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- ▶ 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)

Tue 2nd Mar

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

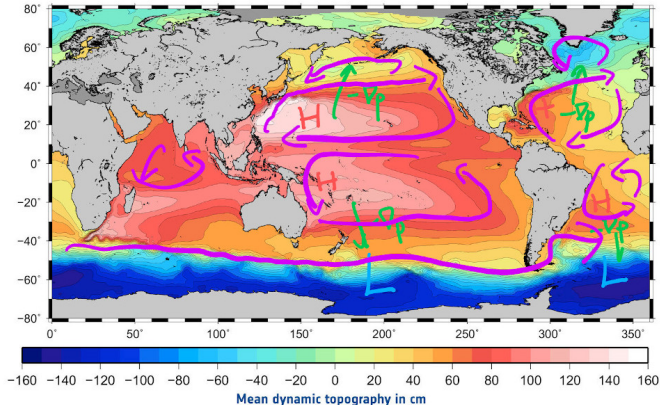
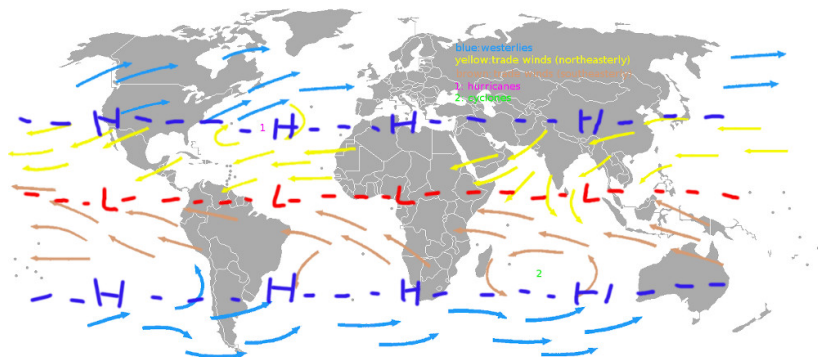


Figure: Time-mean global SSH (also called **mean dynamic topography**, with time-mean currents drawn on (notice the orientation around high/low SSH regions). Modified from Rio *et al* (2011), J. Geophys. Res: Oceans.

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

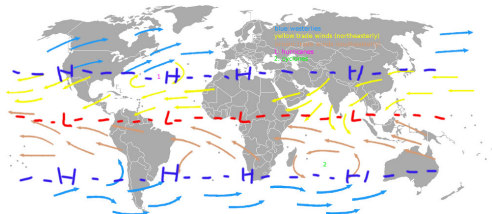
Atmospheric wind patterns

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° 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**)

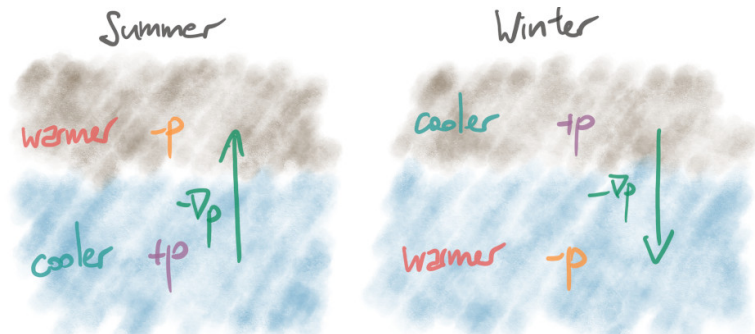


Figure: Schematic of monsoons, arising from changes in pressure gradients largely governed by heat. Actual wind direction slightly deflected because of Coriolis (see schematic in **Ekman spirals** later).

Wind forcing

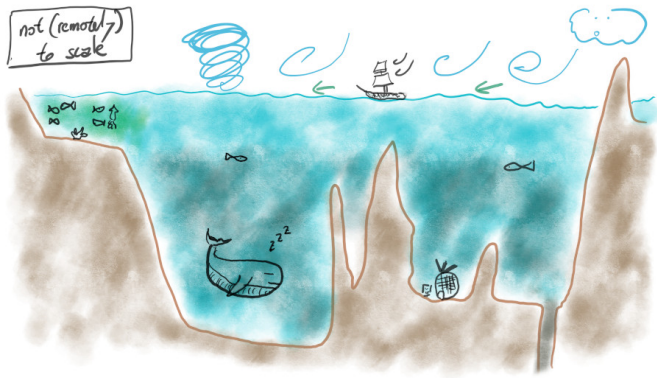


Figure: Schematic of ocean forcing.

- 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

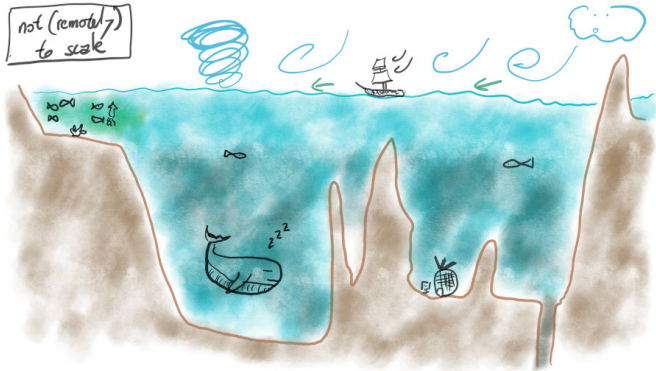


Figure: Schematic of ocean forcing.

