The Use of Tracers as Diagnostics for Model Development

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Abstract

The use of tracers in the development of the NASA/GISS global climate and middle atmosphere models (GCMs) is explained as responses to a series of questions. Tracers are valuable as adjuncts to other more common methods of model evaluation, since their transports are often the result of hard to observe wind fields, wave-mean flow interaction, convection, and turbulence. Discrepancies can suggest closer examination of specific physics parameterizations and dynamical or chemical numerical solutions. Their use is hindered to some degree by inexact specification of sources/sinks and incomplete observational data sets. In addition, the importance of models' transport capabilities vis-à-vis other priorities (e.g., radiative balance) depends on the impact the relevant processes have on the intended model use. Nevertheless, given that many aspects in the model must be acting properly to provide reasonable tracer distributions, tracers can provide a unique perspective on a model's capabilities.

The following is based on work discussed in Rind et al. (1996, 1999, 2001, 2002 and especially 2007), along with evaluations being conducted for the development of the new GISS (AR5) model.

What are tracers?

Tracers as used in this context are substances (trace gases, aerosols) that are advected by atmospheric (or oceanic) motions. From observations of the time variations of tracers, one can deduce the air motions responsible for their distribution.

Why use tracers?

Transports in the atmosphere are influenced by otherwise hard-to-observe processes, including ageostrophic circulations (vertical, meridional winds), convection and turbulence. Tracers can therefore act as adjunct diagnostics to the more easily observable mean fields (temperature, zonal wind) and their variability. Transports also depend on wave-mean flow interactions (which are functions of wave transience and non-conservative processes, such as friction and radiation). To the extent that a model can properly simulate the observed distribution of a tracer it improves our confidence in the modeling/parameterization of these otherwise uncertain features.

Note: Tracers are also useful as a research tool to address scientific questions independent of model development, such as water vapor and oxygen isotopic tracers for paleoclimate research and sources of moisture; cosmogenic isotopes for solar-climate studies; carbon isotopes for CO_2 sources/sinks, etc.

What are the limitations involved with using tracers?

A primary difficulty is that some tracers are not well-observed (e.g., radon-222 in the tropical upper troposphere). In addition, sources and sinks of tracers are not always well-known (e.g., anthropogenic emissions of CFCs and SF_6 are often related to the 'electrical power grid distributions); tropospheric chemical sink of CH_4 is dependent on the unobserved magnitude of tropospheric OH^- value. And given the interactions of the different processes that result in the actual tracer distributions, it may be difficult to determine the cause of any divergence between modeled and observed values.

What is the best way to use tracers?

Their use should be in conjunction with other estimates of the relevant physical processes to produce a coherent evaluation of the process under review. In fact, the tracers can suggest the need for additional observations of specific meteorological phenomena.

Which tracers are used in the GISS model development?

Eight tracers have normally been employed in evaluation of GISS models. They are: CO_2, CH_4, N_2O, CFC-11, SF_6, ^{222}Rn, Bomb ^{14}C, and O_3.They are run 'on-line', being advected along with the standard dynamical fields (momentum, energy, mass and moisture). Tracer advection is accomplished using the quadratic upstream scheme, which is highly non-diffusive. Other tracers have also been employed at times (e.g., Kr85 (Rind et al., 1996) and ^7Be and ^{10}Be (Koch and Rind, 1998) although their sources are more uncertain.

What are the various tracer sources/sinks?

The sources of the tracers are specified; see Table 1 for a review. The sinks are primarily associated with simplified tropospheric and stratospheric chemistry (Table 1).

What length of simulation is used for the tracer evaluation? How much computer time do the tracers add?

We nominally run 12 years, to provide enough time for the evaluation of longer term processes such as the stratospheric age of air, and to provide sufficient time for a climatology to be generated (especially for precipitation). The time step for tracer advection is dependent on a "CFL" condition to avoid instability. Overall, the 8 tracers (and calculation of sources/sinks) take about 25% of the total running time.

What observations are available for the tracers?

