2 Exploring fluid transport using Atmospheric data

We will use EsGlobe to view atmospheric and oceanic flow trajectories and how tracers, such as aerosols, water vapor and particles (e.g. plastics floating in the surface ocean), are dispersed around the globe by winds and currents. In this way we will explore how parcels of fluid carry properties around with them as they move.

2.1 Transport in the Atmosphere

2.1.1 Calculating trajectories from wind observations

We learned in Section 1.1 how to express the rate of change of a property C of a fluid element, *following that element as it moves along*, rather than at a fixed point in space — see Eq.(1) and attendant discussion. It follows from the definition of the Lagrangian derivative, D/Dt, that the position of a parcel of fluid is related to its velocity by Eqs(3 and 4, repeated here for 2-dimensions:

$$u = \frac{D}{Dt}x; \;\; v = \frac{D}{Dt}y,$$

$$x = \int u dt; y = \int v dt,$$

where u is the speed in the x direction and v is the speed in the y direction etc.

Here we will build the trajectory — (x, y) as a function of time — of a hypothetical particle of dust, moving with the wind during June of 2018 when satellite imagery revealed a persistent flow of dust from the Sahara desert moving across the Atlantic over the Southern US. In fact the last 10 days of June were the 10 dustiest for the tropical Atlantic going back 15 years — see Fig.5 — from NASA-Earth Observatory — see https://earthobservatory.nasa.gov/images/92358/here-comes-the-saharan-dust.

Using maps (handed out in class) of the height field and the wind field at the 850 mb level over the Atlantic region at: 180620 (20th June, 2018), 12 GMT; 180620 18 GMT; 180621 00 GMT and 180621 06 GMT, draw by hand the trajectories of chosen particles following the 12z wind for the first six hours, the 18z wind for the second six hours, the 00z wind for the third six hours and the 06z wind for the fourth six hours. In this way, compute a trajectory over a period of 1 day.

Compare your trajectory with one you obtain from the EsGlobe interface by launching a virtual particle in to the same flow field. The two should be rather similar. This is essentially how the EsGlobe computes trajectories: it reads in wind fields at regular intervals

