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

$$\rho_0 \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} \right) = -\nabla p + \mathbf{F}_u + \mathbf{D}_u \quad (1)$$

$$\frac{\partial p}{\partial z} = -\rho g \quad (2)$$

$$\nabla \cdot \mathbf{u}_3 = 0 \quad (3)$$

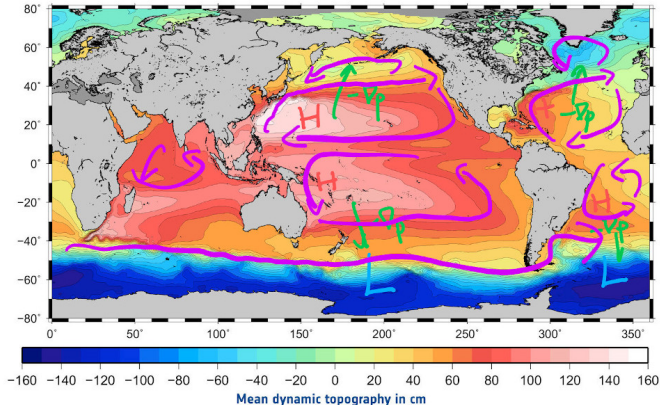
$$\left( \frac{\partial T}{\partial t} + \mathbf{u}_3 \cdot \nabla T \right) = F_T + D_T \quad (4)$$

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

$$\rho = \rho(T, S, p) \quad (6)$$

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

# Recap: Geostrophic flows

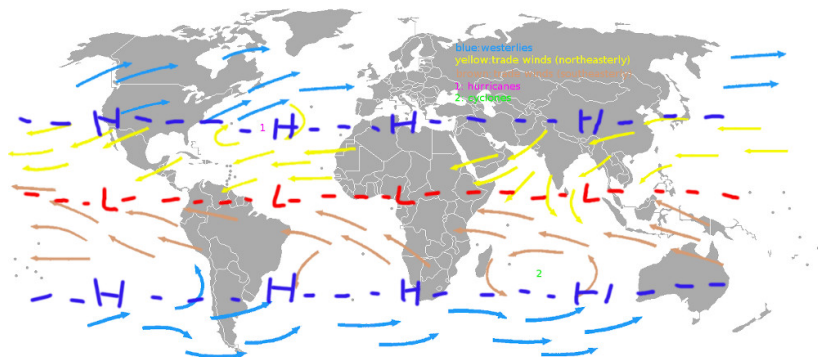


**Figure:** Time-mean global SSH (also called **mean dynamic topography**, with time-mean currents drawn on (notice the orientation around high/low SSH regions). Modified from Rio *et al* (2011), J. Geophys. Res: Oceans.

- contours of SSH related to isobars via **hydrostatic balance**
  - flow is **along** rather than **across** isobars (**Coriolis effect**, see last Lec.)

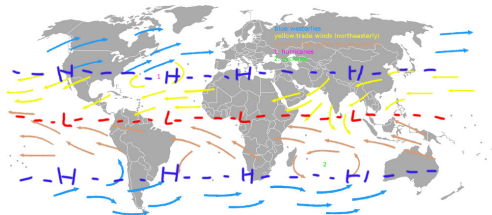
# Atmospheric wind patterns

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

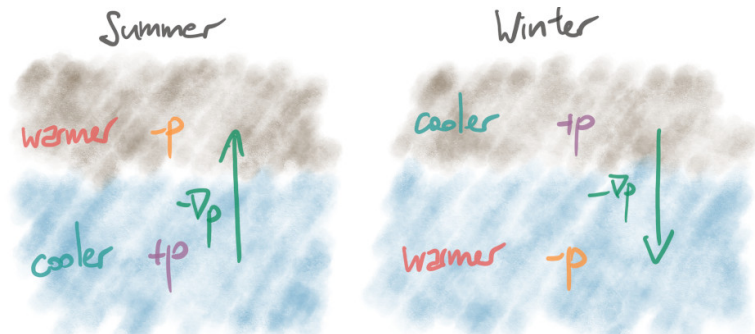


- ▶ EQ is a **low pressure** region  
→ convection, **ITCZ**
- ▶ **subtropical highs** around  $30^\circ$  N/S  
→ edge of **Hadley cell** (see OCES 4001)
- ▶ W to E winds in Tropics and Polar regions are **Easterlies**  
→ coming from the **East**  
→  $u < 0$  and **Westward** here
- ▶ E to W winds 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)
  - 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

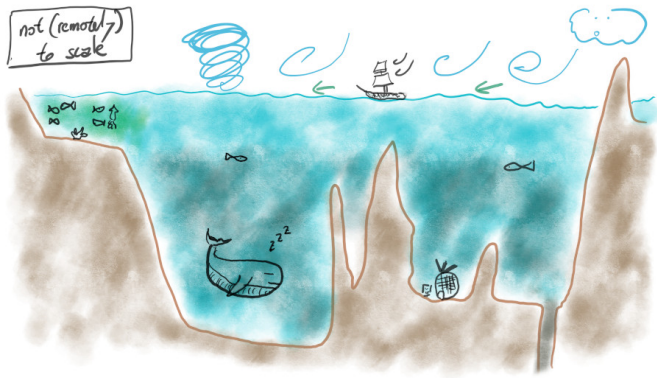


Figure: Schematic of ocean forcing.