A global network of some 100 stations exists for surface observations of CO_2, as well as observations of CH_4, N_2O and CFCs. In addition satellite observations are now being made for CO_2 by SCIAMACHY (on the Envisat), and by IASI (on the European MetOp-A); for CH_4 by SCIMACHY, MIPAS (on Envisat), IASI, AIRS (on the Aqua satellite),and ACE-FTS; for N_2O by MLS (on Aura); for CFC-11 by ACE, MIPAS and HIRDLS; for SF_6 by ACE, MIPAS; and for O_3 by numerous satellite instruments (O_3 is already being assimilated by ECMWF). With most of these species, satellite observations are either for column integrated values, or the vertical profiles are available primarily in the stratosphere. Bomb ^{14}C observations were made at various stations and field studies following the Soviet nuclear explosion in October, 1963. Various field campaigns have also provided in situ measurements for the other tracers.

What observations are needed?

Vertical profiles of most of the above species need to be improved in the troposphere. In addition, ^{222}Rn has been primarily observed at the surface.

Table 1. Tracers used for model development.

TRACER	SOURCE/SINK	REFERENCE
CFC-11	Power usage grid (source); LINOZ strat chem (sink)	Rind and Lerner (1996)
SF_6	Power usage grid (source); half-life of 3000 years	Rind et al. (1999)
^{222}Rn	Decay of radium in soils (source), half life of 3.8 days (sink)	Rind and Lerner (1996)
CH_4	wetlands and tundra, animals, rice cultivation, soil absorption; coal mines, gas leaks and venting, termites, soils, coal combustion, municipal waste, fresh water lakes, biomass burning (sources); ocean, trop chem; strat chem (sinks); half-life of 8-9 years	available from www.giss.nasa.gov/data/ch4fung; trop chem sink as in Fung et al. (1991)
CO_2	fossil fuel, land use modification (sources), ecosystem exchange (neutral), fertilization, northern forest regrowth (sinks), ocean exchange (net sink)	available from www.giss.nasa.gov/data/co2fung; also ocean source from Takahashi (pers. com); CO_2 fertilization source from Friedlingstein (pers. com.)
N_2O	lowest layer reset to 462.2ppbm (net source), strat chem (sink)	initial conditions from SAMS and CLAES data (Shindell, pers. com.)
^{14}C	Initial conditions input, removal at lower boundary (sink)	Rind et al.(1999)
O_3	Monthly mean tropospheric ozone production and loss rates archived from GEOS-CHEM; LINOZ strat chem. source and sink	Bey et al. (2001); Park et al., (2004); McLinden et al. (2000)

What transports are investigated, and what physical processes are involved?

Interhemispheric transport is affected by tropical eddy kinetic energy, convection, the Hadley Cell intensity, and tropical monsoon rainfall. Intrahemispheric transport is affected primarily by mid-latitude eddy processes. Vertical mixing within the troposphere depends on convection, eddy vertical transports, and, at low levels, turbulence. Transport from the troposphere to the stratosphere is affected by tropical and extratropical eddy kinetic energy, and by gravity wave drag in the lower stratosphere. Transport from the stratosphere to the troposphere is dependent on eddy kinetic energy (primarily planetary longwave energy in the stratosphere), and gravity wave drag. And transport within the stratosphere is influenced by planetary longwave energy and gravity wave drag. For non-passive tracers, atmospheric chemistry is important.

Note that transports between the troposphere and stratosphere, and within the stratosphere, are also affected by the stratospheric ozone distribution.

Which models are compared for their tracer transport properties?

The GISS models involved are

1) The standard AR4 GISS Model E (Schmidt et al., 2006) at 4°x5°, 20 layers [E20] with a top at ~55km, and 4°x5°, 23 layers [E23] with a top at ~85km. In addition, new results are provided for the current version of the (AR5) GISS Model E, 2°x2.5°, 40 layers [E40] (top at 55 km).
2) The GISS Global Middle Atmosphere Model 3 at four different resolutions (4°x5°, 23 [M23] and 53 layers [M53]; 2°x2.5°, 53 [F53] and 102 layers [F102]) all with tops at 85km (Rind et al., 2007).

In terms of vertical resolution, the breakdown (in km) is:

Planetary boundary layer: E20, E23, M23: 0.4; M53,F53: 0.3; E40: 0.25; F102:0.2

Free Troposphere: E20: 1.0-2.0; E23, M23: 1.0-1.5; E40: .5-.8; M53, F53: 0.5; F102: 0.3

Stratosphere: E20, E23, M23: 2-8; E40: 1-4.5; M53, F53: 1-3; F102: 0.4-1.4

Mesosphere: E23, M23: 10; M53, F53: 4; F102: 2-3; for E20 and E40: NA

The models differ somewhat in their physics as well as vertical layering. In brief, different choices are made in what is an overall similar cloud and convection scheme, stratospheric gravity wave drag is reduced in Model 3, and there are some differences in surface flux calculations. But the major difference really is one of philosophy: Model E was developed to optimize the accuracy of its radiative fluxes, while for model 3, dynamics and precipitation were a primary focus. See Rind et al., (2007) for more details.

