A-2

Bifurcation Dynamics in Storm Track Systems

Kyle L Swanson
(Department of Mathematical Sciences, University of Wisconsin-Milwaukee)

It is by now well understood that variability in transients drives variability in eddy-maintained jets. An extreme case of transient variability occurs when the properties of transients change dramatically due to an infinitessimal change in an external parameter. Such bifurcations in transient variability occur in quasi-geostrophic systems possessing storm tracks of enhanced synoptic time scale variability, leading to the collapse of the storm track and introducing the possibility for multiple, coexisting chaotic attrators for identicalforcing and dissipation.

A-3
Transport properties of jets in baroclinic systems

P H Haynes
(Department of Applied Mathematics and Theoretical Physics, University of Cambridge)

In atmosphere and ocean there are several important examples of jet-like flows that act as strong barriers to quasi-horizontal transport of chemical and biological species. There are often strong variations of transport properties with height. This talk will discuss a sequence of numerical simulations of a forced-dissipative baroclinic flow in which jets and associated transport barriers naturally arise in the statistical equilibrium flow and the transport properties vary strongly with height (with no barrier at low levels and a strong barrier at upper levels, with a sharp transition between the two regimes).

These simulations were designed to study the problem of what determines the height of the midlatitude tropopause (which might be argued to correspond to the transition from lower to upper regime). However a similar transition in transport properties has been noted in the Gulf Stream and some of our simulations are in a multiple-jet regime more relevant to oceanic flows.

A complete theoretical understanding of these flows (and their associated transport properties) is not yet available. But some relevant dynamical and kinematical ideas will be discussed.

A-4

Potential vorticity staircases in rotating stratified fluids: the role of anisotropic Rossby-wave propagation

T J Dunkerton
(NorthWest Research Associates)
P B Rhines
(School of Oceanography, Univ. of Washington)

In a rotating, stably stratified fluid that supports Rossby waves and instabilities, the planetary vorticity gradient is an unstable equilibrium, in the following sense. If an external perturbation (such as an overturning circulation or deep convection) acts to create a jet in the direction of planetary rotation, lateral mixing due to breaking waves and instabilities involving Rossby-wave propagation (such as barotropic and baroclinic instability) reinforces the jet structure, steepening the potential vorticity gradient at the jet core, while maintaining a well-mixed region on either side of the jet. If the eddies are sufficiently strong and their meridional scale significantly different from that of the external forcing, the number and/or spacing of jets may be determined by the eddies themselves. To the extent that the eddies originate from Rossby waves, and the waves originate from instabilities involving Rossby-wave propagation, the following argument may be offered to explain the existence of pro-grade or "westerly" jets interleaved with mixing zones. Westerly jets experience relatively little meridional displacement of parcels owing to the fact that Rossby waves and instabilities cannot have a critical layer at the core of the jet. The intrinsic frequency of propagating Rossby waves is negative in a region of positive potential vorticity gradient; therefore, if a critical layer existed at the westerly jet maximum, the intrinsic frequency would be positive elsewhere, contradicting the requirement that the intrinsic frequency be negative. The critical layer for barotropic and baroclinic instabilities is located in a region of reversed potential vorticity gradient which occurs, if at all, in the flanks of a westerly jet. Wave breaking and the associated large parcel displacements are, for the most part, confined to critical layers between the westerly jets. Inhomogeneous mixing thereby leads to the formation of a staircase in potential vorticity, the location and number of jets being determined by a combination of external forcing and dissipative processes, wave spectra, eddy scales and mixing intensity. Examples of staircases are described in a model constrained by angular momentum and potential vorticity conservation with eddy fluxes determined by a spectral parameterization of Rossby waves. For a variety of reasons, westerly jets are imperfect barriers to transport in planetary fluids. We discuss the sensitivity of meridional transport to the asymptotic form of eddy fluxes in the vicinity of the jets.

A-5

How Cavity-like is the Winter Stratosphere?

M E McIntyre
(Department of Applied Mathematics and Theoretical Physics, University of Cambridge)

Everything we know theoretically about Rossby-wave dynamics tells us that the wintertime stratospheric surf zone should be a partial reflector of planetary-scale Rossby-wave activity. Matsuno's view of the stratosphere as a more or less weakly resonant cavity should therefore have some validity, implying in turn not only phenomena like the Holton-Tan effect but also that the stratosphere must have some influence on the troposphere. Indeed, some recent models of polar-vortex dynamics that appear to produce qualitatively reasonable behaviour have such downward influence built in from the start, because their "surf zones" are perfect reflectors by construction. These are the contour-dynamics and related models recently studied in the fluid-dynamics literature. I propose to discuss these issues and to illustrate them with some unpublished model results demonstrating resonant effects dependent on surf-zone reflectivity. Such reflectivity is of course a nonlinear phenomenon and outside the scope of linear concepts like refractive index.

B-1

Dynamics of the Antarctic Circumpolar Current, the Ocean's Annular Mode

J C Marshall
(Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology)

A zonal-average model of the Antarctic Circumpolar Current (ACC) and its associated meridional overturning circulation is constructed in the framework of residual-mean theory and used to discuss the processes - wind, buoyancy, eddy forcing and boundary conditions - that control its strength and sense of circulation. The geometry of the thermocline "wedge", set by the mapping between the vertical spacing of buoyancy surfaces (the stratification) on the equatorial flank of the ACC and their outcrop at the sea surface, is seen to play a central role by setting the interior large-scale potential vorticity distribution. It is shown that the action of eddies mixing this potential vorticity field induces a residual flow in the meridional plane much as is observed, with upwelling of fluid around Antarctica, northward surface flow and subduction to form intermediate water. Along with this overturning circulation there is a concomitant air-sea buoyancy flux directed in to the ocean.

B-2
The Antarctic Circumpolar Current

S T Gille
(Scripps Institution of Oceanography, University of California San Diego)

The Antarctic Circumpolar Current (ACC) encircles Antarctica. It is the only annular flow within the Earth's global ocean. Its transport is estimated to be approximately 130 Sv (106 m3/s), making it comparable in size to the Gulf Stream or Kuroshio Extension in the Northern Hemisphere. The ACC consists of multiple filamented jets that correspond to fronts, separating distinct water masses. From north to south the primary jets are commonly identified as the Subantarctic Front, the Polar Front, and the Southern ACC Front. The ACC is forced by some of the strongest surface winds on Earth, and observational evidence suggests that fluctuations in wind accelerate and decelerate the transport of the ACC. Because the Southern Ocean is large, with few accessible ports, in situ observations of the system are limited. Satellite observations of sea surface height (from altimeters) and of sea surface temperature (from the AMSR-E microwave sensor) indicate that the ACC fronts meander with a range of approximately 100 km north and south of their mean positions with timescales on the order of 30 days. The fronts also spawn numerous warm core and cold core rings. Detailed interpretation of satellite data can be difficult, because sea surface temperature sensors cannot see below the ocean surface and altimeters measure variability but not mean dynamic topography. Autonomous floats and drifters provide additional evidence of the structure of the ACC. Comparisons of temperature profiles collected by ships and floats show that the ACC has warmed more rapidly than other parts of the global ocean during the past 50 years, suggesting that it is an important location for studying climate change.

B-3
Jets in the Antarctic Circumpolar Current

Chris W. Hughes
(Proudman Oceanographic Laboratory)

The Antarctic Circumpolar Current is far from being a single broad zonal flow. The current consists of a complicated braiding of jets which are remarkably persistent in time, many of which are clearly influenced by topography. The peak mean flow at some longitudes is faster than 25 cm/s, and at others slower than 10 cm/s. The jets occur within an envelope which undergoes significant meridional deflections as it circumnavigates Antarctica. Many of these features reflect the fact that topographic torques play an important part in the balances of angular momentum and barotropic vorticity in the current. The flow is also suprcritical with respect to the propagation of baroclinic Rossby waves, leading to strong wave-mean flow interactions. Diagnostics of the vorticity balance will be shown which shed light on the various modes of variability which occur in the jets, including standing meanders reminiscent of stationary barotropic Rossby waves, and a residual which appears to reflect frequently large-scale interactions with topography.

B-4

Zonal Jets in Fine-resolution OGCMs

H Nakano
(Oceanographic Research Department, Meteorological Research Institute)

The zonal currents in the subsurface are classified into two parts, one is a series of broad zonal flows that has the meridional pattern slanting poleward with increasing depth, and the other is fine-scale zonal jets with the meridional scale of 3-5 degrees formed within each broad zonal flow.

The fine-scale zonal jets are visible both in one-year average and snapshot fields. These jets occupy the entire domain of the North Pacific model. However, their strength is not homogeneous: they are strong in the western subtropical and subpolar gyres, and weak in the northeast Pacific.

The basic pattern for the broad zonal flows is though to be the response to the wind forcing. A part of zonal jets embedded in each zonal flow is explained by the anomalous local wind forcing. Most of them however, seem to be mainly created by the rectification of turbulent processes on a beta-plane, the Rhines effect, and zonal jets in this study have common features with the zonally elongated flows obtained in previous modeling studies conducted in idealized basins.

B-5

On rectification of randomly forced flows

Pavel S. Berloff
(Woods Hole Oceanographic Institution and Cambridge University)

Nonlinear rectification of the ocean circulation driven by random forcing, which simulates the effect of unresolved eddies, is studied in an idealized closed basin. The results are based on the analysis of randomly forced solutions and linear eigenmodes. Depending on the forcing strength, two rectification regimes are found: zonal jets and isolated gyres. It is shown that both regimes are due to nonlinear interactions of resonant basin modes. In the zonal-jet regime, these interactions involve complex interplay between resonant baroclinic modes and some secondary modes. Both Rhines' scaling for zonal jets and prediction of gyres based on the maximum entropy argument are not confirmed.

B-6

Quantifying Eddy Transport and Mixing in Atmospheric and Oceanic Flows

E F Shuckburgh
(Department of Applied Mathematics and Theoretical Physics, University of Cambridge)

Jets in the atmosphere (e.g subtropical jet, polar night jet) and in the ocean (e.g. Antarctic circumpolar current, Gulf Stream), as well as in many simple chaotic advection flows, have a significant impact on the transport and mixing properties of these flows. A range of particle- and tracer-based diagnostics are used to better understand and characterize the eddy transport and mixing properties of the flows in the vicinity of the above-mentioned jets. Particular emphasis is given to exploring quantitatively how the transport and mixing properties of jets of differing strengths and with differing driving mechanisms vary. Some diverse implications of the results (such as for parameterizations in ocean models and for understanding the residual circulation) are noted.

C-1
The Annular Modes: A Primer

J M Wallace
(Department of Atmospheric Sciences, University of Washington)

The current status of our knowledge of the annular modes will be reviewed, with emphasis on their three-dimensional structure, temporal behavior, amplitude, seasonality, and relevance to weather and climate. The question of whether annular modes are real dynamical entities, as opposed to statistical artifacts will be discussed. Observational data for both the northern and southern hemisphere annular modes will be considered, as well as results from models. Dynamical processes that have a bearing on the structure and temporal behavior of the annular modes will also be discussed.

