single ATMOS profile from 1985 [Rinsland, 1995] and, therefore, its distribution is not well known. For this profile, the models do not agree well except LASP above 33 km. The models tend to agree among themselves between 20 and 30 km in the tropics, however, model differences in SO_2 much like those for OCS are much larger at higher latitudes most likely due to differences in transport. Model-computed aerosol extinctions generally agree with SAGE II and HALOE observations in magnitude and in latitudinal gradients during low aerosol loading periods. This is true above 20 km where the models themselves also tend to agree, but to a lesser degree below 20 km where some substantial divergence between the models themselves can be observed. Compared to SAGE II measurements below 20 km, the model 525 nm extinctions tend to straddle the observations, while the model extinctions at 1020 nm tend to underestimate the observed extinction. This suggests that the models have redistributed some of the aerosol from larger to smaller sizes relate to that suggested by the observations. Above 20 km, the agreement between the models and SAGE II-derived SAD is comparable to the agreement found for extinction. Below 20 km, the SAGE II-derived values are substantially smaller than those computed from the models. Part of this is probably due to limitations in converting from extinction to SAD using SAGE II observations (as discussed above) but may be exacerbated in these comparisons by deficiencies in the models' lower stratospheric size distribution.

ASAP Data Archive

Data sets that comprise the basis for the data analysis will be archived at the SPARC Data Center **(http://www.sparc.sunysb.edu/)** including altitude/latitude gridded fields of aerosol extinction and derived quantities for the SAGE series and HALOE. Data sets used in the trend analysis will also be available at this location. In addition, links to additional sources of aerosol data that appear within this report will be included. Also, at least the SAGE data sets will be available remapped to equivalent latitude and potential temperature.

A final product that will be available is a 'gap filled' data set for the period 1979 through 2002 based on the SAGE record. Gaps exist between the June 1991 eruption of Mt. Pinatubo and the end of 1993 due to instrument saturation and between November 1981 and October 1984, when global space-based aerosol extinction measurements were not available. To fill the missing values, we have used aerosol backscatter profile measurements from sites at Camaguey (Cuba), Mauna Loa, Hawaii (USA), and Hampton, Virginia (USA) and backscatter sonde measurements from Lauder (New Zealand). This period encompasses the El Chichon eruption and the onset of the Antarctic ozone hole and is, therefore, of particular interest. Beginning in April 1982 and through the beginning of SAGE II observations in 1984, we have used a composite of data consisting of SAM II, the NASA Langley 48-inch lidar system, and lidar data from the NASA Langley Airborne Lidar System. Data from this later data set has only been partially recovered for the 1982 to 1984 period. **Figure 5 (p. III)** shows the stratospheric aerosol optical depth for the 1979-2002 period using the gap-filled data product. When more of the airborne lidar data and particularly the revised aerosol product from the Solar Mesospheric Explorer (1981-1986) become available additional work on the El Chichon period will be profitable.

References

Brock. C.A., *et al.,* Particle formation in the upper tropical troposphere: A source of nuclei for the stratospheric aerosol, *Science,* **270,** 1650-1653, 1995.

Deshler, T., *et al.,* Thirty years of *in situ* stratospheric aerosol size distribution measurements from Laramie, Wyoming (41N), using balloon-borne instruments, *J. Geophys. Res.,* **108**(D5), 4167, doi:10.1029/2002JD002514, 2003.

Hamill, P., *et al.,* The life cycle of stratospheric aerosol particles, *Bull. Am. Meteorol. Soc.,* **78,** 1395-1410, 1997.

Hervig, M.E., *et al.,* Aerosol size distributions obtained from HALOE spectral extinction measurements, *J. Geophys. Res.,* **103,** 1573-1583, 1998.

Hofmann, D.J. and T. Deshler, Stratospheric cloud observations during formation of the Antarctic ozone hole in 1989, *J. Geophys. Res.,* **96,** 2897-2912, 1991.