All these models produce relatively similar zonal wind and temperature fields (Rind et al., 2007), hence the tracers provide finer discrimination of the model's capabilities.

How is interhemispheric transport calculated?

Interhemispheric transport is the difference in the hemispheric concentration of a species divided by the transport across the equator, corrected for the percentage of the source in the SH (8% for SF_6 and CFC11, 1% for CH_4).

How do the models' interhemispheric transports differ?

The interhemispheric transports differ by a factor of two, with F102 the fastest, and E23 the slowest (see Table 2). In Model 3, quicker transports occur with finer vertical resolution, while horizontal resolution has little effect on transport times.

Which result is more accurate?

The observed values in the literature vary between 0.7 and 1.8 years (Lintner, 2003), but this includes both 'surface' and '3D' transports. In general, 3D transports are faster as the gradient between hemispheres decreases with altitude. In the TRANSCOM model intercomparisons, the 3D values for SF6 are 0.81±0.2 (Denning et al., 1999) (close to the value for F102). Use of NCEP reanalysis winds with the MATCH model gives a 3D value for CFC11 of 0.8 (Lintner, 2003) (close to the value of M53). The AR4 Model E values appear to be too slow.

Table 2. 3D interhemispheric transport time (years) in the different models. The interannual standard deviation is also shown. Results from the 'interactive' runs (the calculated stratospheric ozone is used in the radiation) in the tables are shown in brackets.

MODEL	SF_6	CFC-11	CH_4
F102	0.78± 0.03 [0.83± 0.03]	0.55 ± 0.06 [0.71± 0.04]	0.61 ± 0.03 [0.65± 0.02]
F53	1.02 ± 0.03 [1.10± 0.04]	0.72 ± 0.03 [0.89± 0.06]	0.82 ± 0.03 [0.84± 0.03]
M53	1.01 ± 0.03 [1.04± 0.02]	0.79± 0.04 [0.90± 0.05]	0.85± 0.04 [0.85± 0.02]
M23	1.11 ± 0.03 [1.16± 0.03]	0.93± 0.04 [1.03± 0.05]	0.95± 0.02 [0.98± 0.04]
E23	1.33±0.04 [1.34± 0.03]	1.21± 0.06 [1.31± 0.05]	1.15± 0.05 [1.14± 0.03]
E20	1.21±0.05 [1.25± 0.03]	0.96± 0.04 [1.13± 0.06]	1.03 ± 0.04 [1.00± 0.04]
E40	0.93	0.79	0.81

What processes are involved in producing interhemispheric transport?

Upper-level convective divergent outflow has been suggested as the initiating mechanism for interhemispheric transport (Hartley and Black, 1995), including convection over land regions (Lintner, 2003). Model studies have found that eddy processes produce 2/3 of the actual cross-equatorial transport, with 1/3 by the zonal average circulation (Denning et al., 1999). Model 3 has both greater tropical eddy energy and stronger June-August Hadley Cell intensity, both associated with greater tropical precipitation over land at 18°N in that season.

What processes are responsible for intrahemispheric transport?

The mixing within each hemisphere is primarily a function of eddy transports from the mid-latitude sources, with subsequent involvement of the mean circulation in the tropics.

How does N.H. intrahemispheric transport vary among the models?

For CFC-11, all models produce a concentration ratio between N.H. mid-latitudes and the equatorial region of 1.1-1.4. Observed values of this ratio covering the analogous time period for the 1980s are ~1.10 (Kaye et al., 1994), while observed values for the SF_6 ratio in the marine boundary layer are similar (~1.06) (Denning et al., 1999), as are ratios for Kr85 (~1.16) (Jacob et al., 1987).

The N.H. mid-latitude/high latitude ratio is again similar in all models, ~1.07±0.01. This is close to the value indicated by the sparse observations (1.02) for an Atlantic transact during two months. All the models, however, show a zonal average maximum of CFC-11 in the mid-latitude source region, while observations indicate a maximum slightly further poleward.

The similarity of model results is due to the similar in eddy kinetic energy among the models; the standard deviation of this value among the models for the N.H. troposphere is ~6%..

