Climatology of the atmospheric circulation of the EBUSs

CLIVAR-ICTP Summer school
ICTP Trieste
15 July 2019

Thomas Toniazzo, NORCE Research, Bjerknes Centre, Bergen, Norway
Köppen climatic zones

Defined on the basis of average monthly temperature and precipitation
Köppen climatic zones

Mediterranean (dry summer)
Semi-arid steppe
Arid desert
Köppen climatic zones

- Mediterranean (dry summer)
- Semi-arid steppe
- Arid desert

Map showing distribution of different climatic zones.
Along-shore winds and upwelling

Figure 1: Intensity of the Ekman transport associated with along-shore wind-stress according to the .25° Scatterometer Climatology of Ocean Winds (‘SCOW’, Risien and Chelton, 2008). Only positive values are shown, defined such that transport is away from the coast. The alongshore direction is given by the closest 500-km long stretch of continuous coastline, and points beyond 500km distance from land or within 5 degrees latitude from the Equator are assigned zero values of offshore transport.
Simple view of upwelling and along-shore wind
Assumption: dynamical balance between Coriolis force and viscous/turbulent stress

Integration over depth $z \in [0, -\infty]$ gives

where $M_{x/y}$ are the depth-integrated zonal/meridional mass transports and $\tau_0$ the stress at the surface i.e. the wind stress:
“Ekman drift”

Assumption: dynamical balance between Coriolis force and viscous/turbulent stress

\[-\rho f v = \frac{\partial \tau_x}{\partial z}\]
\[\rho f u = \frac{\partial \tau_y}{\partial z}\]

Integration over depth \(z \in [0, -\infty]\) gives

\[-f M_y = \tau_{x0}\]
\[f M_x = \tau_{y0}\]

where \(M_{x/y}\) are the depth-integrated zonal/meridional mass transports and \(\tau_{0}\) the stress at the surface i.e. the wind stress:

\[M_x := \int_{-\infty}^{0} \rho u \, dz\]
\[\tau_{y0} := \tau_y(z = 0)\]

Note: the full fluid-dynamical equations are e.g. for the meridional direction:

\[\rho \left( \partial_t + u \cdot \nabla \right) u + \partial_x p + \rho f u = \frac{\partial \tau_y}{\partial z}\]

and the first two terms are not a-priori negligible, so that Ekman theory is in fact **not always applicable in the EBUS**.
“Ekman pumping”

\[ \nabla \cdot (f \, \mathbf{M}) = \nabla \times \tau_0 \]

This relation is a more generally accurate approximation, i.e. always applicable in the ocean.

Upwelling is therefore linked with the **spatial structure** of the wind stress (cyclonic vorticity).
“Ekman pumping”

\[ \nabla \cdot (f \mathbf{M}) = \nabla \times \mathbf{\tau}_0 \]

This explanation of EBUS upwelling is still \textit{incomplete}, but the presence of an \textit{atmospheric long-shore (equatorward) surface jet} is crucial.

Figure 2: Windstress curl (colour maps), surface along-shore windstress (line contours defined as in Figure 1 and the location and intensity of the maximum along-shore windstress (green/white crosses) according to the SCOW climatology.
Figure 5: Zonal section along 22-23S in the Eastern Atlantic, illustrating the distribution of meridional (colour-filled, black dashed contours, spacing 0.5 m/s), zonal and vertical wind components (arrows, in red for ascent and in blue for descent; scale on the bottom left, in m/s for the zonal component, and mPa/s for the vertical component), temperature (black solid contour lines, spacing 2 K, plus 0 °C and 20 °C isotherms as thicker black lines), static stability (white contour lines, spacing $0.5 \times 10^{-2} \text{s}^{-1}$ between $2.25 \times 10^{-2} \text{s}^{-1}$ and $4.25 \times 10^{-2} \text{s}^{-1}$), and cloud concentration (above 0.2, 0.3 and 0.4, colour-filled in green, cyan, and magenta, respectively). October climatology from ERA-Interim data.
Figure 4: Zonal sections of vertical (solid lines) and meridional (coloured areas) winds, averaged between 25 and 35 degrees of latitude, for the Northern Hemisphere (panel (a)) and the Southern Hemisphere (panel (b)), averaged over the respective extended summer. The contour interval is 0.6 cPa/s and 0.6 m/s, respectively, starting from ±0.3 m/s. Climatology for the period 1999-2007 as represented in ERA-Interim.
Conservation of angular momentum

When a body moves in a circle, its **Angular Momentum** \((G)\) is proportional to 

\[
\text{Mass} \times \text{Velocity} \times \text{Radius}
\]

i.e. if radius decreases and mass remains same, velocity must increase to conserve \(G\) and **vice versa**.

\[A\] Air moves towards pole, radius decreases and speed increases (to conserve \(G\))

\[B\] Air moves towards equator, radius increases and speed decreases (to conserve \(G\))
Differential heating and rotation generate the global circulation.

Differential heating starts "cell"-type circulation.

The Coriolis acceleration generates surface Easterlies and anticyclonic flow everywhere. Surface friction then sets the atmosphere in rotation and generates subtropical westerlies.