Rinsland, C.P., *et al.,* H2SO4 photolysis: A source of sulfur dioxide in the upper stratosphere, *Geophys. Res. Lett.,* **22,** 1109-1112, 1995.

Rosen, J.M., The vertical distribution of dust to 30 km, *J. Geophys. Res.,* **69,** 4673- 4676, 1964.

Palmer, K. F. and D. Williams, Optical constants of sulfuric acid: Application to the clouds of Venus?, *Appl. Opt.,* **14,** 208-219, 1975.

Tisdale, R.T., *et al.,* Infrared optical constants of low-temperature H_2SO_4 solutions representative of stratospheric sulfate aerosols, *J. Geophys. Res.,* **130,** 25,353-25,370, 1998.

Thomason, L. W. and G. Taha, SAGE III Aerosol Extinction Measurements: Initial Results, *Geophys. Res. Lett.,* **30,** 33-1 - 33-4, doi:10.1029/2003GL017317, 2003.

Thomason, L. W., *et al.,* A comparison of the stratospheric aerosol background periods of 1979 and 1989-1991, *J. Geophys. Res.,* **102,** 3611-3616, 1997.

Trepte, C.R. and M. H. Hitchman, Tropical stratospheric circulation deduced from satellite aerosol data, *Nature,* **355,** 626-628, 1992.

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Report on Chapman Conference on Gravity Wave Processes and Parameterisation

Waikoloa, Hawaii, USA, 9-14 January 2004

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Introduction

A prominent aspect of the observed circulation in the middle atmosphere is the variance, with periods ranging from minutes to tens of hours, that is most plausibly interpreted as resulting from upward-propagating internal gravity waves largely forced in the troposphere. In the absence of damping or strong basic-state inhomogeneities, the amplitude of the gravity wave wind and temperature fluctuations will vary roughly as the reciprocal of the square-root of mean density. This means that gravity waves that play only an insignificant role in the troposphere can grow to very large amplitudes at high altitudes. Gravity waves act to exchange mean momentum between the surface and the atmosphere and among different layers of the atmosphere and, as such, are crucial in forcing the global-scale circulation in the stratosphere and mesosphere. Since the distribution of many trace constituents involved in ozone chemistry is very strongly affected by the atmospheric circulation, an understanding of gravity wave effects in the middle atmosphere has become a central issue for the practical problem of modelling stratospheric ozone. Much of the gravity wave variance (particularly in the vertical velocity) occurs at horizontal scales too small to be explicitly resolved in current General Circulation Models (GCMs) of the global atmosphere. The development and application of parameterisation schemes to adequately account for the effects of unresolved gravity waves on the mean flow is now a prime consideration for groups involved in numerical modelling of the middle atmosphere dynamics and chemistry.

SPARC has made gravity wave processes and parameterisation one of its focus areas, and SPARC co-sponsored an important workshop in Santa Fe in 1996 that brought together the gravity wave observational and modelling community and the global modelling community (SPARC Newsletter N° 7; Hamilton, 1997). Recently SPARC co-sponsored an AGU Chapman Conference on "Gravity Wave Processes and Parameterisation" that addressed a range of key issues in this area. The meeting was held in Waikoloa, Hawaii, USA, January 10-14, 2004, and attracted 64 participants from 11 countries. This paper summarises just a fraction of the many interesting posters and oral presentations, and briefly discusses some of the major issues raised at the meeting. Also noteworthy were outstanding overview talks on the middle atmospheric gravity wave problem by **R. Garcia** and **T. Dunkerton** and on the oceanic gravity wave spectrum by **E. Kunze**.

Observations

There have been some important developments in observational techniques in recent years. **A. Hertzog** presented some results from long-duration constant-density superpressure balloons. He showed that frequency spectra of the winds following the balloon location - essentially the intrinsic spectrum - can be computed for periods as short as 20 minutes. Particularly exciting is the ability to derive accurate vertical wind velocities at high sampling rates. **Figure 1** shows a time series of the vertical flux of zonal momentum computed from the wind measurements from one balloon as it drifted near the equator and 19 km altitude (the winds were first filtered to include only fluctuations with periods between 1 and 12 hours). Since the balloon drifts westward tens of thousands of km over the period shown, the variation seen in the momentum flux time series reflects both temporal and spatial modulation of the gravity wave field.

