# Improving ozone dry deposition to the ocean and lightning-produced oxides of nitrogen ($NO_x$) in UKCA


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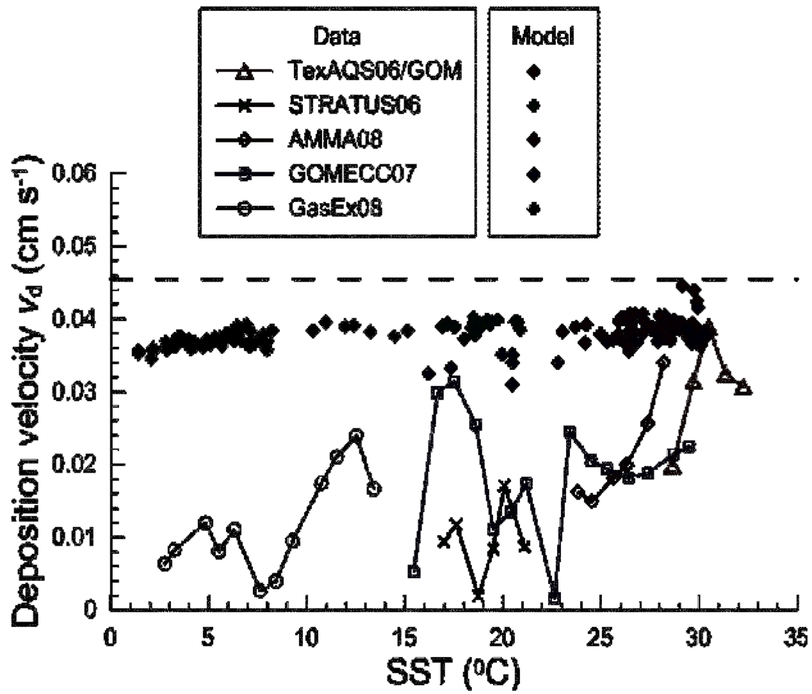
# Acknowledgements


- Martin Dix (CSIRO)
- UK Met Office (Fiona O'Connor, Mohit Dalvi)
- NCI computing facility
- Various data sources as cited

# (1) Dry deposition of ozone ($O_3$) to the ocean

- Dry deposition of ozone at the surface is a significant sink
- Current estimate of global $O_3$ dry deposition (IPCC AR5; Young et al., 2013):
  - 1094 ± 264 Tg $O_3$ $yr^{-1}$, of which 300-350 Tg $O_3$ $yr^{-1}$ is to water
  - Deposition to water has the largest uncertainty (Hardacre et al., 2015)
- Deposition velocity is calculated as $v_d = 1/(r_a + r_b + r_c)$
  - For water, surface resistance $r_c$ is the dominant term
- Most models, including UKCA, assume $r_c$ ~ 2000 s/m (Wesely, 1989)
  - Comparison of the ACCESS-UKCA (essentially UM-UKCA@vn8.4) ozone deposition velocities ($v_d$) with the cruise-based measurements of Helmig et al. (2012)
  - Model overestimates by a factor of 2–4 (Luhar et al., ACP, 2017)