C-2

On the Zonal Structure of the Annular Modes

P J Kushner
(Department of Physics, University of Toronto)

We pursue the ongoing question of the zonal structure of the annular modes (AMs). Although the meridional structure of the AMs is robust, the zonal structure can be hemispheric or regional depending on the analysis technique used. What is the physically meaningful characteristic scale of the AMs? We find a partial answer in a systematic sector-EOF analysis that extracts robust circulation patterns that represent the AM regional signature. These patterns consist of zonally localized, eastward-propagating, structures with the dipolar meridional structure of the annular modes. To our surprise, these patterns have the form of propagating long baroclinic waves that transport heat polewards. The regional patterns exhibit long range correlations in longitude that may account for the annular modes' hemispheric scale.

C-3
Wave-Mean-Flow Interaction and the Annular Modes

D J Lorenz
(Center for Climate Research, University of Wisconsin-Madison)

The dynamics of zonal-mean jet variability are explored using a simple GCM. In this GCM, the leading EOF (the annular mode) represents the north/south movement of the mid-latitude jet. Analysis of the momentum budget demonstrates that EOF1 dominates over other EOFs because of a long-term positive feedback between the EOF1 zonal-mean wind anomalies and the eddy momentum fluxes. To first order, EOF2 represents a strong, sharp jet in one phase and a weak, broad jet in the other phase.

The response of the eddies to the zonal-mean flow is explored using a large ensemble of model runs initialized with a particular zonal-mean state and a large number of different eddy states taken directly from the control run. When initialized with zonal-mean annular mode anomalies, the ensemble mean response shows a transient period of negative eddy forcing (i.e. tending to damp the annular mode) followed, after several days, by a period of long-term reinforcement by the eddies. In contrast, the eddy response to zonal-mean EOF2 anomalies shows only the transient negative response. By increasing the width (meridional-scale) of the initial zonal-mean anomaly, one can reduce or eliminate the transient negative response. In addition, the wide initial anomalies are quickly narrowed by the eddies to scales more like the internal variability of the model.

A different set of ensemble runs were performed where the zonal-mean state is reinitialized at the end of every day during the integration. Thus the zonal-mean state is nearly fixed in time (the eddies are free to evolve just as before). The general behavior of the eddy response to the annular mode is exactly the same as before, but the eddy response to EOF2 is negative for both the transient and the long-term response. In addition, we look at the eddy response to a "barotropic version" of the annular mode anomalies and find that the eddies damp the "barotropic annular mode" for both short and long time scales. This last experiment suggests that changes in baroclinicity are important for the long-term positive eddy response to the annular mode.

The results suggest that baroclinic eddies concentrate the mid-latitude jet until the jet becomes a waveguide, which limits further concentration through a reduction in eddy propagation out of the jet.

C-4

Synoptic Eddy and Low-frequency Flow (SELF) Interaction and Annular Modes

F.-F. Jin
(Department of Meteorology, Florida State University)
L.-L. Pan
(Department of Meteorology, Florida State University)
M. Watanabe
(Graduate School of Environment Earth Science, Hokkaido University)

The two-way interaction between synoptic eddy and low-frequency flow (SELF), which we refer to as the SELF-feedback, plays an important role in the low-frequency variability of the atmospheric circulation. A new linear framework with a stochastic basic flow that captures both the climatological mean flow and climatological measures of the synoptic eddy flow is proposed for studying dynamics of the SELF-feedback and emergence of low-frequency modes from the stormy background flow. A set of linear dynamic equations is derived for the ensemble mean anomalies of the stochastic eddy forcing that is generated by anomalous time-mean flows. An analytical non-local dynamical closure for the SELF-feedback is obtained by assuming that the ensemble eddy-forcing anomalies approximately represent the time-mean anomalies of the synoptic eddy forcing and by using a quasi-equilibrium approximation. This linear closure directly relates time-mean anomalies of the synoptic eddy forcing to the anomalous time-mean flow. The linear framework with the SELF-feedback closure is used to demonstrate that, as the result of a positive SELF-feedback, the annular modes are the least-damped low-frequency modes. The scale-selective SELF-feedback favors annular modes because they organize the synoptic disturbances to facilitate an effective upscale energy cascade from synoptic eddies to the annular modes.

C-5

Annular Modes and Stratosphere-Troposphere Dynamical Coupling

Mark P. Baldwin
(Northwest Research Associates)

In this talk I will discuss annular modes from two perspectives. The first is that we observe that annular modes seem to provide an insightful way of connecting stratospheric variability to tropospheric variability. In the stratosphere, the Northern Annular Mode (NAM) characterizes the strength of the polar vortex, while at Earth's surface the NAM is the Arctic Oscillation pattern, similar to the North Atlantic Oscillation. In observations, the pattern at the surface that follows large disturbances to the strength of the stratospheric polar vortex looks almost identical to the NAM. The second perspective of the talk is that we do not understand why annular modes behave in this way. Unlike fundamental dynamical quantities, annular modes are just statistical patterns (EOFs) that represent the pattern that accounts for the greatest variance in the data. There is no theory (yet) that describes why the observed relationships should be seen.

C-6

Mechanisms for Variability of Annular Modes and Jets

Maarten H. P. Ambaum
(Department of Meteorology, University of Reading)

One of the sources for tropospheric variability associated with the North Atlantic Oscillation or Northern Annular Mode is the stratosphere. This is somewhat paradoxical given the relatively low mass and kinetic energy residing in the stratosphere. In this presentation I will examine this argument in more detail and demonstrate the role of planetary rotation in the connection between the stratosphere and the troposphere.

I will further present some statistical evidence which excludes a linear contribution from tropospheric eddies to variability of the North Atlantic Oscillation amplifying the importance of inherently slow dynamical factors, such as stratospheric variability.

C-7
Annular Structures Associated with Polar Vortex Breakdown

R X Black
(School of Earth and Atmospheric Sciences, Georgia Institute of Technology)
B A McDaniel
(School of Earth and Atmospheric Sciences, Georgia Institute of Technology)
W A Robinson
(Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign)

We examine how interannual variations in the timing of stratospheric final warming (SFW) events affect the stratosphere-troposphere system. Specifically, we isolate the coupled stratosphere-troposphere dynamical evolution observed to occur in association with SFW events in the Northern and Southern Hemispheres. In approaching this problem, we implicitly address the hypothesis that the tropospheric circulation is influenced by interannual variations in the breakup of the stratospheric polar vortex. SFW events are defined in terms of the final weakening of the zonal-mean zonal wind in the subpolar lower stratosphere. Circulation anomalies, taken as departures from long term seasonal trend values, are then composited with respect to SFW onset dates to identify anomaly structures linked to SFW events. The analyses are performed for SFW events in both the Northern and Southern Hemispheres.

SFW events are found to provide a strong organizing influence on the large-scale circulation of the stratosphere and troposphere, acting to accelerate seasonal transitions in comparison to climatological seasonal trends. Annular patterns of westerly (easterly) zonal wind anomalies extend from the high latitude stratosphere to the Earth's surface in the weeks prior to (after) SFWs, associated with accelerated breakdowns in the stratospheric and tropospheric westerly jets. The high latitude stratospheric decelerations are accompanied by opposing zonal wind accelerations in the subtropical stratosphere with downward extensions into the troposphere. The near surface manifestation of SFW events consists of anomalously low (high) sea level pressure over the poles in the weeks prior to (following) SFW events. The composite analyses indicate that SFW events are driven by planetary wave anomaly patterns observed in the extratropical lower troposphere a few days prior to SFW. Eliassen-Palm flux diagnoses confirm the presence of an anomalous upward flux of Rossby wave activity into the stratosphere during this time, which acts to decelerate the stratospheric polar vortex and precipitate the final warming. Our study indicates that polar vortex breakdown is distinguished by a large-scale dynamical coupling of the troposphere and stratosphere. Although this coupling is strongest in the Northern Hemisphere, parallel dynamical signatures are also observed in the Southern Hemisphere circulation.

C-8

Annular Variability in Simulated Contemporary and Warmer Climates, and its Impacts on the Ocean and Seasonal Rainfall Variability

I G Watterson
(CSIRO Marine and Atmospheric Research)

The CSIRO Mk2 GCM simulated a 'high latitude mode' of the southern hemisphere (SH) that impacted on the ocean temperatures and currents, through surface stress and heat flux. A weak feedback on the atmosphere was detected (see Watterson, 2000, 2001, and 2002). New Mk3 GCM 'IPCC' simulations allow these effects to be explored at higher resolution (on a 96 x 192 grid), and extended to the warmer climate modeled for the 22nd century. Focusing initially on monthly means of the zonal mean zonal wind, the structure and temporal behavior of the both first and second annular modes is quite realistic compared to those in ERA40 reanalyses. The second (low latitude) mode of the SH propagates quite rapidly poleward, in lag-regression analysis. These components of variability contrast with those associated with ENSO. In the coupled GCM, the ocean responds to the annular modes. However, comparison with AGCM simulations indicates only a limited feedback on the atmosphere. While the simulated mean climate change projects on the modes, the variability is largely maintained in the warmer climate. Annular variability has a substantial impact on zonal mean rainfall, while local impacts vary seasonally and geographically, particularly for Australia. The associated latent heating, as well as radiative fluxes, are modified by the modes, and have the potential to influence their evolution.

C-9

Tropically Forced Annular Structures

Huei-Ping Huang
(Lamont-Doherty Earth Observatory of Columbia University)

The global atmospheric response to the variability of tropical sea surface temperature (SST) contains a strongly zonally symmetric component that is insensitive to the detail of the SST anomalies. Until recently, this zonally symmetric or "annular" component has not received as much attention as the forced stationary Rossby waves in the context of tropical-extratropical interaction. This presentation surveys the known explanations for the generation and maintenance of the tropically-forced zonally symmetric climate variability and their implications for climate modelling and prediction. After a general review of the subject, a more detailed discussion will be devoted to a particular aspect, namely, why the zonally symmetric component of the tropical tropospheric response is consistently strong regardless of the shape, size, and amplitude of the localized tropical SST anomalies.

D-1
Jets and Annular Structures in Planetary Atmospheres

M Allison
(NASA/Goddard Institute for Space Studies)

The observed ensemble of planetary atmospheres in the Solar System provides a diverse showcase of geophysical jets and annular structures for a wide range of stratification, rotation, and forcing parameters. The latitudinal variation of cloud level motions on Jupiter and the other gas giants is generally well marked by discrete trackable features revealing remarkably steady, multiple current systems, crudely spaced as the Rhines scale, but with meridional curvatures exceeding by a factor of three or more the usual stability limit implied by standard QG theory. Jupiter is the only jovian atmosphere so far sounded by in situ spacecraft but there the measured weak vertical shear and small static stability within the upper troposphere imply a near-unitary Richardson number regime plausibly consistent with an efficient latitudinal mixing of potential vorticity. Venus and Titan both show strongly super-rotational, globally cyclostrophic circulations, as revealed by remote sensing and atmospheric entry probes (including new results from Huygens), while the more Earth-like planet Mars exhibits an IR-sounded thermal structure implying strong polar jets with a large seasonal modulation. There is as yet no coherent theory for the extraterrestrial weather regime, and the largely unknown lower boundary conditions for the jovian circulations and to some extent the uncertain micrometeorology and upper level wave drag on the others continues to limit their definitive simulation with GCMs. PV thinking may, however, provide one pathway toward a more comprehensive understanding, to be illustrated with a selected collection of idealized examples.

