Introduction to Drought Hazard

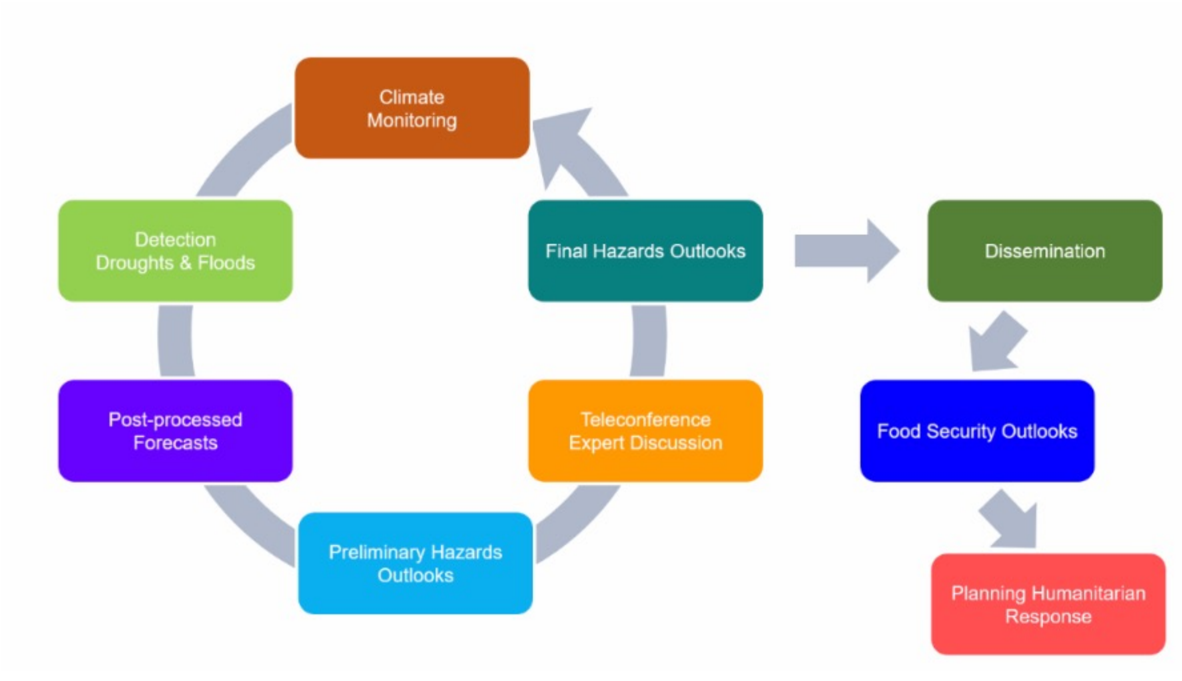
Li Xu [1,2] Miliaritiana Robjhon [1,2] Yutong Pan [1,2] Wassila Thuaw[1] and Yun Fan [1]
1. Climate Prediction Center, NOAA/NWS/NCEP, College Park, Maryland
2.ERT LLC., Laurel, Maryland

PREPARE Drought and Flood Early Warning for Central Pacific Islands
Nadi, Fiji, 15-20 July 2024

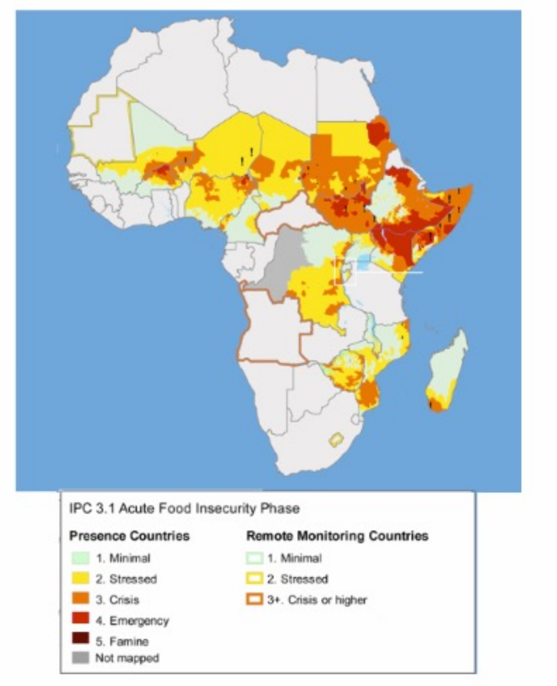
Food Security Early Warning

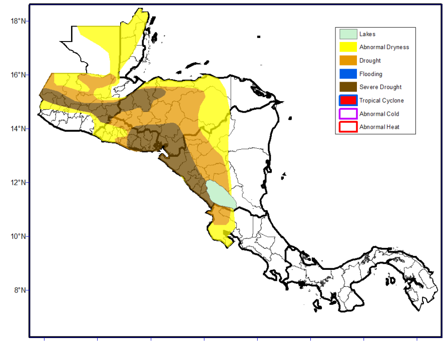
FEWS NET
Famine Early Warning Systems Network

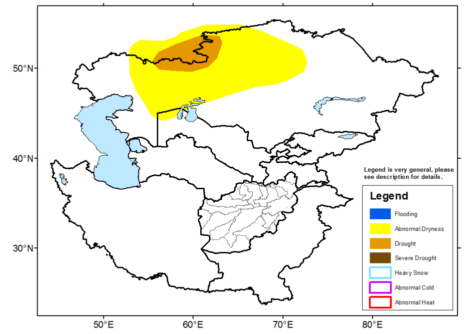
Integrating weather, climate, and land information to inform humanitarian response planning.



(Thiaw and Kumar, 2015)







- CPC International Desk issues hazards outlooks that integrate weather, climate, land surface information and global model forecasts.
- Drought is one of the dominant natural hazards that could devastate many economic sectors, especially in the developing world.
- Drought monitors and outlooks are primary input for the FEWS NET food security outlooks that help decision makers plan for and respond to humanitarian crisis

CPC Global drought monitors and outlooks

- Purpose:
  - To monitor in near-real time drought onset and evolution to support the hazards outlooks over international food insecure regions
  - Hazards outlooks serve as basis for food security outlooks of the USAID Famine Early Warning Systems Network (FEWS NET)
  - To provide access to reliable drought indicators and indices to global stakeholders and international users
  - Global coverage, focus on the regions that exhibit food security vulnerability

https://www.cpc.ncep.noaa.gov/products/international/drought/drought.shtml

Definition of Drought

A period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance. Drought is a relative term, therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. (**American Meteorological Society Glossary of Meteorology**)

- Drought is a complex phenomenon
- No single physical indicator defines all aspects of drought
- There is a need to use multiple indicators including the forecasters/experts judgments

Droughts cause a range of impacts and are often worsened by the effects of climate change on the water cycle: a dry riverbed in France; sandstorm in Somaliland due to drought; droughts negatively impact agriculture in Texas; drought and high temperatures worsened the 2020 bushfires in Australia.

Drought : Convergence of Evidence

- Meteorological drought
  - Precipitation deficient (anomalous, anom. percent etc.) at multiple time scale, from 1week to 2 years
  - Multiple data source: gauge based, satellite retrieval etc.
  - Standardized Precipitation Indices (SPIs), from 1,3,6,12 to 24 months accumulated Prcp
  - Standardized Precipitation-Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010)
- Hydrological Drought
  - Standardized Runoff Indices (SRIs)
- Agricultural Drought
  - Soil Moisture anomalies and tendencies
  - Soil Moisture Percentile (SMP)
- Evapotranspiration related drought indices
  - Evaporative Demand Drought Index (EDDI): (Hobbins et al. 2016)
  - Evaporative Stress Index (ESI)
- Vegetation Health Index (VHI)

Objective Drought Categories

Category	Description	Possible Impacts	Ranges: Palmer Drought Severity Index (PDSI)	CPC Soil Moisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardized Precipitation Index (SPI)	Objective Drought Indicator Blends (Percentiles)
D0	Abnormally Dry	Going into drought: • short-term dryness slowing planting, growth of crops or pastures Coming out of drought: • some lingering water deficits • pastures or crops not fully recovered	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate Drought	• Some damage to crops, pastures • Streams, reservoirs, or wells low, some water shortages developing or imminent • Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe Drought	• Crop or pasture losses likely • Water shortages common • Water restrictions imposed	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme Drought	• Major crop/pasture losses • Widespread water shortages or restrictions	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5

The same as the NDMC standard, but without exceptional drought (D4) due to observational records limitation.

Drought Impacts

D0 - Abnormally Dry

- Short-term dryness slowing planting, growth of crops or pastures.
- Some lingering water deficits
- Pastures or crops not fully recovered

53.3%
of U.S.
(D0–D4)

D1 - Moderate Drought

- Some damage to crops, pastures
- Streams, reservoirs, or wells low, some water shortages developing or imminent
- Voluntary water-use restrictions requested

36.9%
of U.S.
(D1–D4)

D2 - Severe Drought

- Crop or pasture loss likely
- Water shortages common
- Water restrictions imposed

25.9%
of U.S.
(D2–D4)

D3 - Extreme Drought

- Major crop/pasture losses
- Widespread water shortages or restrictions

18.3%
of U.S.
(D3–D4)

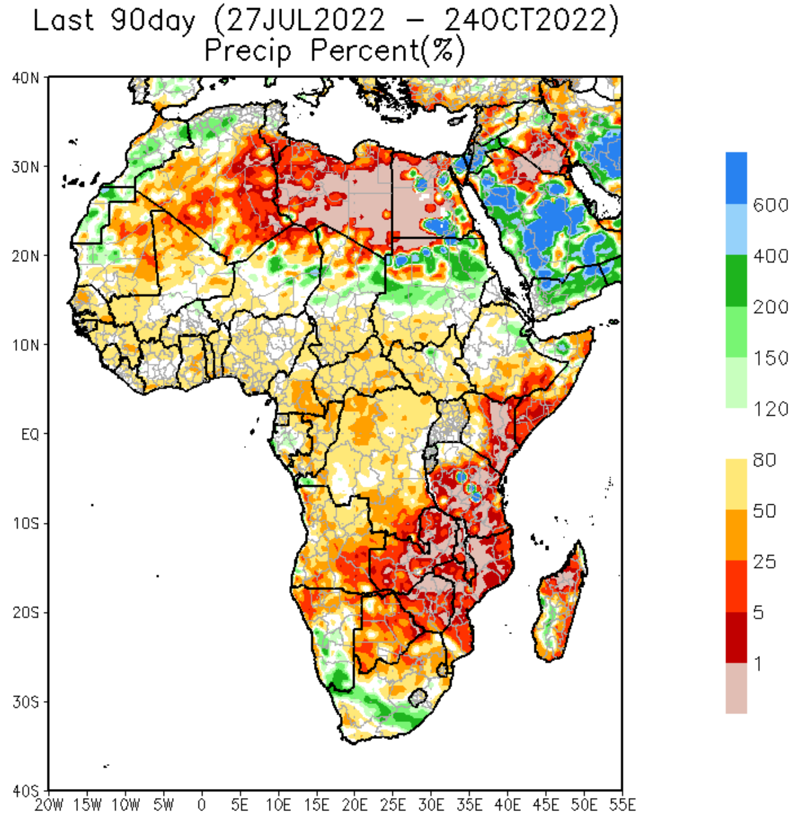
D4 - Exceptional Drought

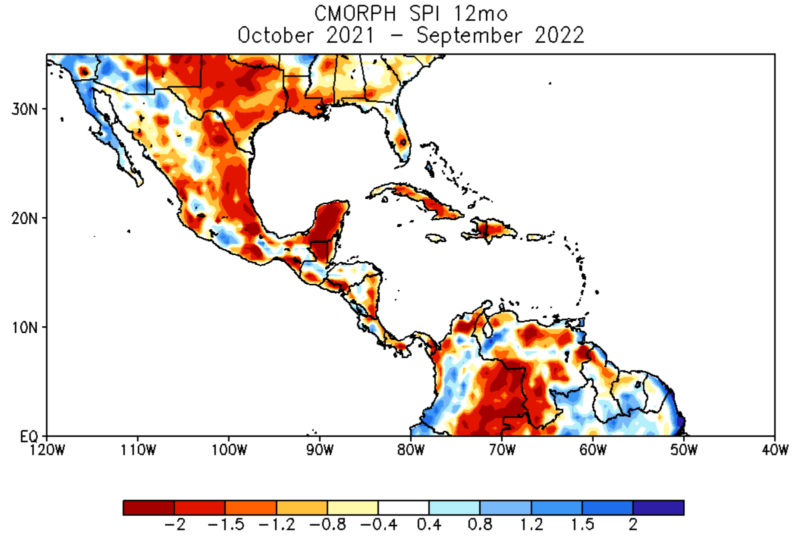
- Exceptional and widespread crop/pasture losses
- Shortages of water in reservoirs, streams, and wells creating water emergencies

