Problem Set 6

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6.1 (a) Use iris to write a function that can calculate the meridional mass streamfunction (see notes for lecture 7 of Atmosphere–Ocean Interactions, Eq. 7.11).

(b) Extend your function (or module) to also optionally calculate the zonal mass streamfunction:

$$\Psi_Z = \frac{a}{g}\int_{\varphi_S}^{\varphi_N}\int_0^p \overline{u}^* dp d\varphi,$$

where φ_S and φ_N are latitudes in the Northern and Southern Hemispheres that are equidistant from the equator and $\overline{u}^*$ is the deviation of the time-mean zonal wind from its zonal mean value (p.163 of Hartmann, *Global Physical Climatology*, 1994).

(c) Use the data provided on the course website to plot the annual mean meridional circulation and the annual mean Walker circulation. For the latter use the average zonal wind anomaly ($\overline{u}^*$) between 5°S and 5°N.

(d) **Extra credit:** the meridional mass streamfunction in isentropic coordinates can be calculated according to the equation

$$\Psi_\theta = 2\pi a \cos\varphi \int_0^\theta [\rho_\theta v] d\theta,$$

where $\rho_\theta = -\frac{1}{g}\frac{\partial p}{\partial \theta}$. Write a function to calculate the mean meridional circulation in isentropic coordinates and use the data provided on the course website to plot this circulation as a function of latitude and θ.

6.2 Energy transport in the atmosphere–ocean system can be estimated using the balance

$$R_{\mathrm{TOA}} = \nabla\cdot\vec{F}_{\mathrm{A}} + \nabla\cdot\vec{F}_{\mathrm{O}} + \frac{\partial E_{\mathrm{AO}}}{\partial t},$$

where R_{TOA} is the net radiation balance at the top of the atmosphere (i.e., energy in minus energy out), $\nabla\cdot\vec{F}_{\mathrm{A}}$ is the divergence of the horizontal energy transport in the atmosphere, $\nabla\cdot\vec{F}_{\mathrm{O}}$ is the divergence of the horizontal energy transport in the ocean, and $\partial E_{\mathrm{AO}}/\partial t$ is the change in energy storage in the atmosphere–ocean system. The divergences of horizontal energy transport can be estimated as

$$\nabla\cdot\vec{F}_{\mathrm{A}} = (R_{\mathrm{TOA}} - R_{\mathrm{sfc}}) + \mathrm{LE} + \mathrm{SH}$$
$$\nabla\cdot\vec{F}_{\mathrm{O}} = R_{\mathrm{sfc}} - \mathrm{LE} - \mathrm{SH}$$

with R_{sfc} the net (downward) radiation flux at the surface, LE the surface latent heat flux and SH the surface sensible heat flux. Ignoring changes in energy storage, the total northward energy transport across the latitude φ can be calculated as

$$\mathcal{E}(\varphi) = -\int_{\frac{\pi}{2}}^{\varphi} \int_{0}^{2\pi} R_{\text{TOA}} a^2 \cos\varphi d\lambda d\phi.$$

For a gridded data set, $\mathcal{E}(\varphi)$ can be approximated by calculating the sum

$$\mathcal{E}(\varphi) = -\sum_{j=\varphi}^{\frac{\pi}{2}} \sum_{i=0}^{2\pi} A_{ij} \cdot R_{\text{TOA}}(\lambda_i, \phi_j),$$

where A_{ij} is the area of the corresponding grid cell in square meters.

(a) Using iris and the provided flux data, calculate and integrate R_{TOA} to determine the implied zonal mean northward energy transport in the atmosphere–ocean system. Plot your results as a function of latitude (this should look like the lower left panel of Fig. 1.14 in the notes from lecture 1). Neglect changes in energy storage.

(b) Use the surface and TOA energy fluxes to calculate $\nabla \cdot \vec{F}_{\text{A}}$ and $\nabla \cdot \vec{F}_{\text{O}}$. Integrate these quantities to calculate the net zonal mean energy transport in the atmosphere and the net zonal mean energy transport in the ocean. Plot these quantities and their sum (atmosphere + ocean) together with your results from part (a). Include a legend.

(c) How do your results compare to Fig. 7.16 in Chapter 7 of Prof. Hartmann's book? Give a possible explanation for any major differences. Come up with a way to eliminate the net energy imbalance in each quantity (so that the area-weighted sum over the entire globe is zero) and replot your results.

(d) **Extra credit:** Use the net surface flux data you calculated in 6.1 to calculate and plot the implied northward energy transports in the Atlantic, Pacific and Indian Oceans. Use 70°W as the boundary between the Pacific and Atlantic Oceans, 25°E as the boundary between the Atlantic and Indian Oceans, 100°E as the boundary between the Indian and Pacific Oceans north of 5°S and 130°E as the boundary between the Indian and Pacific Oceans south of 5°S. Ignore transports north of 65°N.