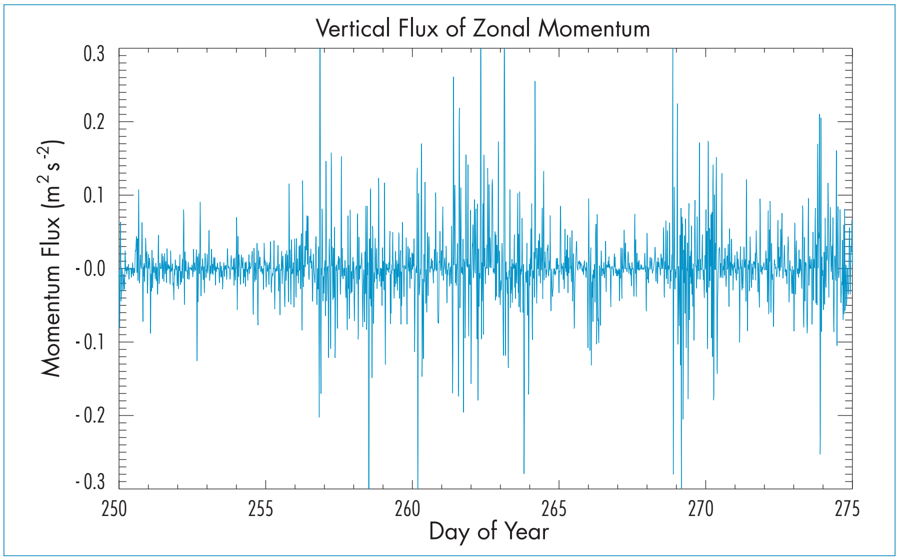

Figure 1. A time series of the product of zonal velocity and vertical pressure velocity from a balloon drifting at constant density (near 19 km altitude). The velocities have been band-passed to include only periods between 1 and 12 hours before the product is computed. [Provided by R. Vincent].

Another technique developed recently is the use of satellite GPS tomography to measure vertical profiles of temperatures in the stratosphere. The measurements can be taken whenever paths between two individual satellites happen to intersect the planetary limb, leading to a widely-scattered geographical coverage that supplements the fixed station distribution typical for many other profiling measurements. **T. Tsuda** reviewed progress so far on two GPS satellite missions and showed that global maps of wave temperature variance can be produced. The upcoming US-Taiwan COSMIC and Brazilian EQUARS satellite missions will provide a much denser data coverage in the near future.

D. Wu presented results from an analysis of horizontal variations in UARS Microwave Limb Sounder (MLS) data and in operational Advanced Microwave Sounding Unit (AMSU) data. These data can provide information on long-vertical wavelength gravity waves in the middle atmosphere. He was able to relate the geographical modulation seen in the MLS and AMSU variability to likely tropospheric sources. Particularly impressive were areas of enhanced variability above regions of significant topography.

Detailed Modelling of Wave Dissipation

G. Klaassen reviewed the very significant progress in understanding the linear normal mode instability of monochromatic plane waves. The problem seems largely solved for the case of no mean shear, and work is now focussing on extending the theory to treat more general mean states. **U. Achatz** described a linear approach based on identifying the optimally growing structures rather than normal modes.

D. Fritts described very fine resolution nonlinear simulations of the single wave breaking phenomenon. The initial evolution of simulated instabilities closely resemble predictions from linear theory, but the nonlinear development leads to a range of interesting phenomena with important implications for parameterisation of wave dissipation, as well as associated heat, momentum and constituent transports. Some results suggest a tendency for instability to largely obliterate individual waves rather than simply limiting their subsequent growth with height.