8.1%
of U.S.
(D4)

Meteorological drought

- Precipitation deficient
  - CPC unified PRCP analysis (gauge based, global 0.5x0.5)
  - CPC CMORPH (satellite retrieval, global 0.25x0.25)
  - African Rainfall Estimation Algorithm Version 2 (**RFE** 2.0)
  - Multi-scale monitor
    - 7day,14day,30day,60day,90day,180day,1yr,1.5yr and 2yr
- Standardized Precipitation index (SPI)
  - SPI1, SPI3,SPI6, SPI12 and SPI24



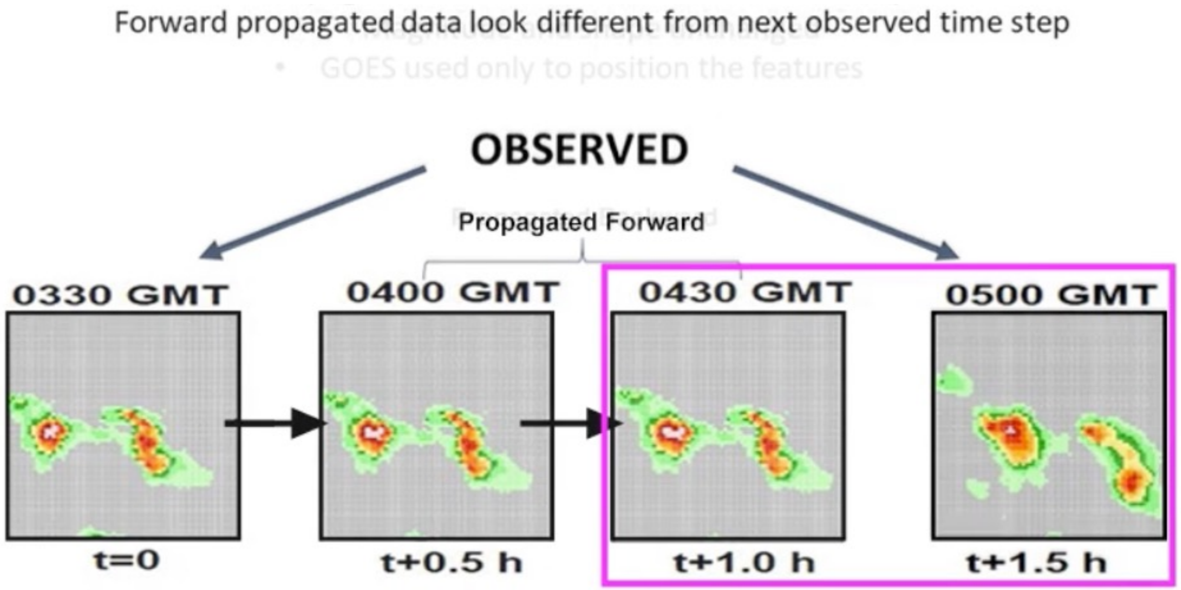


Standardized Precipitation Indices (SPIs)

- a widely used index to characterize meteorological drought on a range of timescales (1-36 months)
- **Key Strengths:**
  - Uses precipitation only; can characterize drought or abnormal wetness at different time scales which correspond with the time availability of different water resources (e.g. soil moisture, snowpack, groundwater, river discharge and reservoir storage)
  - More comparable across regions with different climates than the Palmer Severity Drought Index (PDSI)
- **Key Limitations:**
  - As a measure of water supply only, the SPI does not account for evapotranspiration, and this limits its ability to capture the effect of increased temperatures (associated with climate change) on moisture demand and availability
  - Sensitive to the quantity and reliability of the data used to fit the distribution; 30-50 years recommended

CMORPH（Merged Satellite Precipitation)

- CMORPH (CPC MORPHing technique) is generated by the Climate Prediction Center (CPC) of the U.S. National Oceanic and Atmospheric Administration (NOAA).
- CMORPH uses precipitation estimates that have been derived from low-Earth orbiting microwave satellites and then interpolates the precipitation features in between microwave overpasses based on the higher temporal resolution information from geostationary satellite infrared (IR) data.
- GOES satellite data govern only the movement of precipitation features. For magnitude and shape of the precipitating area at each time step the microwave data become important. A time-weighted interpolation is applied to the two most recent microwave-derived rain rate products. IMERG late (IMERG-L) uses a similar morphing technique with an additional calibration.



Grid Resolution: 0.07277 degrees lat/lon (8 km at the equator)
Temporal Resolution: 30 minutes
Domain: Global (60N - 60S)
Period of Record: December 3, 2002 to present

Joyce, R. J., J. E. Janowiak, P. A. Arkin, and P. Xie, 2004: CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution.. J. Hydromet., 5, 487-503.

Background: Relevance of E_0 to drought

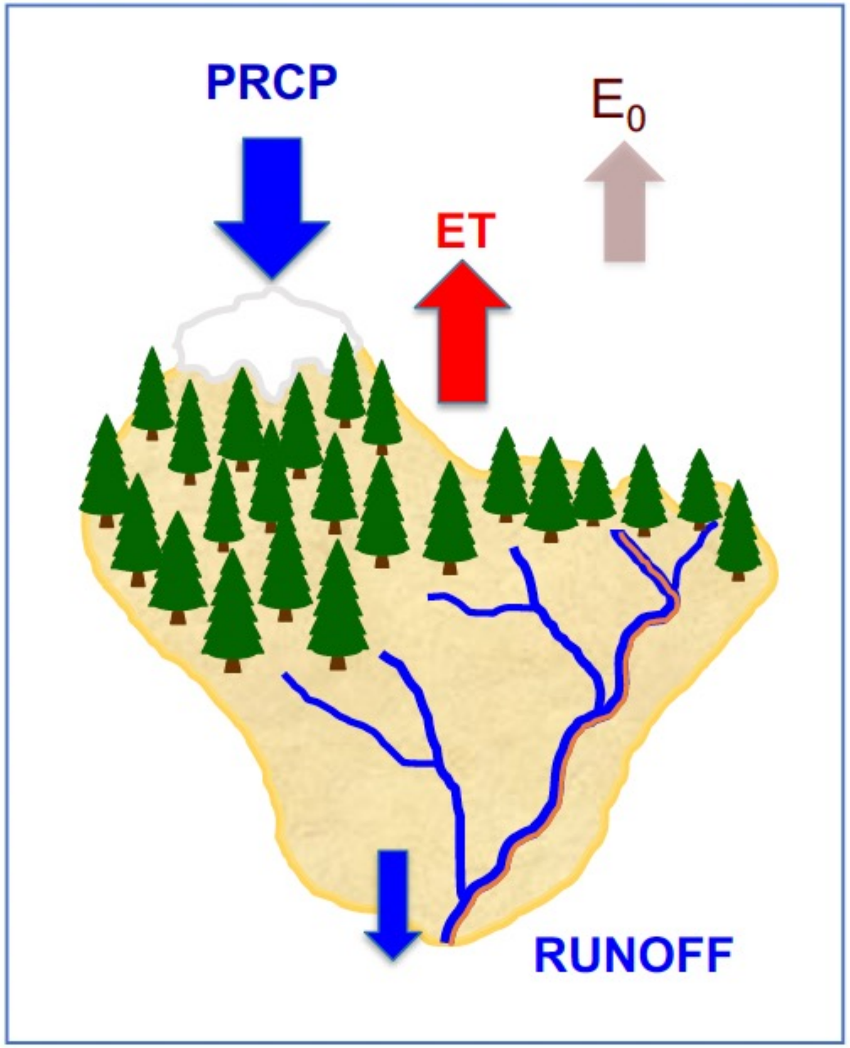
Water balance on a land surface:

~ $f(Prcp, ET)$

where *ET* is driven by:

- evaporative demand (E_0),
- surface moisture status.

Drought = imbalance of supply to, and demand for, surface moisture



Evapotranspiration drought indices

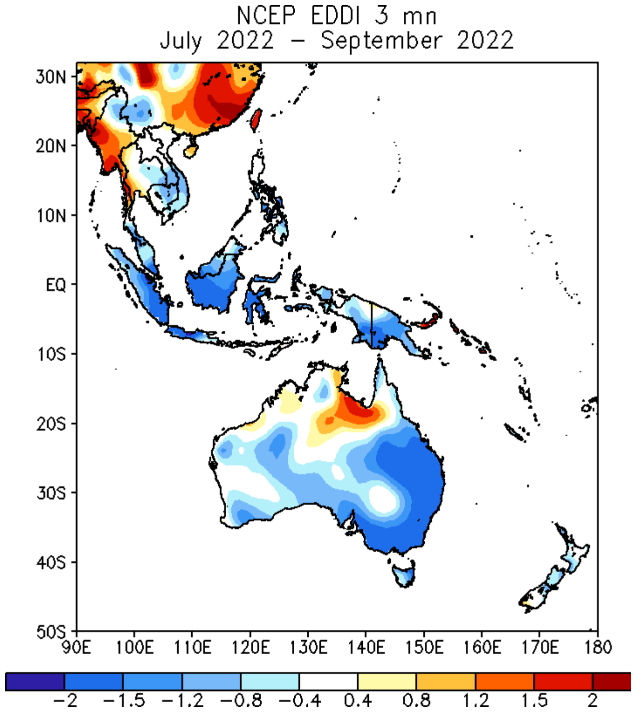
- EDDI
  - Transferred from the PSL (Hobbins et al. 2016)
  - NCAR/NCEP reanalysis as historical input
  - CDAS for real-time
- SPEI
  - reference evapotranspiration (ET_o): FAO **Penman-Monteith equation** instead of Thornthwaite (1948) equation
  - **PRCP:** from CMORPH

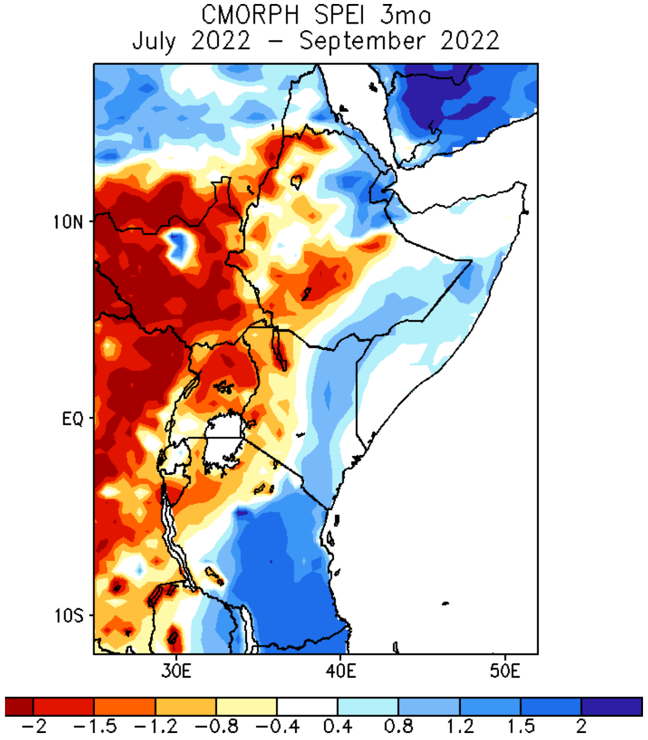
$$E_0 \approx ET_0 = \underbrace{\frac{0.408\Delta}{\Delta+\gamma(1+C_d U_2)}(R_n - G)\frac{86400}{10^6}}_{\text{Radiative forcing (sunshine, } T)} + \underbrace{\frac{\gamma \frac{C_n}{T}}{\Delta+\gamma(1+C_d U_2)} U_2 \frac{(e_{sat}-e_a)}{10^3}}_{\text{Advective forcing (wind, humidity, } T)}$$