What about the S.H. intrahemispheric transport?

There is some variation among the models in the ratio of S.H. mid-latitude to high latitude values, but it is not consistent from tracer to tracer. Observations show little extratropical gradient for SF_6 and CO_2 (Denning et al., 1999). Again, most of the models have similar magnitudes of EKE except for F102, which has about 15-20% more. This difference does not seem to be influencing its result, however.

Overall, the 4x5 versions of Model 3 have slightly less (hence better) variation between the tropics and extratropics in the two hemispheres, while Model E has the largest.

Note: another use for these tracers would be to look at the synoptic variability at particular stations, and compare them with observations. This would comment on the advective transport associated with storm movement – see Bergamaschi et al, (2006). While this was not done here, it is expected that the finer resolution models would have faster movement of storms and hence better synoptic variability.

What is used to measure vertical mixing within the troposphere, and why?

We use ^{222}Rn, which is released from soils (hence a surface source) and has a half-life of 3.8 days. It therefore is a tracer for rapid vertical movement of air, primarily associated with convection, although other processes such as eddies can contribute. Longer lived tracers have a more complicated trajectory for transport to high levels, including horizontal or inclined paths, and are thus less representative of purely vertical advection.

How do the model results compare?

The profiles in model 3 and model E are somewhat different; model E has relatively lower values from 300-500mb and higher values above 200mb than model 3; in fact, model E values are actually a bit larger at 150mb than they are at 300mb. Among the model 3 runs, F102 has greater values from in the 300-400mb layer, and less from 200-100mb.

What are the physical processes involved that cause these differences?

In all the models, both large-scale vertical transport and moist convection remove ^{222}Rn from the region below 800mb. The large-scale transport dominates in lifting ^{222}Rn up to about 500mb, then convective transport dominates above, although both are generally positive throughout. The large-scale vertical transport by eddies is greater than by the mean circulation (which is too slow to be effective given the 5 day e-folding time for this species). The differences that arise in the vertical profiles are thus due to differences in eddy and convective processes

A primary distinction is that the finer horizontal resolution models have more ^{222}Rn in the upper troposphere relative to the lower troposphere than do the coarser models (see Table 3), a combined result of both of the processes. In addition, model E convection (over land) extends to somewhat greater heights, so it has higher concentrations above 200mb.

Which results are more accurate?

We can assess the ratio of ^{222}Rn distribution in the upper/lower troposphere for the different models (Table 3). Unfortunately, observations of ^{222}Rn in the upper troposphere are scarce, especially in the tropics where convection would be expected to dominate the transports. When reanalysis winds were applied to the MATCH model, the ratio of concentration at 300mb to the surface at upper mid-latitudes varied from 12% (with ECMWF) to 20% (NCEP) (Mahowald et al., 1997). However, the MATCH model over-predicted upper troposphere values in specific observations by a factor of 2.5; if that were true for the simulations in general (and assuming the source was not similarly overestimated), then the 'observed' ratio would be 5-8%. This result is closer to that obtained in the 4°x5° models (~9%) than the finer resolution versions (~13%). The sensitivity of these results in that study to the convection scheme used (Mahowald et al., 1997) illustrates that ^{222}Rn observations in the upper troposphere would be of great benefit in validating convective parameterizations in GCMs.

Table 3. Model global results related to ^{222}Rn vertical distribution

Model	Ratio 350-200mb/ 984-844mb	Vertically Integrated Conv. Mass Flux (10^9kgs^{-1})	Global Eddy Kinetic Energy (10^{17}J)
F102	0.280 [0.280]	1429 [1421]	3728 [3683]
F53	0.286 [0.288]	1568 [1563]	3282 [3225]
M53	0.261 [0.260]	1720 [1712]	3259 [3257]
M23	0.226 [0.226]	1323 [1318]	3049 [3021]
E23	0.244 [0.241]	1228 [1232]	3234 [3261]
E20	0.230 [0.227]	1165 [1170]	3241 [3239]
E40	0.289	1147	3510

How are ^{222}Rn observations used to assess boundary layer parameterizations in models?

Since surface layer observations are readily available, ^{222}Rn observations can be used to gauge the variability of boundary layer venting. This has been done at some mid-latitude locations. Aspects such as the magnitude of the diurnal and synoptic variations (Bergamaschi et al, 2006) can be compared with observations to determine if the venting is too effective (hence resulting in smaller than observed variations) or too restrictive.

