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The atmospheric general circulation: Some unresolved issues

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Abstract

Several questions concerning the general circulation for which satisfactory answers are not yet available are discussed. The focus is on the zonal mean heat balance, since problems in our understanding of this balance are a fundamental limitation on our ability to model climate and climate change. The questions are: How strong is the atmosphere's poleward heat transport? What are the relative roles of large-scale eddies and small-scale convection in stabilizing the mid-latitude atmosphere? What are the dynamical mechanisms that maintain the time mean zonal mean state in mid-latitudes? Some suggestions for addressing these questions are given.

Keywords: Mid-latitude atmosphere; Small-scale convection; Northern Hemisphere; Atmospheric heat transport

1. Introduction

This paper is an outgrowth of a course on "The General Circulation of the Earth's Atmosphere" that the author taught at the Massachusetts Institute of Technology for 32 years (1974–2005). This course was a continuation of a course started by Victor Starr who retired in 1974. For all but the last 3 years the teaching duties were shared with Rick Rosen, who was one of Victor Starr's students. A total of 143 students took the course for credit during those 32 years.

The course focused on diagnostic studies that describe and elucidate how the zonal mean, time mean state of the atmosphere is maintained, including the seasonal cycle. Starr pioneered this

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kind of study; during the period 1950–1990 Starr and his students published a large number of these studies-based mainly on rawinsonde data. The culmination of this work was the textbook "Physics of Climate," published in 1992 by two of Starr's students, José Peixoto and Abraham Oort.

In the past 20 years "re-analysis" data sets produced by national centers have appeared that include other data sources, most notably satellite observations. One would expect these data sets to be superior to the earlier rawinsonde-based data sets. However many of the earlier diagnostic studies have never been updated. In addition the re-analysis data sets are not free of errors. They rely on imperfect models to fill in data-sparse areas and they violate some of the required physical constraints, such as mass conservation (e.g., see Trenberth and Caron, 2001). These problems lead to significant problems, for example in their representation of the momentum cycle (Huang et al., 1999) and the hydrological cycle (Andersson et al., 2004).

Because of these problems there are still gaps in our knowledge and understanding of the general circulation. In this paper we will discuss three questions about the general circulation that have not yet been fully resolved and which are particularly important for climate modeling. They are:

(i) How strong is the atmosphere's poleward heat transport? (Section 2).
(ii) What are the relative roles of large-scale eddies and small-scale convection in stabilizing the mid-latitude atmosphere? (Section 3).
(iii) What are the dynamical mechanisms that maintain the zonal mean time mean state in mid-latitudes? (Section 4).

We conclude in Section 5 with some discussion of how one might proceed to address these questions.

2. How strong is the atmosphere's poleward heat transport?

The total poleward heat transport in the climate system is strongly constrained by external parameters, and quite different climates can have the same poleward heat transport (Stone, 1978). The climate is instead much more sensitive to the efficiency of the transport, i.e., to how sensitive it is to changes in the meridional temperature gradient (Stone, 1978), and to the partitioning of the transport between the atmosphere and the oceans (Seager et al., 2002). This makes it particularly important to determine the poleward heat transport in the atmosphere accurately. The inclusion of satellite data after 1979 has made the re-analyses less dependent on the rawinsonde data, but as discussed below the re-analyses are still subject to analysis and model error in data-sparse regions. Because of the relative sparseness of the rawinsonde data in the Southern Hemisphere in this section we focus on results for the Northern Hemisphere.

The total poleward heat transport in the Northern Hemisphere atmosphere peaks at about 40–45° latitude, but estimates of its magnitude have varied considerably over the years. The rawinsonde-based estimates yielded values of about 3.0 PW for the Northern Hemisphere peak (e.g., Carissimo et al., 1985). An early estimate using the ECMWF re-analysis yielded a stronger value, 3.9 PW (Trenberth and Solomon, 1994). However these estimates did not appear to be irreconcilable. Oort (1978) used an atmospheric GCM to examine how much error would be introduced by the gaps in the rawinsonde network. If one averages together his results in the Northern Hemisphere in January and July, one can estimate that the rawinsonde-based analysis underestimates the (model's) annual mean Northern Hemisphere peak by about 20%. (The situation in the Southern Hemisphere was of course much worse.) The ECMWF model that was used by Trenberth and Solomon (1994) also participated in the first Atmospheric Model Intercomparison Project (AMIP I) and in that simulation the model produced a peak transport in the Northern Hemisphere of 4.4 PW (Gleckler et al., 1995). The excess of 0.5 PW compared to the re-analysis result is evidently due to model bias; one might reasonably suppose that not all the bias had been removed by the data assimilation, since there are gaps in the rawinsonde network over the ocean. Thus in the mid-1990s one could have concluded that a peak value of the atmosphere's poleward transport in the Northern Hemisphere of 3.7 PW was reasonably consistent with all the analyses, given their errors.