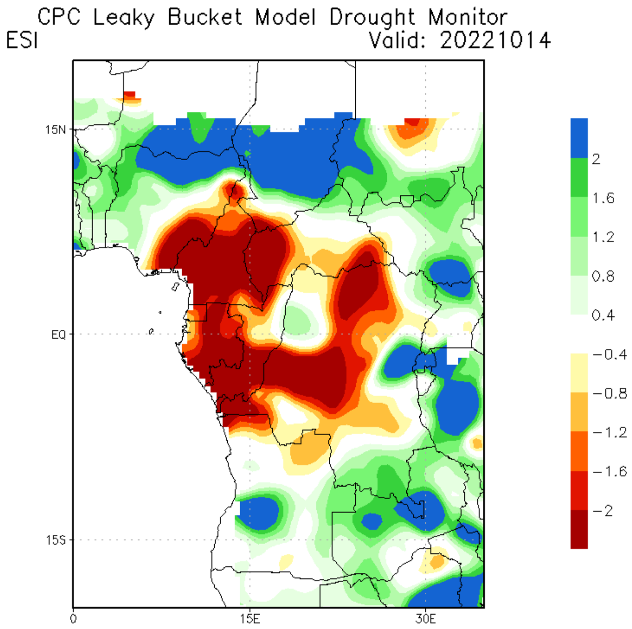
Radiative forcing (sunshine, *T*)

Advective forcing (wind, humidity, *T*)

- ESI
  - Based on the evaporation from Leaky Bucket model







Standardized Precipitation-Evapotranspiration Index (SPEI)

- Vicente-Serrano et al. (2010), Beguería et al. (2010), Beguería et al. (2014)

$$D_i = P_i - PET_i$$

- **PET estimation**
  - **Thornthwaite (1948)** : only for month mean estimate
  - **Hargreaves (1985):** improved for the daily estimation by energy balance, need extra Tmax/Tmin (FAO **alternative equation for ET_o when weather data are missing),** ***solar Radiation data derived from air temperature differences,*** tendency to underpredict under high wind conditions (u_2 > 3 m/s) and to overpredict under conditions of high relative humidity
  - **Penman-Monteith (1965) FAO recommendation,** required more meteorological variables, i.e. solar radiation, specific humidity and wind speed etc. Tons of assumptions. vegetation, ground heat flux, albedo etc. reference ET which assumes constant vegetated land surface (i.e., by definition, does not include and consider effect of any land surface heterogeneity)
  - **Model explicit physics by Penman equation:** consider global land surface heterogeneity

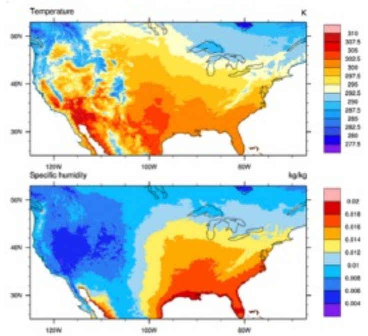
- **Distribution**
  - Negative values, P<PET
  - Highly skewed, Pearson III, Lognormal, Log-logistic(fisk)
  - Rank-based non-parametric standardized indices (Hao Z., AghaKouchak A., 2014)

Background: How is EDDI calculated?

Meteorological Inputs

temperature, humidity, wind speed, solar radiation

NLDAS-2, 12-km gridded, daily



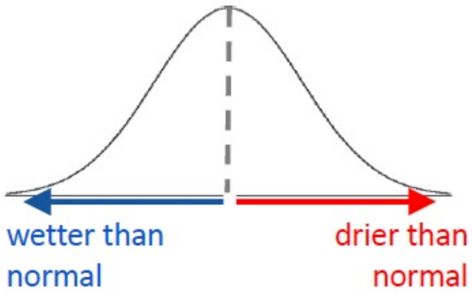
Reference Evapotranspiration calculation

Penman-Monteith FAO56

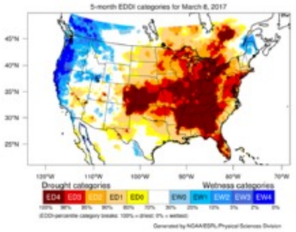
$$E_0 \approx ET_0 = \underbrace{\frac{0.408\Delta}{\Delta+\gamma(1+C_dU_2)}(R_n - G)\frac{86400}{10^6}}_{\text{Radiative forcing (sunshine, } T)} + \underbrace{\frac{\gamma\frac{C_n}{T}}{\Delta+\gamma(1+C_dU_2)}U_2\frac{(e_{sat}-e_a)}{10^3}}_{\text{Advective forcing (wind, humidity, } T)}$$

Rank-based non-parametric standardization

based on historic climatology of ET_0



EDDI

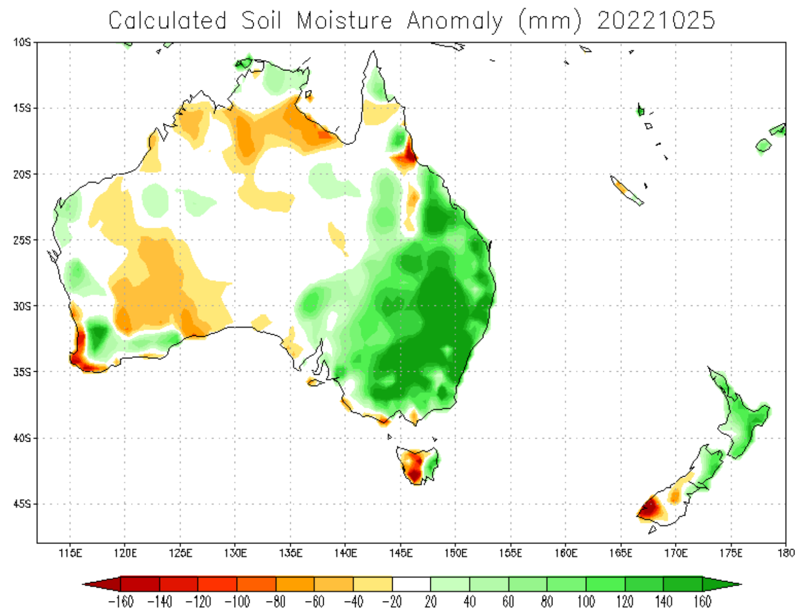


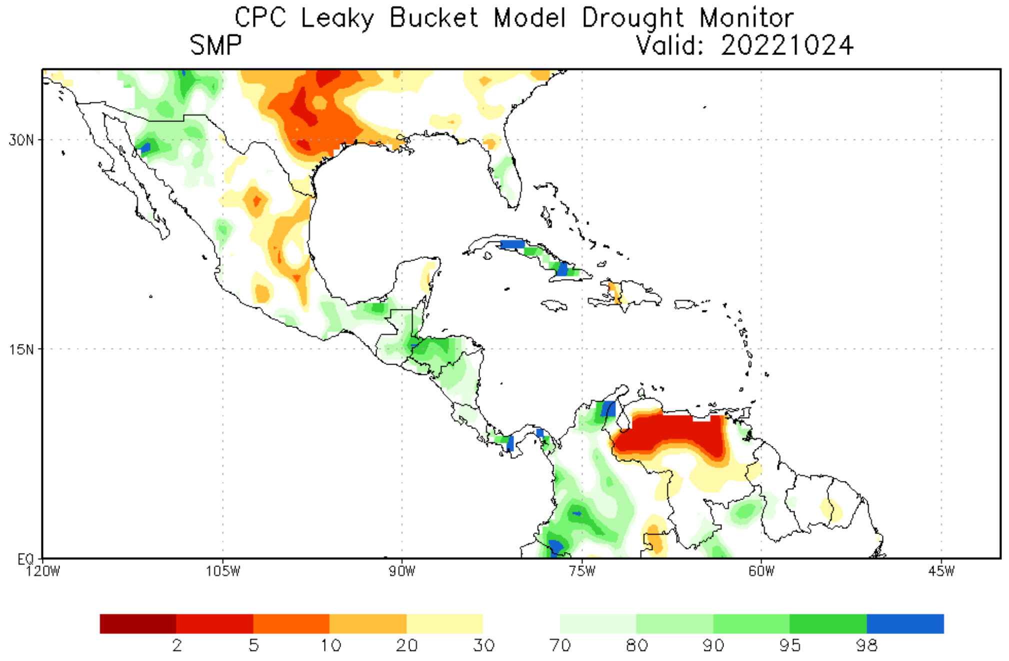
Agricultural Drought

- Main focus future development
- Global Land Data Assimilation System (GLDAS)

from NASA rough 30 days Latency

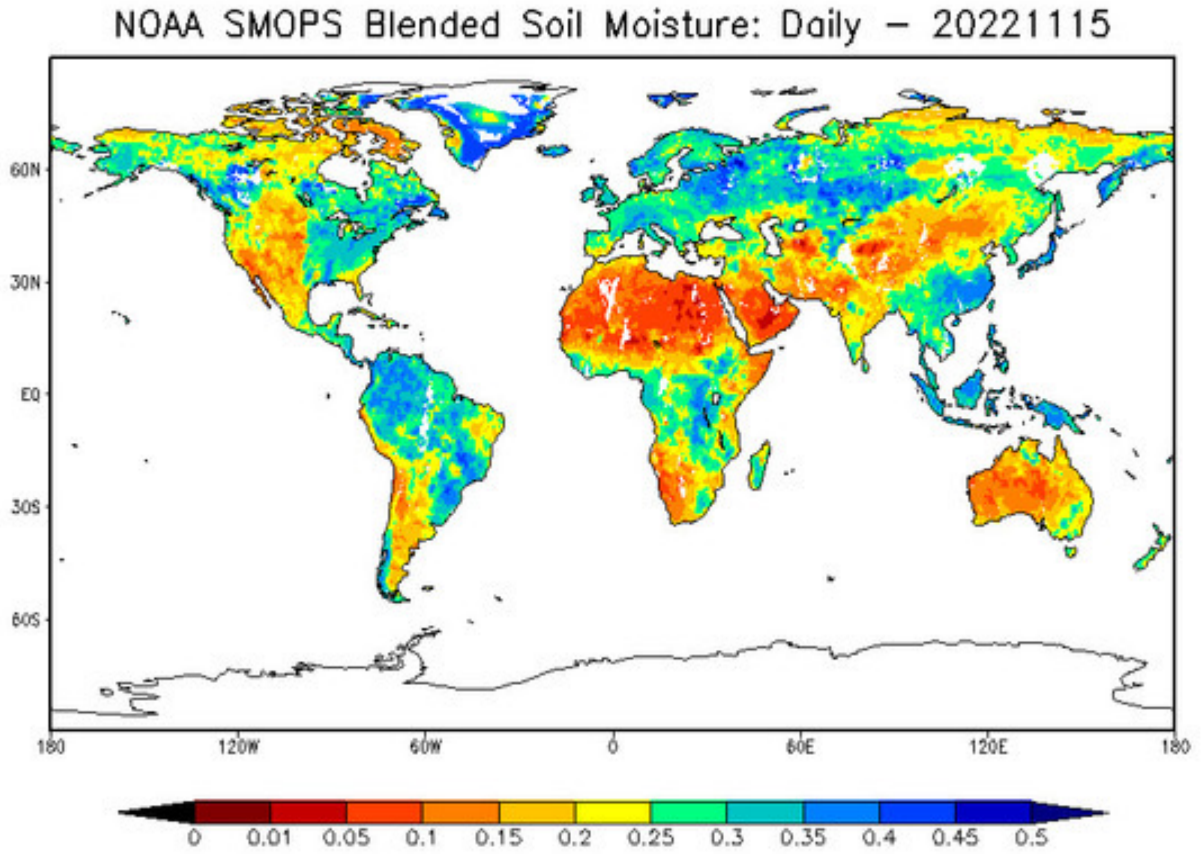
- CPC Leaky bucket model (global 0.5x0.5 analysis)
- UFS land model
    - Recent NCEP/EMC UFS FV3 land model
    - Noah (Prototype 6)
    - NoahMP (HR1)
    - Conventional Observation *Reanalysis* (CORe)
    - New generation CPC Hourly P/T analysis





