Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR

Ivy Tan\textsuperscript{1,2}  Lazaros Oreopoulos\textsuperscript{1}  Brian H. Kahn\textsuperscript{3}  Mark D. Zelinka\textsuperscript{4}  Daniel T. McCoy\textsuperscript{5}

\textsuperscript{1}NASA GSFC  \textsuperscript{2}UMBC  \textsuperscript{3}NASA JPL  \textsuperscript{4}LLNL  \textsuperscript{5}University of Leeds

MODIS/VIIRS Science Team Meeting
Silver Spring, MD
October 16, 2018
Part I: Background & Motivation

- Previous work

Part II: Plans for TASNPP

- Current work using MODIS C6 cloud products

Summary

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Cloud feedbacks remain the largest source of uncertainty in climate sensitivity estimates

- Climate sensitivity: the ultimate increase in global mean surface air temperature in response to atmospheric CO$_2$ doubling.

![Diagram showing climate sensitivity results from CMIP5 models](image)

- **Mean**: 3.4°C
- **Max**: 4.7°C
- **Min**: 2.1°C

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Cloud feedback

The surface temperature-mediated response of clouds to warming induced by atmospheric \( \text{CO}_2 \) doubling. Unit: \([\text{Wm}^{-2}\text{K}^{-1}]\)
Extratropical net $\lambda_T$ in CFMIP1 & CFMIP2 is negative — why?

Zelinka et al. (2016), GRL
Why is $\lambda_\tau < 0$ in the extratropics?

Optical thickening of clouds (ice to liquid phase transitions) $\Rightarrow$ more shortwave reflection

Global warming

Cloud Phase Feedback

Replacement of ice with liquid

Cooling

More sunlight reflected

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Why is $\lambda_\tau < 0$ in the extratropics?

Optical thickening of clouds (ice to liquid phase transitions) $\Rightarrow$ more shortwave reflection

Correction of ice:liquid overestimate implies weaker (less negative) cloud phase feedback

Global warming

Cloud Phase Feedback

Cooling

Replacement of ice with liquid

More sunlight reflected

Correct model overestimate in ice:liquid

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Possibility of $\lambda_T > 0$ in the extratropics?

Study #1: Tan et al. (2016), Science

- CAM5/CESM model confirms that reducing high ice:liquid bias in clouds weakens the cloud phase feedback
- But $\lambda_T$ flips sign and becomes $>0$ — why? Are the CMIP models getting the sign of $\lambda_T$ wrong because they overestimate ice:liquid?

⇒ TASNPP addresses this

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Possibility of $\lambda_\tau > 0$ in the extratropics?


- CAM5 + slab ocean — reduced high ice:liquid bias via the model’s shallow convective detrainment scheme

(c) Experiment SW Cloud Feedback
Possibility of $\lambda_\tau > 0$ in the extratropics?

Study #3: Terai et al. (2016), JGR

- Constrained $\lambda_\tau$ using multiple satellite observations of $\tau$

![Graph showing SW Low Cloud Optical Depth Feedbacks Predicted from Variability]

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Role of Thermodynamic Phase Shifts from MODIS record

Cloud optical depth feedback, $\lambda_\tau$

(proxy

Gordon & Klein (2014), JGR
Terai et al. (2016), JGR

$\frac{d\ln \tau}{dT}$ (from MODIS)

Thermodynamic phase shifts
(ice to liquid transitions)

Liquid cloud processes

Ice cloud processes

decompose

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Decomposition of $\frac{d \ln \tau}{dT}$ using MYD L3 (daily)

\[
\ln \tau(T) = k_i(T) \ln \tau_i(T) + k_l(T) \ln \tau_l(T)
\]

N. B.: $k_i + k_l = 1$

\[
\ln \tau(T) = k_i(T) \ln \tau_i(T) + (1 - k_i(T)) \ln \tau_l(T)
= k_i(T) \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + \ln \tau_l(T)
\]

\[
\frac{d \ln \tau}{dT} = \frac{dk_i}{dT} \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + k_i(T) \frac{d \ln \tau_i}{dT} - k_i(T) \frac{d \ln \tau_l}{dT} + \frac{d \ln \tau_l}{dT}
= \frac{dk_i}{dT} \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + k_i(T) \frac{d \ln \tau_i}{dT} + k_l(T) \frac{d \ln \tau_l}{dT}
\]

thermodynamic phase shifts  ice  liquid

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Decomposition of \( \frac{d \ln \tau}{dT} \) using MYD L3 (daily)

\[
\ln \tau(T) = k_i(T) \ln \tau_i(T) + k_l(T) \ln \tau_l(T) \tag{1}
\]

N. B.: \( k_i + k_l = 1 \)

\[
\ln \tau(T) = k_i(T) \ln \tau_i(T) + (1 - k_i(T)) \ln \tau_l(T)
= k_i(T) \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + \ln \tau_l(T) \tag{2}
\]

\[
\frac{d \ln \tau}{dT} = \frac{dk_i}{dT} \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + k_i(T) \frac{d \ln \tau_i}{dT} - k_i(T) \frac{d \ln \tau_l}{dT} + \frac{d \ln \tau_l}{dT}
= \frac{dk_i}{dT} \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + k_i(T) \frac{d \ln \tau_i}{dT} + k_i(T) \frac{d \ln \tau_l}{dT} \tag{3}
\]

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Decomposition of $\frac{d\ln \tau}{dT}$ using MYD L3 (daily)

$$\ln \tau(T) = k_i(T)\ln \tau_i(T) + k_l(T)\ln \tau_l(T)$$  \hspace{1cm} (1)