- 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

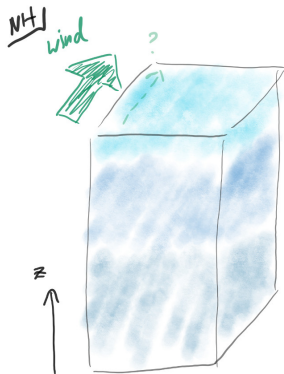


Figure: Schematic of Ekman spiral.

Ekman spiral

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

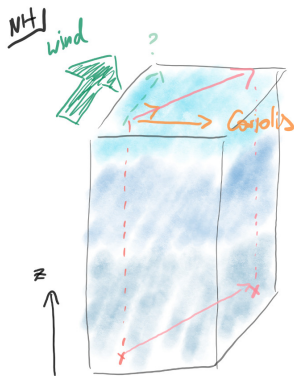


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Ekman spiral

- ▶ near the surface the flow is roughly in direction of wind
→ wind not negligible in Ekman layer, geostrophic balance modified
- ▶ geostrophy \Rightarrow flow perpendicular to wind (to the right in NH) in deep parts

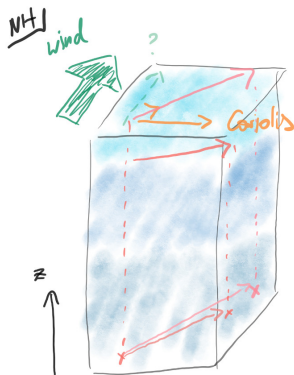


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Ekman spiral

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- ▶ geostrophy \Rightarrow flow perpendicular to wind (to the right in NH) in deep parts
→ connect the two (actually a bit more than that) \Rightarrow a **spiral** structure

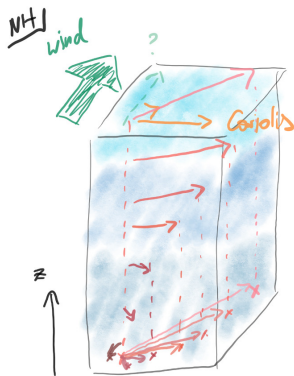


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Ekman spiral

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→ wind not negligible in Ekman layer, geostrophic balance modified
- ▶ geostrophy \Rightarrow flow perpendicular to wind (to the right in NH) in deep parts
→ connect the two (actually a bit more than that) \Rightarrow a **spiral** structure
- ▶ the **Ekman transport** (mass flux) perpendicular to wind vector (why?)

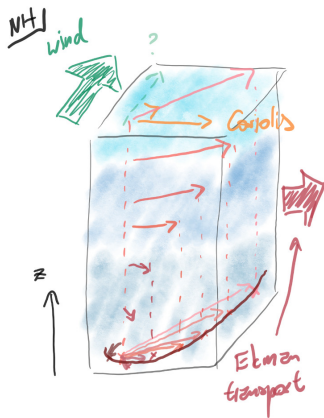


Figure: Schematic of Ekman spiral.

Ekman pumping + suction

Consider the following scenario:

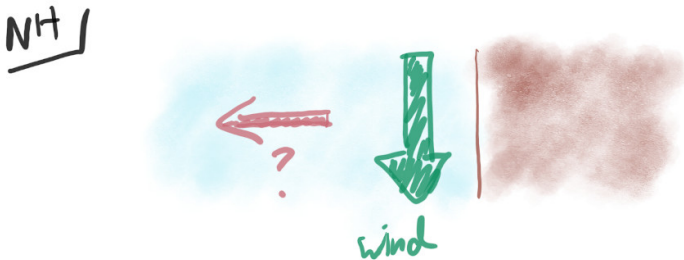


Figure: Schematic of Ekman suction (top-down view).

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

Ekman pumping + suction

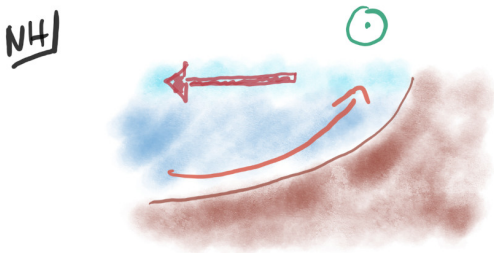


Figure: Schematic of Ekman suction (across-slope view; wind is coming out of the page).