NOAA NESDIS global topsoil moisture monitor (FY23)

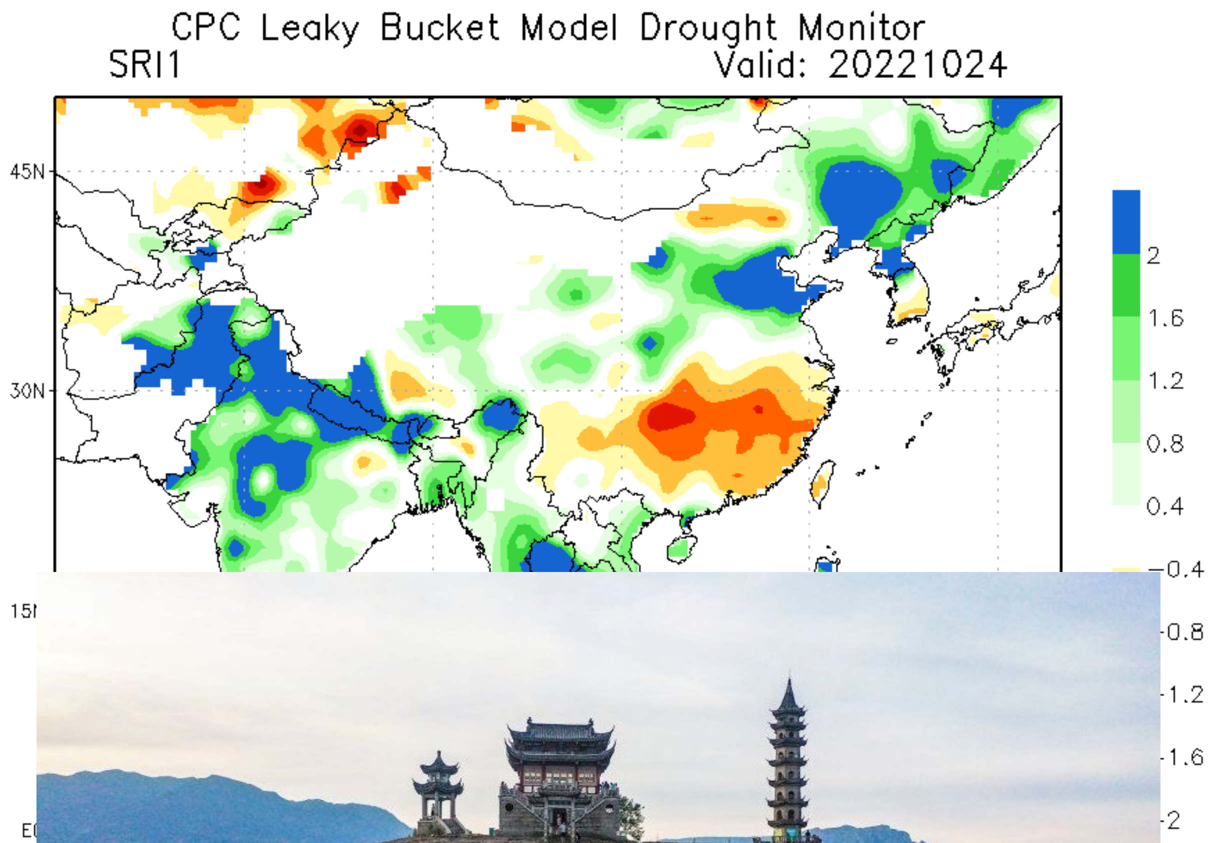
- Topsoil: 5cm depth
- Spatial: Global ¼ degree
- Temporal: daily update
- Data length: 2014- current
- provides a seamless soil moisture map over global land from five satellites, including GPM, SMAP, GCOM-W1, SMOS, and MetOp-B.



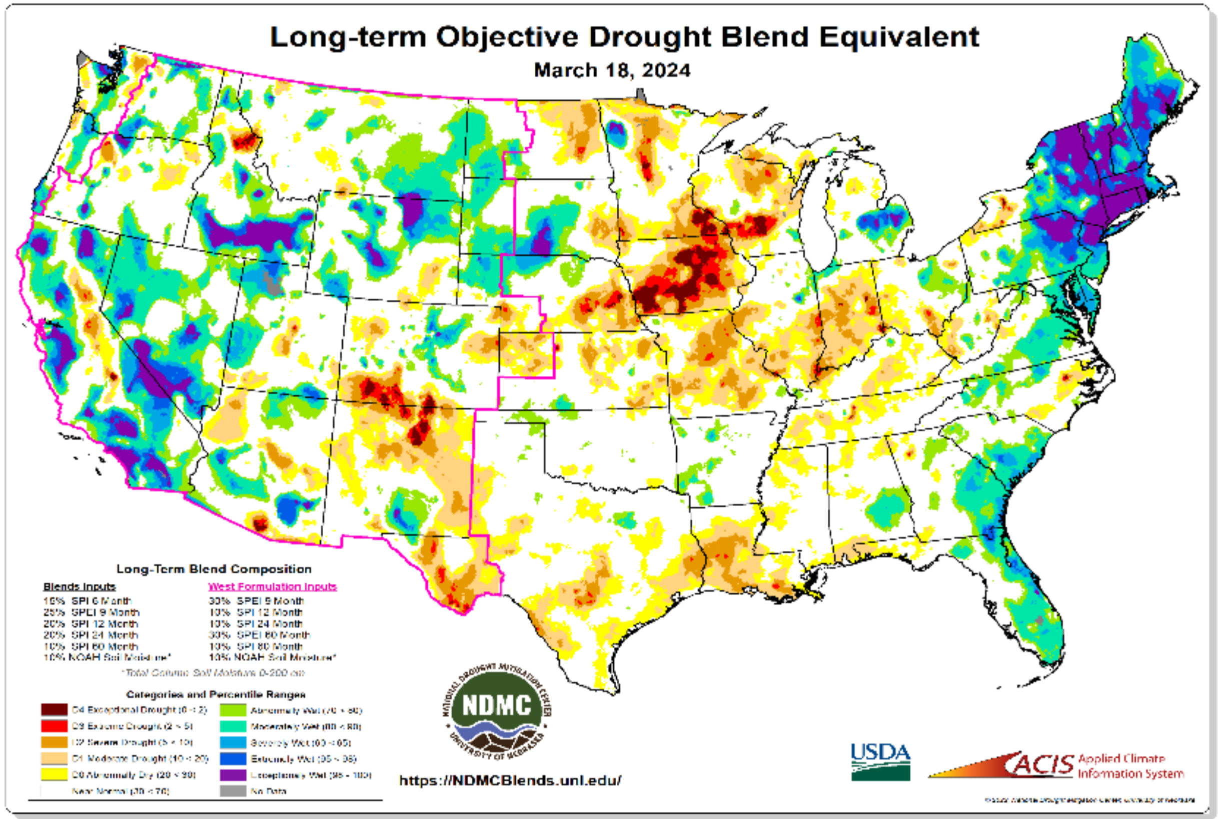
https://www.ospo.noaa.gov/Products/land/smops/figures/SMOPS_ATBD_v4.0.pdf

Hydrological drought

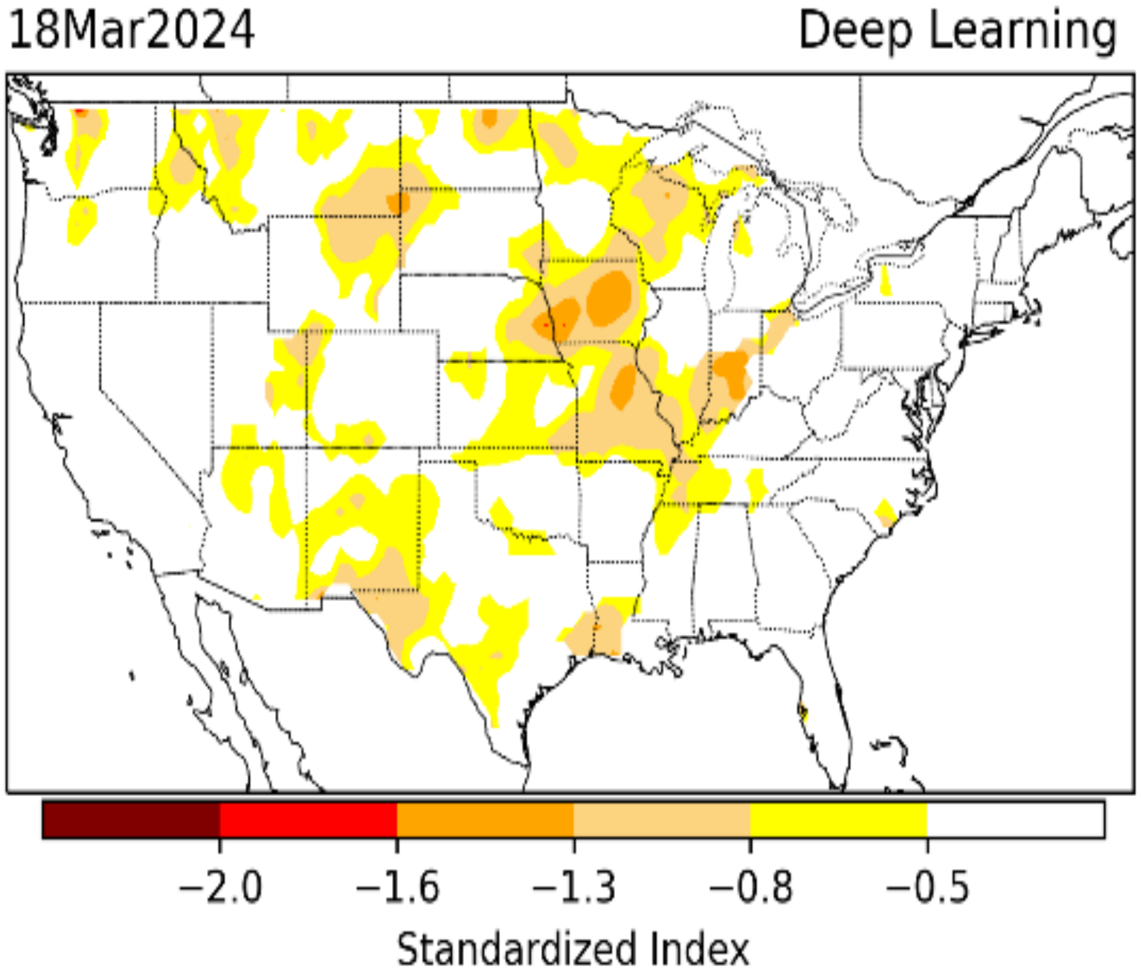
- Weak in drought monitor
- Difficult in real-time global runoff/streamflow data
- runoff estimation from the land surface model



Objective drought integration (blending)