- 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**  $\Rightarrow$  much 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

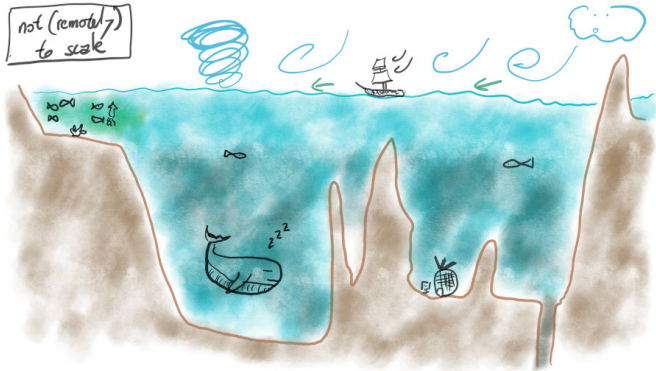


Figure: Schematic of ocean forcing.

- 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

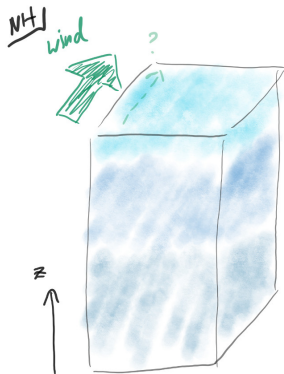


Figure: Schematic of Ekman spiral.

# Ekman spiral

- ▶ near the surface the flow is roughly in direction of wind  
→ wind not negligible in Ekman layer, geostrophic balance modified

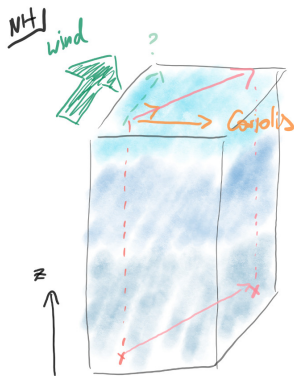


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# Ekman spiral

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- ▶ geostrophy  $\Rightarrow$  flow perpendicular to wind (to the right in NH) in deep parts

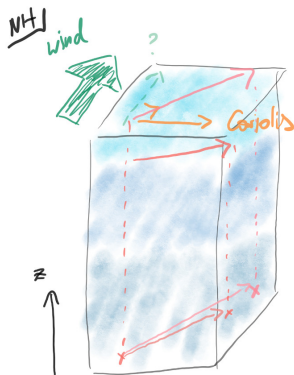


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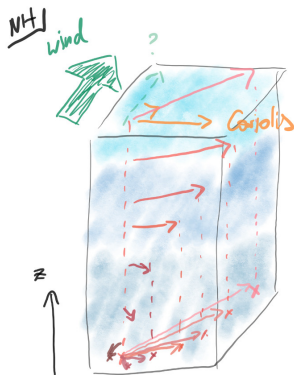


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→ connect the two (actually a bit more than that)  $\Rightarrow$  a **spiral** structure
- ▶ the **Ekman transport** (mass flux) perpendicular to wind vector (why?)

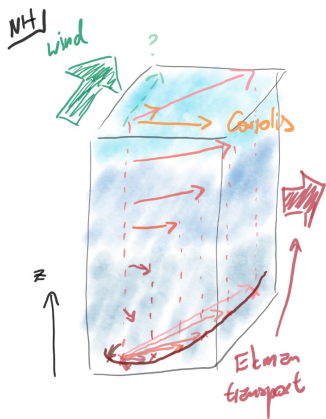
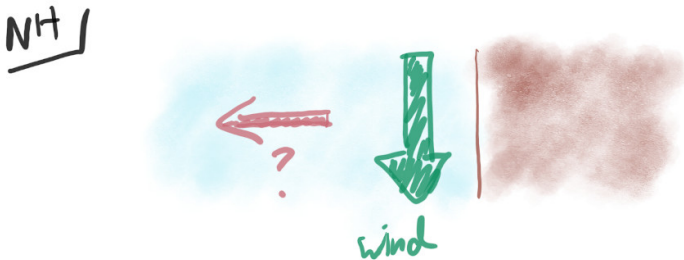


Figure: Schematic of Ekman spiral.