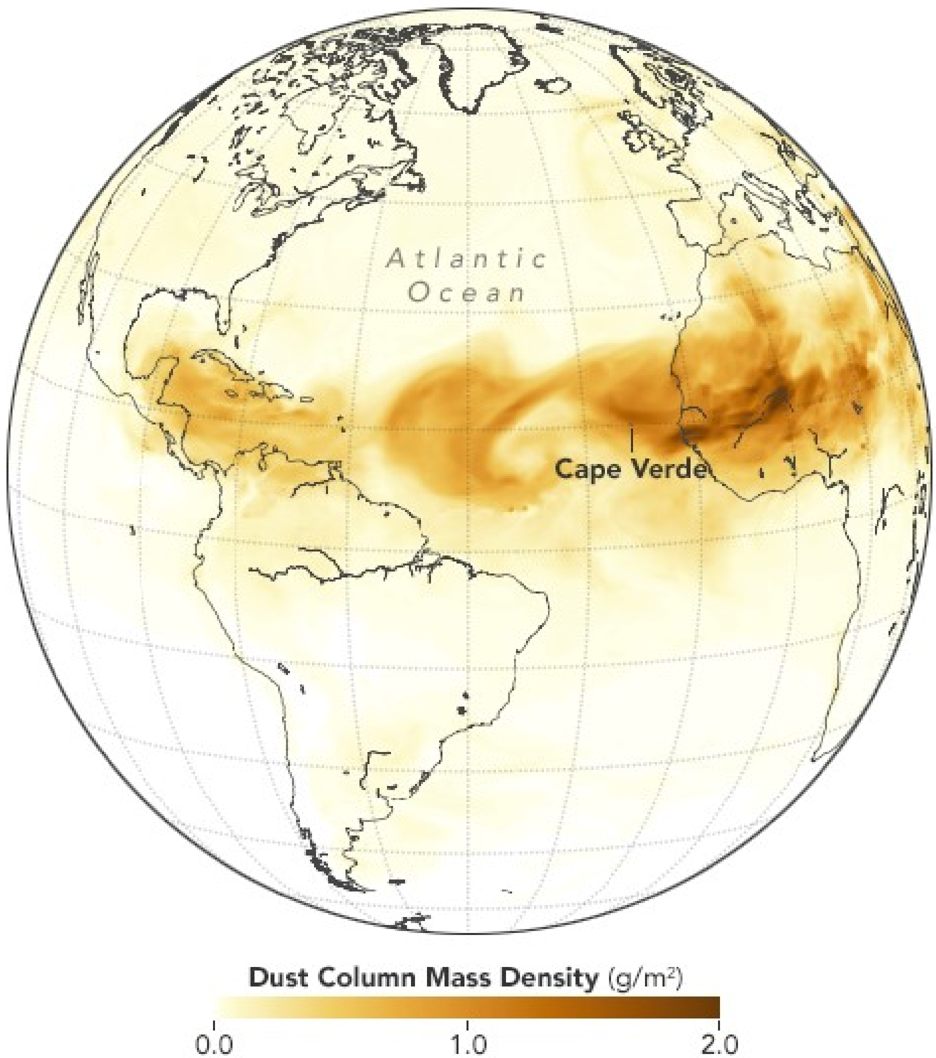

Figure 5: A cloud of dust, whipped up winds from the Sahara Desert, being carried by the trade winds over to the Caribbean, and on toward Texas. The map is from June 28, 2018: from NASA-Earth Observatory — see https://earthobservatory.nasa.gov/images/92358/here-comes-the-saharan-dust.

and performs the above integrals numerically, plotting out the positions as it goes.

Finally, estimate how long it will take for your particle of dust to reach Texas. Is your estimate consistent with what was observed by satellite, as described in the article above?

2.1.2 Rate of change of temperature at a point: temperature advection

More often than not, it becomes cold over Boston, say, because winds carry low temperatures from places where it is cold. We say that cold air is advected (carried) by the winds. We can write this down mathematically as:

$$\frac{D}{Dt}T = 0, \tag{6}$$

assuming that air parcels conserve temperature as they move. If the winds are predominantly horizontal (a good approximation) then:

$$(\partial T/\partial t)_{\text{at Boston}} = -u\partial T/\partial x - v\partial T/\partial y \tag{7}$$

where u is the zonal (west to east) component of the wind and v is the meridional (south to north) component of the wind, T is temperature and t is time.

If the temperature at Boston increases with time:

- then $\partial T/\partial t > 0$ and is associated with warm temperature advection (winds blowing from higher to lower temperature)

Vice versa, if the temperature at Boston decreases with time:

- then $\partial T/\partial t < 0$ and is associated with cold temperature advection (winds blowing from lower to higher temperature)

Let's test these ideas out using data by comparing the local temperature tendency at a few locations to that implied by horizontal temperature advection, as expressed in Eq.(7).

A Schematic front. Suppose a cold front has just passed over Boston. The front is oriented west to east and the temperature drops 5^oC every 100 km (as sketched in Fig.6). As the wind blows from the NW at $15kts$, where $1kts = 0.5m/s$, infer how much the temperature will be expected to drop in 12 hours due to cold air advection?