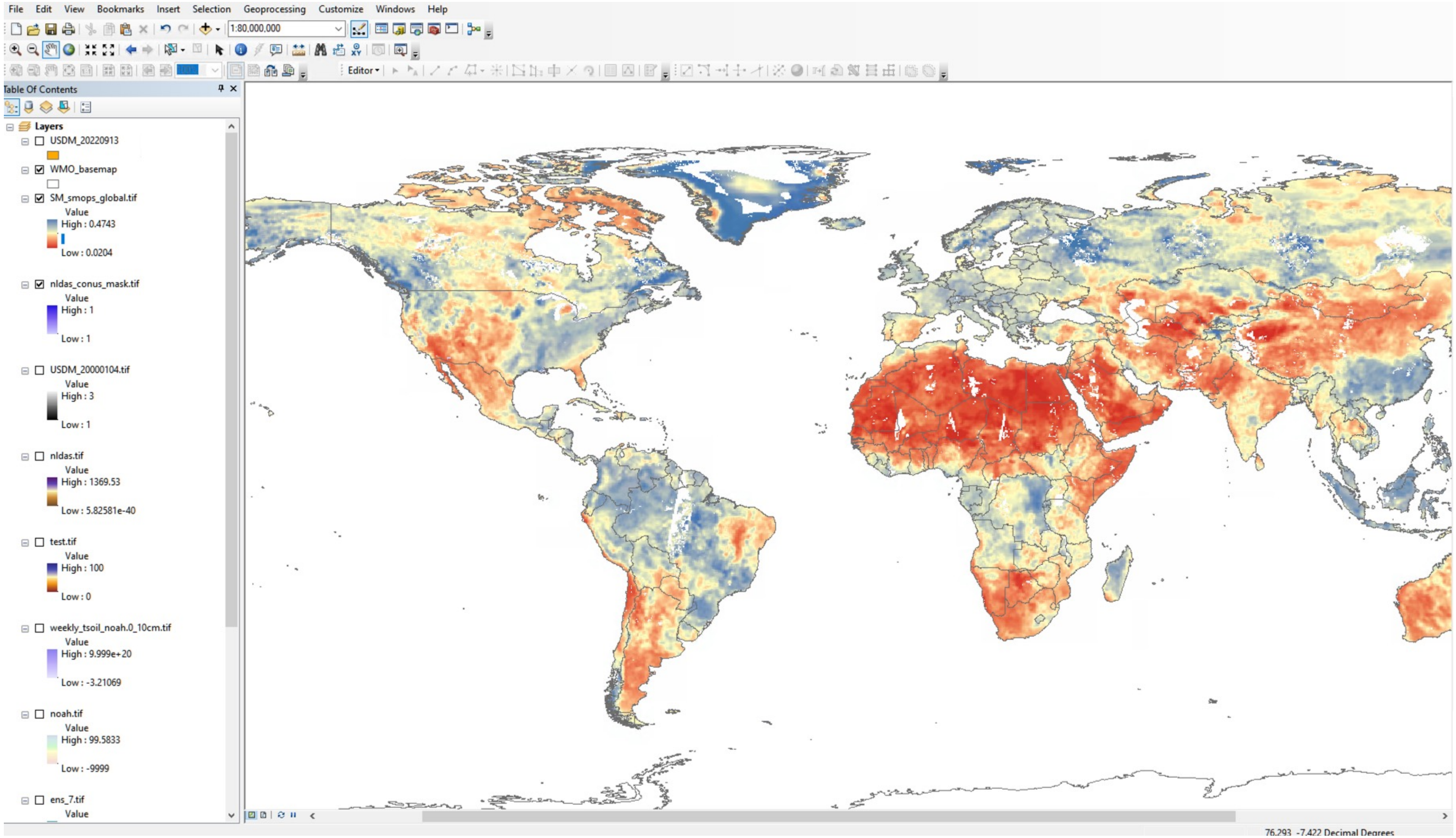


Weight blending



Deep Learning model

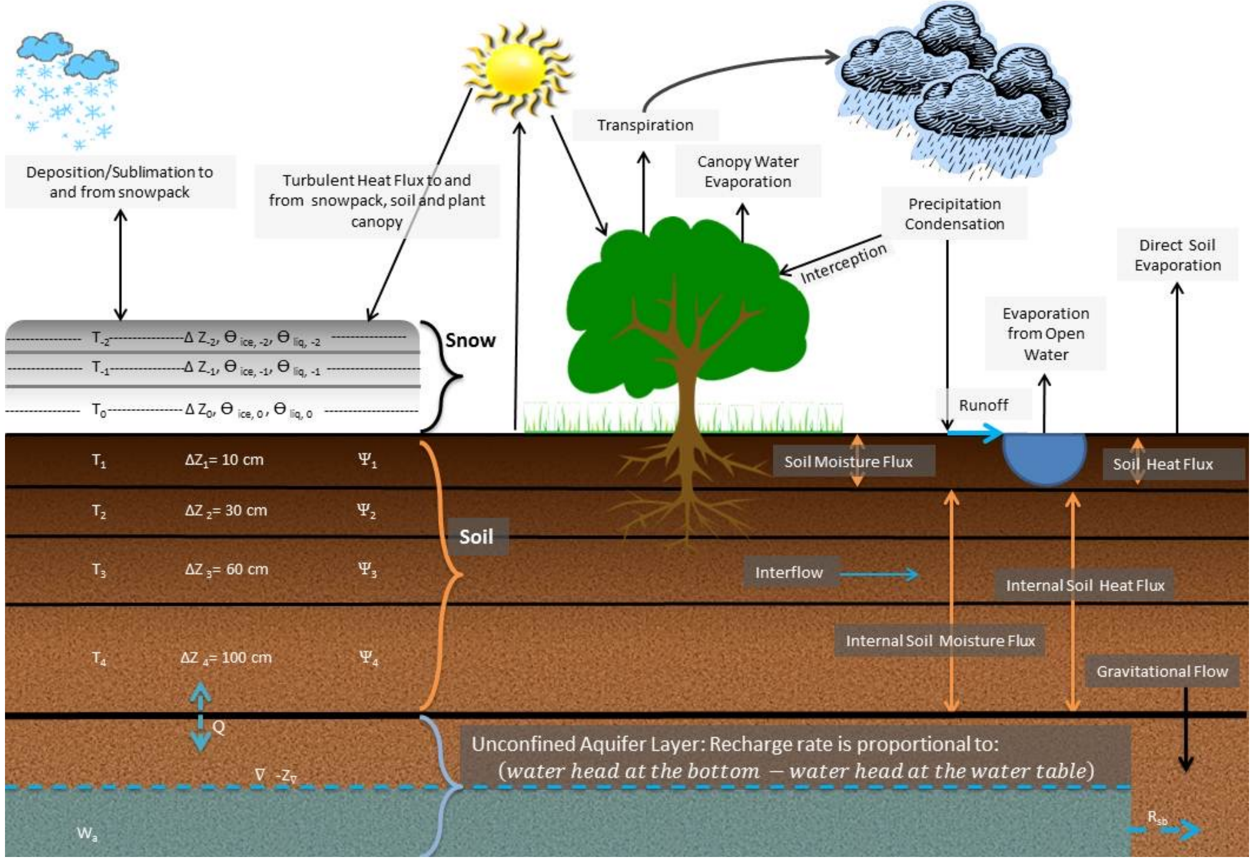
GeoTiff for the GIS users



https://ftp.cpc.ncep.noaa.gov/fews/DroughtMonitor/gis/

Land surface model (LSM)

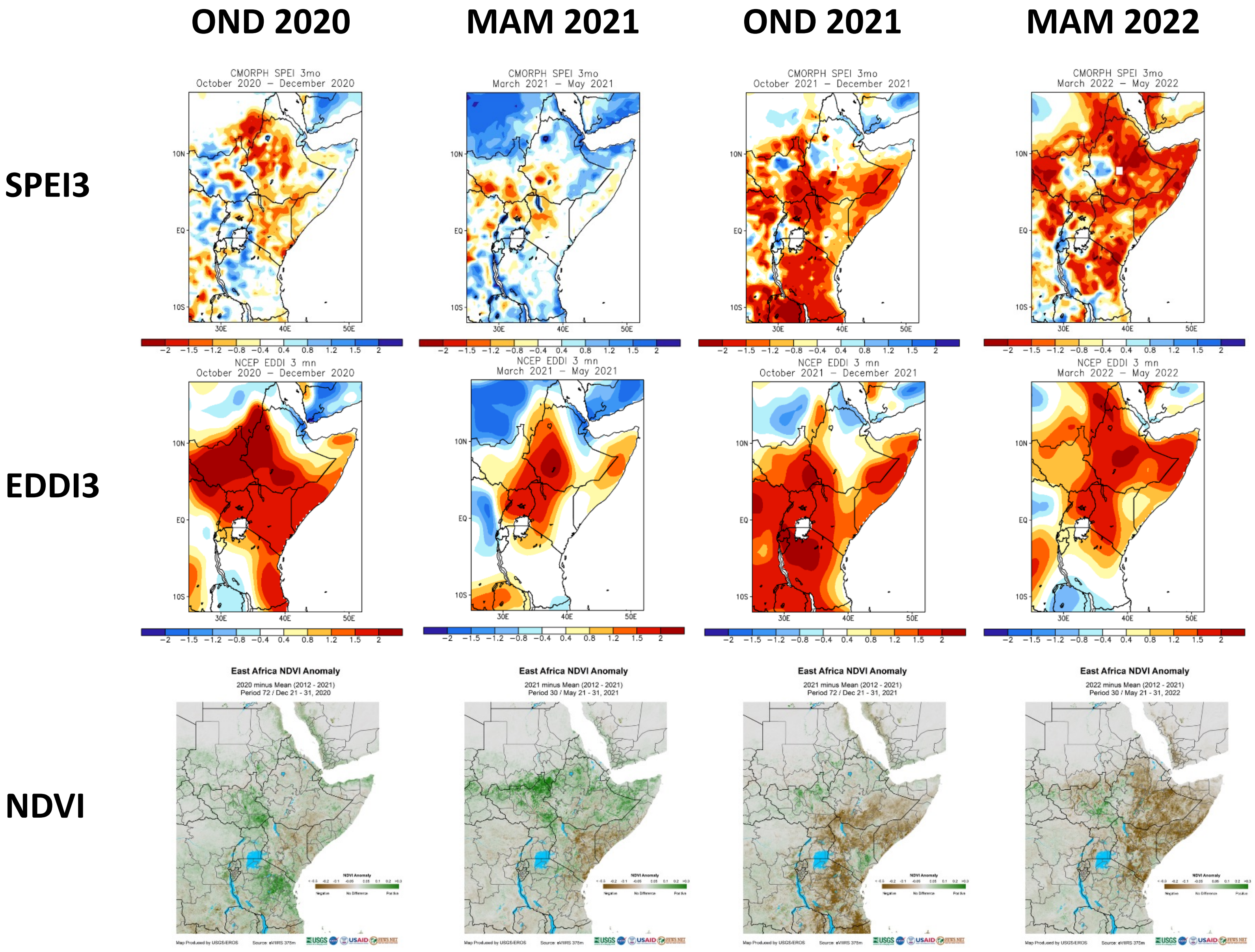
- CPC leaky bucket model (LB)
  - Focus on the water balance
- VIC mesoscale hydrological model
  - Variable infiltration, excellent in runoff fcst
  - Downgrade to water balance mode
- NCEP UFS land model:
  - Noah model
  - NoahMP (HR1 version)
  - Operational model (CCPP package)
  - Full water and energy balances



