Understanding midlatitude climate change in a hierarchy of models

Todd Mooring, Orli Lachmy, Zhihong Tan, Tiffany Shaw

Department of the Geophysical Sciences, The University of Chicago

Introduction

A key feature of the Earth's extratropical (poleward of ~30° latitude) climate system is transient eddy activity. **Transient eddies are defined as the time-varying component of the atmospheric flow**, and they are responsible for much of the atmosphere's poleward energy flux. They also transport water vapor that ultimately condenses to form precipitation and momentum that maintains the midlatitude westerly winds. The eddy activity is concentrated in specific latitude-longitude regions known as storm tracks (Figure 1).

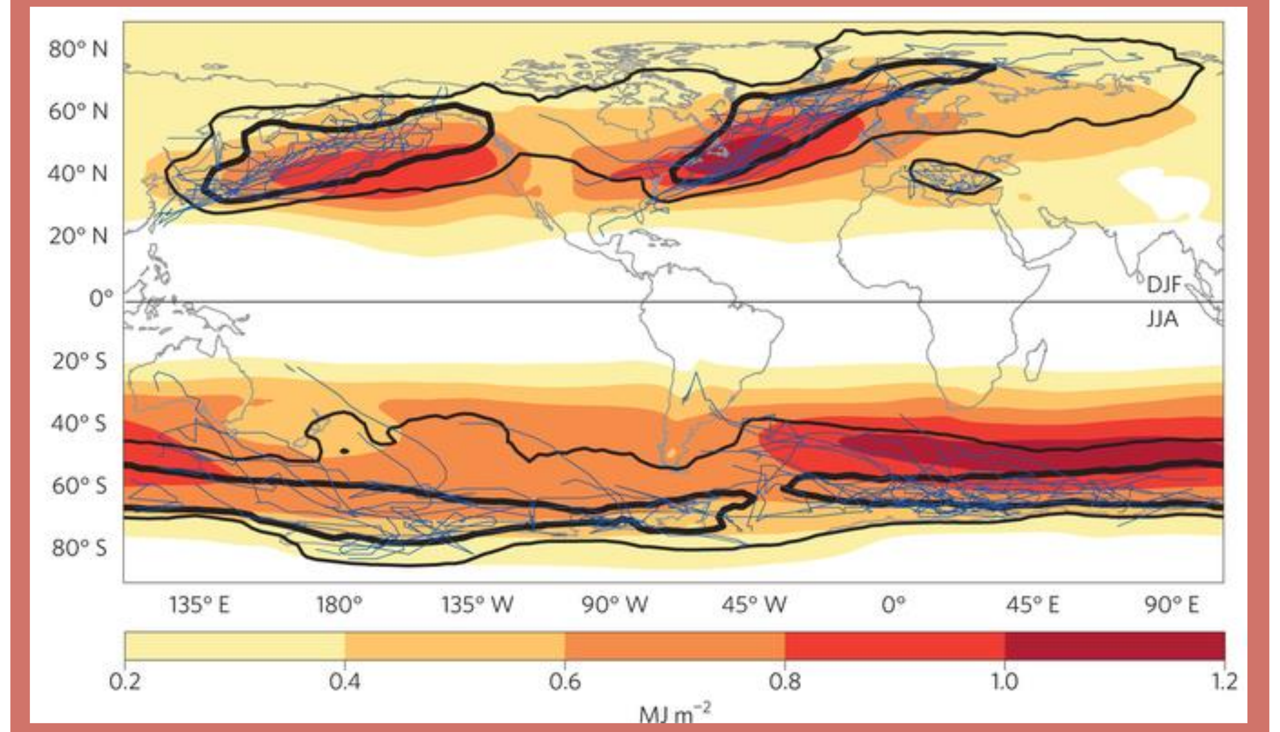


Figure 1: Wintertime storm track activity quantified via eddy kinetic energy densities (shading) and density of tracks of individual cyclones. Data are from the ERA-Interim reanalysis, figure is modified from Shaw et al. (2016).