Topographic Wave Drag Parameterisations

S. Webster reviewed recent progress in parameterising the effects of unresolved topographic effects on atmospheric flow. In the 1980's the first simple parameterisations were devised based on (i) an assumption that all the topographic flow perturbations project on to gravity waves, and (ii) idealised notions of wave amplitude saturation. The predictions of such parameterisations have now been tested against explicit very-high resolution regional models. It appears that the predictions of the total surface topographic drag is reasonably accurate, but that in reality much of the drag is likely attributable to “flow blocking”, meaning that the stress divergences should occur principally near the ground. So the simple parameterisation schemes overestimate the gravity wave stresses in the stratosphere. This conclusion is supported by global model forecast experiments, wich suggest that only modest topographic gravity wave drag is required in the lower stratosphere.

Basic Issues Concerning Wave Effects on the Mean Flow

There have been recent concerns about the adequacy of the traditional paradigm for treating gravity wave effects, *i.e.* that, in steady-state, waves transfer mean momentum from the regions where they are forced to the region where they are dissipated. New effects are introduced when waves refract in such a way that the wavevector at absorption is no longer parallel to that at forcing. **O. Buhler** reviewed recent work on this subject including some idealised calculations of the effects of a wave train that refracts as it propagates through the periphery of a circular vortex. Some of the wave rectification effects in this case are felt remotely by the vortex as a whole. **C. Warner** presented some preliminary calculations that suggest that this effect might plausibly be significant for gravity waves propagating through the middle atmosphere, but much more work will be necessary to establish how large the effect really is in practice.

Gravity Wave Parameterisations

C. Hines discussed developments in Doppler-Spread Theory (DST) for gravity waves. As originally advanced, the theory used heuristic arguments to determine the effects of the nonlinear advection terms from a spectrum of vertically-propagating waves on the high vertical wavenumber tail of the spectrum, all within an Eulerian framework. The result suggested that a saturated tail with something close to the observed m^{-3} vertical wavenumber dependence should result. In more recent work C. Hines has re-examined the problem in a Lagrangian framework in which the wave dynamics can be treated approximately as linear. The result is a more rigorous derivation of the roughly m^{-3} dependence of the tail. C. Hines finds that these new developments have only modest implications for the practical Doppler-Spread Parameterisation (DSP) scheme that he had developed earlier on the basis of the DST.

C. McLandress discussed a comparison of the drag computed using the Hines DSP and the Warner-McIntyre parameterisation (WMP) for particular example mean flow profiles. The Warner-McIntyre scheme uses an empirically-based saturation condition that limits the energy in the tail of the spectrum. The momentum flux spectra imposed near the tropopause level was prescribed to be identical in the two schemes. There were systematic differences between the performance of the two schemes, with much more of the wave spectrum being removed lower down in the atmosphere by the WMP than the DSP. The profiles of flux and flux divergence computed by the two schemes become similar when the saturation fluxes for the WMP are raised by a factor of 25 over their standard values.

An important development described in several talks at the workshop has been the systematic application of known constraints on the mean flow forcing to adjust aspects of parameterisations. **J. Alexander** presented calculations in which the input spectrum of momentum flux versus horizontal phase speed for the Alexander-Dunkerton Parameterisation (ADP) is adjusted to account for the needed gravity wave mean-flow forcing in the middle atmosphere (determined through analysis of large-scale observations). The results were somewhat different in midlatitudes and the tropics, with a broader phase speed spectrum indicated for low latitudes. **D. Ortland** discussed a systematic approach to the inverse problem of finding input spectra in the ADP that can reproduce the required wave drag as determined from simulations of the middle atmospheric circulation obtained with a two-dimensional (zonally-averaged) model.

R. Vincent and **P. Love** discussed the use of mesospheric radar measurements of the winds near the equator to constrain the tropospheric input spectra employed in a ray-tracing model (with sources associated with regions of convection as seen in satellite imagery). It appears that, with appropriate assumptions about the source spectra, much of the observed mean-flow forcing inferred from wind observations in the equatorial mesosphere can be explained by tropospheric convective sources.