The build-up of T gradient and westerly momentum aloft leads to jet-stream formation and the split-up of the Hadley cell into a second, thermally indirect Ferrel cell in which momentum and heat transport is effected by waves.
Large-scale setting of the trade inversion

The energy cycle of the Hadley cell

**Hadley Cell Cross-Section**

- **LW radiative cooling**
- **SW radiative heating**
- **Warm, humid**
- **Cool, dry**
- **Deep cloud**
- **Ocean current**
- **Warm**
- **Cool**
- **Clear sky, dry**
- **Reduced LW, reduced SW**
- **LW radiative cooling**
- **Hot, dry**
- **Cold, dry**
- **Warm, dry**
- **Warm, humid**
- **+ Latent heat**

**30°N**
**0° (EQ)**
**30°S**

**Horse Latitudes**
**The Doldrums**
Schneider (1977), Held & Hou (1980) model

a) momentum conservation

\[ 0 = -\nabla \cdot (\mathbf{v} M) + \frac{\partial}{\partial z} \left( \nu \frac{\partial M}{\partial z} \right), \quad (7) \]

\[ M = \Omega a^2 \cos^2 \theta + u a \cos \theta \]

b) thermal wind balance

\[ f u + \frac{u^2 \tan \theta}{a} = -\frac{1}{a} \frac{\partial \Phi}{\partial \theta}. \]

\[ R = \frac{g H \Delta H}{\Omega^2 a^2} \]

\[ R^2 \left( H \Delta H / Ct \Delta v \right) (a \Omega) \]
Schneider (1977), Held & Hou (1980) model

- To leading order, tropical winds are controlled by **advection of zonal momentum** and **surface stress**
- The meridional circulation exists to satisfy local heat balance (**cold/warm advection**)
- The “mean” circulation is perturbed by mid-latitude transport due to baroclinic waves (poleward displacement of surface W'lies)
The planetary-scale mean meridional circulation

Precipitation

DJF

PPT [mm/day]: DJF

JJA

PPT [mm/day]: JJA

Vertical velocity

DJF

ω at 500hPa [Pa/s]: DJF

JJA

ω at 500hPa [Pa/s]: JJA
Differential heating sustains the Hadley circulation
Hadley circulation from the satellite

1. Warm and moist, convection, rainfall, large-scale ascent, large release of latent heat
2. Dry and warm, mild conditional instability, strong positive radiative imbalance
3. Dry and cool, large-scale descent, inversion-capped low stratus cloud, weak radiative warming
EBUS and cloud

Land and cloud radiative effects in the visible and thermal bands

23 Sept 2007, 0600 UTC
Convergence and ascent in the ITCZ is matched by divergence and descent in the subtropical highs, mainly in the winter hemisphere.

The ITCZ is near, but poleward of, the warmest water.
Hadley circulation

The STAs are surface expressions of the Hadley circulation where low-level divergence matches the convergence in the ITCZ.
Surface and upper level winds (December)

- Tropical Easterlies (trades)
- Mid-latitude Westerlies
- Sub-tropical jet stream
- Sub-polar jet stream
Upper tropospheric winds (December)

NCEP/NCAR Reanalysis
250mb Vector Wind (m/s) Composite Mean

Dec: 1980 to 2000
Surface winds (December)
NCEP/NCAR Reanalysis
1000mb Vector Wind (m/s) Composite Mean

Dec: 1980 to 2000
Surface winds (December)

NCEP/NCAR Reanalysis

1000mb Vector Wind (m/s) Composite Mean

Dec: 1980 to 2000
Structure of the trade-wind regions

1. Inversion-capped PBL, Scu and shallow ("trade") cumulus
2. Inversion strength of several °C, often 10 °C or more in the East
3. Raises in height and weakens towards the West
4. Maximum wind speed at the inversion base
Hastenrath 1982: “Climate dynamics of the tropics”
Characteristics of the PBL inversion

A typical vertical temperature profile in the STAC

- The PBL is nearly dry-adiabatic
- The cloud layer is moist-adiabatic
- The FT is superadiabatic, due to radiative cooling
- A miracle happens when plotting $\theta_w$
General circulation and the poleward edges of the EBUS

(Northern Hemisphere)

Major overturning cells and upper waves

Main airstreams (as seen in vertical section)

Surface pressure systems and winds
(A = mid-latitude anticyclones, C = mid-latitude depressions)
General circulation and the poleward edges of the EBUS
Upper tropospheric winds (December)

NCEP/NCAR Reanalysis

250mb Vector Wind (m/s) Composite Mean

Dec: 1980 to 2000
“This winter east wind of the Namib belongs to those great movements of air which maintain a changing equilibrium between the air masses over land and sea. When [...] the air over the uplands grows colder than the air over the Atlantic [...] it races out over the sea [...] as a hot, sand-laden storm [...]. [...] it usually takes three days for a new equilibrium to be established between land and sea. In summer the same process takes place but in the opposite direction. [...] For these reasons the prevailing winds in the Namib are east in winter and west in summer.”


“We knew that rain storms in the Namib usually lasted three or four days [...] On the third day the west wind got the upper hand, the sun established its reign again, and a hot, light-blue sky spread out over the thirsty wilderness.”


https://archive.org/details/shelteringdesert007109mbp
A few important points

I. EBUSs are characterised by intense extreme arid conditions and equatorward surface winds

II. Their location is largely controlled by the large-scale Hadley-Walker circulation

III. Their circulation is strongly baroclinic, coupled with strong descent driven by radiative cooling

IV. The winds are embedded in a strong, sloping inversion which weakens and flattens into the trade-wind inversion towards the west

V. They sit at the eastern edge of the surface STA and below and east of semi-permanent upper-level troughs (equatorward excursions of the STJs)

VI. In contrasts with the large-scale trade winds, the surface winds of the EBUS undergo significant high-frequency variability (synoptic, mesoscale, and diurnal)