What do the model results show?

Compared to observations in Chester, Pa. (Jacob and Prather, 1990), the F102 model seems to show the right amount of venting, and also the proper seasonal variation (with maximum values in summer). However, in general the diurnal variations are similar in the different models, and the peak values recorded at the surface do not depend on either resolution (vertical or horizontal) or boundary layer physics. This is consistent with the conclusion that boundary layer heights (peak or minimum) also do not depend primarily on resolution.

What are the processes involved that produce this result?

Venting of the boundary layer, and boundary layer heights, are the result of both turbulence and convection. Apparently, changes in vertical resolution affect these processes in compensating ways – or they are simply not sensitive to it. While surface wind values do increase somewhat with finer horizontal (and to some extent vertical) resolution, it does not result in greater venting in these models.

How does transport from the troposphere to the stratosphere occur?

Species in the troposphere are moved into the tropical upper troposphere via convection and the large-scale circulation. From there, they are transported into the tropical lower stratosphere by a circulation primarily driven within the stratosphere. Planetary wave energy flux convergences 'spin-up' a residual (Lagrangian) circulation with rising air in the tropical stratosphere and sinking air at high latitudes (on the annual average). From a Eulerian framework the actual transport is due to both mean circulation and planetary wave transport effects – but the stratospheric mean circulation itself is primarily driven by planetary wave convergences.

How do the different models vary in the magnitude of this transport?

The finer resolution models tend to have weaker transports into the stratosphere; see Table 4, where the lower the percentage, the weaker the net transport for these species which all have tropospheric sources. This is especially true for increased vertical resolution, but additional changes result when both vertical and horizontal resolution is increased (e.g., F102).

What is the observed magnitude of transport?

Observations of the growth of CFC-11 with time in the troposphere (Kaye et al., 1994), the distribution of CH_4 in the troposphere and stratosphere, and the value of the SF_6 gradient between the troposphere and mid-stratosphere (Bergamaschi et al, 2006) all indicate that the finer resolution model results are more realistic. In particular, the result for F102 appears approximately correct.

Why do the finer resolution models have reduced transport?

Comparison of the transports as a function of latitude and longitude show that the finer resolution models have less transport upward (and greater downward velocities) in the tropical Western Pacific near the tropopause. They also have colder temperatures in that region, which is inducing the subsidence. The colder temperatures arise from an energy divergence associated with vertical eddy energy transports, which in turn are largest in F102 due to its greater tropical eddy energy and finer vertical resolution to resolve the divergence.

Table 4. Percent of species at altitudes above the 100mb level.

Model	CFC-11	CH_4	N_2O	SF_6
F102	5.27 [5.01]	8.59 [8.37]	8.13 [7.85]	7.19 [6.74]
F53	5.37 [5.03]	8.84 [8.56]	8.35 [8.03]	7.60 [7.06]
M53	5.45 [5.10]	8.86 [8.56]	8.37 [8.02]	7.78 [7.22]
M23	5.52 [5.16]	8.92 [8.62]	8.44 [8.09]	8.16 [7.63]
E23	5.81 [5.52]	9.08 [8.87]	8.64 [8.40]	8.29 [7.90]
E20	5.86 [5.61]	8.96 [8.75]	8.50 [8.24]	8.42 [8.10]
E40	5.32	8.64	8.23	7.77

What other features contribute to the net transport into the stratosphere?

In association with the upward transport through the tropical tropopause, there is downward transport back into the troposphere in the vicinity of the subtropical jet (in effect, through a latitudinal discontinuity in the altitude of the tropopause, higher in the tropics, and lower in mid-latitudes).

How does this aspect differ in the models?

E23 has anomalously large transports in this region, both downward and upward; averaging out the oscillations, its downward transport in this region is stronger than in the other models, helping balance to some extent its large upward transport in the equatorial region. This is the result of the large gravity wave drag parameterization in the lower stratosphere used in this model, which, due to its relationship to topography (i.e., mountain wave drag), has a similar oscillation with latitude, resulting in alternating convergences and divergences. When the gravity wave drag is reduced, this effect is muted, and hence more realistic.

How does transport from the stratosphere into the troposphere occur?