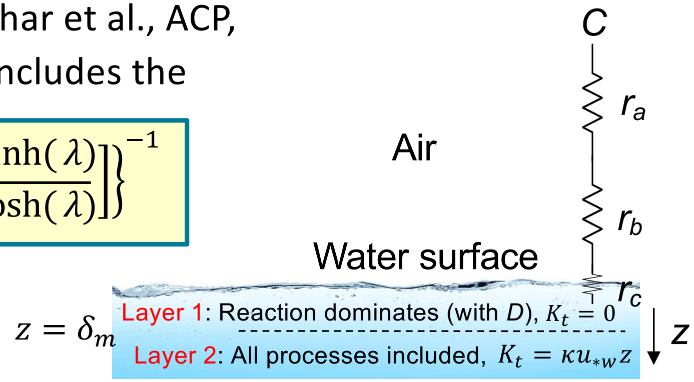


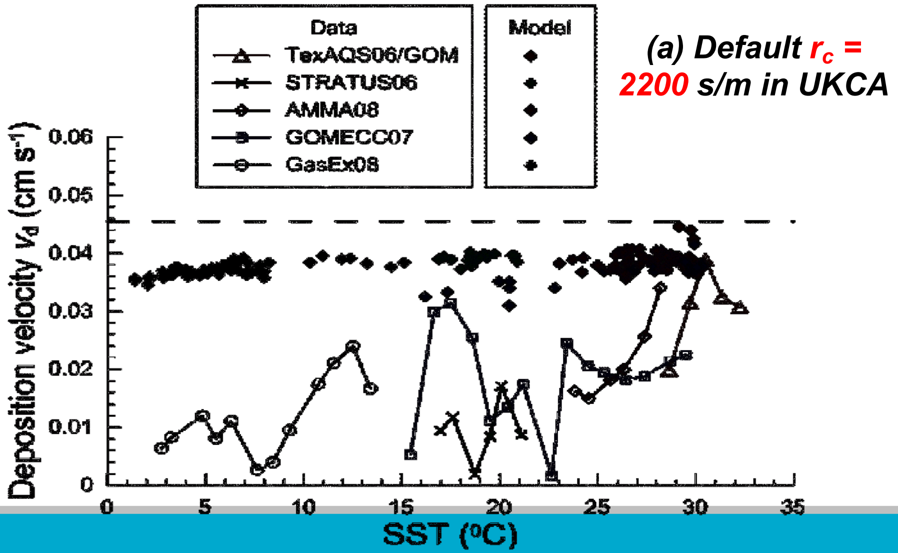
# Improving $O_3$ dry deposition to the ocean

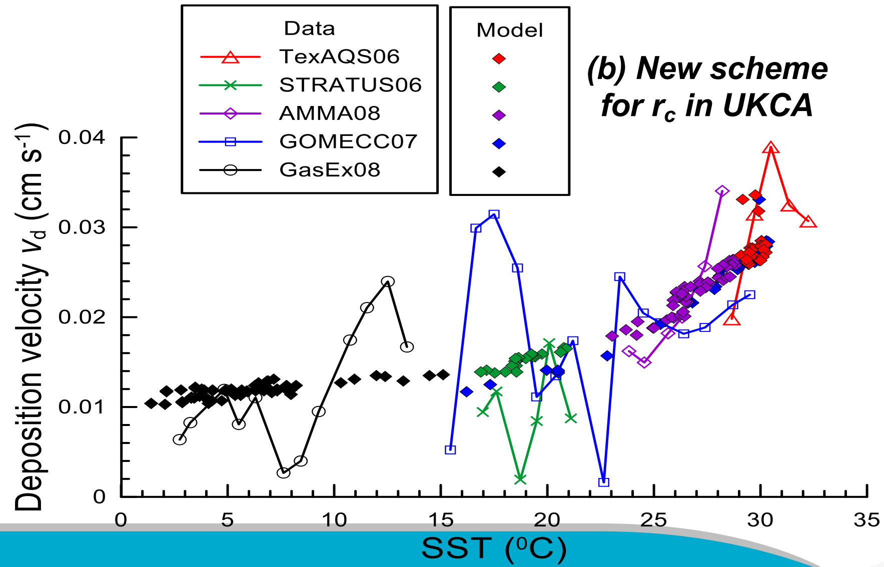
- A new process-based two-layer scheme for $r_c$ for seawater was developed (Luhar et al., ACP, 2018) based on mass and flux conservation equations (Fairall et al., 2007). It includes the following waterside processes:
  - solubility of ozone ($\alpha$)
  - molecular diffusion ($D$)
  - turbulent mixing ($K_t$)
  - chemical reaction of ozone with dissolved iodide ($a = k.\,[I^-]$)

$$r_c = \frac{1}{\alpha}\left\{(aD)^{1/2}\left[\frac{\psi K_1(\xi_\delta)\cosh(\lambda) + K_0(\xi_\delta)\sinh(\lambda)}{\psi K_1(\xi_\delta)\sinh(\lambda) + K_0(\xi_\delta)\cosh(\lambda)}\right]\right\}^{-1}$$