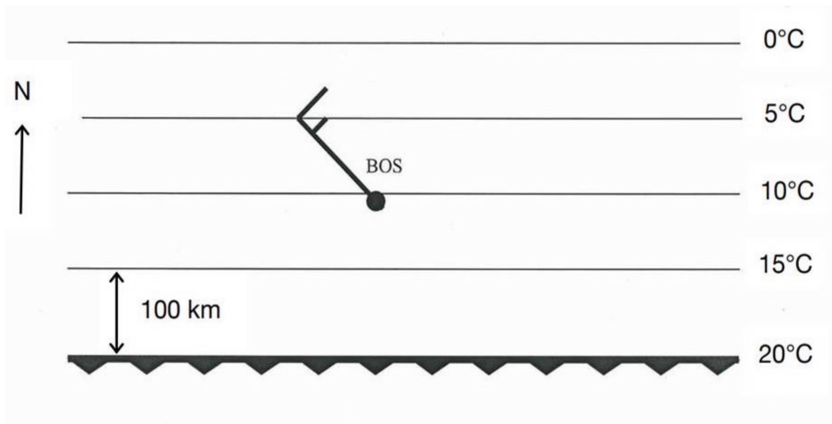

Figure 6: Sketch of a front (indicated by the thick serrated line) oriented west to east across which the temperature drops 5^oC every 100 km. The wind is blowing from the NW at $15kts$.