One issue that is involved in such adjustment of parameterisations is the determination of how much of the mean flow forcing is attributable to gravity waves versus the motions that should be resolved in current climate models (or current global observational analyses). This determination has typically been based on monthly-mean data used to infer the Coriolis and advective effects of the residual mean meridional circulation along with some other observational estimate for the contributions of planetary waves. In principle, a more satisfying approach might be based on the analysis increments obtained in data assimilation procedures within a forecast-analysis cycle. **W. Tan** discussed this issue but noted that the inadequacy of current data sources and assimilations may severely limit the utility of this approach, at least at present.

J. Beres discussed linear theory results for the gravity wave field forced by localised transient heating. She then used these results as the basis for a practical scheme to determine the input spectrum appropriate for convective forcing. Her approach basically takes the grid-scale latent forcing computed in the convective parameterisation and assumes some subgrid-scale structure for the heating. Then the linear theory is used to obtain a source spectrum for the gravity wave parameterisation that depends on the grid-scale heating and the resolved horizontal winds. This is a rational way to begin to consider the effects of variability of convection in the gravity wave parameterisation problem. J. Beres presented some preliminary results obtained with the NCAR Whole Atmosphere Community Climate Model that incorporated a version of the ADP with source spectra calculated with her scheme.

H.-Y. Chun discussed another parameterisation for convective gravity waves that also related the source spectrum to grid-scale winds and convective heating. **I.-S. Song** discussed results with this source spectrum determination incorporated into Lindzen and Warner-McIntyre parameterisations.

Implementation of Parameterisations in Models

T. Shaw discussed the issue of how gravity wave drag parameterisations are affected by the effective truncation of the model domain at some finite altitude that is inherent in the numerical discretisation. She showed that the residual meridional circulation differs dramatically if the parameterised gravity wave fluxes that reach the model top are assumed to be absorbed at the top level or are simply neglected. It seems that, in terms of simulating the residual circulation, assuming that the flux is absorbed at the top will lead to a result much closer to what would be obtained by explicitly including a very high model domain.

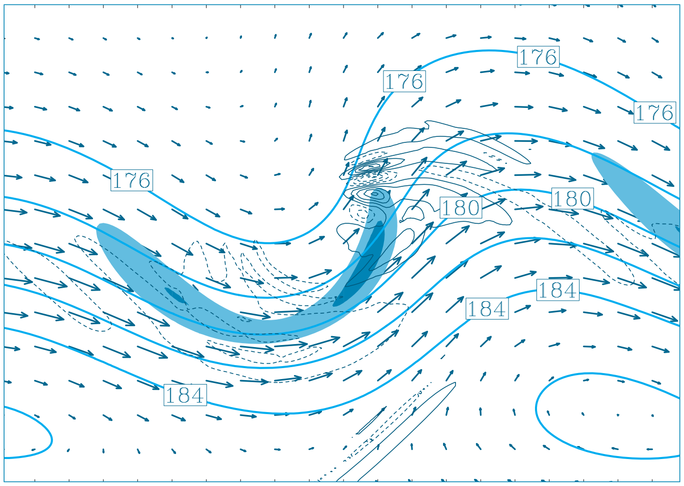

Figure 2. The 13-km pressure (thick blue line, every 2 hPa), horizontal divergence (thin blue line; solid, positive; dashed, negative; every 5x10^{-6} s^{-1}) and wind vectors (maximum of 25 ms^{-1}) simulated from the triple-nested mesoscale model MM5 with horizontal (vertical) resolutions of 10 km (360 m). The wind speed at 8 km (near the maximum jet strength level) greater than 45ms^{-1} is shaded in blue (every 5 ms^{-1}). The distance between tick marks is 300 km [adapted from Figure 12d of Zhang (2004)].