N. B.: $k_i + k_l = 1$

$$\ln \tau(T) = k_i(T)\ln \tau_i(T) + (1 - k_i(T))\ln \tau_l(T)$$
$$= k_i(T) \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + \ln \tau_l(T)$$  \hspace{1cm} (2)

$$\frac{d\ln \tau}{dT} = \frac{dk_i}{dT} \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + k_i(T) \frac{d\ln \tau_i}{dT} - k_i(T) \frac{d\ln \tau_l}{dT} + \frac{d\ln \tau_l}{dT}$$
$$= \frac{dk_i}{dT} \left( \ln \tau_i(T) - \ln \tau_l(T) \right) + \underbrace{k_i(T) \frac{d\ln \tau_i}{dT}}_\text{thermodynamic phase shifts} + \underbrace{k_l(T) \frac{d\ln \tau_l}{dT}}_\text{ice} + \underbrace{k_l(T) \frac{d\ln \tau_l}{dT}}_\text{liquid}$$  \hspace{1cm} (3)
Decomposition of $\frac{d\ln \tau}{dT}$ using MYD L3

- **Thermodynamic phase shifts from ice to liquid**
  
  $\left( \frac{dk_i}{dT} \left( \ln \tau_i(T) - \ln \tau_l(T) \right) \right)$ always *increase* cloud optical depth as temperature warms (expected)

- **Liquid cloud processes** ($k_l(T) \frac{d\ln \tau_l}{dT}$) always *decrease* cloud optical depth as temperature warms — *what are the processes?*

- **Ice cloud processes** ($k_i(T) \frac{d\ln \tau_i}{dT}$) usually *decrease* cloud optical depth as temperature warms

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Hypothesis

**Boundary layer decoupling** drives a net positive extratropical cloud optical depth feedback by optically thinning clouds through Sc to Cu transitions that occur more frequently in a warmer climate.
MODIS Cloud Regimes (CRs) — constrain meteorology

Oreopoulos et al. (2016), JGR

$$\Delta \tau = \sum_{i} \left(\bar{f}_i \Delta \tau_i + \Delta f_i \bar{\tau}_i\right)$$
## Correlation Analysis

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Source of Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau )</td>
<td>MODIS</td>
<td>Cloud optical depth</td>
</tr>
<tr>
<td>SST</td>
<td>AVHRR</td>
<td>Sea surface temperature</td>
</tr>
<tr>
<td>PBL depth</td>
<td>MODIS, AVHRR, AIRS</td>
<td>Planetary boundary layer depth = ( \frac{CTT - SST}{\Gamma} )</td>
</tr>
<tr>
<td>U</td>
<td>AMSR-E/AMSR2</td>
<td>Surface wind speed</td>
</tr>
<tr>
<td>LWP</td>
<td>AMSR-E/AMSR2</td>
<td>Grid-mean liquid water path</td>
</tr>
<tr>
<td>EIS</td>
<td>AIRS</td>
<td>Estimated inversion strength = ( LTS - \Gamma_m^{850}(z_{700} - LCL) )</td>
</tr>
<tr>
<td>LTS</td>
<td>AIRS</td>
<td>Lower tropospheric stability = ( \theta_{700} - \theta_s )</td>
</tr>
<tr>
<td>( \Gamma_m^{850} )</td>
<td>AIRS</td>
<td>Moist-adiabatic ( \theta ) gradient at 850 hPa</td>
</tr>
<tr>
<td>( z_{700} )</td>
<td>MERRA-2</td>
<td>Height of the 700 hPa pressure level</td>
</tr>
<tr>
<td>LCL</td>
<td>AIRS</td>
<td>Lifting condensation level ( \approx 125(T - T_d) )</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>AIRS</td>
<td>CTEI threshold = ( \frac{\Delta \theta_e}{(L/c_p)\Delta q_t} ), ( L ) and ( c_p ) are constants</td>
</tr>
<tr>
<td>( \Delta \theta_e )</td>
<td>AIRS</td>
<td>Changes in potential temperature across inversion</td>
</tr>
<tr>
<td>( \Delta q_t )</td>
<td>AIRS</td>
<td>Change in liquid + vapour water across inversion</td>
</tr>
</tbody>
</table>

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Inferring Cloud Feedbacks

Method #1: Cloud radiative kernel

- $\frac{\partial R}{\partial C} \times \frac{\Delta C}{\Delta T}$ — Cloud radiative kernels, $\frac{\partial R}{\partial C}$ were computed using an offline radiative transfer model

- Multiple kernels with CR histograms ($\Delta C$) and normalize by $\Delta T$ to get cloud optical depth feedback from shifts within and in between Sc and Cu-containing CRs

- Modify kernels & CRs to make them compatible


Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
Inferring Cloud Feedbacks

Method #2: Compositing by EIS and PBL depth

- Variation of Norris & Iacobellis (2005), J. Clim.
- Split EIS, PBL depth and SST into terciles
- Analogous to computing a partial derivative
- Additional control over meteorology

Hold M constant & Compute \( \bar{\tau}_H - \bar{\tau}_L \)

Investigating the extratropical cloud optical depth feedback with MODIS, AIRS, CERES and AMSR
The CMIP5 models show a robustly negative extratropical cloud optical depth feedback (likely mostly due to an overestimated cloud phase feedback).

Recent studies have suggested the possibility of a positive extratropical cloud optical depth feedback, potentially arising from liquid cloud processes.

The goal of TASNPP is to determine the role of boundary layer decoupling in contributing to a positive extratropical cloud optical depth feedback.