Because controlled experiments with the actual Earth are impossible, numerical modeling with high-performance computers plays a critical role in climate science. The most sophisticated numerical models are referred to as **global climate models (GCMs)**, but are themselves so complicated that their output can be difficult to understand. Accordingly a **hierarchy of models** including various simpler levels is employed, analogous to the use of bacteria and small mammals by biologists. Part of a climate model hierarchy is illustrated in Figure 2. Much of the current work in the Shaw group uses the aquaplanet (ocean-only lower boundary) part of the hierarchy. Each of the next three sections of the poster describes one of our projects.

Are eddy energy transports a form of diffusion?

GCM simulations typically predict that eddy activity will shift poleward with warming, a phenomenon we are attempting to understand by considering the poleward energy transport to be diffusive. The diffusivity can be estimated from GCM output, and we find that a specified increase in ocean temperatures of 4K results in a poleward shift of the diffusivity (Figure 3) for one important form of energy (moist static energy). This shift is not simply a thermodynamic response to the increased ocean temperature, but is also driven by cloud and/or water vapor radiative feedbacks.

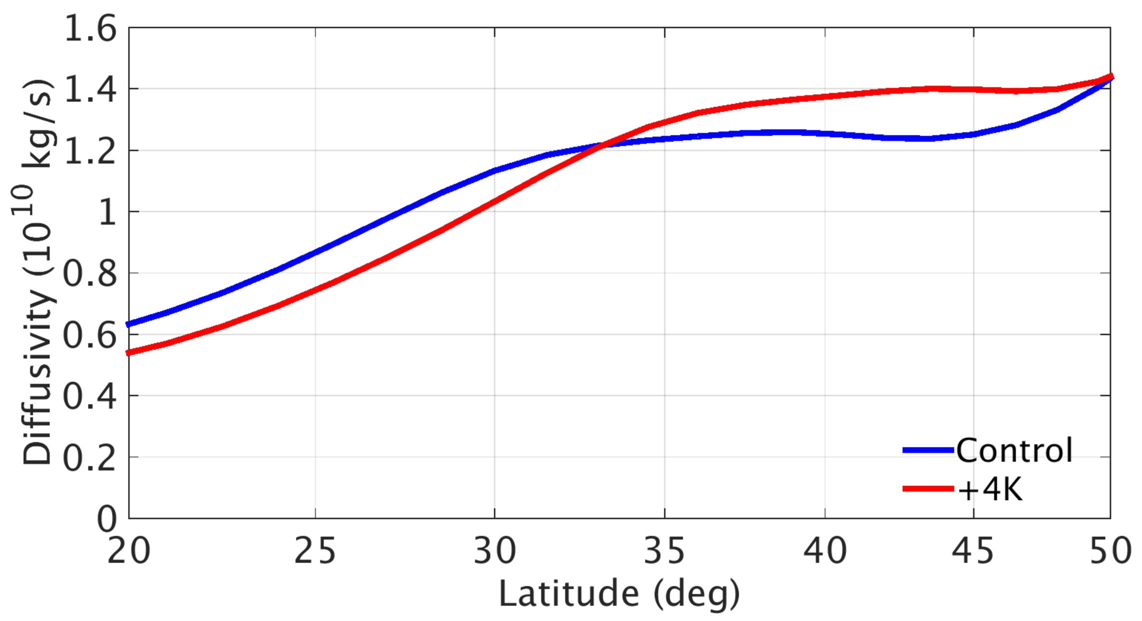


Figure 3: Midlatitude moist static energy diffusivities averaged across 10 different GCMs. Blue (red) line is for simulations with control ocean temperature fields (ocean temperatures raised 4K everywhere).