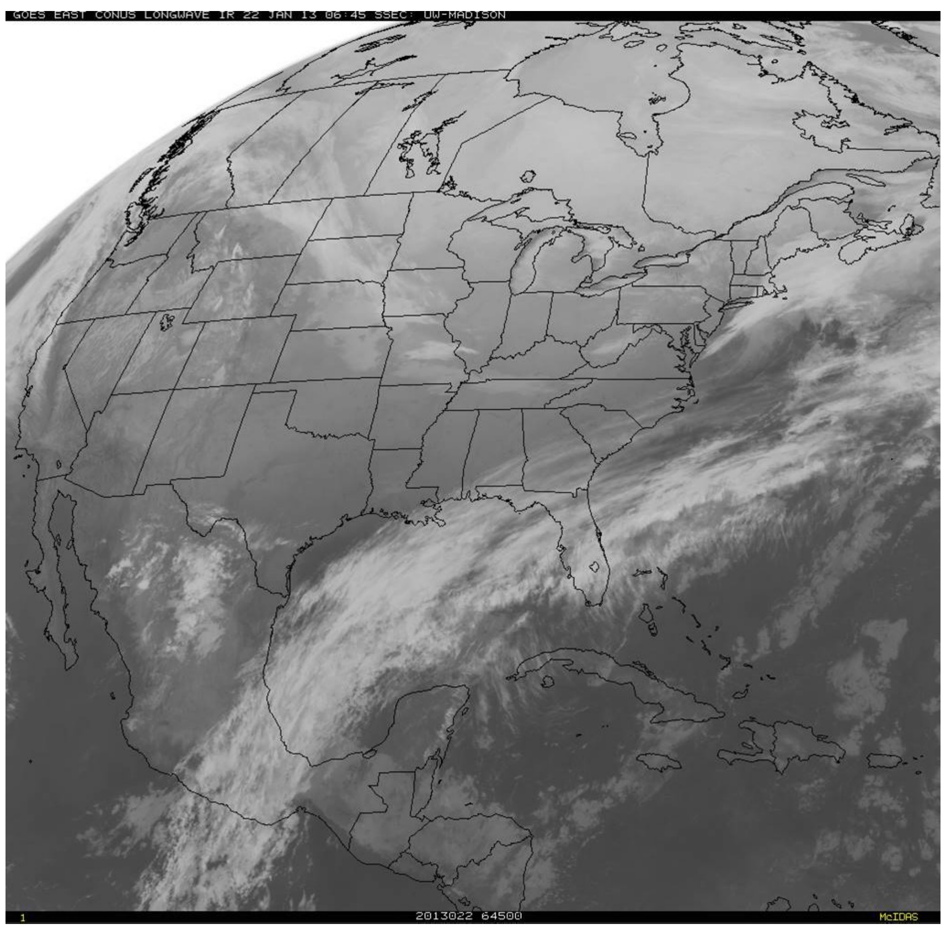

Figure 7: IR satellite image for January 22, 2013 at 06z

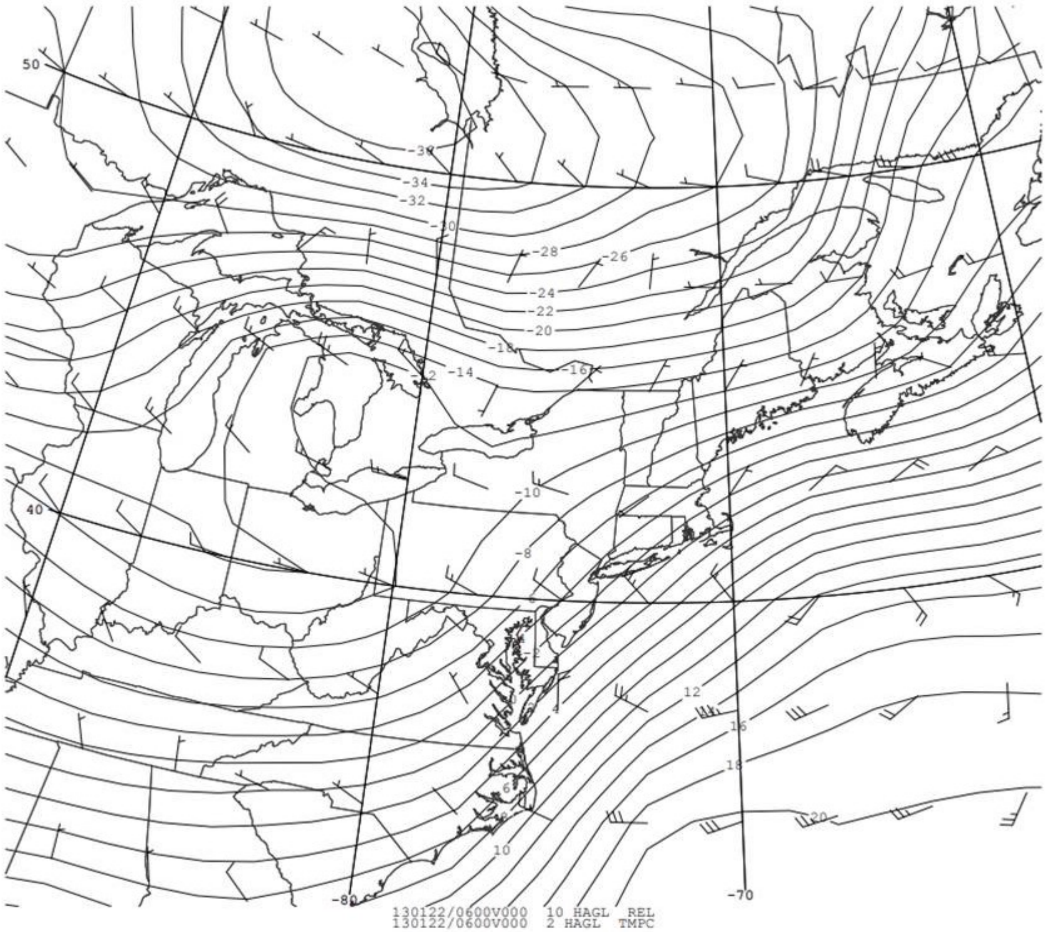

Figure 8: Analyzed surface temperature (contored in ^oC) and surface wind (vectors in kts) for the same time, as in January 22, 2013 at 06z.

A 'Real' front. Fig.7 is an IR satellite image for January 22, 2013 at 06z, showing a band of clouds, associated with a pronounced northerly flow along the east coast of the US.

Fig.8 shows analyzed surface temperature (in ^oC) and surface wind (in kts) for the same time, January 22, 2013 at 06z. Estimate the horizontal temperature advection at Chicago-O'Hare, IL (ORD) and Pittsburgh, PA (PIT). What is the expected 6-hour temperature change due to this horizontal temperature advection?