D-2
Zonal Flows in the Solar Interior

Mark Miesch
(HAO/NCAR)

The outer 30 percent of the solar interior by radius is convectively unstable. Global-scale convective motions continually redistribute angular momentum in this solar envelope, producing differential rotation which can be probed with surface measurements and helioseismic inversions. The solar rotation profile is remarkably steady but systematic variations of a few percent have been detected. Near the base of the convection zone there is a transition to nearly uniform rotation across a thin layer known as the solar tachocline. This layer is characterized by strong vertical and horizontal shear, a highly stable (subadiabatic) background stratification, and a strong rotational influence, making it similar in many respects to the Earth's stratosphere. However, magnetism profoundly influences the dynamics of the solar tachocline and sets it apart from many geophysical applications. For example, it can induce jet formation through the gyroscopic stablization of tipping instabilities in banded toroidal fields. After a brief review of observational evidence for zonal flows in the solar convection zone and tachocline, I'll discuss current theoretical and numerical modeling efforts on how such flows may be generated by convection and MHD shear instabilities.

D-3

Dynamics of Convectively Driven Banded Jets in the Laboratory

P L Read
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Y H Yamazaki
(Atmospheric, Oceanic & Planetary Physics, University of Oxford)
R Wordsworth
(Atmospheric, Oceanic & Planetary Physics, University of Oxford)
J Sommeria
(LEGI/CORIOLIS (INPG-UJF-CNRS))

The banded organization of clouds and zonal winds in the atmospheres of the outer planets has long fascinated atmosphere and ocean dynamicists and planetologists, especially with regard to the stability and persistence of these patterns. Several recent studies in the theory and idealized modelling of geostrophic turbulence have suggested some possible explanations for the emergence of such organized patterns. Such theories typically involve highly anisotropic exchanges of kinetic energy and vorticity within the dissipationless inertial ranges of turbulent flows dominated (at least at large scales) by ensembles of propagating Rossby waves.

In this work we present results from an attempt to reproduce such conditions in the laboratory. Achievement of a distinct inertial range, which is relatively free of viscous dissipation, turns out to require an experiment on the largest feasible scale. In our case, salt-driven rotating convection was induced by gently and continuously spraying dense, salty water onto the free surface of the 13m diameter cylindrical tank on the Coriolis Platform in Grenoble, France. A 'planetary vorticity gradient' or 'beta effect' was obtained by use of a conically-sloping bottom and the whole tank rotated at angular speeds up to ~0.15 rad/s. Over a period of several hours, a highly barotropic, zonally banded flow pattern was seen to emerge, indicating the development of an anisotropic field of geostrophic turbulence. In this talk we will review the analysis of this flow from measurements of velocity fields using PIV techniques, in order to elucidate the nature of dynamical interactions between Rossby waves, turbulent eddies and zonal jets. The implications of these results will also be discussed in light of zonal jets observed in planetary atmospheres and, most recently, in the terrestrial oceans.

D-4
Anisotropic Large-Scale Turbulence and Zonal Jets in Flows With Beta-Effect

B Galperin
(College of Marine Science, University of South Florida)
S. Sukoriansky
(Department of Mechanical Engineering, Ben-Gurion University of the Negev)
N. Dikovskaya
(Department of Mechanical Engineering, Ben-Gurion University of the Negev)

Barotropic two-dimensional turbulence with Rossby waves is distinguished by strong anisotropy and energetic zonal jets in alternating directions. Flows on the beta-plane and in thin shells on the surface of a rotating sphere develop strongly anisotropic spectrum with steep, n^(-5), slope for the zonal flows and Kolmogorov-Kraichnan, n^(-5/3), slope for the residuals. The n^(-5) zonal spectrum was found on the outer planets of our solar system, both with regard to its slope and the amplitude. This spectrum can be used to analyze some basic characteristics of large-scale circulations on giant planets and for interplanetary comparisons. Recently, it was found that the mid-depth ocean currents in the North Pacific ocean also develop a system of alternating zonal jets and build up the same n^(-5) and n^(-5/3) zonal and residual spectral distributions. Similar subsurface jets were found in other terrestrial oceans using other eddy-permitting models. The alternating zonal flow signature has also been found in currents maps deduced from satellite altimetry data. The main characteristic of the planetary and oceanic flows under consideration is the smallness of their Burger number, Bu = (Ld/R)^2, where Ld is the first baroclinic Rossby radius of deformation and R is the planetary radius. Exploring the planetary-ocean analogy, it is concluded that the fine-scale oceanic zonal jets are driven by strongly nonlinear, anisotropic dynamics of quasi-2D turbulence with Rossby waves and argued that the latitudinal scaling of these jets is determined by the large-scale friction processes. Using computer simulations of barotropic turbulence on the surface of a rotating sphere, parameter range has been identified where the flow regime with the anisotropic (-5/3, -5) spectra can be expected to develop. Also, it is shown that the emerging quasi-steady-state flows are stochastic albeit slowly changing and that their equatorial jets may be either westward or eastward. Recent experiments in the largest in the world rotating platform in Grenoble, France, have confirmed many of the above results. The general conclusion is that all presented types of flow are governed by the same strongly nonlinear dynamics that features anisotropic inverse energy cascade and Rossby waves.

E-1
Orographic forcing of jets: simple experiments

P B Rhines
(School of Oceanography and Dept. of Atmospheric Sciences, University of Washington)

Earth's topography interacts with fluid circulations in many ways. Coriolis effects promote 'tall structures' in the fluid through the stiffening effect of planetary vorticity, enhancing the effects of mountains in both oceans and atmosphere. With separated wakes and lee-waves that may be ageostrophic, topography presents a severe modeling challenge. Here we describe (a) upstream blocking and downstream wakes with mountains on a polar beta plane, which involve low-intrinsic-frequency Rossby waves upwind, with topographic waves locally organizing the wake, and (b) some aspects of topographic form drag that arise in the case of Greenland, an ice-mountain greater than 3 km tall, which extends more than ¼ of the distance from Pole to Equator. Jet-like structures form in company with blocking in (a), both upstream and downstream of topography. In (b) the topography interacts with the entire polar vortex and jet stream, enhancing its asymmetries. Potential vorticity transport and accompanying meridional circulation accompany this orographic flow. Laboratory experiments viewed with the new technique of optical altimetry will be used as illustration.

E-2

Rossby Waves and Acceleration-deceleration of Jets on a Sphere or in a Spherical Shell

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M Yamada
(Research Institute for Mathematical Sciences, Kyoto University)
S Takehiro
(Research Institute for Mathematical Sciences, Kyoto University)
S Yoden
(Graduate School of Science, Kyoto University)
K Ishioka
(Graduate School of Science, Kyoto University)

Redistribution of angular momentum on a rotating sphere or in a rotating convective spherical shell is reviewed from the view point of Rossby waves. Numerical experiments presented so far demonstrate that, when the rotation rate of the system is large, easterly (retrograde) circumpolar jets emerge for a decaying turbulence of a two-dimensional non-divergent flow on a sphere. When the system allows surface elevation, that is, for a decaying turbulence of a shallow water system on a sphere, not a circumpolar but an equatorial easterly jet with a latitudinal scale of the equatorial deformation radius emerges. For a three-dimensional flow in a rotating spherical shell convectively driven by given temperature at the inner and the outer boundaries, an equatorial westerly (prograde) jet appears. These rather robust features can be naively explained in the same framework of the angular momentum transport associated with Rossby wave propagation on top of the local mixing of potential vorticity. However, even for the decaying turbulence of two-dimensional non-divergent flow, we still do not seem to understand clearly the detailed evolution of the spectral powers, energy transfer toward large eddies or Rossby waves, and their relationships to the formation of zonal jets. Some of those issues are summarized and tried to be examined.

E-3

Asymmetrization of Jet Profiles in Beta-plane Turbulence

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J Hasegawa
(Japan Meteorological Agency)
S Yoden
(Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University)

Spontaneous zonal jet formation is an well-known significant feature in two-dimensional beta-plane turbulence (Rhines, 1975; Vallis and Maltrud, 1993). The formation itself is considered due to energy upward cascade which is in favor of zonal components by the existence of beta term. Why the formed zonal jets are maintained in the turbulence, however, has been an open question. Therefore, we study the maintenance mechanism of the zonal jets in in two-dimensional beta-plane turbulence numerically, conducting a number of ensemble experiments. We find asymmetry of jet profiles between eastward and westward jets with sufficient statistical validity. That is, westward jets are narrower and more intense than eastward jets. Theoretical explanation of the asymmetrization is developed using WKB wave propagation theory and wave mean-flow interaction theory. The theoretical explanation also makes clear the maintenance mechanism of the zonal jets.

E-4

A Mechanism for the Formation of Jets and Vortices from Small-Scale Fluctuations

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Numerical simulations on a beta-plane are used to isolate the mechanism for the formation of zonal flows from small-scale fluctuations. The dynamics of `reduced models' are computed by restricting the nonlinear term to include a subset of triad interactions in Fourier space. Reduced models of near-resonant triads are considered, as well as the complement set of non-resonant triads. At moderate values of the Rhines number (approximately 0.5) measuring the ratio of linear to nonlinear time scales, near resonances are shown to be responsible for the generation of large-scale, zonal flows from small-scale, random forcing. Asymmetry between eastward and westward jets is also discussed. In simulations of 3D rotating flows at moderate Rossby number, near resonances lead to the formation of large-scale, cyclonic vortical columns. Thus near resonances appear be a generic mechanism for the self-organization of large-scale, coherent structures in rotating flows.

P1-1
The QBO Influence on the Extratropical Circulation in MAECHAM5 GCM

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The QBO signature in extratropics has been analyzed using the MAECHAM5 GCM. Composites have been computed for the west and east QBO phase during the winter months of the period 1979-1999.

Results show that the north polar stratosphere is characterized by a significant weaker polar vortex and a warmer polar stratosphere during the east QBO phase. These anomalies are more pronounced in late winter (January-February) than in early winter (November-December). During the west QBO phase, anomalies in MAECHAM5 show the opposite sign but are not significant. The analysis of the EP flux and its divergence shows a different behavior depending on the QBO phase, with changes in the effective wave guide. During the east QBO phase, wave propagation occurs at high latitudes (around 60-70ºN) and reaches heights up to 50km. Waves deposit easterly momentum decelerating the polar vortex and making the polar temperature higher. During the west QBO phase, waves are refracted equatorward and dissipated in the subtropical region at lower levels than in the east QBO phase (below 40 km) which make the polar vortex stronger, in good agreement with QBO theory.

Therefore, MAECHAM5 results corroborate the assumption that a great part of the extratropical QBO signature occurs through the modulation of the Rossby wave propagation related to changes in the zonal-mean winds in tropics and show that the model is able to represent accurately the wave-mean flow interaction necessary to simulate a realistic QBO in extratropics.