$K_0$, $K_1$ modified Bessel functions, $\delta_m = c_0(D/a)^{1/2} \approx 3\ \mu\text{m}$

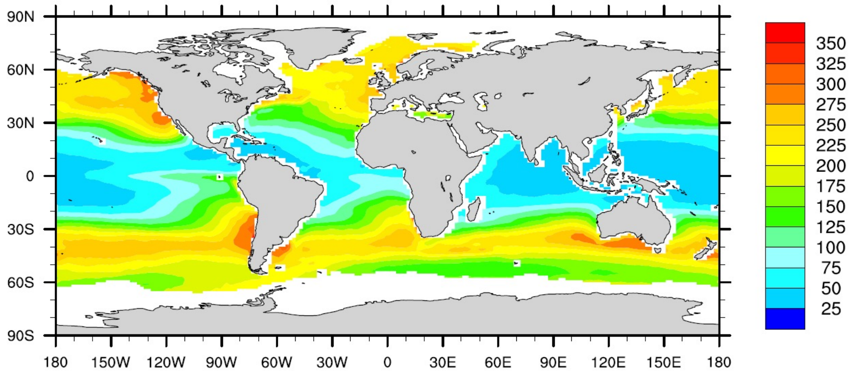


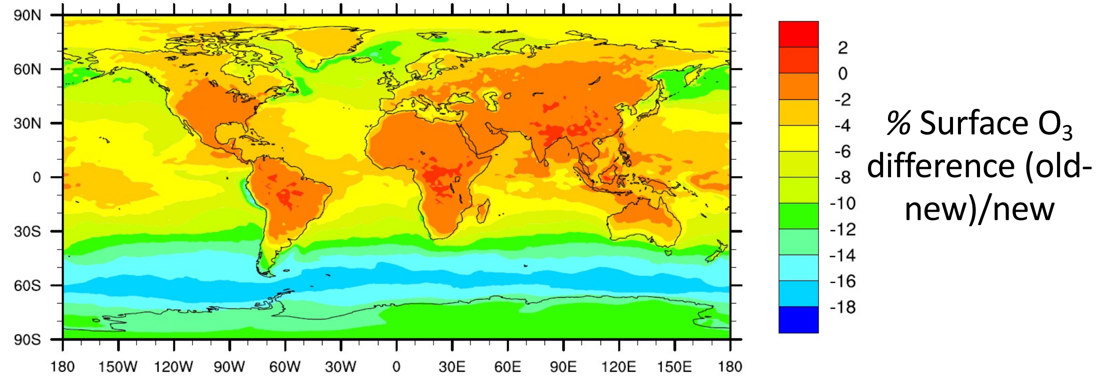



# Impact of the new oceanic deposition scheme

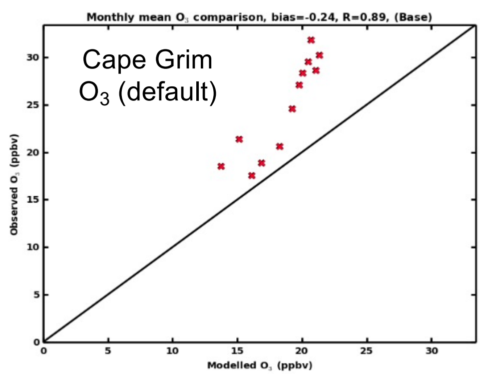
- % Overestimation of deposition velocity by the default scheme ($r_c$ = 2200 s/m) compared to the new scheme