Compare your results with the observed temperature changes revealed in the surface meteograms shown in Figs.9 and Fig.10.

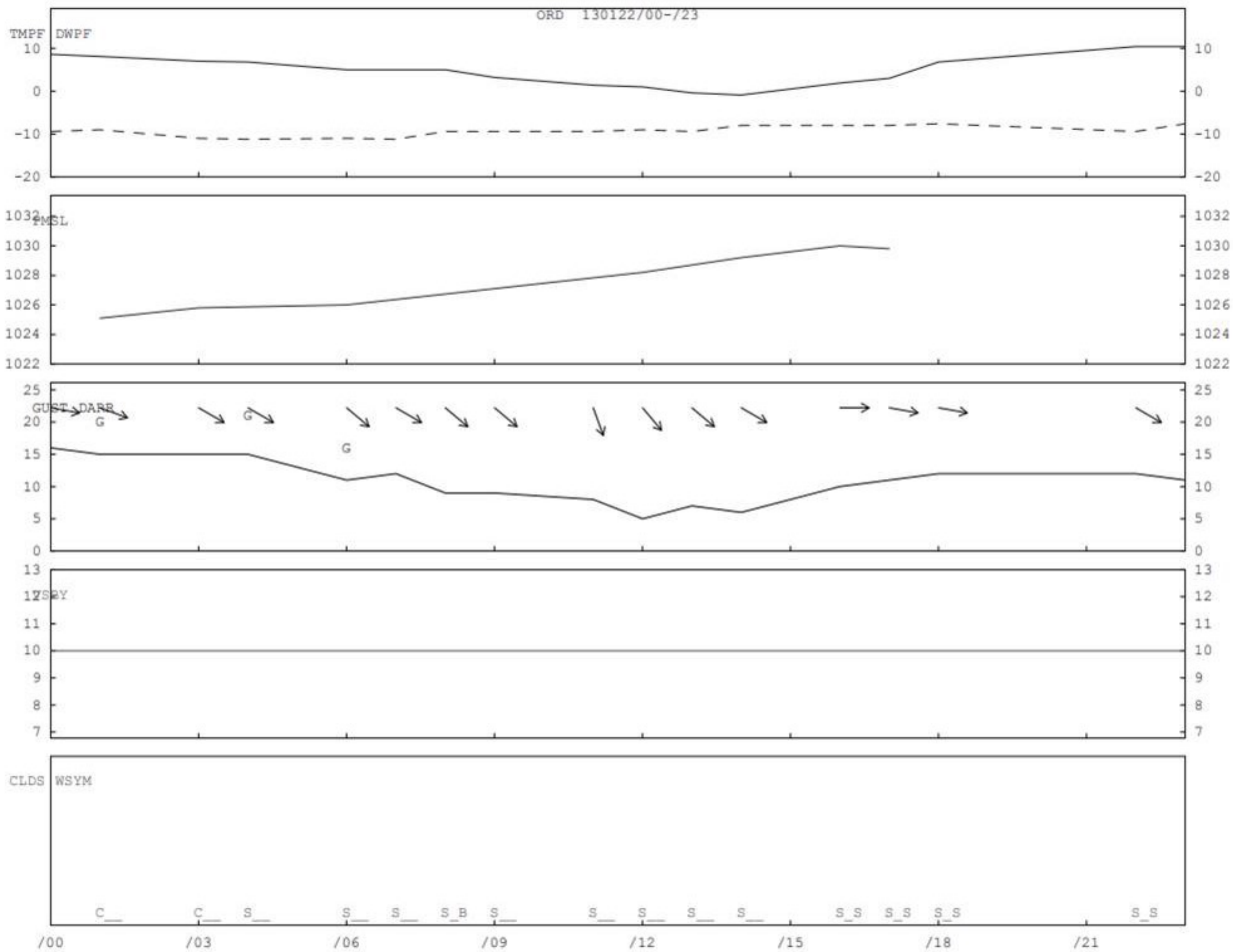

Figure 9: Surface meteogram for Chicago O'Hare (ORD) on January 22, 2013 showing temperature (continuous line) and dewpoint temperature (dashed line), surface pressure, wind speed and direction, visibility and cloud cover.