Transport downward into the troposphere is primarily an extratropical feature that occurs in conjunction with events such as tropopause folding with severe storms (or the tropopause discontinuity discussed above in conjunction with the subtropical jet). It is investigated in models with species that originate in the stratosphere – in the experiments here, bomb ^{14}C and ozone, both of which have high latitude peak concentrations in the lower stratosphere.

What do the model results show?

The finer resolution models tend to have longer residence times for bomb ^{14}C, and less ozone transport down into the troposphere, but in this case the effect is more pronounced for vertical resolution (see Table 5).

Table 5. Residence time (yrs) for Bomb ^{14}C in the stratosphere, and net ozone transport.

Model	**Bomb ^{14}C Residence Time first 36 months**	**Bomb ^{14}C Residence Time 90 months**	**Net Ozone transport(Tg/yr) through 117mb**
F102	3.75 [4.08]	4.42 [4.92]	536 [454]
F53	3.03 [3.64]	4.00 [4.50]	643 [514]
M53	2.98 [3.68]	3.86 [4.47]	678 [533]
M23	2.73 [3.30]	3.67 [4.11]	801 [634]
E23	2.73 [3.23]	4.15 [4.52]	902 [725]
E20	2.78 [3.24]	3.81 [4.07]	855 [706]
E40	2.90	3.71	764

Which result is more accurate?

The observed short-term (36 month) residence time for bomb ^{14}C (for the October 1963 event) was about 4 years, while the longer term residence time (90 months) was about 5 years (Prather and Remsberg, 1993). In general, the observed downward flux of ozone (through the tropopause) is 400-

600 Tg/yr (Olsen et al., 2004). F102 therefore looks like it has the best values. The larger values for model E even with similar resolution (E23 vs. M23 for ozone) result from its larger gravity wave drag, as noted above.

In addition, comparison can be made with modeled ozone profiles in the tropopause. These results also show that F102 provides the best results, although the larger-than- observed values suggest that ozone transport downward at the highest latitudes is still excessive (or it is happening in the middle of winter, when photochemistry is not available to destroy the ozone). Note that while F102 has both finer horizontal and vertical resolution, there is little difference in the results for F53 and M53, which differ only in horizontal resolution – and both are in general better than the other models with coarser vertical resolution.

Why is vertical resolution important?

In the model simulations conducted here, the reduced downward transport is associated with a greater reduction of eddy energy with altitude in the upper troposphere/lower stratosphere. As the eddy energy peaks in the troposphere, the finer resolution allows for a more detailed resolution of the fall-off with height. In addition, it also allows for a more rapid reduction in the upward planetary wave energy flux providing eddy energy for the stratosphere.

It was mentioned in the introduction that the tracer advection scheme used, the quadratic upstream scheme [also known as the ‘second order moments’ scheme (Prather, 1986)] is highly non-diffusive. With a more diffusive scheme, such as centered differences, the vertical resolution would be important for that reason as well.

How is transport within the stratosphere assessed?

One method is to use an ‘age of air’ diagnostic, which indicates the length of time the air parcel spends in the stratosphere after entering from (and before exiting back into) the troposphere. For this we use a passive species (not susceptible to photochemistry), SF_6.

How do the model results compare?

In general, the finest resolution models have the oldest age of air throughout the middle atmosphere, due at least in part to their influence on troposphere/stratosphere exchange. Other factors also play a role. The model E values which have strong gravity wave drag have more ‘leaky tropical pipes’ which mix air out of the tropics and make it more susceptible to be returned to the troposphere. The location of the model top near the stratopause in some of the model E configurations influences movement of air in the upper stratosphere; it also reduces the amplitude of the planetary waves responsible for mixing and circulation within the stratosphere.

Which results are more realistic?

Comparison with observed ranges (Andrews et al., 2001) (and also with results from a “Models and Measurements” study, Hall et al., 1999) is shown in Figure 1. It can be seen (Figure 1, left) that the finer resolution versions of Model 3 produce the most realistic results. [As indicated by the “Models and Measurements” range, a primary difficulty for many models is that the age of air is not sufficiently old.] However, E40, despite its finer resolution, does not show as much improvement at 45mb due in part to the inhibiting factor of its model top being at the stratopause.

The right-hand panel of Figure 1 provides the results from the simulations in which the calculated ozone interacted with the radiation field. The LINOZ ozone scheme used did not allow for the ‘ozone hole’ phenomenon, hence it had more ozone. This resulted in warmer temperatures in the S.H. lower stratosphere, reduced wave energy flux into the stratosphere, and a weaker residual circulation. The net result was increased (and more realistic) age of air in the stratosphere. This is an example of how stratospheric ozone can affect the circulation in the stratosphere. The reduced circulation also affects transport between the troposphere and stratosphere (Tables 4 and 5, values in brackets), so it impacts tracer distribution in the troposphere as well.