However, later analyses called this neat conclusion into question. In particular Trenberth and Caron (2001) re-calculated the transport from the ECMWF re-analysis using a more recent version of the ECMWF model and re-analysis. The result for the peak transport in the Northern Hemisphere was 4.6 PW for the new analysis. It is not clear why this estimate was 0.7 PW greater than Trenberth and Solomon's (1994). The latter analysis did use only a single year of data, but Trenberth and Caron (2001) estimated an interannual standard deviation for the Northern Hemispheric transport at its peak latitude of only about 0.07 PW. The more recent analysis also had higher resolution, but spectral analysis indicates that the T42 resolution of Trenberth and Solomon should be adequate (Solomon, 1997). There are a variety of problems with the re-analysis data sets, discussed by both Trenberth and Solomon (1994) and Trenberth and Caron (2001) which might affect the transports. For example, mass is not conserved in the re-analyses, and this bias must be removed because it strongly affects the heat transport by the zonal mean circulation. However there is no unique way to remove this bias. The heat transport by the meridional velocity depends on the variations of the meridional velocity with height, but mass conservation only constrains the vertical integral of this velocity. Another problem is that the annual mean surface flux over land is not zero. Since this flux interacts with the local divergence of the atmospheric heat transports, there is the potential for corresponding errors in the transports. Finally Trenberth and Caron also calculated the transports from the NCEP re-analysis, and found a peak transport in the Northern Hemisphere 0.6 PW greater than that in the ECMWF re-analysis. This is another sign that the transport does depend on the analysis method and the model used. Unfortunately there is no comprehensive assessment of the errors in the re-analyses.

Given the lack of any such error estimate for the atmospheric heat transports Wunsch (2005) took another approach which does not rely on the re-analyses. In particular he calculated the poleward heat transport in the atmosphere as a residual from the total poleward heat transport implied by the radiative heat flux at the top of the atmosphere (taken from ERBE data) and the poleward heat transport in the ocean (calculated by Ganachaud and Wunsch, 2003). Wunsch simply propagated the error estimates from the two (independent) data sets.

Wunsch's results for the plus-or-minus one standard deviation range of the peak values of the transports were 3.0–5.2 PW for the Northern Hemisphere and 4.0–6.7 PW for the Southern Hemisphere. The ranges do encompass all the earlier estimates. Wunsch's method may not be ideal for estimating the errors in the atmospheric transports, but in the absence of any comprehensive analysis of the errors in the re-analyses, we are left with estimates of atmospheric heat transports with such large uncertainties as to make them not very useful for testing climate models.

3. What are the relative roles of large-scale eddies and small-scale convection in stabilizing the mid-latitude atmosphere?

In low latitudes the lapse rates are close to moist adiabatic (Stone and Carlson, 1979) and large-scale eddies are very weak (Peixoto and Oort, 1992, Fig. 7.22), so there is not much doubt that lapse rates in low latitudes are stabilized (compared to radiative equilibrium) primarily by moist convection. In mid-latitudes lapse rates are much less than the moist adiabat and large-scale eddies are very active (op. cit.). These facts imply that the large-scale eddies play a more important role in stabilizing the mid-latitude atmosphere. Indeed both simple models (Stone, 1972) and more sophisticated numerical models (Schneider, 2004) suggest that large-scale eddies can turn statically unstable radiative equilibrium states into dynamically very stable states (with Richardson numbers much greater than unity) in mid-latitudes without the help of moist convection and associated mesoscale systems. However the lapse rates in these models are still significantly less stable than in the observations. These results suggest that both large-scale eddies and moist convection contribute significantly to stabilization in mid-latitudes, but as yet there is no definitive analysis of the relative importance of these two dynamical processes.