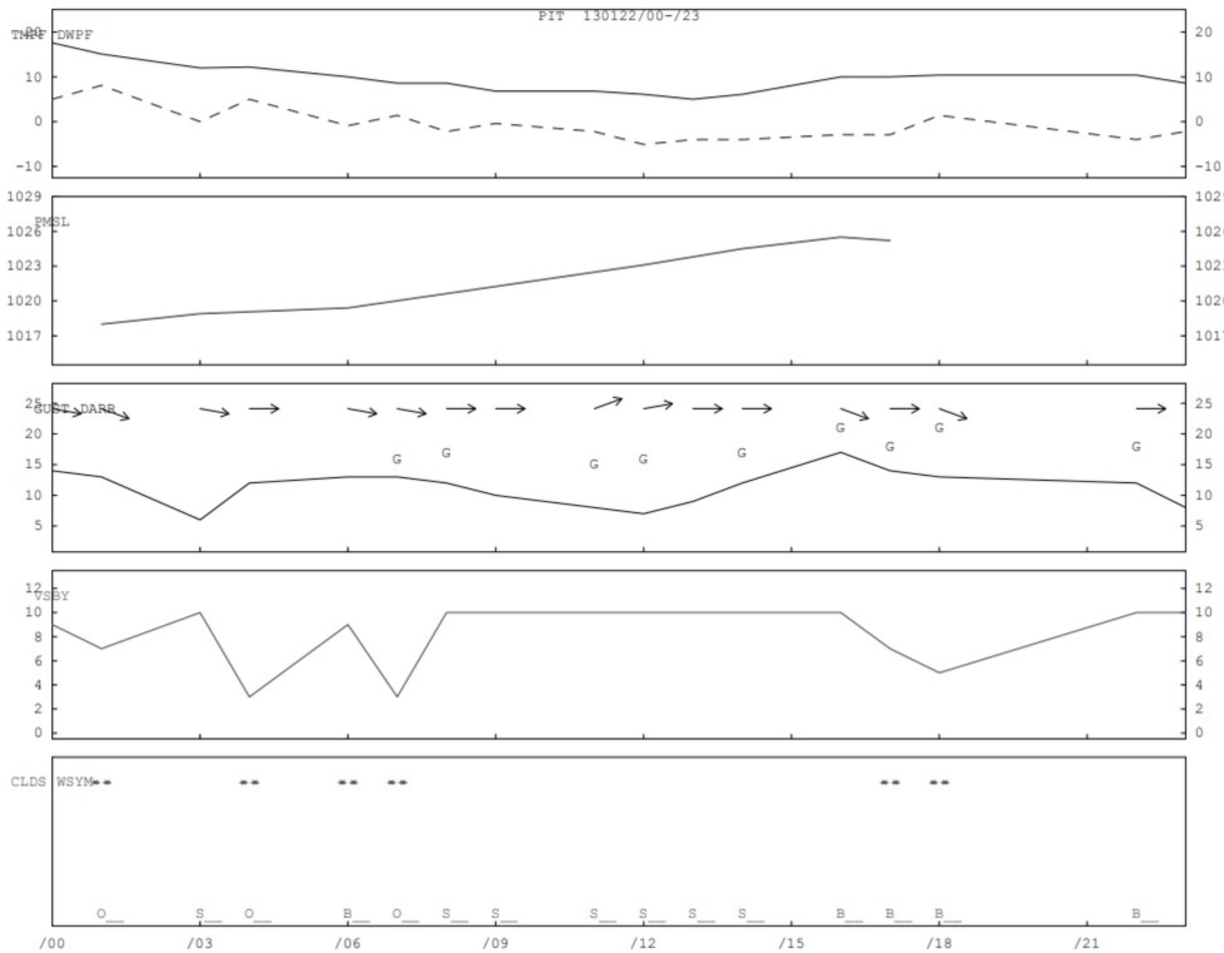

Figure 10: Surface meteogram for Pittsburg (PIT) on on January 22, 2013 showing temperature (continuous line) and dewpoint temperature (dashed line), surface pressure, wind speed and direction, visibility and cloud cover.