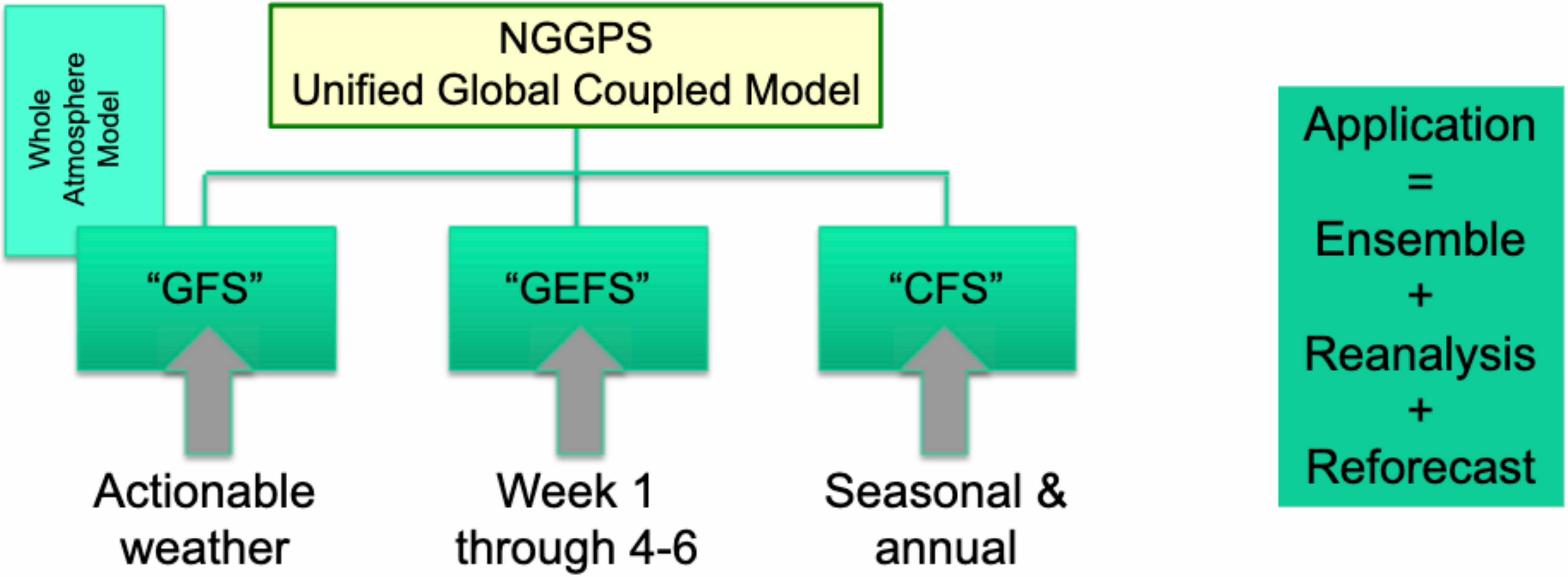
The Greater Horn of Africa Multi-Year Droughts

The Greater Horn of Africa has experienced several consecutive failed seasons in the past few years.

Evapotranspiration related drought indices such as SPEI and EDDI encapsulated the droughts, which led to stressed and degraded vegetation in parts of Kenya, Ethiopia, and Somalia since OND 2020



NOAA Global Ensemble Forecast System (GEFS)



S2S forecast

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

GEFSv12 Updates

	GEFSv11 (PROD)	GEFSv12 (RETRO)
Model	GSM (hydro)	FV3 (non-hydro)
Microphysics	ZHAO-CARR MP	GFDL MP
IC uncertainty	EnKF TC perturbed after relocation	EnKF No relocation
Model uncertainty	STTP	Stochastic physics (SPPT + SKEB)
Resolution	TL574L64 (~33km), 0-8 days TL382L64 (~50km), 8-16 days	C384L64 (~25km)
Forecast days	16 days	16 days (06Z, 12Z and 18Z) 35 days (00Z)
Ensemble size	21 members	31 members
Ocean forcing	Persistent + relaxation SST	NSST and 2-tiered SST

Land:
Noah LSM

GEFSv13:
NoahMP LSM

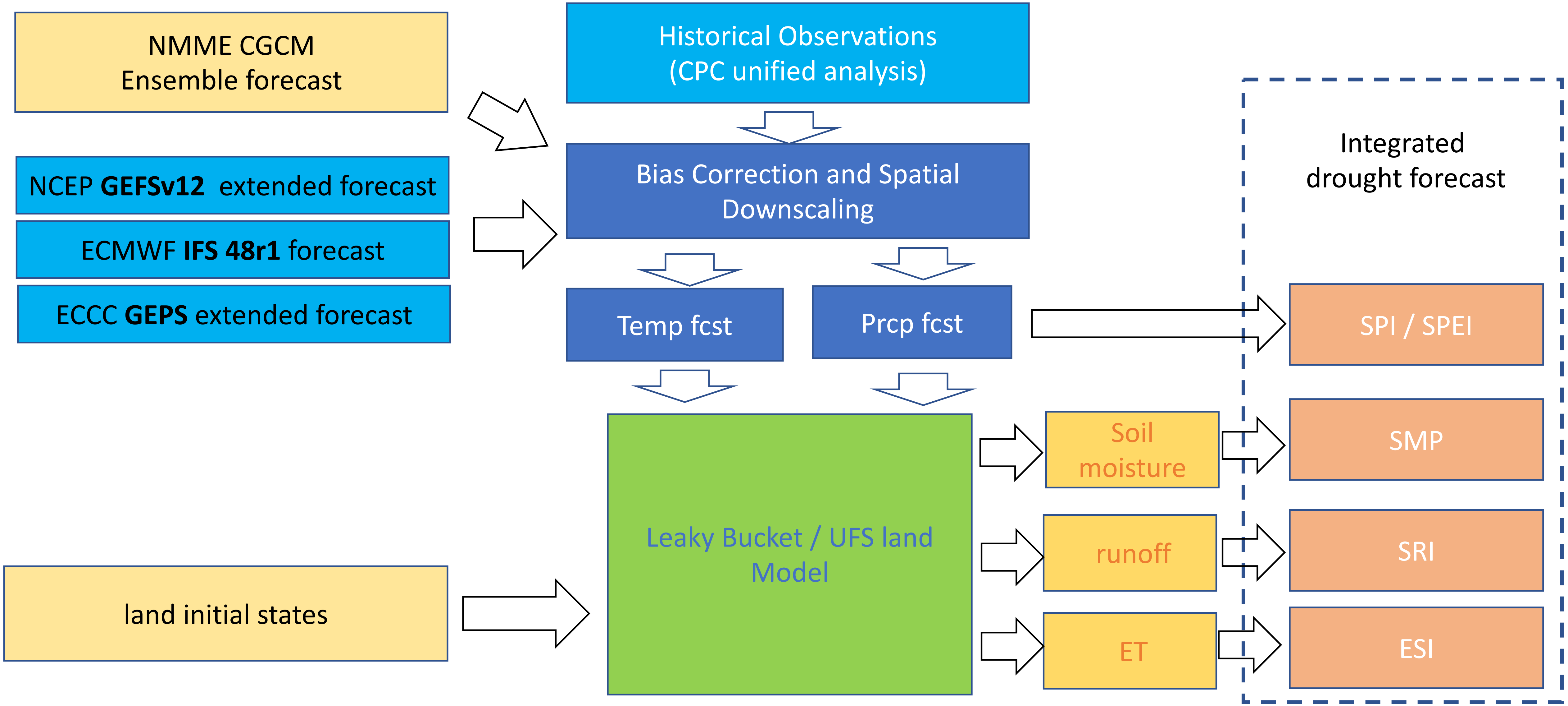
Model	Hindcast Period	No. of Member	Arrangement of Members	Lead (months)	Model Resolution: Atmosphere	Model Resolution: Ocean	Reference
NCEP-CFSv2	1982-2010	24(20)	4 members (0,6,12,18Z) every 5th day	0-9	T126L64	MOM4 L40 0.25 deg Eq	Saha et al. (2010)
GFDL-CM2.1	1982-2010	10	All 1st of the month 0Z	0-11	2x2.5deg L24	MOM4 L50 0.30 deg Eq	Delworth et al. (2006)
CMC1-CanCM3	1981-2010	10	All 1st of the month 0Z	0-11	CanAM3 T63L31	CanOM4 L40 0.94 deg Eq	Merryfield et al. (2012)
CMC2-CanCM4	1981-2010	10	All 1st of the month 0Z	0-11	CanAM4 T63L35	CanOM4 L40 0.94 deg Eq	Merryfield et al. (2012)
NCAR-CCSM3.0	1982-2010	6	All 1st of the month	0-11	T85L26	POP L40 0.3 deg Eq	Kirtman and Min (2009)
NASA-GEOS5	1981-2010	11	4 members every 5th days; 7 members on the last day of the previous month	0-9	1x1.25deg L72	MOM4 L40 1/4 deg at Eq	Rienecker et al. (2008)

Model upgrade and reprocessing :

- NCAR-CCSM4: May 2014
- GFDL-FLOR: March 2014
- NCAR-CESM1: June 2014
- NASA-GEOS5v2 : 2018
- CanCM4i: 2019 June
- GEM5_NEMO: 2019 June
- GFDL-SPEAR: 2021
- NCAR-CCSM4: 2023 re-processing