P1-2

A new approach to study the intensity of the polar night jets and the stratospheric polar vortices

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The narrow stream of strong winds blowing from west to east during winter surrounding the polar stratospheric regions of both hemispheres is usually called polar night jet. This jet stream develops along the temperature gradient along the line between sunlight and the 6-month long, wintertime polar night. Regions insides these jets (poleward) are called stratospheric polar vortices. Very cold temperatures are contained inside the polar vortex region. The polar night jet is important for many reasons, it acts as a barrier in the mass-exchange between polar regions and midlatitudes, what is important for instance to explain the distribution of ozone. The polar night jet over the Arctic is not as effective as over the Antarctic in keeping out intrusions of warmer midlatitudes air, because there is more wave activity and hence more north-south mixing of air in the northern hemisphere than in the southern hemisphere. It is also important by the strong evidence that the state of (mainly) the northern hemisphere vortex in boreal winter influences tropospheric variability. The stratospheric polar vortex can be disturbed by tropospheric planetary waves entering the stratosphere, whose effect can be the formation of "regimes" of the stratospheric circulation (characterized by either a strong or a weak polar vortex) (Christiansen, 2003; Perlwitz and Graf, 2001). According to the polarity of the stratospheric circulation regime, NAO index can be of different sign, (Baldwin and Dunkerton; 2001). So, for strong polar vortex, the NAO index tends to be positive. This implies that the intensity of the polar vortex in winter might he a harbinger for tropospheric climate related to the NAO.

The polar night jets and the vortices have been studied by analyzing the zonal winds at different levels and altitudes, so jets can be estimated as zonal means of zonal wind close to 50 mb and 70º latitude (Walter and Graf, 2005). Other approaches are based on the area enclosed within a given potential vorticity contour, for instance the use of elliptical diagnosis of isopleths of potential vorticity (e.g. Waugh and Randel, 1999). In this study we use a different approach based on defining the jet stream as the geostrophic streamline of maximum average velocity. It was used for detecting and tracking the tropospheric jets in the Southern Hemisphere (Gallego et al, 2005). The jet detection procedure is designed to identify geostrophic streamlines of maximum velocity around an hemisphere. Starting from an arbitrarily chosen meridian (in this case 0), a number of 50-hPa geostrophic streamlines are computed. The algorithm computes the average latitude and geostrophic wind along every streamline fulfilling several restrictions. An analysis was done to study several relevant characteristics of polar night jets and vortices, such as the climatological location and persistence of polar vortices, the temporal evolution of the area occupied by them or the interannual variability in their decay. For instance, the algorithm was very efficient to calculate the spring and fall onset for both hemispheres with concordant results to Black et al (2005) and it was able to detect jet bifurcations such as the occurred when 2002 September Southern Hemisphere sudden stratospheric warming.

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P1-3

Quasi-periodic poleward propagation of zonal mean anomalies

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Observational studies have shown that tropospheric zonal mean flow anomalies frequently undergo quasi-periodic poleward propagation. A set of idealized numerical model runs is examined to investigate the physical mechanism behind this poleward propagation. This study finds that the poleward propagation is caused by an orchestrated combination of linear Rossby wave propagation, nonlinear wave breaking at critical latitudes, and radiative relaxation. The importance of the meridional wave propagation and breaking is consistent with the fact that the poleward propagation occurs only in the parameter space where the potential vorticity gradient is of moderate strength.

P1-4
Rossby wave dynamics - case studies and climatology

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Rossby Waves (RWs) residing at tropopause-levels are a key meteorological feature closely associated with both surface baroclinic development and quasi-horizontal atmospheric energy transport. From the PV perspective, these waves exist and travel on the band of maximum PV gradient at the tropopause break, sic. the jet stream, and their propagation characteristics are in line with properties inferred from linear theory.

We present results from a climatology of RWs derived from the ERA40 data set on a 6-hourly basis. Their propagation is depicted in a novel form of Hovmoller diagram that accounts for the instantaneous shape of the PV waveguide. This eliminates the effect of meridional averaging and non-zonal wave propagation and precludes attenuation of the amplitude by spurious cancelling of wave peaks, inaccurately determined wave numbers and hence propagation velocities.

Rossby Waves (RWs) can link high-impact weather events around the hemisphere, that occur most severely at the location of the wave breaking. The RW climatology provides information on the phase and group velocities and their spatial and temporal distribution. It can be used for instance to enhance our dynamical understanding of the origin and development of heavy precipitation events and provides a means to investigate the dynamics of RWs that propagate in complex multiple-jet environments.

P1-5
Zonal Equatorial Deep Jets formation mechanism

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Currently proposed formation mechanisms for mid-latitude zonal jets are based on an anisotropic, nonlocal energy transfer between small-scale shear-straining and the large-scale zonal jets. Using similar concepts for the equatorial case, a new mechanism of zonal equatorial deep jets formation is proposed based on the destabilization of short Mixed Rossby Gravity waves. This rationale can provide an explanation for the factor of 2 in vertical scales that is observed between the Pacific and Atlantic deep equatorial jets. Results of numerical simulations performed on the Earth Simulator are presented enabling to validate the analytical theory.

P1-6

Zonal Jet and Recirculation Gyres From the Rectification of Localised Oscillatory Forcing: A Laboratory, Numerical and Theoretical Study

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The generation of a time-mean zonal jet and a pair of recirculation gyres from the rectification of a vorticity forcing that is localised in space and oscillatory in time is re-examined via laboratory experiments, numerical simulations and analytical analysis. Lab experiments verified that a small patch of oscillatory Ekman pumping, noted to produce a time-mean jet in numerical simulations, also produces this rectified flow in a real fluid, and also demonstrated that the jet strength and pattern are sensitive to various parameters of the forcing, such as amplitude, frequency and length scale. Numerical simulations gave insight into the rectification mechanism, namely the up-gradient turbulent transport of relative vorticity in the forcing region, and provided a means by which to relate forcing parameters to properties of the mean-flow generated. Finally analytical analysis of the problem gave further understanding, emphasising the localised nature of the rectification mechanism.

The problem is idealised but has general application in the understanding of eddy-eddy and eddy-mean flow interaction as the contrasting limit to that of spatially broad (basin-wide) forcing, and is relevant given many sources of oceanic eddies are localised in space. Experiments in the laboratory and with the simulations suggest that essential characteristics of the mean flow generated are unchanged through the transition from a weakly nonlinear to strongly nonlinear regime, and that understanding of the rectification mechanism gained in the weakly nonlinear wave limit remains valid in the fully turbulent (and more oceanically relevant) system. The problem's potential importance in the dynamics that drive the deep recirculation gyres associated with western boundary current jet extensions is currently under investigation.

P1-9

Nonlinear Relation of the Arctic Oscillation (AO) With the Quasi-Biennial Oscillation (QBO)

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A Nonlinear Principal Component Analysis (NLPCA) is applied to the monthly-mean Arctic Oscillation (AO) index, computed using the 1000-hPa geopotential height anomalies pole-ward of 20N, and the monthly-mean zonal winds, observed at seven pressure levels from 10 to 70 hPa near the equator, to investigate the nonlinear relation of the AO with the QBO. The NLPCA is conducted using a two-hidden-layer, feed-forward neural network model that has no encoding layer and no bias term for bottleneck and output neurons. This type of simplified neural network model alleviates the problems of data over-fitting and non-unique model solutions plaguing nonlinear techniques of principal component analysis.

The NLPCA solution of the dataset composed of the AO index and the QBO winds clearly shows that the phase of co-variation of the AO and the QBO has a predominant 28.4-month cycle and that this cycle is modulated by cycles with periods of 11 years and 22.5 years. Large positive (negative) values of the AO index occur when westerly (easterly) winds prevail in the equatorial stratosphere during November-April (and particularly January-March). Otherwise, the AO is rather quiet. Implications for the dynamical coupling of the troposphere and stratosphere will be described.

P1-10

Leading modes of variability of the extratropical circulation linked to the breakup of the stratospheric polar vortex

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The fact that extreme stratospheric events are followed by tropospheric anomalies up to 60 days suggests that the study of stratospheric variability could be the central point to extend weather prediction in extratropics. Among the extreme stratospheric events the breakup of the wintertime stratospheric polar vortex in the winter to summer transition has gained recently a considerable interest. Black et al (2005) showed that the regional tropospheric manifestation of these breakups consists on an NAO-like phase transition in the near-surface geopotential height field, with height rises over polar latitudes and height falls over the northeast North Atlantic and eastern North Pacific.

In this work we examined the leading modes of variability of the extratropical circulation linked to the breakup of the stratospheric polar vortex using the same data of breakups as Black et al. (2005) and EOFs analysis previous and after these dates. To do this, we have used the 15 days pre- and post-breakups for every year and for 1000, 500, 50 and 10 hPa. The greatest differences are found in 50 hPa, being the structure in 1000 hPa for both periods very similar to the typical NAO pattern. Furthermore we also use eddy heat fluxes at 100 hPa as Polvani et al (2004) to know if the signal has a previous tropospheric origin. Although there is a certain interannual variability, composites of eddy heat fluxes at 100 hPa before and after the breakup show that anomalously strong eddy heat fluxes most often precede the breakup of the vortex (about 3 days), but anomalously weak eddy heat fluxes precede the breakup a little earlier (about 10 days).

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P1-11

The Response of the Northern and Southern Hemisphere Annular Modes to Anthropogenic Forcings

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Observations show an increase of the westerlies at tropospheric mid-latitudes which is consistent with a positive trend in the index of the tropospheric Annular Modes. Past studies suggested that stratospheric dynamics plays an important role in understanding the observed changes of Annular Modes if caused by increased anthropogenic forcing. It has been suggested that the Northern Hemisphere Annular Mode can be attributed to the increase of greenhouse gases while the increase of the Southern Hemisphere Annular mode is mainly caused by ozone depletion. We use experiments with the GFDL model in order to investigate the nature of these dynamical changes in more detail. Two sets of ensemble simulations are carried out, one with observed changes in atmospheric composition, and a second one with increase in SST at the Indian Ocean. Recent studies have shown that the warming of the Indian Ocean is a clear greenhouse gas signal. We will compare changes in tropospheric and stratospheric circulation between these experiments, and between experiments and observations. The results will allow us to distinguish between effects due to ozone depletion and increase in greenhouse gases, and to understand better the role of stratospheric circulation changes in observed tropospheric trends.

P1-12
Impact of Long-Range Correlations on Trend Detection in the Total Ozone

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For the purpose of trend analysis memory is an issue. For time series with strong serial correlations it is difficult to distinguish a trend from natural variability. All previous studies of trends in total ozone used either an ordinary least squares trend estimate assuming that residuals are a white noise or a generalized least squares estimate with autoregressive model of the first order for the residuals. Based on the calculated in this way variance of the trend one can derive the number of years required to detect an expected positive trend in total ozone at a certain level of statistical significance. In our study we revise these results starting with the assumption that residuals of the total ozone time series are long-range correlated, i.e. their autocorrelation function decays by the power law.

P1-13
Baroclinic Instability as a Source for Jupiter's Zonal Jets

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Jupiter's atmosphere is dominated by strong zonal jets. We propose that baroclinic instability plays an important role in the generation and stability of these jets. We model the atmosphere as a two layer structure, where the upper one is a standard quasi-geostrophic layer on a beta plane, and the lower layer is parameterized to represent a deep interior convective columnar structure. Linear stability theory predicts that the high wave number perturbations will be the dominant unstable modes for a weak vertical wind shear like that inferred from observations. We develop an analytical nonlinear model truncated to one growing mode which generates a multiple meridional jet structure, driven by the nonlinear interaction between the eddies. In the weakly supercritical limit this model agrees with previous nonlinear theory, but it can be explored beyond this limit allowing the multiple jet zonal flow to be stronger than the eddy field. Then we use a fully nonlinear pseudo-spectral model which reproduces a stable meridional multi-jet structure when beginning from a random potential vorticity perturbation field. The instability removes energy from the mean state weak baroclinic shear and generates turbulent eddies that undergo an inverse energy cascade and form stable multi-jet zonal winds. We show that the basic physical mechanism for the generation of the jets in the full numerical model is similar to that of the truncated model.

