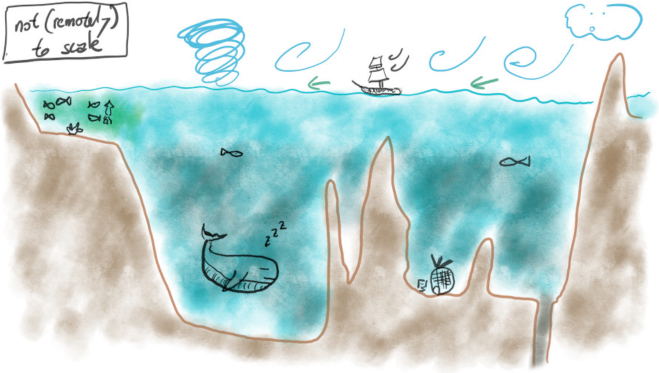


Figure: Schematic of ocean forcing.

- forcing in direction of wind but geostrophic balance, so transport perpendicular to wind forcing?

Ekman spiral

- near the surface the flow **is** roughly in direction of wind

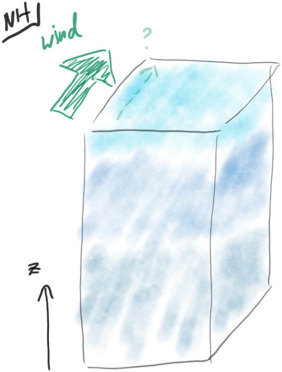


Figure: Schematic of Ekman spiral.

Ekman spiral

- near the surface the flow **is** roughly in direction of wind

  $\rightarrow$ wind not negligible in Ekman layer, geostrophic balance modified

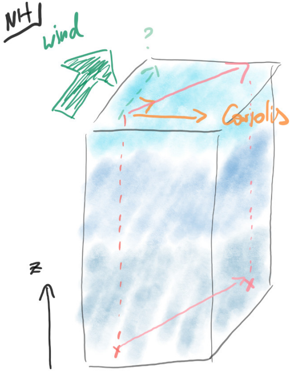
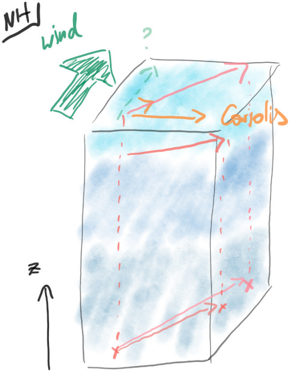


Figure: Schematic of Ekman spiral.

Ekman spiral

- near the surface the flow **is** roughly in direction of wind

  $\rightarrow$ wind not negligible in Ekman layer, geostrophic balance modified
- geostrophy $\Rightarrow$ flow perpendicular to wind (to the right in NH) in deep parts



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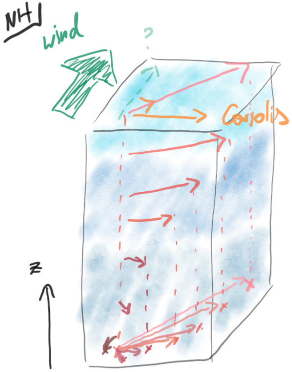
  $\rightarrow$ connect the two (actually a bit more than that) $\Rightarrow$ a spiral structure



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- the Ekman transport (mass flux) perpendicular to wind vector (why?)

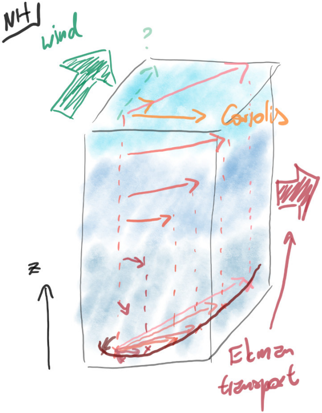


Figure: Schematic of Ekman spiral.

Ekman pumping + suction

Consider the following scenario:

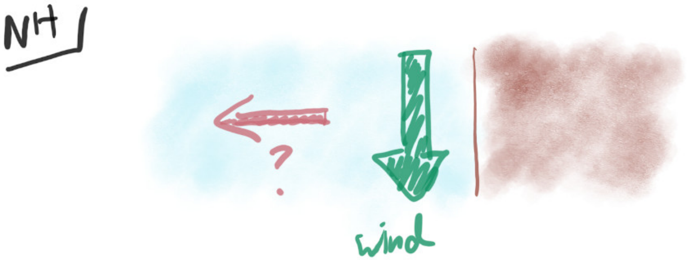


Figure: Schematic of Ekman suction (top-down view).