Currently: CFSv2, NCAR_CCSM4, GFDL_SPEAR, CanCM4i,GEM_NEMO, NASA_GEOS5v2

CPC global drought forecast system



HSS

Verification of SPEI forecast

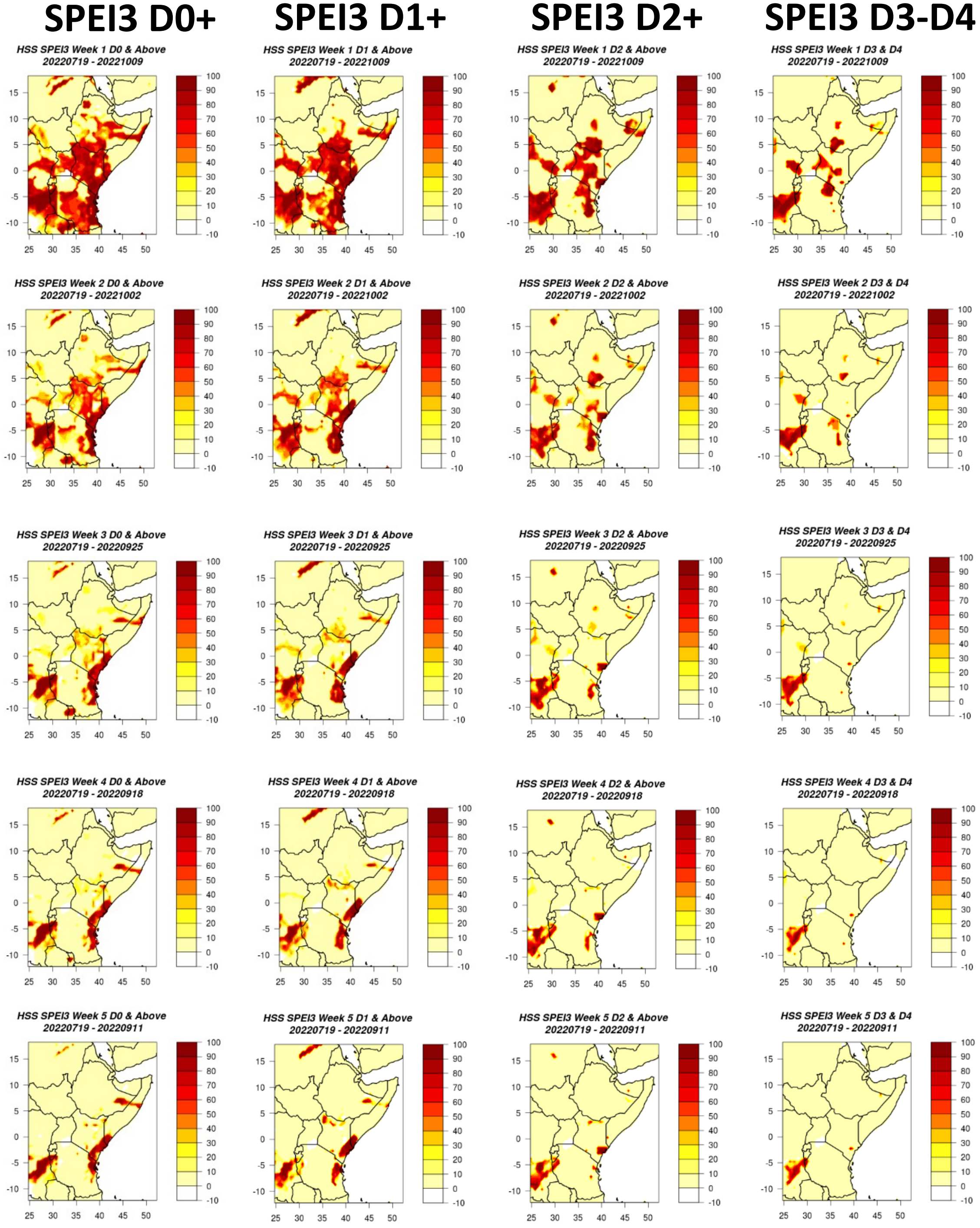
Week 1

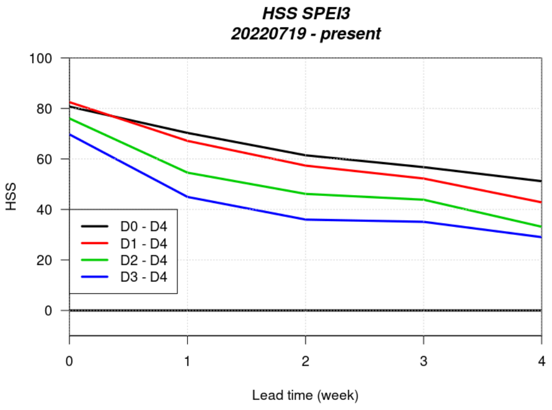
Week 2

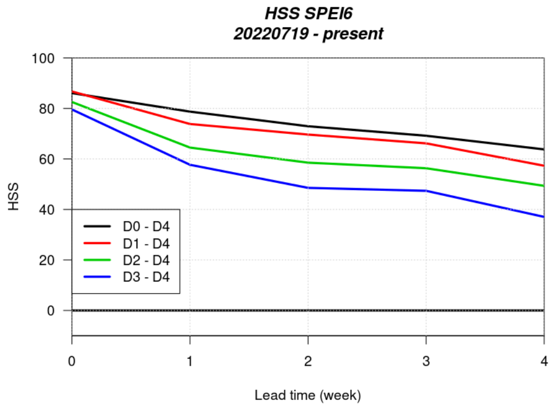
Week 3

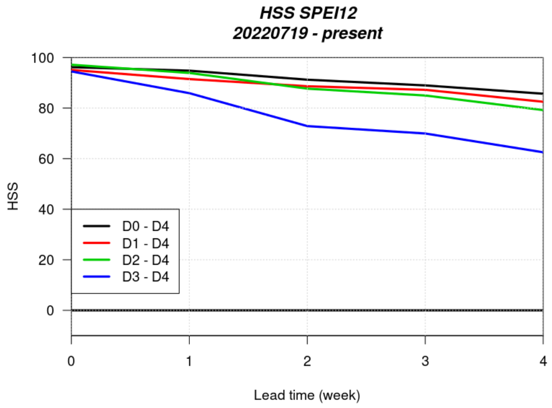
Week 4

Week 5







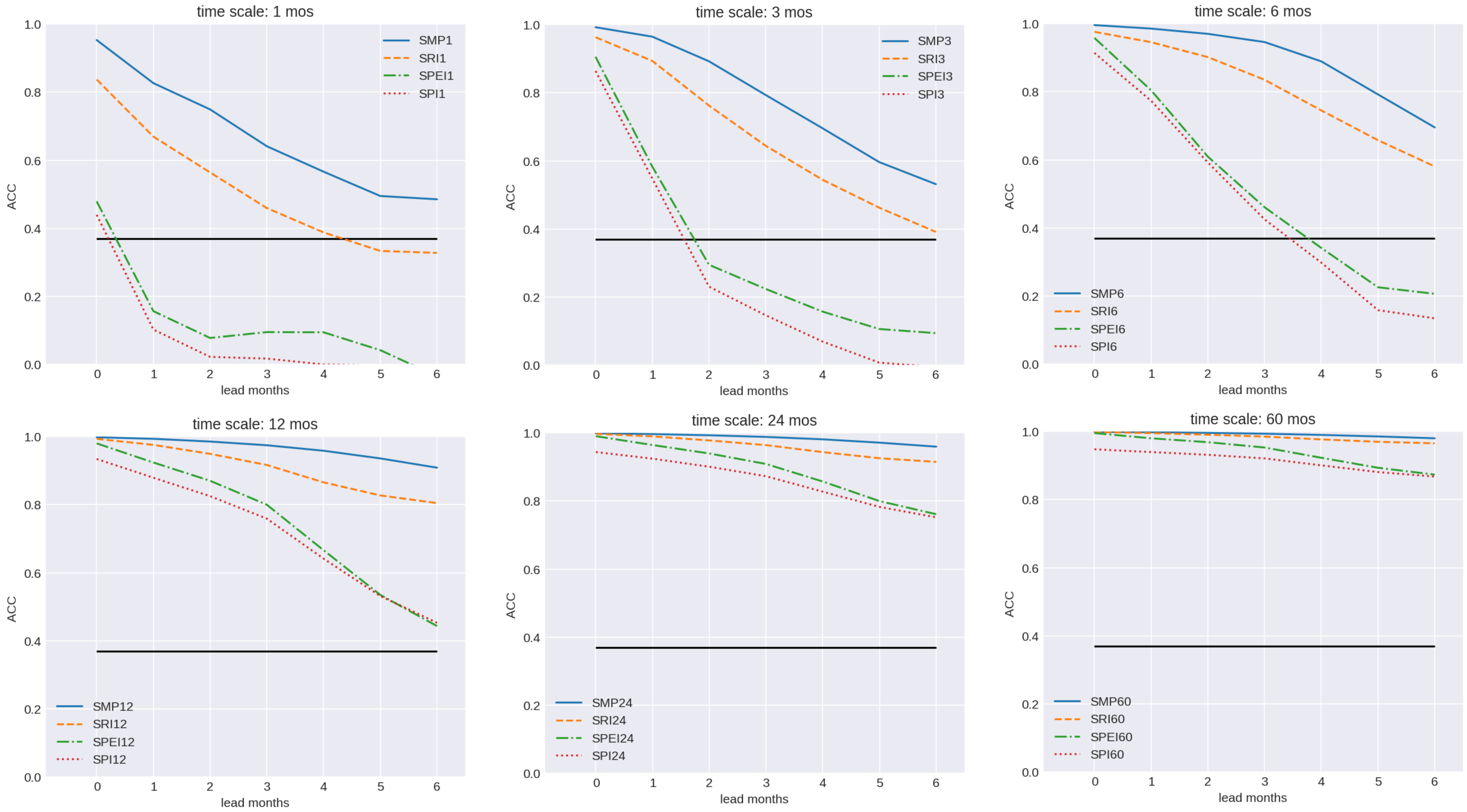


Results showed that the system captured the spatial locations of dryness/drought over the HOA. The forecast skills degraded as a function of lead time and drought category but remained above 40% for D0+ and D1+ for SPEI3 even at 4-week lead time

Lead 0-6 months drought forecast : Jan IC for 1991-2020 CONUS mean ACC

Short-term drought

Long-term drought



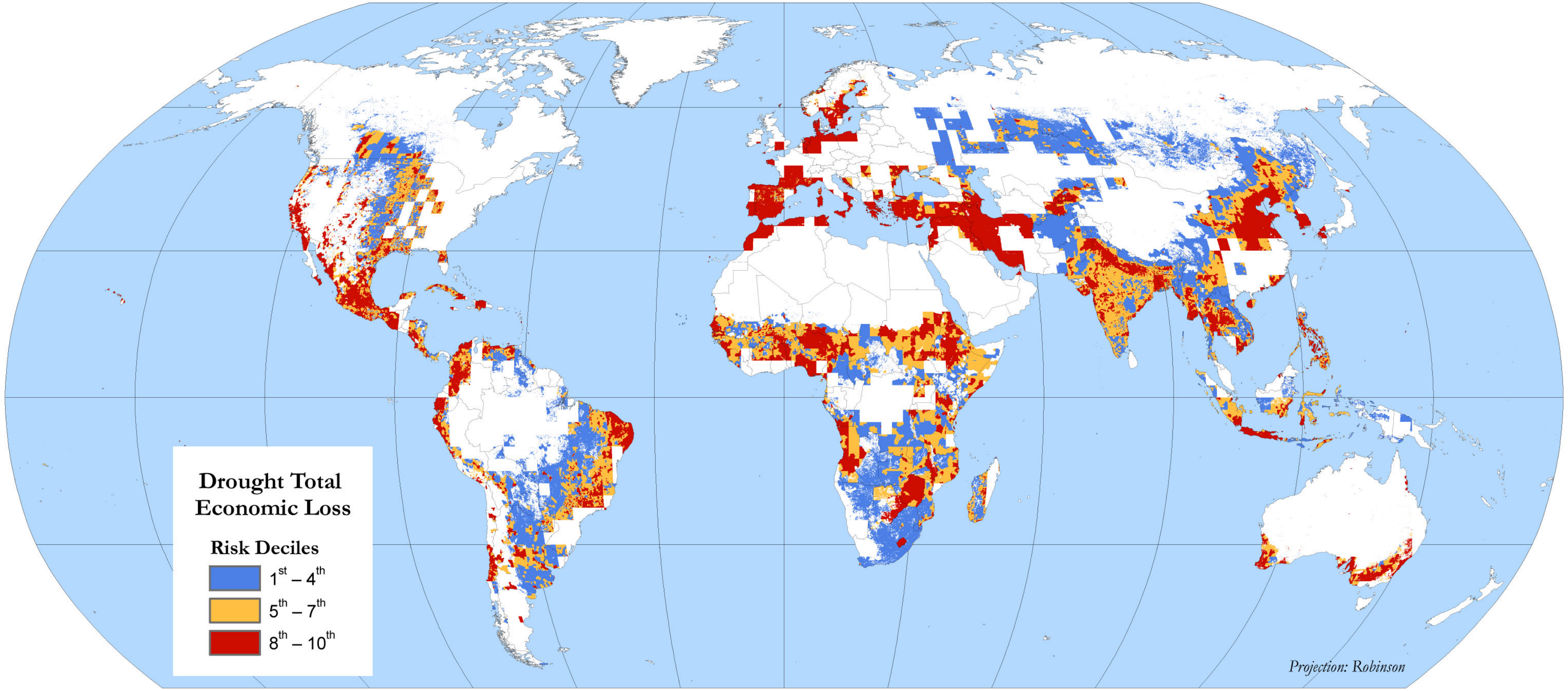
Skills of S2S prediction: SMP > SRI > SPEI > SPI