P1-14

Beta-plane Turbulence in a Basin with No-slip Boundaries

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On a domain enclosed by no-slip boundaries, two-dimensional, geostrophic flows have been studied by numerical simulations of the Navier-Stokes equation with the beta-plane approximation at intermediate Reynolds numbers and a range of values for beta. While most of the results are in agreement with other studies which use different boundary conditions, some aspects show a different and unexpected behavior.

In a bounded domain without the beta-plane the flow is characterized by the formation of a single domain-sized coherent vortex due to the inverse energy cascade. From the simulations with the presence of the beta-effect it can be observed that the inverse cascade is clearly impeded by the presence of a beta-plane. This leads to a refinement of the flow structures, which scales are in agreement with the Rhines scale. Frequency spectra of the flow profoundly exhibit the existence of basin modes, which excitation is favoured above the formation of vortices. The presence and apparent stability of basin modes on a domain with no-slip boundaries is a rather surprising observation, because these modes are solutions of the inviscid equations.

The time-mean flow in forced simulations shows a zonal band structure which resembles the flow on a periodic domain (although the kinetic energy of the mean flow represents only 2-4% of the kinetic energy of the turbulent flow field itself). This a rather surprising result as numerous other simulations show a mean flow consisting of a dual gyre on a closed domain. The difference can be subscribed solely to the applied no-slip boundary conditions.

P1-15

Spontaneous zonal current in two dimensional turbulence on a rotating hemisphere

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Flow pattern of 2D decaying non-divergent turbulence is studied numerically on a rotating hemisphere with the rigid/stress-free boundary at the equator. A stereographic projection of the hemisphere to a plane disk, followed by Fourier-Chebyshev expansion method, is employed for the numerical calculation. It is observed that an eastward flow is formed in the rigid-boundary case, while a westward flow in the stress-free-boundary case, from randomized initial conditions.

P2-1
Energy Cycle Associated with the Polar Night Jet

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The dynamical linkages between the annular variability in the troposphere and stratosphere are very strong, and changes above or below the tropopause influence the behavior of the annular modes at all levels. The diagnosis of wave propagation influencing this interaction are usually studied by means of Eliassen-Palm flux, since it approximate the direction of the total wave activity flux. However, some questions arise about this method: 1- Are the differences between strong and weak stratospheric vortices due to wave generation, wave refraction/reflection or to both factors?. 2- The E-P flux is generally calculated using eddy deviation from the seasonal cycle mean. This procedure neglects the contribution of the climatological waves for the E-P composites. Are those contributions unimportant?

It may be shown that the squared expansion coefficients of the normal modes of the linearized primitive equations are proportional to the total (i.e. Kinetic + Available Potential) energy per unit area associated with the respective mode. The energy of wave number 1 and 2 for the first three vertical modes was correlated with Northern Annular Mode (NAM) index at 7 levels in the stratosphere. An increase (decrease) in the total energy of wave number 1 tends to be followed by negative (positive) NAM anomalies with a downward propagation. A strong (weak) vortex is followed by an increase (decrease) of the total energy associated with these waves. These correlations are in part expected from the quasi-periodicity of Polar Night Jet Oscillation. However, the correlations for negative lags (NAM leads) seem too high compared with those for positive lags (energy leads). We hypothesize that the downward effect of vortex anomalies on the tropospheric circulation results in variations of wave generation. Also the lags found for wave number 2 agrees with the hypothesis of an increase of tropospheric wave generation: the time of energy increase is closer to the instant the vortex reaches the lower stratosphere.

P2-3

A Numerical Analysis of the First-Order Closure for Synoptic Eddy and Low Frequency Flow (SELF)-Feedback

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The two-way interaction between synoptic eddy and low-frequency flow (SELF), has been recognized to be important for the low-frequency variability of the atmosphere circulation. By considering a stochastic basic flow that captures the observed synoptic eddy statistics, we obtained both first and higher order approximations for a linear closure for the SELF feedback. The validity of the first order approximation depends on the intensity of the eddy variance. The first order approximation breaks down only when the level of eddy variance is unrealistically large. Under observed level of the synoptic eddy variance, we demonstrated that the first-order approximation is largely as good as high order approximations. Direct numerical ensemble simulations of the linearized model with stochastic basic state also confirm the validity of the first order approximation. Moreover, forced solutions under idealized external forcing are analyzed to delineate the importance of the SELF feedback in generating the patterns of low-frequency modes.

P2-4

A Consistent Poleward Shift of the Storm Tracks in Simulations of 21st Century Climate

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A consistent poleward and upward shift and intensification of the storm tracks is found in an ensemble of 21st century climate simulations performed by 15 coupled climate models. The changes in the storm track are accompanied by a poleward shift and upward expansion of the midlatitude baroclinic regions associated with enhanced warming in the tropical and subtropical upper troposphere and increased tropopause height. These changes are also accompanied by poleward shifts of the eddy-driven jets and surface wind stress, and a shift towards the high index state of the annular modes. Hypotheses for the poleward shift of the storm tracks and associated dynamical changes are presented and explored.

P2-5

Storm Tracks and Eddy-Jet Interaction: a Comparison Between Atmosphere and Ocean

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Energetic eddies on the scale of the internal Rossby deformation radius are prevalant in both the atmosphere and ocean, mainly formed through baroclinic instability. In the atmosphere the largest time-mean eddy variability is confined to zonally-extended mid-latitude regions called 'storm tracks'. The persistence of the storm tracks is thought to be related to localised regions of baroclinicity, orographic forcing and the structure of the mean standing Rossby wave pattern.

We analyse observational data to examine whether time-mean ocean eddy variability is similarly confined to storm tracks and to study their dynamical nature.

We compare atmospheric and oceanic storm tracks for the same period, 1992-2002, using ERA-40, altimetric and surface drifter datasets. The surface drifters provide information about the mean jets and we study the relationship between eddies and jets in both systems, examining the eddy vorticity feedbacks within the vorticity budget.

We recover the usual observation that atmospheric storm track eddies act to accelerate the mean flow along the core of the storm track, but bring new emphasis to the comparative role of forcing by planetary vorticity advection. The primary atmospheric balance is for the mean advection of absolute vorticity to be zero, with the eddy forcing playing a relatively minor but significant role. The eddy vorticity forcing acts to shift the jet poleward, as the storm track is poleward of the jet core.

Oceanic storm track eddies act in a variety of ways. Unlike atmospheric eddies, their maximum variability tends to coincide with the jet core and they may act to accelerate, decelerate or steer the jet. The storm track eddy vorticity forcing is of a comparable magnitude to the mean advection of planetary and relative vorticity, although it is finer scale in places.

We discuss the range of eddy-jet regimes present in oceanic storm tracks and relate them to baroclinicity, topographic forcing and the structure of the mean standing Rossby wave pattern.

P2-6

The role of the Southern Mode in the barotropic adjustment of the Southern Ocean.

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Recent investigations have shown that the so-called Southern Modeplays an important role in the barotropic adjustment of the Southern Ocean. This study addresses this adjustment in more detail. Results will be presented of experiments with a constant-density, multilayer model, which is forced by a stochastic wind stress. It will be shown that the area around Antarctica where contours of f/H are continuous (the free-mode region as defined by Hughes et al., JPO 1999) is relatively unimportant, and that the dominant response is in the `almost-free-mode' region. Topographic form stress, rather than friction, can be identified as the dominant damping mechanism.

P2-7

The role of the stratosphere in extended range forecasts of the near surface weather

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We investigate the potential for using the downward propagation of anomalies from the stratosphere to the troposphere in extended range forecasts. Considering the near surface zonal mean zonal wind at 60 N and the near surface temperature in northern Europe as predictands we find that the inclusion of stratospheric information increases the skill of simple statistical forecasts on lead times larger than 5 days. We show that the simple linear statistical forecast based on stratospheric winds compares favorably to a state-of-the-art dynamical ensemble prediction system. To further improve the forecasts it is necessary to investigate when the downward propagation reach the surface and when it stops in the tropopause region. To this end other tropospheric and stratospheric predictors, such as the phase of the QBO and the ENSO or the wave forcing at the tropopause, will be included. We also investigate if non-linear schemes based on neural nets and local methods improve the forecasts.

P2-8

The Persistence of the Annular Modes and NAO - Interactions Between Synoptic Eddies and Low Frequency Variability Patterns in a Simplified GCM

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The behavior of the annular modes and localized patterns of variability resembling the observed NAO are investigated in a dry primitive equation model, the GFDL dry dynamical core. Particular emphasis is focused on developing a better understanding of the processes that sustain these patterns at low frequencies. Their persistence is in part due to a positive feedback between the patterns and high frequency eddies. Wave activity is produced by baroclinic instability at the latitude of the strongest winds, which are colocated with the strongest temperature gradients by thermal wind balance. Waves propagate out of the jet at upper levels and damp on the flanks, leading to a convergence of momentum that reinforces the position of the jet. This potential positive feedback, however, is opposed by the tendency of the eddies to break down the temperature gradients that maintain the jet. The balance between to the two effects and the large scale forcing is probed by varying the equator-to-pole temperature gradient of the model. When the gradient is increased, the annular modes become less persistent, suggesting limitations in the ability of the momentum fluxes to sustain the jet away from the equilibrium position. Diabatic heating anomalies, which approximate the effect of land-sea contrast, and simplified topography are then introduced to break the zonal symmetry of the forcing, generating zonally localized storm tracks and NAO-like patterns of low frequency variability. The zonal anomalies interfere with the positive eddy feedback, limiting the persistence despite changes to the temperature gradient. Topography, in particular, prevents the downstream propagation of eddy energy around the latitude circle, which appears to be important in maintaining the positive feedback in the model.

P2-9

On the Relationship Between Polar Stratospheric Zonal Flow and Surface Cyclonic Activity

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We examine the nature of the correlation between the lower and middle stratospheric NAM index and SAT gradients. Statistical analyses demonstrate that SAT gradients in the tropics are highly correlated with strain in the middle (10 mb) and, to a lesser extent lower (50 mb) polar stratosphere, while SAT gradients in high-latitude regions are highly correlated with polar middle and lower-stratospheric zonal winds. Also of interest are time lags between stratospheric and surface processes: investigation of stratospheric and surface wavenumber correspondence suggests that a two-way exchange mechanism exists between high-latitude surface and stratospheric polar processes, in contrast to a unidirectional exchange mechanism between low-latitude surface and polar stratospheric processes.