- Ekman transport away from boundary, but how to conserve mass/water?

Ekman pumping + suction

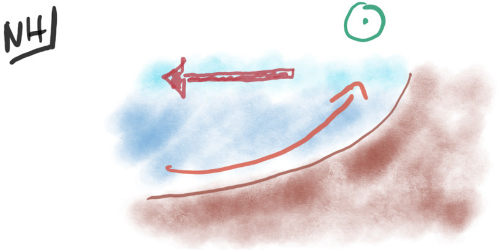
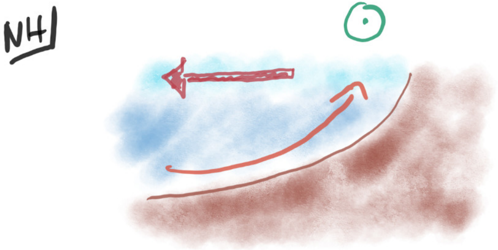


Figure: Schematic of Ekman suction (across-slope view; wind is coming out of the page).

- Ekman suction $\sim$ Ekman upwelling
  $\rightarrow$ sometimes this is referred to as Ekman pumping...?
- Ekman pumping $\sim$ Ekman downwelling

Ekman pumping + suction



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- Ekman suction $\sim$ Ekman upwelling
  $\rightarrow$ sometimes this is referred to as Ekman pumping...?
- Ekman pumping $\sim$ Ekman downwelling

- Ekman upwelling $\Rightarrow$ upwelling of nutrient-rich waters
  $\rightarrow$ importance for biogeochemistry

Ekman pumping + suction: flow divergence

Figure: Schematic of Ekman suction in equator (across-slope view; wind is going into page).

- example over the Equator
  $\rightarrow$ Ekman transport divergence ($\nabla_h \cdot \boldsymbol{u} > 0$)
  $\rightarrow$ $w_e \sim \nabla_h \cdot \boldsymbol{u} > 0$, i.e. upwelling

up/downwelling $\sim$ flow div/convergence

Ekman pumping + suction: wind stress curl

Figure: Schematic of wind shear (wind stress curl) with Ekman up/downwelling.

- shear in wind $\sim$ con/divergence in flow
- shear in wind $\sim$ wind stress curl
- $w_e \sim \nabla_h \cdot \boldsymbol{u} \overset{?}{\sim} \nabla_h \times \boldsymbol{\tau}$

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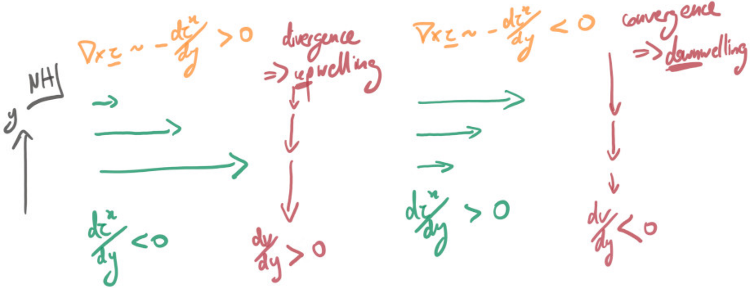

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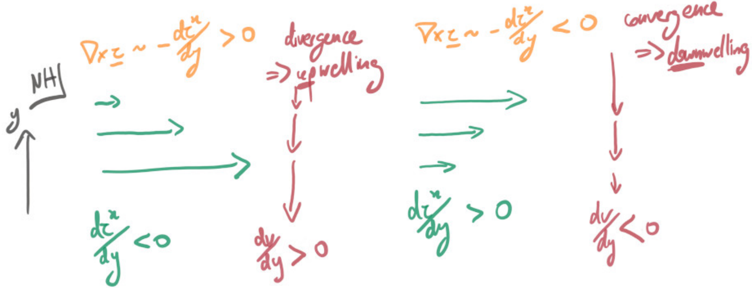
Ekman pumping + suction: wind stress curl



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- shear in wind $\sim$ wind stress curl
- $w_e \sim \nabla_h \cdot \boldsymbol{u} \overset{?}{\sim} \nabla_h \times \boldsymbol{\tau}$

  $\rightarrow$ actually (see bonus exercise)

$$\boxed{w_e = \frac{1}{\rho f} \boldsymbol{e}_z \cdot (\nabla \times \boldsymbol{\tau})}$$

Recap: Shear, spin and vorticity (more in Lec 11 + 12)

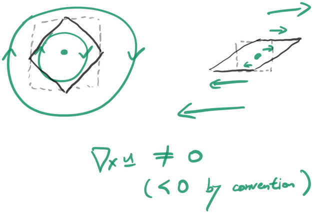

Figure: Schematic of shear and curl.

