Tropical Pacific responses to Neogene Andean uplift and high-latitude sea ice expansion

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Reconstructions of Neogene equatorial Pacific SSTs

Increasing east-west equatorial SST contrast by 2 - 5 °C since the late Miocene with accelerated increase since the middle Pliocene (~3 Ma).

Zhang et al., 2014
Changes in subsurface (thermocline) temperature

~10 °C cooling

~7 °C cooling

How did the tropical Pacific climate evolve into present-day asymmetric state?
Hypotheses

• Existing hypotheses
  – Long-term shoaling of thermocline resulting in cooling due to upwelling of high latitude cold water (Philander and Fedorov, 2003)
  – Closure of the Central American and Indonesian sea way (Cane and Molnar, 2001; Steph et al., 2010)
  – Ocean heat gain due to hurricane mixing (Fedorov et al., 2010),
  – Reduction of meridional gradient of cloud albedo (Fedorov and Burl, 2014)

• Other hypotheses (less studied, but have better proxy support)
  – Uplift of the Andes (Takahashi and Battisti, 2007)
    • An order of 2 km Andean uplift since the 15 Ma agrees with most reconstructions (e.g., Insel et al., 2012)
  – High latitude sea ice expansion (Lee and Poulsen, 2006)
    • Arctic and Antarctic sea ice expansion since ~3 Ma, summer ice free condition during the late Miocene (Polyak et al., 2010) and early Pliocene (13 - 4 Ma) (Mckay et al., 2012)
## Experiment design

- CESM-1.05, 1.9 x 2.5 ° CAM4 and 320 x 384 POP2
- Pre-industrial boundary conditions
- Sensitivity experiments varying the height of the Andes and sea ice extent

<table>
<thead>
<tr>
<th></th>
<th>FltAnd (300 yr)</th>
<th>HlfAnd (300 yr)</th>
<th>ModAnd (300 yr)</th>
<th>HghAnd (300 yr)</th>
<th>CNTL (0.9 x 1.25°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of the Altiplano (15 ° - 23 °S, 65 ° - 70 °W)</td>
<td>144 m</td>
<td>1059 m</td>
<td>2272 m (default)</td>
<td>3184 m</td>
<td>3015 m</td>
</tr>
<tr>
<td>“Sea-ice expansion” experiments</td>
<td>ModIce (default albedo, 500 yr)</td>
<td>LowIce (700 yr)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm ice</td>
<td>0.68</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold ice</td>
<td>0.7</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm snow</td>
<td>0.77</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold snow</td>
<td>0.81</td>
<td>0.1</td>
<td></td>
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</tr>
</tbody>
</table>

Reported results are the last 40-yr averages.
Simulated polar summer sea ice

~50% annual sea ice reduction in LowIce and summer ice free condition
Atmospheric responses to uplift of the Andes

- ~1 °C increase in east-west equatorial SST contrast

Feng and Poulsen, 2014
Atmospheric responses to sea ice expansion

- An 1 °C increase in east-west equatorial SST contrast
- Atmospheric wave responses to the locally enhanced eastern equatorial cooling
Surface energy budget across the eastern equatorial Pacific

<table>
<thead>
<tr>
<th>Radiative fluxes averaged over (10°S – 10°N, 120° - 90°W)</th>
<th>SW (W/m²)</th>
<th>LW (W/m²)</th>
<th>LH (W/m²)</th>
<th>SH (W/m²)</th>
<th>Net surface fluxes (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ModAnd - NoAnd -8.2 -1.7 -2. -0.2 -11.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ModIce - LowIce 1.6 5.6 -8. 0.9 0.1</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- In response to Andean uplift, cooling is primarily a result of reduction of solar flux at the surface → atmospheric driving process
- In response to sea-ice expansion, net surface flux contribution is minimal or even opposite to cooling → primarily ocean driven process.
Reponses of clouds and zonal circulation to Andean uplift

- Development of anomalous **zonal circulation cell** along the flank of Andes leads to **reduction of deep convection and increase in low clouds**.