P2-10

The Summer Northern Annular Mode and Abnormal Summer Weather in 2003

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The summer Northern Hemisphere annular mode (summer NAM), a new mode determined through empirical orthogonal function (EOF) analysis for each individual calendar month, can describe aspects of anomalous summers such as the summer of 2003, which featured warm temperatures in Europe, Canada and Russia and cold temperature in Japan. Atmospheric circulation anomalies of the summer NAM closely resemble the anomalies in the summer of 2003 and the summer NAM index was quite large during the period from mid-July to early August when abnormal weather took place in Europe, Canada and Russia. The index includes representations of hemispheric double-jet streams and blockings that support extended periods of abnormal weather. The double-jet is formed and maintained by wave forcing during the period. In contrast to the Arctic and North Atlantic oscillations, the summer NAM pattern accounts for many of the anomalous weather features observed during summer of 2003.

P2-11
Forced Annular Mode Patterns in a Simple Atmospheric General Circulation Model

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The dynamics of the annular modes produced by a simple atmospheric general circulation model are examined. A robust annular mode, similar to that observed in the real atmosphere, is the dominant pattern of variability in the model (Kushner and Polvani, 2004).

The behavior of the model in response to an artificial forcing is tested to determine whether the annular mode is "mode-like", in that it appears in response to a variety of perturbations. Momentum forcing with a structure different than that of the annular modes produces an annular mode-like response in the zonal wind so long as the forcing projects upon the annular mode itself.

Zonally symmetric runs of the model are conducted to determine the role of eddies in maintaining the annular modes. An eddy feedback is present as the inserted forcing alone does not reproduce the annular mode patterns; instead the changes in eddy forcing between unforced and forced runs must be included to produce the correct wind anomalies. Both eddy momentum and heat anomalies must be included in order to produce the wind changes generated by the full model runs; including solely the quasi-geostrophic terms is also insufficient.

As a further test of the robustness of the annular mode, model runs with barotropic momentum forcing, and runs which force the model through temperature instead of momentum, are also considered.

P2-12
Empirical Study of Atmospheric Responses to the Tropical SST Forcing

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Recently GCM studies have indicated that there exist additional atmosp heric response patterns to tropical SST forcings beyond the linear ENSO signal and that the Arctic Oscillation (AO) is one of extratropical atmospheric signals. The main purpose of this study is to investigate the additional atmosphere patterns separate from ENSO due to tropical SST forcing that can be found in the observed Northern Hemisphere (NH) wintertime variability. Singular value decomposition (SVD) analysis between SST and the NCEP-NCAR reanalyzed 500-mb height (Z500) at both interannual and interdecadal time scales is used to identify these patterns.

At interannual time scales, the leading SVD mode of Z500 pattern exhibits a clear ENSO signature and the corresponding SST pattern resembles the ENSO signature. The 2nd SVD mode of Z500 pattern is virtually identical to the AO pattern and the SST pattern reveals the northern tropical Atlantic mode in the Atlantic. The expansion coefficients are highly correlated with AO indices. The 3rd SVD pattern for Z500 is moderately successful at specifying the Pacific North America (PNA)-like pattern. An alternative SVD analysis between Z500 and the outgoing longwave radiation indicate that the above SVD modes of SSTs are significantly correlated with the direct thermal forcing in the Tropics.

At decadal timescales, the leading SVD mode is indicative of strong linear coupling between the NH 500-mb height and the Pacific ENSO-like SST field. The SST pattern in the Pacific is seen as Pacific Decadal Oscillation mode and the 500-mb pattern appears most similar to the PNA pattern. The 2nd leading SVD SST pattern has its significant negative loadings in the Pacific south of the equator and in the eastern Atlantic Ocean. The 500-mb height pattern appears most similar to the AO.

Also, we explore the roles of these atmosphere response patterns on connecting the tropical and extratropical SSTs. The composite anomalies indicate that fluctuations in the midlatitude SST are caused by variability in the overlying atmosphere, which in turn originates from oceanic forcing in the Tropics. Both AO and PNA-like atmosphere response patterns function as a link or "bridge" whereby tropical non-ENSO SST anomalies induce the dominant pattern of SST anomalies in the extratropical North Pacific and Atlantic.

P2-13
Multiple Jets, Separation Scales, and Weather-Layers in an Idealized GCM

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We consider the organization of jets and baroclinic zones in an idealized general circulation model. We use a multi-level primitive equation model with zonally symmetric statistics and a simple radiation scheme. For each simulation the planetary radius or rotation rate is chosen to be large so that there are several jets in each hemisphere. The scale of the meridional inter-jet spacing is found to be similar to the energy- containing scale and the scale of the most unstable wave, but it may be larger than the Rhines scale.

We also describe a series of simulations where there is Newtonian relaxation to a radiative-convective equilibrium with no meridional temperature gradient in a layer of substantial mass above the lower boundary. Baroclinic eddies are then confined to an upper weather-layer, and so unlike in the terrestrial troposphere do not cause isentropes to intersect the lower boundary. We study the resulting effects on the large scale turbulence.

Both the multiple-jet and weather-layer simulations may be relevant to circulations on gas planets.

P2-14
Jets and geostrophic turbulence: Spherical geometry vs the beta-plane

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We consider the evolution of forced two-dimensional turbulence on the surface of the sphere. In particular, we examine the extent to which the development of flow anisotropy and zonal jets are controlled by two separate effects, (i) the latitudinal variation of the background planetary vorticity gradient and (ii) the latitudinal variation of the Rossby radius of deformation. On the beta-plane, scaling arguments predict a dependence on beta (in conjunction with some form of large-scale friction) of the length scale and intensity of zonal jets, and this dependence has been observed recently in various numerical studies of beta-plane turbulence. These results suggest that in spherical geometry a transition latitude will exist separating an isotropic flow regime in polar regions from an anisotropic flow regime in midlatitudes. Similarly, different behavior is expected at low latitudes, where the Rossby radius becomes large.

We present the results of high resolution numerical experiments designed to examine the above behavior in more detail. Two systems of equations are considered: (i) the equivalent barotropic system, which is the simplest system in which both beta and Rossby radius vary with latitude; and (ii) the shallow water equations, in which beta and Rossby radius vary in the same way as in the equivalent barotropic model, but which also allows for divergent flows and provides a more realistic representation of the dynamics at low latitudes. The flow is forced stochastically at small scales and energy is dissipated at large scales by a scale-selective hypodiffusion to allow a statistically stationary state to be reached. In addition to the question of the latitudinal dependence of the anisotropy of the stationary flow, we also consider regimes in the two-dimensional parameter space spanned by Rossby and Froude numbers that have been previously unattainable due to prohibitive computational costs.

P3-1

The Effect of Moisture on the Jet Latitude

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A robust result of global warming experiments is a poleward shift of the midlatitude eddy-driven jet. This has an important impact on such aspects of the climate as precipitation regions, ocean circulation, regional climate, and climate variability, but the theoretical basis for such a shift remains obscure. Here we investigate the effect of moisture on the jet latitude in an idealized GCM. The model consists of gray radiative transfer, a zonally symmetric mixed layer aquaplanet lower boundary, and simplified physical parameterizations. As moisture content is increased in the model through a parameter in the Clausius-Clapeyron relation, the jet shifts significantly poleward. We investigate a theory for the shift based on the thermodynamic structure of the midlatitudes, and a related theory involving shifting dry static energy fluxes. The poleward movement can be reproduced within an energy balance model which makes no reference to momentum fluxes. We additionally study the importance of static stability on the jet shift.

P3-2

Tropical/High-Latitude Dynamical Connections in the Winter Stratosphere

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Using climatologies of inertial instability and Rossby wave breaking using United Kingdom Met Office (MetO) assimilated analyses from November 1991 through March 2004, we have identified specific, deep regions of possible dynamical connections between the tropics and the high latitudes in the winter hemispheres.

Our results for the upper and middle stratosphere indicate deep poleward-and-eastward channels of higher inertial instability frequency extending from the central equatorial Pacific during November-March in the Northern Hemisphere, and July-September in the Southern Hemisphere. These corridors of enhanced inertial instability frequency are generally found just poleward of regions of frequent Rossby wave breaking. Both the poleward-eastward channels and the slight poleward offset of the instability versus the Rossby wave breaking region are evident from the stratopause downward into the middle stratosphere.

Furthermore, inertial instability episodes are observed in concert with stratospheric sudden warmings, with the inertially unstable region typically developing along the poleward-and-eastward channels noted above.

The existence of these chronic channels of heightened Rossby wave-triggered instability raises the possibility of narrowly focused regions of tropical-extratropical interactions in the stratosphere. Because the Rossby wave breaking trigger is anchored spatially and temporally, these results suggest very specific regions and times in which to look for these interactions.

P3-3

The Generation and Evolution Mechanism of Meso-alpha-scale and Meso-beta-scale Vortex Disturbances

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When winter pressure pattern grows stronger around Japan, cold monsoon outbreaks from Eurasian Continent and a striking cloud band called "Convergent Cloud Band" is formed over the western Japan Sea. Previous observations showed that frontal structure is found in the convergent cloud band and meso-alpha-scale and meso-beta-scale vortex disturbances often appear. As a study of generation mechanism of such disturbances, we calculated the linear stability of several basic flows with frontal structure under quasi-geostrophic system which includes both barotropic and baroclinic instabilities. We obtained the following results. The linear stability analysis and energy conversion analysis show that both meso-alpha-scale unstable modes, which are generated by baroclinic instability, and meso-beta-scale unstable modes, which are generated by barotropic nstability, occur in the same basic field. Meso-alpha-scale unstable modes dominate in basic fields where frontal transition layer is thick and stability of atmosphere is weak, meanwhile, meso-beta-scale unstable modes dominate when frontal transition layer is thin or stability of atmosphere is strong. Horizontal potential temperature difference does not have substantial effect on growth rate of unstable modes but affects the structure of meso-alpha-scale disturbances. We are now promoting non-linear evolution mechanism of vortex disturbances by considering three-dimensional non-hydrostatic equation system and heat effect. We will also present the role of heat flux and dynamical instability in non-linear evolution term of vortex disturbances.

P3-4

A Parameter Sweep Experiment on Quasi-Periodic Variations of a Circumpolar Vortex due to Wave-Wave Interaction in a Barotropic Model

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Quasi-periodic variations of the winter circumpolar vortex in the Southern Hemisphere are characterized by the wave-wave interaction between quasi-stationary planetary wave of zonal wavenumber 1 (Wave 1) and eastward traveling Wave 2 as studied by Hio and Yoden (2004; JAS). In that paper we showed an example of periodic solution of a barotropic model in which stationary Wave 1 forced by surface topography interacts with eastward traveling Wave 2 generated by the barotropic instability of a forced zonal mean zonal flow.

In the same barotropic model with zonal-flow forcing, dissipation, and surface topography, several types of time-dependent solutions, such as stationary-wave solution, periodic solution, quasi-periodic vacillation solution, and irregular non-periodic solution, are obtained for the combination of external parameters of the height of sinusoidal surface topography and the width of eastward zonal jet. Details of the wave-wave interactions are described for the transition from periodic solution for finite amplitude of surface topography to quasi-periodic solution for smaller amplitude of topography. Variations of mean zonal flow and topographically forced Wave 1 synchronize with periodic progression of Wave 2 in the periodic solutions, while variations of mean zonal flow and amplitudes of Waves 1 and 2 are independent of the progression of Wave 2 in the quasi-periodic vacillation. Dominant triad interactions are obtained for each of these solutions.