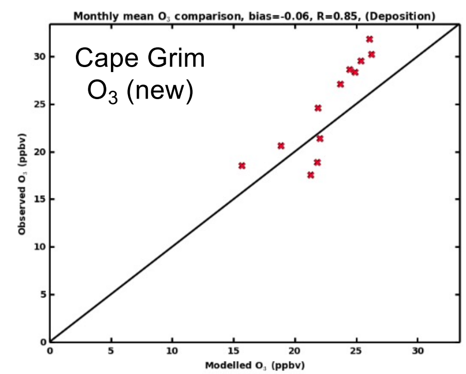



- Increase in near-surface $O_3$, by up to 16% in the mid to high latitudes in the Southern Hemisphere




- Tropospheric ozone improves compared to measurements (e.g. Cape Grim, Tasmania)



| *Method* | *Ocean* | *Land* | *Global total* |
|---|---|---|---|
| **Galbally and Roy (1980)** | **491** | **600** | **1091** |
| **Stevenson et al. (2006)** | **-** | **-** | **1003 ± 200** |
| **Wild (2007)** | **-** | **-** | **949 ± 222** |
| **Ganzeveld et al. (2009)** | **291.5** | **543.5** | **835** |
| **Hardacre et al. (2015)** | **340** | **638** | **978 ± 127** |
| **IPCC AR5** | **-** | **-** | **1094 ± 264** |
| **ACCESS-UKCA (new)** | **98.4 ± 30** | **624.4 ± 82** | **722.8 ± 87.3** |

- **Impact of the new oceanic deposition scheme**
  - The ozone deposition to the ocean is reduced from ~300 to ~100 Tg $O_3$ $yr^{-1}$ (by ~65% over the current estimates)
  - 20% reduction in total global deposition (~1000 to ~800 Tg $O_3$ $yr^{-1}$)
  - Deposition to land is similar to other studies
  - Tropospheric $O_3$ burden increases from 252 Tg to 273 Tg (correct trend compared to $O_3$ climatologies)
  - Impact on tropospheric $O_3$ radiative forcing

- **Adoption of the new scheme**
  - Committed to the UM trunk@vn11.4 (ticket #4020)
  - In the GEOS-Chem model (Pound et al., 2020, ACP)
  - In the WRF-Chem model (Barten et al., 2020, ACPD)

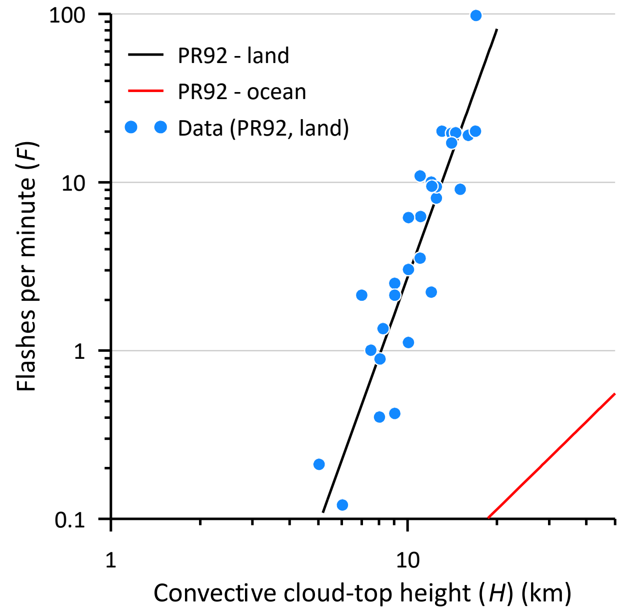
# (2) Lightning-produced $NO_x$

- Lightning-produced $NO_x$ (or $LNO_x$) is ~ 10% of the global $NO_x$ source, but its ozone production efficiency per unit $NO_x$ is an order of magnitude higher than the surface $NO_x$
- Of all $NO_x$ sources, $LNO_x$ is the biggest contributor to tropospheric ozone in the Southern Hemisphere (Grewe, 2007)
- $LNO_x$ is a major source of ozone bias in global chemistry models – large uncertainty: 2 – 8 Tg N $yr^{-1}$ (Schumann and Huntrieser, 2007)
- $LNO_x$ = Lightning flash rate x NO emitted per flash
- Most global chemistry models, including UKCA, use Price and Rind's (1992, PR92) parameterisations for lightning flash-rate (*F*) which are functions of convective cloud-top height (*H*)