E. Manzini described the role of parameterised gravity waves in the simulation of the near-mesopause circulation in the Max Planck Institute HAMMONIA coupled circulation-chemistry GCM. In particular, she investigated the issue of interhemispheric asymmetry in summer mesopause temperatures. **M. Giorgetta** discussed results with a version of the ECHAM model showing that a combination of resolved equatorial waves and an appropriately tuned gravity wave parameterisation could allow the model to produce a quite realistic quasi-biennial oscillation (QBO) of the tropical stratosphere. He then used the model to investigate the effect of changed carbon dioxide concentrations on the QBO.

Explicit Simulations of Wave Forcing in Regional Models

A number of papers dealt with detailed simulations of gravity wave generation and propagation in high-resolution limited-area models. **T. Horinouchi** discussed 3D cloud-resolving simulations of gravity waves forced by convection in a tropical squall line. He showed that the model can convincingly simulate the entire life cycle of convectively-forced waves: generation, propagation through the middle atmosphere, and nonlinear breakdown near the mesopause. He showed that his simulated meteorological fields could be used as the basis for a calculation of airglow emission, thus, allowing a direct comparison of his model results near the mesopause with airglow imager observations.

The convection and convectively forced gravity waves in springtime in northern Australia were the subjects of the recent Darwin Area Wave Experiment (DAWEX) field campaign. Two papers dealt with model studies of the convectively-generated gravity waves during this experiment. J. Alexander discussed the wave field computed for one day in DAWEX using a dry model forced with time-dependent, 3D heating fields based on detailed meteorological radar observations of precipitation. The radar can be expected to give a good estimate of the overall space-time evolution of the pattern of precipitation, but J. Alexander notes some uncertainty in overall amplitudes. **G. Stenchikov** described a simulation of the circulation and convection for one day during DAWEX using a 3D cloud-resolving mesoscale model.

T. Lane simulated isolated convection and resultant stratospheric gravity waves in a 2D version of a cloud-resolving model. The restriction to 2D allowed him to examine results obtained over a range of model grid resolutions. He finds that the momentum flux spectrum of the waves emerging into the stratosphere above the convection depends significantly on model resolution even down to rather fine grid spacings. Notably, convergence of results for the momentum flux occurs only when the horizontal grid spacing is reduced substantially below 1 km (which is typical of the horizontal resolution of most 3D models that have been applied to this problem).

Z. Chen discussed the generation of stratospheric gravity waves by a typhoon simulated in the MM5 mesoscale model. He finds the typhoon acts as a strong source for relatively large horizontal wavelength waves (~500-1000 km) and that the features of the simulated stratospheric waves have some similarity to those seen in earlier aircraft, dropsonde and radar observations in the vicinity of tropical cyclones.

F. Zhang discussed a dry simulation of a growing baroclinic wave in a multiply-nested version of the MM5 regional model. This multiple nesting allowed him to consider motions from the continental scale down to quite small scales (his most ambitious experiment had quadruple nesting and a finest grid with 3.3 km horizontal and 180 m vertical grid spacing). He found that there was a very significant flux of gravity waves above the jet exit region and that the waves had dominant horizontal wavelengths of about 150 km, vertical wavelengths of about 2.5 km, and intrinsic horizontal phase speeds of about 8 ms^{-1}. **Figure 2** shows results from a triply-nested version of his model experiment. F. Zhang found that a measure of the deviation from diagnostic dynamical (cyclostrophic) balance in the jet-level flow provides a good indication of the regions of strong gravity wave generation.

Explicit Simulations of the Middle Atmospheric Gravity Wave Field in Global Models

J. Scinocca discussed the role of moist processes in exciting the explicitly-resolved gravity (and equatorial planetary) waves in a global atmospheric GCM. He found that the assumption often made that waves are forced primarily by heating in the convective parameterisations may be somewhat over- simplified, and that there may be a significant role for the large-scale condensation heating as a wave excitation mechanism.