2 Exploring fluid transport using atmospheric data latex

In Section 2.1 we learned about tracer transport in the atmosphere. We studied the Lagrangian derivative, how to calculate trajectories from wind observations, and how to estimate local temperature change due to temperature advection. In the following sections, we will see how the meridional temperature gradient is related to the vertical wind shear through thermal wind balance, and how observed temperature variance can be understood, to first order, by meridional temperature advection. We will first use the EsGlobe to examine the mean climatological structure of atmospheric temperature, and verify the thermal wind balance. We will then use data from state-of-the-art global circulation numerical models to examine the mean temperature and temperature variance in the historical simulations, as well as their projected changes in the future. We will see how simple meridional temperature advection arguments can help us understand the projected temperature variance changes.

2.2 Thermal Wind Balance

Thermal wind is the most fundamental and significant dynamical balance controlling the large-scale circulation of the atmosphere and ocean. It is a consequence of hydrostatic and geostrophic balance, and relates horizontal temperature gradients to changes in the horizontal wind with height or pressure. For a detailed derivation please read the course notes on Thermal Wind.

The thermal wind balance equation are given by:

$$\frac{\partial u_g}{\partial p} = \frac{R}{fp}\frac{\partial T}{\partial y}, \tag{1}$$

and

$$\frac{\partial v_g}{\partial p} = -\frac{R}{fp}\frac{\partial T}{\partial x}, \tag{2}$$

where u_g and v_g are the geostrophic velocities in the zonal (x) and meridional (y) directions, p is pressure, f is the Coriolis parameter, T is temperature, and R is the gas constant. Note that the horizontal temperature gradients are taken at *constant pressure*.

The thermal wind balance relates horizontal temperature gradients to changes in the horizontal wind with pressure. It explains why the northward decrease of temperature implies westerly winds must be increasing with height (i.e., $\frac{\partial u_g}{\partial p} < 0$), consistent with Eq.(1).

2.2.1 Mean temperature and thermal wind balance

1) Using EsGlobe http://eddies.mit.edu/307/, examine the climatology of temperature and zonal and meridional winds at different pressure levels. Note the difference between the hemispheres, with the Northern Hemisphere (NH) being less zonally symmetric than the Southern Hemisphere (SH). Where are the jet streams located? Can you explain why? Why do the zonal winds peak around 200 mb? Note that the gradients and jets are strongest during winter. Contrast the NH winter (e.g., January) with the NH summer (e.g., July).

2) Verify the thermal wind balance by estimating-

$$\frac{\Delta u}{\Delta p} = \frac{R}{fp}\frac{\Delta T}{\Delta y} \tag{3}$$

You can use $R_d = 287\ \frac{\mathrm{m}^2}{\mathrm{Ksec}^2}$, $f = 10^{-4}\ \frac{1}{\mathrm{sec}}$, and $1°$ latitude is roughly equal to 110km. You will need to choose a pressure level on the EsGlobe, which will appear in the vertical cross section and aid you in the estimation. Note that for a more accurate finite differences estimation (centered finite difference method), the point you are estimating the derivatives for should be in the middle of the (lat1,lat2) and (p1,p2) you are choosing (so, if you used p=500mb, Δp=1000-500=500mb, but for the RHS of Eq. () you should use a pressure level between 500mb and 1000mb for the estimation of ΔT and Δy.