Price and Rind (1992)

$$\text{Land} \quad F_L = 3.44\times10^{-5}\, H^{4.9}$$

$$\text{Ocean} \quad F_O = 6.4\times10^{-4}\, H^{1.73}$$

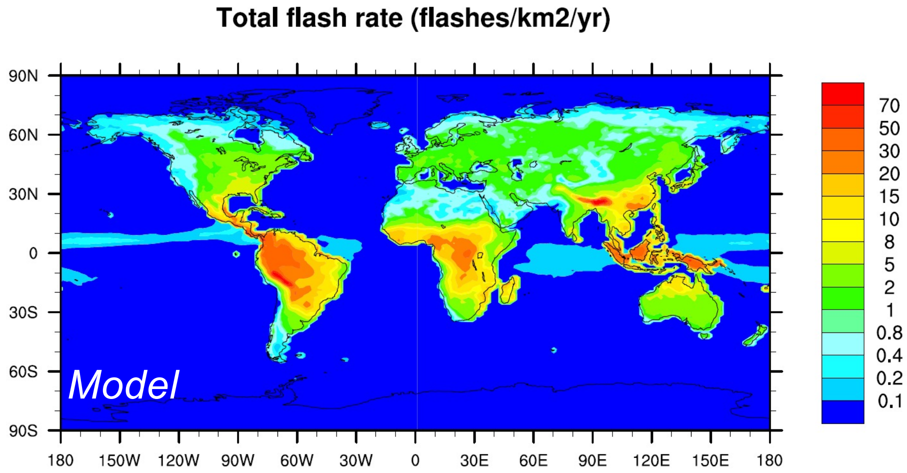


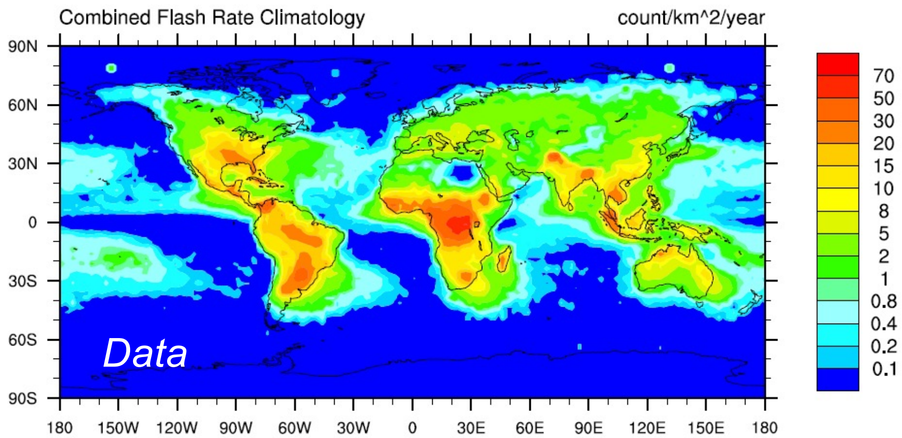

Oceanic flash rates smaller by 2 orders of magnitude

# ACCESS-UKCA performance for lightning flash rate

– UM-UKCA vn 11.0 lightning routines backported to vn 8.4; year 2006

– Comparison with LIS/OTD satellite data (Cecil et al., 2014)




– The simple PR92 parameterisation work rather well over land, but the observed oceanic flash rate is severely underestimated (a known result)