Table 5.1—Sectors affected by drought

TYPE OF EFFECT	SECTOR OR ASPECT AFFECTED	MECHANISM	EFFECTS
Direct	Streams	Less rainfall for sustaining streamflow	Less streamflow and groundwater recharge, more conflict over water use
Indirect	Stream habitat	Higher stream temperatures, less connectivity, threatened stream fauna	Higher management cost for species identified as threatened or endangered; potential loss of species
Indirect	Wildfire management	More wildfire activity	Spread of fire-adapted, often fire-promoting, invasive grasses and shrubs; forest degradation and species loss
Indirect	Invasive species management	Dry conditions favor invasive species that out-compete native species	Higher management cost for species identified as threatened or endangered; potential loss of species
Indirect	Pest and disease management	More pest and disease activity	Native plants vulnerable to infestation and mortality
Direct	Agriculture—farming	Less soil moisture	Crop-yield losses in rain-fed systems
Indirect	Agriculture—ranching	Reduced growth of vegetation (forage) needed by livestock	Lower livestock production, higher livestock prices
Direct	Drinking water	Less rainfall (supplying water to reservoirs, catchments, and groundwater recharge), higher water demand	Water shortages for water catchment users; voluntary water reductions
Indirect	Nearshore habitats	Wildfires expose soils to rain, increasing erosion and sediment delivery to nearshore areas	Sediment exacerbates other climate-driven stressors for nearshore reefs, e.g., warming that can cause coral bleaching and ocean acidification
Direct	Traditional cultural practices	Less rainfall and streamflow reduce available water (stream) for domestic uses and irrigation; less groundwater discharge to nearshore fishpond environment	Lower yields of traditional food sources (e.g., taro, breadfruit); lower aquaculture yields in native fishponds; negative impacts to other ceremonial and medicinal plant species
Direct	Threatened and endangered species	Lack of water	Death of endangered nēnē goslings (Hawaiian goose, *Branta sandvicensis*), and endangered plants (seedlings and adults)

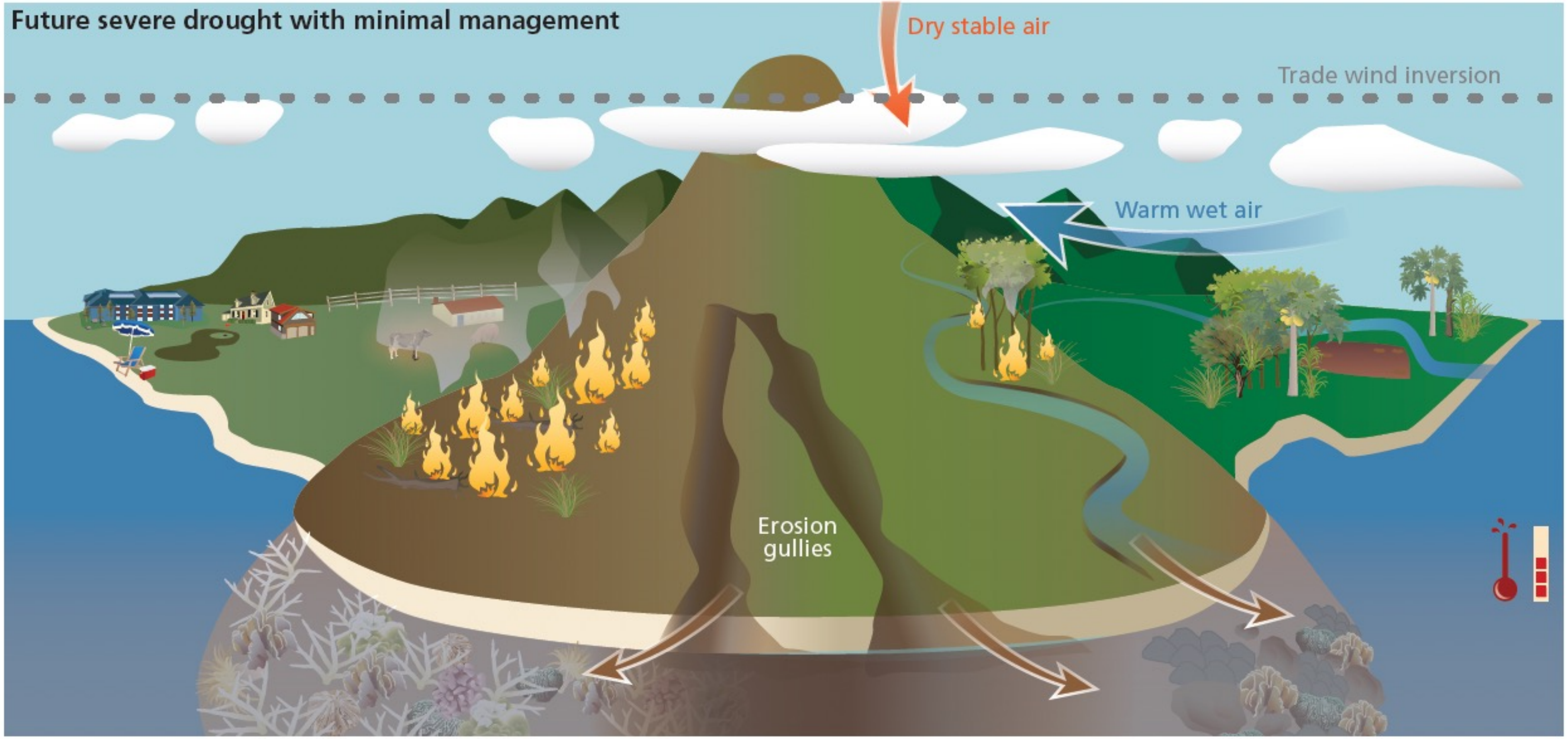
Table Source: Frazier et al. 2019

Global Drought Total Economic Loss Risk Distribution



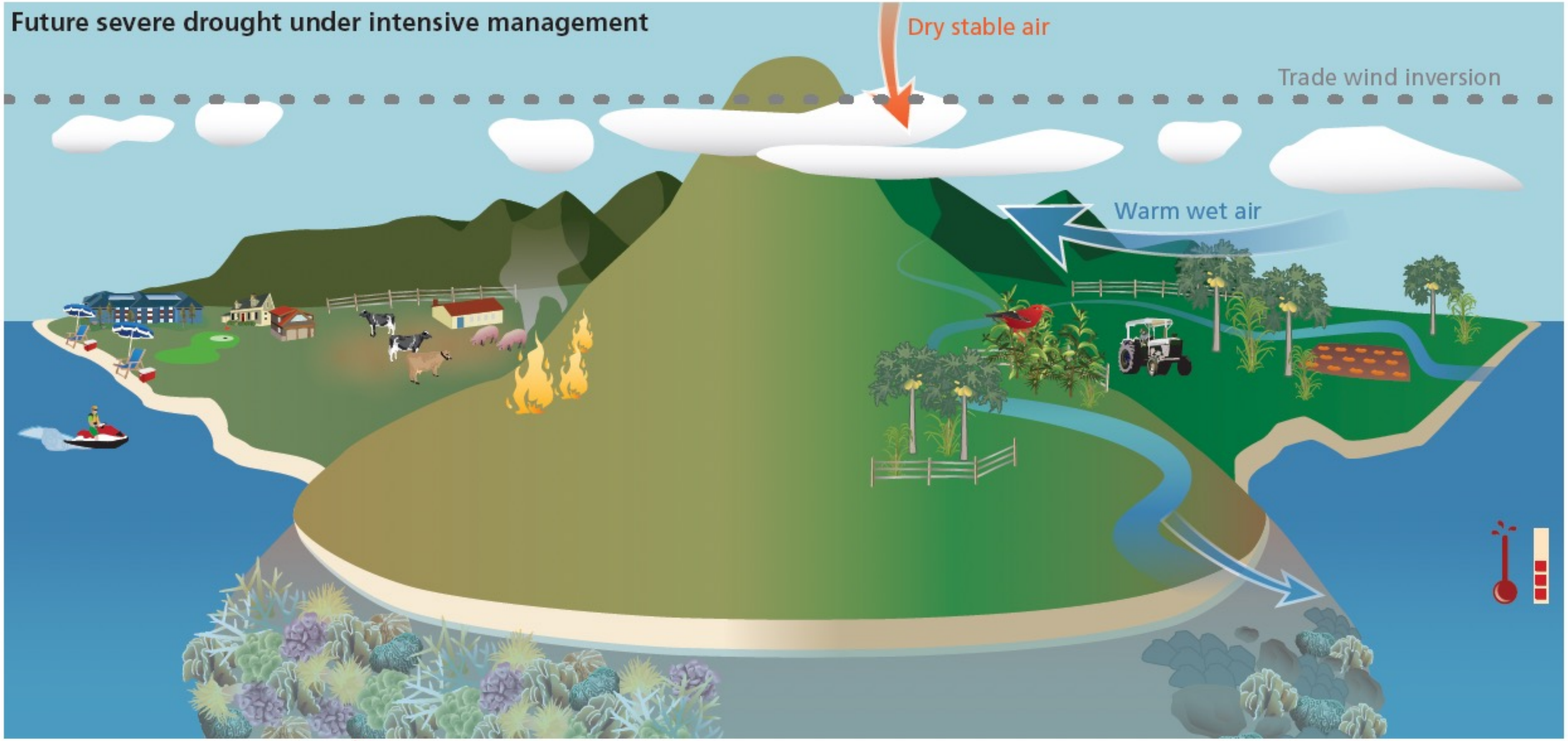
Total Economic Loss is found by weighting the value of GDP exposure to drought for each grid cell by a vulnerability coefficient to obtain an estimate of risk. The vulnerability weights are based on historical economic losses in previous disasters. The economic loss risks are applied to GDP per unit area exposure to obtain economic loss risks. The weights are an aggregate index relative to losses within each region and country wealth class (classifications based on 2000 GDP) over the 20-year period from 1981 – 2000.

Source:
Dilley, Maxx, Robert S. Chen, Uwe Deichmann, Arthur L. Lerner-Lam, and Margaret Arnold. 2005. *Natural Disaster Hotspots: A Global Risk Analysis*. Washington, D.C.: World Bank.



Under severe drought, freshwater availability for ecosystems and drinking water is reduced. Reduced surface water, and resulting declines in groundwater recharge also negatively impacts agriculture and ranching. Warmer and drier conditions often favor invasive plant species which typically use more water, and in leeward areas, increase the risk of wildfire. Expanding invasive species cover increases areas where native species regeneration is prevented by competing invaders. These degraded native forests are less able to support the rich flora and fauna that depend on intact forests systems. Increased fire danger and the expansion of wildland-urban inferfaces, typically in leeward areas, reduces the attractiveness of these areas for residences or as destinations for tourists. Even wet, windward areas become susceptible to wildfire without effective management, education, and outreach. Drought and wildfire increase erosion and sediment delivery to streams and nearshore areas. For nearshore reefs, erosion and sedimentation exacerbate other coral reef stressors including warming, which can cause coral bleaching and ocean acidification.

source: 2017 Pacific Islands Climate Adaptation Science Center Newsletter https://pi-casc.soest.hawaii.edu/wp-content/uploads/2021/01/Pacific-Islands-CSC-Drought-Newsletter.pdf



Mitigating the effects of warming and drying requires research and careful application of innovative methods. Reducing the cover of invasive species through physical, chemical, and biological methods enhances resiliency by reducing competition, allowing native species to regenerate and thrive. This practice can also indirectly work to prevent and reduce the spread of wildfires. There is a strong link between drought and El Niño events which provides some advanced warning for managers and researchers to prepare and perform outreach activities. Intensive wildfire management can help protect infrastructure and reduce erosion and sediment delivery to nearshore areas, and proactive water resource management can help increased surface water availability for agriculture and ranching.

source: 2017 Pacific Islands Climate Adaptation Science Center Newsletter https://pi-casc.soest.hawaii.edu/wp-content/uploads/2021/01/Pacific-Islands-CSC-Drought-Newsletter.pdf

References

- SPI, Standardized Precipitation Index, utilizing both gamma and Pearson Type III distributions
- SPEI, Standardized Precipitation Evapotranspiration Index, utilizing both gamma and Pearson Type III distributions
- PET, Potential Evapotranspiration, utilizing either Thornthwaite or Hargreaves equations
- PNP, Percentage of Normal Precipitation
- PDSI, Palmer Drought Severity Index
- scPDSI, Self-calibrated Palmer Drought Severity Index
- PHDI, Palmer Hydrological Drought Index
- Z-Index, Palmer moisture anomaly index (Z-index)
- PMDI, Palmer Modified Drought Index