2.3 Temperature Advection and Variance

In the previous section, we examined the climatological mean temperature structure. We can define temperature anomalies T' as deviation from that climatology, i.e.:

$$T' = T - T_{\mathrm{clim}}, \tag{4}$$

where $T_{\mathrm{clim}} = \overline{T}$ is the averaged temperature.

The temperature anomalies that we experience on a daily basis are closely related to passing cyclones and anticyclones, and similarly have typical timescales of a few days.

In a climate sense, we can quantify the strength of fluctuations around the average temperature using the *variance* ($\overline{T'^2}$), the average of the square of T' (note that by definition, $\overline{T'} = \overline{T - T_{\mathrm{clim}}} = \overline{T} - T_{\mathrm{clim}} = 0$). The temperature variance is a measure of the spread of temperatures around the mean.

Considering the Lagrangian derivative of temperature, and assuming that it is nearly conserved (which is not generally correct), we can write-

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = 0. \tag{5}$$

Assuming further that:

$$T' << \overline{T},\ \text{temperature anomalies are smaller than the mean temperature,} \tag{6}$$

$$\frac{\partial \overline{T}}{\partial x} << \frac{\partial \overline{T}}{\partial y},\ \text{meridional temperature gradient is larger than the zonal gradient,} \tag{7}$$

$$\overline{v} << \overline{U},\ \text{is the mean meridional velocity is smaller than the mean zonal velocity,} \tag{8}$$

Eq. (5) reduces to

$$\frac{\partial T'}{\partial t} \approx -v'\frac{\partial \overline{T}}{\partial y}. \tag{9}$$

Noting further that $v' = \frac{d\eta'}{dt}$, where η' is the displacement of the air parcel, and approximating $v' \approx \frac{\partial \eta'}{\partial t}$, we can write

$$T' \approx -\eta' \frac{\partial \overline{T}}{\partial y}. \tag{10}$$

Thus, temperature variance is proportional to the square of the meridional temperature gradient,

$$\overline{T'^2} \sim (\frac{\partial \overline{T}}{\partial y})^2. \tag{11}$$

2.3.1 Temperature-Variance Exercise:

1) How justified are the assumptions we made in deriving the relation given in (11)? Can you verify the assumptions given in (7) and (8) using the EsGlobe?

2) We will be using data of near-surface temperature (T_{2m}, the temperature 2-meters above the ground) from 7 state-of-the-art global circulation models, which are used in current research to study our climate and its projected changes. The data cover the period of 1980-2014 for the historical simulations, and for 2065-2099 for the projected climate. The data you will be working with is based on 3-hourly near-surface temperature data, downloaded from https://aims2.llnl.gov/search/cmip6/. It is pre-processed such that it contains the mean temperature and the temperature variance as a function of longitude, latitude, year, and model. [1],

Go to the course website (2nd project, Observation Data page) and download the zip folder "temperature_variance". Unzip the files and put them in the same folder. Run the file plot_T2m.m (in MATLAB) or plot_T2m_python.py (in python). This should produce a figure showing the historical mean T_{2m} data for one model in the first data year. Now, modify the script so that it calculates the mean over all models and all years, and plot the historical mean T_{2m}, historical T_{2m} variance, and their projected changes. There are some further instructions on the script.

3) Questions:

- What do you find for the T_{2m} mean temperature and variance in the historical simulations? Is it similar to what we saw in class for the 850mb level?
- What do the projected mean temperature and variance show? Can you explain this response using temperature advection arguments?
- **Optional**: Examine the model-to-model spread and the year-to-year variability of global mean temperature. Do all models agree on the changes? Can you observe a trend in the historical/projected data? Is the trend larger than the year-to-year variability?

[1] The models used are: CMCC-CM2-SR5, CanESM5, MIROC-ES2L, MIROC6, MPI-ESM1-2-HR, MPI-ESM1-2-LR, and MRI-ESM2-0