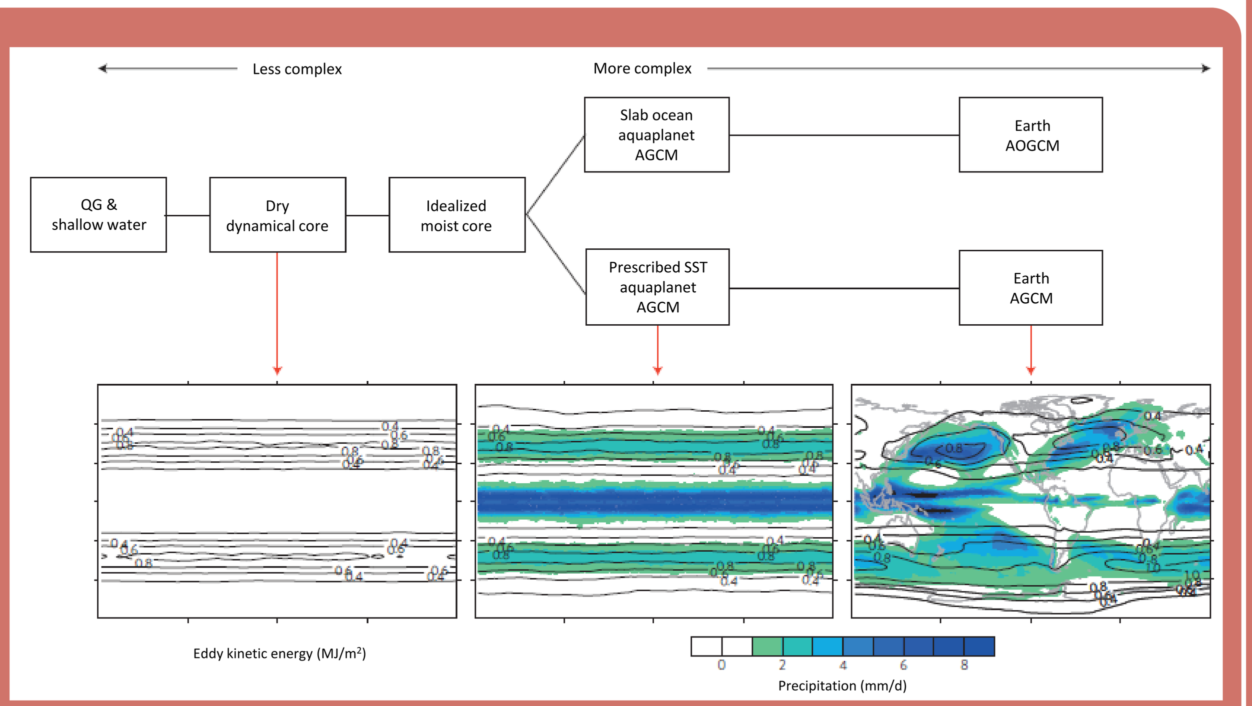
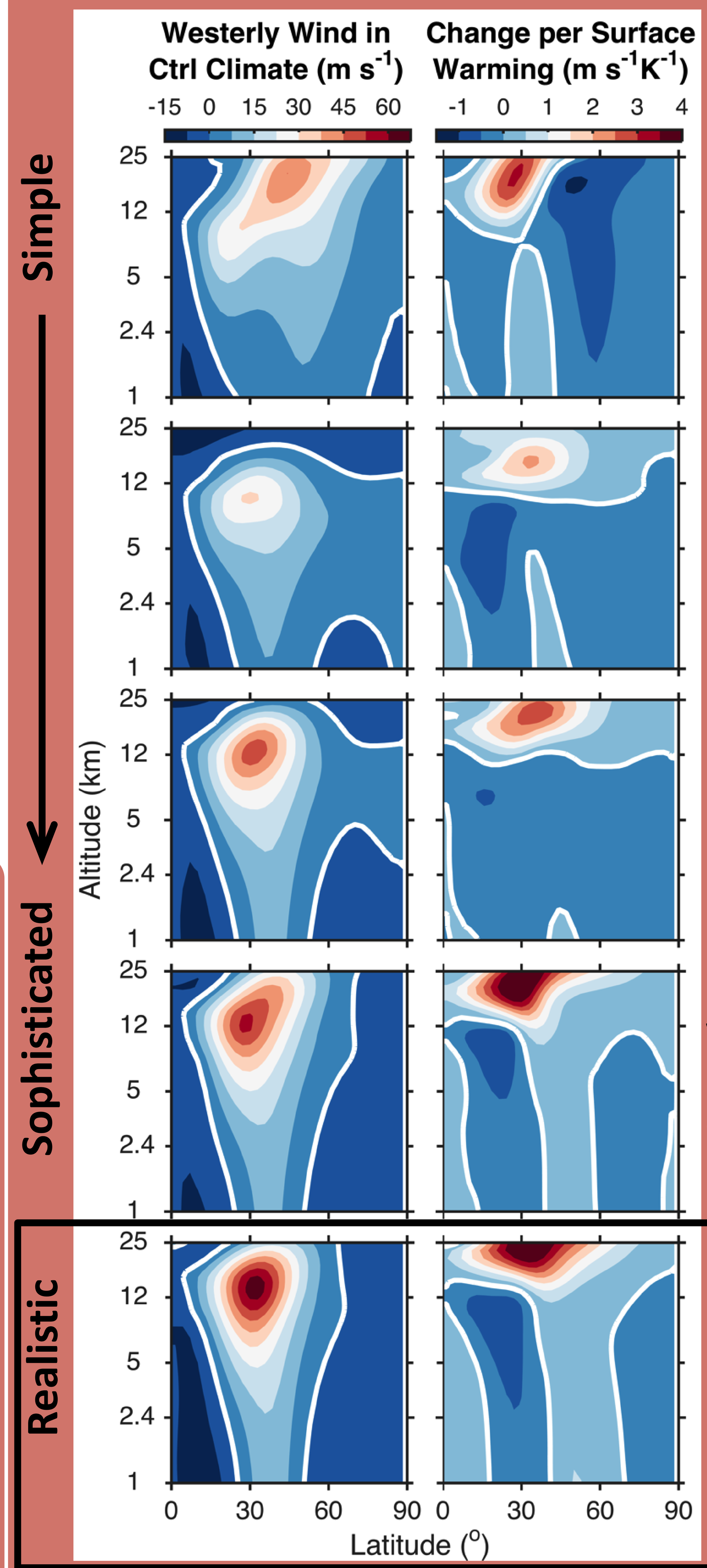