## Ekman pumping + suction

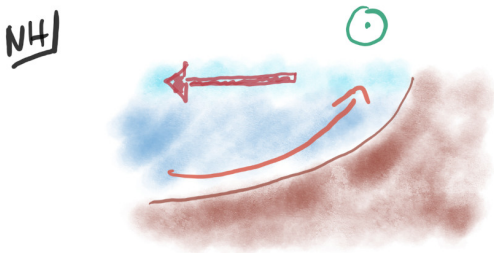
Consider the following scenario:



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

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

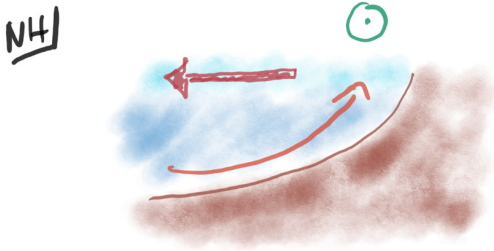
# Ekman pumping + suction



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

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

# Ekman pumping + suction



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- ▶ Ekman pumping  $\sim$  Ekman downwelling
- ▶ Ekman upwelling  $\Rightarrow$  upwelling of nutrient-rich waters  
→ importance for biogeochemistry (see Lec. 22)

# Ekman pumping + suction: flow divergence



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

## ► example over the Equator

→ Ekman transport **divergence** ( $\nabla_h \cdot \mathbf{u} > 0$ )

→  $w_e \sim \nabla_h \cdot \mathbf{u} > 0$ , 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
- ▶  $w_e \sim \nabla_h \cdot \mathbf{u} \stackrel{?}{\sim} \nabla_h \times \boldsymbol{\tau}$

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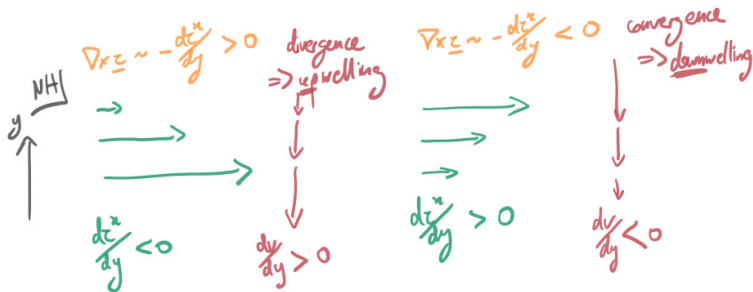


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# Recap: Shear, spin and vorticity (more in Lec 11 + 12)

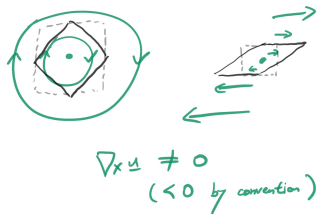


Figure: Schematic of shear and curl.

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

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

- 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)



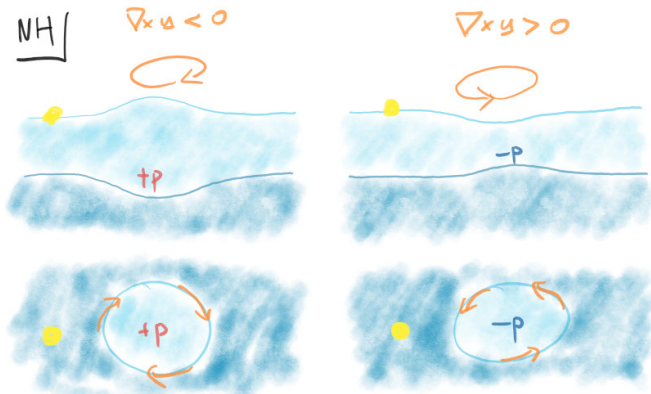
**Figure:** Schematic of wind shear (wind stress curl) with Ekman up/downwelling.

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

convince yourself that

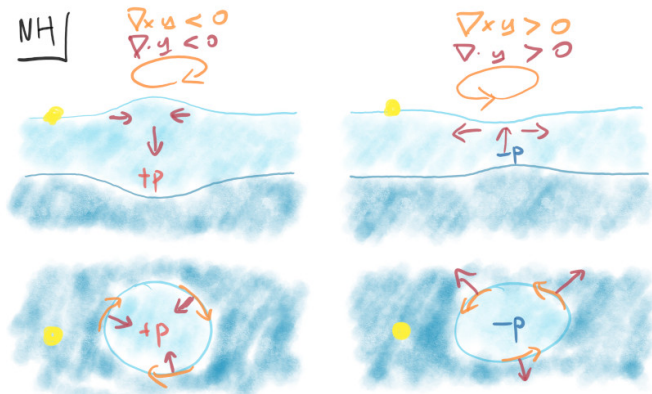
- ▶ left case has **positive** wind stress curl
- ▶ right case has **negative** wind stress curl

# 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  $w \sim (1/f)\mathbf{e}_z \cdot (\nabla \times \mathbf{u})$  is satisfied here  
(remember that  $f > 0$  in NH)

# Summary

- ▶ wind a chief source of momentum into the ocean
  - direct influence only over **Ekman layer**
  - vertical transfer through a (turbulent) **friction** (more next Lec)
- ▶ geostrophic balance modified over Ekman layer
  - **Ekman spiral** structure
  - **Ekman transport** is in direction of geostrophic flow
- ▶ (Ekman) up/downwelling associated with **wind/velocity curl** and **flow divergence** (be careful of sign of  $f$ !)

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

$$w \sim \frac{1}{f} \mathbf{e}_z \cdot (\nabla \times \mathbf{u})$$

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