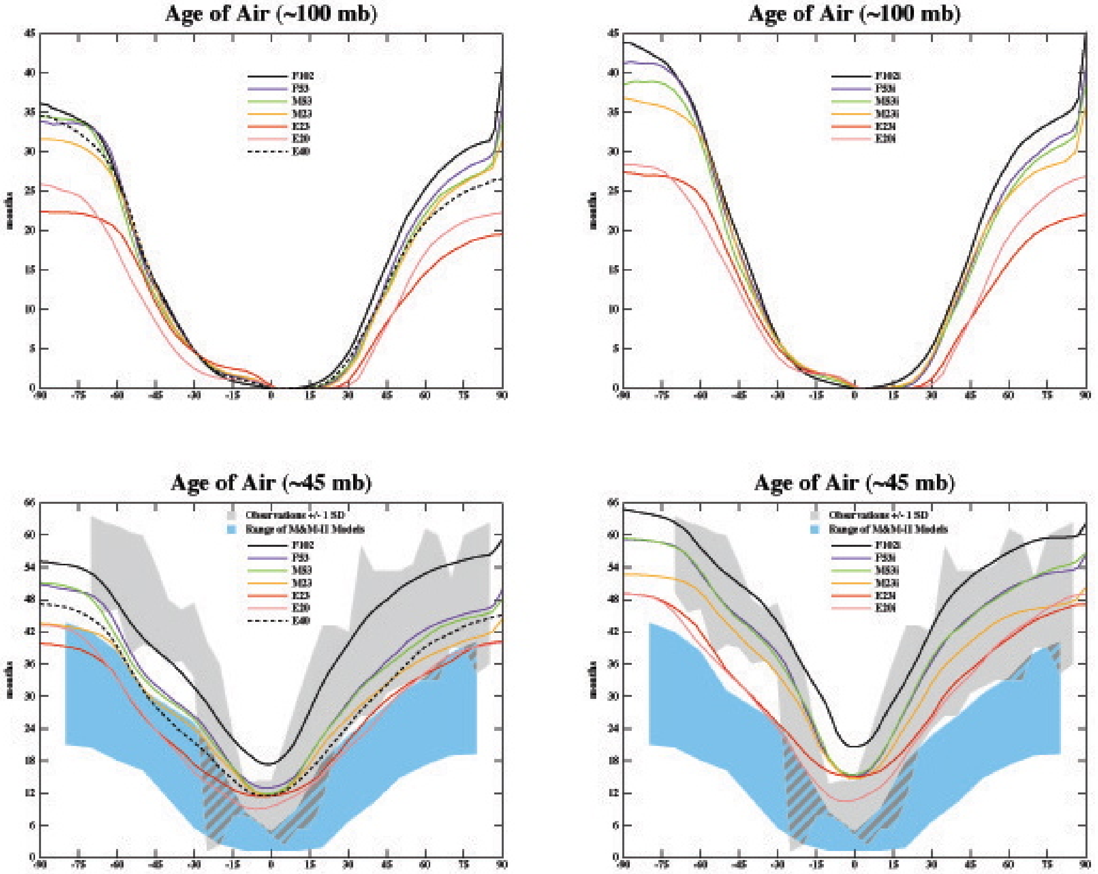

Figure 1. Stratospheric Age of Air in the different models, at 100mb (top) and 45 mb (bottom). Results using observed ozone to drive the radiation are shown on the left, while results for LINOZ calculated ozone driving the radiation are given in the right-hand panels. Gray shading shows the observed range, blue shading the results from the “Models and Measurements” intercomparison.

Do the differences in the model capabilities affect their assessment of how transports will change as climate changes?

To assess this possibility, simulations were run with all of the model 3 configurations incorporating doubled atmospheric CO_2, and using sea surface temperatures and sea ice changes derived from a $2xCO_2$ simulation with the M53 model (so they all used the same alteration in boundary conditions). The results showed that some of the tendencies in the control run continued in the ‘climate change’ experiment. For example, while all the models showed a decrease in the stratospheric age of air, the model with the oldest age of air (F102) (and thus the most to lose) had the greatest decrease in age.