To quantify their roles, ideally one would like a data set that included or allowed one to calculate the vertical flux of heat due to both large- and small-scale processes. Such data sets are available from model simulations, but the results are sensitive to the convection scheme used (Stone and Yao, 1991). The re-analysis data sets do not include the convective fluxes. In an attempt to get at least a rough estimate, two students who took the MIT general circulation course (William Boos and Yang Zhang) used Hantel's (1976) method for calculating an unknown vertical flux, in this case the small-scale convective flux, as a residual from the heat budget. They took the other components of the budget from the re-analyses, except for the radiative fluxes which are also not included in the re-analyses. Thus they took the radiative fluxes from Hantel (1978). The results from the two re-analyses were generally similar. In the tropics the small-scale fluxes dominate, in mid-latitudes the large-scale flux is slightly larger, and in high latitudes the large-scale flux was larger in winter, but the two fluxes were comparable in summer.[1]

These results are however subject to considerable uncertainty. First, Hantel's radiative fluxes may not be compatible with the re-analyses' other data. Second, one again has to be concerned that the result is sensitive to the parameterizations of moist convection used in the re-analysis models. For example no re-analysis models or climate models include any representation of slantwise moist convection (Emanuel, 1988). This is a form of small-scale mixing that arises under statically stable conditions as a result of nongeostrophic instability (Stone, 1966). Emanuel (1986) has estimated that this process could produce static stabilities as large as 3 K/km in mid-latitudes. In addition, the hydrological cycle in at least the ECMWF model is known to have biases related to tropical convection (Andersson et al., 2004).

4. What are the dynamical mechanisms that maintain the time and zonal mean state in mid-latitudes?

One useful way of describing how the general circulation is maintained in mid-latitudes is the Lorenz energy cycle (see Fig. 14.8 in Peixoto and Oort, 1992). Energy is put into the general circulation by differential radiative heating, and removed from it by small-scale dissipation. The time scale associated with the generation and dissipation are of order 1 month, whereas the time scales associated with the motions themselves are of order 3 days. Thus the circulations are dominated by dynamical processes, and involve strong interactions between the zonal mean flow

[1] More details of these calculations can be found at the course's website (http://ocw2.mit.edu/OcwWeb/Earth–Atmospheric–and-Planetary-Sciences/12-812Fall-2005/CourseHome/index.htm). The calculations are discussed in the lecture notes for the heat budget, on pages 34 and 35.

and eddies of various scales. The eddies are primarily transient (see Fig. 7.23 in Peixoto and Oort, 1992), but stationary eddies do play an important role in the Northern Hemisphere in winter (op. cit.). Calculations of the divergence of the Eliassen-Palm flux indicate that the forcing of the zonal mean zonal wind and temperature fields is strongly dominated by the eddy heat fluxes (Edmon et al., 1980; Stone and Salustri, 1984), with very little contribution from the Eddy momentum fluxes. Thus the main interaction of the eddies with the zonal mean flow is due to the transient eddy fluxes of heat. These eddy fluxes are associated with high-frequency eddies that are deep and have large zonal scales, >3000 km (Randal and Held, 1991; Solomon, 1997), i.e., not with the intense cyclones that are responsible for severe weather.

The large-scale transient eddies are often identified with baroclinic instability, because their energy cycles and scales resemble those predicted by baroclinic instability theory (Peixoto and Oort, 1992). However the instability theory only applies to small amplitude eddies superimposed on a zonally uniform flow, and it is clear that the actual flow in the atmosphere is far more complicated. In fact numerical models which neglect stationary waves, the hydrological cycle, and seasonal changes simulate qualitatively the observed features of transient eddies and the general circulation in mid-latitudes, but they also show that baroclinic instability is only responsible for the transition from a zonally symmetric flow to a fully three-dimensional quasi-turbulent flow; the resulting mean states have zonal mean flows which are generally stable (e.g., Solomon and Stone, 2001).

Farrell (1985) has suggested that such time-varying states can be described as a linear response of a slightly stable flow to stochastic forcing. Farrell and Ioannou (1993) showed that indeed one can reproduce qualitatively the main features of the transient eddy-mean flow interactions in mid-latitudes with such a model. The flow is dominated by the least stable modes, which necessarily resemble the modes that would dominate if the flow were baroclinically unstable. However their approach requires the specification of the properties of the stochastic forcing, whereas a true theory would have this forcing determined internally.

Solomon and Stone (2001) found that the equilibrium in their model was maintained in part by the instability of some of the large-scale three-dimensional waves, which led to the growth of smaller-scale waves, and by a nonlinear cascade of energy from the smaller-scale waves back to the larger scales. This latter process plays a role analogous to the stochastic forcing in the model of Farrell and Ioannou (1993). They also found that the vertical eddy heat flux played an important role in homogenizing the potential vorticity gradient in the lower troposphere. However in order to get realistic states Solomon and Stone (2001) had to add to their model an artificial stabilization of the lapse rates, presumably because their model had no hydrological cycle.