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

Ekman pumping + suction

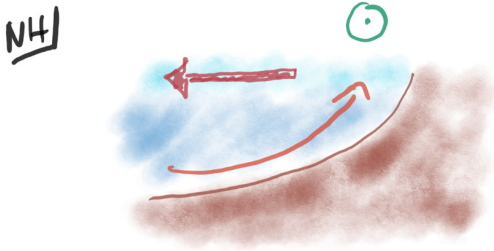


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- ▶ Ekman suction \sim Ekman upwelling
→ sometimes this is referred to as Ekman pumping...?
- ▶ Ekman pumping \sim Ekman downwelling
- ▶ Ekman upwelling \Rightarrow upwelling of nutrient-rich waters
→ importance for biogeochemistry (see Lec. 22)

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
- $w_e \sim \nabla_h \cdot \mathbf{u} \stackrel{?}{\sim} \nabla_h \times \boldsymbol{\tau}$

Ekman pumping + suction: wind stress curl



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Ekman pumping + suction: wind stress curl

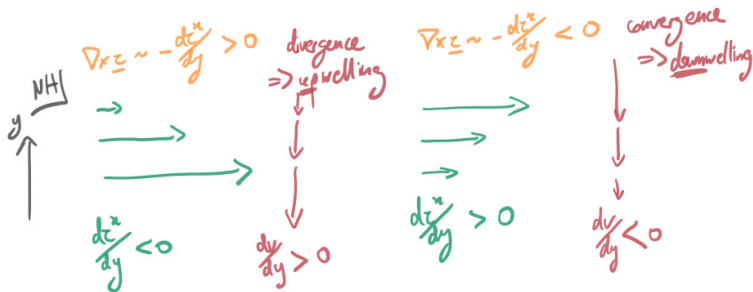


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Ekman pumping + suction: wind stress curl

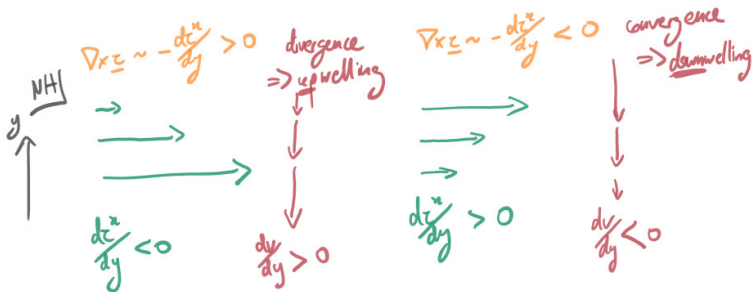


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- ▶ shear in wind \sim con/divergence in flow
- ▶ shear in wind \sim wind stress curl
- ▶ $w_e \sim \nabla_h \cdot \mathbf{u} \stackrel{?}{\sim} \nabla_h \times \boldsymbol{\tau}$
 → actually (see bonus exercise)

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

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

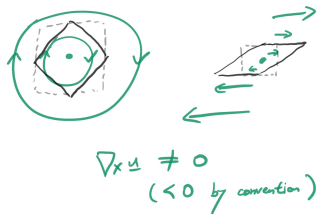


Figure: Schematic of shear and curl.

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

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

- 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

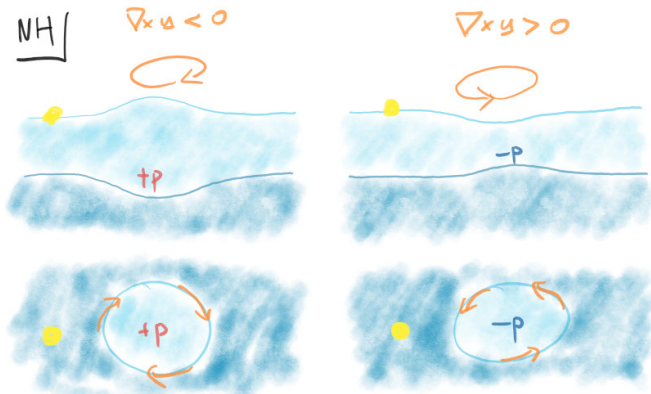


Figure: Up/downwelling associated with anti-cyclonic (left) and cyclonic (right) eddies (since we are in NH).

Up/downwelling with eddies

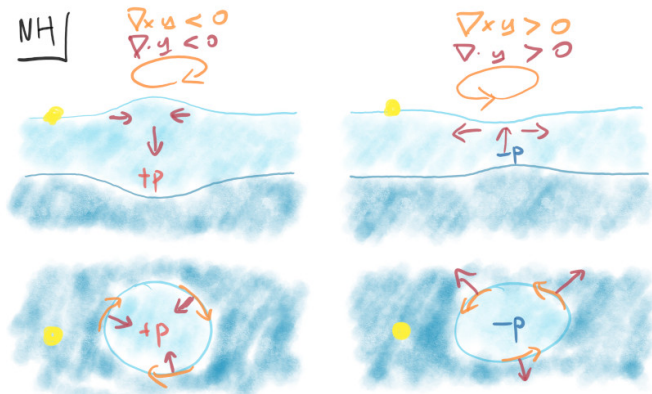


Figure: Up/downwelling associated with anti-cyclonic (left) and cyclonic (right) eddies (since we are in NH).

- 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)