The models with higher concentrations of ^{222}Rn in the upper troposphere showed greater increases in the warmer climate. The small interhemispheric transport time changes, however, showed no such correlation, nor did the small increase in percent of species above 100mb, or even the more noticeable increased downward flux of ozone (8-12% in Model 3 runs).

Conclusions

The primary results discussed here were:

- Tracers are useful for model development by providing glimpses into otherwise hard to observe wind fields/processes, including ageostrophic circulations, wave-mean flow interaction, convection and turbulence. Their best use is in conjunction with meteorological observations relevant to the same phenomena.
- Both surface and satellite observations of tracers are available, although some gaps still exist (e.g. ^{222}Rn in the tropical upper troposphere). For some tracers, uncertainties in sources/sinks can make interpretation of results somewhat problematic.
- Interhemispheric transport is particularly affected by tropical convection, the Hadley Circulation and tropical eddy kinetic energy.
    - A deficit of monsoonal rainfall or tropical EKE can lead to excessively slow transports; finer horizontal and vertical resolution can lead to improved results
- Intrahemispheric transport occurs primarily in response to extratropical eddies.
    - In the studies conducted here, climatological results were insensitive to resolution changes although finer resolution models should produce more realistic synoptic variability
- Vertical mixing of species with short lifetimes is provided primarily by convection and eddy transports in the free troposphere, with the addition of turbulence in the boundary layer.
    - Details of the convection and turbulence schemes, rather than resolution, appear to dominate the results
- Transport from the troposphere to the stratosphere occurs through the tropical tropopause, with convection and the large scale circulation bringing material into the upper troposphere, and planetary wave energy flux convergences (with the help of gravity wave drag) generating a tropics-to-pole stratospheric residual circulation.
    - Finer resolution models have better (reduced) transport in these runs due to tropical eddy-induced subsidence at the tropopause
    - Reduced gravity wave drag also leads to better transports
- Transport from the stratosphere to the tropopause is related to eddy energy variations with altitude, with results improved with finer vertical resolution.

- Transports within the stratosphere can be assessed with ‘age of air’ diagnostics for passive species (e.g., SF_6); results are affected by the model top and gravity wave drag characteristics.
    - Older (more realistic) ages of air arise with finer resolution (which affects stratosphere/troposphere exchange) and positioning the model top near the mesopause, and
    - Reduced gravity wave drag in the lower stratosphere, which helps limit the ‘leakiness of the stratospheric tropical pipe’
- Ozone in the stratosphere influences troposphere/stratosphere exchange and the stratospheric circulation by affecting the vertical stability and hence eddy energy in the upper troposphere/lower stratosphere.
- Overall, finer vertical resolution seems to play a greater role in affecting tracer transports than finer horizontal resolution, although when both are increased, additional effects arise.
- Characteristics of the current climate model tracer transports can affect their climate change assessments by exaggerating current tendencies, but often do not.

The current frozen version of the GISS AR5 model whose results are shown here was developed with the aid of these tracer diagnostics, and as can be seen, its transports are in general superior to those of the AR4 model. This was not always the case, but the development was torqued in that direction due in particular to the desire to use it for chemistry/aerosol climate interactions. However, as also can be seen, it is still often not as good as the GISS Global Climate/Middle Atmosphere model 3. Another version of model E exists, with 53 layers and a top at the mesospause which actually performs better than E40 in this regard, especially for interactions with the stratosphere; but the improvements were not deemed worth the extra computer time involved in its usage, as the AR5 model will have to be run for many multi-century simulations. Even in its current 40 layer configuration, Model E could have produced better transports utilizing some of the physics choices made for model 3, but that might have come at the expense of its radiation field, which as noted earlier was deemed the top priority for a climate model. In particular, a trade-off between the accuracy of tropical precipitation over land and marine stratus clouds appears to arise in many simulations.

All this emphasizes that the tracer transports are just one type of diagnostic to be considered in model development, with its importance depending on how the processes involved in these transports relate to the intended model usage. With respect to weather forecasting at ECMWF, one would assume that would be closer to the needs of Model 3 for optimal dynamics and precipitation in the troposphere, but not necessarily for Model 3's concern with the stratosphere. Ideally improving transports would also improve everything else, but in practice, as GISS model development illustrates, with our current state of knowledge, choices often have to be made in light of the operational goal. The use of tracers provides an additional perspective and insight to help make those choices.

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