- recall (from lec 4) that curl is to do with spin
- vorticity is defined as

$$\boldsymbol{\omega} = \nabla \times \boldsymbol{u}$$

- usually deal with vertical component

$$\omega \equiv \omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

- convention is anti-clockwise = positive curl

Recap: Shear, spin and vorticity (more in Lec 11 + 12)

Figure: Schematic of wind shear (wind stress curl) with Ekman up/downwelling.

$$(\nabla \times \boldsymbol{\tau})_z = \frac{\partial \tau^y}{\partial x} - \frac{\partial \tau^x}{\partial y}$$

convince yourself that

- left case has **positive** wind stress curl
- right case has **negative** wind stress curl

Up/downwelling with eddies

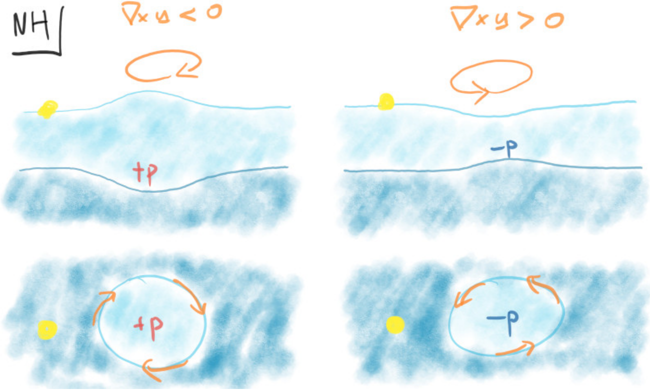

Figure: Up/downwelling associated with anti-cyclonic (left) and cyclonic (right) eddies (since we are in NH).

Up/downwelling with eddies

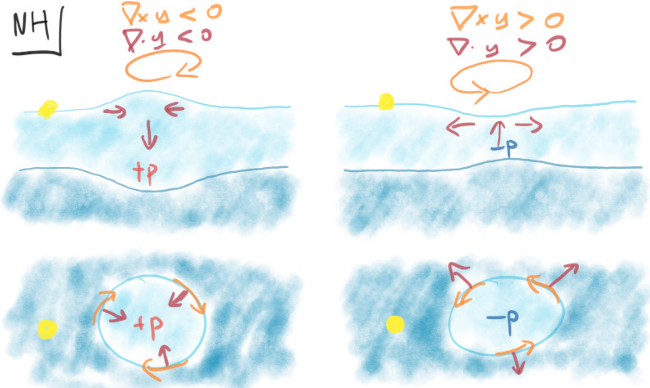

Figure: Up/downwelling associated with anti-cyclonic (left) and cyclonic (right) eddies (since we are in NH).

- exercise: check that $w \sim (1/f)\boldsymbol{e}_z \cdot (\nabla \times \boldsymbol{u})$ is satisfied here

(remember that $f > 0$ in NH)

Summary

- wind a chief source of momentum into the ocean

  $\rightarrow$ direct influence only over Ekman layer

  $\rightarrow$ vertical transfer through a (turbulent) friction (more next Lec)
- geostrophic balance modified over Ekman layer

  $\rightarrow$ Ekman spiral structure

  $\rightarrow$ Ekman transport is in direction of geostrophic flow
- (Ekman) up/downwelling associated with wind/velocity curl and flow divergence (be careful of sign of f!)

$$w_e \sim \frac{1}{f}\boldsymbol{e}_z \cdot (\nabla \times \boldsymbol{\tau}), \qquad w \sim \frac{1}{f}\boldsymbol{e}_z \cdot (\nabla \times \boldsymbol{u})$$

- vertical transfer beyond Ekman layer? (see Lec. 14)
- bottom boundary Ekman layers? (very briefly in Lec. 14)