Figure 2: Diagram of one possible hierarchy of climate models and some associated model output. Models in the left side of the diagram have strongly simplified thermodynamics and/or hydrodynamics, while the two right branches differ in whether ocean temperatures are computed (upper) or simply prescribed (lower). Figure is modified from Shaw et al. (2016).

How is the jet stream affected by infrared radiation?

The **jet stream** (a band of strong westerly wind in the upper troposphere, Figure 4) is linked to the storm track and has important impacts on midlatitude weather and climate.

Using a hierarchy of GCMs with radiation schemes of different complexities, we find that the **vertical profile of infrared cooling** and the **water vapor feedback** are essential to the jet pattern and its shift under climate change.



Gray (opacity constant w/ wavelength) scheme: Jet is too poleward and split; jet shifts equatorward under warming.

Reduce stratospheric opacity: Latitude and split biases are fixed.

Spread cooling vertically: Height and strength biases are reduced.

Include water vapor feedback: Poleward jet shift is recovered.

Realistic scheme: Jet is strong and merged; it shifts poleward under warming.

Figure 4: (left) Mean westerly wind (m/s) in the control climate, and (right) its change per 1K global mean surface warming.

What controls the direction of jet stream shift with warming?

Question: Is the jet stream response to warming predictable given the climatological mean flow and the energy transport response?

Approach: Analyze energy and momentum transports and jet shifts in idealized global warming simulations.

Results: The opposite jet shift directions in response to warming in gray radiation and realistic radiation models (Figure 4, top and bottom rows) are qualitatively explained via a relation between the energy and momentum transports. The climatology and response of eddy potential energy flux are approximately equal to those of the eddy momentum flux times the Doppler-shifted eddy phase speed (Figure 5, top and middle rows). The vertically integrated eddy potential energy flux is shifted poleward in both models (Figure 5, bottom row). The different mean flows, which determine the Doppler-shifted eddy phase speed, account for the opposite directions of momentum flux shift in the two models. The momentum flux shift in turn drives the jet shift.