P3-5

Zonal jets in observations and models of the Earth's ocean

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Zonal jets have been detected recently in data from satellite altimetry in all parts of the world ocean. They span a broad range of spatial and temporal scales and are governed by a set of different physical mechanisms. Modern fine-resolution/low dissipation numerical models of the general circulation of the ocean are found to reproduce a good deal of the observed structure of the jets. These models are used to study the vertical structure and dynamics of the jets. Presented are preliminary results of spectral and statistical analyses of the jets in the Pacific on time periods of one year or longer. We discuss possible mechanisms of the jets' formation and the effect of the jets on the intensity and anisotropy of horizontal mixing of tracers in the deep ocean.

P3-7
Relations Between the Annular Modes and the Mean State

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We study the influence of the background state on the structure and dynamics of the southern hemisphere annular mode (SAM), defined as the first EOF of monthly 850hPa geopotential anomalies. Subsets of the climatology are constructed for different seasons and for contrasting polarities of the ENSO cycle. The analysis is based both on observations and on perpetual-state GCM experiments.

During the austral summer, the climatology is characterized by a single, well-defined, eddy-driven jet centered at a varying mean latitude between subsets. It is found that in all the cases, the SAM is characterized by latitudinal shifts of the jet about its mean position, reinforced by a positive momentum flux feedback from baroclinic waves. This result, consistent with previous studies of the zonally-averaged dynamics, is found here to hold over all longitudes and for different positions of the mean jet.

The strong differences in the amplitude of the SAM among the various climatologies seem to be determined by a combination of (1) the variance of the "random" forcing by transient eddies, and (2) the strength of the positive feedback component of this forcing. The latter mechanism tends to become stronger when the mean jet moves equatorwards.

During the austral winter, a strong subtropical jet lies over the Indo-Pacific sector in addition to the eddy-driven jet. The SAM keeps a quasi-zonally-symmetric structure in geopotential and zonal wind anomalies, but it exhibits two different behaviors: (1) over the sector in which the subtropical jet is weak, the SAM represents shifts of the midlatitude jet about its mean position. (2) It becomes instead a see-saw between the midlatitude and subtropical jet over the longitudes where the latter is strong.

P3-9

On the Spatiotemporal Behaviour of Sea Ice Concentration Anomalies in the Northern Hemisphere

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In this study we examine the spatiotemporal variability of SIC anomalies in the northern hemisphere during the onset of ice formation. Examined in particular are time scales associated with coherent regions of persistence in an e-folding time spatial distribution (EFSD). Annual variations of weekly SIC anomalies are studied and spatial relations between positive and negative SIC anomalies explored on a hemispheric scale. Here we find that time scales on the order of 4 - 7 weeks prevail in the northern hemisphere, with regional differences in forcing mechanisms. Spectral analysis of hemispheric-scale waves (wavenumbers 1 - 4) and comparison with SIC anomaly extrema suggests a correspondence between waves 1-3 phase and SIC spatial variability. An eastward shift in phase during the 1990s is also observed for all three wavenumbers.

P3-10
On the Seasonality of Northern Annular Mode (NAM)

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Data analysis show that both the climatological background flow and synoptic eddy activity (or storm track) are strongest in winter, decrease in strength in spring, and are weakest in summer. The NAM is also known to have substantial seasonality, with the strength of the signal at its peak in winter, then decreasing in spring, and at a minimum in summer. We propose that the observed seasonality of NAM may be attributed to the seasonal changes in the background climate state and the two-way interaction between synoptic eddy and low-frequency flow (SELF), which depends on climatological cycles of the background flow and the synoptic eddy activity. Our research shows that that the SELF interaction has a pattern-selective effect and a positive feedback in the momentum field. The SELF feedback is essential for the formation of NAM in all the seasons. Although the strength of synoptic eddy flow is weaker in summer than in winter, the positive SELF feedback associated with NAM in summer can be as strong as that in winter. The seasonal variations of the leading singular mode simulated by a linear dynamic system with the SELF feedback resemble the observed NAM patterns very well. In other words, the seasonal changes in spatial patterns of NAM are found as the result of the seasonal shifts in climatological stationary waves and storm tracks patterns.

P3-11
Arctic Oscillation Analyzed as a Singular Eigenmode of the Global Atmosphere

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In this study, eigenmodes and singular modes are analyzed for a dynamical system of the atmosphere linearized about a winter basic state in order to understand the dynamics of the Arctic Oscillation (AO). Since the fluctuations of the sea-level pressure are dynamically linked with the barotropic component of the atmosphere, the AO is investigated in the framework of a barotropic model. As a result of the analysis, we find multiple eigenmodes which are similar to the AO with a negative pole in the Arctic and positive poles in the Pacific and Atlantic sectors. Since some of the eigenmodes are unstable, a linear drag is introduced to shift the eigenvalues in order to pick up different eigenmodes as a singular mode with resonant behavior. It is demonstrated that the singular eigenmode of the dynamical system emerges resonantly as the AO in response to the arbitrary forcing. The resonant growth is allowed for multiple eigenmodes including the unstable modes, and therefore the AO described by the neutral mode under the strong friction is recognized as the least damping mode excited by the tail of the resonant response curve of the singular eigenmode. In reference to the result of the nonlinear simulation of the AO using the same barotropic model, we may conclude that the AO is a physical mode of a dynamical system for the global atmosphere.

P3-12
AO, COWL, and Observed Climate Trends

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The linear trends for a number of fields obtained from the reanalyses of the National Centers for Environmental PredictionNational Center for Atmospheric Research (NCE-PNCAR) are calculated for the Northern Hemisphere winter months (January-March) from the 55-yr period of 1948-2002. The fields include sea level pressure (SLP); geopotential height at 500 and 50 hPa; temperature at 500 and 50 hPa; zonally averaged height; temperature; zonal, meridional, and vertical velocities from 1000 to 50 hPa; and surface air temperature (SAT). The trend fields are expressed in terms of two alternate expansions: (i) contributions from the Arctic Oscillation (AO) and cold oceanwarm land (COWL) patterns, as defined from the leading modes of an empirical orthogonal function (EOF) analysis of sea level pressure; or (ii) contributions from the modified AO (AO*) and modified COWL (COWL*) patterns, defined from the leading EOFs of 500-hPa height. The residuals in each expansion are considered, and the completeness properties of the expansions are discussed.

Long-term linear trends of various fields at mid- and lower-tropospheric levels project well onto the AO (AO*) and COWL (COWL*) modes. The AO contribution accounts for most of the SLP falls over the Arctic and half of the SLP rise over the North Atlantic, while the COWL pattern represents the entire negative pressure trend over the Pacific and half of the rise over the Atlantic. In the expansion into AO* and COWL* patterns, the latter represents most of the SLP trend. Similar remarks hold for the height trend at 500 hPa. In each case the residual is a small fraction of the trend. The observed SAT trend (warming over most of North America and Asia, cooling over northeast Canada and the Pacific) is partitioned nearly equally between contributions from the AO and COWL, although the COWL contribution dominates over North America. In the alternate expansion, the COWL* dominates nearly all of the warming over North America and Asia. The midtropospheric (500 hPa) temperature trend is mostly due to the COWL (or COWL*) patterns, with the AO representing only the local cooling over Greenland.

The 50-hPa height and temperature trends are not well represented by either set of patterns. The links of the trends in the zonal-mean fields and the AO (AO*) and COWL (COWL*) are weaker than those in the mid- and lower troposphere.

P3-13

Potential Vorticity Distribution of a Vortex Street Formed by Instability of a Quasi-Geostrophic Jet

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Statistic features of a vortex street formed by instability of a quasi-geostrophic jet is investigated by numerical calculation and statistic theory. First, numerical calculation is performed: a jet in the initial state begins to meander and steady vortices are formed. In order to explain the calculated potential vorticity distribution, we compared this result with statistic theory of vorticity mixing for two-dimensional fluid (Robert and Sommeria 1991) and its application to a jet (Thess et al. 1994). Their theory describes that the statistically steady state is characterized by maximum mixing entropy. The theoretically derived stream function vs. potential vorticity relation explains the result in the numerical calculation very well. However, in the numerically calculated vortex street, there remained regions where the fluid is not well mixed. The width of this region affects the features of the vortex street such as distance between vortices.

P3-14

Eddy amplitudes in baroclinic turbulence driven by non-zonal mean flows: Shear dispersion of potential vorticity

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As in the midlatitude atmosphere, midocean eddies are generated by baroclinically unstable mean currents. In contrast to the atmosphere, as pointed out by, e.g., Spall (2000) and Arbic and Flierl (2004), oceanic currents are significantly non-zonal. Even weak non-zonal currents are linearly unstable, since beta does not suppress growing meridional waves. Theories for the nonlinear equilibration of baroclinic instability, and hence theories for the amplitudes of midocean eddies, must therefore take into account the different dynamics of non-zonal flow. It is shown here that the amplitude of fully developed baroclinic turbulence due to non-zonal shears differs from that due to zonal shears primarily in the nature of the eddy generation. Since beta will act to create large-scale zonal elongation regardless of the generation source, the eddy velocities in the zonal and meridional directions are fundamentally different, the former being jet-like, and the latter being nearly random and isotropic. Thus the flux of potential vorticity in each direction (equivalent to the eddy energy generation rate) occurs through different processes. The cross-jet mixing has been shown previously to obey a mixing-length scaling, and this corresponds to the generation due to unstable zonal flow. The along-jet mixing, by contrast, is shown here to be a best described by a shear dispersion model, and this corresponds to the generation due to the unstable meridional shear. The resulting flux is far higher than in the cross-jet direction, and thus eddy energies driven by baroclinically unstable mean flows with a non-zero meridional component are much larger.

P4-1

A Simple Model for the Dynamics of Upper Troposphere and the Implication for Surface Westerly Shift

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An idealized model is constructed to help understanding why the surface westerlies are displaced poleward in the general circulation models when the surface friction is reduced. The dynamics of upper troposphere is idealized as one shallow water isentropic layer forced by random stirring in the divergence field. Two important factors are included in the model: 1) the stirring moves with a prescribed phase speed; 2) surface wind is inferred from the eddy momentum convergence and is allowed to feedback on the upper tropospheric wind by the thermal wind balance.

The model can generate coherent Rossby wave packets in the midlatitudes, propagating eastward and equatorward. The basic dynamical process in the model involves the wave breaking near the critical latitude. The wave breaking homogenizes the potential vorticity irreversibly, and thus produces the poleward momentum flux that determines the location of the surface westerlies.

This simple model is utilized to understand the shift and variability of surface westerlies with surface friction. As surface drag is reduced with fixed phase speed, surface westerlies increase proportionally but display no shift. However, if the phase speed is increased with fixed surface drag, surface westerlies displace poleward. The cospectra of eddy momentum flux shows that the shift is due to the poleward displacement of the critical latitude.

P4-2
Restratication Forced by Ageostrophic Fronts and Eddies

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The oceans and atmosphere are characterized by layers with large vertical gradients (the thermocline in the ocean and the tropopause in the atmosphere) separating the fluid in different dynamics. These layers play the role of vertical barriers to mixing. Different processes are responsible to the maintenance of these layers and, more generally, to the vertical stratification of the atmosphere and the oceans. However the influence of baroclinic jets and eddies on the stratification of the fluid has been given little attention until recently.