**Total observed and modelled lightning flash frequency (count $s^{-1}$)**

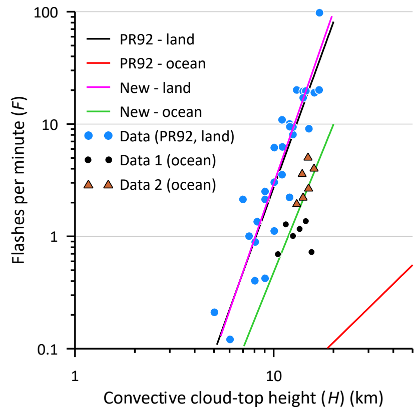
| | Global | Land | Ocean | Northern Hemisphere | Southern Hemisphere |
|---|---|---|---|---|---|
| Data - climatology | 46.2 | 38.3 | **7.9** | 27.0 | 19.2 |
| ACCESS-UKCA | 32.9 | 32.5 | **0.4** | 16.2 | 16.7 |

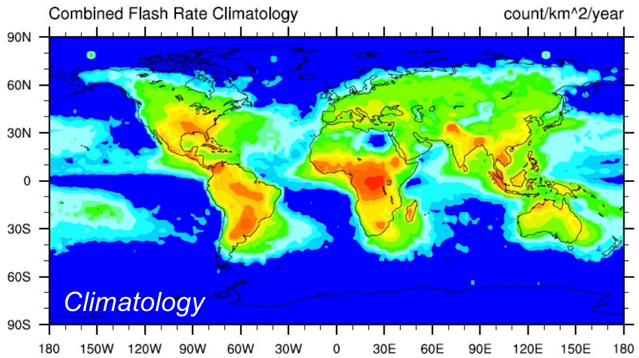
# Improving the lightning flash-rate parameterisations

- Boccippio (2002) derived a fundamental scaling relationship between thunderstorm electrical generator power and storm geometry:

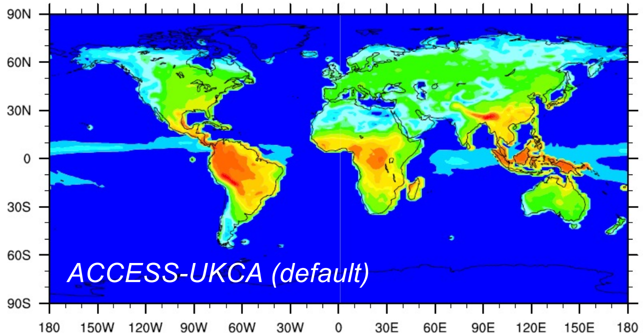
$$F_{L,O} = k_1 \, k_{L,O} \, H^{a_{L,O}+4}$$

- Using intermediate steps and available data the coefficients are derived
- New relationships: $F_L = 2.4 \times 10^{-5} H^{5.09}, \; F_O = 2.0 \times 10^{-5} H^{4.38}$

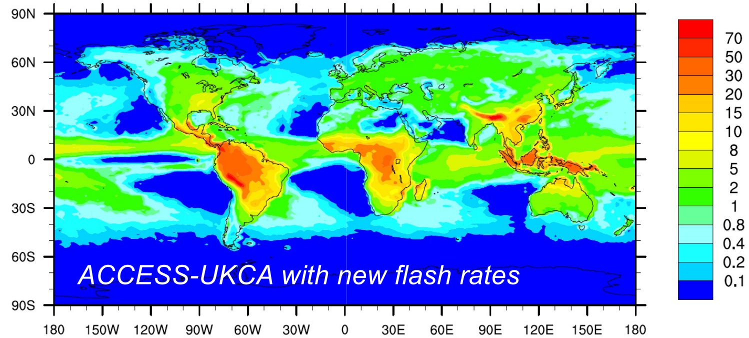



**Total flash rate (flashes/km2/yr)**




**Total flash rate (flashes/km2/yr)**




**Observed and modelled lightning flash frequency (count $s^{-1}$)**

| | Global | Land | Ocean | N. Hemisph. | S. Hemisph. |
|---|---|---|---|---|---|
| Data – climatology | 46.2 | 38.3 | **7.9** | 27.0 | 19.2 |
| Data – year 2006 | 43.4 | 34.5 | **8.9** | 24.3 | 19.1 |
| ACCESS-UKCA | 32.9 | 32.5 | **0.4** | 16.2 | 16.7 |
| ACCESS-UKCA (new) | 45.0 | 36.0 | **9.0** | 23.1 | 21.9 |