S. Watanabe discussed the middle atmospheric gravity wave field in a T106-L250 global GCM. He showed that the model simulates a realistic m^{-3} vertical wavenumber spectrum. He went on to use the gravity wave properties in the T106 model as the basis for specifying the input spectrum in a Hines parameterisation that was implemented in a T42 version of the model.

K. Hamilton showed that the m^{-3} spectrum appears in a very fine vertical resolution (L160) simulation with the GFDL SKYHI model. He also discussed initial results with a global model of unprecedented spatial resolution (T1279-L96) that has been developed and run at the Earth Simulator Center. He showed that the near-tropopause gravity wave field in this model had encouragingly realistic features, at least in terms of overall space and time variance spectra.

Summary

The essential problem behind the many uncertainties in adequately treating gravity wave effects is a lack of detailed empirical information about the gravity wave field in the middle atmosphere. While much progress has been made in observational methods, each technique applied has very significant limitations in terms of geographical and temporal sampling, and in terms of the spatial wave scales that can be detected. Even the appropriate basic conceptual framework for understanding the middle atmospheric gravity wave field is not clearly determined from current observations. It is conceivable that the field at any point may typically be dominated by quasi-monochromatic waves, but the opposite view, in which a fully-developed broad spectrum of waves dominates virtually everywhere, is also possible. It was apparent from the presentations at the conference that the observation of the m^{-3} dependence of the average vertical wavenumber spectrum does not, by itself, clearly differentiate among various possible views of the basic physics of the wave field.

A great deal of progress was reported on practical parameterisations that can be implemented in current models. The first generation of such parameterisations discussed at the Santa Fe workshop typically made very simple and arbitrary assumptions about the source spectrum and its geographical and temporal variability. There has been important progress towards more physically-based source spectra and towards more systematic application of observed constraints to pin down the parameters employed.

Perhaps the most impressive recent progress has been made using explicit limited-area, high-resolution nonlinear simulations of wave generation and dissipation. Since the Santa Fe workshop there has been a major increase in activity devoted to explicit simulation of gravity waves forced by convection and other sources. In the case of topographically-forced gravity waves, results from limited-area simulations have been used very successfully to redesign the gravity wave parameterisations employed in global models. For the nonstationary wave field forced by convection and other sources, the interaction between detailed simulations and design of practical parameterisations is in a less-developed stage, but useful progress has already been made. Similarly, the impressive explicit high-resolution simulations of wave breaking that have been produced in recent years will ultimately have implications for the design of gravity wave parameterisations.

References

Zhang, F., 2004: Generation of mesoscale gravity waves in upper-tropospheric jet-front systems. *J. Atmos. Sci.,* **61,** 440-457.

Hamilton, K., editor, 1997: Gravity Wave Processes: *Their Parameterization in Global Climate Models.* Springer-Verlag, 401 pp.

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Solar Variability and Climate: Selected Results from the SOLICE Project

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1. Introduction

The SOLICE (Solar Influences on Climate and the Environment) project was funded by the European Community Framework 5 programme with the stated objectives:

- To extract the stratospheric solar signal in datasets of ozone, temperature, geopotential height, vorticity and circulation.
- To assess the impacts of solar variability in the troposphere.
- To investigate the response of stratospheric composition and climate to variations in solar ultra-violet radiation using General Circulation Models (GCMs), Coupled Chemistry-Climate Models (CCMs), Chemical Transport Models (CTMs) and mechanistic models.
- To develop a more complete understanding of the mechanisms by which solar variability influences the natural variability of the stratosphere and troposphere.

The project, involving eight European institutions and two American collaborators, was initiated in April 2000 and has recently been completed. Here we report on a selection of the results. Full results and further project details are available at **http://www.imperial.ac.uk/research/spat/research/SOLICE/index.htm.**

2. Solar signal in the middle atmosphere

2.1. Observations of temperature

The response of the middle atmosphere to solar variability has been estimated from a variety of different datasets including lidar, rocketsonde, SSU/ MSU, FUB, as well as the NCEP