The results of studies like those cited do suggest some of the elements that might be relevant to equilibration in the real atmosphere. However even in simplified models like these, which exclude stationary eddies, the hydrological cycle, and seasonal changes, the mechanisms by which the time mean zonal mean flow and the transient eddies equilibrate are not fully understood. Thus the question posed at the beginning of this section remains open.

5. Discussion

Are there ways of answering the questions posed above? In the case of the poleward heat transports it would be particularly helpful to compare the re-analysis results to the results obtained when the re-analysis models are run in climatological mode, without any data being assimilated. Indeed older versions of the NCEP and ECMWF models participated in AMIP I, and this led to the useful comparison of the ECMWF re-analysis with the results of the ECMWF model run in AMIP mode (Gleckler et al., 1995). However the more recent models that were used in the re-analyses that Trenberth and Caron (2001) analyzed have not yet participated in AMIP. An alternate, and computationally less costly approach, is that used by Huang et al. (1999) where the NCEP model was run on its own, but using the NCEP analysis for the initial condition. In both types of simulations looking at how the model diverges from the analysis in data-rich regions would yield data about the model's biases, which would be useful for deducing how much bias remains in the re-analysis in data-poor regions. Integrations in which the re-analysis models are coupled to ocean general circulation models would be much more problematic because of the large uncertainties associated with the ocean models (Stone, 2004).

Of course, steps to minimize the existence of data-poor regions around the globe would also be welcome, and plans continue to evolve to make use of new technologies to reduce the presence of data gaps in the observational network. MacDonald (2005) has proposed, for example, that a network of high-altitude long-endurance unmanned aerial vehicles be deployed over the oceans and polar regions, from which dropsondes could be launched to make routine vertical profiles of atmospheric temperature, winds, and humidity. Such a network, which MacDonald suggests could become operational by the middle of the next decade, would form a central piece of the Global Earth Observation System of Systems (GEOSS; Clery, 2005).

In the case of vertical fluxes, it would be helpful for the forecast centers to supply the vertical fluxes of radiation and convection that their analyses produce. This would at least tell us how dynamical processes contribute to the stabilization of lapse rates in the models, although it would not get around the problem of the dependence of the models on uncertain parameterizations, particularly of moist convection. Also the role of slantwise moist convection needs to be explored. Parameterizations of its effect that can be used in general circulation models are available (Nordeng, 1993; Chou and Thorpe, 1993). Although there are a variety of regional experiments which can be used to constrain the parameterizations, global constraints have to rely on satellite observations which are not so good at giving good information on vertical structure. New advances in assimilating observed precipitation within the context of at least a regional reanalysis system (Mesinger et al., 2006) offer the potential for improved estimates of vertical fluxes of latent heat. Presumably, these advances will be exploited in new generations of integrated Earth system analyses and reanalyses (Trenberth et al., 2002), in which precipitation and other quantities that define the state of the coupled atmosphere–ocean–land system will be assimilated into Earth system models to yield internally consistent fields including convective and other fluxes that link the Earth system components.

With regard to dynamical equilibration in the atmosphere, this is an inherently difficult problem given the quasi-turbulent rapidly varying nature of the motions. State-of-the-art general circulation models are almost as difficult to analyze as the real atmosphere. In the short term the best way to progress may be to rely on somewhat simplified process models.

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References

Andersson, Erik, et al., 2004. Assimilation and modeling of the atmospheric hydrological cycle in the ECMWF forecasting system. Bull. AMS 86, 387–402.