- Although there are some significant spatial differences, the new oceanic flash rate parameterisation in ACCESS-UKCA gives much better results

# Impact on tropospheric composition

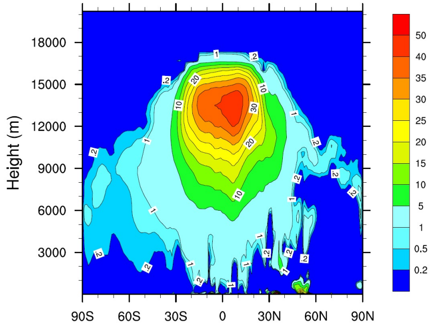
- Total $LNO_x$: 38% increase from 4.8  to 6.6 Tg N/yr (cf. 6.3 ± 1.4 Tg N/yr, Miyazaki et al., 2014, based on satellite data assimilation in a global CTM); 330 moles NO per flash used in both (cf. 310 by Miyazaki et al.)

- $NO_x$ (pptv, as $NO_2$)

  Global increase by 15.7% (8.7 pptv)

  An increase by as much as 40 pptv in the mid to upper troposphere

Zonal $NO_x$ difference (new – default), pptv



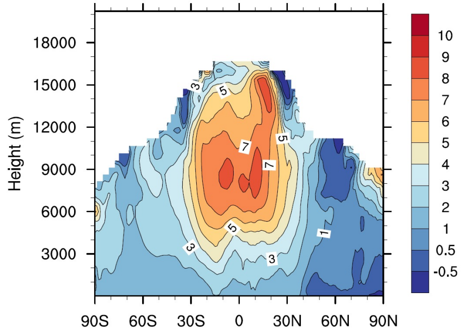

- Ozone (ppbv)

  A global $O_3$ increase by 8% (4.1)

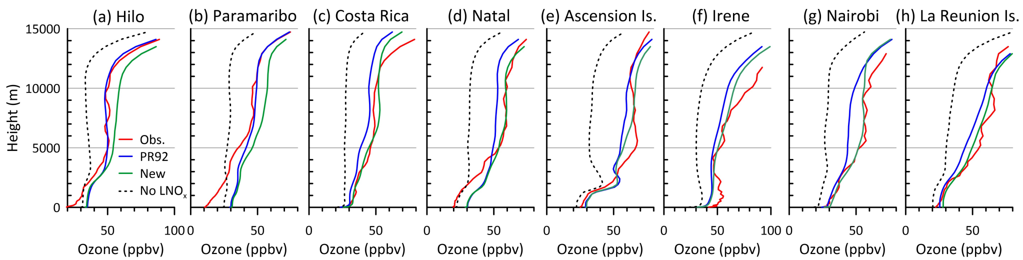
  Surface $O_3$ increases by 2 ppbv in the Southern Hemisphere, and 0.5–2 ppb in the Northern Hemisphere.

  Tropospheric $O_3$ burden increases from 284 to 308 Tg (cf. 337 Tg, IPCC AR5)

Zonal $O_3$ difference (new – default), ppbv




Comparison with Southern Hemisphere ADditional OZonesondes (SHADOZ) ozonesonde data



- **Other species**
  - Hydroxyl (OH) radical increases by 13% globally (16.3% over the ocean and 7.6% over land)
  - Methane lifetime decreases by 6.7%
  - Carbon monoxide (CO) decreases by 5.6% globally (6.2% over the ocean and 4.5% over land)
- Larger impact over the southern hemisphere
- Implications for radiative forcing

- Paper in ACPD (Luhar et al., 2020, https://acp.copernicus.org/preprints/acp-2020-885/)
- The new lightning scheme has been committed to the UM trunk@vn11.8 (ticket # 5713)