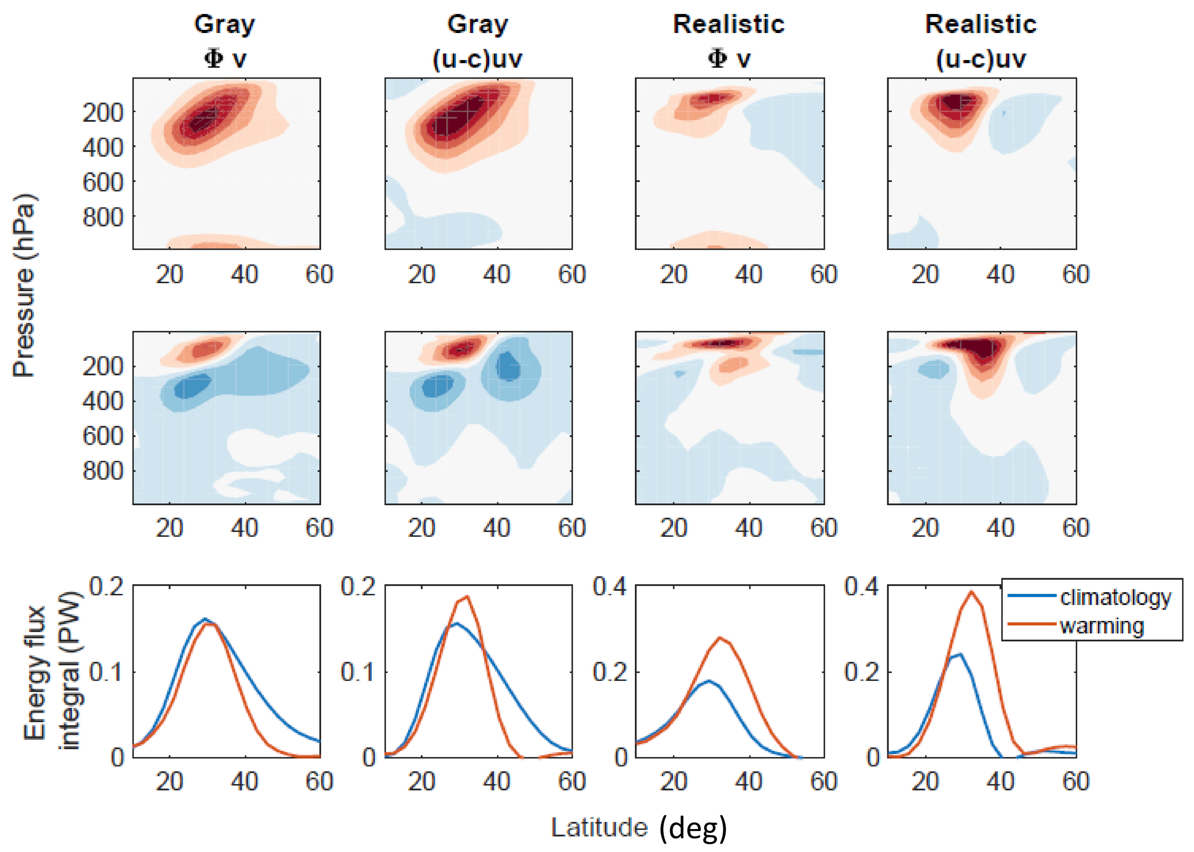


Figure 5: Eddy potential energy flux (Φv) and product of the eddy momentum flux and Doppler-shifted eddy phase speed ((u-c)uv) in gray and realistic radiation models. The three rows are climatological values, changes with warming, and vertical integrals respectively. Red (blue) shading indicates positive (negative) values. Contour interval is 200 (400) m^3/s^3 for gray (realistic) radiation.