Feng and Poulsen, 2014
Ocean responses to sea ice expansion

- High latitude cooling due to sea ice expansion
- Strengthened Southern Ocean westerlies due to increasing meridional SST gradient
Both Andean uplift and sea-ice expansion lead to an increase of equatorial Pacific SST asymmetry by ~1 °C. The collective effect of both is close to the reconstructed lower bound of the late Neogene SST proxies (~2 – 3 °C, Zhang et al., 2014).

However, neither of these processes by itself leads to coupled ocean-atmospheric responses to enhance the original cooling. Yet, it is possible that the combination of both may lead to synergy effects, which requires further tests.

Conclusion
Thank you!

• Questions?
Simulated SST of the mid-Pliocene warm period

Sea surface temperate change

mPWP – pre-Industrial

CCSM4 almost produces opposite changes in equatorial Pacific SST asymmetry mPWP simulations.
Andean elevations in the model
Global mean surface temperature

- FltAnd: 288.0672651040455
- ModAnd: 287.8775810598528
- ModIce: 287.6187308262697
- IntIce: 290.0289917545709
- LowIce: 291.6596174844995
### Summary of the atmospheric responses

<table>
<thead>
<tr>
<th></th>
<th>Western equatorial pacific</th>
<th>Middle equatorial Pacific</th>
<th>Eastern equatorial Pacific</th>
</tr>
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<tbody>
<tr>
<td><strong>Uplift of the Andes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clouds</td>
<td>Little</td>
<td>Reduction</td>
<td>Increase in low cloud</td>
</tr>
<tr>
<td>Sea level pressure</td>
<td>Little</td>
<td>Little</td>
<td>Higher by up to 1.5 hPa</td>
</tr>
<tr>
<td>Circulation</td>
<td>Enhanced surface easterlies and upward motion</td>
<td>Tropospheric subsidence</td>
<td>Subsidence branch of diabatic cell</td>
</tr>
<tr>
<td>SST</td>
<td>Little</td>
<td>Small cooling (0.4 °C)</td>
<td>Cooling (0.4 – 0.8 °C)</td>
</tr>
</tbody>
</table>

### Sea ice expansion

<table>
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<th>Eastern equatorial Pacific</th>
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<tr>
<td>Clouds</td>
<td>Enhance high cloud formation</td>
<td>Reduction</td>
<td>Increase in deep convection</td>
</tr>
<tr>
<td>Sea level pressure</td>
<td>-25 ~ -50 Pa</td>
<td>Similar to eastern side</td>
<td>-25 ~ -50 Pa</td>
</tr>
<tr>
<td>Circulation</td>
<td>Enhanced surface easterlies and upward motion</td>
<td>Subsidence, lower troposphere divergence</td>
<td>Lower troposphere convergence</td>
</tr>
<tr>
<td>SST</td>
<td>Cooling by ~1 – 2 °C</td>
<td>Similar to eastern side</td>
<td>Cooling by ~2 – 3 °C</td>
</tr>
</tbody>
</table>
Ocean responses to Andean uplift

- Tropical-subtropical cell
- Northward migration of subsidence source water and weakening of the cell
- Warmer tropical Pacific subsurface water due to weakened tropical-subtropical cell and northward migration of subtropical source water
Andes elevation and simulated sea ice coverage in the CCSM4 mPWP simulations

Simulated mPWP sea ice reduction is far less than suggested by proxies. Perennial and extensive summer sea ice still persists in the model results.
Late Neogene Andean uplift

An order of 2 km Andean uplift since 15 Ma agrees with most reconstructions.

linkage to the long-term cooling trend in the eastern equatorial Pacific?
Response of strength of boundary cap

- Stronger convective cap above the boundary layer

Denser contour: higher moist static stability
Response of AMOC to sea ice expansion

~20% reduction in AMOC strength
Summer sea-ice free arctic and southern ocean during the early and middle Pliocene (prior to ~ 3 Ma)

Linkage to more recent accelerated increase in tropical Pacific climate asymmetry?
Wara et al, 2005

Zhang et al., 2014