We investigate how ageostrophic dynamics associated to frontogenesis is able to maintain the sharpness of the vertical barriers. Frontogenesis is the general process of formation of steep horizontal gradients in density or potential temperature, due to the stirring action of eddies. We show that Ertel potential vorticity (PV) conservation implies a strong constraint on the mean stratification profile. In the absence of sources and sinks of PV, the time evolution of the mean density only depends on two terms, namely the time evolution of the product between density anomaly and relative vorticity, and, the vertical PV flux. The first term can be related analytically to the strength of frontogenesis while the second term is related to interior dynamics. These results are illustrated by numerical simulations of the evolution of baroclinic jets and demonstrate that frontogenesis at surface (or at the tropopause) creates and maintains regions of strong stratification.

P4-3
Eddy Forcing of the Zonally-Symmetric Atmospheric General Circulation

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The interactions between the zonally-averaged flow and the various eddy circulations in the atmosphere are studied using NCEP/NCAR Re-analysis data. The contributions to zonal and potential temperature tendencies and zonal kinetic energy production due to both the Ferrel and Hadley circulations are determined. Inferences are then made regarding the processes that affect the strong cores of the jet stream and the forms of zonally-averaged models of the atmosphere that are appropriate for studies of this type. It will be shown that there is considerable wave-mean flow interaction in the atmosphere, with the circulation induced by eddy motions being primarily responsible for the maintenance and seasonal variations of the zonally-averaged jet core.

P4-4

Annular Modes in a Multiple Migrating Zonal Jet Regime

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Persistent multiple migrating zonal jets are investigated using an ocean GCM, forced at the surface by an atmospheric wind stress and by relaxation to an imposed meridional temperature profile. Analysis of the momentum budget shows that the model's prescribed wind stress transfers momentum from the atmosphere into the ocean, at which point, eddies then transfer the momentum downward and equatorward. Since the jet scales are about 50 times larger than the Rossby radius of deformation, the jets are maintained (in part) by Rossby waves leaving the jet providing momentum fluxes into the jet consistent with the theory provided by Held and Andrews (1983).

Similar to the annular modes in the atmosphere, the leading mode of variability is associated with the primary jet's meridional displacement. This north-south oscillation from its time-mean location is related to secondary jets migrating equatorward toward the primary jet. The dynamics into the equatorward bias in the migration of the zonal flow anomalies will also be discussed.

P4-5

Oceanic Jets Around Bottom Topography in an Oceanic General Circulation Model

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Topography forces vortex stretching which can be the dominant term in the vorticity dynamics of deep oceanic flows. In turbulent quasi-2D flow, it has long been argued from several points of view (maximum entropy, heuristically) that this should lead to jets aligned along the topography in the sense of anticyclones (cyclones) around mountains (valleys). Vallis and Maltrud (JPO 1993) showed that similar effects occur under topographic beta and planetary beta and demonstrated these effects in QG models, but called for similar studies with models with more complete physics. Here we analyze jet structures around topography in high-resolution, eddy-active simulations of wind-forced circulation in an idealized ocean basin using the GFDL ocean general circulation model MOM4.

P4-6

Transient Eddies and Teleconnection Patterns; Studying Their Interaction.

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Teleconnections, such as the North Atlantic Oscillation, are related to low-frequency anomalies in the tropospheric circulation that influence the observed weather over large areas. This connection, however, may not be one way only; high-frequency transient eddies (synoptic time scale) are believed to show a positive feedback with the low-frequency anomalies. Through systematic eddy fluxes, and/or other nonlinear processes, synoptic eddies may partly drive the low-frequency variability. This would be an intrinsic atmospheric process in contrast to other proposed driving mechanisms such as the interaction with the oceans.

In this study atmospheric variability has been decomposed into non-overlapping frequency bands and the corresponding variability patterns have been explored applying EOF analysis as well as a teleconnection approach. ERA-40 daily reanalysis data are used spanning the years 1957-2002 for the period December to Mach in the N. Hemisphere. The results show that high-frequency variability (periods of 2-10 days) has no linear contribution to the known teleconnections. It is only the low frequencies (periods over 20 days) that follow the teleconnection patterns with the intermediate frequency band exhibiting a mixed behavior.

To assess the significance of a possible eddy forcing of the low-frequency variability a potential vorticity (PV) analysis is employed. Partitioning quantities into low and high frequency components a PV budget equation is achieved relating the low-frequency PV tendency to three other terms corresponding to advection, total eddy forcing and the unresolved processes term calculated as a residual. Regressions of these terms on the low-frequency PV tendency show that the latter is predominantly driven by the advection term whilst the eddy forcing and the residual terms have no significant contribution contradicting the idea of eddy maintained variability patterns.

P4-8

Stratospheric Influences of Cold Surges in East Asia in association with Northern Annular Mode

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The occurrence of extreme cold surges (CS) in East Asia is explored in association with the propagation of northern annular mode (NAM) from stratosphere to troposphere. Based on the isentropic potential vorticity (IPV) analysis, it is found that the many of extreme CS are initiated and amplified under the influences of the upper level circulations. During the phase of negative propagation of NAM, strong upper-level negative IPV anomalies induce lower tropospheric cold vortex over northeastern Siberia and propagate to lake of Baikal where the climatological Siberian High is usually located. Deepening of upper level trough in east coast of Asian continent, which is also related with upper level IPV anomalies in negative NAM phase, may influence the southern intrusion of the Siberian High.

P4-9

A Climatological Analysis of Stratospheric Intrusions and their link to Large-scale Climate Modes

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Meridionally elongated intrusions of stratospheric air into the troposphere (i.e. stratospheric streamers) form during the breaking of synoptic-scale tropopause-level Rossby waves. The streamers are an important component of several synoptic and larger-scale phenomena, and the nature of the wave-breaking is linked to the structure of the ambient flow. On the monthly to inter-annual time-scale streamer variability is closely linked to different large-scale climate modes, and in turn their their distribution and form can influence the large-scale modes.

Here a study is undertaken of the monthly to inter-annual variability of the spatial distribution of stratospheric intrusions. A PV-based climatology is derived for the northern hemisphere for the ERA-40 (1958-2002) data set, and used to examine the "streamer-climate modes" link to shed light on the nature of the two-way interaction.

P4-10
A climatology of the QBO through the MTMSVD

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A climatology of the QBO signal has been constructed through the multitaper method-singular value decomposition (MTMSVD). Two different datasets were used: data from the high vertical resolution configuration of the atmospheric general circulation model MAECHAM5 (M5) and from the ERA40 reanalysis. Zonal monthly mean data for 21 years (1979 -1999) and for 18 stratospheric and lower mesospheric levels between 100hPa and 0.1hPa for ERA40 and 22 levels between 100hPa and 0.01 hPa for MAECHAM5 have been used.

The MTMSVD is used to detect and reconstruct the QBO signal in the zonal wind over the tropics and also the variability induced in this field at middle and high latitudes and in other variables as meridional wind, temperature and Eliassen Palm flux components and divergence for each season independently. The results provide a consistent picture of the tropical QBO structure and of its signal induced at higher latitudes in each season. In general, the spatial patterns obtained for both datasets show similar characteristics. However, some differences are found between the QBO signal reconstructed for M5 and ERA40 data as for the EP flux components and the QBO structure at mesospheric levels.

The results show a strong seasonal dependence, mainly at middle and high latitudes. The QBO modulation of the polar vortex is found more intense in the winter of the northern hemisphere in agreement with previous studies and the highest anomalies located around the level of 0.5 hPa for both datasets. The results also show important differences in the secondary meridional circulation strength between the summer and winter hemisphere that are less intense during spring and autumn.

P4-11

Modified Lagrangian-Mean Analysis of the Arctic Oscillation

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The Arctic Oscillation is attracting much attention since the work of Thompson and Wallace (1998), because it is not only the primary pattern of the atmospheric variability in the northern hemisphere but also a representative process of the troposphere-stratosphere coupling. A downward propagation of the Arctic Oscillation from the stratosphere to the troposphere (Baldwin and Dunkerton, 1999) is attempted to be explained from the viewpoint of wave-mean flow interaction using the transformed Eulerian-mean diagnostic in
many previous studies (e.g., Limpasuvan et al., 2004). In this study, the modified Lagrangian-mean diagnostic is applied to the Arctic Oscillation to examine the role of nonconservative processes such as wave breaking (i.e., part of wave-mean flow interaction) and radiation on the downward propagation of the Arctic Oscillation.

P4-12

What kind of sudden stratospheric warming propagates to the troposphere

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The factors affecting the downward propagation of sudden stratospheric warming (SSW) events to the troposphere are studied through composite analysis of 45-year reanalysis data from the European Centre for Medium-Range Weather Forecasts. During the growth stage of SSW, events that propagate into the troposphere exhibit enhanced upward flux of the wavenumber 2 wave, while events that do not propagate downward display reduced wavenumber 2 flux. In both events, upward flux of the wavenumber-1 wave is enhanced, but the enhancement is stronger in the non-propagating event. The composite for propagating events reveals a negative Eurasian pattern of horizontal geopotential anomalies in the troposphere during the growth stage, and a negative Arctic Oscillation pattern following the event, while non-propagating events are preceded by a positive Eurasian pattern. In both types of event, the tropospheric anomalies are generated mainly by tropospheric planetary wave forcing prior to the emergence of SSW.

P4-13

An equatorial jet emerged in shallow-water turbulence on a rotating sphere

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Cho and Polvani (1996) reported that a retrograde equatorial jet emerges in shallow-water turbulence on a rotating sphere. We perform ensemble experiments with various initial states to investigate robustness of emergence of the retrograde jet and examine how emergence of an equatorial jet and its magnitude depend on an initial state.

Our results indicate that the frequency distribution with magnitude of an equatorial jet depends on Rossby number. While the distribution is narrow and there is no prograde jet for small Rossby number, a prograde jet can be formed and maintained for large Rossby number.

Further, a zonal mean flow induced by wave-wave interactions is examined with a linearized model to investigate acceleration mechanisms of the equatorial jet. The second-order acceleration is almost induced by the Rossby and Rossby-gravity waves and its mechanisms can be categorized into two types. First, the local meridional wavenumber of a Rossby wave packet propagating toward the equator increases due to meridional variation of the Rossby deformation radius and/or the retrograde mean flow so that the wave packet dissipates in the equatorial region. This mechanism always contributes to retrograde acceleration of the equatorial jet. Another mechanism is derived from equatorial waves tilting due to meridional shear of the mean flow. In this case, a zonal mean flow induced by Rossby waves intensifies a given basic flow.

P4-14

Circumpolar Jets Emerging in Two-Dimensional Barotoropic Decaying Turbulence on a Rapidly Rotating Sphere

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A series of numerical experiments on two-dimensional decaying turbulence is performed for a non-divergent fluid on a rotating sphere, with an attention focused on scaling properties of spontaneous circumpolar jets. Numerical calculations show that strong circumpolar westward jets emerge clearly in high latitudes at a large rotation rate. A theoretical scaling theory is proposed for the jet width proportional to the minus one-fourth power of the rotation rate, and the jet strength to the plus one-fourth power. These theoretical exponents agree well with the numerical results. A noteworthy asymptotic feature is that the kinetic energy becomes concentrated entirely on the circumpolar jets under large rotation rates.