Carissimo, Oort, Vonder Haar, 1985. Estimating the meridional energy transports in the atmosphere and ocean. J. Phys. Ocean 15, 82–91.
Chou, S.C., Thorpe, A.J., 1993. A parameterization scheme for symmetric instability: tests for an idealized flow. The representation of cumulus convection in numerical models. In: Emanuel, K., Raymond, D. (Eds.), Meteor. Monogr. 24 (46), 203–217.
Clery, D., 2005. Forging a global network to watch the planet. Science 292, 1182.
Edmon Jr., H.J., Hoskins, B.J., McIntyre, M.E., 1980. Eliassen-Palm cross sections for the troposphere. J. Atmos. Sci. 37, 2600–2616.
Emanuel, K.A., 1986. Convective Adjustment in Baroclinic Atmospheres. The Jovian Atmospheres, vol. 2441. NASA Conference Publication, pp. 163–173.
Emanuel, K.A., 1988. Observational evidence of slantwise convective adjustment. Mon. Weather Rev. 116, 1805–1816.
Farrell, B., 1985. Transient growth of damped baroclinic waves. J. Atmos. Sci. 42, 2718–2727.
Farrell, B.F., Ioannou, P.J., 1993. Stochastic dynamics of baroclinic waves. J. Atmos. Sci. 50, 4044–4057.
Ganachaud, A., Wunsch, C., 2003. Large-scale ocean heat and freshwater transports during the World Ocean Circulation Experiment. J. Clim. 16, 696–705.
Gleckler, P.J., et al., 1995. Cloud-radiative effects on implied oceanic energy transports as simulated by atmospheric general circulation models. Geophys. Res. Lett. 22 (7), 791–794.
Hantel, M., 1976. On the vertical eddy transports in the northern atmosphere I. Vertical eddy heat transport for summer and winter. J. Geophys. Res. 81, 1577–1588.
Huang, et al., 1999. The balance of global angular momentum in a long-term atmospheric data set. J. Geophys. Res. 104, 2031–2040.
MacDonald, A.E., 2005. A global profiling system for improved weather and climate prediction. Bull. Am. Meteor. Soc. 86, 1747–1764.
Mesinger, F., DiMego, G., Kalnay, E., et al., 2006. North American regional reanalysis. Bull. Am. Meteor. Soc. 87, 343–360.
Nordeng, T.E., 1993. Parameterization of slantwise convection in numerical weather prediction models. The representation of cumulus convection in numerical models. In: Emanuel, K., Raymond, D. (Eds.), Meteor. Monogr. 24 (46), 195–202.
Oort, A.H., 1978. Adequacy of the rawinsonde network for global circulation studies tested through numerical model output. Mon. Weather Rev. 106, 174–195.
Peixoto, J.P., Oort, A.H., 1992. Physics of Climate. American Institute of Physics, New York, pp. 520.
Randal, W.J., Held, I.M., 1991. Phase speed spectra of transient Eddy fluxes and critical layer absorption. J. Atmos. Sci. 48, 688–697.
Schneider, T., 2004. The tropopause and the thermal stratification in the extratropics of a dry atmosphere. J. Atmos. Sci. 61, 1317–1340.
Seager, R., Battisti, D.S., Yin, J., Gordon, N., Naik, N., Clement, A.C., Cane, M.A., 2002. Is the Gulf Stream responsible for Europe's mild winters? Q. J. Roy. Met. Soc. 128 (586), 2563–2586.
Solomon, A., 1997. An observational study of the spatial and temporal scales of transient Eddy sensible heat fluxes. J. Clim. 10, 508–520.
Solomon, A., Stone, P.H., 2001. Equilibration in an Eddy-resolving model with simplified physics. J. Atmos. Sci. 58, 561–574.
Stone, P.H., 1966. On non-geostrophic baroclinic stability. J. Atmos. Sci. 23, 390–400.
Stone, P.H., 1972. A simplified radiative-dynamical model for the state stability of rotating atmospheres. J. Atmos. Sci. 29, 405–418.
Stone, P.H., 1978. Constraints on dynamical transports of energy on a spherical planet. Dyn. Atmos. Oceans 2, 123–139.
Stone, P.H., 2004. Climate prediction: the limits of ocean models. The state of the planet: frontiers and challenges in geophysics. Geophysical Monograph 150, vol. 19. IUGG, pp. 259–267.
Stone, P.H., Carlson, J.H., 1979. Atmospheric lapse rate regimes and their parameterization. J. Atmos. Sci. 36, 415–423.
Stone, P.H., Salustri, G., 1984. Generalization of the quasi-geostrophic Eliassen-Palm flux to include Eddy forcing of condensation heating. J. Atmos. Sci. 41, 3527–3536.
Stone, P.H., Yao, M.-S., 1991. Vertical Eddy heat fluxes from model simulations. J. Clim. 4 (3), 304–317.
Trenberth, K.E., Caron, J.M., 2001. Estimates of meridional atmosphere and ocean heat transports. J. Clim. 14, 3433–3443.
Trenberth, K., Solomon, A., 1994. The global heat balance: heat transports in the atmosphere and ocean. Clim. Dyn. 10, 107–134.
Trenberth, K.E., Karl, T.R., Spence, T.W., 2002. The need for a systems approach to climate observations. Bull. Am. Meteor. Soc. 83, 1593–1602.
Wunsch, C., 2005. The total meridional heat flux and its oceanic and atmospheric partition. J. Clim. 18, 4374–4380.